Sustainable Feedstocks for Advanced Biofuels

Sustainable Alternative Fuel Feedstock Opportunities, Challenges and Roadmaps for Six U.S. Regions

Proceedings of the Sustainable Feedstocks for Advance Biofuels Workshop

SOIL AND WATER CONSERVATION SOCIETY®

Edited by Ross Braun, Doug Karlen, & Dewayne Johnson

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Introduction

Thank you for being interested in one of the most overlooked aspects of the emerging biofuels industry – sustainable feedstock supplies. The seeds for this workshop were planted more than four years ago, shortly after the U.S. Department of Energy (DOE) - USDA "Billion Ton Report" rekindled biofuels research and development efforts around the world. Leadership within the Soil and Water Conservation Society (SWCS) began to ask what we, as a professional society focused on soil and water conservation, should do that would be different from the myriad of activities being sponsored to support this emerging industry. Slowly it became evident that most bioenergy conferences and workshops were focused on conversion technology options and implicitly assumed that if a facility were built, the feedstock would automatically appear. From a soil and water conservation perspective, we didn't believe that was appropriate, so a plan was initiated to develop a different type of workshop that focused primarily on the sustainability of feedstock supplies. With the support of the USDA- Agricultural Research Service (ARS), DOE Energy Efficiency and Renewable Energy (EERE), Monsanto, Sun Grant Initiative, International Plant Nutrition Institute (IPNI), Ernst Seed, USDA- Natural Resources Conservation Service (NRCS), and the SWCS, the workshop and proceedings became a reality.

The workshop goal was to create a directed, outcome- based product in the form of regionally specific Roadmaps for sustainable feedstock production and delivery. The goal for the Roadmaps was to provide science- based strategies that would enable agriculture, in its broadest sense, to help solve our nation's bioenergy challenges. To do so, it is imperative that we come as close as possible to achieve the feedstock supplies projected by the joint DOE- USDA Billion Ton Report. The National Academy of Sciences (NAS) "Liquid Transportation Fuels from Coal and Biomass" report identified more than 500 million tons of readily available feedstock. Participants preparing the workshop Roadmaps were challenged to identify the best management strategies to produce and deliver the remaining 500 million tons to centralized, distributed, or other types of processing facilities. The SWCS agreed to lead this endeavor because to be sustainable, feedstock must be obtained in ways that protect soil, water, and air resources, while also sustaining or improving all conditions for producers, local communities, wildlife, and other ecosystem services. To do so, well- conceived Roadmaps were needed to help guide feedstock harvest, storage and transport for the next 20 years.

Thanks to the efforts of an excellent planning team, the core workshop program consisted of a series of invited presentations that provided both a national perspective and regional strategies that recognize differences, benefits, challenges, and subtleties within and between regions of the United States. Each presentation was the basis for a chapter in this Proceedings. An additional chapter was added after the regional breakout teams pointed out that sorghum was a potential feedstock that had not been adequately covered in the presentations. The final section consists of the regional roadmaps prepared by break- out groups who addressed the specific needs for six geographic regions throughout the U.S. and into Canada. These Roadmaps, each reflecting the presentation style chosen by the group, are the core strength and primary outcome of this workshop. On behalf of myself and the rest of the planning team, we want to thank everyone who helped make this workshop a useful and effective planning process.

Douglas L. Karlen, Co- Chair

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Chapter 1

Sustainable Feedstocks for Advanced Biofuels

Landscape Management and Sustainable Feedstock Production: Enhancing Net Regional Primary Production while Minimizing Externalities

Richard Lowrance [1]*, William Anderson[2], Fernando Miguez[3], Timothy Strickland[1], Joseph Knoll[2], and Thomas Sauer[4]

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Introduction

The U.S. federal government and numerous states have adopted standards that require various levels of renewable energy supplies, generally within the next 10-20 years. The Federal Energy Independence and Security Act of 2007 (EISA) requires the production of 136 billion liters of liquid biofuels by 2022 with 79 billion liters from feedstock other than corn starch and at least 61 billion liters from lignocellulosic feedstocks (Sissine, 2007). Renewable Electricity Standards or Renewable Portfolio Standards have been adopted by up to 30 states and the District of Columbia although no federal standard currently exists for renewable electricity. National and state plans to meet these Renewable Portfolio Standards will depend heavily on bioenergy feedstocks, especially for the production of liquid transportation fuels. Although current liquid biofuels are almost exclusively corn starch based ethanol, future liquid biofuels will depend heavily on both sugar and lignocellulosic feedstocks in new conversion technologies that produce "drop-in" biofuels that directly replace gasoline, diesel, and jet fuel and thus can use the existing transportation fuel infrastructure. Conversion technologies such as Virent's BioForming® Technology using aqueous phase reforming (Blommel et al. 2008) and multiple catalyzed reactors to produce non-oxygenated biofuels (Kunkes et al., 2008) will make use of both lignocellulose and simple sugars. Thus, feedstock production systems that produce feedstock materials ranging from sugar solutions to dried biomass will be useful in various types of "drop-in" biofuels production plants.

Reaching these national and state goals will require production of unprecedented amounts of biomass for energy. The "Billion Ton Feedstock Report" (USDA and USDOE, 2005) lays out a plan for this that includes using forestry waste, crop residues, grain crops, dedicated bioenergy feedstock crops, and animal waste to produce a billion or more tons of feedstock. Recent policy discussions have stressed the need to use feedstocks from numerous sources including perennial crops grown on marginal lands, crop residues, sustainably harvested wood and forest residues, double crops and mixed cropping systems, and municipal, industrial, and agricultural wastes (Tilman et al., 2009). From a purely agronomic perspective, dedicated bioenergy feedstocks can be grown on a wide variety of lands including land already in production for food and forest products and land that has been taken out of production for various reasons (Evans et al., 2010). However, it is increasingly recognized that careful research is needed to ensure the development and adoption of regional cropping systems that maximize feedstock productivity without posing unreasonable risks to the environment and human well-being.

Because of the relatively low energy content of biofuel feedstocks, they will necessarily be grown within a short distance of bioconversion plants. This means that the location of a biofuels conversion plant can have a large impact on the land use within a limited distance from the plant. In order to minimize the loss of existing agricultural production in these areas there is interest in growing feedstock on marginal, abandoned, and under-used cropland with minimal land use change in the existing cropland (Regalbuto, 2010, USDA and USDOE, 2005). The potential for feedstock production on marginal lands has been estimated globally based on the extent of abandoned agricultural land and could supply about 8% of current primary energy demand globally (Campbell et al., 2008). *"Raising bioenergy crops on agriculturally degraded and abandoned lands is emerging as a sustainable approach to bioenergy that provides environmental benefits and climate change mitigation without creating food-fuel competition or releasing the carbon stored in forests"* (Campbell et al., 2008).

In this paper, we will examine the change in land use for feedstock production from a landscape perspective. We will discuss attributes of agricultural landscapes and how knowledge of net primary productivity in natural and managed systems can guide the placement of feedstock production among different parts of the country and within a region, landscape, and watershed. Finally, we will discuss what is known about the potential effects of feedstock production choices on landscape and watershed scale processes and the need for conservation practices which enhance environmental sustainability at these larger scales.

Agricultural Ecosystems and Landscapes

An ecosystem is any area in nature where living organisms interact with the abiotic environment to produce an exchange of materials between the living and nonliving parts (Odum, 1953). At a different level of organization, "a landscape is a heterogeneous land area comprised of a cluster of interacting ecosystems that is repeated in similar form throughout" (Forman and Godron , 1986). The concept of landscape thus focuses on groups of ecosystems and the interactions among those ecosystems. A landscape is a non-random mosaic of interacting elements (and associated networks) over kilometer wide areas (Baudry, 1989). Networks are features such as streams, fence lines, hedgerows, and roads which can form either corridors or barriers for transfers among ecosystems. Both the elements and associated networks can be ecosystems or not, depending on the setting. In "natural" landscapes all elements and networks would be ecosystems or ecotones, the boundary between ecosystems. In human dominated landscapes, such as agricultural landscapes, the elements and networks may be ecosystems (forests, fields, streams) or not (fertilizer plants, feed mills, roads). According to Troll, 1968, (cited in Ryszkowski, 2002) the landscape can be studied in terms of its morphology, classification, and changes in time (history) as well as the functional relationships between its components which Troll (1968) called Landscape Ecology. In agricultural landscapes both the internal dynamics in ecosystems and the interactions of the ecosystems in the landscape are largely determined by technological factors (crops, domestic animals, fertilizer, tillage) interacting with weather, hydrology and edaphic conditions. Many internal attributes of ecosystems can be affected by the exchanges with other ecosystems and in the case of agricultural landscapes the rates and magnitudes of these exchanges are generally regulated by management practices. Interactions among individual fields within a farmstead have to be considered as interactions among landscape elements as do interactions between agroecosystems and non-agroecosystems that are part of the landscape. These interactions are exchanges of energy, matter, plant propagules, insects, vertebrates, etc. (Baudry, 1989). Perhaps the most overlooked attributes of agricultural landscapes are the human resources and the infrastructure support system for modern agriculture which are essential parts of agricultural landscapes.

Nationwide, there are over 373 M ha in farms (USDA, 2007). Of this total, 164 M ha (44%) are cropland (USDA, 2007). Harvested cropland is only 125.3 M ha. As of April 2010, 12.7 M ha of land remained in the USDA Conservation Reserve Program (CRP) after reaching a peak of 14.9 M ha in Fiscal Year 2007 (USDA-FSA, 2010). These figures indicate that in 2007 there was a total of at least 23.8 M ha of cropland that was not harvested and not in CRP. The totals are not known for 2010 but if the land that came out of CRP (2.2 M ha) is not back in row crop production then as much as 26 M ha of cropland will not be harvested in 2010, which includes CRP land and the rest of the marginal, abandoned, and under-used land that has not been put into perennial vegetation and is still included under the cropland base of a farm. This 24-26 M ha of land is critical in the effort to provide sustainable production of biofuels without undue impacts on the current crop production capability. If agriculture is going to meet the feedstock goals implicit in the EISA and meet the next round of bioenergy production goals, there will be large scale changes in farmland use in agricultural areas of the country. Just to provide some notion of the scope of these changes, it is likely that these changes in land use will be equal to or greater than the changes experienced in the past 25 years of the USDA Conservation Reserve Program, which at its peak had approximately 10% of the cropland in the country enrolled in the program (Figure 1).

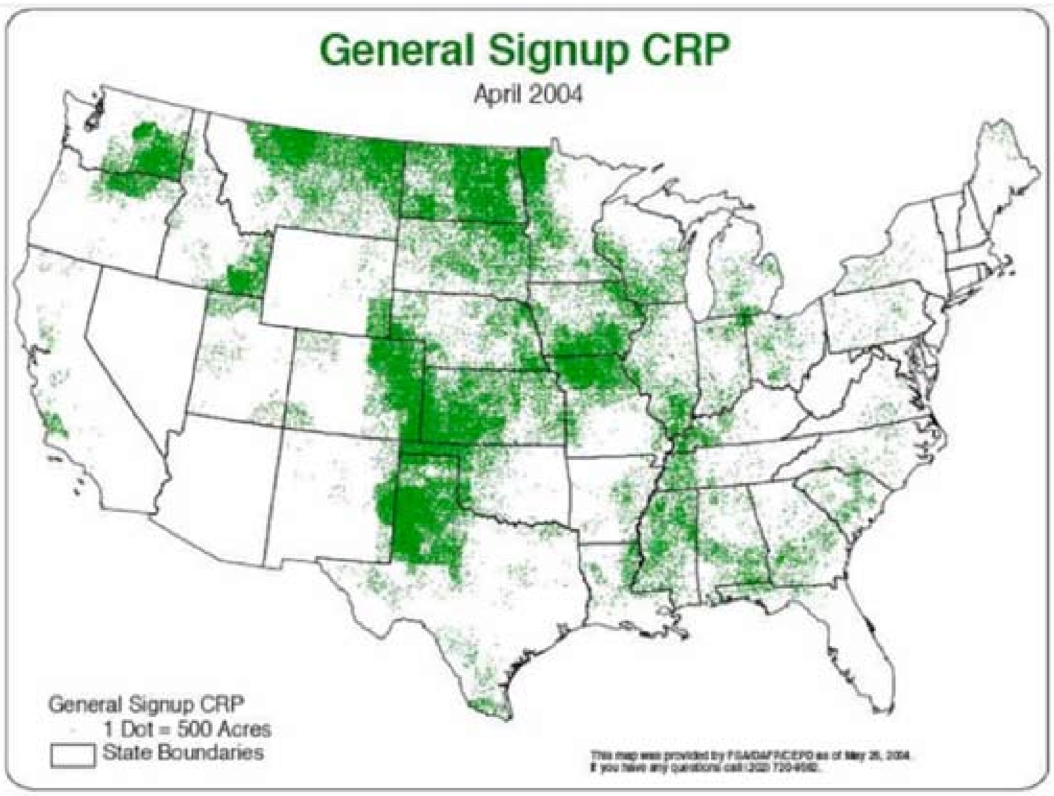

Figure 1. Distribution of Conservation Reserve Lands.

The key difference is that during the 10-15 year period that the CRP land was put in place, land was coming out of production based on USDA incentives, while current government incentives provide the opposite pressure, i.e. to bring marginal land back into production. Intensifying land use on this scale may require the development and implementation of conservation practices targeted to bioenergy crops to avoid losing the improvements in soil and water quality which have resulted from the past 70 plus years of natural resources conservation.

Relationship of NPP to Feedstock Production

The net primary productivity (growth) for a plant community is simply:

NPP (Growth) = Assimilation – Respiration

NPP is almost always an extrapolation from Aboveground Net Production (ANP) based on relationships between above and belowground production (Mitchell, 1984). ANP is the most widely measured and modeled attribute of community production. The natural time unit for the gross production of a plant community is either the natural growth cycle (breaking dormancy to senescence) for perennials or the life cycle of the plants (germination to death) for annuals. Patterns of natural NPP are controlled by five major factors: climate, nutrients, year to year variation in production, community structure, and time scale (Mitchell, 1984). Agronomic plant production is controlled both by these factors and the genetic traits of plants. Management of these factors is central to modern agronomy.

ANP is relatively easy to measure and a large database of NPP measurements exist (e.g. Oak Ridge National Laboratories Distributive Active Archives Center, http://daac.ornl.gov/NPP/npp_home.shtml). Models allow the prediction of NPP based on fundamental controlling factors on plant growth and models can predict changes in NPP based on changing factors such as rainfall, CO2 concentration, etc. One such model Biome 3 (Haxeltine and Prentice, 1996) has been used to predict the effects of changing climate on NPP. Output from this model in association with measured NPPs is shown in Figure 2 from Izaurralde et al., 2005. These patterns of NPP show clearly that natural NPP is greater in some parts of the country than others. The greatest natural NPP is generally in the humid southeast, consistently 1000-1200 g C m^{-2} yr^{-1} or approximately 20-24 Mg green biomass ha^{-1} yr^{-1} (based on a carbon mass to green biomass conversion of 2).

NPP of currently produced agricultural crops show very different patterns (Hicke et al., 2004; Figure 3). In general, crops grown in the southeast have lower NPP per unit area and coupled with lower proportion of land in crops, the current crop NPP of the southeast is much lower than for the corn belt and other areas of the country with lower natural NPP. Given the current plan to produce nearly 50% of the feedstock in the southeast from dedicated bioenergy crops (USDA, 2010); achieving NPP more consistent with natural NPP is essential to current national goals.

For at least the past 75 years, crop production has been driven by the concept of yield goals, with inputs provided (within the constraints of soil and water availability) to produce maximum yield. It has only been in the past 25 years, generally, that crop production has focused at all on input management, largely because of the dual concerns of maximizing net economic return and reducing the external effects of agriculture (water and air pollution). Thus as non-renewable resources shrink, become more expensive, or become subject to more competition, the focus on input management increases. With biofuels, a new dimension is added because of the need to grow biofuel feedstocks that are carbon negative (releases fewer greenhouse gases in the life cycle from seed to combustion than fossil fuel alternatives). Therefore input management is of utmost importance. Bioenergy feedstock production is also constrained in a way not typical of conventional crop production. Notably, attention must be paid to three issues that have been a source of significant controversy in scientific and policy literature about biofuels: 1) achievement of greater net energy benefits than current biofuel processes, particularly corn ethanol, that show relatively low net energy yields (Hill et al., 2006; Evans and Cohen 2009) or potentially even net energy losses (Giampetro and Ulgiati 2005; Pimentel and Patzek, 2005, 2007); 2) avoidance of land use changes that could increase soil erosion, forest losses, and greenhouse gas fluxes due to loss of soil and biomass carbon stores (Fargione et al., 2008; Searchinger et al., 2008); and 3) use of lands and crop types that minimize morally problematic “food vs. fuel” conflicts (Naylor et al., 2007; Runge and Senauer, 2007). Studies are now being conducted on how feedstocks can be produced without reducing crop acreages and without creating large carbon debts associated with land clearing and land use change. “USDA assumes that biomass may be grown on defined agriculture cropland (agriculture cropland where crops are produced and agriculture cropland in pasture). … Importantly, USDA will assess the acreage of fallow and underutilized lands that can be sustainably converted into dedicated energy crops” (USDA, 2010).

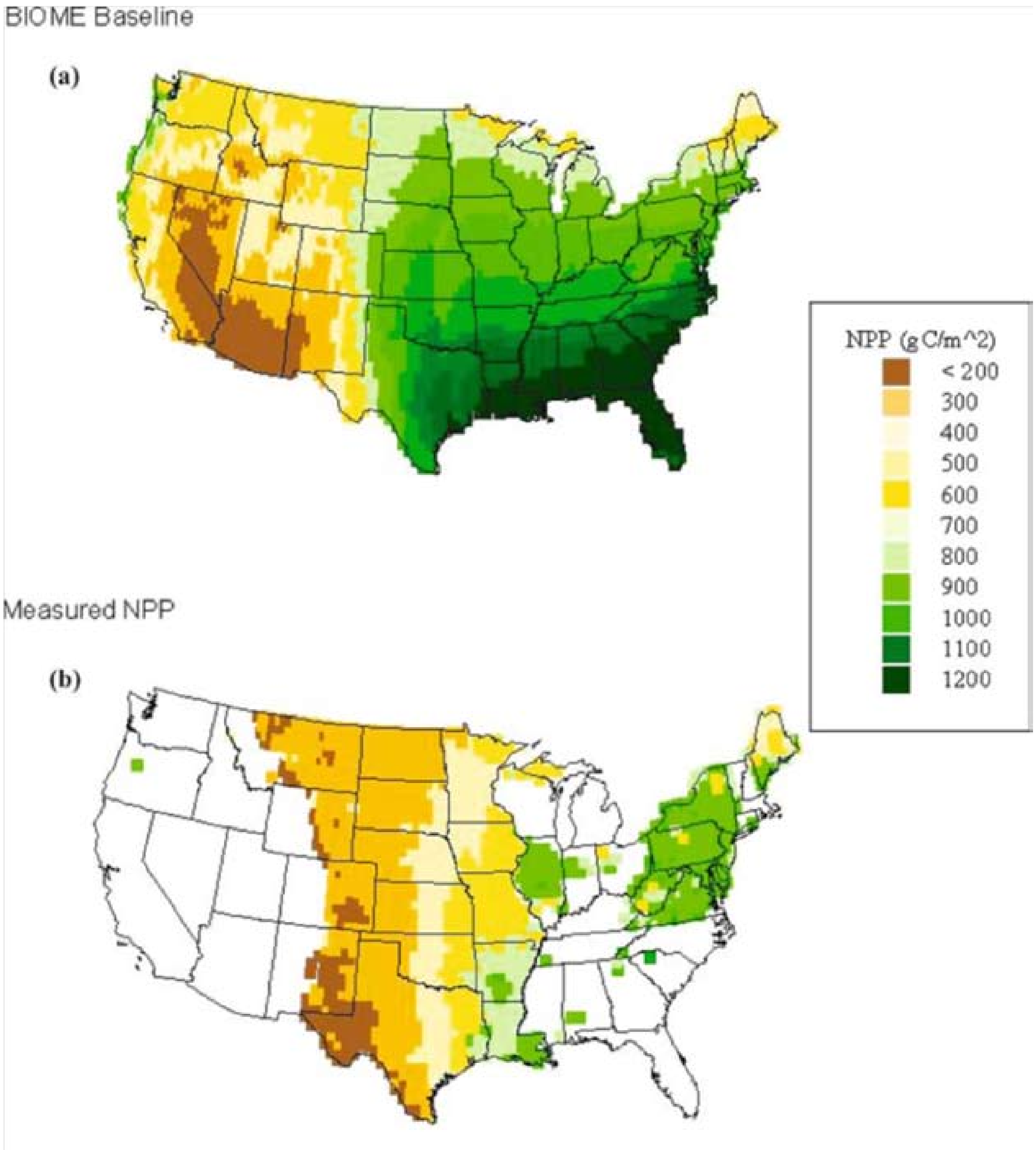

Figure 2. Annual net primary productivity (NPP, gCm−2) of unmanaged ecosystems under (a) current (baseline) climate as predicted by BIOME 3 and (b) as reported by Zheng et al. (2001). From Izaurralde et al., 2005.

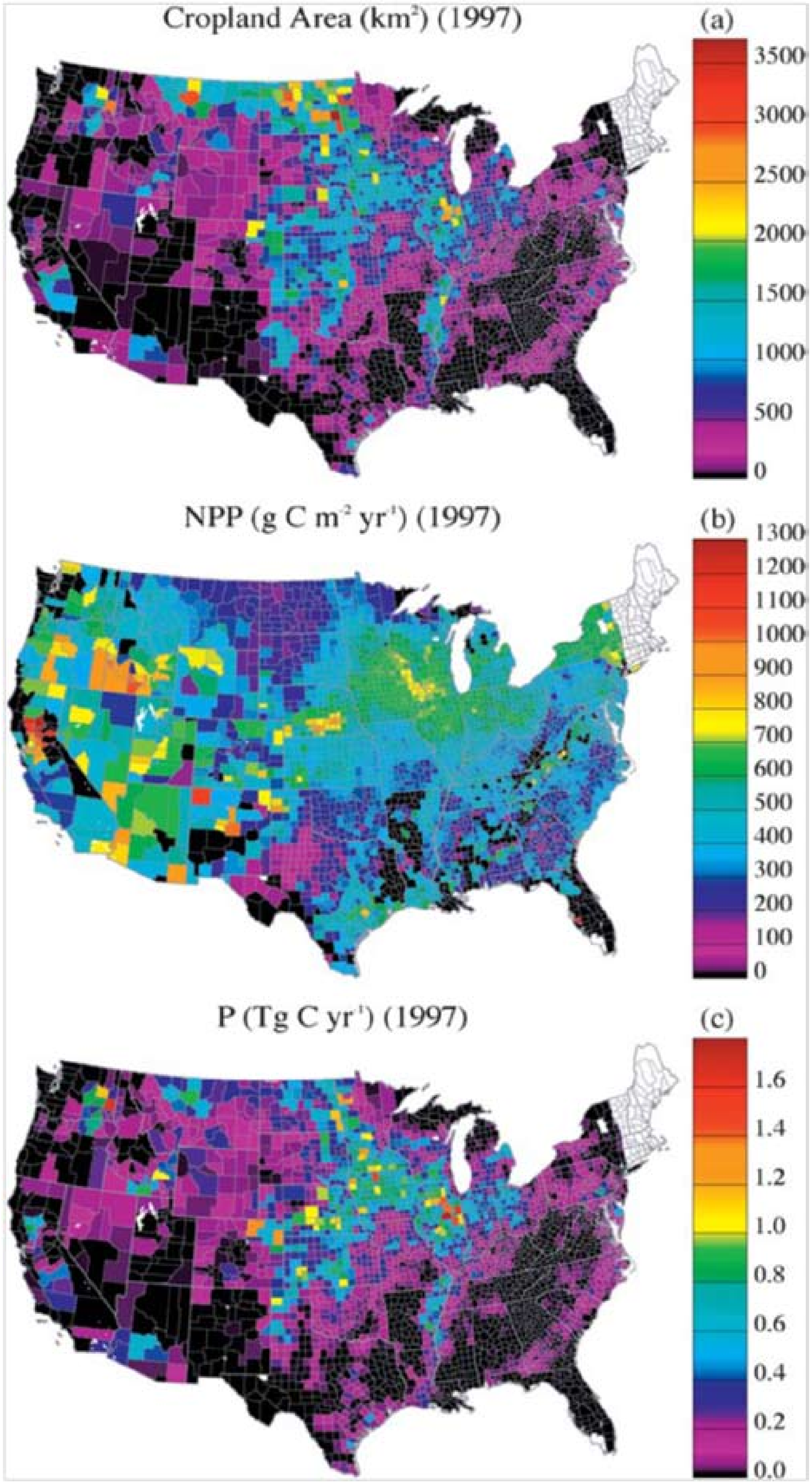

Figure 3. Cropland Area, NPP from cropland, and total production by county. From Hicke et al., 2004.

Because of the factors discussed above that are critical to the sustainability and acceptability of bioenergy, it is anticipated that much of the dedicated crop feedstock production will be accomplished with lower external inputs from areas that are not currently in crop production or which are underused land. Thus regional comparisons of natural NPPs are expected to be a better guide to production of feedstocks such as perennial grasses and short rotation woody crops than current crop NPP. Modeling of miscanthus (Miscanthus x giganteus) and switchgrass (*Panicum virgatum L.*) show just this pattern with the high yields predicted for parts of the Southeast and South Central regions and the biggest difference between corn biomass yields and miscanthus biomass yields predicted for the Southeast and South Central areas. (Figures 4, 5, and 6, F. Miguez et al., unpublished).

NPP on Marginal and Underused Lands

Clearly there are challenges to growing a substantial amount of the nation's biofuels feedstocks on marginal, abandoned, and underused lands. In many cases these lands include soils that are not in use because they are less productive either due to inherent characteristics or due to earlier resource degradation. Additionally, these lands may be comparatively less productive and require higher levels of input to bring into production because they have not received soil amendments such as lime and fertilizer. Marginal cropland in uplands may be more prone to soil erosion or nutrient and pesticide leaching and require more careful management and more extensive buffer systems to produce feedstocks sustainably. Finally, although previously cultivated, the re-conversion of marginal lands to annual crops for feedstock production could lead to decreases in SOC pools (Davidson and Ackerman, 1993).

In some cases ecosystem services from marginal lands may be enhanced through production of perennial feedstock crops. Perennial crops generally have advantages over annuals in maintaining important ecosystem functions, particularly on marginal landscapes or where resources are limited (Tilman, 2009). In addition to marginal lands as defined above, other land at the margins of fields can be used as buffers to provide water quality and wildlife habitat benefits as well as providing long term feedstock production. Riparian and edge of field buffers as well as grass waterways are of great importance to water quality in many agricultural landscapes and these benefits have been documented in both empirical field studies and modeling studies (for reviews, see Mayer et al., 2007 and Vidon et al., 2010). If these buffers can be used to produce feedstocks without additional inputs, multiple benefits can be achieved in intensively managed agricultural watersheds.

Although a review of all studies of potential bioenergy crop production will not be attempted in this chapter, we will discuss a number of studies that focus specifically on marginal lands or low inputs. More complete reviews are available (e.g. Sanderson and Adler, 2008).

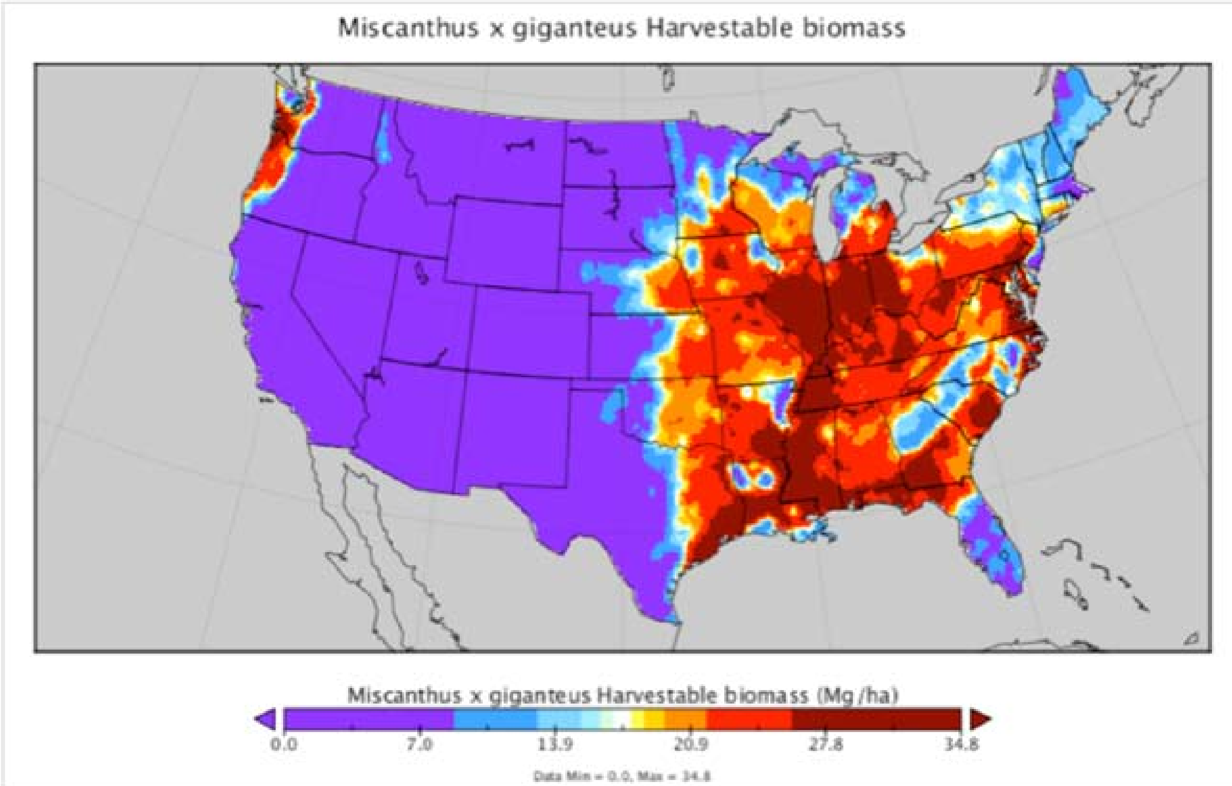

Figure 4. Predicted Miscanthus X giganteus production, harvestable biomass (F. Miguez, unpublished).

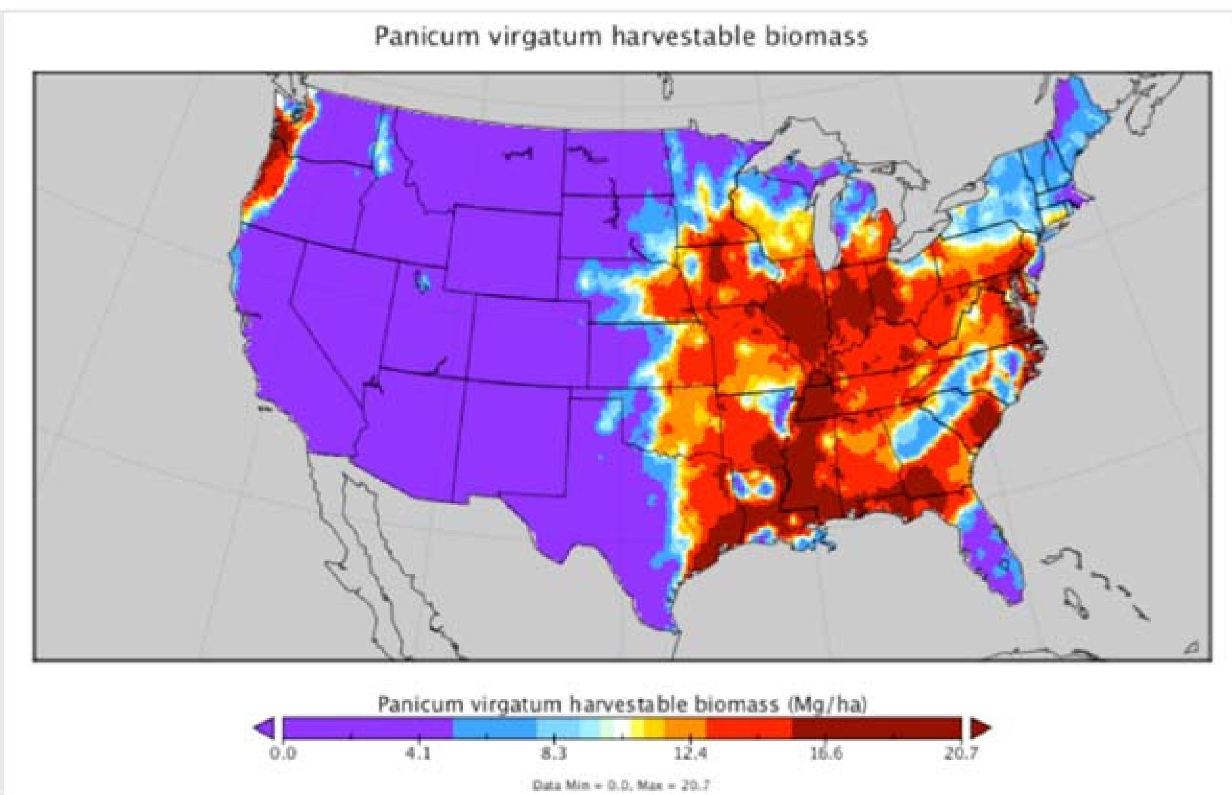

Figure 5. Predicted switchgrass production, harvestable biomass. (F. Miguez, unpublished.)

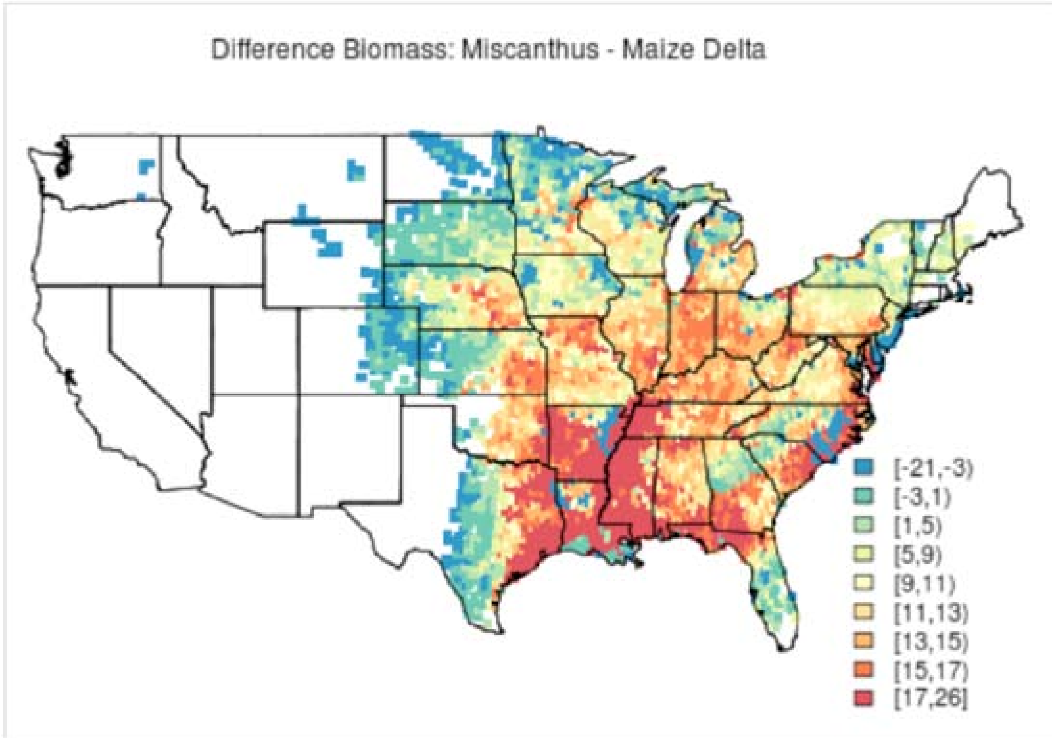

Figure 6. Difference in Maize and Miscanthus production (F. Miguez, unpublished).

Estimates of natural NPP on marginal lands are important because with minimal inputs, the amount of feedstock produced on marginal lands may be similar to that amount of ANP achieved in natural ecosystems. Campbell et al. (2008) used the natural production (ANP) as an upper limit on the production of biomass from marginal lands because on a global scale, agricultural harvest is about 65% of natural ANP. Estimates ranged from negligible to 23 Mg ha^{-1} yr^{-1} with a global average of 4.3 Mg ha^{-1} yr-^{1}. Their estimates did not account for irrigation or high fertilizer application which could increase yields. DeBolt et al (2009), in a similar study for the state of Kentucky used estimates of biomass production by three native warm season grasses; switchgrass, eastern gamagrass (*Tripsicum dactyloides* L.), and big bluestem (*Andropogon gerardii* Vitman) that ranged from 10.2 to 14.5 Mg ha^{-1} yr-1dry matter. These yield estimates were based on fertilized plots (N- 67 kg ha^{-1} yr^{-1}, P and K to soil test recommendation) of the grasses grown as monocultures (Stork et al., 2009). DeBolt et al. (2009) estimated that the abandoned land would yield 65% of the field trial yields (8.0 to 9.4 Mg ha^{-1} yr^{-1}). Gopalakrishnan (2009) estimated yields of biomass crops in Nebraska on marginal land resources as 4 Mg ha^{-1} yr^{-1} with rain fed systems and 8 Mg ha^{-1} yr^{-1} where degraded water resources (nitrate contaminated groundwater and livestock/municipal wastewater) were used for irrigation. Schmer et al. (2008) grew switchgrass on field scale plots on marginal lands with fertilizer rates up to 212 kg N ha^{-1} yr^{-1} in the Great Plains and found yields of 5.2 to 11.1 Mg ha^{-1} yr^{-1}. Ongoing research on biofuels crops in the Southeastern Coastal Plain has shown the potential for production of warm season grasses such as elephant grass (*Pennisetum purpureum* Schum.) in buffer areas on marginal or non-prime land. Preliminary data show that yields of elephant grass in buffer areas are similar to yields in upland row-crop fields receiving N fertilizer and greater than yield of the grass in upland area receiving no fertilizer (Anderson et al., unpublished). In the second year of production, elephant grass in unfertilized fields averaged about 22 Mg ha^{-1} yr^{-1} dry matter while elephant grass in buffers below a fertilized field averaged about 33 Mg ha^{-1} yr^{-1} dry matter. Five potential feedstock grasses were grown with no fertilizer applications or irrigation on a well drained agricultural soil near Tifton, GA and all showed yield declines by the 4th year of no-fertilizer application (Figure 7; Knoll et al., 2010). Yield maxima ranged from 40 Mg ha^{-1} yr^{-1} dry matter for erianthus (*Erianthus arundinaceum* Retz. Jesw.) to less than 10 Mg ha^{-1} yr^{-1} dry matter for one of the giant reed (*Arundo donax* L.) entries. By the fourth year of no fertilizer application (2009) all plots had yields less than 10 Mg ha^{-1} yr^{-1} dry matter.

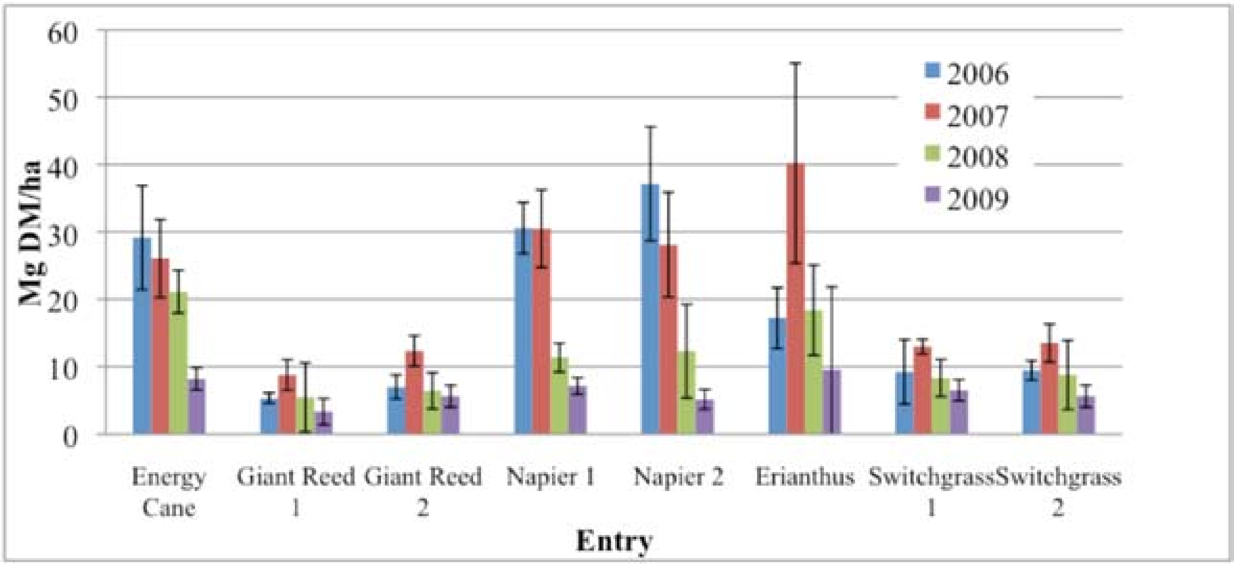

Figure 7. Annual production of perennial grasses under no-fertilizer and no-irrigation (Knoll et al., 2010).

Regional Examples

Regional examples can help illustrate both the potential and challenges for producing bioenergy feedstocks without major changes in land cover and without impacting the production of food, fiber, etc from agricultural lands and the production of wood and paper products from forest lands. At this point, few studies have been done to address whether feedstock production on marginal or underused land would be adequate to meet supply needs and what would be the sustainability challenges for this type of production. In a study of global potential of bioenergy on abandoned agricultural lands, Campbell (2008) estimated that the energy content of biomass grown on 100% of the abandoned agricultural land generally accounted for less than 10% of the primary energy demand for most developed countries. Although the biofuels produced on marginal lands could provide a larger proportion of energy demand in less developed countries, challenges exist to increase per ha production on marginal land and to determine how to bring other lands such as marginal forests into production.

Studies of how marginal lands could contribute to biofuels production in at least two U.S. states are available. Debolt et al. (2009) estimated that abandoned agricultural and mine land in Kentucky comprised over 2.2 M ha, or 21% of the total area of the state. They estimated that the biomass produced from those lands could account for 13 to 17% of the state's aggregate energy demand depending on whether the biomass was converted to cellulosic ethanol or burned to generate electricity. In a study of marginal lands in Nebraska, up to 22% of the total energy demand and the majority of feedstock for biorefineries could be produced on marginal and degraded lands, road rights of way and buffers (Gopalakrishnan, 2009).

Identification of marginal lands will vary from region to region. In portions of the country such as the Upper Midwest where the best agricultural soils are prairie soils, marginal soils may be those developed under original forest cover. Sauer et al., (2008) used the Iowa Soil Properties and Interpretations Database to identify soils that were a) formed under forest cover, b) have a corn suitability rating (CSR) less than the county average and c) which were highly erodible. Of the 14.5 million ha of land in Iowa, 1.05 million ha or 7.2% of the state land area was identified as marginal using these criteria. Using 2004 National Agricultural Statistics Service (NASS) data, 64% of this marginal land was still under agricultural land use (row crops, small grains, and pasture). Study of four representative soils of these marginal lands indicated that most of these soils were highly eroded but that soil organic carbon had increased on soils which have had reestablished forest compared to soils which have stayed in agriculture. This study points out the potential to derive multiple ecosystem services from these marginal lands if forests are re-established for bioenergy crops (Sauer et al, 2008).

The use of current agricultural landscapes for production of dedicated bioenergy feedstocks is expected at least in part because of the existing infrastructure and equipment available on the farms and in the communities of existing agricultural regions. The more agricultural parts of the Southeastern U.S. are areas where both the infrastructure and the farmers exist to produce bioenergy feedstocks in a part of the country that has some of the highest natural NPPs. To illustrate the potential in this region, we have used data on land cover and soils for the Little River Experimental Watershed (LREW, near Tifton, GA) to estimate the availability of land for feedstocks. The soils of the watershed have been grouped into prime farmland soils, non-prime farmland soils, and other soils based on county soil survey data (Calhoun, 1981, 1983; Stoner, 1990). The prime soils are listed in the Soil Survey as "prime farmland"; the non–prime soils are listed in the soil surveys as "other important agricultural soils." The other soils are generally wetland and riparian soils or soils associated with the wetland and riparian soils. Land use land cover is based on the year 2005 land cover from the Georgia Land Use Trends Project (http://narsal.uga.edu/glut.html).

Soils of the watershed are shown in Figure 8. Exactly half of the watershed is classified as prime soils and 76% of the prime soils and 54% of the non-prime soils are already in row crops/pastures (Table 1). The non-prime soil already cleared (in row crop/pasture) would be the most likely areas for producing bioenergy feedstocks while minimizing the impact on either conventional crop production or changing land cover from forest. The challenges of using these non-prime soils are illustrated by more detailed examination of the Coastal Plain Landscape (Figures 9 and 10). In the northern part of the watershed most of the non-prime and substantial portions of the prime soils are in forest cover. In the southern part of the watershed most of the non-prime soils are in crop/pasture. Producing feedstocks on non-prime land in the southern part would mainly impact existing crops while in the northern part would mainly impact forest land.

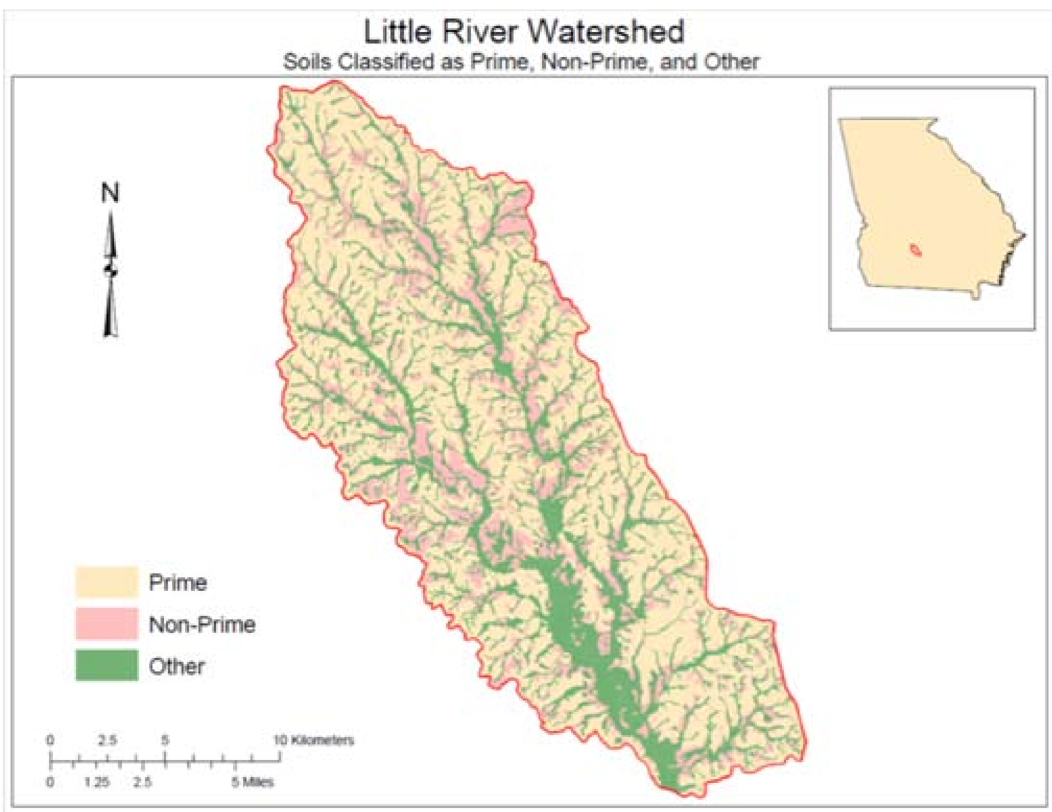

Figure 8. Soils of the Little River Watershed grouped as prime, non-prime, and other.

Land Use	Soil Classification			
	Prime (50%)	Non-Prime (19%)	Other (31%)	All Soils (100%)
Upland Forest	15%	29%	28%	22%
Row Crop/Pasture	76%	54%	26%	56%
Wetland Forest/Wetland/Open Water	2%	6%	39%	14%
Clear Cut/Sparse	1%	4%	4%	3%
Urban	6%	8%	3%	6%

Table 1 – Percentages of land cover classes in the three groups of soils in Little River Watershed in the Georgia Coastal Plain.

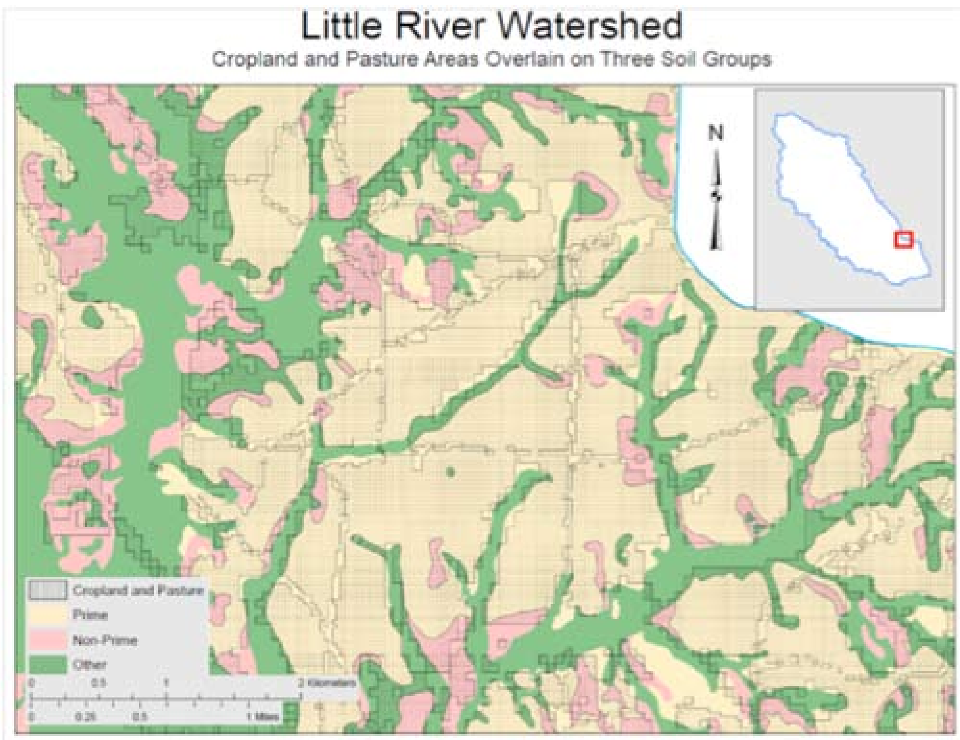

Figure 9. Land used for crops and pasture overlaid on soil groupings in southern part of LRW.

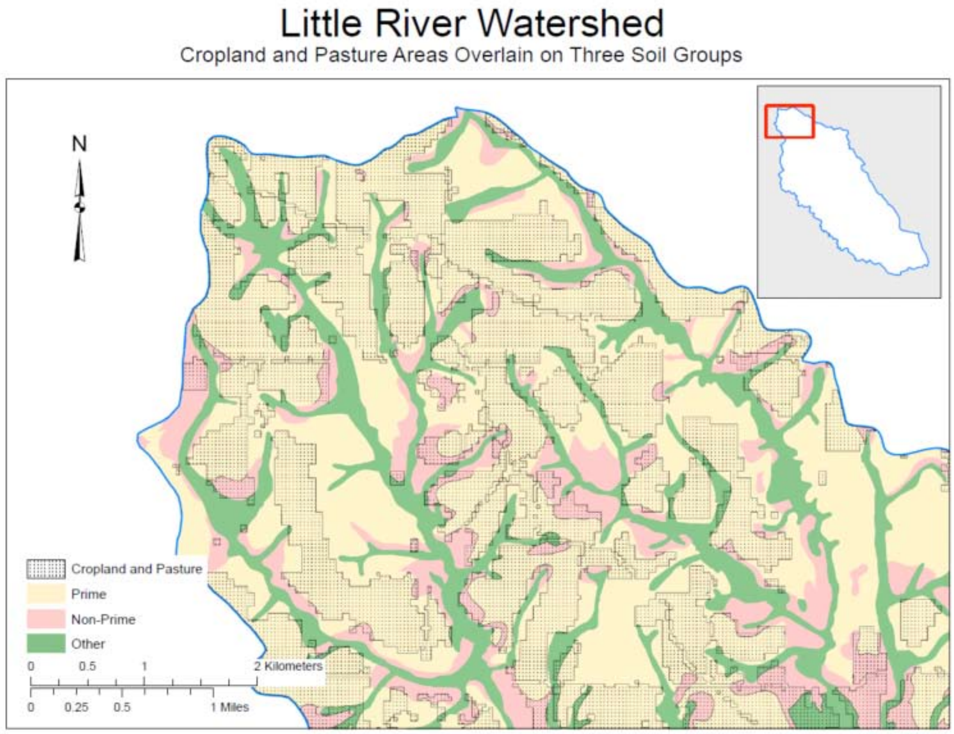

Figure 10. Land used for crops and pasture overlaid on soil groupings in northern part of LRW

Further analysis for the entire Georgia Coastal Plain region has focused on the use of non-forested riparian zones and grass waterways as feedstock production areas. Assuming that feedstock production on 14,160 ha would be necessary within 40 km of a 136 million liter per year biofuel conversion facility (criteria based on projections by Vercipia Biofuels, Tampa, FL; http://www.vercipia.com/pdfs/Highlands_FactSheet_080410_Final.pdf), we determined how much of the feedstock could be produced by re-vegetating riparian zones in 10 m buffers and grassed water ways (Figure 11). Based on land cover and hydrography, anywhere from 6% to 38% of the 14,160 ha could be gained from buffers and waterways (Table 2). The remaining acreage, if taken from agricultural land in the 40 km radius would be from 3% to 18% of the agricultural land. More heavily agricultural areas would need to devote a much smaller percentage of the total agricultural land to feedstocks under these scenarios. Based on the analysis of soil groupings in the LREW discussed above, there would be an estimated 51,750 ha of crop/pasture on non-prime land within a 40 km radius of Tifton. If the additional feedstocks (8,779 ha) were grown on these marginal lands, it would represent conversion of at least 17% of the non-prime soils to feedstocks. It should be noted that some of the area counted in buffers and waterways is on non-prime land so the total conversion of non-prime acres from current crop/pasture to feedstocks would be greater than 17%. This analysis suggests a potential for producing about 215 million liters of ethanol per year (at 270 liters per Mg dry matter and 33 Mg ha^{-1} yr^{-1} dry matter; see Strickland et al., 2010) from 10 m riparian buffer strips below fields in the Coastal Plain of Georgia.

	Area of 10 m Buffer & Grass Waterways	Total Cropland & Pasture Area	Area of Non-Buffer Cropland & Pasture Remaining	Area of Cropland & Pasture Needed	Remaining Cropland & Pasture needed for feedstock crops
Location of Biorefinery	----------------------------hectares----------------------------------				%
Tifton	5,385	269,170	263,784	8,779	3
Albany	2,669	250,740	248,071	11,496	5
Waycross	994	72,640	71,646	13,171	18
Americus	1,459	198,927	197,468	12,706	6
Camilla	1,649	224,573	222,924	12,516	6
Eastman	1,440	150,176	148,736	12,725	9
Douglas	1,705	132,542	130,837	12,459	10
Vidalia	1,162	119,702	118,539	13,002	11
Ashburn	2,740	231,226	228,485	11,424	5
Fitzgerald	2,172	189,663	187,491	11,993	6
Soperton	843	107,580	106,737	13,322	12

Table 2 – Potential changes in land use for 14,165 ha of feedstock production within 40 km of eleven cities in the Georgia Coastal Plain.

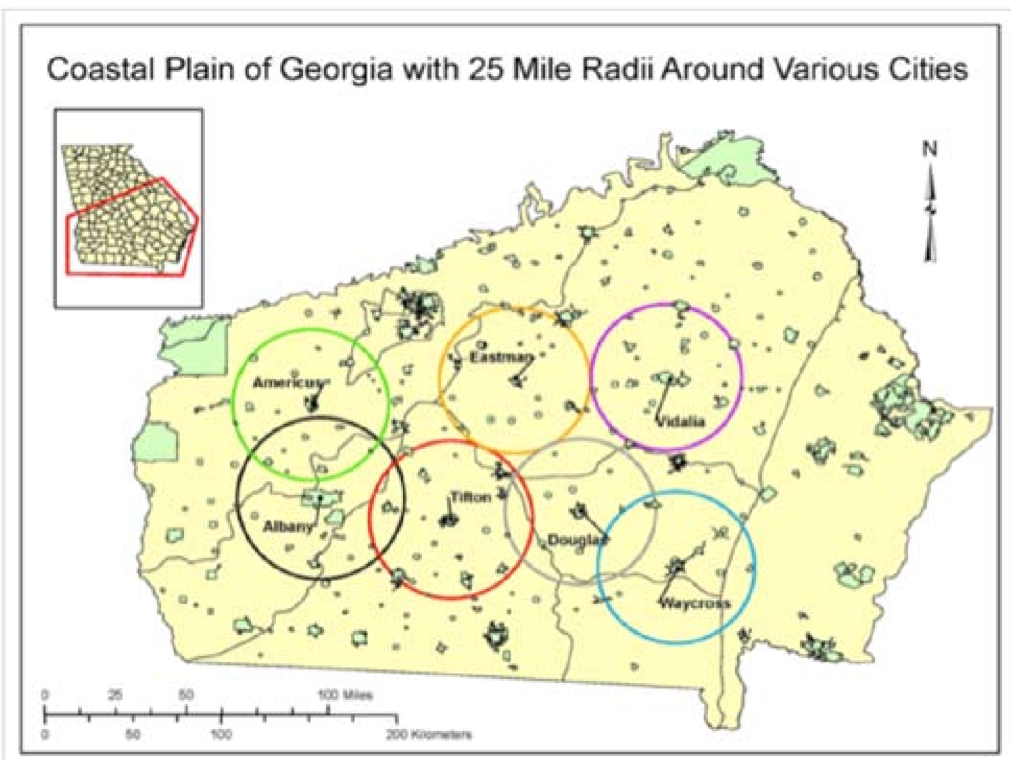

Figure 11. Coastal Plain of Georgia with 25 mile (40 km) radii around 7 of the 11 small cities.

Landscape Management and Conservation

Conservation practices are applied both at the agroecosystem level and at the agricultural landscape level. In general, for a given field, increasing the proportion of the year when vegetation is actively growing or has a living root system in place will generally lead to gains in natural resource conservation. For a landscape increasing the proportion of the landscape where vegetation is actively growing or has a living root system for most of the year will also lead to gains.

Examples of conservation practices at the agroecosystem level are numerous-nutrient management, pesticide management, residue management; contour plowing, terracing, etc. At the landscape level, conservation practices include those aimed at restoration/management of the non-agroecosystems (e.g. riparian forest buffer, wetland restoration, tree planting) as well as those practices that are designed to affect the network connecting landscape elements (e.g. grass waterways, field borders, stream bank restoration). In many cases, such as wetland restoration or enhancement, the non-agriculture portions of the landscape are needed to compensate for functions and values lost from the larger agricultural landscape.

The use of marginal, abandoned, and underused land for bioenergy feedstock production is likely to lead to the need for more conservation practices applied on both existing cropland (e.g. prime farmland) and in the bioenergy production on marginal lands. The need for conservation practices on marginal lands will be mitigated by the use of perennial crops, especially perennial native species. To the extent that sequestering of nutrients is enhanced by removal of biomass, there may be improvements in chemical water quality in areas where bioenergy crops can be grown as buffers and nutrients are harvested with biomass. In contrast, where early native successional ecosystems such as old-fields are replaced with bioenergy crops, one would expect a loss of ecosystem services. Where buffer services are lost from marginal lands, they may need to be replaced with enhanced conservation practices on existing cropland.

Landscape management conservation practices (Lowrance et al., 2006) are generally compatible with increased bioenergy feedstock production on marginal lands or on prime land. Landscape management seeks to direct the interactions among ecosystems to achieve societal objectives. Landscape management conservation practices differ in two key ways from conservation practices applied at the field-scale: (1) landscape management typically involves practices outside the main production units of a farm and (2) landscape management often requires long-term (or permanent) commitment of land to ecosystems other than those that might provide the highest short-term economic return (Lowrance et al., 2006). For this reason, landscape management generally is implemented through a series of transfer payments from society to farmers. If it is possible to produce feedstocks and achieve other landscape management goals centered on increasing the perennial coverage of the landscape, society will derive a double benefit.

Summary and Conclusions

Potentially productive lands are available for bioenergy feedstock production in many agricultural and other rural landscapes. The special sustainability constraints placed on the emerging bioenergy industry make it more likely that sustainability problems will be recognized and solved as the industry moves forward. In response to one of the first sustainability problems, the effects of feedstock production on food, feed, and fiber supplies, there is considerable interest in how bioenergy feedstocks can be produced on marginal and underused land. The advantages of using marginal lands in agricultural landscapes are numerous. First and foremost, it will provide a means of producing feedstocks without substantially reducing agricultural outputs to other sectors. This should provide both enhanced income for farmers and farm communities while also maintaining food, feed and fiber production. Second, marginal lands and buffers are embedded in an agricultural landscape where infrastructure exists for ongoing agricultural production. Thus fertilizer and chemical dealers, transportation and processing infrastructure and water supply infrastructure will generally be available. Thirdly, when marginal lands and buffers are brought into production in areas of existing agricultural production, the feedstocks grown on the expanded land base can be integrated with feedstocks produced on existing agricultural lands, especially feedstock crops that are grown in rotation with existing non-feedstock crops. Finally, establishment of perennial feedstock crops such as native warm season grasses and short rotation woody crops on marginal lands and buffers may provide environmental benefits such as increased soil organic carbon sequestration and improvements in wildlife habitat on those lands (Blanco-Canqui, 2010).

Substantial challenges exist for use of abandoned, marginal, or underused land for feedstock production. In the U.S. these marginal lands or non-prime farmlands defy easy definition. In many landscapes the marginal lands are either eroded, have leaching problems, or have wetness constraints. In some landscapes they are scattered at the margins of prime farmland or may be linear corridors such as utility rights of way and roads. To the extent that perennial vegetation can be grown and achieve simultaneous conservation benefits associated with perennial growth habits, feedstock production may provide multiple societal benefits of replacing fossil fuels, holding soil in place, and building soil organic carbon.

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Chapter 2

Bioenergy Sustainability at the Regional Scale

In press with Ecology and Society as an Insight Article

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Abstract

The establishment of bioenergy crops will affect ecological processes and their interactions and thus has an influence on ecosystem services provided by the lands on which these crops are grown. The regional-scale effects of bioenergy choices on ecosystem services need special attention because they often have been neglected yet can affect the ecological, social and economic aspects of sustainability. A regional-scale perspective provides the opportunity to maximize ecosystem services, particularly with regard to water quality and quantity issues, and also about other aspects of ecological, social and economic sustainability. We give special attention to cellulosic feedstocks because of the opportunities they provide.

Keywords: bioenergy crops, ecosystem services, landscape, management

Introduction

The expansion of biomass production to provide feedstocks for biofuel refineries will induce complex interactions among a large number of ecological processes that are important but, as yet, poorly understood. Currently most liquid biofuels use sugar, grain and vegetable oils as feedstocks. However there is great potential to expand feedstocks to herbaceous and woody ligno-cellulosic crops and agricultural and forest wastes, in particular (NRC 2009). Bioenergy crop expansion will influence local and regional sustainability via impacts to socioeconomic systems and will also change the delivery of ecosystem services provided by current landscapes (Robertson et al. 2008). Many of these alterations could be positive if managed appropriately (Kline et al. 2009). They include effects on water quality and quantity, soil conditions, greenhouse gas emissions, air quality, and biodiversity.

The shift from a preexisting crop or from a relatively unmanaged ecosystem to a bioenergy crop will be accompanied by changes in land management that will include altered fertilization, irrigation, cultivation, and harvesting regimes. These changes will affect a number of ecosystem components and the magnitude and efficiency of the ecological services they provide. Changes in soil composition and structure, for example, will affect nutrient cycling, runoff characteristics, soil erosion, downstream surface waters and aquifers, and greenhouse-gas emissions. Where the transition is to a perennial cellulosic crop, bio-geochemical changes are likely to be positive as carbon is sequestered belowground, greenhouse gas emissions are abated, and less nitrate and phosphorus are delivered to surface and ground waters (Robertson et al. 2011). Hydrologic changes are also likely as altered water demands influence the availability of water for other potential uses, and biodiversity changes will affect the delivery of ecosystem services such as pest suppression in surrounding ecosystems (Landis et al. 2008, Gardiner et al. 2010). Of course, changes due to bioenergy need to compared to the environmental effects of using other energy sources such as petroleum, including exploration, drilling, production, transport, and use, but many of these effects are poorly documented (Ramseur 2010).

These aspects of ecological systems are complex, and how they interact can vary widely from one ecosystem to another. Different components, individually or in combination, provide a suite of ecological services such as water and air purification, wildlife habitat improvement, biodiversity maintenance, waste decomposition, pollination of crops and other plants, seed dispersal, groundwater recharge, greenhouse gas emissions and climate change regulation, food, fiber, and fuel production, aesthetics and cultural amenities (Millennium Assessment 2005, Swinton et al. 2007). Many effects of traditional agriculture on ecosystem services are known (e.g., Dale and Polasky 2007, NRC 2010), yet only recently have researchers begun to explore how bioenergy crops, specifically cellulosic feedstocks, will affect these services (Hecht et al. 2009). The assessment of where bioenergy crops can best be grown and how they can influence ecosystem services on a regional scale requires integrated consideration of both typical agriculture and land not traditionally used for crops.

An example of a process that interacts with several others and that can be considered at many scales is the fate and transport of carbon and nitrogen during biomass production. The carbon and nitrogen cycles are driven by factors such as precipitation, temperature, topography, soil characteristics, the presence and activities of soil microbes and invertebrates, and land management. Changes to any of these factors can have significant effects on biofuel crop growth and on local carbon and nitrogen cycles. These local changes, when implemented across millions of hectares, will either mitigate or exacerbate atmospheric greenhouse gas concentrations, for example; or abate or accelerate nitrate contributions to eutrophication of inland waters and the extent of coastal dead zones; or increase or lessen sediment loads to streams and reservoirs. A corollary is that carbon and nitrogen cycles also vary depending on the type of feedstock planted and management practices.

Our perspective of bioenergy sustainability at a regional scale is built upon the concept that lands should be used for their most appropriate purpose and management decisions made in hierarchical fashion (Dale et al. 2011). This premise derives from Forman's (1995) suggestion that, under ideal circumstances, land decisions occur hierarchically: first addressing water and biodiversity concerns; second-food cultivation, grazing, and wood products; third-sewage and other wastes; and fourth-homes and industry. In this paradigm, decisions about energy use and other natural resources extractions would likely fall into a secondary tier under the second category. That is, after decisions are made about the locations for natural resource protection and about food and fiber, then decisions are made about fuel. As such, energy crops might be placed best on lands of marginal use for other purposes (including land less appropriate for growing food).

Landscape-level decision making is relatively rare, but access to science-based scenario forecasting can provide regional stakeholders and policy makers an opportunity to envision the long-term outcomes of contemporary land-use decisions (e.g. Baker et al. 2004), and thereby an opportunity to shape policy to enhance the delivery of ecosystem services in future landscapes. Of course, for science to influence decision making processes, it needs to be clear who makes decisions and how permanent and far reaching those decisions are (a topic that is beyond the focus of this paper, but one that needs to be addressed for bioenergy sustainability to be achieved).

Growing crops for bioenergy offers an opportunity to rethink, from a regional perspective, how and where feedstocks can sustainably be produced. The debated concepts on indirect land-use effects (Mathews and Tan 2009) cause us to consider how even unmanaged ecosystems are influenced by human activity. The concept of "emerging ecosystems" recognizes that the majority of the Earth is affected by human activities with broad-scale effects poorly understood (Hobbs et al. 2006, Hobbs et al. 2009). The properties of these novel systems may not be the same as the characteristics of natural ecosystems that ecologists have long studied. While there is a rich literature on old field succession, recovering wetlands, and some other managed systems, growing bioenergy feedstocks will involve ligno-cellulosic crops and management practices for which there is relatively little information or experience. Furthermore the focus on sustainability provides an opportunity to decide how biofuels might be "done right" (Kline et al. 2009) and thus to provide a positive example for other cropping systems. The principles and processes of these human-managed, emerging ecosystems need to be better understood, especially in view of the regional landscape, which may contain a mix of agriculture, forest, urban, and other land uses. This lack of insight makes it difficult to develop land-management goals for such ecosystems. Production of bioenergy crops and even use of residues of traditional crops for biofuels may produce many such emerging ecosystems, and research on the regional implications of those emerging ecosystems will be required to extend current ecological knowledge to these new situations.

Information Needs for Regional Perspective

In a regional context, it is important to consider ecological, societal, and economic issues and to address the tradeoffs among those issues, including the potential unintended consequences. For example the 19 percent increase in corn acreage in the U.S. from 2006 to 2007 reduced crop diversity and appears to have reduced biological pest control services by as much as 24% with an estimated cost of $58 million y^{-1} in reduced yield and increased pesticide use for Iowa, Michigan, Minnesota, and Wisconsin (Landis et al. 2008). By contrast, if more perennial grasses are grown in a region, it is not now clear how such a change in landscape diversity might affect insect populations. Science must provide information about such consequences before inappropriate conclusions are drawn and policies set.

Research also needs to address both short-and long-term perspectives. For example, longer term goals need to be considered in order to grow crops in an ecological as well as socio-economic context. Over time, the knowledge base about these bioenergy crops will grow, and management practices can adjust to improve ecological, social, and economic well-being. To build this knowledge, planting and management regimes can be treated as experiments under which data can be collected to build or refute our current understanding of how ecosystem services are affected by certain practices. In other words, treating bioenergy cropping systems under an adaptive management approach (Gunderson 2000) fosters learning about appropriate ways to manage these systems at the same time that bioenergy cropping is expanding. In particular, it is important to document ways in which these bioenergy cropping systems can be resilient in the face of changes in climate, biodiversity and management practices and still provide key ecosystem services (Folke et al. 2004).

Science Needed for Biofuel Systems to Facilitate Decision Making at Different Scales

To influence biofuel management practices, science needs to be integrated into decision making processes before decisions are formed and implemented. To influence decisions about bioenergy crops and their management, models need to be constructed and tested so that they reflect the fact that all potential biofuel crops have costs and benefits with respect to socioeconomic systems as well as ecosystem services. The regional-ecology approach should take into consideration possible competition with current social and economic activities, organizations, methods of production, and infrastructures that serve the population of the region and that help provide livelihoods. For example, such an approach should consider not only land-management activities and how they might affect ecological systems but also how farmers might be able to use the equipment, seeds, processing plants, and labor pool they already have.

A series of independent regional studies will help foster development of understanding about general ecological, societal, and economic principles and processes, particularly how, when, and where they operate across regions. Because these ecological, societal, and economic processes will differ across regions, the details of implementing biofuel production and the tradeoffs that will need to be made will also vary from region to region. In many cases, science will be able to provide information to identify tradeoffs and to guide decisions. There will be some places where biofuel crops can be grown sustainably and some where they cannot. In many cases, such judgments about crop sustainability will need to be made not for entire regions but for fractions of the landscape. These areas and the percentages of suitable land for biofuel-feedstock production will differ by region and will be determined by landscape quality, current and past land use, and socioeconomic capacities of the region.

Opportunities for research exist at this regional scale, which is less understood than either smaller or larger scales. The components of the regional-scale ecosystem (water, nutrients, vegetation, air, biodiversity, landforms, and soil) as well as their interactions are important to study and model. This research will provide several benefits. It will help to prioritize the individual components and develop ways to investigate their actions. It will lead to new ways to measure the components' salient characteristics. It will also allow scientists to study the interactions among the components so that the entire system can be understood. The research process should lead to ways to determine when sufficient understanding of the ecosystem exists to allow confidence in a resulting model's ability to predict the reaction of a region to changes that exceed the conditions for which data have already been collected. Finally, the scientific investigations should identify several disparate regional-sized units in which comparisons can help formulate a fundamental understanding of landscape processes and conditions.

A Case Study Regional Water Issues

An example of the research opportunities existing in the regional ecology of biofuel production is offered by a consideration of the more limited component of water quality, demand, and supply for biofuel production in the U.S. Assessing how an expansion of biomass and biofuel production will affect water quality, demand, and supply in a specific area depends on a wide range of issues that will vary considerably by region. These issues include existing pressures on water supply, biomass feedstock type and management, the types of lands devoted to biomass production, precipitation patterns and climate change, and technical methods used to convert biomass to biofuels. The overarching consideration that integrates all these issues is what type of ecosystems will be displaced by biomass production systems and whether the water quality and quantity effects of these conversions be negative, positive or some combination of both. Increased areas of crops that are unable to retain soil and nutrients and that require irrigation or high fertilizer applications could threaten water quality and supply. The synchrony between plant available nitrogen and crop demand is a critical part of the plant-soil environment e.g. Cassman et al. 2002).

Biofuels based on cellulosic feedstocks such as woody vegetation (e.g., intensive, short rotation forestry) or perennial grasses (e.g., switchgrass) have the potential to reduce storm runoff, soil erosion by water runoff, and nutrient and pesticide exports to surface and ground waters in agricultural areas. Yet most studies of cellulosic feedstocks have limited their focus to optimizing growth conditions and output, and relatively few have examined the impacts of biomass production on water quality and availability. This lack of data limits our ability to make reliable assessments about future water impacts for different cellulosic feedstocks suited to the different growing conditions around the country.

Land Management and Water Quality

Application of fertilizers, pesticides, and other agrochemicals has become a standard practice for the production of both annual and perennial crops, but the needed amount of these inputs varies greatly by crop type and location. Nutrient runoff from fertilized crops within river basins has been one of the factors contributing to oxygen-deprived “dead zones” that threaten marine life (e.g., in the Gulf of Mexico) (Diaz and Rosenberg 2008). Studies conducted only at fine scales of plots or fields are not able to capture how sedimentation and nitrogen and phosphorus concentration at multiple scales are influenced by various cropping practices (Robertson et al. 2007). Yet at the scale of large watersheds (e.g., the Mississippi River watershed), farm practices have environmental effects-such as on the size and extent of the Gulf of Mexico hypoxia zone (Donner and Kucharik 2008, Dale et al. 2010). The pattern, type, and management of bioenergy crops can affect coastal eutrophication, either negatively (if crops that require large amounts of fertilizer are expanded) or positively (if bioenergy crops that need little fertilizer are planted in large areas or as stream buffers) (Dale et al. 2010). Modeling and field experiments at intermediate and large scales are needed to characterize the landscape design for planting and management that would reduce hypoxia conditions and benefit other ecosystems services. This is a scale-dependent issue because the amount of nutrient and sediment transported to the Gulf is not simply a direct function of what is coming off the field but must also include what’s lost along the way as water moves through the drainage network (Alexander et al. 2000).

Soil erosion that moves sediments and sediment-bound nutrients and pesticides into waterways is another factor influencing water quality. About half of the sediment deposited in U.S. surface waters is estimated to come from cropland erosion (Terrell and Perfetti 1993). Management practices used on croplands largely determine the extent of erosion. For example, more intensive agricultural practices, such as tillage of row crops, over-harvesting of corn stover and other cellulosic residues, or annual crop production on erodible marginal lands, can cause erosion and sediment deposition in waterways. Conservation practices with cover crops, vegetative filter strips, and riparian buffers can substantially reduce nutrient and sediment export in agricultural catchments (Dillaha et al. 1989, Rasse et al. 2000, Kaspar et al. 2007), and changes to local catchments in which the management occurs can accumulate into changes for entire watershed (even for areas as large as the 48% of the U.S. that drains into the Gulf of Mexico).

Several studies have used the SWAT (Soil and Water Assessment Tool) watershed-scale model to predict water quality changes resulting from conversion of corn or other annual crops to switchgrass in the U.S. Midwest (e.g., Vadas et al. 2008, Nelson et al. 2006). The SWAT model relies on input from an economic model to identify specific agricultural lands for conversion to switchgrass on the basis of growth conditions and an assumed crop price. Modeling studies for Iowa, Kansas and the upper Mississippi River valley suggest that 17 to 43% of current cropland could potentially be converted to switchgrass, resulting in erosion rate reductions from 20% to more than 90% and nitrogen-and phosphorus-export reductions of up to 60% if fertilizers are not used. However, nitrogen and phosphorus export from switchgrass fields is highly dependent on how fertilizer is applied. Future research should focus on land-use designs, site preparation, use of cover crops, and fertilizer and pesticide management approaches that minimize surface runoff, erosion, and the export of sediments, nutrients, and pesticides from biofuel feedstock crops. To reduce or eliminate the need for fertilizer inputs in bioenergy crops, future research should also include understanding molecular mechanisms underlying plant-root, fungal, and microbial-community symbioses that enhance plant-nutrient availability. Finally, there are very few watershed-scale field studies that provide real-world data that can be used to validate the model results showing water quality benefits of conversion to cellulosic bioenergy crops, and such studies are urgently needed.

Despite a long history of forestry research, few studies have examined the water-quality impacts of intensive, short-rotation silviculture for bioenergy production. Conversion of unmanaged forests to biomass production for biofuels could produce negative effects, depending on where those lands are located and how they are managed. An East Texas study of intensive-forestry impacts indicated significant increases in storm runoff, erosion, and nutrient loss relative to reference sites, but the impacts were highly variable over time because of the influences of the harvest cycle and weather and varied with management practices such as site preparation, burning, fertilization, and harvesting McBroom et al. 2008a, McBroom et al. 2008b).

Water Demand and Supply

In the U.S., agriculture is the second largest consumer of water from aquifers and surface supplies (blue water) and is the major industry using water stored in soil and transpired by plants (green water) (Falkenmark and Rockstrom 2006). The future biofuel production industry will create new demands on the quantity of water used by agriculture and production forestry. Globally, commercial bioenergy production is projected to consume 18 to 46 percent of the current agricultural use of water by the year 2050 (Berndes 2002). New tools are needed to account for these demands and to guide management strategies as the nation implements sustainable biofuel production. Water requirements for processing biomass into biofuel are also important, but the quantity of water consumed by processing facilities is considerably less than that consumed by crop cultivation, and the efficiency of water use in biorefineries continues to increase (Wu et al. 2009, Robertson et al. 2007).

In many parts of the U.S., the agricultural sector already faces water shortages. In the arid west, agricultural withdrawals account for 65 to 85% of total water withdrawals (Hutson 323 et al. 2004, data analyzed by ERS). In the east, supplies are under pressure from competing uses, especially in periods of drought. Although overall water use in the U.S. decreased in 1985 and has remained steady since then (Hutson et al. 2004), efficiency improvements are still possible in irrigation and other use sectors.

The amount of both green and blue water needed for a biofuel-based energy supply is greater than that used historically by the fossil-fuel-based economy. For instance, the consumptive water use in corn based bioethanol is about 4 gallons of water per gallon of ethanol compared to consumptive water use of about 1.5 gallons per gallon for typical petroleum refining (Pate et al. 2007). Other biorefinery technologies have various consumptive uses (volume water/volume fuel) of water. Current estimates for cellulosic conversion to ethanol and for thermochemical conversion range from 2 to 6 gallons/gallon (Pate et al. 2007). These figures do not include either green or blue water used for feedstock production or blue water used for petroleum extraction. Blue water use can range from zero for feedstocks grown without irrigation to very high values such as the estimate of 780 liters per liter for irrigated corn grown in Nebraska (NAS 2008).

The data needed to assess future impacts of cellulosic feedstock production on the water supply will require investigation of mixed agricultural systems that vary by location and could be difficult to monitor. Although some water inputs from rainfall or irrigation are incorporated into crop biomass, most are lost through evapotranspiration (ET, soil evaporation and plant transpiration), runoff to surface waters, or infiltration of ground water. ET rates vary by crop, and perennial bioenergy crops (both woody and herbaceous) have shown higher ET and less infiltration than have annual crops or natural ecosystems (Rowe et al. 2009, Robertson et al. 2011). One concern is a reduction in stream baseflows with conversion of agricultural lands (particularly pasture and other low-intensity agriculture) to perennial bioenergy crops. However, modeling for ET and water use of different crops, which has largely been limited to the field scale, has shown that expansion of perennial crops did not decrease water flow to streams, rivers, lakes, and groundwater. A SWAT modeling study in Minnesota (Folle and Mulla 2009) showed only a 0.35 percent decrease in streamflow when 27 percent of the watershed was converted to switchgrass instead of conventional crops. Methods for linking data from the field scale to the watershed level are needed to validate these modeled results.

Analysis of benefits and costs of future bioenergy feedstock production will better represent water-resource tradeoffs when carried out on a watershed basis. Combining life-cycle analyses and environmental-cost accounting with watershed hydrologic and water-quality modeling will provide appropriate tools for the analysis of the water requirements of biofuel conversion plants and their needed feedstock supplies. Research is under way at the watershed-scale level to develop the methods needed (Steiner et al. 2008) to understand the implications of future biofuel production on systems and make science-based decisions that will lead to greater sustainability. Also, results of forest conversion experiments from long-term monitoring catchments (e.g., gauged catchments on experimental forest within the U.S. Forest Service) are providing historical data that can be used for improved models. Research is needed to expand methods and information systems to extend evapotranspiration, runoff, and infiltration models from watershed scales to greater regional scales across the entire country. Furthermore, the combination of life cycle analysis and environmental cost accounting with watershed hydrological and water-quality modeling will provide improved tools for analyzing the water requirements of feedstock supplies as well as biofuel conversion plants. A critical research need is to examine how the expansion of biofuels and more intensive agriculture will affect the water cycle and future precipitation patterns, especially within the context of the uncertainty in future climate change.

Research Opportunities

Within this regional framework of scientific inquiry, four pressing research needs can be identified.

(1) Understanding the data and knowledge requirements for quantitative modeling is necessary to improve projections of different land management practices on the delivery of ecosystem services. This effort will require adaptation or development of models that reflect the effects of converting agricultural crops, forests, and other land uses to bioenergy feedstock production under a variety of management conditions. The model projections must be validated with data obtained from watershed-scale field studies. Developing such an understanding will also enable determining the influence of future climate change scenarios on hydrology and bioenergy production and the potential impact of landscape alteration due to fuel crop conversion on local precipitation and other weather variables.

(2) Understanding the impact of biofuel production on the many aspects of sustainability will improve via adaptive management. It will require field trials that generate near real time data for identifying the impact of bioenergy crop production on environmental parameters and expansion of models to include these new data. Furthermore, linking watershed-scale field research and modeling of water quantity and quality with information on soil processes, crop growth, and biodiversity fosters more accurate projections of the effects of biomass management options.

(3) Improvements are needed in approaches to bioenergy feedstock management at a regional scale. New approaches need to be developed for agricultural and silvicultural land-use design and management practices that reduce runoff of sediments, nutrients, pesticides, or other inputs; that minimize the greenhouse gas emissions from current and future cropping systems; and that enhance the delivery of biodiversity services such as pollination and biological pest control. Integrated decision-making tools at farm, regional, watershed, state, and national levels can be developed by integrating data from appropriate spatial and temporal scales of water use, supply, and quality. Strategies for site preparation, management, and harvesting for bioenergy crops and forestlands can be developed to protect and improve water quality; to mitigate greenhouse gas concentrations in the atmosphere; and to enhance other services provided by agricultural landscapes.

(4) Landscape ecology approaches at regional scales need to be applied in order to develop an understanding of relationships among diverse processes. Analytical frameworks can be designed for regional-scale ecological models. These models can then be linked with biophysical and economic models to understand how key aspects of bioenergy production affect the multifunctional roles of agricultural and forest landscapes. Finally, regional models can also enable the evaluation of management options for climate change scenarios.

Conducting broad-scale research requires both a plan and a focus on regional effects of bioenergy decisions. Critical thinking should be carried out for all the other components of the regional-scale ecology of biofuel production and consider sustainability from cradle to grave of the fuel cycle as compared to effects of using other sources of energy. Biofuel-production research directions and agendas should be developed for those other components, as is discussed here for U.S. water quality, demand, and supply. It is only with the full system perspective at appropriate scales for considering effects and decision making that sustainability of the bioenergy system can be addressed.

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Chapter 3

Feedstock & Conversion Interactions – Identifying Industry Needs

Douglas L. Karlen

One of the primary goals for this workshop was to actively involve biofuel industry representatives in all phases of planning, presenting, and discussing what is needed to ensure the U.S. has sustainable feedstock supplies for advanced biofuels. The planning team's specific goal for this chapter was to encourage industry representatives to let the research community and decision makers know what is needed from their perspective to achieve sustainable feedstock supplies and appropriate conversion platforms for the various materials. We sought to learn what the biofuels industry needs to encourage and sustain the fiscal and human investment that will drive development of advanced biofuels. We also wanted to know what they considered to be the primary knowledge gaps or unanswered research questions from their perspective. A writing team was identified and an outline was prepared, but due to the possible perception that any of the potential authors would be speaking for their industry rather than as an individual, a facilitated discussion rather than a presentation was used to examine this topic. This chapter captures the essence of that discussion.

Industrial use of biomass falls into two general categories based on potential processing platforms-biochemical or thermochemical. Both categories can be further subdivided by processing options (i.e. burning to create electricity, using various forms of pyrolysis to produce bio-oil and char, and gasification to produce syngas can all be classified as different forms of thermochemical decomposition) that will ultimately affect the value of every possible biomass feedstock source. Furthermore, as biomass proceeds from a specific type of plant material or feedstock to a specific type of fuel (e.g. ethanol, butanol, biodiesel, or jet fuel) the ultimate economic value of both the feedstock and the proprietary processing operations become increasingly business sensitive. Therefore, the first lesson learned was that when you cross over from the public to the private sector, issues of confidentiality, proprietary knowledge, and public perception become increasingly important for all potential feedstock sources, conversion platforms, and the interaction between feedstock and conversion platform. The second lesson was that there will be, and in fact has to be, multiple feedstock materials. As indicated by the regional roadmaps, there will be no "silver bullet feedstock" that's going to work nationally or internationally with regard to advanced biofuels production. Rather, optimum feedstock selection will be regionally or even locally specific in some situations.

Building upon these two lessons, the biofuels industry does have a lot of research needs and unanswered questions, but because most industrial biofuels profit centers are still "in the red," it was difficult for team members to express those needs without alluding to proprietary information. Sharing current, cutting-edge results may be desirable in an academic or public sector environment, but since the answers may be the difference between staying in business and redirecting investments, team members were either reluctant or unable to do so. For example, to accurately categorize feedstock and conversion technologies according to the theoretical percent conversion (i.e. gallons of a specific fuel per ton of feedstock), proprietary and business sensitive information would undoubtedly have to be shared or at the least would be brought into question.

One of the most direct research and policy questions that the writing team identified with regard to feedstock and conversion platform interactions was the current need for a standardized, government-accepted, and non-changing carbon intensity protocol that could be applied by feedstock, region, and agronomic practice (e.g. tillage practice, fertilization, drainage, irrigation, crop rotation) when making life-cycle analyses for their various proprietary business decisions. This was closely followed by the need to know the trending capabilities for those calculations, to have a better understanding of what policies would likely be implemented for updating those predictions and to have reasonable guidelines with regard to the expectations for responding to future policy issues. The third critical need was for agreed upon protocols that could be used to calculate the realistic costs of feedstock production. For example, what is the fair and equitable distribution of feedstock payments to growers, consolidators, or investors? The writing team also questioned if feedstock supplies would eventually be traded as a commodity like corn, soybean, wheat, and cotton, or if the biofuels feedstock supply would be dominated by vertical integration. The fourth need was for independent, third-party services to provide accurate, reliable and readily-available feedstock quality parameters such as: (1) ultimate and proximate analyses, (2) biochemical composition, and (3) ash or other contaminate assessments. The writing team suggested that industry representatives would want access to the feedstock materials that were analyzed by the approved independent services for subsequent in-house evaluation and process testing. One way to accomplish this would be to include Material Transfer Agreement (MTA) guidelines in the rules and regulations established to oversee the biofuels feedstock conversion processes.

After presenting the research and policy questions developed by the industrial writing team, a facilitated discussion enabled workshop participants to further discuss these issues. The remainder of this report consists of an edited transcript from that discussion.

Participant A

We have heard of several different platforms for conversion of feedstock to biofuels, but why do some consider them to be mutually exclusive? I am familiar with a local ethanol plant that wants to make their grain-based ethanol “greener” by using corn cobs in their gasifiers. The company went out and developed contracts with farmers to supply cobs so that the plant could determine what problems might be encountered with this plan. The first issue was permitting, an issue that has prevented this small company from using corn cobs as a feedstock. There are no standards, so this has become a major issue. Furthermore, natural gas prices have recently plummeted, so now there is even less incentive for trying to advance a technology that would be beneficial to producers, processors, and consumers. These are issues that must be answered through research and policy. How do we most efficiently integrate across these complex issues?

Furthermore, at a recent USDA Farm Services Agency (FSA) meeting there was a lot of discussion regarding the Biomass Crop Assistance Program (BCAP) and the perception that those developing the program were getting “cold feet” with regard to a commodity support program for feedstock. Maybe this isn’t the forum to discuss those interactions, but from research, industry, and government agency perspectives, what are some of the limiting factors that need to be thought of? If we want to get feedstock supply and biofuels production industries together, we have to make sure those partnerships are supported in all aspects of their decision making, especially with regard to long-term risk and return on investment. Furthermore, there’s not going to be one model for the United States or for the Midwest or one model for the Southeast. Natural resources differ and therefore, we’re going to have to look at multiple models. What works in one state is not going to work everywhere. There simply will not be one silver bullet.

Participant B

I see the issue of feedstock and commodity interactions as a battle focused on the economy of scale. With regard to feedstock production that is undeniable diversity across landscape and among feedstocks that must be integrated using landscape concepts. As was just stated, there is no one-size-fits-all with regard to feedstock conversion to biofuels. Nature provides us with tremendous diversity, but most discussions with industry representatives focus solely on economies of scale. The perception is that you've got to get big to be economically viable and therefore we need commodity feedstocks. But how do you make number two yellow switchgrass? How do you develop commodity markets for all of the different feedstocks? I think that dichotomy between distributed and consolidated conversion is a major hurdle that currently blocks many of our discussions with industry and must be overcome by bringing feedstock producers and consumers to the same table. Natural diversity means that for any geographic region there will be different qualities, quantities, and types of feedstock. The research challenge is how to fit that diversity into a broad national program where economically viable conversion systems may require 2,000 tons per day of nicely-packaged, uniform biomass?

Participant C

I'm with the Soil and Water Conservation Association and would like to know if current efforts to achieve standardized, government-accepted uniform capacities and intensities, including carbon intensity calculations and other regional feedstock issues, are considering what others have already done or if we even know what they are doing. The last thing I want to see as an outcome from this Workshop is an effort to reinvent the wheel.

Participant D

I will try to address that question because it is one that we are also running into very often. There are a lot of company models, whether they are biophysical, economic, or legal. We also generate several within our own group. But, then, I also have to think about how those models are going to be reconciled with other national, international, government or academic groups. We also have to think of that as well, and, I don't know if anyone would like to comment on that situation.

Participant E

I've been on the receiving end for some of those different models. One area that I think is important from a research community point of view is that a more standardized way of modeling would really benefit all of us. It seems that every time I encounter a new model, there are at least 50 assumptions and data to confirm those assumptions may or may not be easily available. From my perspective we need some way to more clearly display the assumptions if possible, and when you see the modeling results, they need to be presented in a way that is specific to the question being asked. In a project we have run with corn stover, we are trying to compare a lifecycle analysis of our corn stover harvest operation with other publically available estimates of corn stover from throughout the U.S. What I have found is that as soon as you start to use the information in those papers as a starting or stopping point, then your intermediates are all different and the numbers are just not comparable. Therefore, I think there's a real need for standardization of models. We need to make it easier to show your assumptions and easier to exchange assumptions. Think about it as if you did transcript profiling (a technique for complete characterization of plants in a breeding program). When we began, we tried to profile everything in some experiments but nothing in others. Since then, we've developed a procedure so that we can work very nicely with different divisions within the company. I think that in modeling, particularly with large integrated datasets, some sort of ability to move across models is what we really need to develop.

Participant F

This has already been said, but I want to make sure it's heard by everyone at this Workshop. When you look at any value proposition (i.e. putting together a business proposal for driving steel into the ground), it's absolutely essential to know how big the project is. What are the expectations? Is it a billion, is it two, or is it half of that? With regard to biofuels, it's going to come down to knowing how your fuel module is going to be regulated and what feedstock is going to go into it. Currently, at the research level, we know that we are under RFS2 (Renewable Fuel Standard 2) guidelines. If those rules are applied exactly as written for any crop, we can develop a reasonable conclusion. We can say what the crop is worth, what the fuel is worth, and therefore we can develop an accurate value proposition. This is straight forward, easy to understand, and in theory everyone could agree that the calculation is as it should be. But, as the regulatory framework moves on, the same stroke of a pen that resulted in a decision to invest and build something can suddenly make that investment a dinosaur. From an industry perspective, we want to make sure that everything is calculated correctly up front and that the rules will not be changed. This is the only way to decrease investment risk and be sure the best options are chosen. For illustration, let's say that CO_2 is worth between $0 and $600 per ton. By knowing the carbon value, certain types of conversion platforms will ultimately win out, and they will be most applicable for certain types of biomass. Based on this industry need, it is important for an independent, science-based group such as this to be certain that the same rules and assumptions used for a business decision are applied throughout the life of the investment. A standard or other government accepted rule that has already gone through regulatory process is absolutely essential. The biofuels industry must therefore know how to estimate the delta around for any carbon intensity rule in order to know how any proposed fuel module will be regulated.

Participant G

From my point of view, if you look at where some of the big oil companies are doing their research and making their investments of billions of dollars, it's easy to see that this is not in the U.S. but rather in places such as Brazil. As a result, I think there are some examples that could be examined to develop a better understanding of what it takes to develop a viable biofuels infrastructure. By looking at the various policies to determine what has worked and what has not worked, we could learn a lot. If the oil companies can go to where the feedstock is already in the ground and take an existing infrastructure and either convert it to a more advanced biofuels themselves or work with groups that can, that is the option they will take rather than coming to or staying in the U.S. and trying to build the infrastructure from the ground upward. With the exception of a recent development in Florida, I think it is likely that we will have to look primarily at examples from outside the U.S.

Participant H

I would like to share some of the questions that I have been asked by my industry colleagues as well as state regulators. When you have one of these facilities proposed in the state, how much water is it going to use? What are the atmospheric emissions from this plant going to look like? What sort of waste products is it going to produce and where are they going to go? Be they ashes or some sort of digestive substrate, it's very ironic that I get the questions from industry or the people proposing the plants and then, maybe three months later, the state regulators call up and ask me the exact same questions. I tell them both, I really have no idea! We don't have anything like this yet, so, where do you go to get those types of answers? I haven't been asked about the carbon footprint or those types of things just yet. They're more interested in where the rubber meets the road. If this is what we are regulated on today, I need to permit this facility-how do I do it?

Participant I

I think we have kind of a dichotomy if we are trying to compare the current fuel/oil industry that operates on a colossal scale with the emerging biofuels industry. They operate with a uniform product that is distributed through an established infrastructure, whereas biomass is inherently local, inherently diverse, and if we are harvesting it sustainably, is going to be site-adaptive. So, I'm not sure how we standardize biomass that comes from inherently variable landscapes. As agronomists, the problem is, how do you match that inherent variability with a fuel industry that is highly uniform, massive in scale and nonexistent at the small local scale.

Moderator

We have obviously just begun to tap a very challenging chapter to this whole endeavor. The easy way out is to divert further discussions to the regional groups and in order to stay on time, that's what I'm going to do. However, I want to emphasize again that the primary outcome from this workshop will be the Regional Roadmaps that I expect to be "living documents" and accessible to all participants on the website for years to come. Hopefully many of the industry needs and excellent questions raised by this dialog will be answered through subsequent presentation and the regional deliberations. There will also be opportunities through the Regional Roadmaps to continue this excellent dialog.

Chapter 4

Sustainable Feedstocks for Advanced Biofuels: Water Resource Impacts of Feedstock Production and Conversion

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Introduction

Global biofuel production has increased six-fold in the last decade (Fingerman et al., 2010). The 2007 U.S. Energy Independence and Security Act (EISA) calls for 9 billion gallons (gal) of renewable fuels in the U.S. for 2008 and 36 billion gal by 2022, of which 21 billon gal is to be obtained from cellulosic ethanol or other advanced biofuels (Congressional Research Service, 2007). Similarly, the European Union recently established a binding target of 10 percent biofuels for transport fuels for each member state by 2020 (Commission of the European Communities, 2008).

The production of biofuel feedstocks and conversion of these feedstocks to biofuel can have profound effects on water resources at local to regional scales, although the manner in which a shift to biofuel feedstocks affects water availability and quality is complex, difficult to measure and predict, and varies regionally (National Research Council, 2007). The effect of biofuel feedstock production on water-resources is a function of the interdependences among annual weather conditions, long-term climate variations, feedstock type, feedstock and energy prices, environmental setting, and other factors.

The purpose of this white paper is to summarize current understanding of the effects of biofuel production on water resources, including both quantity and quality in the ground-and surface-water systems. The focus of the paper is on production of biofuel crops, with some limited discussion on conversion of feedstocks to biofuel. Moreover, we address what is known, with limited speculation about future climate, energy prices, and changes in biofuel feedstock type.

Water budgets

Water budgets provide an approach for evaluating the availability and sustainability of water supplies (Healy et al., 2007). A basin or regional water budget states that the rate of change of water stored in a region is equal to the sum of the total rate of water inflows to and outflows from the region. A water budget can be developed for any geographic unit, although budgets are most readily developed for surface water basins. Temporal changes in water budgets are used to assess the effects of climate variability and human activities on water resources.

Biofuel production, as well as any land-disturbing activity or water diversion activity, modifies water budgets in a variety of ways. Water budgets change in response to changes in plant communities, which affects evapotranspiration (ET), soil moisture, groundwater storage, and surface runoff; alterations in natural drainage patterns through ditching, subsurface drainage, channel straightening, and clearing and snagging of streams; irrigation; and modifications to the land surface, which changes infiltration rates and runoff patterns.

Generalized water budget

The water budget for a basin unaffected by withdrawals, diversions, or return flows (Figure 1) is relatively simple, although components of the budget can be difficult to measure. Water enters the basin through precipitation and perhaps through regional groundwater flow if the groundwater divide is not coincident with the topographic basin divide. Water is stored in a number of reservoirs in the basin, including primarily the unsaturated zone, saturated zone (or shallow groundwater system, which fluctuates in thickness), groundwater system, and surface water system, including flowing streams and surface depressions (e.g. ponds or lakes). Water exits the basin through ET, streamflow, and groundwater flow. The rate at which water moves through each reservoir is a function of climate and weather; vegetation; surface and subsurface geology, including soil and aquifer properties; and topography.

Biofuel production and the water budget

Water budget changes resulting from conversion of land to biofuel (or any) crops can occur in the absence of irrigation. Changes in the water budget can be associated with (1) changes in the amount of water removed from the basin in biofuel feedstock, (2) changes in ET, potentially affecting soil moisture, groundwater recharge, and streamflow (Figure 2), and (3) changes in soil properties resulting from compaction and tillage, which can affect infiltration and thus recharge and streamflow. Removal of plant material from the land also affects rates at which water moves across the land surface and into the soil.

Changes in irrigation practices can occur when crops or fallow lands are converted to biofuel feedstock production, although this could be either an increase or decrease in irrigation depending on the crop and the region of the country. The distribution of water stored in the various reservoirs is modified by groundwater pumping and surface-water withdrawals, as discussed below. The situation is further complicated when interbasin transfers are used to supply irrigation water (Figure 2).

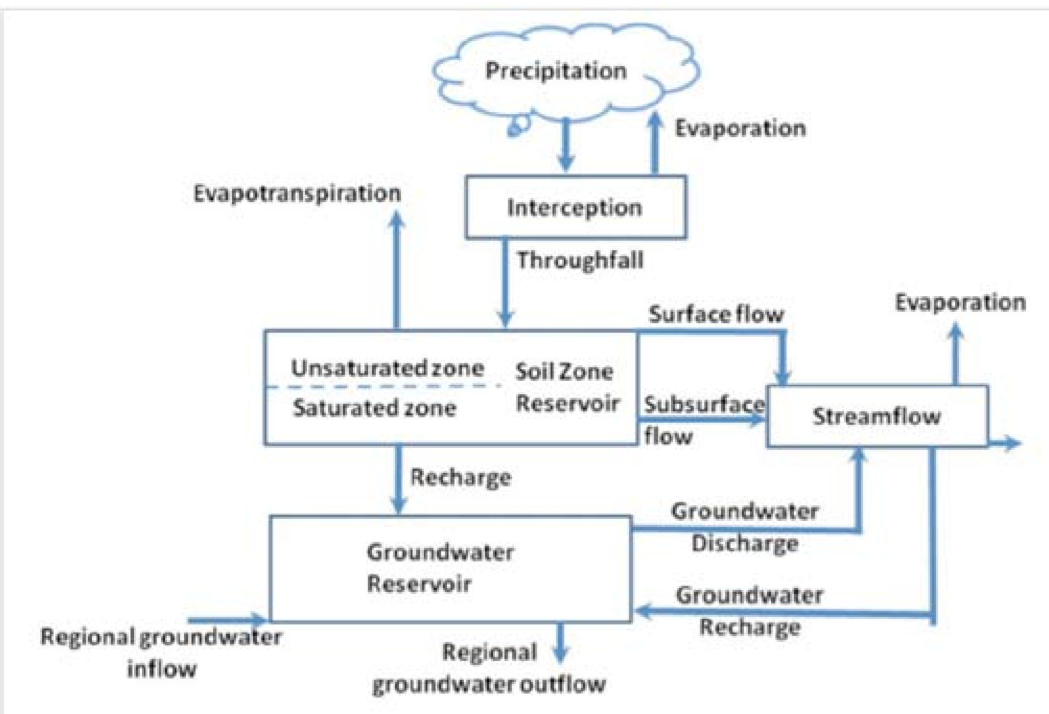

Figure 1. Generalized water budget for basin with no withdrawals or return flows (modified from Healy et al., 2007; and Fingerman et al., 2010).

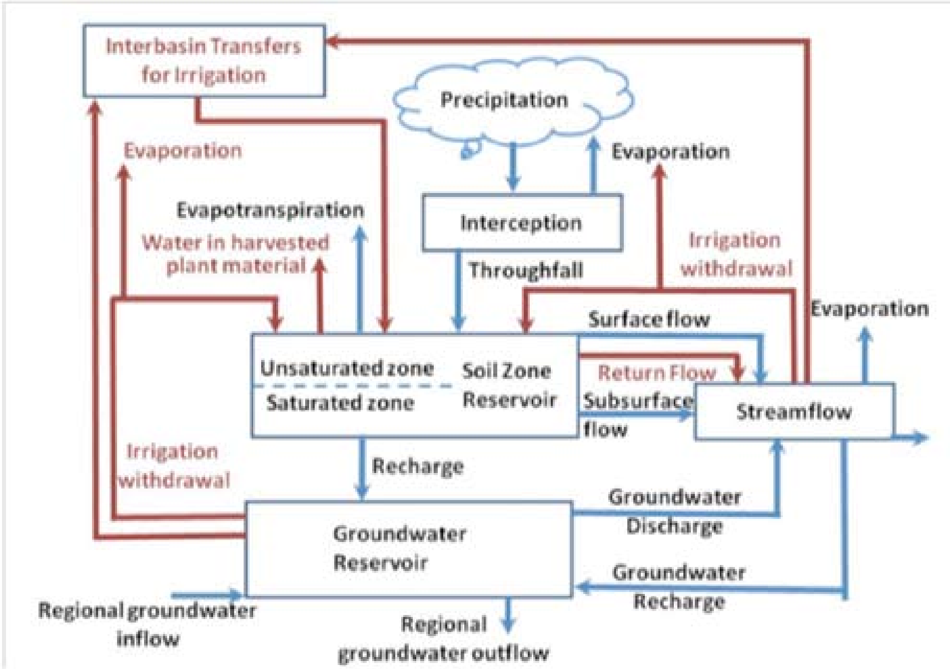

Figure 2. Generalized water budget for basin with irrigation (modified from Healy et al., 2007, and Fingerman et al., 2010).

Groundwater Withdrawals and the Water Budget

About 25 percent of all freshwater is stored as groundwater (Alley et al., 1999). Additionally, groundwater contributes, on average, about 40 percent of total streamflow in the U.S. (Alley et al., 1999), and as much as 80 percent of total streamflow in some parts of the Nation (Winter et al., 1998), indicating the large role of groundwater in the water budget.

In 2005, about 128,000 million gallons per day (Mgal/d) of water was withdrawn in the U.S. for irrigation, compared to about 44 Mgal/d withdrawn for public water supply (Kenny et al., 2009). About 40 percent of irrigation withdrawals were from groundwater. Primarily because of withdrawals for irrigation, groundwater levels have declined dramatically in many parts of the U.S., including more than 100 feet (ft) in parts of the High Plains aquifer in Kansas, New Mexico, Oklahoma, and Colorado (McGuire et al., 2000); and more than 70 ft in parts of the Central Valley of California (Faunt, 2009). Because of the important role of groundwater in the hydrologic budget and because of the large withdrawals of groundwater for irrigation, the sustainability of groundwater withdrawals is an important consideration for biofuel production.

Under pre-development conditions, the amount of recharge to an aquifer is approximately equal to the discharge, with the storage in the aquifer fluctuating about a long-term mean (for example, Figure 3). Water that is withdrawn from the aquifer must be offset by an increase in recharge, a decrease in storage, a decrease in discharge from the aquifer, or a combination of these three (Alley et al., 1999).

Figure 4 illustrates some of the effects of pumping on groundwater and surface water. In the pre-development condition (Figure 4A), the groundwater divide is coincident with the topographic, or surface water divide. Groundwater discharges to both the stream and the lake. With the initiation of pumping (Figure 4B), the groundwater level declines indicating a loss of storage, and the amount of groundwater discharging to the stream decreases because the groundwater divide moves closer to the stream resulting in a smaller volume of contributing aquifer. Whereas groundwater was discharging to the lake under natural conditions, pumping can cause the groundwater flow direction to reverse such that the well is capturing water from the lake. (The same situation would exist if the lake were a stream).

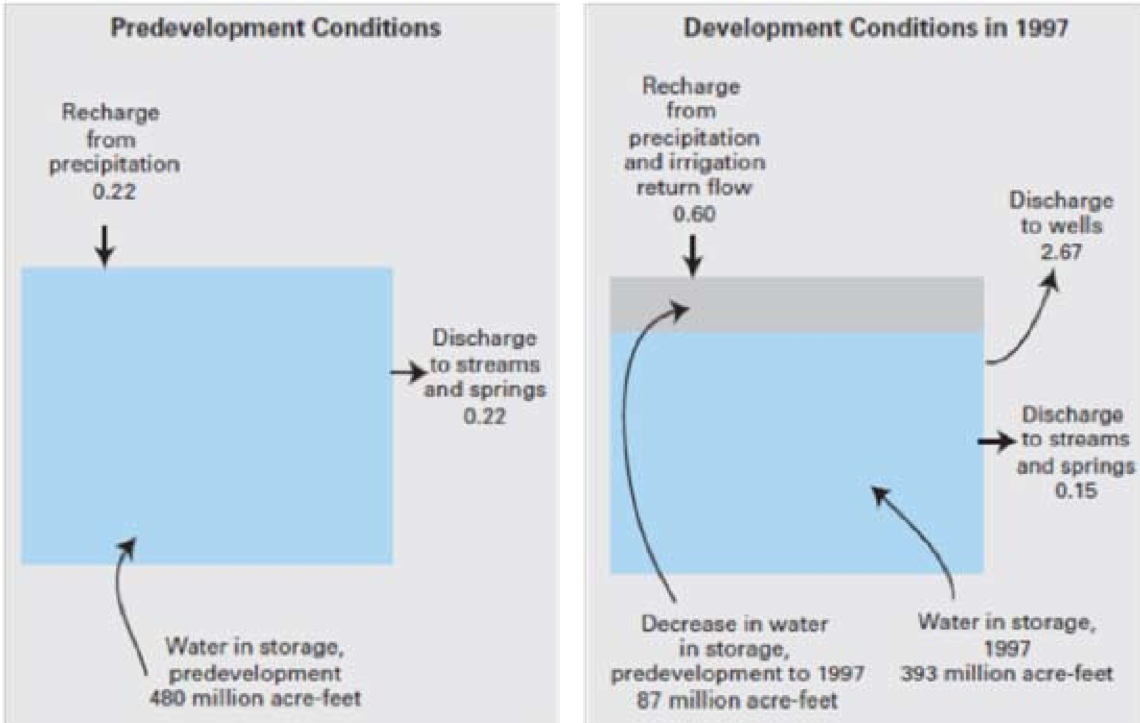

Figure 3. Groundwater budget for the south-central High Plains aquifer during pre-development and in 1997; values are in million acre-feet per year (from McGuire et al., 2000).

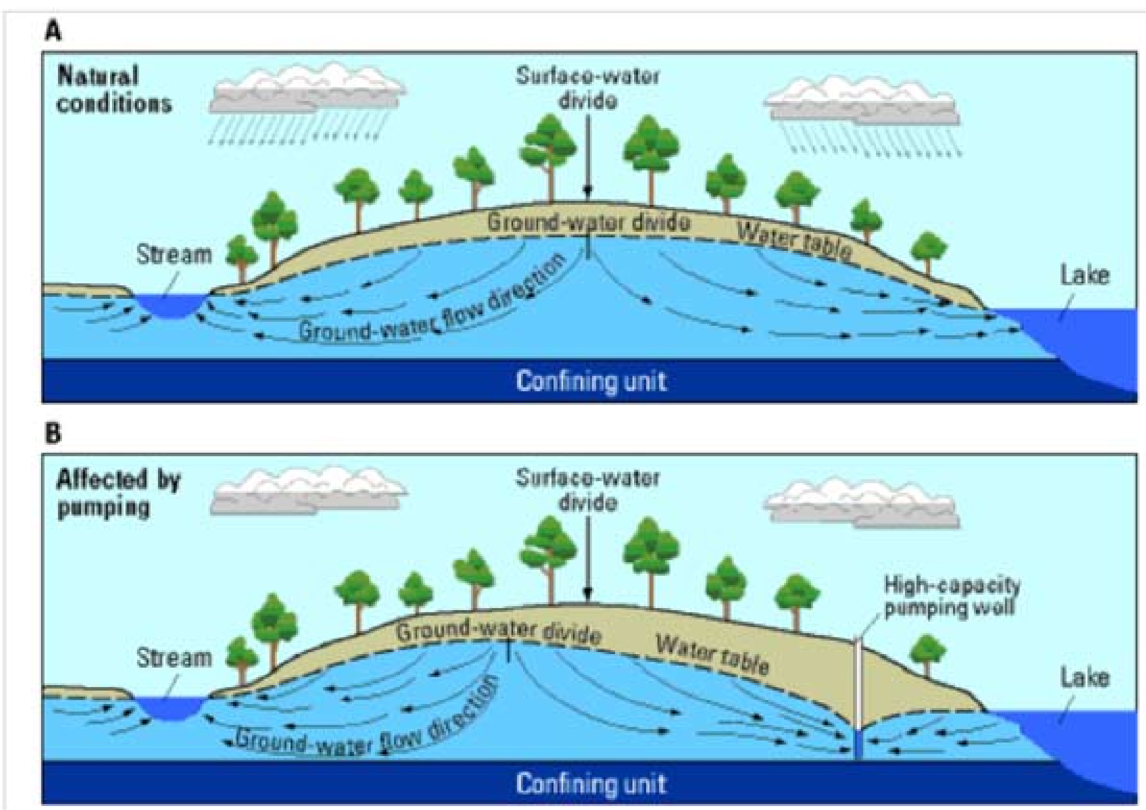

Figure 4. Generalized groundwater flow for (A) natural conditions and (B) pumped conditions. Note that the topographic and groundwater divides are coincident in A but not in B. (from Grannemann et al., 2000).

In general, the source of water to the well comes entirely from aquifer storage when pumping is initiated, resulting in declines in the aquifer water level, which translate to greater energy costs for pumping. As pumping continues at a steady rate, more of the withdrawal is captured from streamflow and less is removed from storage. In most cases, change to natural recharge is negligible, although, as in the example (Figure 3), recharge resulting from changes in surface conditions can occur. At steady state and over a long period of time, the amount water withdrawn by pumping approximates the streamflow (or lake) capture. The amount of time for this to occur, however, depends on many factors, including characteristics of the aquifer, the distance from the well to the surface water body, and the number of other withdrawals from the aquifer. This means that effects of pumping may not be seen in streamflow for many years, or even decades (Alley et al., 1999), but the effects can be dramatic (Figure 5).

A common misconception about groundwater budgets, however, is that the pre-development water budget can be used to determine the amount of sustainable groundwater development (e.g., Theis, 1940; Bredehoft et al., 1982). The magnitude of sustained withdrawal is dependent on the amount of aquifer discharge that can be captured, but many years of pumping may be required before that dynamic equilibrium is reached or the effects of pumping are fully known. Numerical models typically are used to evaluate the potential long-term effects of groundwater withdrawals.

Climate change and water budgets

Water has been called “the Nation’s fundamental climate issue” (Lins, et al., 2010). Effects of climate variability and change on agriculture, as well as ecosystems and energy production and use, are mediated by water. Although global air temperatures are showing an unambiguous increase in response to increased greenhouse gasses and aerosols (Karl et al., 2009), climate change effects on water resources currently are less evident. It is apparent, however, that past water resources (and climate) conditions are no longer a reliable indicator of future conditions (Milly et al., 2008). In addition, one clear effect of increased air temperatures will be an increase in ET, although effects of increased CO2 in the atmosphere could have compensating effects on stomatal openings and thus ET (Gedney et al., 2006). As suggested by the water budget in Figure 1, an increase in ET will, for the same amount of rainfall, result in a decrease in soil moisture, runoff to streams, and groundwater recharge. Reduced streamflow and groundwater recharge could mean less water for irrigation and other purposes. Decreased soil moisture could mean an increased demand for irrigation for the same crop. Additional effects of climate change are discussed in subsequent sections.

Water use

In this section, we discuss water use for biofuel production and conversion in the context of total water use by the Nation. Information on irrigation and factors affecting irrigation is discussed, along with a discussion of water use by biorefineries. Because precise information is not available on the purpose for which individual crops are grown (i.e., biofuel or food), it can be difficult to identify direct effects of biofuel feedstock production on water resources. We do, however, discuss trends in crop production and irrigation for 2002-2007, a period during which demand for biofuel feedstock increased.

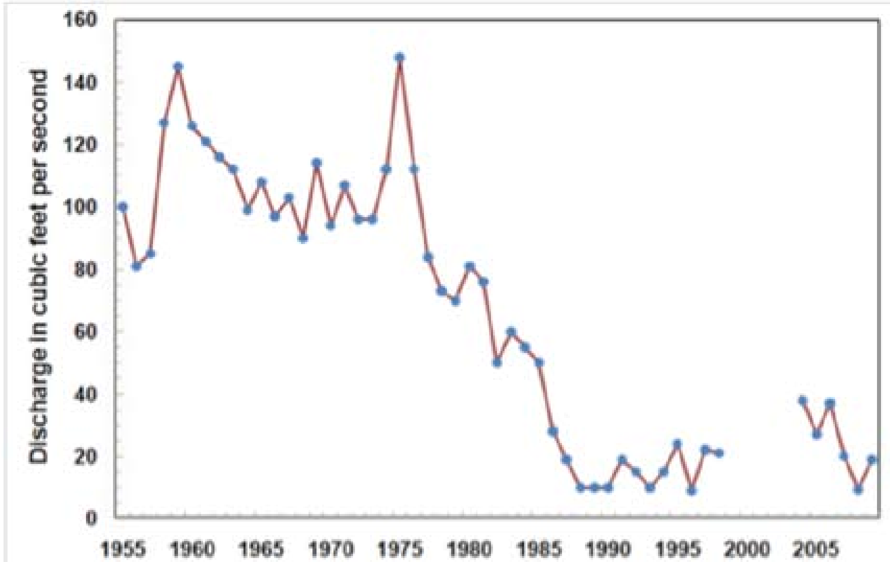

Figure 5. Minimum annual streamflow for the Sunflower River at Sunflower, Mississippi, showing effects of withdrawals from the Mississippi River Valley alluvial aquifer on streamflow (from Welch et al., 2010).

Total withdrawals for the Nation by Sector

The United States has extensive freshwater resources, but the water often is not where we want it, or available when we need it, or suited for the purposes for which we need it. Water use most commonly is reported as a withdrawal amount and sometimes as a consumptive use. Water withdrawals for out-of-source use (away from the stream or aquifer), whether for irrigation, municipal, or another type of use, currently are measured in terms of the quantity of water diverted or withdrawn from the source (Kenny et.al., 2009).

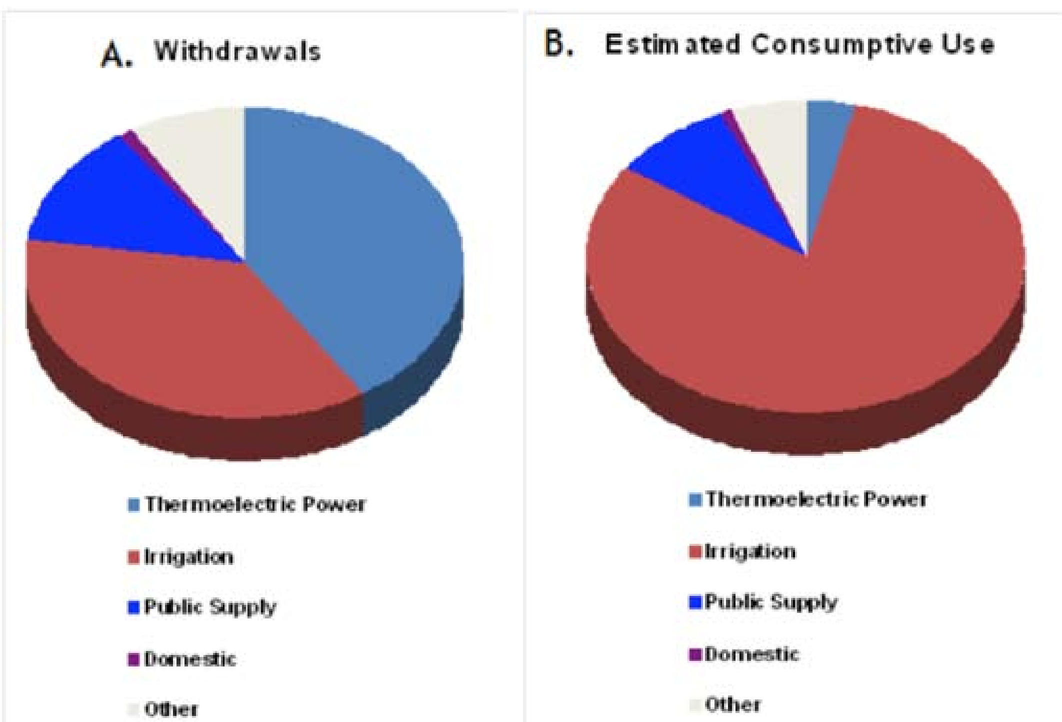

Figure 6. 2005 water withdrawals and 1995 estimated consumptive use, by sector (Natural Resources Conservation Service analysis of U.S. Geological Survey water use data; Kenny et al., 2009)

In many cases, states and other institutions regulate the quantity of water extracted from a water source by issuing withdrawal permits according to state laws and interstate compacts, although not all withdrawals require permits. For example, California does not have a process for regulating groundwater withdrawals (California Environmental Protection Agency, 2010), and storage in parts of the Central Valley Aquifer declined more than 60 million acre-feet between 1962 and 2003 (Faunt, 2009).

Irrigation accounts for about 37 percent of U.S. withdrawals (Figure 6A). Nationally, irrigation accounts for the second largest amount of water withdrawn from the Nation's rivers and aquifers, and is exceeded only by water withdrawn for thermoelectric power production (41 percent). Although water withdrawals are the basis for legal water use rights and the most convenient and widely used measure of water use, withdrawals are only part of the hydrologic picture.

Consumptive use, the portion of withdrawals that is evaporated, transpired or otherwise lost to the immediate basin, is an important hydrologic measure of water. Consumptive use (CU) is difficult to quantify and estimates are hard to verify. However, CU is the more significant hydrologic measure for the water balance because some of the withdrawn water is returned to the system and is available for other uses, whereas water that is consumptively used is unavailable for subsequent uses in the basin.

The U.S. Geological Survey (USGS) National Water Use Program provided estimates of CU for 1960-1995 (Solley, Pierce, and Perlman, 1998). CU estimates made for 1995 and earlier indicate that irrigation has a significantly higher ratio of CU to withdrawals than other sectors. Based on the 1995 estimates, irrigation CU is more than 80 percent of all water withdrawals in the Nation (Figure 6B) and more than 90 percent of all withdrawals in some arid locations. Although withdrawals for thermoelectric power generation are the largest for any of the sectors, the CU is small because most of water is returned to the hydrologic system (albeit generally at warmer temperatures), whereas most of the water withdrawn for irrigation is utilized by crops and evaporated or transpired back to the atmosphere. To provide a common basis for comparison, the share of withdrawals reported as CU in 1995 was applied to the 2005 withdrawal levels as shown in Figure 6B.

Irrigated agriculture will continue to face pressure from competing uses for both surface and groundwater supplies. Agriculture accounts for the highest CU both in absolute terms and as a share of withdrawals. When other sectors seek additional water resources, they often turn to agriculture as a potential source of water to meet growing needs. Continued pressure on agricultural water supplies from competing water uses is assured because of the lower economic return per unit water, high current use, and the volume of water controlled by agriculture.

Irrigation Withdrawals and Return Flows

Current agricultural practices rely heavily on irrigation (Figure 7) to (1) maintain high crop yields in regions that, prior to large-scale adaptation of land to irrigated agriculture, were relatively unproductive and (2) boost crop yields in areas which were previously productive without irrigation. Irrigation is common not only in the arid west, but also in the Midwest and South, where annual average precipitation is 40-60 inches. In the absence of irrigation, it is unlikely that crop productivity could be maintained at current levels over much of the agriculturally intensive areas of the United States. Irrigation in most regions of the U.S. relies heavily on groundwater withdrawal, for which recharge rates often are orders of magnitude lower than withdrawal rates.

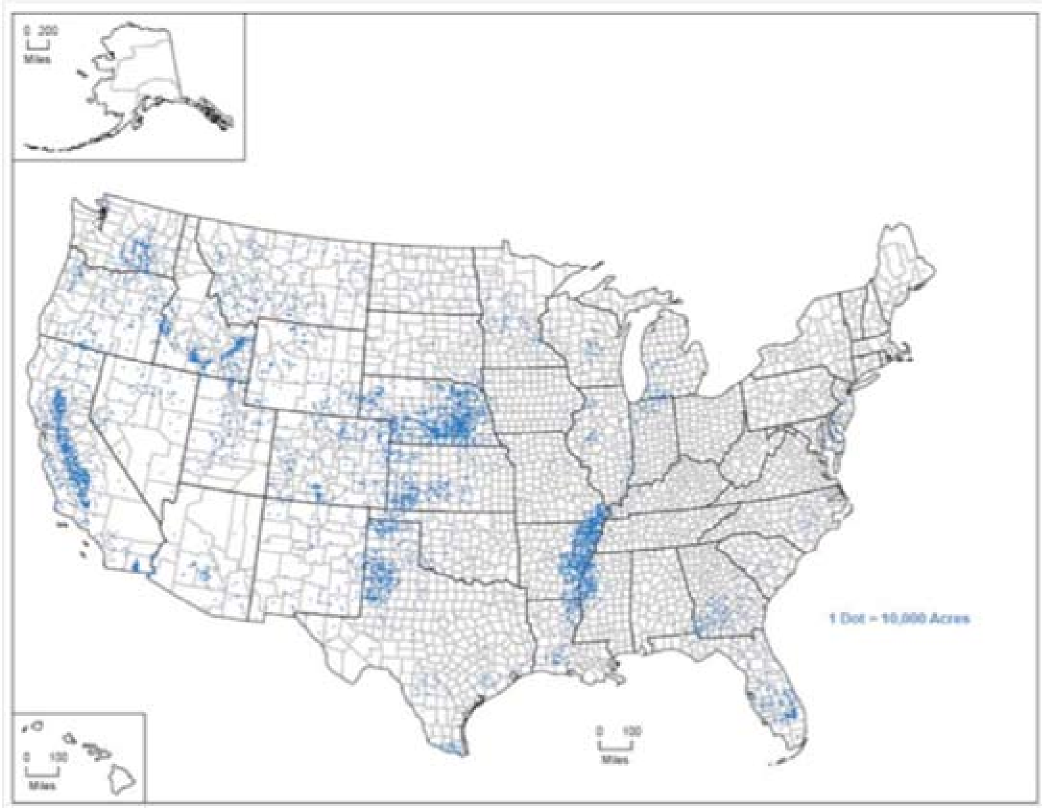

Figure 7. Acres of irrigated land, 2007. (Source: U.S. Department of Agriculture, 2007 Census of Agriculture).

Water that is applied to agricultural fields through irrigation will eventually either be evapo-transpired into the atmosphere, replenish groundwater, run off through streams or other water ways, or leave the watershed in plant material (Figure 2). The relative distribution of these fates will vary with a wide range of environmental conditions and topographical and edaphic features. In any given region, the consequences of irrigation result in deviation from the natural water cycle. For example, if water used for irrigation is extracted from groundwater, then any water that is evapo-transpired away or flows into streams likely will affect the long term sustainability of that aquifer.

Issues related to large-scale use of irrigation are not limited to the sustainability of the source of water, but also to the impacts that occur when the natural hydrologic cycle is perturbed. A large proportion of irrigation water is returned to the atmosphere through ET. This increases latent heat flux and is likely to influence the tropospheric moisture and temperature profiles, precipitation patterns, and other climatic components of the atmosphere (e.g., Boucher et al., 2004). Further, the effects of altering ET due to irrigation may have consequences that extend beyond where irrigation is used, to have non-local impacts on climate (e.g., Sellers et al., 1997).

The demand for irrigation likely will increase as more pressure is placed on crops to meet benchmarks established for renewable fuels. The potential for increased irrigation can be driven by both increases in the land area devoted to ethanol production and higher water use requirements for second generation biofuel crops (e.g., Hickman et al., 2010; Van Loocke et al., 2010). The short-term issues related to irrigation likely will focus on grain-based ethanol production; corn currently dominates as the feedstock from which most ethanol is produced in the U.S. As a result, any significant change in the grain market could result in the conversion of fallow lands to agriculture or vice versa. Given the increasing role of ethanol as a fuel source, the economics could favor an increase in land area devoted to corn production, at least in the short term. In regions where irrigation is required, this can result in increased demand for water.

The higher rate of water consumption associated with irrigated versus non-irrigated practices is likely to extend to any biofuel feedstock. The role of corn as the dominant feedstock for ethanol production is likely to subside in the longer term as other feedstocks, particularly from cellulosic plant material, become more commonplace. Despite the numerous potential advantages of a cellulosic-based renewable fuel industry (U.S. Department of Energy, 2006), there are many uncertainties associated with the viability and impacts of these second generation feedstocks, particularly on the hydrologic cycle.

Factors Affecting Irrigation

Weather and Climate

Factors that determine the rates at which irrigation is applied are numerous and a large amount of research has gone into developing models to dictate optimal timing and amounts of irrigation (e.g., Food and Agriculture Organization of the United Nations, 2010). A major confounding issue surrounding irrigation is the uncertainty regarding future environmental conditions. Specifically, large-scale changes in the global climate system can influence rates at which irrigation will need to be applied, as well as the amount of water available for irrigation. For example, it has been predicted that increased CO2 concentrations will decrease ET from ecosystems in North America (Bernacchi et al., 2007), although, conversely, higher temperatures may lead to higher ET rates. Modeling analyses suggest that the rise in CO2 from pre-industrial levels already has increased the runoff into major rivers as a result of lower rates of ET (Gedney et al., 2006). The rates at which plants evapo-transpire, however, is only one factor determining irrigation rates for a given crop. For example, as climate warms, there is considerable uncertainty regarding changes in vapor pressure deficit (Parry, et al., 2007) raising uncertainty about whether more irrigation will be required. Precipitation patterns in a warmer climate also are uncertain, but current model projections suggest that areas that currently have high amounts of precipitation will experience more precipitation and typically arid areas (e.g., areas that may rely heavily on irrigation) will experience less precipitation (Parry et al., 2007). Therefore, any decision to establish large-scale plantings of cellulosic bioenergy crops should consider the current sustainability of existing irrigation as well as issues that might affect sustainability of irrigation under a range of future conditions.

Crop Type

Whereas the majority of the current U.S. ethanol is produced from corn grown in the Midwest, the use of cellulose as a feedstock for ethanol could rely on vegetation grown in all regions of the U.S. (U.S. Department of Energy, 2006). With the large range of species identified as sources of cellulose, consideration of the necessary implementation of infrastructure to establish and maintain high rates of productivity will be required.

The amount of water required to grow biofuel crops varies, of course, with crop and region, because precipitation, evapotranspiration, and soil conditions vary regionally. Corn requires about 642,000 gal of water per acre, not including water loss through runoff and aquifer recharge. This equates to 168 gal per pound of corn produced, or about 23.6 inches of rainfall during the growing season, although corn can reportedly suffer from lack of water even if the annual precipitation is as much as 39.4 inches (Pimentel et al., 1997). Soybeans require approximately 491,000 gallons of water per acre, but soybean yield per acre is less than half that of corn by weight. Hence, one pound of soybeans requires approximately 240 gallons of water (Pimentel et al., 1997). Water use by cellulosic feedstocks requires further research (Powlson et al., 2005).

Any alteration to species composition is likely to have an impact on ecosystem hydrology, but the extent of the effect depends on local conditions. Key changes likely are to be attributed to three factors: the ability of a species to acquire water (e.g., root distribution and depth), the duration of the growing season, and the physiological control of ET. A recent comparison of ecosystem water use (i.e., ET) by vegetation growing in Central Illinois shows that the second generation biofuels feedstocks miscanthus and switchgrass use more water than corn (e.g., Hickman et al., 2010). In this study, it was shown that an extended growing season for the perennial grasses was the dominant factor behind the increased water use, but also that the rate of water use during peak season was higher for miscanthus than for corn. Although irrigation is not commonly used in the location where this study was conducted, it is predicted that these species will have higher ET rates across nearly the entire Midwest, suggesting that perennial grasses could require more intensive irrigation in locations where precipitation is limiting. Kinry et al. (2008) evaluated corn and switchgrass biomass yields for 4 different regions (Nebraska, Missouri, Iowa, and Texas), and found that switchgrass biomass yields per unit of water were greater than for corn at all sites except Texas.

Regional ecosystem modeling has shown that the impact of altering landscapes to accommodate the perennial grass miscanthus would increase annual evapotranspiration throughout most of the Midwestern U.S., but only when planting density increases above 25% (Van Loocke et al., 2010). Although this planting density is higher than most predictions of land cover devoted to perennial grasses, it is possible, and perhaps likely, that 'hotspots' of perennial grasses will be established in areas surrounding biorefineries. Thus, the possibility of having areas with planting density surpassing 25% coverage is probable. The issue of water use by biofuel crops, however, is not limited to perennial grasses in the Midwestern U.S. Rather, any change in the species composition of an ecosystem has the potential to alter the amount of water required by vegetation to maximize growth, and thus affects the overall water budget.

Energy Costs

Energy costs are an important factor influencing irrigation water withdrawals and, ultimately, the CU of water. However, energy costs, whether for equipment use or pumping irrigation water, are but one element of the total cost of producing a crop. The U.S. Department of Agriculture's (USDA) Farm Income projections report that 9-11 percent of the purchased inputs used in agriculture are direct energy sources (Economic Research Service, 2010).

Although there is a direct connection between increasing energy prices and increasing costs of production, this connection does not necessarily translate into changes in water use. There are several reasons for the potential disconnect between energy costs and water use, including: (1) not all irrigation requires energy to move water, (2) irrigation may be required for the physical production of a more profitable crop, or (3) the crop being grown can have an economic response (combination of yield increase or quality improvement) that justifies irrigation even at higher energy costs.

Costs of supplying irrigation water vary widely, reflecting different combinations of water sources, suppliers, distribution systems, and other factors such as field proximity to water, topography, aquifer conditions, and energy source. Expenditures for irrigation water usually reflect accessibility of the water and delivery costs alone. Thus, costs to irrigators usually do not reflect the full social cost of water use, and because prices paid for water are rarely set in a market, water prices do not convey signals about water scarcity. States generally administer water resources and grant (not auction) rights of use to individuals without charge, except for minor administrative fees.

Cost Category	Farms Incurring Costs		Acres of Cropland Incurring Costs		State-level cost range	National average cost	Total national costs
	Number (1,000 farms)	Percent of total	Number (million acres)	Percent of total	Dollars per acre	Dollars per acre	$ million
Energy expenses for pumping groundwater	97.7	47.2	37.28	67.8	12 to 132	60.90	2,677
Energy expenses for lifting or pressurizing surface water	n/a	n/a	11.62	21.1	14 to 129	36.13	1,549
Water purchases from off-farm sources	80.5	38.9	13.07	23.8	1 to 630	70.00	720
Maintenance and repair expenses	126.6	61.2	45.1	82.1	7 to 179	18.20	821
Total costs							5,767

Table 1. Energy and other variable costs of irrigation water by source and category, 2008, for states with more than 5,000 irrigated acres (n/a, not applicable; Source: National Agricultural Statistics Service, 2009).

To generalize, groundwater typically is pumped on-site, and there will be an associated energy cost. Some surface water will have an energy cost if it is pressurized or pumped to other areas. Water is provided from two potential sources, on-farm (ground or surface) and off-farm. Off-farm sources often provide water through extensive storage and canal systems. In 2008, the average cost of water from off-farm sources exceeds that of on-farm sources despite the energy costs for pumping. Costs to agricultural producers can be examined for the costs associated with irrigation using data from the Farm and Ranch Irrigation Survey (National Agricultural Statistics Service, 2010).

Groundwater is used on more than two-thirds of U.S. irrigated acres, with the pumped groundwater supplying more than 37 million acres of cropland (Table 1). Energy costs in 2008 for states with more than 5,000 groundwater-supplied acres ranged from $7 per acre in Iowa to $132 per acre in Arizona. Average costs nationwide were about $60 per acre, and total expenditures for the sector exceeded 2.6 billion dollars.

Surface-water energy costs reflect pumping and pressurization requirements for conveyance and field application. More than 11.6 million surface-supplied acres incurred these costs in 2008, at an average cost of $36 per acre (Table 1). Costs ranged from $14 per acre in Illinois to $129 per acre in Wisconsin. Costs were $47 in California, $40 in Idaho, and $43 in Washington, three states of significant cropland irrigated by surface-water supplies. In general, energy costs are less for pumping surface water than groundwater because less vertical lift is required.

Nearly 40 percent of irrigated farms received water from off-farm water supplies, accounting for more than 13 million irrigated acres. Irrigators paid an average of $70 per acre for water from off-farm suppliers, including the 17 percent of farms reporting water at zero cost. Average costs ranged from $1 per acre in Minnesota to $630 in Hawaii. Average costs were $140 in Arizona and $143 in California, two states that apply more than 40 percent of the total off-farm supplied water in the Nation.

Changes in Crops and Irrigated Lands, 2002-2007

The primary biofuel feedstock over the past decade was corn processed into ethanol through a fermentation and distillation process. Acres planted to corn for all purposes (human, livestock and poultry feed, industrial, export, and ethanol) peaked at 93.5 million acres in 2007 with 86.5 million acres harvested. Since 2007, corn acres have declined slightly, with about 88 million planted in 2010. Between 2009 and 2010, the quantity of corn devoted to ethanol increased from 4.5 billion bushels in 2009 to 4.7 billion bushels projected for 2010.

The peak in corn acres in 2007 corresponds to the 5 year cycle of the Census of Agriculture, which collected data for 2007 (National Agricultural Statistics Service, 2009). The increase in corn production between 2002 (the prior Census of Agriculture year; National Agricultural Statistics Service, 2004) and 2007 is substantial:

- Planted corn acres increased by 19 million acres (about 25 percent);
- Harvested corn acres increased by 17 million acres (about 25 percent);
- Irrigated corn acres harvested increased by 3.4 million acres (about 35 percent);
- Corn production increased by 3 billion bushels (about 33 percent);
- Corn exported increased by 1 billion bushels (about 50 percent);
- Corn used as an ethanol feedstock increased by 2 billion bushels (about 200 percent); and
- Corn prices per bushel increased by $1.88 (about 80 percent).

The increase in corn acres from 2002 to 2007 is the result of both an increase in acres farmed and a shift of other crops to corn on currently farmed acres. The increase in corn acres was driven by many factors, including the increased corn prices from higher demand for both exports and ethanol use. Although the increase in the ethanol-driven demand was certainly an important factor in the increase in quantity of corn produced and the associated resources required, it is not the sole factor. With the available data, it is not possible to allocate the exact change in resources (land and water) used in corn-to-ethanol demand or to other drivers. It is possible, however, to gain some insight into the effects of biofuel policies on crop production from crop statistics, as suggested by the 2004-2007 changes in corn production shown above, and analysis of the 2002-2007 presented below.

Increase in Acres

Over the 5-year period from 2002 to 2007 there was an increase in harvested cropland of almost 7 million acres, a growth of about 2 percent. Of that increase, about 1.2 million acres were irrigated harvested cropland, also a growth of about 2 percent. The increase in harvested cropland was not uniform across the Nation, with some regions experiencing increases, and others declines (Figure 8). The increase in total acres, although significant, represents only about one third of the increase in corn acres in 2007.

The greatest increase in harvested cropland acres, both irrigated and non-irrigated, occurred in the Northern Plains (Figure 8). Irrigated harvested cropland increased more than 1 million acres, with about 90 percent of the increase occurring in Nebraska. Non-irrigated harvested cropland increased by about 4.6 million acres, with the greatest increases in North Dakota (more than 2 million acres) and South Dakota (more than 1.8 million acres).

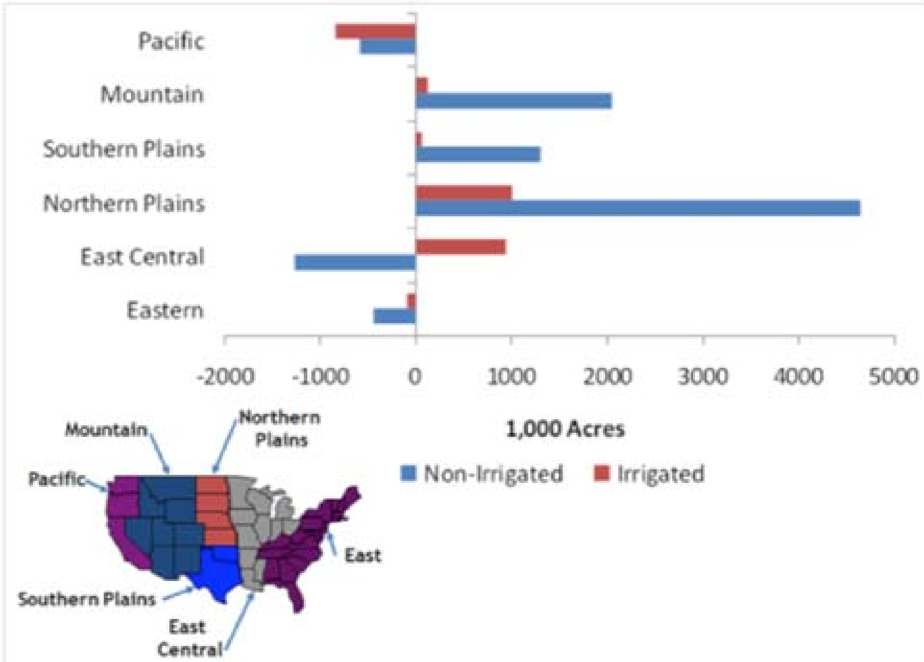

Figure 8. Regional changes in irrigated and non-irrigated cropland between 2002 and 2007.

Other regions also reported increases in harvested, non-irrigated cropland. The Mountain region increased by 2 million acres, with acreage increases in east-slope states and 70 percent of the increase in Colorado. In the Southern Plains, Texas accounted for the largest increase in non-irrigated cropland. The only region reporting significant increases in irrigated harvested cropland, other than the Northern Plains, was the East Central region. Within that region, 70 percent of the growth in irrigated area occurred in Arkansas, Mississippi, and Missouri. There were declines in both non-irrigated and irrigated cropland harvested in the Pacific and Eastern Regions.

Shift in Crop Type

Over the 5-year period from 2002 to 2007, there was a significant shift in the crops planted to enable the increase in planted corn acres. The major shift of increased non-irrigated corn acres and decreased soybean acres occurred in East Central region (Figure 9). The increase of 8.6 million corn acres was largely offset by the decline of 7.4 million soybean acres as producers responded to market conditions. The Northern Plains and Eastern region also increased their non-irrigated corn acres, but the amount of land shifted, although regionally significant, is not of the magnitude in the East Central region.

The shift in non-irrigated acres, which was critical to meeting the biofuel production objectives, also has a potential impact on the water resources of the region. One important effect is related to water quality, as corn has higher nutrient and chemical needs than soybeans, as discussed below. There also is a potential water quantity effect resulting from a higher corn evapotranspiration rates than soybeans, affecting groundwater recharge and streamflow conditions (Figure 1).

The most direct effect of crop shifts on water resources, however, is the change in irrigated acres. The change in irrigated acres is difficult to detect in Figure 9 because the change in non-irrigated acres establishes the scale of the Figure. Figure 10 provides a focus on only the shift in irrigated acres from 2002 to 2007. Figure 10 shows a similar soybean-to-corn pattern that was present for non-irrigated cropland. The Northern Plains had the greatest irrigated crop shift. Irrigated corn increased in all regions and irrigated cotton decreased in all regions. Irrigated wheat and soybeans were more variable, increasing in some regions and decreasing in others. This highlights the need for regional or smaller-scale analyses of cropland data.

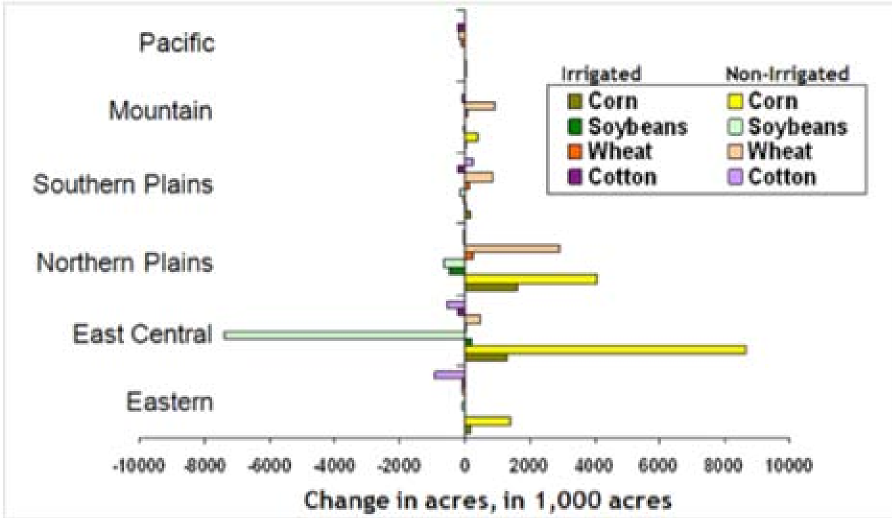

Figure 9. Regional changes in harvested crops, 2002 to 2007, for selected crops (see Figure 8 for explanation of regions).

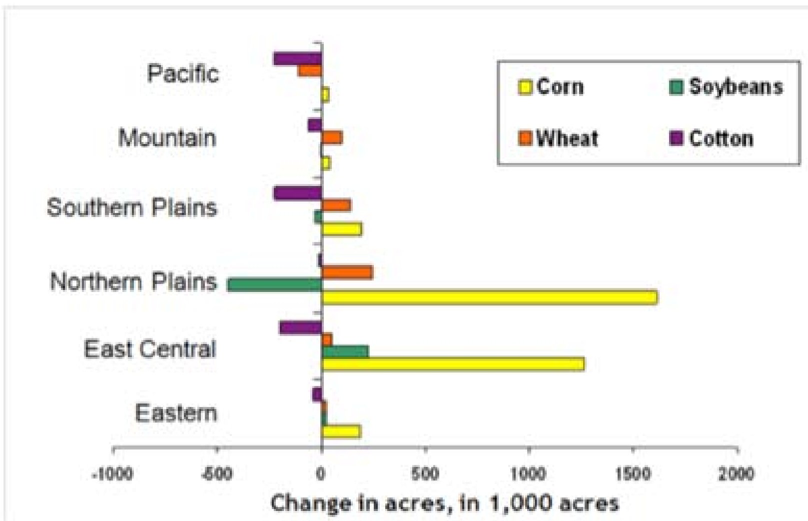

Figure 10. Regional changes in irrigated crops, 2002 to 2007, for selected crops (see Figure 8 for explanation of regions).

Changes in Water Use

The shift to irrigated corn acres between 2002 and 2007 does not necessarily mean that there is an increase in irrigation water applications or CU. The net change in consumptive water use depends on the irrigation applications and CU of the crop that is being replaced with corn. This also will be true for the next generation of biofuel feedstocks: if they are irrigated, the change in water use will depend on the crop being replaced as well as the crop being grown for biofuel.

Figure 11 displays the national average per acre water application by crop from the 2008 Farm and Ranch Irrigation Survey (National Agricultural Statistical Service, 2010). This figure illustrates that corn is among the crops with lower water application amounts and that some of the crops grown for high forage production, such as alfalfa and other hay, have higher water applications. These application rates have implications regarding changing irrigated crop acres to produce corn for ethanol and next generation crops for cellulose production. Application rates depend not only on the crop, but on the setting in which the crop is grown, and application rates for specific regions or states could be substantially different from the national average values in Figure 11. In some locations, Kansas for example, corn has some of the higher water application of the current set of irrigated crops in that state.

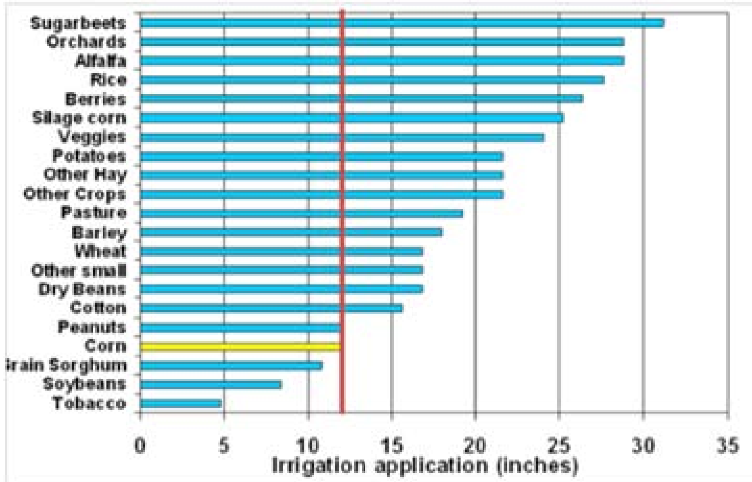

Figure 11. National average irrigation water application amounts for selected crops, 2008 (Source: 2008 Farm and Ranch Irrigation Survey, National Agricultural Statistics Service, 2010).

In order to examine the effect of increased corn production in 2007 to meet the demands for that period, among them biofuel feedstocks, the per acre water applications amounts (from the 2008 Farm and Ranch Irrigation Survey) were applied to the change in acres observed from the 2002 to 2007 (Table 2). Given the differences in time periods for the two data sets, the absolute changes should be interpreted with caution, but the values are illustrative of the potential changes in irrigation water requirements associated with increases in irrigated corn for ethanol production. The change in total water applications shown in Table 2 represent the net increase in water applied as a result of the increase in irrigated acres from 2002 to 2007, and the change in water applications from a cropping pattern shift to greater irrigated corn acreage.

The shift to more irrigated corn, driven in part by the increased demand for biofuels, increased water applied to corn nationally by about 13 million acre feet, which is an increase in the total corn water applications by an estimated 31 percent. This substantial increase in corn water applications needs to be placed in context, however. Given the net shifts in acreage and in irrigated acres across the four major crops (corn, soybeans, wheat, and cotton), there was a 3 percent increase in irrigation water applied for all crops (Table 2).

Total water applied to all crops in the conterminous U.S. exceeds 90 million acre feet (Table 2; National Agricultural Statistical Service, 2010). The estimated change in corn water applications relative to the total irrigation water applications ranges from an increase of 13 percent in the Northern Plains to less than one percent in the Mountain and Pacific regions. Nationally, the shift to irrigated corn from 2002 to 2007, whether on existing or new irrigated land, increased the water applications for corn by about 3 percent relative to the water applied to irrigate all crops. (To compute the change relative to the total water withdrawn for irrigation use, conveyance losses would need to be considered.) Because irrigation accounts for about 37 percent of total water withdrawals, the change in corn water applications to total water withdrawals would be less, on the order of 1 percent-a large volume of water but small in relative terms.

The acres devoted to corn for grain has declined since 2007 due to yield increases, adjusting corn utilization shares, and strong prices for other commodities. State-by-state data indicate that the acres of irrigated corn have followed the national trend, and that water applications on corn have declined (National Agricultural Statistical Service, 2008, 2009, 2010). The period 2000-2010 was marked, however, by wetter than normal conditions throughout much of the Northern Plains and parts of the Midwest, which likely affects irrigation applications.

Region	Corn		Soybeans		Wheat		Cotton		Four-Crop Total		All Crops	Change in corn irrigation relative to total irrigation (percent)
	Total Water Applied (1,000 acre-ft)	Change (percent)	Total Water Applied (1,000 acre-ft)	Change (percent)	Total Water Applied (1,000 acre-ft)	Change (percent)	Total Water Applied (1,000 acre-ft)	Change (percent)	Total Water Applied (1,000 acre-ft)	Change (percent)	Total Water Applied (1,000 acre-ft)	
Eastern	432	72	102	10	24	47	290	-8.3	849	25	3,106	5.8
East Central	2,115	93	5,572	9.2	62	53	968	-12	5,718	24	13,746	7.6
Northern Plains	6,867	25	1,239	-19	690	43	7.0	-58	8,803	17	10,342	13
Southern Plains	1,588	26	26	-52	716	23	1,877	-12	4,207	4.7	7,344	4.5
Mountain	1,376	5.4	2	-58.4	1,778	6.1	919	-23	4,075	-2.5	26,856	0.3
Pacific	485	23	1	0.0	1,108	-16	1,461	-32	3,055	-21	29,658	0.3
TOTAL	**12,863**	**31**	**3,942**	**-2.2**	**4,378**	**6.4**	**5,523**	**-20**	**26,706**	**7.4**	**90,781**	**3.4**

Table 2. Change in irrigation water applications resulting from changes in irrigated acres, selected crops, 2007 (see Figure 8 for explanation of regions; Sources: National Agricultural Statistical Service, 2008, 2009, 2010).

As the next generation of biofuel feedstocks comes closer to commercial production levels, the degree to which these crops increase pressure on irrigation water supplies will depend on the location, crop type, and incentive structure under which the crops are grown. The location of the next generation of feedstock will influence decisions about irrigation, including irrigation quantity. As observed in the corn expansion, however, irrigated corn expanded in traditional corn production areas (Northern Plains and East Central regions) and not uniformly across all irrigated areas. As observed in the per acre water applications for corn, the irrigation application levels vary greatly by state and many forage production alternatives have higher water needs than grain crops. The extent to which irrigation is needed for crop establishment also is crop dependent, and could potentially be a major new water demand. The incentive structure for payment of the next generation of feedstock will influence the irrigation water demand. If contracts are structured with price penalties for failure to deliver specified levels or qualities of feedstocks, an irrigation incentive will be developed. In turn, the need for facilities to incentivize local production will depend on the availability of a regional or national market for feedstocks, which will, in part, depend on the development of a harvesting and transportation system.

Water Use by Biorefineries

Various estimates of CU by biorefineries (Figure 12) have been developed (Wu et al., 2009), with older corn dry mill plants consuming up to 11 gal of water per gal of ethanol produced (Shapouri and Gallagher, 2005), while newer plants typically consume 3 gal of water per gal of ethanol (Kwiatkowski et al., 2006). Not included in these estimates is the CU associated with natural gas production, which typically is used to produce steam for the conversion process, and electrical power, which averaged about 1.5 Kilowatt hours (Kwh) per gallon ethanol produced in 2002 (Shapouri and Gallagher, 2005). Consumptive water use in corn biorefineries has been declining during the last 10 years, with a 21 percent decline in seven years reported for biorefineries in Minnesota (Keeney and Muller, 2006). It appears that process modifications will lead to lower water use in the future.

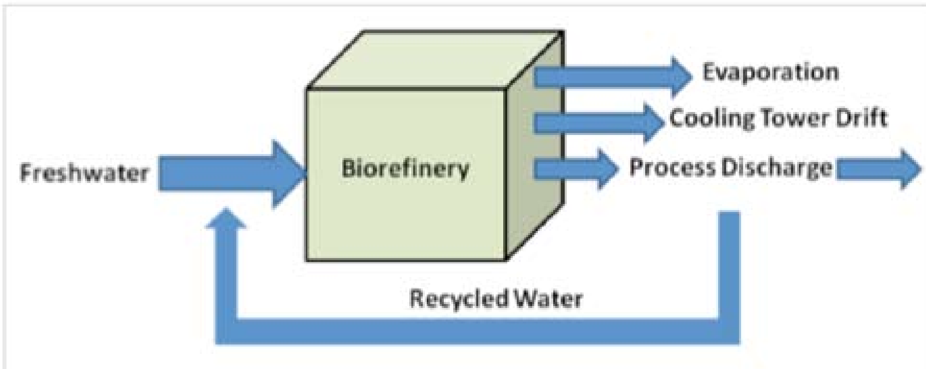

Figure 12. Water budget for typical biorefinery (modified from Wu et al., 2009)

Ethanol can be produced from cellulosic feedstocks by several processes, and the amount of water required for production is a function of the process, as well as the extent of recycling (Wu et al., 2009). The average consumptive use by biorefineries for cellulosic ethanol production ranges from about 2 to 10 gal of water per gal of ethanol produced (Wu et al., 2009). As with corn biorefineries, these consumptive use values do not account for water used in energy production required for biorefinery operation.

King and Webber (2008) provide a useful analysis of the water withdrawals and CU of a broad range of transportation fuels in the U.S. The analysis includes (1) mining and farming (including irrigation) of feedstock; (2) processing and refining feedstock to fuel; and (3) relative fuel efficiency of the fuel. Results are given in gallons of water per mile. The analysis does not include (1) transportation of feedstock to refinery or of fuel to purchase point; (2) water used in installation of capital equipment for mining, farming, and processing; and (3) effects of mining and farming on the water budget, i.e., the effects of mining and farming on ET, streamflow, and aquifer storage and recharge.

Results from King and Webber (2008) are instructive. The lowest water CU fuel is biodiesel processed from non-irrigated soybeans, with a CU of less than 0.05 gal of water per mile. Other low CU transportation fuels include conventional petroleum based gasoline and diesel, at less than 0.15 gal water per mile, and ethanol from non-irrigated corn at less than 0.4 gal water per mile. Water consumption for irrigated corn ethanol is as much as 38 gal water per mile, and plug-in hybrid cars obtaining electricity from the U.S. grid consume 2-5 times more water per mile than do vehicles using conventional petroleum fuels. As previously noted, this analysis does not include the effects of mining and farming on the local water budget, which can be substantial, as previously shown.

Water quality

Land-use conversion invariably affects water quality, whether indirectly through changes to the water budget, or directly through changes in the quality of surface runoff, soil water, and groundwater. Here, we address two water-quality issues-nutrients and pesticides-that could be affected by biofuel production.

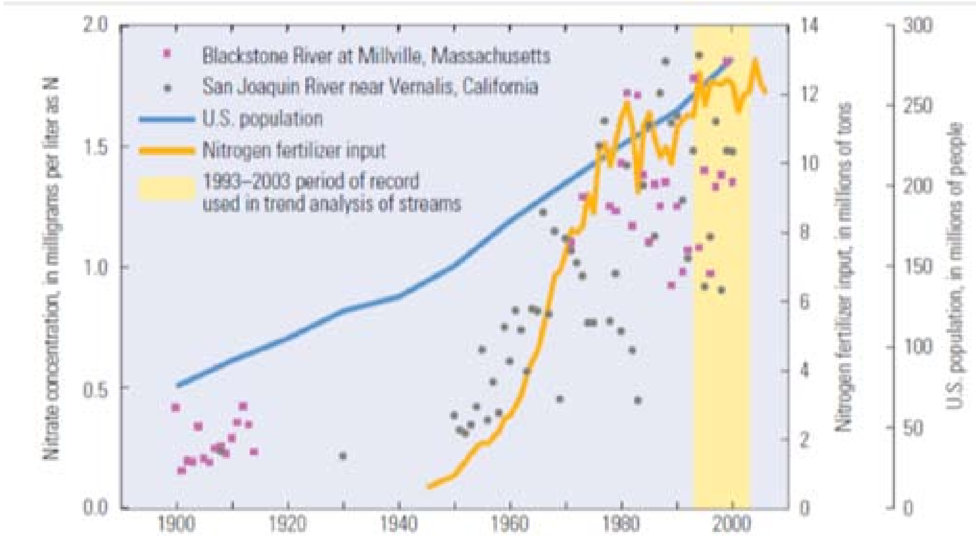

Figure 13. Long-term nitrate concentration in the Blackstone River, Massachusetts and San Joaquin River, CA, showing increases in U.S. population and total national fertilizer inputs (from Dubrovsky, et al., 2010).

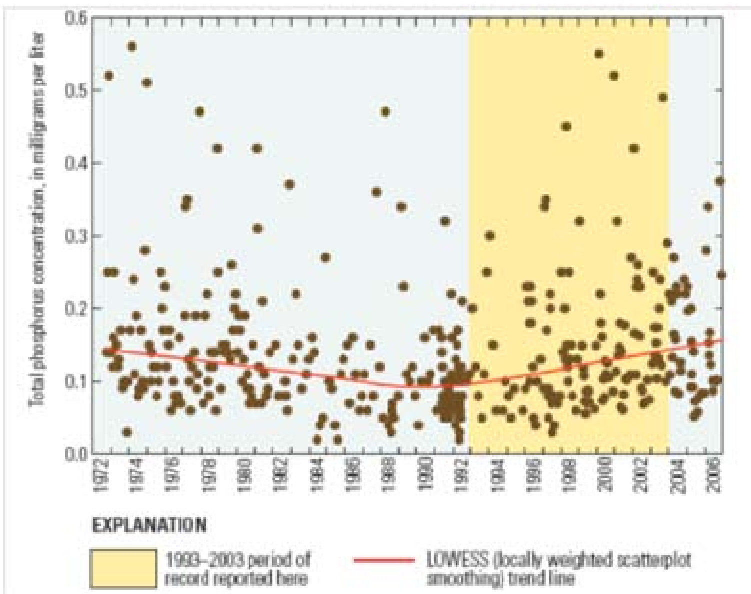

Figure 14. Total phosphorus concentrations in the Ohio River near Grand Chain, Illinois, 1972-2007 (from Dubrovsky, et al., 2010).

Nutrients

The dominant ethanol feedstock in the United States, corn, has been bred to maximize the allocation of carbon and nitrogen into the grain (Davis et al., 2010). As a result of this allocation of nutrients into the grain and the annual lifespan of corn, significant fertilizer application is required to maintain high yields. In fact, of the annual row crops, corn has the highest nutrient application rate and the highest nutrient loading to surface water per unit land area (U.S. Environmental Protection Agency, 2008). Each grain harvest results in the large-scale removal of nutrients from the agricultural land, requiring the reapplication the following year. Fertilizer application rates in a basin are good predictors of stream nutrient concentrations (Dubrovsky et al., 2010).

Concentrations of nutrients (nitrogen and phosphorus) are increasing in many of the Nation's streams, and much of this increase is attributable to changes in nutrient inputs (Figure 13; Dubrovsky et al., 2010). Although some progress was seen in reducing nutrients following enactment of the Clean Water Act in 1972, particularly in streams and rivers receiving treated wastewater, recent data indicate the nutrient concentrations are increasing again in some locations (Figure 14). Dubrovsky et al. (2010) found that, although nitrogen concentrations were decreasing at some urban, mixed land use, and undeveloped sites, there were no decreasing nitrogen trends in streams draining agricultural lands (Figure 15), despite years of best management practice implementation. Nitrate concentrations in groundwater also are elevated and, in some cases, increasing. Given the delay between the time contaminated groundwater is recharged and the water moves into surface waters (Figure 16), groundwater likely will be a continuing source of nitrogen to streams for many years. In fact, groundwater currently is the source of about 40 percent of the total nitrogen load to streams (Dubrovsky, et al., 2010).

The demand for renewable fuels may eventually lead to the implementation of advanced biofuels, with grain-based ethanol production ultimately representing a minority of the total ethanol produced (U.S. Department of Energy, 2006). Until advanced biofuels mature, it is likely that the land area in the Midwestern U.S. planted in corn will fluctuate based on the profitability of producing grain. Under such scenarios, an increase in the land area devoted to grain will lead to higher rates of nutrient application and could lead to further degradation of water quality in streams, rivers, aquifers, and ultimately coastal regions where rivers drain, as well as in shallow groundwater. Predictions of the effects of additional nutrient application to meet the increasing demands for grain-based ethanol production suggest that between 10 and 34% more nitrogen could enter the Gulf of Mexico annually, potentially enlarging the Gulf's hypoxic zone (Donner and Kucharik, 2008).

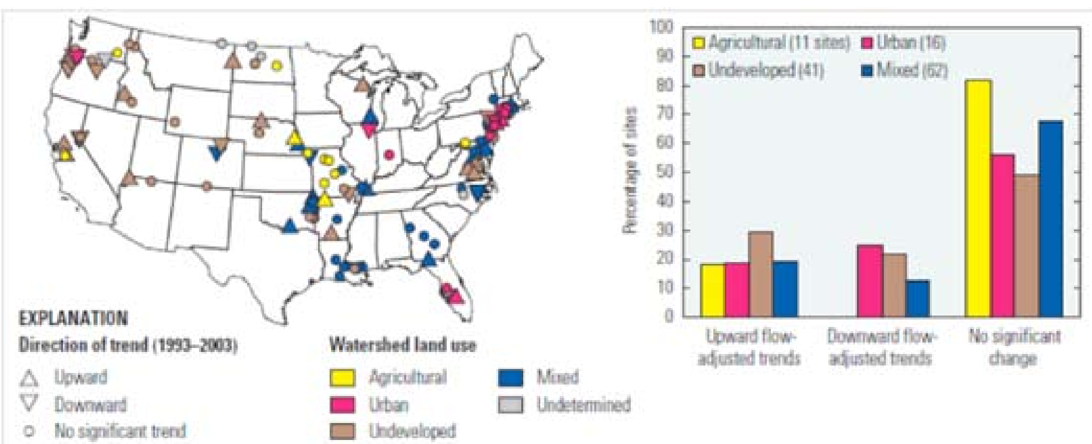

Figure 15. Flow-adjusted trends for total nitrogen in streams, 1993-2003 (from Dubrovsky, et al., 2010).

In addition to potentially increased nutrient loadings from conversion of fallow land or exiting crops to corn, there are other potential impacts of biofuel feedstock production. Harvesting crop residue for biofuel feedstock could increase sediment loadings because of reduced ground cover and require an increase in fertilizer inputs to maintain production (Costello et al., 2009). Collection of forest residues could affect water quality, as these residues reduce sediment (and nutrient) loadings to streams in some settings, and collection could increase land disturbance (Costello et al., 2009; Williams et al., 2009; Havlik et al., 2010). The effect of reduced residues on forest fires might offset impacts of collection, again, depending on the setting (Williams et al., 2009; Havlik et al., 2010).

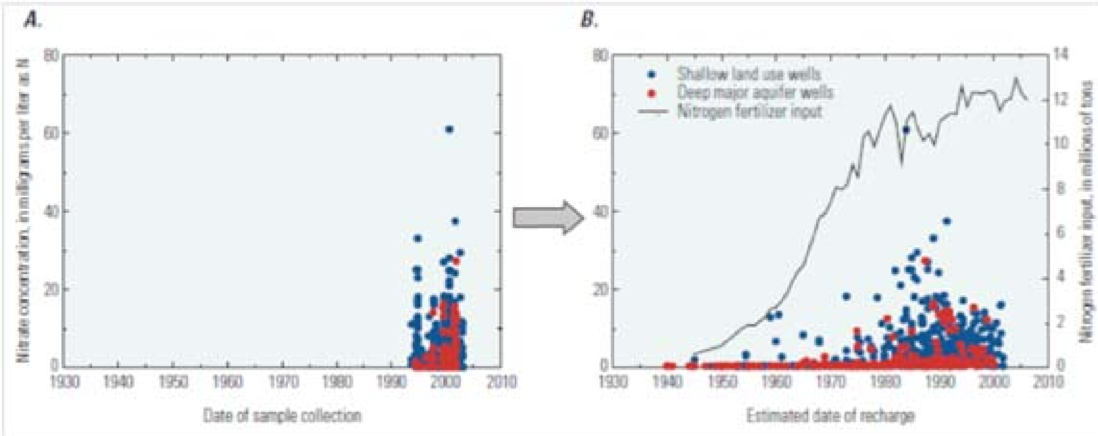

Figure 16. Measured nitrate concentration in shallow groundwater and deep aquifers by (A) date of sample collection and (B) estimated date when the groundwater was recharged (from Dubrovsky, et al., 2010).

The move toward cellulosic based ethanol production could potentially lead to opportunities to reduce the effect of large-scale agriculture on water quality in all regions where biofuel crops will be planted. A report outlining steps needed to achieve benchmarks for ethanol production identified a list of species dominated by perennials that are well suited in each region of the U.S. for cellulosic ethanol production (U.S. Department of Energy, 2006). One of the key benefits of using perennial species as cellulosic feedstocks involves the internal recycling and storage of nutrients, allowing for the removal of biomass at the end of the growing season with minimal loss of nutrients from the ecosystem (Heaton et al., 2004). While short rotation coppice (growth originating from roots or shoots) agro-ecosystems may have a larger proportion of nutrients removed during harvest, the nutrients remaining after coppice harvest will primarily be found in the living roots from which future growth will reduce the amount of nutrients entering streams and groundwater.

Pesticide Use

Corn is a chemically-intensive crop, requiring applications of insecticides, herbicides, and plant growth regulators. Commonly used pesticides for corn include the herbicides acetochlor, atrazine, glyphosate, and metolachlor; commonly used insecticides include malathion, chlorpyrifos, and permethrin.

Gilliom et al., (2006) summarized information on pesticide data collected in streams, groundwater, bed sediments, and fish tissue during 1992-2002, as well as the effects of pesticides on aquatic organisms. More than 90 percent of the water samples collected from agricultural, urban, and mixed land use streams contained detectable levels of at least one pesticide, although typically at concentrations below those likely to affect human health. Pesticides also were detected in about 80 percent of the groundwater samples collected in agricultural and urban basins. Highest concentrations typically were detected in agricultural streams, and some of the most frequently detected pesticides were those associated with corn production, with atrazine detected in almost 90 percent of the samples collected from agricultural streams, and about 40 percent of the groundwater samples from agricultural lands.

Unlike nutrients, there are indications that concentrations of some pesticides in streams is declining, most likely due to decreased application rates, and changes in usage. Sullivan et al. (2009) evaluated trends in pesticide concentrations at 31 sites in corn-belt streams for 1996-2006, although this preceded the 2007 EISA, when biofuel production substantially increased. In general, pesticide concentrations decreased through the period. Glyphosate applications increased, however, but glyphosate concentrations in streams were not measured. In summary, atrazine, metolachlor, alachlor, cyanazine, EPTC, and metribuzin-all major corn herbicides-showed more prevalent decreasing trends during 1996-2002 than during 2000-2006. Alachlor and cyanazine were, however, removed from the market, and alachlor was replaced by acetochlor.

As with the impact of increasing grain production on fertilizer application and nitrogen runoff, similar trends toward a higher rate of application of pesticides and subsequent contamination of water have been projected (Payne 2010). Contrary to the majority of perennial species where nutrient recycling might favor diminished nutrient runoff from croplands, the application of pesticides can vary substantially depending on the species grown, region, the species being replaced, and a range of other factors. Many of the species proposed as feedstocks for cellulosic ethanol production are grown currently in the U.S. (e.g., switchgrass, poplars) and the diseases and pests are well characterized. If the areas planted with these species are expanded to areas that currently are fallow, then any application of pesticides will further degrade water quality. Alternatively, the use of existing ecosystems to provide sustainable cellulose for bioenergy production might have no net change in pesticide use. Of course, many situations exist where the effects of altering an ecosystem to meet the demands for cellulose production are uncertain.

Summary

The production of traditional petroleum-based fuels has had relatively little direct effect on water-resources of the U.S., other than those effects associated with fuel spills, and indirect effects associated emissions. Most alternatives to traditional transportation fuels, including nontraditional hydrocarbon transportation fuel sources (coal, shale oil, tar sands, etc.) and biofuels, likely will have greater effects on water availability and quality (King and Webber, 2008). Data from 2004-2007 do indicate, however, that corn production increased, water use increased by 3 percent, and most likely fertilizer and pesticide application increased in response to a variety of factors, including increased corn prices.

The impacts of irrigation and crop water use influence and are influenced by many facets of the hydrologic cycle in a variety of environmental settings. These factors need to be considered when projecting estimates of land-cover changes to accommodate a growing demand for alternative fuel sources. Given the variability in the potential biofuels landscape, the implications of altering land-cover to accommodate biofuel production will need to be considered for each region, crop, management strategy, etc. on a case-by-case basis.

As biofuel production increases, and as more feedstocks are generated from cellulosic materials, there is a need to measure effects of changes in land use on water availability and quality. Without this information, decisions about water availability and quality often are made without adequate supporting information. It is striking that data from a relatively small number of sites were available for a recent assessment of trends in nutrient concentrations in streams (Figure 15). Information needed for making sound water resources decisions requires a long-term commitment to consistent data collection and analysis.

Three points in the preceding discussion bear emphasizing. First, the water budget is a useful tool for evaluating effects of biofuel production on the total water resource, but application of the water budget requires sound, long-term data on water withdrawals and CU. Second, the total effect of biofuel production, conversion and use on water availability and quality should be considered. In other words, total life cycle evaluations are appropriate (Harto et al., 2010). Finally, effects of biofuel production (not necessarily conversion and use) on water availability and quality generally are manifested locally or perhaps regionally, although the effects can have national implications (e.g. the Gulf of Mexico hypoxic zone). As a result, the specific combination of biofuel feedstock in combination with local water-resources conditions needs to be considered. This cannot be done without carefully collected, thoughtfully analyzed environmental and agricultural data. In many locations throughout the U.S., such data are unavailable or sparse.

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Chapter 5

Crop Residues of the Contiguous United States: Balancing Feedstock and Soil Needs With Conservation Tillage, Cover Crops, and Biochar

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Abstract

Crop residues are among the cellulosic feedstocks expected to provide renewable energy. The availability of crop species and residue availability varies across the United States. Estimates of harvestable residues must consider all the residues produced during the entire rotation. Inclusion of fallow or low residue producing crops requires that less feedstock be harvested. A re-occurring theme among the regions is that soils need to be safeguarded against erosion and against loss of soil organic matter (SOM). First, highly erodible lands are categorically excluded from harvesting residues in all regions. The minimum of residue needed to meet soil needs is highly variable. Where sufficient residues are produced to meet soil conservation and SOM considerations, harvesting of a portion may be considered. Soil conservation practices include eliminating or at least reducing tillage to keep the soil covered, avoiding fallow and adding perennials, applying amendments (manure, biochar) and planting cover crops in areas with sufficient moisture. Calculating regional or national availability of residue feedstock is valuable for evaluating the feasibility of bioenergy production; however, on a field basis, site-specific decision aids will be needed.

The United States is seeking to replace/supplement fossil fuel with renewable energy including cellulosic feedstocks. Cellulosic feedstocks can be used for production of liquid fuels (e.g., ethanol), syngas, or as feedstock to produce combined heat and power. The U.S. Department of Energy (DOE) and U.S. Department of Agriculture (USDA) "Billion Ton Report" estimated annual feedstock supplies at 175 million dry Mg (193 million tons) or about 16 percent of the biomass produced (Perlack et al. 2005). This value included crop residue, grain for ethanol and animal wastes. Estimates for available biomass (excluding dedicated perennials) ranged from about 360 to 500 million dry Mg (400 to 550 million dry ton) and excluded harvesting residues from lands classified as highly erodible (Perlack et al. 2005). Corn (*Zea maize* L.) stover on a national level is the largest untapped agronomic feedstock, although other feedstocks could be primary at a local or regional scale such as sugarcane (*Saccharum officinarum* L.) bagasse in the southeast, or wheat (*Triticum aestivum* L.) and grass straw from seed grasses production in the northwest (Perlack et al. 2005). An integrated or landscape approach to safeguard soil and environmental resources is vital for a sustainable bioeconomy which balances energy and conservation needs (Dale et al. 2010; Johnson et al. 2010a; Mitchell et al. 2010).

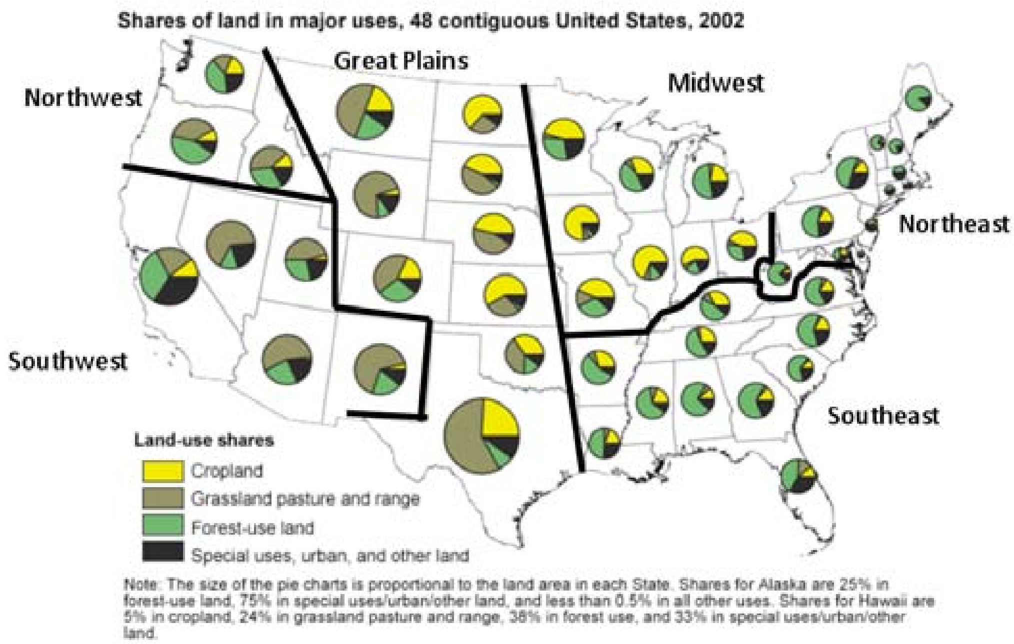

Figure 1. The major land use area of the United States. The six geographical regions are arbitrary and intended to provide the reader with a visual representation of the regions Source: USDA-Economic Research Service http://www.ers.usda.gov/Data/MajorLandUses/map.htm verified September 7, 2010.

In the United States about 373 million hectares (922 million acres) were classified as farm land in 2007 (USDA-NASS 2007). About 44 percent of this land is designated cropland with another 48 percent designated as pasture land; however this varies dramatically among states and regions (Figure 1). The United States has a wide range of climatic zones allowing production of a vast array of crops. The major row crops are corn, soybean (*Glycine max* L. [Merr.]), wheat, cotton (*Gossypium hirsutum* L.), sorghum (*Sorghum bicolor* L.), and rice (*Oryza sativa* L.). Corn and soybean are grown in most regions of the country; the majority of wheat is produced in the Great Plain and Pacific Northwest, sorghum is more common in the south Central Plains, while rice and cotton are restricted to Southeast. The Midwest and Central Plains have the largest percent of land designated to crop land, whereas the southeast and northeast proportionally consist of more forest land (Figure 1).

Concerns that harvesting crop residue can promote excessive erosion, reduce soil quality, undermine soil productivity and disrupt ecosystem services is a reoccurring theme among residues and regions. The specifics of those risks, agronomic consequences and mitigation strategies will interact among crops and climatic conditions. Harvesting crop residues needs to be managed to avoid accelerating erosion or reducing soil organic matter (SOM), and safe-guarding soil productivity (Lal 2004; Nelson et al. 2004; Wilhelm et al. 2004; Lemus and Lal 2005; Steiner et al. 2006a; Steiner et al. 2006b; Graham et al. 2007; Johnson et al. 2007b; Wilhelm et al. 2007; Lal 2008; Blanco-Canqui and Lal 2009). Other considerations on the amount of residue to harvest include potential nutrient removal (Hoskinson et al. 2007; Banowetz et al. 2009b; Johnson et al. 2010b), negative impacts on soil biota (Johnson et al., 2009) or loss of wildlife habitat (McLaughlin and Walsh 1998). Studies reviewed by Johnson et al., (2009) suggested that removing residue can negatively impacts soil biota, but most of these studies were outside of the U.S. There are situations where environmental and/or agronomic risks should out-weigh any potential benefits associated with harvesting crop residue and, thus, is not recommended (Lal 2004; Wilhelm et al. 2007; Lal 2008; Huggins and Kruger 2010; Johnson et al. 2010a). Indeed even when all crop residues are returned to the land, biomass input can be insufficient as soil erosion and SOM depletion are symptomatic of many production systems (Mann et al. 2002; Montgomery 2007). However, there may be mitigating options that can be adopted that facilitate harvesting some crop residues. The mitigation or compensating strategies will vary among crops, climate, topography and landscape.

Southeast and Northeast

Most states within the Northeast and Southeast regions have considerably more land area in forest or urban land use compared to cropland (Figure 1). Soils in both regions are largely Ultisols (http://www.cei.psu.edu/soiltool/), which are well weathered with low SOM. Annual precipitation in the Southeast and Northeast regions ranges from 1,000 to 1,500 mm, with more precipitation in the Southeast (Owenby et al. 2001). Although climate and parent material are partially responsible for the low SOM contents, decades of cultivation with conventional tillage practices, as well as low biomass production and high erosion levels, have led to large portions of these regions having degraded soils, especially in the Southeast.

Crops in the Southeast vary corn, cotton and soybean are commonly grown throughout the region (Table 1). Other crops are more geographically restricted due to specific soil and/or climatic requirements (Table 2). For instance, peanut (*Arachis hypogaea* L.) is grown mainly in the Coastal Plain, sugarcane in Louisiana and Florida, and rice in Arkansas, Louisiana and Mississippi. Livestock production is an economically vital component of the agricultural sector (Kemper et al. 2006) that also has potential as a bioenergy feedstock (Ro et al. 2009).

The Northeast is characterized by a cooler climate compared to the Southeast. Major crops in this region include corn, soybean, and wheat (Table 3) but barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), and potato (*Solanum tuberosum* L.) are also commonly grown.

Crop	Regional Yield Average	Regional Yield Std. dev.	Land area
	----------------Mg ha^{-1}	-----------------	Million ha
Corn	8.13	1.24	2.25
Cotton†	0.93	0.14	1.28
Soybean	2.55	0.40	5.26
Total area			8.79

Table 1. Average 2009 crop yield and acreages for the three most common crops in the Southeast states of Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia*. * www.nass.usda.gov/quickstats/verified August 25, 2010 †Cotton not reported for Kentucky in 2009.

Crop	States	Regional Yield Average	Regional Yield Std. dev.	Land area
		------------Mg ha^{-1}	------------	Million ha
Peanut	Alabama, Florida, Georgia, Mississippi, N. Carolina, S. Carolina, Virginia,	3.74	0.34	0.37
Rice	Arkansas, Mississippi, Louisiana	7.40	0.30	0.88
Sugarcane	Florida, Louisiana	15.21	1.20	0.33
Total area crops				1.59

Table 2. Average 2009 crop yield and acreages for important specialty crops with potential as a local cellulosic feedstock in the Southeast region*. * www.nass.usda.gov/quickstats/verified August 25, 2010.

Crop	Regional Yield Average	Regional Yield Std. dev.	Land area
	------------Mg ha^{-1}------------		Million ha
Corn	8.74	0.52	0.89
Soybean	2.87	0.12	0.59
Wheat	3.85	0.41	0.23
Total area in row crops			1.72

Table 3. Average 2009 crop yield and acreages for the three most common crops in the Northeast states Delaware, Maryland, New Jersey, New York, Pennsylvania and West Virginia* * www.nass.usda.gov/quickstats/verified August 25, 2010.

A key component to crop production in these regions is the use of conservation agriculture, which incorporates the use of no-till and/or reduced tillage. Additionally, winter cover crops are often integrated with these production systems. The additional residues on the soil surface create a mulch layer that restricts weed growth and improves available plant water during the summer growing season. Legumes are sometimes used to provide additional nitrogen for the cash crop, but their residue decomposes faster compared to other cover crops, such as rye (*Secale cereale* L.), oats, and wheat.

Soils are most susceptible to erosion when they have limited residue cover or few actively growing crops. Campbell et al. (1979) estimated that 60 percent to 90 percent of crop residues grown in the summer were needed to control erosion, thus leaving 40 percent or less that may be available for harvest. This work assumed conventional tillage and considered erosion control, but it did not take into consideration protecting SOM content nor did it consider mitigating strategies such as conservation tillage or cover crops. Dabney et al. (2004) measured more water runoff on a silt loam in Mississippi managed without tillage but lower sediment loss was observed compared to conventional tillage. They estimated that soil disturbance increased sediment loss by 26 to 47 percent, and concluded that the reduced erosion in no-till (NT) was caused by improved soil properties and greater crop residue amounts on the soil surface. Similarly, Truman et al. (2009) found lower runoff and sediment losses with strip-till than conventional tillage for three soils in the Southeast. Nevertheless, chemical compounds that are highly soluble in water might have a greater potential to be lost by runoff with NT and strip-till (Potter et al. 2006; Franklin et al. 2007), but chemicals that tend to bind to soil particles have a greater risk to be lost from erosion with conventional tillage (Potter et al. 2004).

Research on crop residue harvest in the southeast and northeast is limited. However, current available information is in agreement that conservation systems can help offset any negative impact of crop harvest. A four-year study on a South Carolina sandy loam, found that although harvesting corn stover increased N, P and K removal rate, there was no corresponding difference in soil N, P and K due to stover harvest (Karlen et al. 1984). Removal of secondary and micro-nutrients was increased but only slightly. They estimated that between 3 and 7 Mg ha^{-1} of corn stover could be harvested as long as conservation tillage practices were used to help control erosion. The authors concluded that current fertilization practices were adequate to cope with nutrient losses. Moebius-Clune et al. (2008) studied the effect of harvesting corn stover for 32 years on 25 soil quality indicators of a silt loam in New York. Stover harvest was more sustainable without tillage than with plow tillage but the authors did not directly evaluate the impact of soil erosion in this study. Retaining mulch residue reduced sediment and P losses by 95 and 50 percent, respectively, compared to burying the residue, a common practice in potato production systems (Griffin and Honeycutt 2009). Studies mentioned above reported that no tillage was effective in reducing erosion, but water runoff might be increased under certain circumstances (Potter et al. 2006; Franklin et al. 2007). However, Truman et al. (2009) reported significant reductions in runoff and sediment loss for three different soils in the Southeast with the use of conservation tillage practices and winter cover crops.

Crops respond differently to cover crop use and residue management. For example, yields of a two-year potato-barley rotation were not significantly affected by the use of cover crops. The exception was red clover (*Trifolium pratense* L.) that reduced some disease pressure (Griffin et al. 2009). Delaying tillage increased ground cover and did not adversely affect yields. Griffin et al. (2009) concluded that cover crops and delaying tillage could be used as conservation practices for potato production in Maine without adversely affecting yields. Commonly sugarcane crop residue is burned since yield is reduced by leaving residue over the top of the row (Judice et al. 2007; Viator et al. 2008). However, burning crop residues reduces the amount of organic matter in the soil and creates air quality issues. An alternative management option is to mechanically remove the residue from the top of the sugarcane rows, which leaves large amounts of residue on the row middles that can interfere with other field operations (Judice et al. 2007). Therefore, it may be feasible to remove some sugarcane residue to avoid yield reductions and disruptions to field operations.

The Southeast and Northeast regions have adequate precipitation for biomass production. Further, winter temperatures in the Southeast are mild enough that certain winter crops, including cover crops such as cereal rye and wheat, can be grown during this time of the year and be harvested in the spring for their biomass. This approach protects the soil from erosion during the winter and increases organic matter inputs. A five-year study found that planting a rye cover and harvesting its biomass in the spring is better for a Coastal Plain soil in terms of soil quality and cotton production compared to having no cover (F.J. Arriaga, unpublished data). Both regions present significant opportunities for biomass harvest, but care must be taken to balance long-term productivity, environmental impacts and biomass production.

Midwest/Corn Belt

The Midwest region has a large amount of land area dedicated to row crops (Figure 1). The region is dominated by Mollisols and Alfisols, many of which have an inherently high SOM content (http://www.cei.psu.edu/soiltool/). Precipitation ranges from 500 to 1000 mm, and mean annual temperature ranges from 1.7 to 12.8°C. Both parameters increase as you move east and south across the region (Owenby et al. 2001). In general, the use of no tillage production systems increases as you move east and south across the region, with the least in Minnesota and the most in Indiana and Ohio (Johnson et al. 2005).

Crop	Regional Yield Average	Regional Yield Std. dev.	Land area
	------------Mg ha^{-1}	------------	Million ha
Corn	10.42	0.80	19.80
Soybean	3.01	0.31	18.18
Wheat	4.00	0.72	2.22
Total area in row crops			47.03

Table 4. Average 2009 crop yield and acreages for the three most common crops in the Midwest states Indiana, Illinois, Iowa, Michigan, Minnesota, Missouri, Ohio and Wisconsin*. * www.nass.usda.gov/quickstats/verified August 25, 2010.

There are many crops grown in the Midwest region but corn and soybeans represent the overwhelming majority, followed by wheat (Table 4). Over 90 percent of the acreage is rainfed (USDA 2009). Corn grown in rotation with soybean is common, but continuous corn or a three-year corn, soybean, and wheat sequence is also practiced. This region has been targeted for both production of grain-based ethanol and second-generation bioenergy production because of the extensive production acreage and high yields (Table 4), especially for corn (Nelson 2002; Perlack et al. 2005; Graham et al. 2007; Johnson et al. 2007b).

Numerous classical and recent articles have been published about potential environmental risks of harvest or over harvesting of crop residues for the Midwest and other locales (Larson 1978; Larson 1979;

Lal 2004; Wilhelm et al. 2004; Johnson et al. 2006; Johnson et al. 2007b; Wilhelm et al. 2007; Lal 2008; Johnson et al. 2010a). Crop residues are the first line of defense against erosive forces in annual row crops systems (Larson 1978; Merrill et al. 2006; Cruse et al. 2009), thus feedstock estimates limit residue harvest to avoid increasing wind or water erosion (Nelson et al. 2004; Perlack et al. 2005; Graham et al. 2007). The rate of wind and water erosion decreased in the Midwest between 1982 and 2007 (USDA 2009); for this trend to continue adequate residue needs to remain on the landscape. Furthermore, there are cases where the amount of residue needed to avoid loss of SOM exceeds that needed to control erosion (Wilhelm et al. 2007).

Empirical estimates of the average annual above ground biomass inputs necessary to maintain SOM ranged from 4.0 to >20 Mg dry residue ha^{-1} yr^{-1} in the Midwest region (Johnson et al. 2009). The very high estimate was from a study in Minnesota which examined a larger portion of the soil profile than many of the other studies (Huggins et al. 2007). Excluding this high estimate, the regional average annual above ground biomass inputs necessary to maintain SOM averaged 6.7 Mg dry residue ha^{-1} yr^{-1} (Johnson et al. 2009). Assuming a harvest index of 0.5, this corresponds to a grain yield of 7.8 Mg ha^{-1} (124 bu $acre^{-1}$ at 15.5 percent moisture) or if a harvest index of 0.53 is used the grain yield increases to 8.7 Mg ha^{-1} (140 bu $acre^{-1}$ at 15.5 percent moisture). This is a very crude estimate; site specific estimates considering local erosion risk and management factors (e.g., tillage, crop rotation) are required for local or field-scale recommendations.

Harvesting crop residue has direct impacts on soil properties but also has indirect impacts through modifications of microclimate effects (Johnson et al. 2009). Changes in microclimate interact with climatic condition for negative or positive agronomic consequences (Hillel 1998). A dark soil surface is desirable especially in cool, wet climates as it hastens soil warming and drying; thereby, creating a more favorable early-season growing conditions. However, the same processes can increase evapotranspiration and may exacerbate water deficits. The complex microclimate interactions may explain the variability in yield response to residue harvest. Yield responses to residue harvest in the Midwest ranged from decreases in Minnesota (Linden et al. 2000), Ohio (Blanco-Canqui and Lal 2007), Wisconsin (Swan et al. 1994), to no response in Indiana (Barber 1979), Minnesota (Linden et al. 2000; Wilts et al. 2004; Johnson and Barbour 2010), Ohio (Blanco-Canqui and Lal 2007), and Wisconsin (Swan et al. 1994), to an increase in Iowa when stover was selectively removed form over the row (Kaspar et al. 1990).

Corn and soybean production is the largest contributor to nitrogen (N) deposition in the Mississippi River Basin (Alexander et al. 2008). Nutrients, pathogens, pesticide and turbidity from agricultural sources contribute to the impairment of surface and ground water (US-EPA 2009). However, use of cellulosic biofuels (i.e., corn stover and switchgrass) is predicted to decrease nitrate loading in the Mississippi Basin. Therefore, combined with aggressive nutrient management strategies, biofuel production could reduce the hypoxia zone in the Gulf of Mexico (Costello et al. 2009).

The amount of nutrient removed by crop residue harvest is a function of concentration and rate. Nutrient concentration varies by crop (Johnson et al. 2009) and plant fraction harvested (e.g., cob, stover cutting height), and for some nutrients, plant maturity at harvest (Johnson et al. 2010b). It is easy to measure the rate of nutrient removal, but predicting the impacts on soil fertility is more challenging. The impact of nutrients removed with crop residues varies by soil type, specific nutrient, crop rotation, climatic conditions and other management variables (Johnson et al. 2010b). Replacement cost for nitrogen (N), phosphorus (P) and potassium (K) ranged from about \$12 to \$18 Mg^{-1} for cobs and total stover, based on five-year average fertilizer costs (Johnson et al. 2010b), which is slightly more than was replacement cost estimated by Hoskinson et al. (2007). Micronutrient status may also be impacted, and at the very least crops need to be monitored for micronutrient deficiencies that were not an issue when residues were returned.

The general principles for avoiding or mitigating environmental consequences of harvesting residues apply in the Midwest (Johnson et al. 2010a). First, all residues need to be returned on highly erodible land. Those areas with relatively low erosion risk may be considered for crop residue harvest provided sufficient residue covers the soil for erosion control and for maintaining SOM. Reducing or eliminating tillage, adding cover crops, and applying soil amendments such as biochar or manure will also be useful for maintaining soil productivity. Mitigation by no tillage and use of cover crops becomes more challenging in the north and west portions of the Midwest regions, due to shorter growing season and potential competition for soil water. Assuming manure application is managed following environmentally sound practices, it may substitute for some of the removed residue. However, those farms that have manure may also have a demand for the crop residue for bedding and/or feed. Transportation costs restrict use of manures to a relatively small geographical region near their production site.

Great Plains

The Great Plains region as defined in this paper includes North and South Dakota, Nebraska, Kansas, Oklahoma, Texas, Colorado, Wyoming and Montana (Figure 1). The continental climate of this region is characterized by highly variable seasonal precipitation and temperatures (Varvel et al. 2006). Annual precipitation averages <250 mm in the northwestern to >1500 mm in the southeastern part of the region. Average annual temperatures increase from 3.5°C in the north to 21°C in the southern part of the region. Prairie was the dominant pre-settlement vegetation with short grass prairie in the west and tall grass prairie in the east. Soils are primarily Mollisols with areas of Alfisols, Vertisols, and Ultisols (http://www.cei.psu.edu/soiltool/).

The climatic patterns of the Great Plains were a strong determinant of the vegetation and soils present and influenced cropping practices. When the prairie was plowed, farmers planted a combination of small grains and row crops; however, the limited and variable growing season precipitation resulted in low yields and crop failures. Crop-fallow was established to manage soil water. The practice resulted in higher yields and lower incidence of crop failure during the year a crop was planted. Unfortunately, crop-fallow systems also resulted in extensive wind erosion (Merrill et al. 1999), loss of SOM (Bauer and Black 1981), loss of soil structure (Skidmore et al. 1975), and the development of saline seeps (Halvorson and Black 1974).

Improved reduced tillage practices and the availability of effective herbicides led to the development of more intensive cropping systems, with reduced use of fallow and improved precipitation use efficiency (Peterson et al. 1996). Cropping intensification resulted in increased annual yields, increased annual returns and reduced risk (Dhuyvetter et al. 1996; Helmers et al. 2001), reduced wind erosion, and improved soil quality (Campbell et al. 1998; Wienhold and Halvorson 1998; Varvel 2006). The success of these more intensive cropping systems is largely dependent on producing and maintaining sufficient crop residue to protect the soil from erosion, reduce evaporation, and sustain the soil biota. On a regional basis cropping systems that use reduced tillage and more diverse rotations have improved physical (Pikul et al. 2006), chemical (Mikha et al. 2006), and biological (Liebig et al. 2006) soil properties.

The Great Plains is underlain with extensive groundwater resources and numerous rivers traverse the region. These water resources are used extensively for irrigation and agriculture is the dominant water user in the region. Irrigation stabilizes crop yields and allows growing of higher water demanding crops. Within the region, excessive irrigation with surface water can result in reduced water flows for downstream users and excessive use of groundwater can result in aquifer depletion requiring pumping from greater depths and eventually exhaustion of the resource (McGuire 2007). Irrigation in excess of crop demand results in leaching of nutrients and agricultural chemicals through the root zone resulting in contamination of groundwater resources.

Crops differ in their production potential and water availability is most commonly the factor limiting yield in this region, hence yield can be very different between irrigated and rainfed systems (Table 5). Residue remaining after harvest also varies greatly across the region. Residue amounts are dependent on crop production levels but also vary among species. Crops such as wheat, corn, and sorghum produce nearly as much straw and stover as grain. Other crops such as cotton or soybean produce much less residue.

Crop	States	Irrigated Yield	Dryland Yield
		-----------------Mg ha^{-1}--------------	
Wheat	North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Colorado, Wyoming, Montana, and Texas.	3.0 – 4.6	1.5 – 3.0
Corn	Nebraska, Kansas, Texas.	8.8 – 12.9	2.4 – 9.4
Soybean	Nebraska, Kansas, Texas.	2.1 – 3.3	1.1 - 2.6
Sorghum	Nebraska, Kansas, Oklahoma, Colorado, and Texas	4.7 – 6.5	2.4 – 5.6
Cotton	Oklahoma and Texas.	1.1 – 1.4	0.3 - 0.4

Table 5. Range of state average yields in 2008 for crops commonly grown in the Great Plains*.

* www.nass.usda.gov/quickstats/verified August 31, 2010.

Residue produced in rainfed systems in the western part of the region is essential to protecting the soil from wind and water erosion, improving soil water storage, and sustaining soil biota. Blanco-Canqui et al. (2009) measured runoff, sediment, and nutrient loss from no-tillage wheat and tilled sorghum and concluded that residue removal could not exceed 25 percent without significantly increasing the potential for erosion losses. In the low rainfall area of the Texas Rolling Plains, residue removal in wheat and grain sorghum decreased the saturated hydraulic conductivity (Ks) and micro-aggregation of the soil (Bordovsky et al. 1999). Crop residue also reduces evaporative losses from the soil, increases snow capture, and use of reduced tillage maintains infiltration capacity (Smika and Wicks 1968). The increase in cropping intensity resulting from improved precipitation capture and storage positively effects soil microbial communities and has resulted in soil C sequestration in the region (Halvorson et al. 2002; Acosta-Martinez et al. 2010). In these systems there is limited potential for using crop residue as a feedstock without negatively affecting the soil resource.

In the eastern part of the region where greater precipitation occurs and in irrigated systems yields are greater and significantly more straw and stover may be produced. In these systems residue production may reach levels that interfere with planting and slow warming of the seedbed in the spring. Under high production conditions a portion of the residue may be available for use as a feedstock (Graham et al. 2007). Wilhelm et al. (2004) identified soil compaction, nutrient removal, increased susceptibility to wind and water erosion, and negative effect on SOM as concerns associated with corn stover removal. A subsequent study estimated the amount of stover that needed to be retained to provide conservation functions and sustain the SOM (Wilhelm et al. 2007). This study also provided a model for estimating harvestable stover from continuous corn or corn-soybean rotations under plow or conservation tillage.

The cob fraction of corn stover has recently been proposed as a residue component that could be utilized as a feedstock without raising the concerns raised by Wilhelm et al. (2004). The cob fraction represents a consistent fraction of stover (20 percent) and the cob:grain ratio (17 to 20 percent) is similar across years and management (Varvel and Wilhelm 2008; Halvorson and Johnson 2009). Cob removal from plots where residue was removed or retained did not increase runoff, sediment, or nutrient loss from a silt loam soil on a 7 percent slope (Wienhold and Gilley 2010). Using the cob:grain ratio reported above and 2008 grain production data from York County Nebraska Wienhold and Gilley (2010) estimated that cob production was twice that needed to meet the feedstock needs of a cellulosic plant similar to that being built near Emmetsburg, IA. As cellulosic biofuel plants come on line the cob fraction may be a viable feedstock.

Residue removal effects on the soil resource may be ameliorated using cover crops or manure. Cover crops serve as a source of additional C, utilize residual soil nutrients reducing the potential for leaching losses, and provide protection from wind and water erosion. The main limitation to the use of cover crops in the Great Plains is competition between the cover crop and the cash crop for available water. In irrigated systems of the Great Plains, cover crops have been used successfully to reduce wind erosion and utilize residual fertilizer (Delgado et al. 2007). The Great Plains is a major beef, swine, and poultry production region. Livestock manure is readily available for use as a nutrient and C input that may offset residue removal effects. Ginting et al. (2003) applied beef feedlot manure or compost at rates to replace 150 kg N ha^{-1} removed in corn grain harvest. At this application rate microbial biomass increased 20 to 40 percent, mineralizable N increased 40 to 70 percent, and pH increased 0.5 units compared to soil without manure. Additional research is needed to assess the role of manure application as a mitigating strategy to compensate for the additional nutrient removal due to biomass harvest.

Southwest

The southwestern United States, for the purposes of this paper, includes the states of Arizona, California, New Mexico, Nevada, and Utah (Figure 1). This region encompasses a large geographical area with natural vegetation types ranging from desert to forest (Figure 1). However, crop production in this region occurs primarily in arid to semi-arid areas with low SOM. Literally hundreds of crops are grown in this region using a myriad of crop rotations. The most widely planted crops in this region that may contribute residue feedstocks are corn, sorghum, wheat, and barley, which require irrigation (Table 6). A common crop rotation would be cotton for a few years rotated to wheat or barley, then to corn or sorghum before being planted back to cotton or a forage crop. On a local scale vegetable residue could be harvested. However, this region is not likely to have extensive crop residues available compared to other regions.

Crop	Dry land Yield	Irrigated Yield	Dry land	Irrigated
	------------Mg ha^{-1}------------		Million ha	
Wheat	1.5	5.9	0.10	0.30
Barley	1.9	5.1	0.02	0.04
Corn	3.4	10.7	0.02	0.22
Total			6.2	4.4

Table 6. Harvested crop land area and average grain yield for irrigated and dryland wheat, barley and corn in the Southwestern states of Arizona, California, New Mexico, Nevada and Utah*. * www.nass.usda.gov/quickstats/survey (2008) and census (2007) data verified September 7, 2010.

Conservation tillage is not widely adopted in the southwest for various reasons. In California, for example, conservation tillage adoption was estimated at 2 percent of the farmland in 2004 (Horwath et al. 2008). The farmland is level or not as steep as farmland in areas where conservation tillage is more widely practiced. Furthermore, conservation tillage does not lend itself to flood or furrow irrigation systems, which is widely used in this region, where residue may impede irrigation water movement. Also, conservation tillage may result in poor stand establishment of small seeded crops or interfere with conventional cropping practices of certain crops.

There is scant literature on the impact of harvesting crop residue in this region. However, residue removal often has had negative impacts on soil properties and crop performance in arid and semi-arid areas around the world with a climate similar to the southwestern region (Dalal 1989; Radford et al. 1992; Thompson 1992; Yamoah et al. 2002; Shafi et al. 2007). Thus, potential negative consequences should be anticipated if crop residues are harvested in this region without mitigation strategies.

Potential mitigation strategies for residue removal include conservation tillage, cover crops, and the addition of carbon-rich soil amendments. Conservation tillage may mitigate some but not all negative aspects of crop residue removal. In a cotton-tomato (*Lycopersicon esculentum*) rotational system in California's Central Valley, conservation tillage alone did not increase soil organic carbon (SOC) (Veenstra et al. 2007), similar to results obtained in other arid and semi-arid regions (Buschiazzo et al. 1999; Chan et al. 2001). Conservation tillage has been shown to reduce wind erosion and dust particles in the air in California's Central Valley (Baker et al. 2005). In Arizona, reduced tillage of a previous barley crop increased water infiltration in cotton (Martin et al. 2003). However, no-till systems in Arizona may reduce cotton yields (Adu-Tutu et al. 2005). One of the problems with widespread adoption of conservation tillage is management of the residue in flood and furrow irrigation systems. Irrigation is necessary for high productivity (Table 6). In flood systems, the residue can float in the irrigation water and form an impenetrable barrier to emerging seedlings. In furrow systems, the residue can accumulate in the furrow and block water movement. So, in these cases, removal of the residue may encourage the implementation of conservation tillage.

The use of cover crops appears to have more potential to increase SOM in the southwestern region than conservation tillage. The use of cover crops in a cotton-tomato rotation in the Central Valley of California increased SOC (Veenstra et al. 2007). In the Coachella Valley of California, the use of cover crops increased SOM, but also increased horticultural crop yields (Wang et al. 2008). In California, a combination of cover crops and organic amendments increased SOM by 36 percent (Horwath et al. 2002). Despite their advantages, cover crops are not widely used due to their cost of establishment and maintenance, and since the economic returns are not realized directly on the crop itself.

Northwestern Region

The Northwest region is defined for this paper as Washington, Oregon, Idaho and far western Montana (Figure 1). This region has a wide range of climatic conditions. East of the mountains annual precipitation ranges from 200 to 500 mm and winter temperatures frequently drop below 0°C and snow cover is common. In contrast, western Oregon annual precipitation in the range of 850 to 1700 mm and winter temperatures seldom fall below 0°C with average daily high temperatures frequently exceeding 8°C in December and January. Soils in the region include Mollisols, Inceptisols, Entisols and Aridisols (http://www.cei.psu.edu/soiltool/).

Both dryland and irrigated small grains including wheat and barley are major components of the region's agronomic cropping systems. A typical system (90 percent of cropland) is a two-year, tillage-based, winter wheat-summer fallow rotation (Schillinger et al. 2003). This region also produces forage and turf grass seed. Kentucky bluegrass (*Poa pratensis* L.) seed production occurs in the relatively dry, semi-arid regions of eastern Washington, northern Idaho, and central and eastern Oregon. Perennial (*Lolium perenne* L.) and annual ryegrass (*Lolium multiflorum* L.), bentgrass (*Agrostis* sp.), tall (*Schedonorus phoenix* (Scop.) Holub) and fine (*Festuca* sp.) fescues, and orchardgrass (*Dactylis glomerata* L.) seed production occurs in the high rainfall areas of western Oregon.

Crop	Dry land Yield	Irrigated Yield	Dry land	Irrigated
	------------Mg ha^{-1}------------		Million ha	
Wheat	3.1	6.5	1.40	0.44
Barley	2.3	5.1	0.16	0.17
Corn	n†	12.0	n	0.08
Total			4.77	2.73

Table 7. Harvested crop land area and average grain yield for irrigated and dryland wheat, barley and corn in the Pacific Northwest states of Idaho, Oregon and Washington *. * www.nass.usda.gov/quickstats/survey (2008) and census (2007) data verified September 7, 2010. † n = no data, little to none grown.

Crops that produce high amounts of residue that could be used as bioenergy feedstocks are wheat, barley, corn and perennial grasses raised for seed. Regionally, dryland and irrigated wheat produce the greatest quantities of straw (Table 7). Dryland wheat (1.4 million ha yr^{-1} harvested) and irrigated wheat (0.44 million ha yr^{-1} harvested) produce about 6.44 and 4.22 Mt yr^{-1}, respectively, of dry wheat straw assuming a grain to straw ratio of 0.59 and a harvested grain water content of 12.5 percent. Grass-straw production across the region average 2.4 Mg ha^{-1}, with an average annual production of about 2.24 Mt yr^{-1} (Banowetz et al. 2008). The grass straw yield ranged from 3.5 to 7.5 Mg ha^{-1} in the drier eastern portion and 9 to 13 Mg ha^{-1} in the wetter western portion of the region; as most grass seed crops are produced under dryland condition (Banowetz et al. 2008). Irrigated barley (0.17 million ha yr^{-1}) produces 1.12 Mt yr^{-1} of dry barley straw and dryland barley (0.16 million ha yr^{-1} harvested) produces 0.49 Mt yr^{-1} of dry straw assuming a barley grain to straw ratio of 0.67 and a harvested grain water content of 12.5 percent. The region's corn is grown almost exclusively under irrigation (0.082 million ha yr^{-1} harvested) and assuming a corn grain to stover ratio of 1:1, and a grain water content of 15.5 percent, about 0.83 Mt yr^{-1} of dry corn stover are produced.

Irrigation increases the concentration of residue stocks (Table 7), which has important economic and environmental implications. From an economic standpoint, concentrated feedstocks reduce harvest and transportation costs and bioenergy facilities could be strategically located in areas where feedstock supplies would be greater and more stable (less yield variability due to weather) (Kerstetter and Lyons 2001). Environmentally, a smaller proportion of total crop residues would need to be returned to the land to provide agro-ecosystem services and maintain soil productivity (Huggins and Kruger 2010). In locations with sufficient rainfall or irrigation, a portion of the grass straw may be harvested and still provide enough residue to meet USDA-NRCS conservation guidelines (Banowetz et al. 2008; Mueller-Warrant et al. 2010).

Removal of grass straw and other agricultural residues from production systems is accompanied by the removal of macro– and micronutrients that accumulate in the biomass during the growing season. Straw harvested from dryland Kentucky bluegrass in eastern Washington removed 48 to 96 kg of K, 2 to 10 kg of P, and 662 to 1029 kg C ha^{-1} (Banowetz et al. 2009a). In the high rainfall area of western Oregon, harvest of 2.4 Mg ha^{-1} of perennial ryegrass removed 40 to 47 kg K, 3.4 to 3.8 kg P, and 922 to 986 kg C ha^{-1} (Banowetz et al. 2009b). Similar quantities of P and K were removed during harvest of a selection of native grasses that are used in roadside and buffer areas of the west (El-Nashaar et al. 2009). These nutrients have value for soil productivity and their replacement increases production costs.

Research to quantify the impact of straw removal from perennial grass seed production systems has focused on full removal of the straw by baling or returning all chopped straw to the field. A ten year study at three locations of western Oregon found that seed yield of perennial ryegrass, tall fescue, and creeping red fescue was unaffected by residue management but returning straw combined with direct seeding, reduced soil erosion from 40 to 77 percent (Steiner et al. 2006a; Steiner et al. 2006b). Residue management did not alter meadowfoam (*Limnanthes alba* Hartw. ex Benth.) biomass or oil yield when it was produced as a rotation crop with these three grasses. A subset of this long-term study found that SOC, microbial biomass C, dissolved organic C, soil K and the activity of soil enzymes ß-glucosidase and arylsulfatase activity in the 0-10 cm were greater when straw was returned to compared to when straw was harvested (Richard Dick and Steve Griffith, unpublished data). In contrast, a four-year study of the impact of high versus low residue management on soil C in the low rainfall areas of eastern Washington showed no significant differences in soil C associated with straw residue or tillage methods (Griffith, unpublished data).

Amounts of crop residue required for conservation needs and other agroecosystem services are still under debate (Huggins et al. 2011). Kerstetter and Lyons (2001) estimated that leaving 3.4 to 5.6 Mg ha^{-1} yr^{-1} of dry straw is required to soil for conservation purposes in western states, whereas Banowetz et al., (2008) reported 4.5 Mg residue ha^{-1} yr^{-1} were needed. These numbers are similar to the 4-5 Mg residue ha^{-1} yr^{-1} reported by Rasmussen and Collins (1991) to be required in dryland cropping systems near Pendleton, OR. Yields of cereal crops under irrigation often produce large amounts of residue. For example, a wheat yield of 6.5 Mg ha^{-1} may produce 9.7 Mg ha^{-1} of straw (Tarkalson et al. 2009; Tarkalson et al. 2011). Harvesting straw in irrigated situations does not appear to adversely affect SOM (Tarkalson et al. 2009; Tarkalson et al. 2011).

Kerstetter and Lyons, (2001), Western Governors' Association (2006), and Banowetz et al., (2008), assumed similar quantities of straw are produced in the region year-to-year. However, due to crop rotation and wheat-fallow systems, straw production does not occur in the same field every year. Typically dryland cereal crops are grown in rotation or combined with fallow periods (Schillinger et al. 2003). While a typical wheat yield of 3 Mg ha^{-1} will produce about 4.5 Mg ha^{-1} of residue, this is only sufficient if a crop is grown annually on the same fields. Thus, residue production must be considered over the entire rotation when calculating available feedstocks (Johnson et al. 2006; Huggins and Kruger 2010). Johnson et al. (2006) estimated that straw yield may be adequate for sustaining SOC provided wheat is grown continuously without fallow, assuming a biomass return rate of 4.5 ± 2.5 Mg straw ha^{-1} yr^{-1} (n=9). They further suggested that critical source C for wheat-fallow maybe twice that in continuous wheat. Neglecting the impact of fallow or rotation in considering the amount of biomass needed to be returned will over estimate the amount of residue that can be sustainably harvested.

Estimating available residue as a percentage (e.g., 10 to 50 percent) of the total residue and assuming the remaining unharvested residue is sufficient for meeting conservation and soil maintenance needs (Berndes et al. 2003; Frear et al. 2005; Fischer et al. 2007), underestimates available feedstocks when residue production is high (e.g. irrigation) and overestimating available feedstocks when residue levels are low (e.g. dryland with fallow). It neglects that the percentage of crop remaining is not the same as percent soil coverage. Calculating the regional availability of residue feedstocks is important for evaluating the feasibility of bioenergy production. However, on a field basis considerable variability can exist in both feedstock production and availability, thereby requiring residue harvest decision aids that are site-specific (Huggins and Kruger 2010; Johnson et al. 2010a).

Other issues that need consideration include economic savings that result from residue removal in terms of subsequent field operations; time and cost for field operations (Western Governors' Association 2006); disease and weed factors that can be ameliorated by removing crop residues; the value of nutrients removed in harvested residues (Patterson et al. 1995; Banowetz et al. 2009a; Banowetz et al. 2009b; Huggins and Kruger 2010); soil water conservation that results from maintaining surface residues; and mitigating practices such as the use of conservation tillage, site-specific nutrient management (Huggins and Kruger 2010) and cover crops.

Biochar: a Potential Mitigation Strategy

Co-products of lignocellulosic feedstock conversion to bioenergy vary by platform. The high lignin by-product of fermentation, although could be applied to soil (Johnson et al. 2007c) is more likely to be used for feedstock on-site for its energy value (Sheehan et al. 2004). Gasification processes that strive for high energy conversion result in a low carbon ash that has potential as a source of inorganic minerals (P and K) (Johnson et al. 2007b). In contrast, pyrolysis, which is the thermo-chemical decomposition of organic compounds in the absence of oxygen at temperatures typically above 400ºC, produces biochar (a.k.a., charcoal, char, agri-char, green coal, and black carbon), bio-oil and syngas. Slow pyrolysis produces approximately equal masses of all three co-products, whereas fast pyrolysis is optimized for the production of bio-oil, gasification is optimized for syngas production, and flash carbonization is optimized for biochar production (Laird et al. 2009).

Quality of the biochar, bio-oil and syngas co-products depends on properties of both the feedstock and the thermo-chemical reaction conditions during pyrolysis. Biochars made from low-ash woody feedstocks can be used to replace pulverized coal. Generally biochars, produced from crop residues and most herbaceous biomass, are not suitable for use as green-coal because they contain too much silica, which scales the walls of combustion chambers. However, they do have potential to be used as a soil amendment.

Soil biochar application recycles most of the nutrients that are removed by the harvesting of biomass. During pyrolysis over 90 percent of the K, P, Ca, Mg, and most micronutrients, and about half of the N in the biomass feedstock are partitioned into the biochar fraction (Mullen et al. 2010). When biochar is applied to soils, most of these nutrients are bioavailable. The N, however, is bound in recalcitrant biochar fractions and is not biologically availably to plants on agronomically significant time scales. Many biochars are alkaline and as such they also function as a liming agent when added to soils.

Soil biochar applications are a highly effective means of increasing the level of SOC. The C content of biochar ranged from 40 to 80 percent by mass depending feedstock and pyrolysis conditions (Spokas and Reicosky 2009). Most of the C in biochar is present as complex compounds that are either not biologically available or are mineralized slowly in soil environments. A portion of the C in the biochar is readily degraded by soil microorganisms. As a general rule, the fraction of this easily degraded C in biochar decreases as the pyrolysis temperature increases. Literature estimates of the half-life of biochar C in soils range from decades to millennia (Swift 2001; Hamer et al. 2004; Kuzyakov et al. 2009; Steinbeiss et al. 2009) due to differences in biochar quality. By contrast the half-life of C in fresh crop residues is typically measured in months to years (Johnson et al. 2007a). Thus, pyrolysis of biomass transforms easily degraded C into highly stable C and this change in stability accounts for most of the ability of soil biochar applications to increase SOC levels. Complex interactions exist between biochars and biogenic soil organic C, and between biochars and net primary productivity. Therefore, it is difficult to predict the impact of amending soils with a specific biochar on C input and subsequent SOC levels.

Soil biochar applications may increase the nutrient and water holding capacities of soils and reduce soil bulk density. Low particle density and high internal porosity allow biochar to function as a soil conditioning agent (similar to exfoliated vermiculite). The reduction in soil bulk density resulting from biochar applications is more than can be explained by simple dilution (Laird et al. 2010). Fresh biochar contains little oxygen and has a low cation exchange capacity (CEC), however surfaces of biochar are oxidized as it ages in soil environments creating carboxylate and phenolate groups that add CEC to soils (Cheng et al. 2006; Liang et al. 2006). Therefore, the impact of biochar amendments on soil CEC's is influenced by both biochar quality and the length of time the biochar are in a soil environment. The application of pecan shell-biochar to a Norfolk sandy loam improved soil fertility but did not increase the CEC after incubating for 67 days (Novak et al. 2009). By contrast, a 500-day incubation of a Clarion soil with a hardwood biochar increased the soil's CEC by almost 20 percent, and the effective CEC of the hardwood biochar was estimated to be 187 cmol kg^{-1} (Laird et al. 2010). As surfaces of biochar particles oxidize, they are transformed from hydrophobic to hydrophilic, which along with a reduction in soil bulk density and the high internal porosity of biochar particles, facilitates the retention of plant available water by when amended to soils.

Biochar quality varies substantially depending on the nature of the feedstock and the condition during pyrolysis. Concerns have been raised that some biochars may have detrimental impacts. Biochars that contain significant levels of polyaromatic hydrocarbons, for example, are potentially hazardous (Dellomo and Lauwerys, 1993). The production of polyaromatic hydrocarbon can be controlled by maintaining pyrolysis temperatures below 700°C (Garcia-Perez et al., 2008). Furthermore, toxicity studies conducted with two biochars, one from poultry litter and the other from pine chips, increased mortality and weight loss of earthworms (*Eisenia fetida*) (Liesch et al. 2010). In contrast, there are reports that biochar can promote colonization by beneficial mycorrhizal fungi (Warnock et al. 2007) and increase microbial activity (Focht 1999). Clearly, there is a need for continued research on the biochar properties from a range of feedstocks and thermochemical conditions, and the responses of soils to biochar applications.

The fundamental hypothesis underlying "The Charcoal Vision" is that applying biochar to soil will recycle nutrients and sustain or even enhance soil quality even when surface residues are harvested for bioenergy production (Laird 2008). Biochar research published to date strongly supports this hypothesis with two important caveats; 1) biochar quality is very important, there are good biochars and bad biochars, and 2) biochar will not protect soils from erosion. Soil biochar applications may allow a greater fraction of total crop residues to be sustainably harvested for bioenergy production relative to systems in which biochar is not applied to soil. However, even with biochar applications, a fall cover crop must be grown or enough residues must be left on the surface, to protect the soil from erosion.

Summary

Regardless of the region controlling erosion, safeguarding SOM and related soil productivity issues are reoccurring themes. There is a need for controlled studies that compare the impact of residue removal or retention on SOC, soil biota, and other physical parameters. Additional quantification of macro- and micro-nutrient removal associated with residue harvest is needed. As well as studies to assess how nutrient management may need to be altered.

A key mitigation strategy is to follow standard conservation practices established by the USDA-NRCS. Eliminating or at least reducing tillage keeps crop residue on the soil surface. Cover crops are another strategy to keep the soil covered; thereby, reducing erosion risk and sequestering more carbon. Although, not discussed at length as the discourse focused on crop residues, adding perennials within a rotation and/or on the landscape can improve soil and water quality. The mitigation strategies proposed for supporting crop residue harvesting are applications of standard soil conservation practices and the use C-rich soil amendments such as manure or biochar to build soil C levels. Calculating regional or national availability of residue feedstock is valuable for evaluating the feasibility of bioenergy production. Nevertheless, on a field basis site, specific decision aids will be needed. Harvesting crop biomass requires aggressive conservation practices to avoid unintended environmental degradation in all regions.

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Chapter 6

Herbaceous Perennials: Placement, Benefits and Incorporation Challenges In Diversified Landscapes

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Abstract

Herbaceous perennial feedstocks will fill numerous and critical roles in the bioenergy landscape. Our objective is to present the benefits and challenges of growing herbaceous perennials and provide regionally-specific scenarios for their use at the landscape scale. The primary herbaceous perennial feedstocks will vary by agro-ecoregion and will include switchgrass, Miscanthus, alfalfa, native polycultures, sugar cane, and energy cane. In the near term, optimizing sustainable yield will drive the economic feasibility of herbaceous perennials. However, within agro-ecoregions, feedstock selection will be site-specific based on landscape position, potential ecosystem services, and producer-driven acceptance such as economics, familiarity, and committing land to long-term feedstock production. For example, in the central and northern Great Plains, managed switchgrass monocultures produce three times more dry matter and provide fewer establishment and management challenges than extensively managed native polycultures. Since yield is of paramount importance, native polycultures may be suited only to situations where ecosystem restoration and increased plant species diversity are primary objectives. In the Midwest, Miscanthus *x giganteus* produces more biomass with fewer inputs than other herbaceous perennials, though the cost of establishment and time required to keep stands in production to offset the cost of establishment may limit producer acceptance on a large scale until non-invasive, seeded varieties can be developed. In the Gulf Coast states, sugar cane has been in production for more than 200 years, so expanding production for bioenergy provides fewer barriers. The Southeast has the most diverse selection of herbaceous biomass crops which will be determined by local growing conditions, available harvest technology, and environmental considerations. Challenges in the Southeast include reluctance to adopt novel crops and the predominance of degraded soils on sites available for cultivation. Balancing biomass production, ecosystem services and producer acceptance will be major challenges for a diversified landscape in the new bioeconomy.

Keywords: switchgrass, Miscanthus, sugar cane, energy cane, sustainability

Abbreviations: C, carbon; **DM**, dry matter; **N**, nitrogen; **SOC**, soil organic carbon

Introduction

Although there is no one-size-fits-all bioenergy feedstock, herbaceous perennial feedstocks will fill numerous and critical roles in the bioenergy landscape. Mitchell et al. (2008) identified four primary advantages perennial feedstocks have over annual row crops. First, perennials do not have the annual establishment requirements and associated economic and net energy inputs. Second, they require fewer chemical inputs (herbicide and fertilizer) than annual row crops. Third, perennials produce large quantities of biomass. Finally, perennials provide a number of important ecosystem services such as soil stabilization, soil carbon sequestration, and wildlife habitat beyond what annual crops are capable. Although these characteristics are important, herbaceous perennial crops must be economically viable to be acceptable to producers and biorefineries, and environmentally sustainable to be acceptable to society.

Arguably, the 2006 Presidential State of the Union Address can be identified as the catalyst for increasing research and development into biomass feedstocks. The President said, "We'll also fund additional research in cutting-edge methods of producing ethanol, not just from corn, but from wood chips and stalks, or switchgrass. Our goal is to make this new kind of ethanol practical and competitive within six years". This address accelerated herbaceous feedstock research efforts, including the first significant research investments in switchgrass and other feedstocks by private companies.

Our objective in this paper is to present the benefits and challenges of growing herbaceous perennials and provide regionally-specific scenarios for their use at the landscape scale. In the near term, biofuel feedstocks in an agro-ecoregion must have a limited impact on the production of traditional agricultural crops: i.e. not displace currently utilized agricultural land for biomass-specific crops (so-called leakage), and not utilize edible (food or feed) crops for biomass. Consequently, optimizing sustainable yield will drive not only the economic feasibility of selected herbaceous perennial feedstocks, but also the capacity of the landscape to meet all other necessary agricultural and social demands. Within agro-ecoregions, feedstock selection will be site-specific based on yield potential, climate, landscape position, potential ecosystem services, and producer-driven acceptance such as economics, familiarity, and willingness to commit land to long-term feedstock production.

Candidate Feedstocks

Numerous herbaceous perennial species have been considered as biomass feedstocks (Somerville et al. 2010). However, since yield is the most important characteristic for biomass feedstocks, a limited number of candidate feedstocks will comprise a majority of the available land. The primary herbaceous perennial feedstocks will vary by agro-ecoregion and landscape position within an agro-ecoregion. Land availability, climatic variables, and available research information will determine which specific feedstocks will be grown in different regions (Heaton et al. 2004; Dien et al. 2006; Somerville et al. 2010). Switchgrass (*Panicum virgatum* L.), polycultures of native prairie species, Miscanthus (*Miscanthus* species, primarily M. x giganteus Greef et Deu.), sugar cane and energy cane (*Saccharum* spp.), and alfalfa (*Medicago sativa* L.) will dominate most landscapes in the new bioeconomy. All are perennials and all but alfalfa are C4 grasses. A brief description of each feedstock follows.

Switchgrass and Native Polycultures

Switchgrass and native polycultures are well adapted to marginally-productive cropland. These species are native to the U.S. and have been planted on millions of acres of land enrolled in the Conservation Reserve Program (CRP). Research on switchgrass has been conducted continuously since 1936 by the USDA location in Lincoln, Nebraska and more bioenergy research has been conducted on switchgrass than any other herbaceous perennial feedstock. Switchgrass has been identified as the model herbaceous perennial feedstock because it is broadly adapted and has high yield potential on marginal croplands (Vogel 2004). Switchgrass is productive in most rain-fed production systems receiving at least 600 mm of annual precipitation, east of the 100th Meridian, or anywhere dryland corn can be grown reliably (Mitchell et al. 2010). Although switchgrass and other native polycultures tolerate low fertility soils, optimizing biomass and maintaining quality stands requires nitrogen (N) fertilizer inputs and proper harvest management (Mitchell et al. 2010). The fertilizer N requirement for these native warm-season grasses is a function of the yield potential of the site, productivity of the cultivar, and management practices such as time of harvest (Vogel et al. 2002). The optimum N rate generally increases from north to south and ranges from 56 kg N ha^{-1} in South Dakota (Mulkey et al. 2006) to 120 kg N ha^{-1} in Nebraska (Vogel et al. 2002) to 224 kg N ha^{-1} in Alabama (Ma et al. 2001). About the same amount of N needs to be applied as was removed by the previous crop. For example, harvesting a switchgrass field producing 11 Mg ha^{-1} of DM with 1.2% N removes 132 kg of N ha^{-1}. Soil should be sampled and N fertilization based on the difference between crop N needs and available soil N. Low input native polycultures have been evaluated in a limited number of sites and species mixes, but may reduce life-cycle greenhouse gas emissions, fertilizer and pesticide inputs, and irrigation requirements (Tilman et al. 2006). However, low input native polycultures have severely limited yields, but with some inputs, production compares with native monocultures. Both systems lack multi-location comparative evaluations against other high-yielding perennial monocultures (Mitchell et al. 2010).

Miscanthus

Miscanthus is a genus of grasses that is not native to North America, but *Miscanthus* species, primarily *M. sinensis*, have been grown as ornamentals across the USA for a century. Miscanthus is used for paper and thatching in China and for small-scale energy production in Europe. A sterile, vegetatively-propagated triploid clonal variety, *M. x giganteus* (*Mxg*), a hybrid of diploid *M. sinensis* and tetraploid *M. sacchariflorus*, has been studied for over 30 years in Europe and for a decade in the U.S.A. These and other *Miscanthus* species are being evaluated for biofuel production and electricity cogeneration with coal. The *Mxg* clone maintains high photosynthetic rates in cold environments (Beale et al. 1996) making it a desirable crop in temperate zones, but is expensive to establish and has relatively low yields in the planting and establishment year. However, Heaton et al. 2004 reported 3rd year peak biomass of *Mxg* in multiple environments averaged 22 Mg ha^{-1}. New sterile triploid clones of *Mxg* have been developed with comparable yields, but with improved growth in first year stands [Mendel Biotechnology, unpublished data]. Additionally, seeded *Miscanthus* varieties are being developed, but literature to date is limited. Recent research in five European countries reported eight seeded *M. sinensis* genotypes had 3rd year biomass of 10-20 Mg ha^{-1} (Clifton-Brown et al. 2001). There are reports of N fertilizer increasing biomass (Ercoli et al. 1999), but nearly 100 European trials report no relationship between *Mxg* yield and N application (Heaton et al. 2004). Fourteen years after planting there was no yield difference in *Mxg* fertilized with 0 or 120 kg N ha^{-1} annually Christian et al. 2008. Even with low biomass N concentration (0.4% DM) (Christian and Haase 2001), a 20 Mg ha^{-1} biomass harvest removes 80 kg N ha^{-1} supporting the hypotheses that associative N fixation may provide some N for *Miscanthus* (Miyamoto et al. 2004; Davis et al. 2010). *Miscanthus* has greater evapotranspiration than a corn-soybean rotation due to the longer growing season and greater biomass, which could reduce annual drainage water by 32% (McIsaac et al. 2010), but may limit the cultivatable range to regions with high growing season precipitation. The accumulation of SOC has been modeled to exceed corn-soybeans, switchgrass and mixed prairie (Davis et al. 2010), although field data is limited.

Sugar Cane

Sugar cane is a large-stature grass cultivated as a perennial row crop, primarily for its ability to store sucrose in the stem. Sugar cane (2n=100-130) is genetically complex with a genomic makeup that results from interspecific hybridization, primarily involving *S. officinarum* as the female parent with the wild *S. spontaneum* as the male parent (Dunckelman and Legendre 1982; Tew and Cobill 2008). Early generation F1 progeny have exhibited high levels of hybrid vigor, which is hypothesized to potentially impart cold tolerance; greater ratooning ability; enhanced tolerance to moisture extremes, insects, and diseases; and more efficient nutrient utilization (Legendre and Burner 1995). In traditional breeding programs, the hybrids with the greatest yield potential are selected over a 5-year period and backcrossed with elite sugar cane varieties in an attempt to increase sugar yields while retaining some of the traits from the wild parent. These early generation hybrids, though not desirable as sugar cane cultivars, are ideal candidates for cellulosic biomass production (Bransby et al. 2010). Many of these hybrids produce over 30 Mg/ha DM biomass annually over four autumn harvests, with about 20 Mg/ha being fiber and 10 Mg/ha being Brix (Anonymous 2007). These high-fiber sugar canes are often distinguished as "energy cane" since the major use of these cultivars would be for bioenergy production. Production and harvesting practices developed for sugar cane can be adapted for energy cane. Sugar cane is vegetatively planted by laying stalks end-to-end in a planting furrow along rows spaced 1.5 to 1.8 m apart and covering the stalks with 5 to 10 cm of soil. Commonly applied nutrients are N, phosphorus (P), and potassium (K) with N rates of 78 to 100 kg/ha being applied to the plant-cane crop (first growing season) and 100 to 134 kg/ha being applied to the subsequent ratoon crops to insure sustained yields.

Alfalfa

Alfalfa is one of the oldest and most widely grown perennial forage crops in the world (Sanderson and Adler 2008). It is well adapted to most areas in the continental U.S., and public and private breeding programs have developed varieties to fit diverse climatic and environmental conditions. In the U.S., alfalfa was produced on 8.6 million ha in 2009, ranking only behind corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], wheat [*Triticum aestivum* (L.)], and other hay in terms of harvested area (USDA NASS, 2009). Some key benefits of alfalfa for bioenergy include: 1) the ability to biologically fix N, 2) the potential to be used as a dual purpose crop (stems for bioenergy and leaves for animal feed), and 3) ease of establishment, production, and management. Biological dinitrogen (N2) fixation in alfalfa generally eliminates the need for N fertilizer. Estimates of N2 fixation in alfalfa vary widely (50 to 463 kg N^{-1} ha^{-1} y^{-1}) due to bacterial strain by plant interactions and differences in management practices (Vance et al. 1988). Furthermore, in crop rotations, alfalfa is able to meet much of the N demands of a succeeding corn crop. A dual-use system has been proposed where the stems and leaves are separated and used for biomass energy and a high protein animal supplement, respectively (Wilbur et al. 1998). Sheaffer et al. (2000) reported stem yields increased and leaf yields decreased when alfalfa was harvested two times y^{-1} at late flower rather than three times y^{-1} at early flower. They concluded that producers could alter the proportion of stems or leaves simply by adjusting their harvest regimes. Utilizing four unique alfalfa germplasms, Lamb et al. (2003) found that planting alfalfa at 180 plants m^{-2} and harvesting twice per year at later stages of maturity (green pod) is an effective strategy for maximizing yield in a bioenergy production system. Unlike some other potential biomass crops (e.g., switchgrass, Miscanthus, prairie cordgrass), many producers understand alfalfa establishment, production, and management strategies.

Feedstock	Switchgrass	Native Polyculture	Miscanthus	Alfalfa	Sugar cane
Native	+	+	–	–	–
Yield Potential	+	+ (-)	++	+	++
N Fertilizer	–	–	++	+	–
Rapid/Economical Establishment	+	+	–	+	–
Producer Experience	+	+	–	++	++
Field Scale	+	+	–	++	++
Ecosystem Services	++	+	+	+	+
Alternate Use	+	+	–	++	+
Multiple Conversion Platforms	–	–	–	–	++

Table 1. Positive (+) and negative (-) attributes of selected herbaceous perennial feedstocks. Native polyculture = low diversity polyculture (negative with no inputs) ++ = very positive attribute -- = very negative attribute

Positive Attributes of Herbaceous Perennials

All herbaceous perennials have the potential to provide ecosystem services such as C sequestration, soil erosion control, and some level of wildlife habitat that exceed those provided by current cropping systems. Additional positive attributes for many bioenergy crops include being native to North America, rapid and economical establishment, high yield, field scale production, producer experience with the feedstock, limited N fertilizer requirement, alternative uses other than bioenergy, and multiple conversion platform options (Table 1). Comparisons of these positive attributes can help inform the decision-making process for candidate feedstocks within an agro-ecoregion. The value placed on each attribute will vary by perspective (i.e., farmer, policy maker, environmental activist), but understanding the importance of these attributes will help guide the feedstock selection process in the emerging bioenergy landscape.

Regional Considerations

In the central and northern Great Plains, managed switchgrass monocultures produce three fold more dry matter and provide fewer establishment and management challenges than extensively managed native polycultures. Since yield is of paramount importance, native polycultures may be suited only to situations where ecosystem restoration and increased plant species diversity are primary objectives. However, intensified management will increase yield in native polycultures. In the Midwest, *Mxg* produces more biomass with fewer inputs than other herbaceous perennials. However, the cost of establishment and the time required to keep stands in production to offset the cost of establishment may limit producer acceptance on a large scale until non-invasive, seeded varieties can be developed. In the Gulf Coast states, sugar cane has been produced for more than 200 years, so expanding production for bioenergy provides fewer barriers. The Southeast has the most diverse selection of herbaceous biomass crops which will be determined by local growing conditions, available harvest technology, and environmental considerations. Challenges in the Southeast include reluctance to adopt novel crops and the predominance of degraded soils on sites available for cultivation. Management practices such as harvest date will be important considerations for bioenergy crops. Herbaceous perennials can be harvested green or following senescence after significant nutrient remobilization has occurred to the rhizome/root system. Balancing biomass production, ecosystem services and producer acceptance will be major challenges for a diversified landscape in the new bioeconomy.

Sugar cane production in the Gulf Coast states provides an interesting overview of the required regional breeding efforts for bioenergy feedstocks. Sugar cane currently is grown in Florida, Hawaii, Louisiana, and Texas with the Louisiana sugar cane industry being located in the most temperate climate. Two types of cold tolerance are needed if sugar cane is to be grown sustainably as a perennial in more temperate climates. First, it is a perennial that requires below-ground buds to produce the subsequent ratoon crops, which must survive when the soil freezes. Second, as biomass yields are positively correlated with the length of the growing season, below-ground buds should become active when soil temperatures are cooler and the above-ground shoots should be able to tolerate frosting in the spring at the beginning of the growing season and autumn frosts and freezes as the harvest season begins and the growing season ends. Enhancing cold tolerance in new varieties has been a major focus of the USDA-ARS Sugarcane Research Unit at Houma, Louisiana since the 1960's (Dunckelman and Legendre, 1982). Cold tolerance is obtained by the introgression of traits from S. spontaneum and its related genera, *Miscanthus* and *Erianthus* that were obtained from colder climates in Asia. The F1 hybrids are being grown as far north as Starkville, Mississippi (33° 27′ N. lat.) and Boonville, Arkansas (35° 08′ N. lat.), the former as part of the USDA-ARS Regional Sun Grant Initiative. As the introgression of traits from wild species and related genera is an on-going process, a pipeline of new and genetically diverse energy cane varieties is being developed. Similar regionally specific breeding efforts by public institutions and private companies are in progress for switchgrass, other native prairie species, Miscanthus, and alfalfa.

Economics and Energetics

Cellulosic ethanol production has been achieved at the experimental, pilot, and demonstration scale, but, to date, has not been produced at the large commercial scale (Mitchell et al. 2010). Consequently, cellulosic ethanol conversion for different feedstocks is based on values estimated from the laboratory to demonstration scale (i.e., Dien et al. 2006) and will not be discussed in this chapter except where it clarifies discussions on feedstock energetics.

Economics

The establishment period is the most expensive and uncertain stage of perennial crops. The establishment costs, ranked from the least to most expensive are switchgrass, low diversity native polycultures, alfalfa, sugar cane, and Miscanthus (Table 2). The high cost of establishment for Miscanthus, as well as the specialized equipment needed, is a deterrent for producer acceptance and highlights the need for establishment research or a new seeded Miscanthus production system. Research is on-going to reduce the establishment costs and risks for all of the herbaceous perennial feedstocks, which include techniques such a micro-propagation and new equipment development.

Operation	Switchgrass	Native Polyculture	Alfalfa	Sugar cane	Miscanthus
Seed/Seedstock	48.00	76.00	60.00	70.18	735.90
Planting	15.00	15.00	7.20	269.73	188.69
Fertilizer	0	0	69.25	0	0
Fertilizer application	0	0	11.00	0	0
Herbicide	23.50	11.00	13.10	79.60	29.64*
Herbicide application	6.50	6.50	11.00	20.00	6.50*
Tillage	0	0	14.40	142.09	52.21
Total cost of establishment	93.00	108.50	185.95	581.60	1,012.94

Table 2. Establishment costs ($ per acre) for switchgrass, native polycultures, alfalfa, sugar cane, and Miscanthus (Mxg). All costs are based on best management practices using current market values for switchgrass (4 PLS lbs @ $12/lb) and native polycultures (5 PLS lbs @ $12/lb + 1 PLS lb legume @ $16/lb). All costs for alfalfa are based on current market values using best management practices (Barnhart et al. 2008). All costs for sugarcane are based on current market values using best management practices (Salassi and Deliberto All costs for Miscanthus are based on best management practices (CALU 2006) with current market values for herbicide and application costs*.

Few field-scale studies have evaluated the economic feasibility of producer-grown herbaceous perennial biofuel feedstocks. A field-scale study using known farm inputs and actual harvested switchgrass yields conducted on 10 farms over 5 years in Nebraska, South Dakota, and North Dakota determined switchgrass could be delivered at the farm gate for $54 Mg^{-1} (Perrin et al. 2008). They concluded that new cultivars, improved production practices, and an expanded market for switchgrass will reduce the farm-gate cost (Perrin et al. 2008). They expect that large quantities of switchgrass could be delivered at the farm gate for $40 to $45 Mg^{-1}, a farm-gate feedstock cost of $0.12 to $0.16 per liter (Perrin et al. 2008).

The establishment costs for sugar cane and *Mxg* are significant, with production-scale establishment costs available for sugar cane, but lacking for *Mxg*. Establishment cost for sugar cane is about $1,235 ha^{-1} when the grower uses seed cane from the farm. The amortized planting cost for four annual harvests is about $308 ha^{-1} y^{-1}. With energy cane, one hectare of seed cane plants will yield propagules for about 13 hectares, reducing planting costs to $855 ha^{-1}. Amortizing the cost over the anticipated six annual harvests reduces planting costs to $205 ha^{-1} y. Herbicides are labeled for at-planting preemergence applications in sugar cane; presumably these herbicides can be applied to energy cane with similar results. Because of the vigor (early spring emergence, high stalk population, etc.) of energy cane, herbicide use beyond the first spring after planting is not anticipated. The vigor of energy cane is advantageous because when the crop is planted in the summer it emerges and produces uniform stands quickly. The crop continues to grow until the above-ground portion is freeze-killed. This biomass (2 to 4 dry tons acre^{-1}) could be harvested and converted to fuel in the establishment year. For *Mxg*, establishment cost estimates in the U.S. for rhizome-based establishment ranges from $1750 to $2500 ha^{-1}, and transplant plug-based costs ranging from $3100 to $3700 ha^{-1} (Mendel Biotechnology, unpublished data).

Energetics

Numerous models have evaluated the energy balance of biofuel production systems using estimated agricultural inputs and simulated biomass yields (Farrell et al. 2006). However, few models have been parameterized with actual farm inputs and harvested yields. Schmer et al. (2008) managed fields on 10 farms over 5 years in Nebraska, South Dakota, and North Dakota. They determined switchgrass produced 540% more renewable than non-renewable fuel consumed and estimated on-farm net energy yield was 60 GJ ha^{-1} y^{-1}. The 50 production environments had a petroleum energy ratio (the ratio of the biofuel output to petroleum input) of 13:1. Additionally, switchgrass produced the most net energy followed by an alfalfa-corn rotation then continuous corn in simulated production trials (Vadas et al. 2008). For the central Great Plains and Midwest, switchgrass is an energetically positive biofuel production system. Additional field scale research is needed on the economics and energetics of bioenergy-specific and other regionally-specific herbaceous perennial feedstocks.

Ecosystem Services

The perennial root system of switchgrass and other herbaceous perennials provides two important ecosystem services; protecting soil from wind and water erosion, and sequestering C in the soil profile (Liebig et al. 2005). Frank et al. (2004) reported that soil C increased at a rate of 1.01 kg C m-2 yr^{-1}, and switchgrass plantings in the northern Great Plains have the potential to store significant quantities of SOC. Liebig et al. (2005) reported that switchgrass grown in North Dakota stored 12 Mg ha^{-1} more SOC in the 30 to 90 cm depth than a cropland paired field experiment. They concluded that switchgrass effectively stores SOC not just near the soil surface, but at greater depths where C is less susceptible to mineralization and loss. Lee et al. (2007) reported that switchgrass grown in South Dakota CRP stored SOC at a rate of 2.4 to 4.0 Mg ha^{-1} yr^{-1} at the 0 to 90 cm depth. In a mesocosm study, Barney et al. (unpublished data) found that individual switchgrass plants amass 0.92 kg C per plant in the establishment year in well watered conditions, while in a droughty environment only 0.52 kg C was sequestered belowground, whereas *Mxg* contained 1.16 kg and 0.03 kg, respectively, under the same conditions. In a 5-year study conducted on 10 farms in Nebraska, South Dakota, and North Dakota, average greenhouse gas (GHG) emissions from switchgrass-based ethanol were 94% lower than estimated GHG emissions from gasoline (Schmer et al. 2008). In addition to increasing soil C, growing switchgrass may increase wildlife habitat, increase landscape and biological diversity, increase farm revenues, and return marginal farmland to production (McLaughlin and Walsh 1998; McLaughlin et al. 2002; Roth et al. 2005; Sanderson et al. 1996). Not harvesting some switchgrass each year would increase the habitat value for grassland bird species that require tall, dense vegetation structure (Roth et al. 2005).

Challenges and Potential Difficulties to Incorporating Herbaceous Perennials

The long-term sustainability of the bioenergy industry will be defined by providing a continual source of high quality feedstocks that have a positive carbon balance grown on underutilized land that stimulates depressed economies while minimizing negative environmental externalities. In order to not compete with land demands for food, feed, and fiber production, biofuels will likely be relegated to so-called "marginal" lands, which typically are less productive, have poorer soil (e.g., reduced fertility, rocky, steep slopes), and have high erosion potential (Lemus and Lal 2005). There are 10.8 Mha of degraded land in the U.S., which may be suitable for bioenergy production. However, Roberston et al. (2008), using low yield expectations and long time horizons, estimated 60 Mha may be required to meet EISA mandates. A major challenge will be achieving the year-round yield demands of the local biorefinery or bioelectricity plant with feedstocks that are harvested once or a few times per year Herbaceous feedstocks must therefore store without loss of quality or energy content. Several potential bioenergy feedstocks (e.g., Miscanthus) are not well characterized agronomically, while the traditional practices of others (e.g., sugar cane, switchgrass, alfalfa) may have to be modified to achieve a positive carbon balance-more carbon sequestered than emitted throughout the crop life-cycle (Adler et al. 2007)-as well as cropping in different soil types and management conditions. Planting, harvest, and transport technology may need to be developed for novel crops or land types (e.g., steep slopes). A major challenge for herbaceous perennial feedstocks will be in achieving federal mandates in the timeframe outlined in the policy (EISA 2007), which Gressel (2008) argues will require biotechnology to achieve the yield, biomass quality, resource-use efficiency, and conversion efficiency required.

In achieving low-input crops that are productive on marginal land, the risk of escaping cultivation and becoming invasive species cannot be ignored and should be evaluated throughout the biofuel supply chain from crop development to biorefinery gate (Barney and DiTomaso 2008). Many of the agronomic traits desired in biofuel crops (high yield with minimal inputs, tolerance to disturbance, low fertility soils, and rapid growth rates) typify many invasive species. Therefore, care must be taken during development and deployment to insure the “kudzu mistake” is not repeated in the widespread adoption of an (ultimately) invasive species. However, after significant evaluation and due diligence, fear of the “what if” cannot prevent the deployment of the biofuel industry.

Challenges

One of the major challenges for biorefineries is that enormous quantities of reliable and timely biomass deliveries will be needed. Mitchell et al. (2008) calculated a 300 million liter (80 million gallon) per year plant will require 907,000 DM metric tons (one million U.S. tons) of feedstock per year assuming 330 liters of ethanol can be produced from one metric ton of feedstock (80 gallons per U.S. ton). The plant will require 2,490 DM metric tons of feedstock per day, or 222 hectares of feedstock yielding 11.2 DM metric tons per hectare, and will use 152 semi loads of feedstock per day, requiring a semi to be unloaded every 9.5 minutes 7 days per week, 365 days per year (Mitchell et al. 2008).

The local agricultural landscape must have an adequate available land base to produce and store feedstocks. The potential dry matter production, biofuel yield of the feedstock, and capacity of the biorefinery will determine the total land area required for feedstock production. If 48 km is the maximum economically feasible distance feedstock can be transported, all of the feedstock must be grown within that 48-km radius of the bio-refinery, an area containing about 723,823 ha. A feedstock producing 2.24 DM Mg/ha (1 U.S. ton/acre) will need to be grown on 404,686 ha (55% of the land base) to supply adequate feedstock, and is not feasible in most agricultural areas. A feedstock yield of 11.2 Mg/ha (5 U.S. tons/acre), a commonly-achieved yield with most available feedstocks, would require only 11% of the land base to be in feedstock production, and is feasible in most agricultural areas. A feedstock yield of 22.4 DM Mg/ha (10 U.S. tons/acre) would require only 5.5% of the land base to be in feedstock production, and would minimally alter the agricultural landscape. This yield is already attainable for sugar cane, Mxg, and switchgrass for many regions of the U.S.. The importance of high DM yield potential to the agricultural feasibility of biofuels cannot be overstated. Additionally, the producer cannot profit by growing low-yielding energy crops. Most feedstocks likely will be grown on marginal lands that have suboptimal characteristics (i.e., slope, soil depth, etc.) for producing food and feed, or on lands currently enrolled in conservation programs. In most agro-ecoregions, feedstocks are available to meet the food, feed, and bioenergy requirements. However, energy crops must be profitable for the producer, they must fit into existing farming operations, they must be easy to store and deliver to the biorefinery, and extension efforts must be provided to inform producers on the agronomics and best management practices.

Potential Difficulties

There are potential pest and disease issues with large-scale monoculture production of bioenergy feedstocks, but most situations have either been addressed or are speculation at this point. Concerns arise for potential disease and insect pests associated with the production of millions of hectares of monocultures, especially since little research has been conducted in these areas. Most pathogen issues cannot be fully realized until large areas areplanted. However, successful production of switchgrass, native polycultures, alfalfa, and sugar cane to the long-term exposure of pathogens native to North America provides assurance that these feedstocks will have limited negative impacts from native pests, as long as research continues to develop new cultivars with a focus on disease and insect resistance.

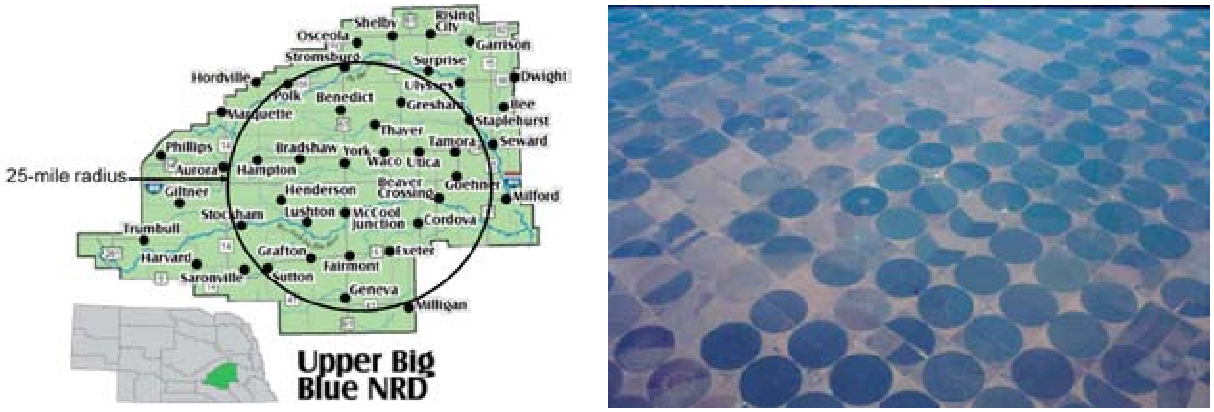

Figure 1. The corners of center pivot irrigation systems are an example of where dedicated herbaceous perennial energy crops will fit in the Great Plains. For example, the Upper Big Blue Natural Resource District (NRD) in east-central Nebraska could grow enough switchgrass in the non-irrigated corners of center pivot irrigation systems to provide the feedstock for one 50-million gallon cellulosic ethanol plant assuming switchgrass production of 5 tons/acre and ethanol yield of 80 gallons/ton. The circle indicates an area with a radius of approximately 25-miles and 1.26 million acres.

An Opportunity for Major Cultural Change in Agriculture

Energy crop production provides unique opportunities for cultural change, operational diversification, and large-scale biodiversity on the agricultural landscape. Bioenergy cropping systems such as switchgrass can provide several environmental benefits compared to annual crops such as stabilizing soils and reducing soil erosion, improving water quality, increasing and improving wildlife habitat, and storing C to mitigate greenhouse gas emissions (McLaughlin et al. 2002; Roth et al. 2005; Liebig et al. 2005). However, agronomic and operational aspects must be developed and accepted by farmers (Jensen et al. 2007). Herbaceous perennial cropping systems will fit well into the production systems of most farmers and even can be incorporated into the non-irrigated land area of center pivot irrigation systems (Figure 1). Handling feedstocks as a hay crop is not foreign to most producers and the economic opportunities presented by herbaceous perennials for small, difficult to farm, or poorly-productive fields will be attractive to many farmers. Grower cooperatives may provide a mechanism for sharing costs and reducing workloads for these small, less productive fields, enabling growers to pool resources to optimize income and provide a reliable feedstock supply, thereby reducing risk for the biorefinery.

The potential change in marginal land use associated with feedstock production could exceed 10%, depending on yield potential, making it important to understand the feasibility and production potential of marginal sites. In a 5-year study in Nebraska, the potential ethanol yield of switchgrass averaged 3,474 L ha^{-1} and was equal to or greater than the potential ethanol yield of no-till corn (grain + stover) on a dry-land site with marginal soils (Varvel et al. 2008). Removing an average of 51% of the corn stover each year reduced subsequent corn grain yield, stover yield, and total biomass yield. Growing switchgrass on these marginal sites likely will enhance ecosystem services more rapidly and significantly than on more productive sites.

Breeding for increased yield is the best mechanism for improving herbaceous perennial feedstocks. Increased yield will reduce the amount of land required for feedstock production and will increase farmer profit per unit area. However, breeding for cellulosic biorefinery traits will likely increase fermentable substrates for ethanol production (Vogel and Jung 2001). Increasing cellulose and hemicellulose and decreasing lignin are logical approaches to increasing cellulosic ethanol yield. Breeding for increased tiller density, phytomer number per tiller, and phytomer mass may provide opportunities for increasing yield (Boe and Beck 2008).

For example, switchgrass is a polymorphic species with two distinct ecotypes, lowland and upland. Selections from each ecotype with the same ploidy level can be crossed to produce a true F1 hybrid that has a 30 to 38% high-parent heterosis (Vogel and Mitchell 2008) and represents the potential increases in perennial grass biomass production in response to plant breeding efforts. Assuming it takes 10 years to develop new cultivars, 30 to 38% divided by 10 years is a 3 to 4% biomass increase per year, and demonstrates the potential for yield improvement in herbaceous perennials.

The hybrid vigor of energy cane, *Mxg*, and switchgrass make them excellent candidate crops for marginal lands where soil type, topography, moisture (too much or too little), and weed, disease, and insect pressures are such that it is difficult to sustain profitability with traditional food and fiber crops, especially in the Southeastern, U.S. These crops offer alternative revenue sources that require very little input. Improved management practices should enable farmers to profitably optimize the bioenergy yield potential of improved plant materials. Additionally, new conversion technologies to produce the next generation drop-in fuels are emerging at a rapid pace and may change the direction of biofuels.

Specific Research Needs

Bioenergy feedstocks must have a positive carbon balance and provide ecosystem services at the landscape scale (e.g., wildlife habitat, runoff, nutrient balance etc.) relative to alternative land-use types. Information needed to assess these impacts is lacking for some of the perennial herbaceous species. Life cycle analyses are an important component in evaluating the impacts on greenhouse gases and the carbon balance, which should be evaluated for each management regime, harvest practice, transportation scenario, and end-product with an agro-ecoregional background. Basic agronomic information regarding nutrient inputs, water demands, and weed management need to be established as well, especially for novel crops.

Bioenergy crops are being selected to minimize inputs, tolerate marginal growing conditions, and exhibit rapid growth rates-agronomically desirable traits that also characterize many invasive species. Some candidate biofuel crops are listed as invasive or noxious species in portions of their non-native range, or have closely related species that are invasive or noxious. Most invasive species were intentionally introduced and cause environmental and economic harm. Necessary elements for sustainable bioenergy production include assessing the invasive potential of biofuel crops prior to large-scale adoption, as these energy crops will be grown in close proximity and often adjacent to food crops. Therefore, the invasive potential for each species should be evaluated within each agro-ecoregion (Barney and DiTomaso 2008).

Sugar cane is one of the most efficient C_4 grasses, with an estimated energy in:energy out (I/O) ratio of 1:8 when grown for 12 months under tropical conditions and processed for ethanol instead of sugar (Bourne 2007; Macedo et al. 2004; Muchow et al. 1994). In sub-tropical environments, I/O ratios of 1:3 are obtainable with current cultivars if ethanol is produced from both sugar and biomass (Tew and Cobill 2008). The theoretical maximum aboveground sugar cane biomass is 139 green tons/ha annually (Loomis and Williams 1963). Sugar cane breeders report sugar yield gains of 1 to 2% per year (Edme et al. 2005). The economic sustainability of growing energy cane in non-traditional cane growing regions will require yearly biomass yield gains of at least 1 to 2%, with a goal of meeting or exceeding the tropical region's I/O ratio of 1:8 in the sub-tropical Southeastern U.S. Developing the ideal energy cane with the right balance of sugar and fiber is difficult because multiple conversion processes are being explored.

In addition to genetically expanding the growing range of energy cane, some agronomic practices could be employed to insure survivability. Adding 2-5 cm of soil cover at planting or shortly after shoot emergence or planting a winter cover crop would provide additional insulation for the first winter. Leaf litter remains after harvest with a conventional sugar cane harvester (Richard 1999; Viator et al. 2009) and could be harvested and converted to fuel, or, in more temperate climates, left on the soil to insulate the belowground buds, reduce erosion, conserve moisture, suppress weeds, and recycle nutrients (de Resende et al. 2006). Field drying is unlikely for energy cane as the stalks are thick and waxy and field conditions at harvest generally are not conducive to field drying. Consequently, energy cane, like sugar cane, will be harvested green and dewatered by crushing, with the fiber stored and processed later. Although water will add to transportation costs, the water contains sugar that is easily and cheaply converted to liquid fuels.

To make energy cane a suitable feedstock for the cellulosic industry and extend its distribution beyond the historic range of sugar cane production will require cold tolerance for expansion outside of tropical areas, drought and flood tolerance since marginal soils likely will be prone to soil moisture extremes, insect and disease resistance, and a further exploitation of some varieties of sugar cane that encourages symbiotic relationships with N fixing bacteria. By enhancing the level of stress tolerance through conventional breeding techniques, the geographic distribution can be expanded to more temperate regions of the U.S. to include those states in Hardiness Zones 8 and perhaps the extreme southern end of Hardiness Zone 7 where low winter temperatures can approach -17ºC. The sugar/ energy cane acreage could triple, making it more attractive for biotech companies with proprietary genes to enhance stress tolerance or introduce genes for the production of saleable byproducts without the food crop labeling restrictions.

Conclusions

Bioenergy feedstocks must be productive, protective of the environment, and profitable for the producer. Enhancing perennial feedstock production will require advancements in agronomics as well as genetics. Farmers and biorefineries must have accurate information on potential feedstocks to determine the profit potential of feedstock production systems. Consequently, DM yield per land area, the amount of C sequestered in a given land area, and the potential energy production per unit of land area are critical in the decision making process. However, the economic value of sustainable energy production, soil stabilization, water quality improvement, habitat enhancement, and energy security are difficult to quantify. The environmental, social, and political considerations will be critical as the next generation of biofuel production moves forward.

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Chapter 7

Woody Feedstocks - Management and Regional Differences

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Introduction

Rising concerns about long-term energy security, human health, global climate change, and a variety of other social and environmental concerns have combined to make developing renewable and sustainable alternatives to fossil fuels a critical national priority. Biomass, as a feedstock for renewable biofuels, bioproducts, and biopower, represents one such alternative, and one that has figured prominently in U.S. energy policy at both the national and state levels (Alavalapati et al. 2009; Aguilar and Saunders 2010; diversify). In addition to addressing the concerns listed above, the use of renewable biomass can help diversity products and markets for agriculture and forestry, create jobs, and promote rural development (Perez-Verdin et al. 2008; Openshaw 2009). Biomass can come from a variety of sources, including forests, agricultural crops, dedicated agriculture and forest energy crops, and various residue and waste streams. Woody biomass, in particular, is an underused resource with a great deal of potential. Although woody biomass can be recovered from a variety of waste and residue streams, emphasis has been placed on sourcing this material from forest management activities and the production of short rotation woody crops (SRWCs) on marginal land. The broad range of climate, soil and land use patterns across the United States means that a range of different forest management activities and SRWCs will be used to supply woody biomass in the years to come. The purpose of this paper is to survey the potential for forest biomass and several of the most promising and well-studied SRWCs across the United States.

Characteristics of Woody Biomass

Woody biomass has several characteristics that make it an appealing feedstock. Wood is harvestable year-round, has low mineral (ash) content (0.2-2.5 percent for most species, Klaas 1998), and a consistent energy (Miles et al. 1996) and sugar content. Short rotation woody crops, in particular, can supply a very uniform biomass feedstock supply of consistent quality because the entire system is managed starting with the selection of varieties to plant through to harvesting. Woody biomass can be harvested from multiple sources and can be mixed by end users, thus avoiding the seasonal harvest cycles and storage issues associated with many agricultural feedstocks. This ensures a consistent feedstock supply, lowers the risk of dramatic price fluctuations, and reduces the need for complicated and expensive long-term storage of material. However, large scale commercial systems for storing woody biomass have been developed by the wood products and pulp and paper industry and can be deployed as needed. The net energy ratios associated with biofuels, bioproducts and biopower from woody biomass are in the 10-20:1 range (Mann and Spath 1999; Keolian and Volk 2005). This means that considerably more energy is produced from these systems than is used in the form of fossil fuels to produce, harvest and deliver the biomass and generate the end product. Because of their perennial nature, inputs to produce and harvest woody biomass from forests and short rotation woody crops are relatively small, which is a major factor in this positive energy balance.

Historical Use of Wood for Energy in the U.S.

Wood was the primary source of fuel in the United States before about 1830 (Fleming 1908 [as cited in Nash and Williamson 1972]). In 1880, wood was still a dominant fuel representing approximately 63 percent of the total U.S. energy consumption, but coal replaced wood as the primary U.S. energy source between 1880 and 1890 (Nash and Williamson 1972). Figure 1 shows U.S. energy consumption by source for 1635-2000. By 1949, wood accounted for approximately five percent of U.S. energy consumption, and by 2009, it accounted for approximately two percent of U.S. energy consumption (EIA 2010).

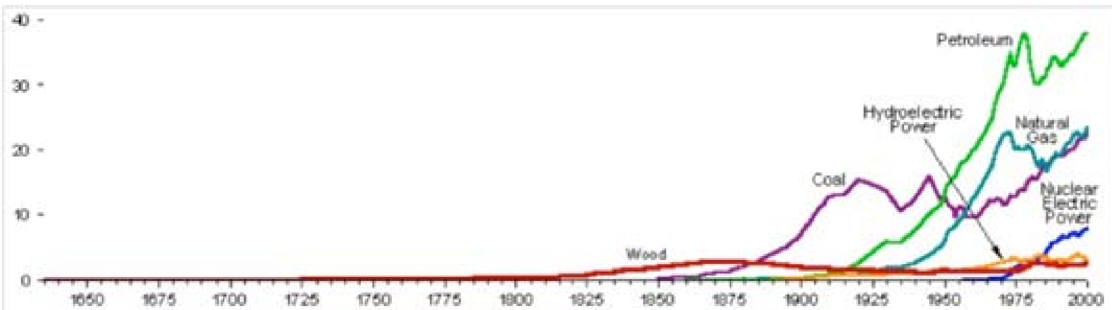

Figure 1: U.S. energy consumption by source, 1635-2000 (quadrillion btu) (EIA 2010).

The consumption of wood as a component of renewable energy is shown in Figure 2. From 1950 to 2010, wood, along with hydroelectricity, has consistently provided the bulk of renewable energy. In 2009 biomass was the largest source of renewable energy in the United States, providing 50 percent of the renewable energy consumed. Wood and biofuels provided 49 percent and 40 percent, respectively, of the biomass energy consumption in that year. (EIA 2010).

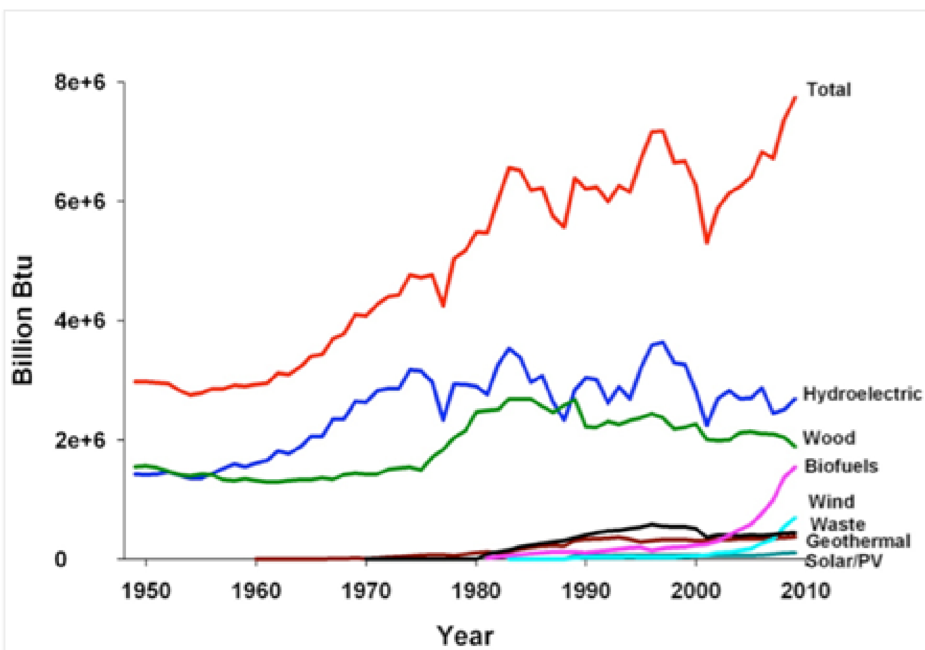

Figure 2: U.S. renewable energy consumption by source (billion btu) (EIA 2010).

Sources of Woody Biomass

Potential sources of woody biomass for energy include materials from both managed forests and SRWC systems. Materials derived from forest management include mill residues and pulping liquors, logging residues, wood from hazardous fuels reduction and forest health treatments, urban wood residues, and conventionally sourced wood (Perlack et al. 2005). Currently, wood used for energy is derived primarily from wastes and materials that are considered unsuitable for other products such as mill residues, pulping liquors, and fuelwood (low-quality wood harvested deliberately for energy production).

Mill residues can be classified into bark, chunks and slabs (course residues) and shavings and sawdust (fine residues). These residues are generally clean, reasonably uniform and dry, and often near existing facilities. While an excellent potential feedstock, much of these materials are in demand for current uses such as fuel in the form of chips or pellets, bedding, and mulch. Pulping liquors are waste products of the wood pulping industry and contain substantial amounts of energy. At this time, this material is used almost exclusively to produce heat and power for pulping and related processes. Urban wood wastes include all manner of discarded wood, yard wastes, and tree trimmings from the urban environment, and could be a potentially large source of energy feedstocks depending on the location, material, and costs (Biomass Research and Development Board 2008). A major challenge associated with urban wood waste is its inconsistent quality and supply.

Logging residues are classified as those materials remaining onsite or at the roadside following a conventional harvest operation, forest management activities, or land clearing. Wood from hazardous fuels or forest health treatments designed to reduce the risk of wildfire and/or losses to insect and disease also constitutes a potential source of wood energy feedstocks, as does wood removed from forest operations intended to restore, create, or maintain wildlife habitat, water quality, recreational opportunities or other ecosystem goods and services. Depending on market conditions and local objectives, conventionally sourced wood could also be used for energy production in some areas.

A range of SRWC systems are being developed across the country to meet the growing need for woody biomass, including eucalyptus, hybrid poplar, shrub willow and southern pine. Other species and systems are also being developed (such as sycamore and sweetgum), but the four listed above are the furthest along and will be the focus of this summary paper. There are research studies and some operational scale plantations of these species as energy feedstocks across the U.S., but large scale production of short rotation woody crops is not generally extant at this time. There are, however, more than 40 million acres of idle or surplus agricultural land available for the future deployment of woody energy crops in the United States (Graham 1994).

Results and Discussion

Estimates of Forest Biomass

There are over 208 million hectares (ha) of timberland (out of 751 million ha of forest land) in the United States with over 21 billion dry tonnes (odt) of aboveground woody biomass (Smith et al. 2009). Figure 3 illustrates the marked regional variation in standing forest biomass across the country. Each year, the amount of growth in these forests is 1.7 times greater than the amount of woody biomass that is being removed. In other words, the net growth to removal ratio across the country is 1.7. This ratio varies across the country from 1.2 in the south central region to 3.3 in the Pacific Northwest (Smith et al. 2009).

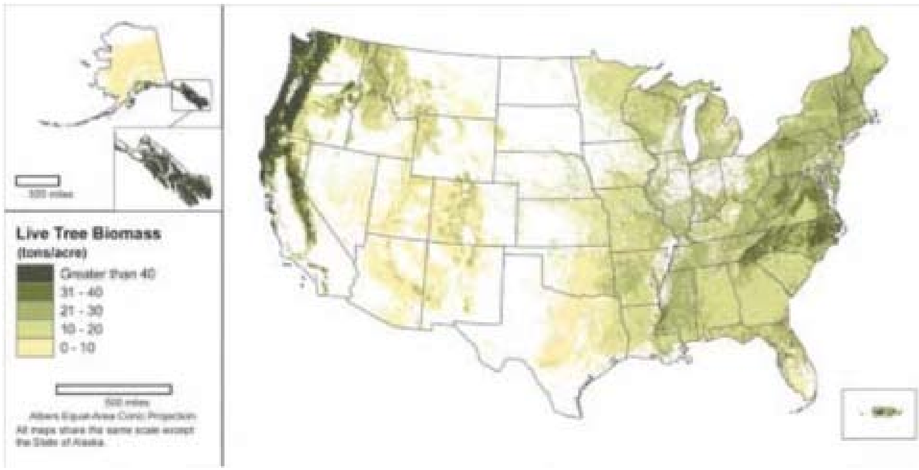

Figure 3: Live-tree biomass across the continental U.S. (tons/acre) (Smith et al. 2009).

In theory, one could harvest the annual surplus growth each year without diminishing the standing growing stock. In reality, however, there are many factors that reduce the amount of biomass that is actually available. In addition to there being a broad range of forest types across the country, silvicultural systems, demand for traditional woody products, land use, landowner attitudes, energy opportunities, and local and state policies vary across the country (Aguilar and Saunders 2010). Each of these factors affect the amount and type of biomass that could be made available (Benjamin et al. 2009; Butler et al. 2011, in press), as well as the cost of removing and utilizing that biomass. Policy factors also limit use. For example, the definition of 'renewable biomass' included in the Energy Independence and Security Act of 2007 (EISA, P.L. 110-140) limits the types of woody biomass from both private and public forests that can be made into biofuels eligible under the national Renewable Fuel Standard (RFS).

By estimating current uses and the magnitude of various reducing factors, a number of authors have estimated the supply of woody biomass that the nation's forest could yield on an annual basis. These include about 59 million odt yr $^{-1}$ of logging residues (Miles and Smith 2009, Smith et al. 2009) and more than 44 million odt yr $^{-1}$ from forest health and hazardous fuels reduction activities alone (Perlack el al. 2005). Estimates of the availability of pulpwood and other sources of conventionally-sourced wood for energy would vary substantially based on local conditions (Biomass Research and Development Board 2008, Conrad et al. 2010). In total, Perlack et al. (2005) estimated a potential supply of approximately 334 million odt yr $^{-1}$ of forest wastes and residues.

Shrub Willows (Northeast, Midwest, Southeast)

Interest in shrub willows (*Salix* spp.) as a perennial energy crop for the production of biomass has developed in Europe and North America over the past few decades because of the multiple environmental and rural development benefits associated with their production and use (Börjesson 1999; Volk et al. 2004; Rowe et al. 2009). Initial trials with shrub willows as a biomass crop were conducted in the mid-1970s in Sweden and in the U.S. starting in 1986 (Volk et al. 2006). Since the initial trials in upstate NY in the mid-1980s, yield trials have been conducted or are underway in 15 states and six provinces in Canada and over 400 ha of commercial scale willow biomass crops have been established.

Shrub willows have several characteristics that make them an ideal feedstock for biofuels, bioproducts and biopower: high yields that can be sustained on three to four year rotations, ease of propagation from dormant hardwood cuttings, a broad underutilized genetic base, ease of breeding for several characteristics, ability to resprout after multiple harvests, and good chemical composition and energy content (three year old willow stems averaged 19.4 MJ kg $^{-1}$ [Miles et al. 1996] similar to other northern hardwood species).

The shrub willow cropping system (Figure 4) is designed to capitalize on several characteristics of shrub willows. It is built around planting genetically improved varieties on fully prepared open land with weed control and managing the crop as coppice using willow's ability to resprout. Willow can be grown successfully on marginal agricultural land across the Northeast, Midwest and parts of the Southeast United States. Weed control usually involves a combination of chemical and mechanical techniques and should begin in the fall before planting if the field contains perennial weeds, which is often the case with marginal land. It is essential to control this competing vegetation and prepare the soil before willows are planted in the spring. Trials incorporating cover crops such as winter rye (*Secale cereale* L.) to reduce erosion during establishment have been successful (Volk 2002). Initial trials using no tillage or conservation tillage techniques have shown some potential, but additional work with precision zone tillage equipment is needed to develop these techniques further. Willows are planted as unrooted dormant hardwood cuttings at about 15,000 plants ha^{-1} in the spring as early as the site is accessible using mechanized planters that are attached to farm tractors and operate at about 0.8 ha hr^{-1} (Figure 5). To facilitate the management and harvesting of the crop with agricultural machinery, willows are planted in a double-row system with 1.5 m between double-rows, 0.76 m between rows and 0.61 m between plants within the rows. Following the first year of growth, the willows are cut back close to the soil surface during the dormant season to force coppice regrowth, which increases the average number of stems per stool from 1-4 to 8-13 depending on the variety (Tharakan et al. 2005). After an additional three to four years of growth the stems are mechanically harvested during the dormant season after the willows have dropped their leaves. Forage harvesters with a specially designed cutting head cut the willow stems 5-10 cm above the ground, feed the stems into the forage harvester and produce uniform and consistent sized chips that can be collected and delivered directly to end users with no additional processing (Volk and Luzadis 2009). The chipped material is then delivered to end users for conversion to biopower and heat, biofuels and/or bioproducts. The plants will sprout again the following spring when they are typically fertilized with about 100 kg N ha^{-1} (Abrahamson et al. 2002; Adegbidi et al. 2003) of commercial fertilizer or organic sources like manure or biosolids. Further research is underway to refine fertilizer recommendations for new willow varieties across a range of sites. The willows are allowed to grow for another three to four year rotation before they are harvested again. Projections indicate that the crop can be maintained for seven rotations before the rows of willow stools begin to expand to the point that harvest equipment access is infeasible. At this point the crop can be replanted by killing the existing stools with herbicides after harvesting, chopping the stools with a heavy disk and/or grinding machine followed by planting that year or the following year.

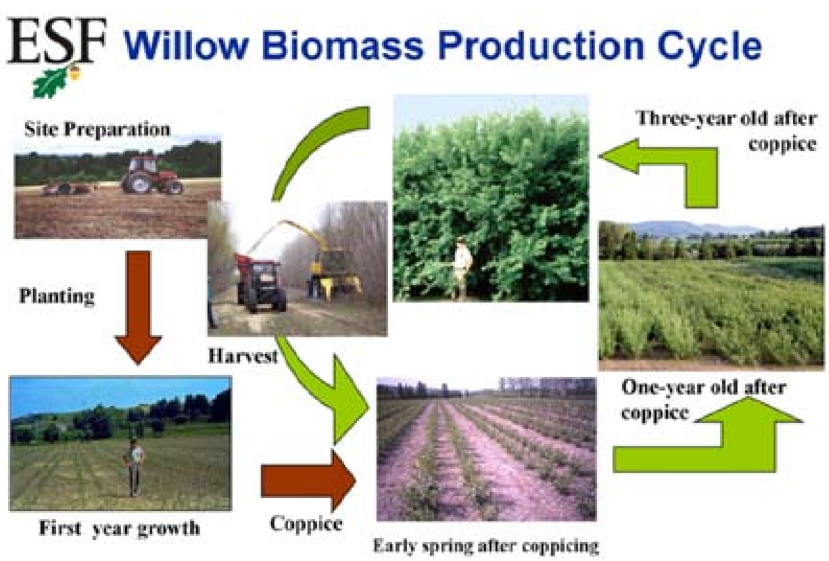

Figure 4: The willow biomass production cycle using current crop management recommendations. Site preparation is done in fall followed by planting in spring the next year. After one year of growth the crop is cut back to encourage vigorous shrub-like growth. After usually 3 to 4 years, the crop is ready to harvest. Then, a continuous harvest cycle of 3 to 4 years (the green cycle of arrows) is possible for more than 20 years without replanting the crop.

Rapid growth is one of the attributes that make shrub willows an appealing biomass crop (Figure 6). Yields from research plots of fertilized (Labrecque and Teodorescu 2003) and fertilized and irrigated (Adegbidi et al. 2001) unimproved varieties of willow grown for three years have exceeded 27 odt ha^{-1} yr^{-1}. Due to the costs associated with irrigation and the relatively low value for biomass, irrigation likely will not be used for most large-scale production operations, with the exception of situations where willow crops could be irrigated with wastewater as part of a nutrient management plan. However, these studies set a benchmark for the potential of shrub willow grown in this type of system, and higher yields will be possible with improved genetic material from breeding and selection programs. First-rotation, non-irrigated research-scale trials in central New York have produced yields of 8.4 to 11.6 odt ha^{-1} $yr.^{-1}$ (Adegbidi et al. 2001; Adegbidi et al. 2003, Volk and Luzadis 2009). Second rotation yields of the five best producing varieties in these trials increased by 18-62 per cent compared to first-rotations (Volk et al. 2001) and in subsequent rotations yields are maintained and largely dependent on weather conditions. The most recent yield trials using improved varieties of willow that have been bred and selected for biomass production at SUNY ESF are showing yield increases of 20-40 percent compared to unimproved standard varieties.

Figure 5. One year old sections of dormant stems are used to establish willow biomass crops using a planter that cuts the stems into 20cm long sections and pushes them into the soil.

Figure 6: Three year old willow biomass crops grown in upstate NY.

Several key bottlenecks in the willow crop production system have been overcome during the past few years making the deployment of willow biomass crops possible on a large scale. One of these barriers has been the availability of large quantities of shrub willow planting stock. Over the past few years a commercial nursery in western New York planted over 40 ha of willow nursery beds to meet the projected annual demand for millions of cuttings for planting stock and several other nurseries are being planned.

Another significant bottleneck in the willow biomass production system has been how to efficiently and economically harvest the crop and produce a consistent quality chip that is acceptable to end-users. Since 2004, Case New Holland (CNH) has been working with SUNY-ESF and other partners to develop a harvesting system for willow biomass crops based on a forage harvester fitted with a specially designed willow cutting head (Figure 7). Trials with this system indicate that for three or four year old willow biomass crops with the majority of stems <75mm in diameter, consistent high quality chips (>95 per cent of the chips being smaller than 37.5 mm) can be produced with the FR series NH forage harvester and NH FN130 woody crop cutting head at a rate of about 0.8-1.6 ha hr^{-1} (unpublished data).

These and other improvements in the system and the growing interest in using willow biomass for the production of biopower, biofuels and bioproducts are spurring large scale deployment. In addition to yield trials and small demonstration plots in 15 different states, over 500 ha of willow biomass crops have been planted in the Northeast and Midwest at a commercial scale. Other projects to deploy large areas of willow biomass crops are being developed in association with public and private entities as well as in Eastern Canada.

Figure 7. Harvesting willow biomass crops with a single pass cut and chip harvester in the dormant season using a system based on a New Holland forage harvester and a specially designed New Holland cutting head.

The economics of willow biomass crops have been analyzed using a cash flow model (EcoWillow v.1.2 (Beta) that is publically available from SUNY ESF (Buchholz and Volk 2011). The model incorporates all the stages of willow crop production from site preparation and planting through to harvesting over multiple rotations, and transportation of harvested chips to an end user. The removal of the stools once the crop has expired at the end of seven rotations is also included in the model. The cash flow model is designed based on experience establishing and maintaining over 200 ha of willow biomass crops in Upstate New York. The model is flexible enough so it can be applied across the range of sites where shrub willow might be grown. Users can vary input variables and calculate cash flow and profits throughout the entire production chain from site preparation and crop establishment to the delivery of wood chips to an end user.

For the base case scenario in EcoWillow, the internal rate of return (IRR) of willow biomass crops over seven three year harvest cycles (22 years) is 5.5 percent (Buchholz and Volk 2011) and the payback is reached in the 13th year with the revenues from the third harvest neutralizing the project's expenses. Harvesting, establishment, and land rent are the main expenses associated with willow biomass crops over their entire lifespan making up 32, 23, and 16 percent of the total undiscounted costs. The remaining costs including crop removal, administrative costs and fertilizer applications account for about 29 percent of the total costs of the project.

Projects are underway to reduce harvesting costs by improving the operation of the cut and chip harvesting system, based on a Case New Holland forage harvester, and optimizing the system to minimize the harvester's unproductive time spent turning around at the end of rows and waiting for wagons to line up to collect chips. Another approach is to reduce the frequency of harvesting operations. Increasing the rotation length from three to four years reduces harvesting costs by 14 percent and increases the IRR by 11 percent (from 5.5 to 6.2 percent).

Establishment costs are the second largest cost in the willow biomass crop production system, accounting for 23% of the total cost. Over 63 percent of these costs are for planting stock, so decreasing this input cost will affect the overall economics of the system. For instance, decreasing costs from a \$0.12 to \$0.10 per cutting reduces establishment costs by \$263 ha^{-1} and increased the IRR of the system from 5.5 to 6.5 percent. In addition, work is underway to quantify the trade-offs between lower per-acre establishment costs and potentially reduced yields resulting from reducing initial planting density.

Several other components of the system need to be developed to improve the overall economics of willow biomass crop systems and one of the main ones is yield. Increasing yields from the base case of 12 odt ha^{-1} yr^{-1} by 50 percent to 18 odt ha^{-1} yr^{-1} increases the IRR from 5.5 percent to 14.6 percent. With ongoing breeding and selection as well as efforts to improve crop management these levels of yield increases should be attainable in the near future.

Willow biomass cropping systems are in their infancy and there is potential for large gains by improving production practices and through breeding. By addressing the components of the system that have the greatest influence on costs, the overall economics of these systems can be improved so they can be deployed across the landscape. As the knowledge base about how willow grows and the roles it plays across the landscape expands, it will be deployed more effectively so that other benefits derived from this system, in addition to biomass, can be optimized.

Willow biomass crops are being developed as sustainable systems that simultaneously produce a suite of ecological and environmental benefits in addition to providing renewable feedstock for bioproducts and bioenergy (Volk et al. 2004; Rowe et al. 2009). The perennial nature and extensive fine-root system of willow crops reduces soil erosion and non-point source pollution relative to annual crops, promotes stable nutrient cycling, and enhances soil carbon storage in roots and the soil (Ranney and Mann 1994; Aronsson et al. 2000; Tolbert et al. 2002; Ulzen-Appiah 2002). In addition, the crop is constantly in its rapid juvenile growth stage, so the demand for nutrients is high, resulting in very low leaching rates of nitrogen even when rates of applications exceed what is needed for plant growth (Mortensen et al. 1998; Adegbidi 1999; Aronsson et al. 2000). The period with the greatest potential for soil erosion and nonpoint source pollution is during the first 1.5 years of establishment of the crop when cover is often limited because weeds need to be controlled and the willow canopy has not closed. The use of a winter rye cover crop has proven to be effective at providing cover for the soil without impeding the establishment of the willow crop (Volk 2002). Since herbicides are only used to control weed competition during the establishment phase of willow biomass crops, the amount of herbicides applied per hectare is about 10 per cent of that used in a typical corn-alfalfa rotation in upstate New York.

Birds are one indicator of the biodiversity supported by willow biomass crops that have been studied in the United States. A study of bird diversity in willow biomass crops over several years found that these systems provide good foraging and nesting habitat for a diverse array of bird species (Dhondt et al. 2007). Thirty-nine different species made regular use of the willow crops and 21 of these species nested in them. The study found that diversity increased as the age of the willows and the size of the plantings increased, and that birds have preferences for some varieties of willow over others (Dhondt et al. 2004). The number of bird species supported in willow biomass crops was similar to natural ecosystems, such as early succession habitats and intact eastern deciduous forest natural ecosystems. A similar study in the United Kingdom found total abundance of butterflies to be 132 percent greater in willow fields as compared to arable crop fields (Haughton et al. 2009). Instead of creating monocultures with a limited diversity across the landscape, deploying willow biomass crops will increase diversity relative to open agricultural land or arable crop fields.

Life cycle analysis of willow biomass crops has shown that they are low carbon fuels because the amount of CO_2 taken up and fixed by the crop during photosynthesis is almost equal to the amount of CO_2 that is released during the production, harvest, transportation and conversion of the biomass crop to renewable energy (Heller et al. 2003). The cycle is balanced for all the CO_2 inputs into the atmosphere from the system, because only the aboveground portion of the willow biomass crop is harvested and used in the conversion process. When willow biomass is used to offset fossil fuels, it can help reduce the amount of CO_2 emitted to the atmosphere. If the 40 million ha of available land in the U.S. were dedicated to the culture of willow or other SRWCs to offset coal use for power production, up to 76 per cent (0.30 Pg of C yr^{-1}) of the carbon offset targets for the U.S. under the Kyoto Protocol could be met (Tuskan and Walsh 2001).

The low inputs required by willow biomass crops relative to agricultural crops as well as their perennial nature results in a large, positive net energy ratio for the biomass that is produced. Accounting for all the energy inputs into the production system, starting with the nursery where the planting stock is grown through to the harvesting of biomass, converting it to chips and delivering it to the side of the field, results in a net energy ratio of 1:55 (Heller et al. 2003). This means that for every unit of nonrenewable fossil fuel energy used to grow and harvest willow, 55 units of energy are stored in the biomass itself. Replacing commercial N fertilizers, which are produced with large inputs of fossil fuels, with organic amendments, such as biosolids, can increase the net energy ratio to 73-80 (Heller et al. 2003). Transporting the woody biomass 40 km from the edge of the field to a coal plant where it is co-fired with coal to generate electricity results in a net energy ratio of 1:11. If a gasification conversion system is used, the net energy ratio is slightly higher (Keoleian and Volk 2005).

Hybrid Poplar (Midwest, Pacific Northwest)

Poplars (*Populus* spp.) are widely distributed worldwide and fossil records indicate that they were distributed throughout North America by 50 million years ago (Eckenwalder 1996). Today, the genus includes more than 20 species representing several taxonomic sections found throughout the northern hemisphere. Hybrids within and among species belonging to two sections, Aigeiros (cottonwoods) and Tacamahaca (balsam poplars), are of greatest commercial interest and are commonly referred to as "hybrid poplars."

Hybrid poplars grown under intensive silviculture have uses including saw-and veneer logs, fiber production for the pulp and paper industry, biofuels feedstock production, and phytoremediation. Large-scale commercial hybrid cottonwood plantations are a reality in Oregon and Minnesota for the production of sawn wood products, fiber and biomass for energy. Genotypes of eastern cottonwood (*P. deltoides* Bartr. ex Marsh) and hybrids between eastern cottonwood and Japanese poplar (*P. maximowiczii* A. Henry), European black poplar (*P. nigra* L.), and black cottonwood (*P. trichocarpa* Torr. & Gray) capable of producing in excess of 15 odt ha^{-1} yr^{-1} by age six have been identified in field tests even in the harsh climate of the North Central region of the United States (Riemenschneider et al. 2001).

Like willow, the unique ability of poplars to propagate vegetatively by adventitious rooting from hardwood cuttings has undoubtedly led to their commercial value and domestication as clones. The most economical means of plantation establishment is to plant dormant hardwood cuttings 22 to 35 cm in length (Heilman et al. 1994). The costs of nursery propagation are reduced and the productivity of the planting crew is high. Thus, just as vegetative propagation can confer significant genetic advantages through clonal propagation, vegetative reproduction offers significant cost reduction during commercial deployment.

In all cases, commercial programs in the United States rely upon high-yielding disease-resistant genotypes adapted to the region. These genotypes have been developed through breeding and field testing in the regions of commercial interest. Many possible breeding strategies can be applied to the development of a hybrid poplar woody biomass crop, but non-recurrent, first-generation inter-specific hybridization has been the predominant approach (Riemenschneider et al. 2001). Yet, all breeding strategies incorporate simultaneous selection for multiple traits through derivation of selection indices. A select variety, or genotype, must produce an adventitious rooting ability, rapid juvenile growth rate, be sufficiently resistant to various insect pests such that limited additional chemical measures can succeed in controlling the pest, and be sufficiently immune to various diseases so that the trees neither die nor have their growth significantly impacted. Rarely do we find a climatic region and species where all necessary attributes are possessed by a single species. Commercial genotypes in use today have most if not all of the important traits affecting production. However, the number of commercial genotypes in use today is relatively low and diversification, as well as yield improvement, is a goal of breeding programs.

Poplar can be managed in a number of ways depending on the desired end product and target rotation age. Plantations grown for the production of larger-diameter trees used in the manufacture of paper and lumber are typically planted at spacings ranging from 1680 trees ha^{-1} to 360 trees ha^{-1}. Plantations of this type are currently being managed commercially in Minnesota for pulpwood production and Oregon and Washington for a mix of products including saw timber and pulpwood. Poplar has the ability to resprout from established stumps after harvest and thus could be managed on repeated coppice rotations for biomass energy feedstock. Owing to the lack of interest in this type of management over the past decades, little additional research has been done on coppice systems due to the fact that the trees are small in diameter and, as such, use is likely restricted solely to energy. In light of the development of new genotypes and increased interest in dedicated energy production systems, the repeated coppice management option is a subject of renewed interest and field research is required to identify optimal plant densities, seasonality of coppicing, nutritional needs associated with repeated coppicing, stand protection owing to repeated coppicing and biomass harvesting systems.

Harvesting of poplar plantations can be accomplished using the same timber harvesting equipment suite found in standard forest pulpwood systems or can be accomplished by purpose-designed equipment that combines felling and chipping or bundling in a single machine. Selection of equipment and method of harvest depends on average tree size and age at harvest which are, in turn, determined by plantation density. A wide array of possibilities can be envisioned.

Yields from commercial plantations range from 10 odt ha^{-1} yr^{-1} in Minnesota to 20 odt ha^{-1} yr^{-1} in the Pacific Northwest. A series of large plot (10 x 10 tree square plots) yield trials conducted in Wisconsin, Minnesota, North and South Dakota from 1987 demonstrated yields as high as 11.0 odt ha^{-1} yr^{-1} by age 7 years (Netzer et al. 2002). Yields of newly selected genotypes in smaller plot experiments have exceeded 16.0 metric tons/hectare/year on good agricultural soil in southern Wisconsin (Riemenschneider et al. 2001). In current practice, sustainable average yields of 10, 13, and 20 odt ha^{-1} yr^{-1} have been achieved in the Midwestern, Southern, and Northwestern United States, respectively. With appropriate research and development investment, these yields can potentially be raised to 18, 27, and 40 odt ha^{-1} yr^{-1} for the same regions, respectively (personal communication, William Berguson, University of Minnesota; Brian Stanton, Greenwood Resources, Randy Rousseau, Mississippi State University). It is important to note that the research and development accomplishments will likely require the application of both classical breeding and field testing as well as discovery of new genetic technologies.

Factors affecting the sustainability of woody energy crops include soil fertility and erosion, water quality impacts and effects on biodiversity. In a summary paper on the subject published by Tolbert et al. (2000), several trends have been identified. Soil structure, total organic content and infiltration rate have been shown to improve under woody crops when compared to the agricultural system being replaced. Inputs of leaf litter and lack of annual site disturbance are thought to be contributing factors. Nutrient content and water yield of short rotation poplar plantations were found to be similar to older natural aspen stands in Minnesota. Increased soil carbon has been documented under short rotation systems particularly in those regions of the country where inherent soil organic content is low such as the South. Over the long term, soil carbon is expected to increase under perennial woody crops due to inputs of leaf and root biomass and lack of disturbance of the soil surface. Oxidation of carbon from upper soil layers has been shown to be a major factor accounting for differences between perennial energy crops and annually-tilled agricultural crops (Alder 2007).

The widespread natural range of eastern cottonwood, plus the possibility of extending the adaptive range by inter-specific hybridization, points to the fact that poplar is one of the most promising species groups for woody crops development nationally. High rates of biomass productivity, amenability to clonal propagation and agricultural management as well as coppicing ability are factors that make poplar a desirable crop to produce biomass for energy as well as other products. Past research has documented acceptable yields of these systems using genetic material that is essentially one generation away from native populations. Genetic improvement research underway in Minnesota and the Pacific Northwest has demonstrated significant gains in biomass yield and the benefits of a concerted breeding and field testing effort. Continued research in genetics and stand management is needed to improve yield and extend the range of high-yielding varieties to all regions where biomass crops may be planted.

Pine and Eucalyptus (Southeast)

The Southeastern United States has abundant land and forest resources, as well as a regionally distributed infrastructure in rural areas with potential for growing and processing biomass feedstocks for the production of biofuels and bioproducts. The region hosts a productive nexus of abundant and highly productive private land with a climate where sunshine and rainfall are plentiful, capable of supporting a variety of SRWC species. Literature suggests that leading SRWC candidate taxa are poplar, sycamore (*Platanus occidentalis* L.), sweetgum (*Liquidambar styraciflua* L.), eucalyptus (*Eucalyptus* spp.), and loblolly pine (*Pinus taeda* L). Black locust (*Robinia pseudoacacia* L.), silver maple (*Acer saccharinum* L.), and shrub willow have also been studied (Dickmann 2006). Loblolly pine and eucalyptus have gained considerable favor as likely purpose grown trees currently able to meet demands for wood, fiber, environmental benefits and energy.

In the southern United States, the forest products industry and forest plantations have a long and successful history. The change from relying on natural pine stands to establishing and intensively managing pine plantations for fiber production is one of the major success stories in the world for plantation forestry (Stanturf et al. 2003; Fox et al. 2007).

In 2007, estimates from the Forest Inventory & Analysis (FIA) data show more than 86 million ha of forestland in the South. Approximately 86 percent of southern forestland is privately owned (Butler 2008). Currently, 91 percent of the Nation's wood output is produced on private lands. In 2007, 95 percent of the forest in the South was classified as timberland (forest land available for and capable of wood production). Also, the region had more than 18 million ha in planted forests, which is 72 percent of all plantations and 71 percent of all planted timberland in the nation. Since 1982, more than 800 thousand ha have been planted annually, virtually all with native species. The South will likely continue its dominance as the nation's wood basket well into the future and this region's high yield planted forests will likely continue to play a crucial role in sustaining U.S. wood production (USFS 2010).

Purpose-grown wood, especially from trees grown through industrial forestry, is an excellent feedstock source for conversion into biofuels and bioproducts. The success of intensively grown pine forests in the South indicates plantations are economically viable under regional conditions of productivity, operational costs, and stumpage price. The dominance of private land ownership combined with an industrial presence strengthens the prospect to continue deploying purpose-grown plantations across the South.

Loblolly pine is the most economically important and widely cultivated timber species in the Southern United States (Figure 8). This tree is dominant on 30 million acres and comprises over half of the standing pine volume in the south (USFS 2007). This widespread cultivation as well as its high growth rates places loblolly pine in a likely position for SRWC culture (Dickmann 2006). The majority of pine planting stock is derived from tree improvement programs emphasizing superior growth rates, form class, and disease resistance - so genetic improvement of this species is highly advanced (Li et al. 1999; McKeand et al. 2003). The magnitude and productivity of existing loblolly plantations provides a standing biomass supply immediately capable of contributing to biofuels and bioproducts markets.

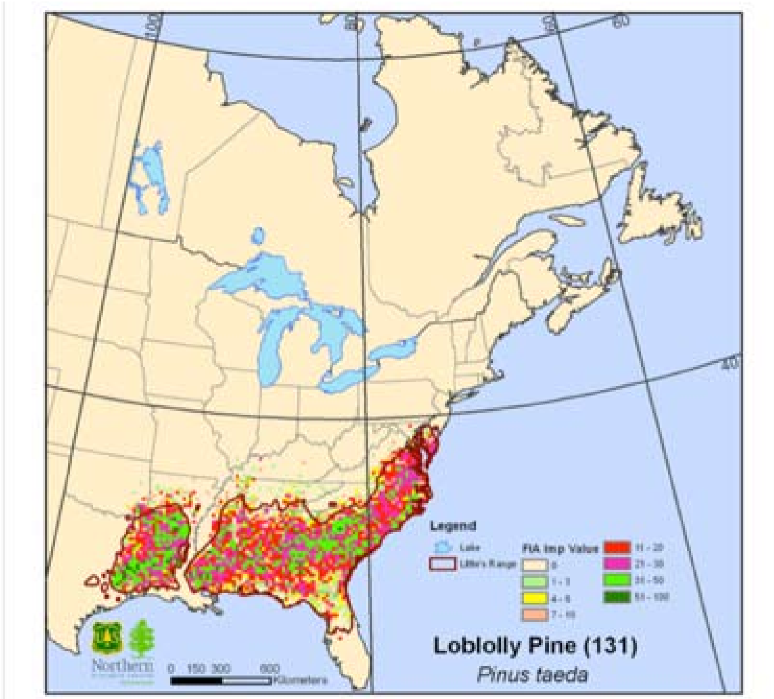

Figure 8: Range of loblolly pine (*Pinus taeda* L.) in the Southern United States. U.S. Forest Service.

Eucalyptus, one of the fastest-growing trees in the world, is an ideal candidate species for biofuels and bioenergy feedstock. Unlike the loblolly seedlings used in Southern forest plantations, eucalyptus can deploy a full canopy of leaves within the first 2 years and in 4 years can grow to 16 m in height, producing more than 32 odt ha^{-1} yr^{-1} under the right growing conditions (Gonzalez et al. 2010).

Figure 9: Eucalptus plantation (*Eucalyptus spp.*) in Florida, United States. ArborGen.

Eucalyptus is the most frequently planted fast-growing hardwood in the world, with an exceptional fiber that is in high demand for pulp and other bioproducts (Figure 9). Eucalyptus meets most of the desired features for a low-cost delivered biomass feedstocks, including the ability to grow more wood on less land (Gonzalez et al. 2009). Nearly 90 percent of U.S. forest landowners own less than 20 ha and the average parcel size is approximately 10 ha (Butler 2008). SRWCs would provide smaller land owners the opportunity to participate and economically benefit in biomass markets.

Recent species test indicate that two species, *E. benthamii* Maiden & Cambage var. *dorrigoensis* Blakely and E. *macarthurii* H. Deane & Maiden, appear to have enough cold tolerance to be considered for use in biomass plantations in the Southeastern United States. Cold-tolerant eucalyptus is currently growing at pilot scale in South Carolina, Florida, Alabama, Georgia and Texas. Wood production rates of 22 to 40 odt ha^{-1} yr^{-1} of total biomass are reasonable for the lower gulf coast region of the south. Eucalyptus biomass can be produced and delivered in the Southern United States at a competitive cost when compared to current biomass delivered costs of grasses and other hardwoods (Gonzalez et al. 2009; Gonzalas et al. 2010).

Forest production systems provide environmental services such as maintenance of hydrologic functions, soil conservation, and atmospheric CO_2 mitigation (Abrahamson et al. 1998). Environmental impacts of the establishment of SRWCs during the first year are not unlike those of the production of annual crops (Joslin and Schoenholtz 1997). SRWC plantations are expected to improve surface runoff and groundwater quality when compared to annual crops following the first establishment year (Thornton et al. 1998). Bioenergy produced from wood energy plantations could add substantially to energy security and be produced sustainably, with minimal adverse environmental effects.

The potential for SRWCs in the southeast is very good, provided that the operation is economical (Volk et al. 2006; Dougherty and Wright 2010). SRWC production costs are high relative to less intensive production systems and emphasize the need to maximize growth rates to lower unit costs. Although less productive sites may provide certain cost savings, they also have a lower yield potential (Gallagher et al. 2006). By initially selecting a good quality site and applying best management practices, intensive pine production can increase biomass yields efficiently, while maintaining or improving long term site productivity (Scott and Dean 2006; Allen et al. 2005).

The source of biomass feedstock should reflect what is locally available and grows well in the region. The practice of plantation forestry as a whole remains controversial to some (Cossalter and Pye-Smith 2003) despite its successful history in the South. Advancement of bioenergy will ultimately be determined by the availability of dedicated cropping systems designed for optimal performance from field production through conversion. Continued research in the arenas of production practices, fiber characteristics, and wood chemistry are strongly needed (Briggs 2010; Vance et al. 2010; Wegner et al. 2010).

The price of any biofuel or co-product use is the major factor determining the total amount of revenue to be divided among the members in the production chain. The single most important concept is that profit accrues to the most restricted resource in the production chain. Forest landowners will likely face two market strategies: 1) grow "traditional market species" (having a wide variety of uses) or 2) grow specialty species (specific properties for specific markets) where performance premiums could accrue. Supplementary markets in traditional forest products sectors provide landowners with flexibility. At the same time leveraging existing forest industry infrastructure provides additional cost savings. Landowners will ultimately benefit if markets develop.

Like other regions, however, a number of factors serve to reduce feedstock availability or increase costs of production or utilization. The Southern Forest Resource Assessment suggests that urbanization will have the greatest impact on the health and extent of southern forests (Wear and Greis 2002). As population density approaches 1 person per 1.7 ha the probability of sustainable timber production approaches zero (Wear et al. 1999). Conditions in land markets (development) and land costs influence forestland values, which in turn dominates the economics of growing biomass. Harvesting, transportation, and storage may double the cost at the conversion facility (Alig and Platinga 2004). To date there has been no decline in timber availability because the loss of forestland to urbanization has been more than offset by the increased productivity of pine plantations and the conversion of marginal agricultural land to forest (Wear et al. 2007). Some argue that increased revenue to landowners would aid in slowing urbanization. Increased valuation of rural production leads to increased valuation of the land. As property values increase, urban sprawl and fragmentation of the landscape decreases (Aronow et al. 2004).

All Southern states have financial incentives promoting bioenergy (Alavalapati et al. 2009). The findings of Conrad et al. (2010) suggest that the southern wood supply chain is in position to take advantage of a wood-energy market. Nearly all respondents reported that their clients are willing to sell timber to energy facilities, and no respondents reported that their clients would not sell to an energy facility. Secondly, nearly all foresters in this study reported that they do not have adequate markets for timber. In order for the forest products and biomass industries to be successful they require harvesting contractors to harvest and deliver wood to their facilities. The long term outlook for southern logging capacity, however, is unclear. (Conrad et al. 2010).

The structure of a mature cellulosic feedstock production and delivery system remains to be determined. Every parcel of private forest in the South is currently used or held for some purpose. If it is to be used to produce biomass feedstock, sufficient revenue will be required to outbid existing uses. If the lowest cost feedstock is a SRWC with a year round stand life and harvest window, markets may drive the structure to vertical integration. As the industry matures, feedstock production, harvest, and transportation will likely be centrally managed mirroring the historical structure of the Southern U.S. wood production industry. Integrated supply chains are not likely to develop without sufficient revenue and market alliances benefiting both buyers and sellers.

Conclusions

Forest biomass and SRWC have enormous potential to improve the long-term success and sustainability of our national energy systems, by providing secure, renewable, and low-carbon sources of transportation fuels, heat, electricity, and products. In addition, markets for these products can provide jobs, bolster markets, and provide much-needed economic outlets in the rural United States. Relative to traditional agricultural crops or open lands, ecosystems dominated by woody species often have the potential to perform better on metrics of biodiversity, soil, and water conservation. For these reasons, woody biomass is often considered (and expected) to be a sustainable energy source. To this point, however, the term sustainable has largely been used to mean that cultivation and harvesting of biomass feedstocks do not *negatively* impact key ecosystem functions and services (Caputo 2009; Elliot 2010; Zabel 2010; Page-Dumroese 2010; Janowiak and Webster 2010). We have only begun to explore another side of sustainability - how biomass cultivation and harvesting can be actively integrated into the bigger picture of land management, serving as an important tool to be used in meeting a wide variety of objectives-including management for ecosystem goods and services, keeping working forest and agricultural lands working, maintenance of ecosystem functions, outdoor recreation, biodiversity conservation, ecological restoration and energy production. To make this happen, it is necessary to better understand how SRWC systems and removal of biomass during integrated forest operations impact the provision and delivery of the goods and services expected. We will need to develop decision-making tools that allow us to intelligently align the production and use of biomass with other existing ecological, social, and economic objectives (Benjamin et al. 2010). These tools will include such things as effective frameworks for developing and evaluating silvicultural alternatives (Long et al. 2010) and multi-criteria analysis tools (Buchholz et al. 2009). Using these tools, the production of energy feedstocks can be integrated into farm and forest operations that provide biodiversity, water quality, traditional and non-traditional products, and other ecosystem services, in addition to renewable energy products.

One area in need of further development is the role that short rotation woody crop systems (including, potentially, the management of natural forests on a coppice system) can play in the overall landscape while providing energy feedstocks. Short rotation woody crop systems can be strategically placed in a variety of landscapes to accomplish specific management goals. Examples can include designing SRWC into agricultural landscapes to protect and enhance water quality and provide more diverse habitats and wildlife corridors, locating SRWC systems to specifically accomplish phytoremediation goals (French et al. 2006; Rockwood et al. 2004), and incorporating SRWC systems into marginal environments to provide diversity and other goods and services (Harper et al. 2010).

To ensure that woody biomass supplies are both consistent and reliable they will need to be economically viable. Currently most of these systems are marginally viable or only viable when biomass for energy is a co-product harvested along with higher value solid wood products. Additional research and development needs to be done to reduce the costs of harvesting, handling and transportation of woody biomass from forests. In SRWC systems the main factors driving the economics of the system are yields and establishment and harvesting costs (Buchholz and Volk 2011). The potential to increase yields dramatically in the near future with focused genetics and breeding and selection programs is large because relatively little work has been done for woody biomass. Since most SRWC systems are in their infancy, there is the potential to improve production systems while reducing production costs. Improving the value of a tonne of woody biomass will also impact the overall economics of these systems. The development of a wood-based biorefinery (Amidon et al. 2008), where multiple high value product streams are produced from the same feedstock, will make this material more valuable and help to create economically viable systems.

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Chapter 8

Oilseed and Algal Oils as Biofuel Feedstocks

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Plant-derived oils, whether from terrestrially-produced oilseeds or aquatic algae, represent an important feedstock for liquid fuels. With the advent of the biodiesel industry over the past decade, a supply chain has been established, linking agricultural oilseed production to the transportation fuel market. Largely supply-side driven, and based on the availability and scale of soybean production, this initial supply chain is currently challenged by policy and related economic, environmental, and energy-related performance. These challenges are being met with new approaches coming from research and development. New sources and production methods for plant-derived oils, the creation of regional supply chains matching sources and uses, improvements in conversion of oils-to-fuels to include new classes of "drop-in replaceable" fuels, and the creation of a customer-driven pull are all being explored in the creation of sustainable biofuel production.

Sourcing Oils from Oilseed Crops

Soybean became a dominant U.S. and world oilseed in the twentieth century, occupying nearly 80 million acres of U.S. cropland (Figure 1) and dwarfing the land dedicated to all other U.S. oilseeds combined. From an oil perspective, soy oil production has been only slightly less than palm oil production in recent years, with the most recent report tallying 41.1 to 47.8 million metric tons, respectively, world-wide (80). Given the scale of soybean production, it has been the feedstock of choice for the emerging U.S. biodiesel industry over the past decade (Figure 2). Soybean has a firm place as a beneficial rotational crop with corn, produces the benchmark high-protein meal for livestock rations, and is an important food ingredient pervasive in the American diet.

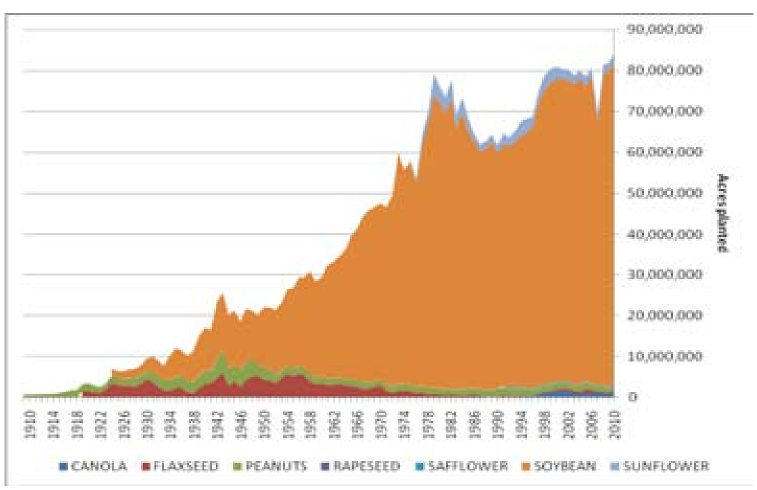

Figure 1. Acres of oilseeds planted in the United States (76).

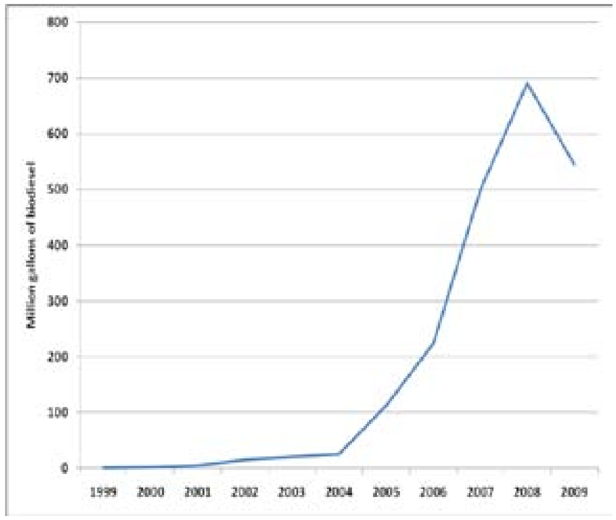

Figure 2. United States consumption of biodiesel from soy beans 1999-2009[1] (51).
[1]1 bushel of soybeans produces 1.5 gallons of biodiesel and 48 pounds of protein-rich meal.

Beyond soybean, there are many other alternative oilseeds if the primary objectives are the production of oil and reduced pressure on food inputs. Numerous comparisons have been made, and most cite the production range from over 600 gallons of oil per acre with oil palm (E. guineensis), to just under 20 with corn (Z. mays) (Table 1). At least two important pieces of information are lost in such general comparisons. First is the actual economic and environmental crop performance in a specific region- yields, productivity, and upside potential from focused research vary significantly. Second, oil is only one source of revenue from the oilseeds supply chain. The value of the resulting oilseed meal after oil removal, as well as other relative cost/benefit ratios throughout the oilseed production system, are critical to be included in any comparison.

Table 1. Oil producing crops (37, 74).

Plant	Latin Name	Gal Oil/ Acre	Plant	Latin Name	Gal Oil/ Acre
Oil Palm	*Elaeis guineensis*	610	Rice	*Oriza sativa L.*	85
Macauba Palm	*Acrocomia aculeata*	461	Buffalo Gourd	*Cucurbita foetidissima*	81
Pequi	*Caryocar brasiliense*	383	Safflower	*Carthamus tinctorius*	80
Buriti Palm	*Mauritia flexuosa*	335	Crambe	*Crambe abyssinica*	72
Oiticia	*Licania rigida*	307	Sesame	*Sesamum indicum*	72
Coconut	*Cocos nucifera*	276	Camelina	*Camelina sativa*	60
Avocado	*Persea americana*	270	Mustard	*Brassica alba*	59
Brazil Nut	*Bertholletia excelsa*	245	Coriander	*Coriandrum sativum*	55
Macadamia Nut	*Macadamia terniflora*	230	Pumpkin Seed	*Cucurbita pepo*	55
Jatropha	*Jatropha curcas*	194	Euphorbia	*Euphorbia lagascae*	54
Babassu Palm	*Orbignya martiana*	188	Hazelnut	*Corylus avellana*	49
Jojoba	*Simmondsia chinensis*	186	Linseed	*Linum usitatissimum*	49
Pecan	*Carya illinoensis*	183	Coffee	*Coffea arabica*	47
Bacuri	*Platonia insignis*	146	Soybean	*Glycine max*	46
Castor Bean	*Ricinus communis*	145	Hemp	*Cannabis sativa*	37
Gopher Plant	*Euphorbia lathyris*	137	Cotton	*Gossypium hirsutum*	33
Piassava	*Attalea funifera*	136	Calendula	*Calendula officinalis*	31
Olive Tree	*Olea europaea*	124	Kenaf	*Hibiscus cannabinus L.*	28
Rapeseed	*Brassica napus*	122	Rubber Seed	*Hevea brasiliensis*	26
Opium Poppy	*Papaver somniferum*	119	Lupine	*Lupinus albus*	24
Peanut	*Ariachis hypogaea*	109	Palm	*Erythea salvadorensis*	23
Cocoa	*Theobroma cacao*	105	Oat	*Avena sativa*	22
Sunflower	*Helianthus annuus*	98	Cashew Nut	*Anacardium occidentale*	18
Tung Oil Tree	*Aleurites fordii*	96	Corn	*Zea mays*	18

Table 1. Oil producing crops (37, 74).

On a regional basis, U.S. oilseed production is highly concentrated. Soybean is among the most broadly distributed, yet most of the U.S. geography is untouched by local supply. The scale of soybean production, however, allows soy oil deliveries to local markets via truck and rail. Compared to soybean, the other major U.S. oilseeds are grown in few locales, and limited to the northern Great Plains and the southeast (Figure 3).

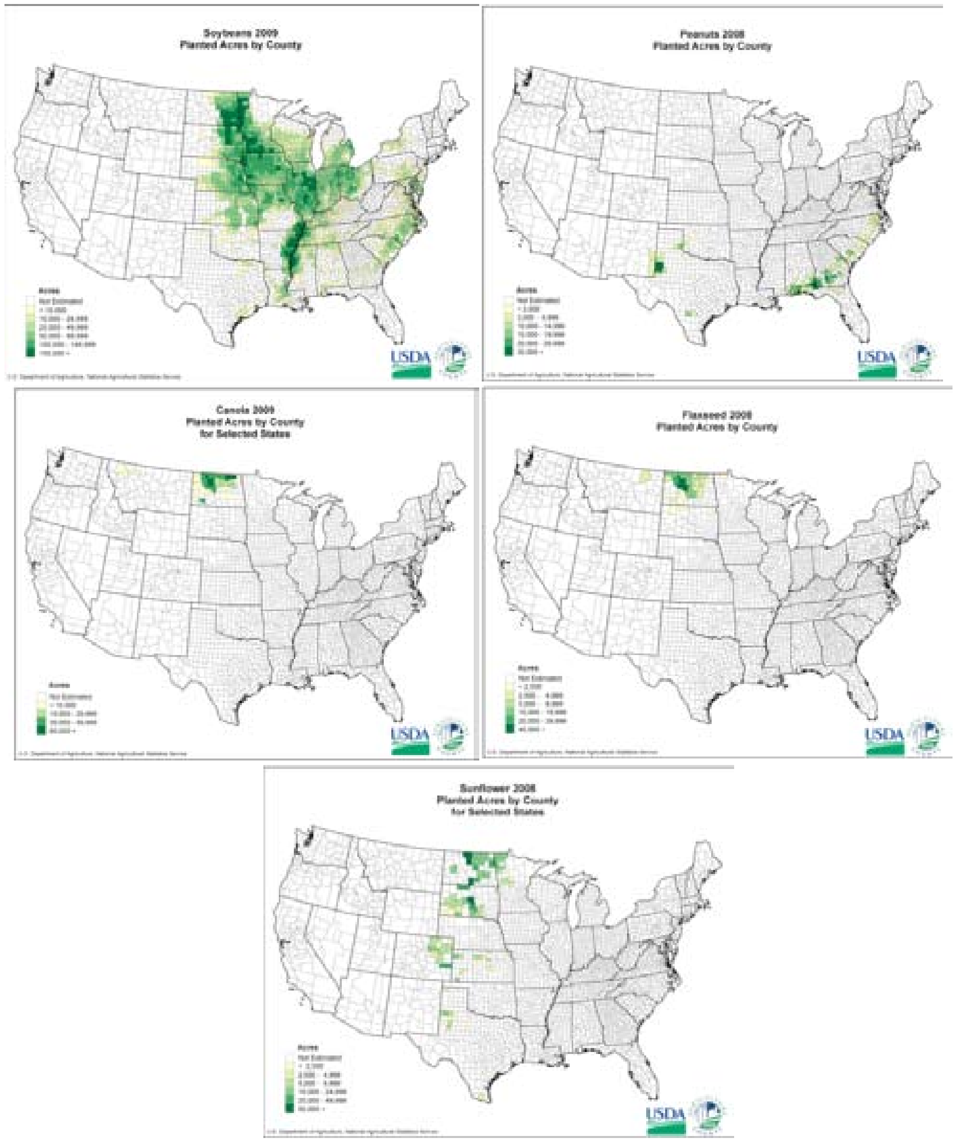

Figure 3. Soybean, peanut, canola, flaxseed, and sunflower acreage planted by county (77).

Other oilseed crops under evaluation for lipid production are best suited to subtropical and tropical regions in the southeastern U.S. and Hawaii. These include palm, coconut, jatropha, and babassu, among others.

Like any new crop, alternative oilseeds must economically compete for land among other crop choices, with each region having its own circumstances driven by markets coupled with price and risk supports. Successful new crops must first have inherent biological production potential, which is further aided by an ecological benefit in rotation with existing crops. Comparative advantages, such as those suggested by Kurki et. al (37), (Table 2), are especially important when weighing the overall performance of a new oilseed candidate. It must contribute to the economic, environmental, and energy performance (a complete life cycle assessment) to be sustainable and considered for policy support.

Oil Seed Crop	Yield (Gal Oil/ Acre)	Rotational Benefits	Management Practices
Rapeseed/Canola	122	Both are cool season crops. Attract hoverflies whose larvae prey on aphids. Has value as green manure because it makes phosphorus available for subsequent year's crops and initial research shows it inhibits growth of small weed seeds. Can serve as a nutrient catch crop. Provides weed control at high seeding rates. Canola is edible version of rapeseed; winter and spring varieties are available. Winter varieties are not as winter hardy as winter small grains (wheat, barley). Tap root breaks up hardpan. Good rotation crop, breaking cycles of weeds, disease and insect pests. Mellows soil.	Sclerotinia-susceptible. Should not be grown within five years of sunflower.
Peanut	109	Peanuts are often grown in rotation with other crops to replace soil nitrogen and decrease the need for synthetic fertilizers.	
Sunflower	98	Catch crop for nutrients, breaks up hardpan and compacted soil, may reduce fusarium when used in rotation with grain crops, can serve as a windbreak. Row-cropping provides opportunity for mechanical weed control during growing season.	Susceptible to sclerotinia and should be grown once every five years. Should not be raised in short rotations with crucifers.
Safflower	80	Breaks up hardpan and compacted soil with its deep roots.	
Crambe	72	Cool season crop—similar to canola, but more disease resistant and is tolerant of flea beetle damage.	
Camelina	60	Cool season crop—a crucifer like canola, rape, mustard, and crambe. Has allelopathic effects and it is somewhat drought resistant. Is fairly weed competitive when winter or very early spring seeded.	
Mustard	59	Primarily a cool season crop. Nutrient catch crop. Has nematicidal properties that reduce soil-borne pathogens. Can smother weeds and has allelopathic effects on weeds.	Sclerotinia-susceptible. Should not be grown within five years of sunflower.
Flaxseed/Linseed	49	A good crop for interseeding or to sow following a competitive crop onto clean field. Not weed competitive on its own. It is a light feeder.	
Soy	46	Fixes nitrogen, although most of the nitrogen is removed with the bean harvest.	Poor choice for controlling erosion or building organic matter levels.
Lupine	24	Moderate nitrogen fixer, takes up soil phosphorus—making it available for subsequent crops; reduces erosion and crop disease, deep taproots can open and aerate soil.	

Table 2. Rotational benefits of temperate-zone oilseed crops (37, 60).

Like all crop plants, oilseeds have and can be incrementally improved with breeding and research. Seed oil content and yield are two critical factors that could be improved within crops that demonstrate other valuable features. Both of these traits are complex, governed by quantitative trait loci (43), but have potential to be rapidly improved with new techniques, such as DNA marker-assisted selection within modern plant breeding programs (20, 47). Genetic improvement-coupled with new cropping systems that introduce reduced tillage; conserve water, carbon, and energy; minimize nutrient requirements; and manage pests with a minimum of subsidy-represents new oilseed feedstock options for regional biofuel production.

Once agriculture produces the oilseed, it must pass through two important phases enroute to market. The first is separation of the oil, done in processing facilities located proximate to agricultural production. The U.S. oilseed processing industry is largely concentrated, with large (>500 oilseed tons per day) hexane extraction facilities processing the vast majority of the crop. Such facilities achieve an economy of scale difficult to match by smaller, local, mechanical separation techniques. These smaller operations generally cater to regional markets for premium oil or meal products, and would find it difficult to compete with the tight margins found in commodity fuel production. Once the crude oil is separated, it then must be converted to the fuel. Given the relatively low-cost of transesterification to biodiesel, economies of scale can be reached at much lower capacities than the processing facilities. Thus, the U.S. biodiesel industry has a broad geographic footprint (Figure 4). The next generation conversion technologies are more capital intensive, with an economic advantage to co-locate with petroleum refineries both for shared resources and distribution logistics. These new 'hydro-treated' fuels are distillates, and fully compatible ('drop-in') with petroleum fuels and associated engines and fuel distribution infrastructure.

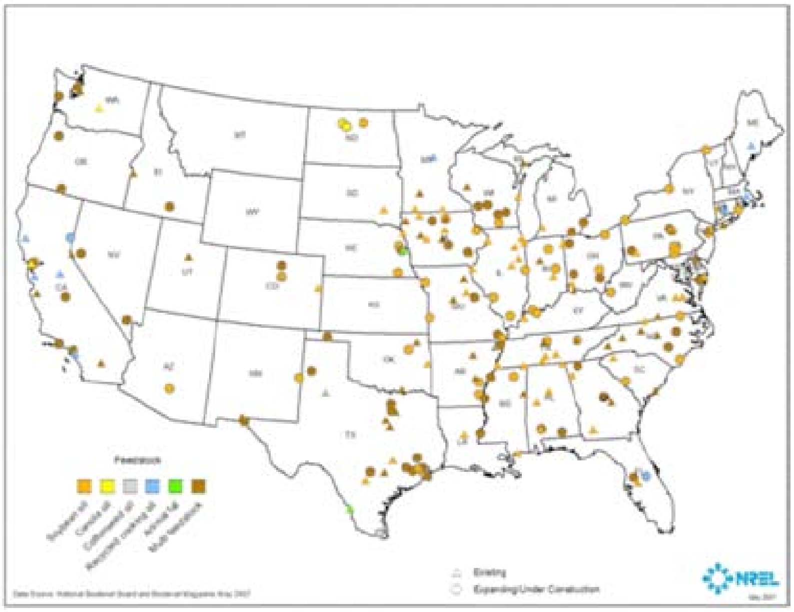

Figure 4. United States Biodiesel Production Facilities 2007 (52).

Another important aspect of viewing agricultural oilseeds as feedstock for sustainable biofuel is the emerging criteria of sustainability. The Roundtable on Sustainable Biofuels (64) is growing in recognition world-wide, and has developed a useful framework among the dimensions of sustainability. The principles for any biofuel production assessment include the following:

Principle 1: Legality-Biofuel operations shall follow all applicable laws and regulations.

Principle 2: Planning, Monitoring and Continuous Improvement-Sustainable biofuel operations shall be planned, implemented, and continuously improved through an open, transparent, and consultative Environmental and Social Impact Assessment (ESIA) and an economic viability analysis.

Principle 3: Greenhouse Gas Emissions-Biofuels shall contribute to climate change mitigation by significantly reducing lifecycle GHG emissions as compared to fossil fuels.

Principle 4: Human and Labor Rights-Biofuel operations shall not violate human rights or labor rights, and shall promote decent work and the well-being of workers.

Principle 5: Rural and Social Development-In regions of poverty, biofuel operations shall contribute to the social and economic development of local, rural and indigenous people and communities.

Principle 6: Local Food Security-Biofuel operations shall ensure the human right to adequate food and improve food security in food insecure regions.

Principle 7: Conservation-Biofuel operations shall avoid negative impacts on biodiversity, ecosystems, and other conservation values.

Principle 8: Soil-Biofuel operations shall implement practices that seek to reverse soil degradation and/ or maintain soil health.

Principle 9: Water-Biofuel operations shall maintain or enhance the quality and quantity of surface and ground water resources, and respect prior formal or customary water rights.

Principle 10: Air-Air pollution from biofuel operations shall be minimized along the supply chain.

Among the principles, it is numbers three and seven which have drawn the most attention within the

U.S. biofuels industry. Energy balances between that consumed and that produced throughout the life cycle of the entire supply chain are critical in estimating the feasibility of any feedstock (24, 44). Recent analyses of soybean revealed an estimated fossil energy ratio (or renewable energy output over fossil energy input) of 4.56 (6). Further, the recent analysis broke down the portions of the supply chain that consumed the energy, with the agricultural production accounting for 18%, oilseed processing 15%, and conversion of the plant-derived oil to diesel for 60%. Thus, most of the energy requirements were near the end of the supply chain, and would not be significantly affected by new oilseed feedstocks assuming they competed with soybean production efficiencies.

With so much energy related to conversion, new technologies and advancements in this portion of the supply chain are critical. Again, using soybean oil-derived biodiesel as the proxy, traditional biodiesel conversion (transesterification) has been compared to the newer process of hydro-cracking and treating (6) with only slight differences in energy efficiency noted. Further, the greenhouse gas emissions from any of the conversion technologies revealed a net reduction from 57-74% as compared to petroleum diesel.

Sourcing Lipids from Microalgae

Microalgae is emerging as a potential high-volume source of lipids for advanced biofuels. While commercial production of microalgae has been established for human nutritional products like spirulina, beta carotene, and omega-3 fatty acids for at least three decades, the concept of using microalgae as an aquaculture source for energy production on the mega-ton scale meaningful to the petroleum industry has enjoyed a recent resurgence. The majority of companies trying to demonstrate commercial production of microalgae for energy and other markets were founded within the past six years. The pace of innovation in systems engineering, cultivation techniques, intracellular productivity improvement techniques, and business model development has been extremely rapid. Production and productivity levels have jumped by orders of magnitude each year over the past three to four years, for example from less than 100 verifiable gallons of algae oil produced by the entire industry in 2009 to over 20,000 gallons delivered to customers in 2010 (32).

Microalgae Business Models

Historical Markets: Human Nutrition and Wastewater Treatment

A small industry has developed for the production of microalgae for human nutritional supplements, about 10,000 mt per year world-wide and even smaller ones for aquaculture feeds. Microalgae production costs are relatively high compared to macroalgae production-for example plant gate prices are estimated at~$10,000/mt dry weight for Spirulina-almost ten-fold higher than for macroalgae (42). Two companies, Earthrise Nutritionals LLC in California and Cyanotech Corp. in Hawaii, are well established in the production of photosynthetic algae for nutritional supplements. Martek is also well-established in the production of nutritional supplements from a heterotrophic algae process. Earthrise and Cyanotech operate less than 40 hectares of algal ponds, both using the traditional paddle wheel mixed-raceway design for algae mass cultivation. In Hawaii, Fuji Chemicals operates a dome-type photobioreactor plant, which produces one to two tons algae biomass per year. A number of wastewater treatment plants use algae ponds and harvest algae from these with chemical flocculants; however the algae biomass-flocculant mixture produced is not currently used for nutritional supplements or energy markets due to difficulties of handling the waste. The estimated total algae wastewater treatment industry size in California for example is close to 1,000 hectares (42).

Emerging Bioenergy Market Niches

The forty-plus companies tackling the concept of algae production on a large scale for energy use have begun to differentiate into market niches, generally according to their founding technical expertise and physical location. Companies where the founding members had deep pharmaceutical or bioengineering expertise tend to build their business models around proprietary genetically modified organisms and closed systems. Examples include Synthetic Genomics, Solazyme, LS9, Targeted Growth, Inc., Amyris, Heliae Development, and Algenol. Companies derived from other industries such as defense, wastewater treatment, and agriculture tend to prefer open pond systems and natural strains. Examples include General Atomics, SAIC, HR Biopetroleum/Cellana, Aquaflow Bionomics, and Phyco Biosciences.

Companies headquartered in colder latitudes tend to focus on closed algae production systems. Examples include Solazyme, Amyris Biotechnologies, Algae@Work, Algaedyne, Heliae, and Greenfuels Technologies Inc (now defunct). Companies headquartered in warmer latitudes in the U.S. tend to focus on open-pond photosynthetic systems. Examples include Sapphire Energy, General Atomics, HR Biopetroleum/Cellana, SAIC, and Seambiotic in Israel. Some companies are pursuing a hybrid approach. One example is Ohio-based Phycal Inc., which plans to use an open-pond system at its Hawaii demonstration site to grow out the algae, then put them into a closed heterotrophic for "fattening" prior to harvest. HR Biopetroleum/Cellana also uses a hybrid system, where the seedstock are grown in closed photobioreactor systems to reduce contamination and then inoculated into open ponds for bulking up in volume prior to harvest.

Every algae company has at least one other major revenue stream in its business model beyond just lipid production for biofuels markets. That co-product tends to affect its selection of sites, strains, production processes, etc. Some examples include a valuable co-product stream from animal feed (General Atomics), human food or nutraceuticals (Solazyme, LiveFuels), specialty chemicals (Amyris), carbon capture and storage (Phycal Inc., Algae@Work), and wastewater treatment (Aquaflow Bionomics) (5).

Within the closed process market niche is a group of companies that use a non-photosynthetic approach to grow their algae. This "heterotrophic" process involves feeding the microalgae sugar in the absence of light to get them to boost their proportion of oil relative to carbohydrates and proteins. An example is Solazyme, which is notable in being the first algae energy company to complete commercial sales of algae oil specifically for fuel, by delivering over 20,000 gallons of JP5 jet fuel and F-76 marine diesel to the Defense Logistics Agency in August and September 2010.

Current Commercial Status

There are as yet no pilot (>100 mt algal biomass/yr) photosynthetic algal biofuels production plants operating in the U.S. The few pre-pilot-scale (e.g. >10 mt) plants have operated for less than a year, with only rather smaller operations of a few hundred square meters operating for two or more years (e.g. Seambiotic in Israel, Aurora Biofuels in Florida, for example). As mentioned above, Solazyme is the front runner with the largest confirmed production of algal lipids for energy customers to date, using a closed heterotrophic process and genetically modified algae. Three fairly advanced developers who are or will be breaking ground on the next scale demonstrations (20-200 acres) within the next year are Phycal, Cellana, Sapphire, and General Atomics. All use open pond designs and natural strains.

The main interest in microalgae stems from its potential productivity on a per acre-year basis. Claims of current and future relative productivity levels range from 1000 to 5000-plus gallons per acre per year and are summarized in Table 3 below. Actual productivity numbers, like other agricultural crops and industrial processes, are highly dependent on the specific site and production process used. At least one company has demonstrated actual productivity in its proprietary process of at least 1400 gal/acre/year in 2010 for a non-optimized small experimental site in a warm-weather location and estimates productivity could be doubled in the next demonstration at the multi-acre scale. These demonstrated results and model for the next phase were validated by an independent federal agency and review team through the U.S. Pacific Command's Green initiative for Fuels Transition (GIFTPAC) interagency working group, under the leadership of the U.S. Pacific Command Energy Office, J81 Joint Innovation and Experimentation Division, Resources and Assessment Directorate. (85) It is important to remember that these productivity numbers are only for the oil; algae organisms range from 10% of their body mass in oil and up, so for each gallon of fuel produced, a significant proportion of protein and carbohydrates are produced as well.

Source	Oil yield gal oil/acre
Soybean	47.7
Canola	127.2
Jatropha	202.3
Coconut	287.5
Oil palm	636.1
Microalgae[1]	6275.0

Table 3. Comparative oil yield from oilseeds and algae (19).
1 Assuming 30% oil (by weight) in biomass.

Cellana Co. in Hawaii (a joint venture of Shell Oil Co. and H.R. Biopetroleum, Inc.) has operated a pre-pilot plant of between one and two acres to grow diatoms using the Mera Pharmaceuticals ponds at the Natural Energy Laboratory of Hawaii Authority (NELHA) near Kona, Hawaii. The technology (31) was based on prior experience with production of *Haematococcus pluvialis* biomass by Aquasearch Co. in Hawaii. Its neighbor at NELHA, Cyanotech, is one of the traditional nutraceutical companies mentioned above; Cyanotech sold $7 million worth of algae-derived astaxanthin in 2009.

Sapphire Energy Co. of San Diego was awarded over $100 million in U.S. government grants and loans and is breaking ground on a 300-acre demonstration pilot plant in New Mexico. Sapphire Energy initially announced that it would produce algae oil with oil-excreting genetically modified algae (GMA), but now intends to follow the standard model of growing unmodified algae with a naturally high oil content. Phycal of Ohio was awarded over $50 million in Department of Energy carbon recycling funds to develop a pilot plant on Oahu, Hawaii. General Atomics, in San Diego, received about $30 million from the U.S. Department of Defense, Defense Advanced Research Projects Agency, (DARPA) in 2008 to develop a low-cost ($3/gallon initially, $1/gallon later) process for microalgae oil production in an 18-month R&D effort to be followed by a demonstration of this technology over a further 18 months in Hawaii, Texas, and California. The economic analysis and underlying assumptions on which current projections of $3/gallon oil are based are proprietary-however they include significant animal feed co-product credits. SAIC Inc. received the same level of first phase funds from DARPA to explore and quantify the benefits of "wild-type algae" harvesting relative to the more traditional farming method used by General Atomics. SAIC also developed a production model that showed the ability to meet the DARPA cost targets, using wastewater remediation funds as its major cost offset, but at much smaller total production volume. DARPA also funded a cellulosic biomass-to-jet fuel consortium headed by Logos Technologies Inc., which has likewise produced a business model that shows the ability to achieve the desired cost targets, albeit not using a lipid pathway.

Validated Information on Actual Costs and Productivity Is Generally Not Publicized

Publicly available information on the state-of-the-art in the field isdeficient. U.S. intellectual property laws affect the amount and type of information that is publicly available. Companies which derive their origins from pharmaceutical/genetic modification expertise and laboratories can receive patent protection for their organisms and are free to publish after that point, whereas the open pond/natural strain companies tend to have to protect their innovations with lesser protection such as trade secrets. As a result, the open pond/natural strain companies, which represent over half the industry, have specific productivity gains, cost reduction methods, and other key developments that cannot and will not be published openly. This paper attempts to list state-of-the-art developments for the latter companies that have been verified through a third party by evaluation or commercial sale, but recognizes that people and companies willing to stake their livelihoods on these new processes bring a market credibility at least as far as determination of intent. Overall, the industry has gone from infancy to crawling, but there is still much work to be done before commercial viability on a scale meaningful petroleum can be achieved.

Algal Types and Phycology

The best understood microalgae species for the production of biofuels are the green algae and diatoms, both eukaryotes (e.g. with a true nucleus) and the cyanobacteria (prokaryotes) (42). There is enormous biological diversity in growth responses to environmental conditions such as light intensity, temperature and nutrients. Microalgae account for about half the total global primary production (mostly in oceans) and are the basis of most of the aquatic food chains supporting fisheries. Prehistoric algae processed by the geological forces of temperature and pressure are the source of petroleum today. Algae are aquatic single-cell plants which capture sunlight and carbon dioxide to feed themselves and subdivide. Like plants, they require sunlight, water, carbon in the form of carbon dioxide, and nutrients to be able to grow. Like other single-cell organisms, microalgae subdivide very quickly and productivity rates can be measured in days rather than seasons. The three major components of algae biomass are protein, carbohydrates and oils.

Biological Research of Microalgae

Oil Content and Productivity in Algal Mass Cultures

Algal oil productivity is an area with a great deal of research intensity at this time. Prior research focused on finding a “lipid (biosynthesis) trigger” that initiated oil production whereas the current thrust of research is focused on the “photosynthesis [shutdown] trigger.” Metabolic signals that tell the cell to up-regulate lipid biosynthesis only come after photosynthesis is already greatly reduced due to lack of the limiting nutrient. The accumulation of lipid bodies (detected by Nile red staining) suggests that once formed, lipids are being stored inside the cell. These lipids are generally triglycerides and more reduced (saturated) than those found in actively growing cells, both key issues in using algal oils for fuels. It may well become possible to produce algal oils suitable for use as fuel in both rather large amounts (e.g. content) and high photosynthetic efficiency-algal production of large amounts of storage carbohydrates can be induced quickly after N limitation, allowing for high productivity during the accumulation phase.

Techniques to Modify Ratio of Oil to Carbohydrates and Proteins

The first attempts at microalgae oil (lipids) production recognized that many species of green algae, when grown with insufficient nitrogen, accumulated oil within the algal cell to levels reaching up to about 70% of dry weight. Not all strains reacted in a similar manner-some accumulated carbohydrates, rather than lipids, under N limited conditions. However, the rate of lipid biosynthesis by the algal cell was typically very slow-algal biomass with a high oil content could be obtained but only at relatively low productivity (68). The first attempts to mass culture microalgae in the 1950's focused on growing algae, specifically Chlorella, for human food. Interest in algae production for oil (lipids) declined in the 1960's but was revived in the early 1980s when the U.S. DOE initiated the Aquatic Species Program (ASP) with the goal of developing cost-effective algae biofuels production (42). The premise was that algae were uniquely able to produce high amounts of oils, and could become competitive with fossil fuels (57, 9). The alternative of producing carbohydrates for ethanol fermentation was not considered at the time, even though there was evidence that some algal species accumulated significant quantities of carbohydrates at high productivity after N limitation (10). Among the many projects supported by the ASP, only a few dealt with the problem of algal lipid productivity. Benemann and Tillett (11) and Rodolfi et al. (63) observed that *Nannochloropsis*, a marine alga with high constitutive triglyceride (oil) content, could be stressed with N limitation in a batch culture to increase lipid productivity when light intensity was also increased. However, the problem of how to achieve high algae oil productivity (measured in g oil/m2-day) remains an unsolved problem and active area of research.

Algae Light Conversion Efficiency

One area of scientific research in microalgae is the mechanism by which algae capture light energy and convert it into stored chemical energy. Oxygenic photosynthesis involves the same fundamental processes of water splitting and CO_2 fixation in microalgae as in all higher plants. Water splitting (into O_2 and a reducing agent) takes place at these centers, where the "dark reactions" are initiated, converting the exitons into chemical energy then converted to metabolic energy sources-reductant (in the form of NADPH) and ATP. These are used, among others, by the enzyme Rubisco and the CO_2 fixation pathway to reduce CO_2 to carbohydrates. The current theory of photosynthesis requires two photons to act in series to transfer one electron from water to CO_2, or a total of eight photons per CO_2. Adding a few photons for the biosynthesis of proteins, lipids, nucleic acids, other cell components, and to maintain cellular function (respiration or "maintenance energy"), results in a maximum theoretical total solar energy into biomass conversion efficiency of about 10% (42). However, such efficiencies are only observed at low light intensity. This is due to the fact that the photosynthetic apparatus collects light, photons, with an array of chlorophyll and other light harvesting pigment molecules arranged as a dish antenna, which then transfer the captured photon energy, the excitons, to the reaction centers. Maximal photon conversion efficiency is observed when light is limiting and maximum productivity at well below maximal growth rates. There is no apparent direct correlation between high maximal growth rate and high productivity or photon conversion efficiency (29). A typical light harvesting antenna consists of 200 chlorophyll molecules, which at full sunlight intensity capture about one photon every half a millisecond. However, the reaction centers can process only one exciton about every five milliseconds. The excess photons, 90%, are still absorbed but cannot be used, and are "wasted" as heat or fluorescence. The best light energy conversions observed to date with either actual or simulated full-sunlight intensities is 1 to 2%. A great deal of research has been carried out for over fifty years to achieve a sunlight dilution effect, such as to expose all the individual cells in a culture to an even low light intensity, and overcome the light saturation effect in order to raise photosynthetic energy capture (42).

Although the light saturation effect is also the major limiting factor in the photosynthetic efficiency of higher plants, it is not as severe as for algal cultures, with reductions in potential productivity of perhaps only 30 to 50%, vs. up to 70 to 80% for microalgae. A reason that higher plants are not as limited as algae is their smaller antenna size (e.g. fewer chlorophylls per reaction center). Algal strains with smaller antenna size would not exhibit this light saturation effect as strongly (34). Large light harvesting pigment arrays provide an evolutionary advantage to algae that have them. It also suggests that these strains could be obtained by mutation or genetic manipulation (13, 42). Thus any such algal strains would be at a significant disadvantage, being quickly replaced by invading weed algae or genetic reversions. This concept has been advanced in Japan by Mitsubishi Heavy Industries, with mutants of cyanobacteria and green algae having small antenna sizes (48, 49, 50) and also at U.C. Berkeley under a DOE algae hydrogen program (14, 29, 53, 66).

Key Components of Microalgae Production Systems

Site Selection-Land, Water, and Light Characteristics, Open Pond Systems

Because of algae's tolerance for water quality ranging from fresh through brackish to hypersaline, the economics of pumping water, and algae's maximum productivity at warm temperatures, open pond microalgae systems are best sited in flat, warm areas that currently are not suitable for traditional agricultural production. Examples of flat, warm areas with brackish ground water that can be ideal for photosynthetic algae production include the Permian basin in Texas, the southwestern U.S., and the western shores of Hawaii. Land for the ponds themselves should be less than 10% grade and ideally less than 2%. Contiguous land areas of at least 2000 acres are best for economy of scale for pumping and related production equipment (92). A cheap water supply, such as brackish water, salt water, wastewater, or abundant rainfall, is important to help keep production costs down. For some systems, treatment of the water supply can provide another revenue source. Finally, for open systems, a year-round temperature within 20-35C is critical; the capital cost of aquaculture systems generally makes a partial-year operation cost prohibitive.

For open pond systems subject to evaporation, there has been much discussion about the potential environmental impact of the salinity and the chemical constituents in return flows from algae production systems. Evaporation increases pond water salinity, theoretically requiring continuous supply of make-up water and disposal of blow-down, which will be concentrated in relation to the input water. Inland, this would theoretically require further concentration to brines to be injected underground or even dry salts which may have to be buried (landfilled). Algae facilities located on or close to a coastline could return concentrated brine to the ocean without large expense or significant environmental impact, but would likely fall foul of environmental laws protecting coastal environments from pollution, even by concentrated seawater. This potential resource issue is being addressed mainly by having closed-loop water recycling systems and to a lesser degree by species selection by the majority of commercial algae companies. As examples, Sapphire Energy, General Atomics and Phycal all include brackish/wastewater/abundant rainfall water sources and makeup water as part of their business plan and site selection criteria. There are algal species that are tolerant of salinities ranging from fresh to highly saline; examples include the native species resident in Cargill Incorporated's salt ponds next to the San Francisco airport.

Closed Systems

Cooler year-round temperatures and a cheap energy source for lighting and pumping are desirable characteristics for the site of a closed photobioreactor (PBR) system. Companies offering PBRs are either focused on optimizing and controlling genetically modified organisms or are targeting a market niche similar to anaerobic digesters: smaller "bolt-on" greenhouse or tank systems integrated with existing dairy or farm operations with wastewater treatment needs. These business models take advantage of the nutrients already present in the wastewater to reduce their fertilizer costs. For heterotrophic systems, land selection is more concerned with selection of an industrial or agri-processing site close to a sugar source. Heterotrophic systems themselves look and operate like specialty chemical or fermentation companies.

Supply of Carbon

Carbon is the most essential nutrient for algae biomass production. Carbon makes up about half the dry weight of algae biomass, and must be supplied as CO_2 for photosynethic systems or as sugar for heterotrophic systems. The majority of companies pursuing photosynthetic production for energy markets look for concentrated sources of industrial CO_2 to support their systems, for example co-location at power plants and refineries in order to utilize smokestack emissions or concentrated CO_2 byproducts. A minority have business models that would use only ambient CO_2 from air; these are generally in the wastewater or effluent treatment market niche. From an engineering perspective, CO_2 supply is perhaps the key issue in the design of algal production systems. The storage capacity of CO_2 in the water is driven in part by the pH of the medium. For example, seawater with an alkalinity of 2.3 meq allows storage of about 0.8 mmole of C between pH 7.3 and 8.8,-a 30 cm deep pond with a maximal productivity of 5 g/m2-hr, and 50% C as algae (ash free dry weight-afdw) would require 2.5 g of C/m2-hr compared with the 2.9 g of C available/m2 in the pond. Once the CO_2 is supplied, the ability to store the CO_2 in growth medium of a standard open-pond aquatic system in order to ensure maximum uptake by the photosynthetic process is limited. Without specialized system engineering to contain the CO_2, much of the concentrated CO_2 would be released back to the atmosphere. New processes are being developed to limit this CO_2 wastage to the atmosphere; at least one commercial company has demonstrated less than 2% loss per year from an open pond system.

Companies pursuing heterotrophic systems have developed experimental systems using sucrose and glucose purchased on the open market; all are now trying to optimize their strains and/or production systems to be able to utilize less costly carbon sources such as five-carbon sugars, vinasse waste from table sugar production, etc.

Ambient Temperature Effect on Productivity

The major environmental factor limiting open-pond algae biofuels production is likely not sunlight but temperature. Pond temperatures that are too low or too high are not conducive to maximal algal productivity. The breakpoint for minimal algal fuel production would likely be somewhat above 5 g/m^2-day, at which point the inputs (in particular energy) required to operate the process would exceed outputs. The optimal temperature regimes for algal strains currently used in mass cultures show steep productivity declines below about 20°C and, on the high end, above about 35°C.

Supply of Other Nutrients

In general the selection of other nutrient inputs is a business decision that takes into account the cost advantages of local sources and synergies. These other nutrients are typically supplied *ad libitum*, as needed. For biofuels, nitrogen is not typically supplied as nitrates (the choice for most algae) because of expense, both in terms of costs and metabolic energy. Ammonia nitrogen can volatilize at higher pH, so can be added at the time of CO_2 injection to maximize utilization. Other nutrients such as phosphorus, potassium, iron, manganese, magnesium, etc. are also required.

The production of methane (and then electricity) by anaerobic digestion from the residual biomass can allow recycling of most of the nutrients in the algal biomass (15). The timing of such recycling should be coordinated with other process parameters for maximum overall effectiveness, such as control of grazers, contaminants and oxygen levels as the digester effluents have a high biological oxygen demand. As much of the nitrogen in the digester effluents is ammonia, this can be coordinated with CO_2 injection to control pH fluctuations. Whether to operate or subcontract to an anaerobic digester to recover nitrogen or simply buy it from a vendor is a business decision that is made at the site-specific level.

Strain Selection

The algae biofuels industry is distinguished by the variety of approaches being taken by its entrepreneurs toward achieving commercial success. Most companies have recognized the importance of utilizing the highest performing algal strains (42). Whereas some favor screening locally-harvested natural strains (Livefuels, Cellana, General Atomics, Phycal), others prefer to genetically modify strains (Solazyme, Amyris, LS9) or retain flexibility to use either depending on the commercial site location and the customer (Sapphire).

To achieve the goal of high microalgae productivity with a high content of oil, molecular genetic manipulation is regarded by some in the industry as a necessary and indispensable tool. Other ways of modifying and optimizing natural strains include high-throughput harvesting and screening of natural strains, inducing mutation, and encouraging sexual recombination. *Chlamydomonas* is at least one variant of algae with a sexual lifecycle.

In all cases of companies with business models that depend on natural strains, screening and selection are a key part of the initial site selection and system design. At least one company, Kuehnle Agrosystems Inc, has specialized into being a “seed company” focused on strain selection, optimization, and certified pure inoculums supply for customers and specific sites. This company uses over 40 selection characteristics to screen natural strains, to include oil yield and composition, protein composition, productivity level at the desired temperature, pH, salinity, etc. (35). “The Aquatic Species Program looked at 8 species over the multi-year program; high throughput screening companies look at 1500 species per week today.” (18)

Algae Production Systems

The main design configurations for algae production are: dedicated open pond photosynthetic systems, dedicated closed photobioreactors, dedicated closed heterotrophic reactors, waste water remediation co-production systems, and remediation systems for treatment of polluted open water. Some examples are shown in Figure 5 below. To illustrate the skewed sense of industry efforts that can be formed by just reviewing published literature, at the 2010 Algae Biomass Organization Finance Summit, a prominent algae industry consulting firm stated that “98% of systems operating today are open ponds, while 98% of research is in bioreactors.” (18)

Figure 5: Sample algae production systems (59).

Dedicated Open Pond Photosynthetic Systems

Raceway, mechanically mixed, so-called "high rate" open ponds are the type pursued by many commercial companies for large-scale, low-cost algal biomass production (41, 42). High rate ponds used in commercial algae production today are typically operated at 20 to 40 cm (6 to 16 inches) liquid depth, mixed with paddlewheels and up to about 0.5 hectares in size. Much larger sizes are planned (Sapphire, Phycal, General Atomics) for full-scale commercial algae energy plants. The main parameters of interest in operations are mixing velocity, with the ponds typically operated at between 15 and 30 cm/sec. Higher velocities require too much energy for mixing, at least for biofuels applications. Circular ponds, used for Chlorella production in Japan and the Far East, do not scale easily above about 1,000 m2 for individual ponds. Companies like Sapphire and General Atomics report that total farm size estimated at this time for a commercial-scale algae biomass facility would be in the 2000-20,000 acre range.

There are myriad problems associated with long-duration single-culture photosynthetic systems such as those used in the ASP and by current commercial nutraceutical algae growers, nearly all of which have been mitigated by process changes in the past six years. Those traditional problems include: predatory invasion, culture crashes, species mutation, weather-driven changes in temperature and salinity, loss of CO_2 from ponds, and loss of water from ponds. For commercial energy/lipid production, these problems are generally mitigated by some proprietary combination of process flow, bioreactor design, and project siting. Many companies, such as Phycal, Cellana, and General Atomics, address contamination and predation by simply designing a process to have a short residence time. It takes about three to six weeks for an open-pond system to develop a commercially significant level of contamination, and so the industrial processes being developed for large-scale energy production are designed to harvest in less than three weeks.

Closed Photobioreactors

Photobioreactors are cost-effective in climates with wide temperature variation. They allow improved control and calibration and make it easier to achieve specific temperature, pH, and nutrient level targets. They also minimize arable land footprint in areas such as the Midwest where land is highly suited for terrestrial crops. Other ways to ameliorate the problem of unsuitable temperatures for optimal algae production include increasing pond depth or the size of the settling ponds, to allow for greater night-time storage.

Tubular reactors are the dominant technology in commercial nutraceutical operations-both small diameter (~5 cm) rigid and larger diameter (>10 cm) flexible bag type reactors. Many other designs have been used in pilot scale production, including various types of flat plate reactors, hanging bag reactors, and hemispherical dome reactors (used in one commercial plant). Alternative production systems using enclosed bioreactors of a large diversity of configurations use tubes, plates, bags, domes, etc., some scaled to considerable size (~1 ha). PBRs have inherently high costs and limitations on scale-up-typically each PBR unit is between 10 and 100 m^2 in size, requiring hundreds to thousands of such units in place of one large pond, each unit requiring its own piping, valving , carbonation, and control system. PBRs can be more productive than open ponds, and thus require less land than open pond systems, if the ambient temperature is less than optimal or if the reactors are oriented vertically, creating some sunlight dilution. However the productivity increase from such vertical orientation is typically not over 50%. Further PBRs are severely mass transfer limited (89).

One often-stated advantage of PBRs is their much lower water use compared to open ponds, given the fact that the system is wholly contained and there are no direct evaporation losses. However PBRs will retain more heat than open systems and the only cost-effective means of cooling the algal biomass in these systems is through evaporative cooling with water sprays, where water consumption ends up being greater than open ponds during peak summer months. If cooling is through immersion in pools (e.g. deeper ponds) of water, then evaporative losses are somewhat lower (due to the higher heat capacity of deeper pools). PBRs are considered to use CO_2 much more efficiently than open ponds-given that CO_2 cannot escape to the atmosphere from PBRs, but does escape from open ponds. However, based on the work of Weissman and colleagues (89, 91), outgassing from open ponds can be minimized; while for PBRs the major issue becomes oxygen management.

Another consideration is the source of light. In sunlight, the system is subject to seasonal variation or to overheating from excess solar gain in the summer months. Some companies pursue greenhouse or indoor PBR designs, and generally use those with artificial light from tunable light-emitting diodes (LEDs) (18).

In practice for commercial energy markets, PBRs are being used for the initial stage of inoculum production into a larger open-pond system, but not for mass production systems (HR Biopetroleum/ Cellana, Sapphire, General Atomics, Phycal, Kuehnle Agrosystems). PBR's are also being designed as small scale additions to existing farm/dairy operations that have effluent disposal problems (Algaedyne, Heliae) in pursuit of the anaerobic digester market.

Waste Water Remediation Co-Production Systems

Wastewater treatment ponds (also called "oxidation ponds"), are best suited for serendipitous use of low-cost water and nutrients to grow relatively dilute, mixed species of algae. Their lack of hydraulic control (e.g. mixing, uniformity) does not allow for a uniform environment and control required for high throughput, dedicated algae production systems. Lack of a predictable algal culture can make harvesting difficult (41, 42), so companies pursuing this route tend to use harvest techniques that are not species-specific.

Harvesting and Oil Extraction Techniques

Most algae companies use some combination of flocculants, belt drying, air drying, chemical extraction with hexane, or proprietary processes that may cover one or all three steps of dewatering, drying, and oil extraction. What no commercially-oriented company plans to do at full commercial scale is centrifuge to remove water. Flocculation uses a chemical to make the algae "clump" or settle for easier removal from the medium and can be species-specific. The decision whether or not to use flocculants depends on the company's desired co-products, since some of these chemicals can interfere with conversion of the biomass to biofuels, animal feed, or nutraceuticals. Chemical flocculation is no longer a major cost driver for several companies that have devoted considerable research and development investments to lowering the cost. Other companies are improving the cost-effectiveness of established processes such as belt drying, air drying followed by chemical extraction with hexane, or other proprietary techniques that extract oil directly from the culture or without drying.

There have been many studies which attempt to estimate algae production costs and find the final production cost to be prohibitive, in large part because they assume that a centrifuge will be used for the dewatering step. These studies tend to be out of date, because they are extrapolated from laboratory environments where centrifuges are uniquely well-suited to separating liquids at very small scale. No viable algae energy company operating today has centrifuging in its business model for full commercial scale production; most have adopted or adapted the other drying technologies from the agricultural or chemical industries discussed above with better economy at larger scale.

Environmental and Economic Costs/Benefits

Considerations for genetically modified algae (GMA): Unlike GMO crops, which have had major support by farmers, governments and large companies (e.g. Monsanto), and, after many years of struggle now dominate several crops, GMAs are unlikely to have such strong advocates. It thus behooves the incipient microalgae industry to move carefully, and prepare the political and social ground for any use of such algae in a commercial, or even large experimental setting, where such strains could plausibly be released to the environment. The perceived political risk from GMO release is a major factor in how companies develop their individual business models. Companies are carving out different niches in the market. Closed photobioreactors are only cosmetically different from ponds, as culture leakage is unavoidable in such systems. The ecological effects of GMA releases cannot be evaluated at this time, but it will be a challenge to develop GMAs that can produce and dominate in the harsh, variable environment of outdoor pond production for sufficient time (e.g. one or two months).

Every potential site where algal biofuels could be produced will have unique characteristics-and thus the environmental impacts to air, soil and water resources will vary. These will also depend on the production technologies, in addition to land, CO_2, nutrient and water inputs.

Regulatory/Policy Hurdles

Microalgae is not consistently eligible for key USDA support programs at this time. In order to achieve parity with traditional crops microalgae needs to be included in key programs such as the Biomass Crop Assistance Program (BCAP), crop insurance, matching payments, establishment payments, and more.

Classification for Water Quality

In some states, algae biofuel production is not classified as agriculture so it may be difficult to obtained required permits. For example, aquaculture is usually classified as an industrial activity and subject to very high effluent standards. Any discharges to streams and receiving waters are more restrictive and must comply with load-based and concentration-based effluent limitations imposed by the federal government and implemented at the same or more stringent level by each state. If a source high in a particular chemical constituent is used as influent to the plant-evaporation from the open algae ponds can potentially result in return flow concentrations that violate water quality objectives (42). This is also true of any residual nutrients or algal biomass in the blow-down waters. Environmental monitoring will be an important function within any future commercial algae biofuel production facility.

Conversion Technologies and Production

Lipids are particularly attractive as sources of biofuel because they can provide liquid products suitable for use in transportation and residential heating with relatively minimal processing that can be accomplished at existing petroleum refineries. Oils and fats and their derivatives do not generally have the volatility demanded by spark-ignited engines, so most attempts to use lipids have focused on replacements for middle-distillate petroleum-based fuels. These include diesel fuel, jet fuel and heating oil.

The middle distillate market is divided into two primary products that can be broadly characterized as No. 1 diesel fuel and No. 2 diesel fuel. No. 1 diesel fuel is a lighter, lower boiling fuel that is the source for jet fuel, kerosene, and winter grades of heating oil and diesel fuel. No. 2 diesel fuel is used primarily for heavy duty diesel applications in the agricultural, construction, logging, trucking and railroad industries and summer grade fuel oil.

Middle distillates are characterized by higher viscosity and lower volatility than gasoline. Their higher specific gravity provides more energy per gallon than gasoline. In diesel engine applications, the requirement for self-ignition, characterized by the cetane number, favors long, straight chain hydrocarbons instead of the highly branched structures found in gasoline. The higher molecular weight compounds in middle distillate fuels can solidify at low temperatures so crystallization onset, as measured by the *cloud point*, is included in most specifications.

Conversion Approaches

A wide variety of process options have been proposed to convert biologically-based materials to fuels (40). The most versatile approach is to convert the biomass to a synthesis gas (carbon monoxide and hydrogen) and then use Fischer-Tropsch chemistry to build hydrocarbon molecules of the size required by the application. This is currently the only process fully certified by the Federal Aviation Administration, U.S. military and commercial airlines, and aviation equipment manufacturers for the production of alternative jet fuel and is governed by the ASTM D7566 standard. While this approach is applicable to almost any type of biomass, the approximately $2 billion capital cost required per plant has been prohibitive to date. In addition, it is a feedstock-flexible process that does not require and therefore does not value biolipids. Finally, the irreversibility of the conversion to synthesis gas causes high energy and yield loss. This yield loss, along with high capital cost, has kept this technology from commercial development in the U.S. Alternative processes, such as pyrolysis and enzymatic hydrolysis of lignocellulosic biomass, produce sugars, acids, and other oxygenated hydrocarbons that can be upgraded either chemically or biologically for use as fuels. These upgrading processes are technically challenging and are only now being demonstrated at commercial scale. Although too viscous to use directly, lipids can be easily converted to middle distillate range products by either transesterification, which produces *biodiesel*, or hydrogenation, which produces *renewable diesel*. Hydrogenation is also in the process of being certified by the U.S. military and commercial airlines and equipment manufacturers for use as an aviation fuel, again under the ASTM D7566 standard. These processes are described below.

Biodiesel

Transesterification is the process of reacting a triglyceride molecule with an excess of alcohol in the presence of a catalyst to produce glycerin and alkyl esters. These alkyl esters are known as biodiesel. Small biodiesel plants of 1 million gallons/year or less typically operate in a batch mode but most plants above 3 million gallons/year operate in continuous flow. Plants in the U.S. vary in size from 500,000 gallons/year to as large as 105 million gallons/year for the GreenHunter Biofuels plant in Houston, Texas.

Figure 6 shows a schematic diagram of a complete biodiesel plant. The reaction of the oil, methanol, and catalyst occur in the reactor and then the separator divides the products into two streams, the methyl esters and the glycerin. The oil, alcohol, and catalyst are most commonly mixed in one or two continuously stirred tank reactors (CSTRs) until the reaction has reached equilibrium. The reaction can reach the 98% completion specified by the standard in a single CSTR step but most producers find using two steps gives a more robust process (87). To drive the chemical reaction to greater conversion of oil to biodiesel, producers add 60% to 200% excess alcohol, with 100% being a common value. Early in the transesterification process the reaction rate is limited by the solubility of the alcohol in the oil. In most cases, this is addressed through vigorous agitation of the reaction mixture (54). Other approaches to address this mass transfer limitation involve oscillatory flow (27), supercritical conditions (38, 66), ultrasonic agitation (70, 71) and use of co-solvents (16, 17).

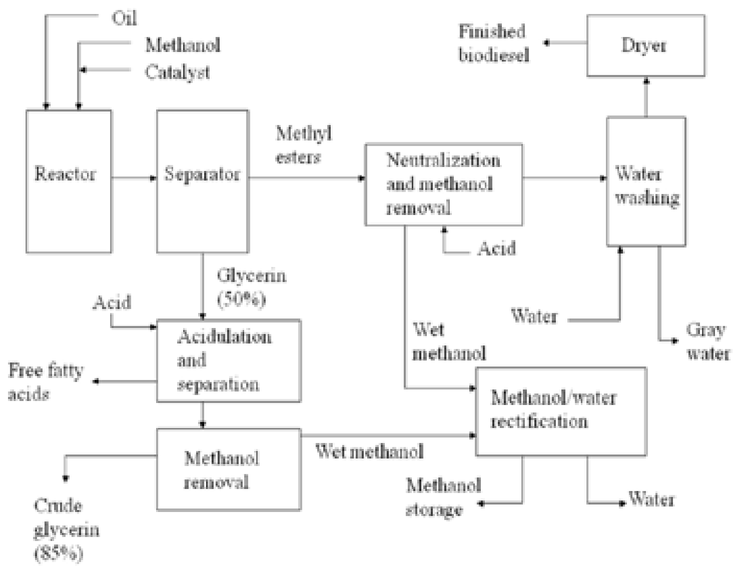

Figure 6. Schematic of biodiesel production plant (87).

The separation of glycerin from the biodiesel can be accomplished using a settling tank with 1 to 4 hours of residence time or with a disk centrifuge. The glycerin stream goes through an acid addition process which neutralizes the catalyst and breaks the soap into free fatty acids and salt. The free fatty acids can be separated and sold as is or converted to methyl esters with an acid-catalyzed esterification process. The methanol can be evaporated from the glycerin and recycled. When it emerges from the glycerin separation process, biodiesel still contains traces of free glycerin, catalyst, methanol, and soap. In order for the fuel to meet ASTM specifications, these contaminants must be reduced to low levels, and this is accomplished with ion exchange resins, solid adsorbents, or water washing.

The alkyl esters in biodiesel are derived from the fatty acid chains on the triglycerides, which came from the original oil or fat. This means the choice of feedstock oil or fat determines the properties of the biodiesel, including cetane number, oxidative stability, and cloud point. Feedstocks that are high in saturated fats are usually less expensive, but produce biodiesel that must be diluted with diesel fuel so the fuel will not gel during winter.

Co-product glycerin will be produced by a biodiesel plant at about 10% (by weight) of the biodiesel production level. Glycerin is a very common industrial chemical with a multitude of uses including food products, cosmetics, toiletries, toothpaste, explosives, drugs, animal feed, plasticizers, tobacco, and emulsifiers. Glycerin is edible and can be fed to animals (33). It has equivalent energy content to corn and has GRAS (Generally Recognized As Safe) status with the Food and Drug Administration (FDA). However, the FDA is recommending that the residual methanol levels be no higher than 150 ppm (62). Achieving a methanol level this low can increase glycerin processing cost. The greatest value for glycerin comes from its use as a chemical feedstock (22).

Renewable Diesel

Hydrotreating is a common process in petroleum refineries and is normally used to remove oxygen, sulfur, nitrogen, and metals from petroleum-based feed streams such as heavy gas oil or vacuum gas oil. It has been known for some time that fatty acid-based materials can be converted to straight chain or "normal" alkanes by hydrotreating (46). Recently, hydrotreating has been proposed to convert bio-based lipids to a hydrocarbon fuel called renewable diesel or renewable jet fuel, sometimes branded "green diesel" or "green jet" (61), which should be distinguished from alkyl ester-based biodiesel.

Huber and co-workers have identified the reaction pathways that are relevant to the conversion of oils and fats to hydrocarbons (28). The first step in the process consists of hydrogenation of the C=C bonds. The number of chains with C=C bonds depends on the level of unsaturation in the fatty acid profile. Eighty-five percent of the fatty acid chains in soybean oil contain one or more C=C bonds. More saturated feedstocks such as animal fats and palm oil contain 55-60% unsaturated fatty acids.

The hydrogenated triglycerides are further reacted with hydrogen to split the fatty acid chains from the glycerin backbone as shown in the first step of Figure 7. The glycerin will go to propane or lighter gases. The saturated fatty acid chains undergo dehydration, decarbonylation, or decarboxylation reactions to produce normal alkanes between 15 and 18 carbons long. These long chain n-alkanes have excellent cetane numbers but also have cold flow properties that are even worse than the normal alkyl esters in biodiesel. The *n*-alkanes are already present in middle distillate fuels, so they can be used directly as a fuel extender where their concentration is low enough not to affect the cold flow properties of the mixture. They can also either be cracked to produce shorter *n*-alkanes, or isomerized to branched alkanes depending on the anticipated final product.

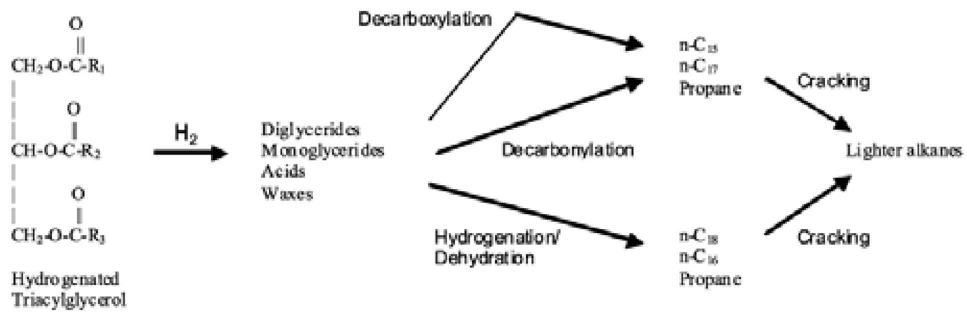

Figure 7. Pathways for Conversion of Hydrogenated Triglycerides to Alkanes (28).

The global reaction for the hydrogenation of a triglyceride such as triolein would be:

$$C_{57}H_{104}O_6 + 6H_2 \longrightarrow C_3H_8 + 3C_{17}H_{36} + 3CO_2$$

which shows that six moles of hydrogen are required for each mole of triolein. This hydrogen requirement should be taken as a minimum, since a portion of the oxygen will also be released as water, thus requiring additional hydrogen. The reaction requires at least a molecule of hydrogen for each double bond plus another molecule to terminate the radical ends created by the decarboxylation. Triolein can be taken as characteristic of a vegetable oil like soybean oil, although a more saturated fat like beef tallow would require less hydrogen.

Hydrogen is readily available in refineries, but it always comes at the expense of salable products. In this case it is likely to be from reforming of methane and other low value short-chain hydrocarbons, possibly including the propane produced in the reaction. In any case, the cost and availability of the hydrogen will be an important factor in the economic viability of this technology.

The n-alkanes provide good cetane numbers and will be compatible with existing engines and fuel distribution infrastructure. Because the oxygen that was originally in the oil or fat has been removed, the energy content of the renewable diesel fuel will be higher than the original vegetable oil or biodiesel. However, alkanes tend to have low densities so the energy content of a gallon of renewable diesel will still be slightly less than conventional diesel fuel, which may contain 25 to 35% high-density aromatic hydrocarbons. This difference is small enough that it is unlikely consumers will see any mileage penalty from using the fuel. One additional caution for the fuel is that n-alkanes tend to have poor lubricity and poor cold flow properties. This can usually be managed with additives.

If a gasoline-grade product is desired, the alkanes may also be isomerized to provide the chain branching needed to raise the octane number to a level that will be suitable for spark-ignited engines. Jet fuel standards currently do require the addition of petroleum-based aromatics in a 50:50 blend to meet Jet A-1 and military JP-5 and JP-8 specifications. Depending on the extent of processing of the long-chain alkanes and the diversity of products produced, a fractionation process might be needed to ensure the quality of the final product. Whether upgrading of the n-alkanes to gasoline or jet fuel is economically viable is unclear, because these products do not currently command the premium price needed to justify the additional processing.

Production of renewable diesel is usually implemented in one of two ways. First, the hydrogenation may occur as a stand-alone process within a petroleum refinery as shown in Figure 8. The hydrotreater is specifically designed and optimized to operate on a triglyceride feedstock.

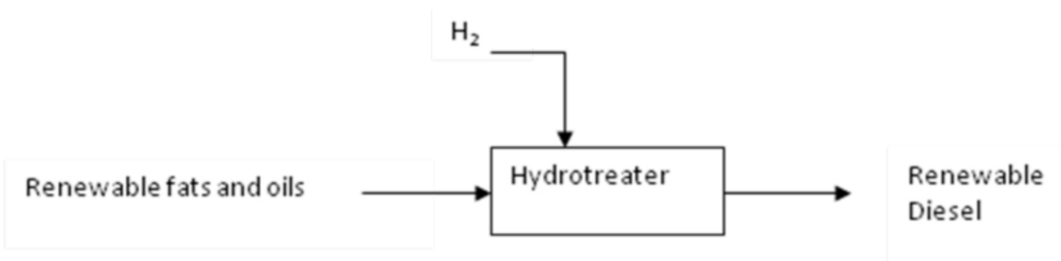

Figure 8. Dedicated hydrogenation of fats and oils.

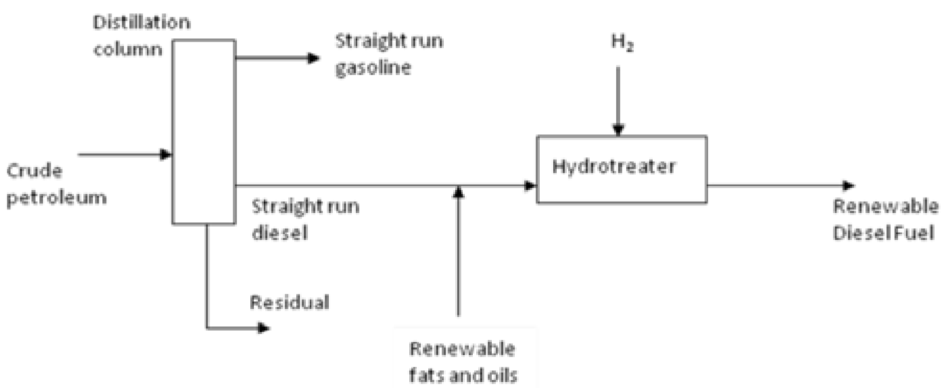

Figure 9. Co-processing of fats and oils with petroleum.

This approach is favored by companies like UOP (75) and Syntroleum (72, 73). The alternative is to co-process the vegetable oils or animal fats with a petroleum-based stream. This is the process favored by companies like ConocoPhillips (21) and BP (7) and is shown in Figure 9. Figure 9 shows a conventional atmospheric distillation column for fractionating crude petroleum. The straight run diesel fuel cut, which would normally be hydrotreated to remove sulfur and nitrogen, is mixed with the stream of vegetable oils or animal fats and the combined stream is co-processed in the hydrotreater and through all subsequent refining steps.

Renewable diesel can be produced from any vegetable oil or animal fat with the primary difference being the lower amount of hydrogen needed for more saturated feedstocks like palm oil and animal fat. Since the fatty acid chains all pass through an *n*-alkane stage during processing, the properties of the final product do not depend on the fatty acid profile of the initial oil or fat. This allows the feedstock to be selected for least cost rather than to assure desirable properties in the final product.

Biodiesel and renewable diesel compete directly for oil and fat feedstocks. Biodiesel produces approximately 100% conversion of the weight of oil into usable fuel while renewable diesel has a 25% weight loss due to glycerin removal and decarboxylation during conversion to *n*-alkanes. Some of this loss can be offset by recovering the propane produced from the glycerin, although this may be needed for hydrogen production within the refinery. In addition, further processing of the *n*-alkanes into finished products such as jet fuel and gasoline entails additional cost and yield loss. Renewable diesel is an attractive option due to its chemical similarity to petroleum-based fuels, but the yield loss may make it more expensive than biodiesel.

Market-Driven Regional Biofuel Supply Chains

Agricultural oilseeds and algal-derived oils represent both existing and potential future capacity as biofuel feedstocks. Deploying new tools and technologies throughout the supply chain have the potential to create sustainable feedstocks for next generation fuels. Beyond the technology, another critical element of the roadmap for next generation biofuels efforts is to implement a market pull. Part of the market can be policy driven, such as the establishment of the renewable fuel standards and the goals set by the Energy Independence and Security Act of 2007. Another dimension can be driven by the market itself. Within the total transportation fuel used in the U.S., just over 7.5% of the total fuel is consumed as commercial jet fuel (81). Commercial aviation and the military combined use approximately 23 billion gallons of aviation jet fuels annually. The niche has scale, a small and sophisticated set of buyers in the commercial airline industry and the military, and a known geography. The largest ten airports utilize nearly half of the commercial jet fuel used, and the forty largest airports consume 90% of all jet fuel used annually (Figure 10).

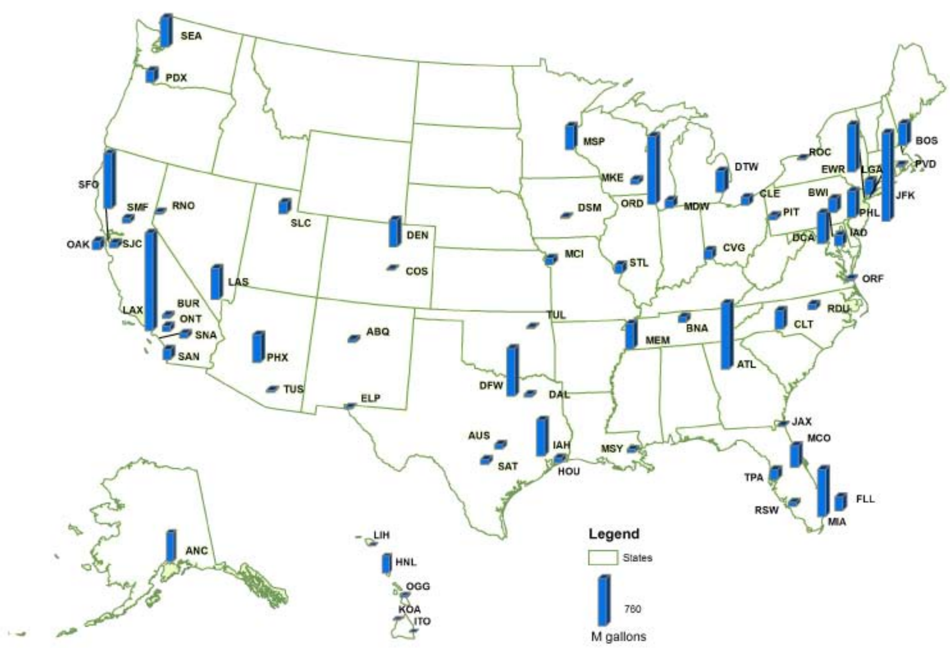

Figure 10. United States airport fuel consumption, millions of gallons 2008 (3).

The lack of predictable pricing, the increasing cost and availability of refined aviation-grade jet fuels, and the scrutiny of the greenhouse gas emissions from aviation have unified both civilian and military markets to explore the development of sustainable aviation fuels. Visioning an industry with a completely distributed and sustainable source of fuel, airplane manufacturers like Boeing, and airline associations like the Air Transport Association (ATA) in the U.S., and the Air Transport Action Group (ATAG) in Europe, have championed next generation fuels based on the principles of sustainability (2). They have partnered with the military to develop conversion technologies, such as the hydro-treated jet fuels and diesel, as well as to seek certification of the finished fuels for the strict requirements of aviation.

Developing the next generation of biofuels could be accelerated by better linking supply and demand. Agricultural oilseeds, though highly concentrated, could be developed for individual regions where demand, such as that from aviation, is known. Already, in the Pacific Northwest, the market represented by 14 Airlines is working to ensure a ten-year market for a sustainable source of biofuels for Seattle's airport (1). Camelina, as a promising new crop candidate that would fit in rotation with dryland wheat in substitution for fallow, is being pursued to open this supply chain. Advanced conversion technologies are being pursued to create 'drop-in' jet and diesel biofuels. Once created, such a chain could help pull the development of algae as the next source of plant-derived oil into commercial reality.

In Hawaii, customer pull generated by electric companies, the military, and commercial airlines is driving the development of a regional market. In March 2010 Hawaiian Electric Company issued a request for proposal for up to 215.5 million gallons of biofuel produced from Hawaii-grown feedstock. Demand signals are also being sent by the PACOM Green Initiative for Fuels Transition (GIFTPAC), which is an interagency group with the goal of using locally produced drop-in biofuels to displace 25% of the military's liquid fuel demand in Hawaii. On the supply side, several demonstration and pilot scale algae projects are in operation or in planning stages. Research is being done on terrestrial oil seed crops, but due to land area restrictions, microalgae and cellulosic crops appear to be the likely options for large scale fuel production.

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Chapter 9

The Role of Sorghum as a Bioenergy Feedstock

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Introduction

Existing economies are tied to the flexibility of non-renewable fossil energy sources primarily in the form of petroleum, coal, and natural gas. Petroleum provides the single largest fraction of the world's energy (40% of total world energy used) and for most countries a large percentage is imported from politically volatile locations (IEA, 2002). Petroleum is also considered one of the largest single contributors to trade deficits in many countries. Burning non-renewable fossil energy sources contributes to carbon dioxide and other greenhouse gas emissions in the atmosphere, raising concerns about global climate change. Non-renewable fossil energy sources are not sustainable therefore it is imperative that renewable, less-polluting energy sources be identified and implemented into current energy markets. Renewable energy sources are needed to address a range of important economic and environmental issues and to insure a continuous energy supply.

Energy security and reducing greenhouse gas emissions are the most important priorities for most countries in the world. Energy security is a concern due to uncertainties in supply and sudden increases in market prices of non-renewable fossil energy sources. These uncertainties stem from geopolitical tensions, weather disturbances, the manipulative behavior of OPEC (Organization of Petroleum Exporting Countries), growth of developing countries like China and India, and declining non-renewable fossil energy reserves. Many countries have embarked on programs to develop alternative energy sources to reduce their dependence on imported fossil energy supplies and reduce the foreign exchange burden.

The United States has established the Energy Independence and Security Act of 2007 amending the Renewable Fuels Standard (RFS)-Energy Policy Act of 2005, in order to reduce its dependence on foreign fossil energy supplies, reduce greenhouse gas emissions, and provide meaningful economic opportunity. The RFS recommendation is to produce 36 billion gallons of biofuels by the year 2022 (RFA, 2010).

The production of biofuel from plant-based biomass is becoming an attractive alternative to non-renewable fossil energy sources. The advantage of plant-based biomass material lies in its photosynthetic ability. Nature has designed a sophisticated solar conversion system that self-assembles from water, nutrients in the soil and carbon dioxide (CO_2) in the air with energy input from the sun. Critical factors in utilizing biomass as an alternative energy source will be the ability of the plant to achieve high biomass yields, grow in diverse climates under various environmental conditions, and be economically converted into a bio-based product.

Sorghum (*Sorghum bicolor L. Moench*) is an herbaceous annual grass of tropical origin that is planted from seed, stores an appreciable amount of sugar with modest water requirements, is tolerant of arid and saline growing conditions, and reaches maturity in 90 to 180 days. It is considered a crop with universal value because it can be grown in tropical, subtropical, temperate, and semi-arid regions of the world. It is adaptable to existing cropping systems, can serve as a secondary crop or a short cycle crop rotation and is used as a source of forage and silage for livestock production systems. The objective of this review is to highlight the unique characteristics of sorghum as a bioenergy feedstock.

Potential Use as Biofuel

Sorghum is characterized by a vastly diverse germ plasm in terms of phenotypic and morphological traits. Sorghums can be classified into four main groups depending on their production characteristics: grain sorghum, forage sorghum (FS), high-tonnage sorghum (energy), and sweet sorghum. Sorghums have generated interest as an alternative bioenergy feedstock since the 1970s.

Sorghum cultivars are primarily processed for production of table syrups and livestock feed. Sorghum cultivars are now being considered as a candidate in the search for efficient energy crops due to an increased interest in the conversion of biomass to energy. Sorghum cultivars possess readily available fermentable sugars within the culm, therefore enzymatic conversion of starch to sugar is not necessary which gives sorghum an economical advantage over starch based crops. The juice from sorghum can be converted to alcohol using currently available, conventional fermentation technology. The bagasse can be utilized to generate electricity or steam as part of a co-generation scheme or as a biomass feedstock for cellulosic biofuel production.

Research interest in sorghum cultivars has focused on the general aspects of sugar production, disease resistance, cultural practices, and agronomic aspects of production such as total biomass yield. Future research into multiple planting dates to increase annual biomass yields and extend seasonal availability of sorghum cultivars needs to be considered because sorghum cultivars have a short growing cycle and are adapted to a wide array of environmental conditions with less nutrient requirements. In the United States, it is estimated that annual combined sorghum production uses seven million hectares of farmland. Currently, sorghum grain makes up 4% of the total grain used for ethanol production in the U.S. (Renewable Fuels Association, 2007).

Sorghum

Sorghum is a C4 crop in the grass family and is characterized by its high photosynthetic efficiency. Sorghum is an annual crop with considerable variability in growth characteristics. Grain, sweet, and forage type sorghums are all compatible with current agricultural production systems. Crops with a four-carbon (C4) photosynthetic pathways produce 30% more dry matter (DM) per unit of water than three-carbon (C3) crops and are more adapted to semiarid production regions (Samson and Knopf, 1994). Sorghum plants have the ability to counterbalance production situations. Habyarimana et al. (2004) reported that lower plant density results in higher leaf weight per plant, higher grain weight per panicle and higher tillering ability. Sorghums have an extensive root system that can penetrate 1.5 to 2.5 meters into the soil and extend one meter away from the stem. The large amount of root material contributes to the build-up of soil organic carbon after removal of the aerial parts of the plant, and can alleviate concerns about depletion of soil organic matter resulting from the removal of stover (Wilhelm et al., 2004). Sorghum requires less fertilizer than corn to achieve high yield (Lipinsky and Kresovich, 1980), can tolerate a wide range of soil conditions, from heavy clay soils to light sand, with pH ranging from 5.0 to 8.5 (Smith and Frederiksen, 2000). Sorghums become dormant in the absence of adequate water but do not wilt readily and are more efficient than corn in utilizing phosphorus and potassium. These characteristics make sorghum suitable for cultivation as a crop in optimal conditions and on marginal lands.

Production of biofuels from plant structural carbohydrates (cellulose, hemicellulose, and lignin) is predicted to increase energy output per unit land area by five percent when compared to biofuels produced from starch and sugar (Farrell et al., 2006; Somerville, 2007). Sorghum has high biomass yield and excellent nitrogen use efficiency (Gardner et al., 1994; Anderson et al., 1995; Bean et al., 2008; Putnam et al., 1991). After harvesting, most varieties will regrow or ratoon. The ability to form a ratoon enables multiple harvests per season in some climates although yields typically decrease in ratoon crops.

Sweet Sorghum

Sweet sorghum yields vary considerably depending on the varieties, location grown (soil, water, climate, pests and diseases), inputs, and agronomic practices. When considering sweet sorghum for biofuel production via conventional fermentation, biomass yield, juice yield, and sugar production per acre are the most important characteristics.

Sweet sorghum cultivars are characterized by the accumulation of high levels of fermentable carbohydrates (FC) (15-23%) within the culm (Sarath, et al., 2008; Smith et al., 1987). Total FC are comprised of three main sugars; sucrose (70%), glucose (20%), and fructose (10%) variation in percentages depends on variety and environmental conditions (Prasad et al., 2007). Sweet sorghum requires less water and contains higher FC levels than corn, making it a favorable biofuel crop for semi-arid temperate climate regions (Reddy et al., 2007). Sugar content in the juice increases with maturity, and is low prior to seed development. Sweet sorghum is typically seeded in widely spaced rows (30-40 inches). The ideal seeding rate for most sweet sorghum varieties is 3-4 seeds per linear foot of row with a final stand of 2-3 plants per linear foot of row. If plant populations are too high, the stalks will be spindly and contain less juice.

Sweet sorghum varieties can grow 14 feet tall and produce 20 to 50 tons of biomass (fresh weight) per acre. Putnam et al. (1991) studied the performance of 13 sweet sorghum cultivars and reported total DM yield (16.1 to 35.8 Mg ha-1), brix values of extracted juice (5.8 to 13.7), harvest stalk moisture (67 to 76%), and extracted FC yields (2.3 to 7.0 Mg ha-1) to vary significantly among cultivars. Sweet sorghum requires less than 50% total nitrogen to produce similar ethanol yields as corn (Anderson et al., 1995) and is capable of removing 62% of total nitrogen with no difference in DM yield (Bean et al., 2008). Reports have shown that sweet sorghum yielding 11-16 Mg ha-1 will remove nitrogen, phosphorus and potassium at the rate of 112, 45, and 202 kg ha-1, respectively (Undersander et al., 1990).

Ethanol production from sweet sorghum (5,600 liters ha-1 year-1from 140 t $^{ha-1}$ per two crop annum-1 @ 40 L t^{-1}) is comparable to ethanol production from sugarcane (6,500 litres $^{ha-1}$ from 85-90 t $^{ha-1}$ per crop @ 75 L t^{-1}). Yield and quality characteristics of sweet sorghum and sugarcane vary with weather conditions and planting dates (Hipp et al., 1970; Broadhead 1972). Poornima et al. (2008) recorded higher grain (2483 kg ha-1) and millable cane yield (37.17 t $^{ha-1}$) for early planting dates of sweet sorghum cultivars due to favorable environmental conditions during the early growing season. Under favorable conditions, sweet sorghum is capable of producing up to 13.2 metric tons per hectare of total sugars, which is equivalent to 7682 liters of ethanol per hectare (Murray et. al., 2009).

As a bioenergy crop, sweet sorghum could be used to provide grain starch for hydrolysis; stem juice for direct fermentation; and bagasse as cellulosic feedstock for fermentation or boiler fuel (Saballos, 2008).

Forage Sorghum

Forage sorghums are coarse, fast growing; warm season grasses that provide livestock feed in mid-summer. Sugar in the stalk is not the primary focus. Sorghum varieties are currently bred to produce high biomass yields (Juerg et al., 2009). Forage sorghum utilized as silage, hay and direct grazing represents approximately five million acres of production. In 2009 over 254,000 acres of sorghum were harvested producing an average of 13.7 tons of silage per acre (USDA National Agricultural Statistics Service, 2008). Forage sorghum has the potential to grow tall (6 to 15 ft) and can produce a large amount of vegetative growth. Compared with corn, forage sorghum is cheaper to produce, has comparable yields and slightly lower forage quality for silage. These qualities give forage sorghum potential for use in biofuel production (Oliver et al. 2005a; Oliver et al., 2005b).

The primary sorghums used for forage are grouped as forage sorghums, sudangrass, and sorghum-sudangrass hybrids with each having specific growth characteristics. Typically forage sorghums are used for silage or for a single hay cutting. Sudangrass is used for grazing, multiple hay cuttings and silage. Sorghum-sudangrass hybrids are a cross between sorghum and sudangrass with smaller diameter stems, high tillering capacity, rapid re-growth potential and low grain yield and are best suited for hay and grazing. Optimum growth occurs in sustained elevated temperatures of 75 to 80 degrees Fahrenheit. Most forage sorghums are grown in the southern Great Plains (Kansas, Nebraska, and Texas). Introduction of traits such as brown midrib and photoperiod-sensitivity have expanded the use of forage sorghums.

The brown midrib (BMR) forage genotypes usually contain less lignin and have reduced lignin chemical composition (Oliver et al. 2005a; Oliver et al., 2005b). The reduced lignin content of BMR sorghum increases its energy conversion efficiency and its nutritive value as a livestock feed (Gressell 2008). The BMR mutant genes most commonly used are BMR-6, BMR-12 and BMR-18, and refer to the reddish-brown pigmentation of the leaf mid-rib (McCollum et al., 2005; Sarath et al., 2008). Decreased DM yield, plant height, and tillering with increased lodging are potential negative characteristics of BMR sorghum (Pedersen et al., 2005). McCollum et al. (2005) reported that BMR forage sorghum varieties produced less total DM (16.8 Mg ha-1) than non-BMR forage sorghum (19.0 Mg ha-1). Lodging potential of BMR forage sorghum can be minimized by adjusting the seeding rate and managing nitrogen fertilization. Bean et al. (2003) concluded that lodging of the 'BMR 100' hybrid increased 25% with increased nitrogen fertilizer rates (56 to 112 kg ha-1). Increasing the seeding rate of 'BMR 100' hybrid from 74,100 to 148,200 seeds ha-1 also increased lodging by 56.6%.

High-Tonnage (Energy) Sorghum

High-tonnage (energy) sorghum can produce increased levels of cellulose material, with reduced grain production depending upon the environment. These are usually classified as hybrid photoperiod-sensitive forage sorghums (PS). Photoperiod-sensitive sorghums delay the flowering which in turn will delay the decline in forage quality providing flexibility in harvest management (McCollum et al., 2005). Photoperiod-sensitive sorghum will not produce grain at most latitudes in the United States. The PS characteristic allows these sorghum hybrids to accumulate vegetative dry matter for longer periods throughout the growing season. Photoperiod-sensitive hybrids can be derived from the cross of two photoperiod-insensitive parental sorghum lines (Rooney et al., 2007). Reported yields of PS sorghum on dry land ranged from 7.6 to 17.5 Mg ha^{-1} and under irrigation ranged from 15.4 to 21.3 Mg ha^{-1}. Dual purpose forage sorghum dry matter yields during the same trial years ranged from 6.4 to 13.7 Mg ha^{-1} on dry land and 14.3 to 19.5 Mg ha^{-1} under irrigation (Roozeboom et al., 2004; Roozeboom et al., 2005). McCollum et al. (2005) reported dry matter yields of PS sorghum to be 26% to 43% greater than non-BMR and BMRs forage sorghums with less overall water use. Blumenthal et al. (2007) reported dry matter yields of PS sorghum to be 30 Mg $^{ha-1}$ in southern Texas. Photoperiod-sensitive sorghum has characteristically high lignin content in the stalks, which minimizes lodging but decreases nutritive quality as a livestock feed.

Although cellulosic biomass is receiving growing attention as a bioenergy feedstock, the concept is not well understood for sorghum biomass because scientific information on using forage sorghums for biofuel production is limited.

Grain Sorghum

Grain sorghum production for the United States ranks fifth and totaled 383 million bushels in 2009 with an average price of $5.90 per cwt (NASS 2010). The Great Plains states produce the largest volume of grain sorghum; however it is also grown from Georgia to California and South Texas to South Dakota. The two top producing states are Kansas and Texas harvesting nearly 84 percent of the U.S. sorghum crop with a total value of $1,050 million. Texas led the nation in area planted and silage production. Nebraska, Oklahoma, South Dakota and Colorado also produced quantities of grain sorghum (NASS 2010). Leading sorghum producers around the world include the United States (18.68%), Nigeria (17.12%), India (11.27%) and Mexico (9.81%) (Sorghum U.S. Grains Council). Grain sorghum use in the United States is primarily as a livestock feed with a higher feed to gain ratio and a lower average daily gain compared to corn.

Ethanol production has become an important new market for grain sorghum due to the classification of grain sorghum as an advanced biofuel feedstock in the 2008 Farm Bill. According to the World Agricultural Supply and Demand Estimate report ethanol production will account for 26 percent of domestic grain sorghum usage. Currently more than one third of the U.S. grain sorghum crop is processed through an ethanol plant making the renewable fuels industry the fastest growing value-added industry for sorghum.

Genetics

Numerous genetic methods can be employed to improve biomass properties. The choice of the method depends on the trait of interest, the biochemical process being targeted, and the plant species. Biomass quality is heavily influenced by the content and composition of lignin, cellulose, and hemicellulose. Biomass yield can be manipulated through genetics and through standard crop management practices that include plant height, stalk diameter, number of leaves, disease and pest resistance, and lodging susceptibility.

Modification of plant biomass through the application of genetic, genomic, and plant breeding approaches to exploit both intraspecific and interspecific variations can aid in the development of bioenergy crops that support physical and chemical characteristics for high biomass yield and quality composition. In the U.S., sorghum has been researched for biofuel for more than 30 years (Lipinsky, 1977), with primary research, development, and breeding starting in the late 1970s through the mid-1980s (Murray et al., 2009).

Sorghum contains both cultivated and wild races and possesses a significant amount of genetic diversity for traits of agronomic importance (Hart et al., 2001). Approximately 4,000 cultivars of sweet sorghum are distributed throughout the world (Grassi et al., 2004), providing a diverse genetic base for the development of highly productive cultivars within various climate regions. Hybrids can be developed by crossing grain-type seed parents and sweet-type pollen parents resulting in higher biomass yields and sugar content when compared to the original grain-type parents (Hunter and Anderson, 1997). Hybrids can also co-produce grain at levels approaching the yields of the grain-type seed parent (Miller and McBee, 1993).

Various biological techniques, including tissue culture (Baskaran and Jayabalan, 2005), genetic transformation (Godwin and Seetharama, 2005), molecular markers, genomics, and proteomics have been successfully exploited in sorghum (Dillon et al., 2005). Knowledge regarding genetic control of perennially has contributed to its promise as a bioenergy crop (Paterson, 2008). The sorghum genome has recently been sequenced, providing a better understanding of genetic and biochemical traits which will assist in developing a better genomics-assisted breeding program in sorghum (Paterson et al., 2009). Most of the bioenergy associated traits like biomass, carbohydrates, and stem juiciness are complex as shown by their continuous variation within a population, indicating that there are several genes responsible for the observed variability. However, there are limited studies regarding the genetics of sorghum carbohydrates and biomass production.

Production Challenges

The United States is considered the world’s top sorghum producer. Sorghum production challenges are focused on optimizing performance of the crop on marginal lands, developing avenues for the efficient conversion of biomass to biofuel, and developing better technologies for harvesting and processing.

The costs associated with transportation of the crop to the mill will be the major limiting factor in the profitability of sorghum production for biofuels. Varieties that have higher sugar contents per ton of biomass will be more efficient to process and haul to the mill. A study by Memphis Bioworks showed that sweet sorghum processing plants should be located within six miles from production fields in the Delta region (Tripp et al., 2009). To utilize the bagasse for livestock feed, cattle should also be in the vicinity. Harvest timing greatly influences total biomass and fermentable carbohydrate contents of sweet sorghum. Lodging combined with rapid fermentable juice degradation after extraction or killing freeze, are issues that must be considered for harvesting and conversion process management. Almodores et al. (2007), Broadhead (1972), and Zhao et al. (2009) found that total dry matter yield, brix value, and sucrose content of sweet sorghum was highest when harvested at physiological maturity. Tsuchihashi and Goto (2004) reported single pass juice extraction rates using a triple-roll mill to be approximately 50 percent. Extracted juice storage issues can be overcome by fermenting the extracted juice immediately, or storing it at temperatures near freezing to impede microbial activity and breakdown of fermentable carbohydrates.

Currently, the only commercially viable harvest method for sweet sorghum is removing the entire crop with a forage harvester and transporting it to a mill or biofuel facility. Using this method, transportation costs and proximity to the facility will play a large role in determining sorghum production profitability.

One of the primary disadvantages of sorghum and other plants rich in soluble sugars is seasonal availability and storage expense. Research has determined that net production cost of fermentable carbohydrate from sweet sorghum calculated at the farm-gate, can be well below typical cost of fermentable carbohydrates derived from corn grain (Bennett and Anex, 2008).

Eight harvest-transport-processing options were modeled to determine the economic feasibility of sorghum to biofuel. Included in the model were 4-row self-propelled and 2-row tractor-pulled forage harvesters, two different modes of in-field transport, fresh processing, on farm ensilage and at-plant ensilage. Monte Carlo simulation and sensitivity analysis are used to account for system variability and compare scenarios. Transportation costs were found to be significant ranging from \$33 to \$71 Mg1 FC, with highest costs associated with at-plant ensilage scenarios. Economies of scale benefit larger milling equipment and boiler systems reducing fermentable carbohydrate costs by more than 50% with increasing annual plant capacity from 37.9 to 379 million liters. Ensiled storage of high moisture sweet sorghum in bunkers can lead to significant losses of fermentable carbohydrates (>20%) and result in systems with net fermentable carbohydrate costs well above those of corn-derived carbohydrates. Despite relatively high transport costs, seasonal, fresh processed sweet sorghum is found to produce fermentable carbohydrates at costs competitive with corn grain derived carbohydrates (Bennett and Anex, 2009).

Costs of producing sorghum for silage vary based on the cultivar, soil conditions, harvesting, and agricultural practices. In the North Florida region, silage sorghum yield ranges from 3.5 to 6.3 dry tons per acre, and production costs, including harvesting, ranges from \$50 to \$90 per dry ton (Hewitt, 2006). Based on results from growing and converting sorghum to ethanol (McBee et al., 1988), 1 acre of sorghum can yield up to 7.59 tons of oven-dried stem and about 1,240 pounds of grain. Costs associated with conversion include transportation to processing facilities, juice extraction, and processing to biofuel. Without a conversion facility to obtain reliable data, any estimates may be speculative.

Summary

The development and use of biofuels from renewable resources is beneficial to the environment while encouraging capital investment and promoting economic development. Sorghum is a water sipping, highly sustainable cropping option for producers in semi-arid regions with limited irrigation capacity or dry land producers with unpredictable rainfall. Compared to many other crops, sweet sorghum has high water and nutrient use efficiencies and is considered environmentally sustainable. In limited water supply regions sorghum can conserve an important natural resource while offering more yield and sustainability.

Sorghum has the potential to be an excellent diversified biofuel crop able to fill the needs of multiple bioenergy conversion process across many environments with reduced energy requirements. Environment, energy inputs, harvesting logistics, specific energy conversion processes, and economics will ultimately dictate which crops are used for renewable fuel production.

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Chapter 10

Nitrogen, Phosphorus, and Potassium Requirements to Support a Multi-Billion Gallon Biofuel Industry

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Abstract

To accomplish the goals for biofuel and bioenergy production, one billion tons of biomass will need to be produced annually by the year 2030. Crop production data from a joint study by the U.S. Department of Energy (US DOE) and the U.S. Department of Agriculture (USDA) demonstrated how this goal could be met by changes in management and cropping strategies in the U.S. Based on this report, changes in nutrient removal were estimated from the baseline 2001 year to 2030. It was found that when published estimates of nutrient removal were used for the various crops, nitrogen (N), phosphorus (as P_2O_5), and potassium (as K_2O) removal were projected to increase by 8.4, 8.8, and 11.6 times, respectively, compared with 2001. Most of these increases were due to corn stover removal and perennial crop harvest. Disparities between published and observed nutrient removals were examined for corn stover. It was found that in at least one set of studies, N and K_2O removal were about half of those typically published, while P_2O_5 removal was only a quarter of the published estimates. Consequently the estimated changes in nutrient removal may be much too high. Greater future nutrient removal by corn stover and perennials will consume a larger portion of fertilizer production capacity, leaving less fertilizer available for export to other countries, and stressing the need to understand how to recycle, to the extent possible, nutrients and byproducts from biofuel production facilities back to the farmland that produces feedstocks.

An Annual Production Goal of One Billion Tons of Feedstock Biomass Has Been Set for 2030.

This production goal arose from the estimated amount of biomass needed to realize the “Vision for Bioenergy and Biobased Products in the United States,” which is for these products to supply the following: (1) 5% of the nation’s total industrial and electric generator energy demand in 2020 and 2030, or 4.0 and 5.0 quads, respectively, where one quad is 10^{15} BTU; (2) 20% of its transportation fuels in 2030, or 9.5 quads; and (3) 25% of its chemical commodities in 2030 (BTAC, 2002). This vision was developed by the Biomass Technical Advisory Committee (BTAC) that was established by the Biomass Research and Development Act of 2000. If biofuels and bioenergy reach these goals, they are expected to replace 30% of the petroleum consumption in the United States. From discussions among stakeholders in the feedstock supply chain, the BTAC determined that one billion dry tons per year (bdty) of feedstock were needed, based on average conversions of lignocellulosic biomass, to reach this goal (BTAC 2003).

The feasibility of producing one bdty of feedstock was investigated by the U.S. DOE and USDA in a joint study (Perlack et al. 2005), which found that the feedstock production goal was attainable. Estimated annual production by 2030 on forest and agricultural lands was 368 million dry tons yr $^{-1}$ (mdty) and 998 mdty, respectively, for a total of 1.37 bdty. Of the 997.6 mdty on agricultural lands, 87.2 mdty were predicted to originate from secondary and tertiary residues from corn grain production, manure, fats and greases, and municipal solid waste (Table 1). The remaining 910.4 mdty were attributed to grains (87.5 mdty), trees and wood fiber (11.4 mdty), perennial forages, including grasses (CRP)(383.7 mdty), and annual crop residues (427.8 mdty).

	Residue sustainably removable			Grains used for bioenergy		
Source	2001	2030	change	2001	2030	change
	(million dry tons yr^{-1})			(million dry tons yr^{-1})		
corn	74.8	256.1	181.3	13.5	74.8	61.3
sorghum	0.0	4.0	4.0	0.5	2.8	2.3
barley	0.7	4.7	4.0	0.2	1.9	1.7
oats	0.1	1.2	1.1	0.0	0.0	0.0
wheat-winter	8.8	40.9	32.1	0.2	0.0	-0.2
wheat-spring	2.2	10.9	8.7	0.0	0.0	0.0
soybeans	0.0	47.9	47.9	0.2	0.0	-0.2
rice	5.7	14.7	9.0	0.0	0.0	0.0
cotton lint	2.7	8.9	6.2	—	—	—
other crops	18.1	23.5	5.4	0.0	4.0	4.0
double crops	0.0	15.0	15.0	0.0	4.0	4.0
grasses (CRP)	0.0	15.4	15.4	—	—	—
trees (CRP)	0.0	2.2	2.2	—	—	—
wood fiber	0.2	9.2	9.0	—	—	—
perennial forages	0.0	368.3	368.3	—	—	—
subtotal A	**113.3**	**822.9**	**709.6**	**14.6**	**87.5**	**72.9**
Corn grain secondary and tertiary residues	6.2	12.3	6.1			
manure	35.1	43.5	8.4	—	—	—
fats and greases	0.9	2.0	1.1	—	—	—
municipal solid waste	23.7	29.4	5.7	—	—	—
subtotal B	**65.9**	**87.2**	**21.3**	—	—	—
grand total* (sum of subtotals A and B)	**179.2**	**910.1**	**730.9**	**14.6**	**87.5**	**72.9**

Table 1-Feedstock production for 2001 and 2030 (Perlack et al. 2005, Tables B.2 and B.6).

To reach the 2030 agricultural production goals in Table 1, several assumptions were made when constructing the high feedstock yield scenario, termed "Scenario 3" in the study (Perlack et al. 2005). Assumptions made for crop production were: (1) yields of corn and small grains were increased by 50%; (2) soybeans were considered to have a greater straw:grain ratio (2.0:1.0 rather than the present 1.5:1.0) due to genetic improvements aimed at increasing straw production; (3) future improvements in residue collection technologies, such as single pass harvesters that simultaneously harvest grain and stover/straw, making it possible to harvest up to 75% of crop residues rather than the current 40%; (4) all cropland was managed with no-till to maximize the quantity of residue that could be sustainably harvested; and (5) 55 million acres of cropland, idle cropland, and pasture were reallocated to the production of perennial bioenergy crops.

The Energy Policy Act of 2005 required that both the vision and the roadmap reports by the BTAC be updated. The vision of the BTAC originally published in 2002 (BTAC 2002) was revised in 2006 (BTAC 2006), and the original roadmap report (BTAC 2003) was revised in 2007 (BTAC 2007). An update to the study of Perlack et al. (2005) is forthcoming and is expected to contain improved estimates for sustainable production, as well as greater spatial resolution (Stokes and Perlack 2010). Until this report is released, the original study provides the best available information for examining future nutrient needs. As shown in Table 1, biomass grown on agricultural lands, when combined with secondary and tertiary residues from corn production, manure, fats and greases, and municipal waste, is capable of nearly meeting the billion ton biomass goal in its entirety.

The objectives of this paper were as follows: (1) calculate feedstock nutrient demand of one bdty biomass production, (2) compare current fertilizer production and capacity to those in the future, considering the projected nutrient demand, and (3) examine the potential of cellulosic end products as secondary nutrient sources for redistribution to feedstock production areas.

Materials and Methods

The approach chosen as a first approximation for estimating nutrient needs in 2030 was to calculate removal of nutrients by crop harvest. Perlack et al. (2005) reported production of all crops on a dry matter basis (0% moisture). For the calculations, the term “residue” in that publication was interpreted as meaning straw or stover for grain crops, stalks for cotton, and as the entire above-ground, harvested plant portion for all other crops. Available nutrient removal rates used in nutrient management planning are often reported on a wet basis and assume some unspecified, normally observed amount of moisture present in the crop at harvest. In such cases, it was necessary to make some assumptions about the moisture levels present in crops at harvest.

Moisture Content Estimates

Estimates of common moisture contents of harvested crop portions were compiled into Table 2, along with the associated references. These are all calculated on a wet weight basis (weight of water per weight of wet residue). Moisture contents for most harvested crop portions were found in Koelsch et al. (2004) and Hirning et al. (1987). Crops not listed in those sources are discussed below.

	Residue			Grain or lint				
Crop	Harvest unit	Moisture content	Moisture ref.	Harvest unit	Moisture content	Moisture ref.	Grain test weight	Grain test weight ref.
		(%)			(%)		(lb bu^{-1})	
corn	wet ton	15	Koelsch et al. 2004	bu	15.5	Hirning et al. 1987	56	US Gov. 1985
sorghum	wet ton	20	Koelsch et al. 2004	bu	14.0	Hirning et al. 1987	55	US Gov. 1985
barley	wet ton	10	Koelsch et al. 2004	bu	14.5	Hirning et al. 1987	48	US Gov. 1985
oats	wet ton	10	Koelsch et al. 2004	bu	14.0	Hirning et al. 1987	32	US Gov. 1985
wheat-winter	wet ton	10	Koelsch et al. 2004	bu	13.5	Hirning et al. 1987	60	US Gov. 1985
wheat-spring	wet ton	10	Koelsch et al. 2004	bu	13.5	Hirning et al. 1987	60	US Gov. 1985
soybeans	wet ton	10	Van Pelt 2003	bu	13.0	Hirning et al. 1987	60	US Gov. 1985
rice	dry ton	0	—	bu	12.0	Slaton et al. 2003	45	US Gov. 1985
cotton lint	wet ton	10	El Saeidy et al. 2003	500 lb	6.50	Valco et al. 2004	—	—
grasses (CRP)*	wet ton	15	Koelsch et al. 2004	—	—	—	—	—
trees (CRP)	dry ton	0	—	—	—	—	—	—
wood fiber	dry ton	0	—	—	—	—	—	—
perennial forages†	wet ton	15	Koelsch et al. 2004	—	—	—	—	—

Table 2-Harvest units and estimated moisture contents of harvested crop portions listed in Perlack et al. (2005).
*Entry for “all hay” was used in Koelsch et al. 2004. †Entry for “switchgrass” was used in Koelsch et al. 2004

Soybean straw moisture of approximately 10% came from Van Pelt (2003). In that study, soybean residue was collected after harvest. Five samples were taken and the average moisture content was 9.7%, with a range of 7.6-11.3%. The 9.7% average was rounded to 10%.

For cotton, moisture of lint was estimated from Valco et al. (2004) which stated that "…the moisture contents for seed cotton cleaning and ginning cotton is best at 6 to 7 percent moisture content (wet basis)…." The average, 6.5%, was used for cotton lint. For cotton stalks, an estimate of approximately 10% moisture was taken from El Saeidy et al. (2003). In that reference, approximately 10% moisture was considered optimal for combustion uses of cotton stalks. In an assessment of the use of cotton stalks as an energy source in Turkey, Akdeniz et al. (2004) assumed a 20% moisture content for cotton stalks. In the study by El Saeidy et al. (2003), a temporal analyses of stalk moisture content after harvest showed that 7 days after harvest, stalk moisture content dropped quickly from approximately 65% to nearly 10% when the cut stalks were left in the field. Consequently, the moisture content of cotton stalks depends greatly on the timing of cutting and collection, as well as upon the environmental conditions present at that time. The 10% moisture level was chosen for the calculations in this paper; however, it must be noted that the supporting data come from climates more arid than those of many of the U.S. cotton producing areas.

The moisture content of a bushel of rice grain was taken from Slaton et al. (2003). In that publication, grain yields were reported on the basis of a 12% moisture level, which was interpreted as being a standard value.

Some of the categories of crops listed by Perlack et al. (2005) were too vague to be associated with a moisture estimate, specifically "other crops" and "double crops." Consequently, these two categories were omitted from the analysis. For the nondescript category "grasses (CRP)" moisture for "all hay" (15%) was taken from Koelsch et al. (2004).

The moisture for the "perennial" category was derived from information in Perlack et al. (2005). In that paper, perennials were projected to be grown on 60 million acres in 2030. Table B.6 in that publication divided 60 million acres into 5 million allocated to wood fiber and 55 million to "perennials." The perennials mentioned in the report were woody species and switchgrass. Since the woody species would have been allocated to the wood fiber category, it seemed logical that switchgrass comprised the perennial category. Consequently, data for switchgrass were used (Koelsch et al. 2004).

Nutrient Removal Rate Estimates

The majority of nutrient removal rates, listed under the headings "Residue nutrient content" (Table 3) and "Grain or lint nutrient content" (Table 4) were found using the Nutrient Uptake and Removal Database (NURD), which is an evolving collection of published estimates, primarily from University Extension (IPNI, 2010). Removal rates originating from this source are listed in Tables 3 and 4 except where noted. When using NURD, all states were selected for which publications were available and their average removal rate was recorded. Sources of nutrient removal information for crop portions not available in NURD are discussed below.

Crop	Harvest unit	Residue nutrient content N	P_2O_5	K_2O	Dry residue nutrient content N	P_2O_5	K_2O
		--------- (lb (harvest unit)$^{-1}$) --------			---------- (lb (dry ton)$^{-1}$) --------		
corn	wet ton	20	7.3	35	23.5	8.6	41.2
sorghum	wet ton	24	9.4	52	30	11.8	65
barley	wet ton	14	4.0	36	15.6	4.4	40
oats	wet ton	13	5.3	42	14.4	5.9	46.7
wheat-winter	wet ton	13	3.2	26	14.4	3.6	28.9
wheat-spring	wet ton	13	3.2	26	14.4	3.6	28.9
soybeans	wet ton	32	6.6	27	35.6	7.3	30
rice*	dry ton	13	4.3	34	13	4.3	34
cotton lint	wet ton	35	4.0	30	38.9	4.4	33.3
grasses (CRP)‡	wet ton	38	14	47	44.7	16.5	55.3
trees (CRP)§	dry ton	7.9	1.1	3.6	7.9	1.1	3.6
wood fiber§	dry ton	7.9	1.1	3.6	7.9	1.1	3.6
perennial forages**	wet ton	21.8	9.3	66	25.6	10.9	77.6

Table 3-Nutrient contents (IPNI, 2010) of crop residues considered by Perlack et al. (2005). Data originated from NURD (IPNI, 2010) unless otherwise noted. *Dobermann and Fairhurst 2002. ‡Estimated from "fescue" in NURD. §Tharakan et al. 2003. **NURD data for switchgrass.

Nitrogen removal data for corn grain in NURD were too high to reflect levels being reported in other sources. The average in the database was 0.84 lb N bu^{-1}, but 0.7 is an average of recent reports (Clark et al. 2001; Ma et al. 2006; Preston 2006; Roozeboom and Herrman 2001; Stock et al. 1995). Consequently, 0.7 lb N bu^{-1} was used (Table 4).

To calculate nutrient removals for the feedstock sources in Table 1, the biomass production data in that Table were multiplied by their respective nutrient removal estimates in Tables 3 and 4 and reported in units of million tons of N, P_2O_5, or K_2O per year in Tables 5, 6, and 7, respectively.

Crop	Harvest unit	Grain or lint nutrient content N	P_2O_5	K_2O	Dry grain or lint nutrient content N	P_2O_5	K_2O
		----------- (lb (harvest unit)$^{-1}$) -------			------------ (lb (dry ton)$^{-1}$) ------------		
corn	bu	0.7*	0.40	0.28	29.6	16.9	11.8
sorghum	bu	0.84	0.42	0.35	35.5	17.8	14.8
barley	bu	0.94	0.42	0.52	45.8	20.5	25.3
oats	bu	0.7	0.34	0.39	50.9	24.7	28.3
wheat-winter	bu	1.3	0.57	0.34	50.1	22	13.1
wheat-spring	bu	1.3	0.57	0.34	50.1	22	13.1
soybeans	bu	3.6	0.82	1.3	137.9	31.4	49.8
rice	bu	0.56	0.29	0.17	28.3	14.6	8.6
cotton lint	500 lb	32	14	19	136.9	59.9	81.3

Table 4-Nutrient contents (IPNI, 2010) of crop grains considered by Perlack et al. (2005). Data originated from NURD (IPNI, 2010) unless otherwise noted. *Average of data reported in Clark et al. 2001; Ma et al. 2006; Preston 2006; Roozeboom and Herrman 2001; Stock et al. 1995

No NURD entry existed for rice straw in Table 3. Dobermann and Fairhurst (2002) in Table 1 of their publication provided ranges of nutrient content for rice straw on a dry matter basis. The midpoint of each range listed in that table was used, and the dry matter basis kept (Tables 2 and 3).

For the "grasses (CRP)" category, the estimated nutrient content came from NURD data for "fescue."

The "trees (CRP)" and "wood fiber" categories were assumed to be wood fiber coming from willow and hybrid poplar. Nutrient contents in these species came from Tharakan et al. (2003). Nutrient contents (Table 3) were calculated by averaging the average willow and poplar concentrations in that publication, which were reported on a dry matter basis, so 0% moisture was also used (Table 2).

Nutrient content for "perennials" came from NURD entries for switchgrass, following the same logic described above when determining moisture for this crop category.

Nutrient removal estimates based on various harvest units described above were converted to a common basis of a dry ton, using the data in Table 2, to match production units in Perlack et al. (2005). These converted estimates are listed under "Dry residue nutrient content" in Table 3 and "Dry grain or lint nutrient content" in Table 4.

To calculate nutrient removals for the feedstock sources in Table 1, the biomass production data in that Table were multiplied by their respective nutrient removal estimates in Tables 3 and 4 and reported in units of million tons of N, P_2O_5, or K_2O per year in Tables 5, 6, and 7, respectively.

	Residue N removal			Grain or lint N removal			Total removal	
Crop	2001	2030	change	2001	2030	change	2001	2030
	(million tons N yr^{-1})							
corn	0.8789	3.0092	2.1303	0.1998	1.107	0.9072	1.0787	4.1162
sorghum	0	0.06	0.06	0.0089	0.0497	0.0408	0.0089	0.1097
barley	0.0055	0.0367	0.0312	0.0046	0.0435	0.0389	0.0101	0.0802
oats	0.0007	0.0086	0.0079	0	0	0	0.0007	0.0086
wheat-winter	0.0634	0.2945	0.2311	0.005	0	-0.005	0.0684	0.2945
wheat-spring	0.0158	0.0785	0.0627	0	0	0	0.0158	0.0785
soybeans	0	0.8526	0.8526	0.0138	0	-0.0138	0.0138	0.8526
rice	0.0371	0.0956	0.0585	0	0	0	0.0371	0.0956
cotton lint	0.0525	0.1731	0.1206	0	0	0	0.0525	0.1731
grasses (CRP)	0	0.3442	0.3442	0	0	0	0	0.3442
trees (CRP)	0	0.0087	0.0087	0	0	0	0	0.0087
wood fiber	0.0008	0.0363	0.0355	0	0	0	0.0008	0.0363
perennial forages	0	4.7142	4.7142	0	0	0	0	4.7142
Total	**1.05**	**9.71**	**8.66**	**0.232**	**1.20**	**0.968**	**1.29**	**10.9**
Percent of 2001 usage	**9.77**	**89.9**	**80.2**	**2.15**	**11.1**	**8.96**	**11.9**	**101**

Table 5-Estimated N removed by the biomass projected to be harvested from agricultural land to reach the one bdty goal by 2030 (Perlack et al. 2005). Note: 2001 usage was 10.7997 mt N.

Calculating Future Nutrient Supply and Capacity

The sustainable supply of N, P, and K needed to support a multi-billion gallon biofuel industry was assumed to come from countries in the Western hemisphere, since most of the current imports are from those countries.

For N, Trinidad and Tobago were considered the primary reliable N production sources for U.S. consumption. Nitrogen production in Canada is limited, and its production capacity is declining. The historical trend of N consumption in the U.S. from 1999 to 2008 was used to estimate U.S. N consumption, as well as U.S., Trinidad and Tobago production in 2030. The 2013 N production capacities of the U.S, Trinidad and Tobago projected by the International Fertilizer Development Center (IFDC) were used for 2030. Differences between production capacity and actual production represent capacity that could be used for production of biofuels.

Like N, estimates of P consumption in 2030 were based on U.S. P consumption from 1999 to 2008. Similarly, estimates of P production in 2030 were estimated from U.S. production during 1999 to 2008. The IFDC's projected P production capacity for 2013 was used for 2030. Both phosphate production and consumption were limited by U.S. production capacity. Production exceeding consumption was considered available for export or other industrial uses. When U.S. consumption increased, P exports were assumed to decrease, due to the competitive advantage of domestic consumption.

Canada was considered the primary, reliable source for supplying U.S. potash (K_2O) consumption. Trends in U.S. K_2O consumption from 1999-2008 were used to estimate 2030 consumption. IFDC's K_2O production capacities for 2013 were used for 2030. Differences between U.S. and Canada's production and U.S. consumption were considered available for other uses, primarily Canada's export of potash to other countries.

Results and Discussion

Estimated Nutrient Removal of 1bdty Annual Crop Production in 2030

Estimated nutrient removals of N, P_2O_5, and K_2O for the one bdty biomass production projected for 2030 (Perlack et al. 2005) are given in Tables 5, 6, and 7, respectively. For all nutrients, 2001 was selected as the year against which to measure changes in nutrient use. This year was chosen to match the baseline year of Perlack et al. (2005).

Total N removal by crop residue, grain, and lint in 2030 was estimated to be approximately 10.9 million tons (mt), which is nearly 8.4 times that in 2001 and represents 101% of the total N fertilizer use in 2001 (Table 5). Crop removal of N in 2001 represented 11.9% of total N use that year.

Crop removal of P_2O_5 in 2030 was estimated to be approximately 4.27 mt, nearly 8.8 times the 0.488 mt removal in 2001 (Table 6). Removal of P_2O_5 in 2001 represented 11.5% of the P fertilizer use in 2001, while the projected removal in 2030 represented 101%.

	Residue P_2O_5 removal			Grain or lint P_2O_5 removal			Total removal	
Crop	2001	2030	change	2001	2030	change	2001	2030
	(million tons P_2O_5 yr^{-1})							
corn	0.3216	1.1012	0.7796	0.1141	0.6321	0.518	0.4357	1.7333
sorghum	0	0.0236	0.0236	0.0045	0.0249	0.0204	0.0045	0.0485
barley	0.0015	0.0103	0.0088	0.0021	0.0195	0.0174	0.0036	0.0298
oats	0.0003	0.0035	0.0032	0	0	0	0.0003	0.0035
wheat-winter	0.0158	0.0736	0.0578	0.0022	0	-0.0022	0.018	0.0736
wheat-spring	0.004	0.0196	0.0156	0	0	0	0.004	0.0196
soybeans	0	0.1748	0.1748	0.0031	0	-0.0031	0.0031	0.1748
rice	0.0123	0.0316	0.0193	0	0	0	0.0123	0.0316
cotton lint	0.0059	0.0196	0.0137	0	0	0	0.0059	0.0196
grasses (CRP)	0	0.1271	0.1271	0	0	0	0	0.1271
trees (CRP)	0	0.0012	0.0012	0	0	0	0	0.0012
wood fiber	0.0001	0.0051	0.005	0	0	0	0.0001	0.0051
perennial forages	0	2.0072	2.0072	0	0	0	0	2.0072
Total	**0.362**	**3.60**	**3.24**	**0.126**	**0.677**	**0.551**	**0.488**	**4.27**
Percent of 2001 usage	**8.53**	**84.9**	**76.4**	**2.97**	**16.0**	**13.0**	**11.5**	**101**

Table 6-Estimated P_2O_5 removed by the biomass projected to be harvested from agricultural land to reach the one bdty goal by 2030 (Perlack et al. 2005). Note: 2001 usage was 4.2382 mt P_2O_5.

Potassium removal exhibited the largest change of the three nutrients. Removal in 2001 by the crops in Table 7 totaled 1.95 mt K_2O and represented 39.8% of the fertilizer use that year. Projected crop removal in 2030 was 22.6 mt, which was an increase of 11.6 times that of 2001 and represents approximately 461% of the fertilizer use in 2001.

	Residue K_2O removal			Grain or lint K_2O removal			Total removal	
Crop	2001	2030	change	2001	2030	change	2001	2030
	(million tons K_2O yr^{-1})							
corn	1.5409	5.2757	3.7348	0.0797	0.4413	0.3616	1.6206	5.717
sorghum	0	0.13	0.13	0.0037	0.0207	0.017	0.0037	0.1507
barley	0.014	0.094	0.08	0.0025	0.024	0.0215	0.0165	0.118
oats	0.0023	0.028	0.0257	0	0	0	0.0023	0.028
wheat-winter	0.1272	0.591	0.4638	0.0013	0	-0.0013	0.1285	0.591
wheat-spring	0.0318	0.1575	0.1257	0	0	0	0.0318	0.1575
soybeans	0	0.7185	0.7185	0.005	0	-0.005	0.005	0.7185
rice	0.0969	0.2499	0.153	0	0	0	0.0969	0.2499
cotton lint	0.045	0.1482	0.1032	0	0	0	0.045	0.1482
grasses (CRP)	0	0.4258	0.4258	0	0	0	0	0.4258
trees (CRP)	0	0.004	0.004	0	0	0	0	0.004
wood fiber	0.0004	0.0166	0.0162	0	0	0	0.0004	0.0166
perennial forages	0	14.29	14.29	0	0	0	0	14.29
Total	**1.86**	**22.1**	**20.3**	**0.0922**	**0.486**	**0.394**	**1.95**	**22.6**
Percent of 2001 usage	**37.9**	**451**	**413**	**1.88**	**9.90**	**8.03**	**39.8**	**461**

Table 7-Estimated K_2O removed by the biomass projected to be harvested from agricultural land to reach the one bdty goal by 2030 (Perlack et al. 2005). Note: 2001 usage was 4.9071 mt K_2O.

These projections indicate that producing one bdty of biomass for the targeted crops will increase nutrient removal by 8.4 to 11.6 times, depending upon the nutrient. Most of these increases are coming from corn stover and harvests of perennials.

Accuracy of Nutrient Removal Estimates*:* A Corn Stover Example

Nutrient removal coefficients used in Tables 3 and 4 were taken from values published in University Extension guidelines. Growth stages represented by these coefficients are not normally stated. For grain, it may be assumed that nutrient concentrations are those present at harvest, when a grain sample is typically collected. However, for the remaining vegetative portion of grain crops, such as corn stover, nutrient concentration data likely come from samples taken at physiological maturity, rather than at harvest. Nutrient content differences between physiological maturity and harvest can be quite large for residues of grain crops, as illustrated below for corn stover.

Extension publications likely contain corn stover nutrient estimates reflective of physiological maturity. Sawyer et al. (2002) explicitly state that the stover nutrient removal coefficients reflected nutrient content at maturity. The P and K content in corn stover in this publication, after being adjusted to the 15% moisture generally assumed present in stover at harvest (Koelsch et al. 2004), was in the lowest quartile of surveyed P and K contents in Extension publications (Table 8). Consequently, it may be inferred that other Extension publications, which typically have even higher estimated nutrient contents, represent conditions at physiological maturity.

		Corn stover at 15% moisture		
Reference	State	N	P_2O_5	K_2O
		(lb ton^{-1})		
Mitchell 1999	AL	15.7	6.5	41.7
Sawyer et al. 2008	IA	—	5.1	21.7
Franzen and Gerwing 1997	Regional	22.4	8.0	32.0
Murdock 2001	KY	12.2	6.1	25.2
Warncke et al. 2004	MI	22.0	8.2	32.0
Oldham 2001	MS	19.1	7.0	27.8
Jacobsen et al. 2003	MT	19.8	8.8	40.0
Zublena 1991	NC	22.2	8.2	32.2
Koelsch et al. 2004	NE	17.7	3.5	—
Stichler and McFarland 2001	TX	15.2	6.5	41.7
75% quartile		22.1	8.2	40.9
50% median		19.1	6.8	32.0
25% quartile		15.5	5.9	26.5

Table 8-Nutrient removal coefficients for corn stover published in university Extension guidelines, adjusted to a consistent moisture basis of 15% when moisture contents were reported.

Because corn is typically harvested a few weeks after physiological maturity to allow the grain time to dry in the field, nutrients, particularly K, can be lost from the standing crop in the interim. Data on nutrient loss during this period are sparse to non-existent in the published literature. To gain insight into this area, nutrient concentration data from on-going, recent studies in Iowa that are examining co-harvesting of stover with grain (Kovar and Karlen, 2010) were compared to the published estimates in Table 8 and are presented in Figure 1. This figure uses box plots to represent the distributions of values for N, P, and K from both data sources. Generally, published estimates of nutrient contents of stover were higher than those currently being measured at harvest. In particular, N and K content observed in harvested stover was approximately half of the content reported in Extension publications. Phosphorus content was nearly a quarter of the Extension publication estimates. If the lower, observed median concentrations were used rather than published estimates, N, P_2O_5, and K_2O removal would be reduced by 0.48, 0.24, and 0.79 mt respectively, for 2001 and by 1.65, 0.83, and 2.71 mt respectively for 2030 (Tables 5, 6, and 7).

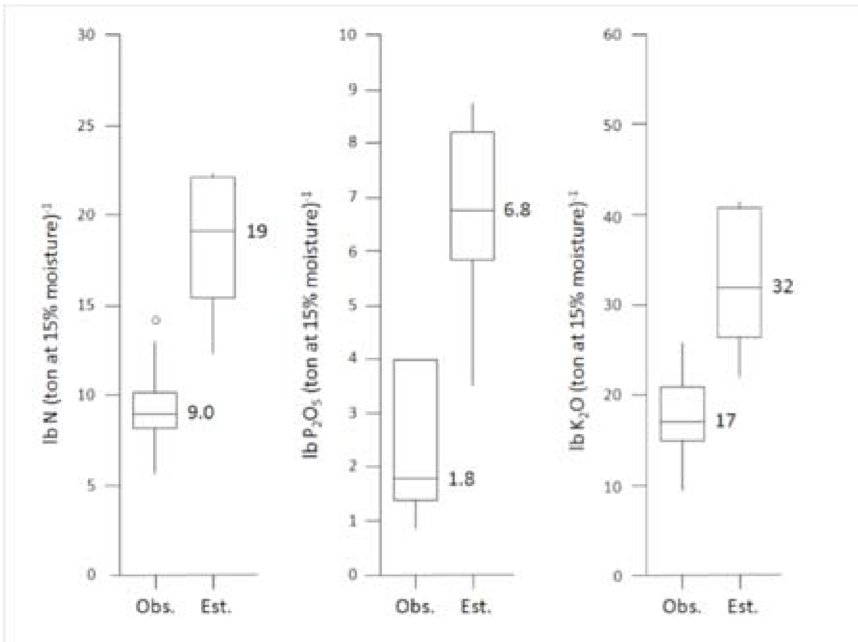

Figure 1. Box plots with labeled medians that compare distributions of observed nutrient removals in corn grain stover (Obs., n=109) to distributions of published nutrient removal coefficients in Table 8 (Est., n=9 for N and K_2O; n=10 for P_2O_5).

This example for corn stover indicates that marked differences can exist between estimated and observed nutrient removal. For grain crops, it is expected that these disparities are greater for stover than for grain, since grain is typically sampled at harvest. As stover becomes more of a marketable commodity to the biofuel industry, there will be a greater need to ensure accurate estimates of removal exist. Until more data are collected and summarized, it may be possible that the removal estimates in Tables 5, 6, and 7 are several times too high for some crop portions listed. If perennials have similar disparities, actual total nutrient removals could be much less than those predicted.

Nutrient Removal as an Estimate of Nutrient Demand

In Tables 5, 6, and 7, nutrient removal changes from 2001 to 2030 provide some indication of possible increases in nutrient demand. However, there can be a significant difference between the recommended rates of nutrients for a particular crop and the quantities of nutrients removed by harvesting that crop. Nutrient recommendations, rather than crop removal, are the primary driver for nutrient use. Consequently, translating nutrient removal to nutrient demand is not direct.

For P and K, recommended rates of nutrients are based on soil test levels. In addition, soil test calibration and correlation data are based on relative grain yields, not relative grain and residue yields. Lower soil test levels reflect lower soil reserves and lead to greater recommended rates. In the lower range of soil test levels, recommended rates often exceed crop removal rates, while at higher soil test levels, rates are less than removal and eventually go to zero. Consequently, whether or not a recommended rate equals a crop removal rate depends greatly on the soil test levels measured for a given unit of land.

Recommended rates of P and K also depend upon the management philosophy of the scientists creating them. The two most extreme philosophies are "build and maintenance" and "sufficiency." In the build and maintenance approach, the primary risk being avoided is poor soil fertility. Fertilizer is applied at rates in excess of crop removal in order to build fertility to levels where no reduction in crop yield would be expected if an annual fertilizer application was omitted. In the sufficiency philosophy, the primary risk being avoided is annual profit loss. Soil reserves are intentionally kept deficient in order to ensure profitable crop responses to fertilizers in the season for which they were applied. Consequently, across lower soil test levels, the build and maintenance philosophy will typically recommend larger amounts of P and K than will the sufficiency philosophy. Additionally, the build and maintenance philosophy has an extended upper range of soil test levels for which rates are nonzero. Across the country, many states have adopted one philosophy or other, and many others have created hybrids of the two. Ideally, estimates of nutrient demand would account for these differences in recommendation philosophy as well as the soil fertility differences across the country.

In the long term, application rates of P and K that are equivalent to crop removal rates are expected to maintain existing soil nutrient supplies (Syers et al. 2008). Therefore, for these nutrients, crop removal rates serve as a reasonable estimate of the nutrient application rates needed to sustain soil fertility in the long term, which is an important aspect of sustainable crop production. Temporal fluctuations around these nutrient use levels are expected, however, because P and K can be available for many years after an application. When market conditions favor capital investments in these nutrients, much more may be purchased than needed to keep up with crop removal for a given crop or rotation. Such applications build soil reserves that can be drawn upon in the future, allowing applications and purchases to be reduced or omitted under unfavorable market conditions. When only production data are available, as is the case in Perlack et al. (2005), crop removal estimates are the only metric that can be used as a proxy for nutrient demand.

Like P and K, crop removal of N provides a convenient and easily calculable estimate of nutrient demand. However, because N does not have nearly the residual value to future crops as P and K, it must be applied to every crop requiring it. There can be significant differences between crop removal of N and the amount of N recommended for profitable crop production. Many factors enter into N recommendation algorithms and they differ among states. Some commonly used factors are previous crop, yield goal, manure history, soil texture, soil organic matter, crop price, and N cost.

To investigate how large the disparity might be between crop removal estimates of N and recommended N rates, algorithms from 22 states in the Mississippi River Basin were examined for continuous corn (C/C) and corn grown in rotation with soybean (C/S). To compare recommendations for various states, a static set of conditions was created that accounted for all factors present in the various recommendation algorithms. These conditions were: silt loam soil with 2% organic matter, corn planted at 32,000 plants acre^{-1}, a nutrient:crop price ratio of 0.1, no manure history, 5 mg kg^{-1} soil NO_3-N in the upper 2 ft., a pre-sidedress N soil test (PSNT) of 10 mg kg^{-1} for corn following soybean and 3 mg kg^{-1} for corn following corn, conservation tillage, irrigation water with 5 mg kg^{-1} NO_3-N, and a previous soybean yield of 40 bu acre^{-1} (for corn following soybean rotation only). Keeping these conditions constant allowed rates to be generated and a sample population of N recommendations constructed for all states for the two yield levels considered by Perlack et al. (2005): 138 bu acre^{-1} for the 2001 baseline yield and 207 bu acre^{-1} for the Scenario 3 corn grain yield included as part of the one bdty biomass production system.

When comparing N recommended to N removed, total N removal (grain + stover) needed to be considered. Perlack et al. (2005) considered logistically possible, sustainable stover harvest to be 33% for the 138 bu acre^{-1} yield in 2001 and 68% for the 207 bu acre^{-1} yield in 2030. Using the 1:1 residue to grain dry matter production ratio used by Perlack et al. (2005), a corn plant would be assumed to produce 0.024 tons stover dry matter for each bushel of grain. On a 15% moisture basis, this stover production rate is 0.027 wet tons of stover. For the 2001 baseline scenario in Perlack et al. (2005), the 33% stover removal resulted in 0.009 wet tons of stover removed for every bushel produced. Similarly, the 68% stover removal predicted for 2030 would remove 0.019 wet tons of stover for every bushel. Multiplying these stover removal tonnages by the published nutrient removal estimate of 20 lb N (wet ton)$^{-1}$ in Table 3 and adding the estimate of 0.7 lb N bu^{-1} led to calculated total (stover + grain) removals of 0.88 lb N bu^{-1} for the 138 bu acre^{-1} yield level of 2001 and 1.07 lb N bu^{-1} for the 207 bu acre^{-1} yield predicted for 2030. These total removal rates were compared to the recommended N rates described above using the ratio of total N removed:N recommended (%). These calculations were performed for both yield levels under C/S and C/C rotation systems.

Figure 2 shows the distribution of total N removed:N recommended (%) for all four combinations of rotation and yield level. At the lower yield level and associated lower stover removal percent, median estimated crop removals for both rotations were less than the median level of recommended N, -7% for C/S and-23% for C/C. The difference was greater for C/C because of the higher rate of N typically applied in this rotation. Many recommendations for C/S included a "N credit" for the previous soybean crop that was subtracted from the recommended rate, reducing it below the N recommended for C/C. The median ratio across both rotations was 83% (not shown). Therefore, it is possible that actual N usage for corn production in 2001 was 0.08 to 0.25 mt higher than the 1.08 mt estimated from removal. In the 2030 estimates, the higher yield level combined with a greater percent stover removal resulted in N removal exceeding N recommendations by 26% and 11% for C/S and C/C, respectively. The lower percentage for C/C reflected the higher rates of recommended N in the rotation. Across both rotations, the median ratio was 120% (not shown). Therefore, actual N use could be 0.45 to 1.1 mt lower than the 4.12 mt estimated from nutrient removal for 2030.

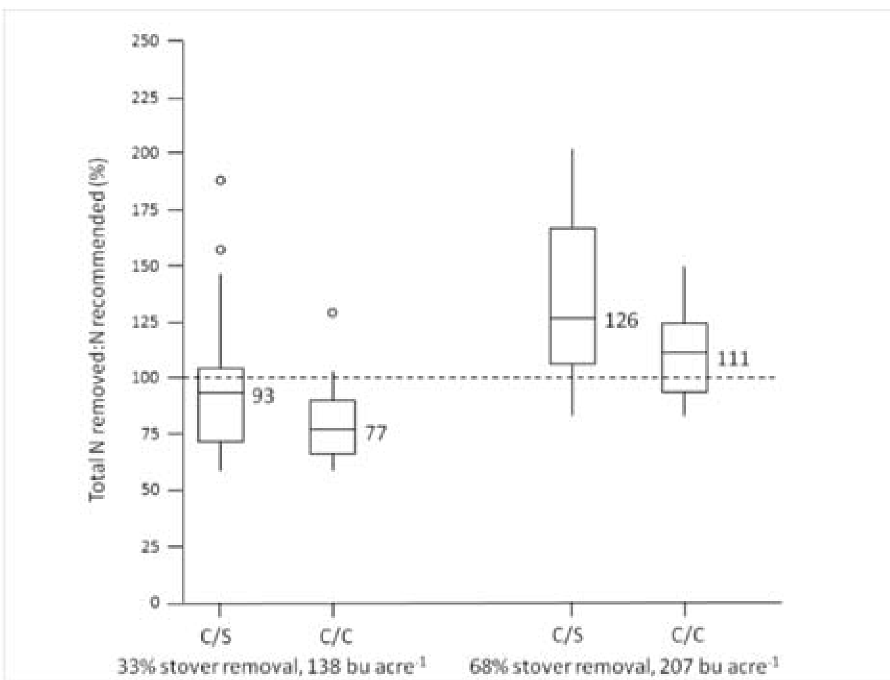

Figure 2. Box plots of the distributions of ratios of total N removed:N recommended for corn for 22 states in the Mississippi River Basin, using yields of 138 bu acre^{-1} with 33% stover removal (the 2001 baseline yield in Perlack et al. 2005) and 207 bu acre^{-1} with 68% stover removal (the yield associated with attaining one bdty biomass in Perlack et al. 2005). Both a corn/soybean rotation (C/S) and a continuous corn (C/C) rotation were considered for each yield level.

Future Fertilizer Production and Capacity

Fertilizer production and production capacity in the U.S. have been declining or stagnant since 1999. Currently, the industry is not equipped to meet a surge in demand and increasingly depends on global trade.

From 1999 to 2008, annual production capacity of nitrogen declined 42%, and annual production declined 37% (Figure 3). In 2005, U.S. production capacity fell below U.S. consumption and has remained there since. The share of U.S. N supply attributed to imports increased during 1999-2008 from 12 to 52%. Trinidad, Tobago, and Canada are the major N suppliers to the U.S. Projecting N consumption from 1999-2008 resulted in an estimated consumption of 14.13 mt N in 2030, assuming an annual, linear increase of 0.07 mt N yr^{-1}. The estimated N removal of total biomass in Table 5 is 10.9 mt, which is equivalent to 77% of the 2030 consumption estimated from historical trends. As a comparison, the 1.29 mt of crop removal in Table 5 represented only 11.9% of 2001 N consumption. Consequently, it is possible that N demand in 2030 could exceed U.S., Trinidad, and Tobago capacity estimated from historical trends; however, U.S. production could increase in the future if market conditions became favorable.

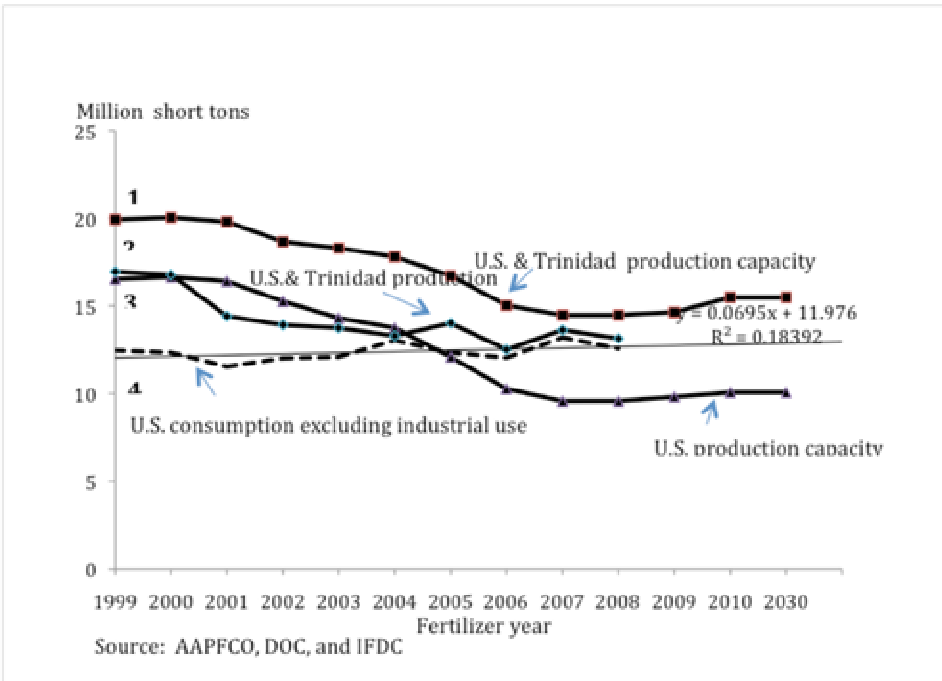

Figure 3. U.S. nitrogen consumption, production capacity, and production as well as combined U.S., Trinidad and Tobago nitrogen production capacity and production. Data sources: American Association of Plant Food Control Officials (AAPFCO), Department of Commerce (DOC) and the International Fertilizer Development Center (IFDC). The x in regression equations denotes the number of years since 1999.

Phosphate production capacity was limited to U.S. sources because the U.S. is the major producer of phosphate fertilizer in the world. During 1999-2008, annual production of phosphate declined 13% while production capacity decreased 23% (Figure 4). Export of diammonium phosphate (DAP) declined from 48% of production in 1999 to 34% of production in 2008 with about 54% of U.S. DAP exports going to India. Based on historical trends, consumption in 2030 is estimated to be 4.98 mt, assuming an annual increase of 0.02 mt yr^{-1}. Historically, there has been a wide margin between production capacity and consumption. If the projected 3.782 mt increase in phosphate removal in 2030 (Table 6) were simply added to the 2001 U.S. consumption, the resulting total of 8.02 mt phosphate is still below projected production capacity in 2030. Historical trends indicate that more phosphate will likely be consumed domestically if one bdty of biomass is produced, leaving less available for export.

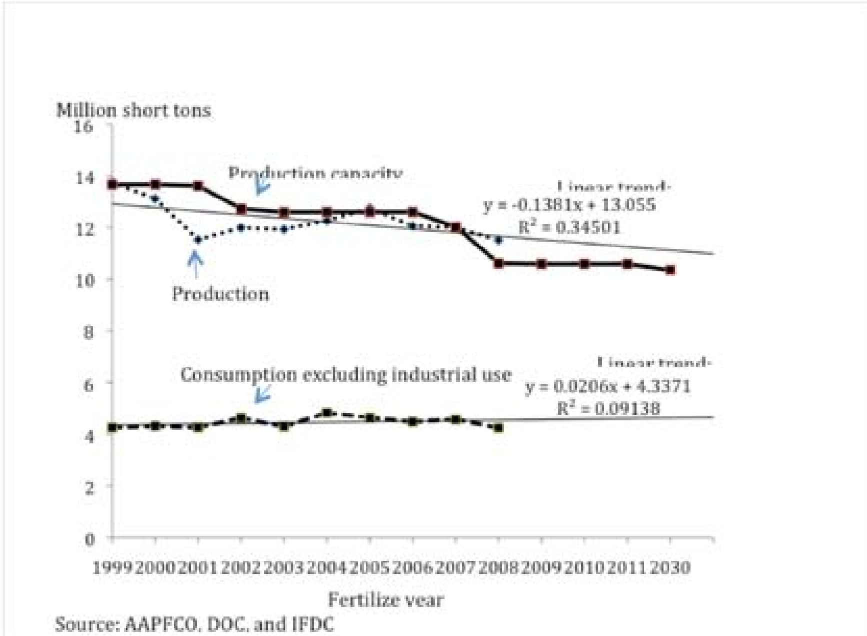

Figure 4. U.S. phosphate consumption, production capacity, and production. Data sources: American Association of Plant Food Control Officials (AAPFCO), Department of Commerce (DOC) and the International Fertilizer Development Center (IFDC). The x in regression equations denotes the number of years since 1999.

The U.S. is the largest importer of potash fertilizer in the world because U.S. production capacity is several million tons below consumption (Figure 5). During 1999-2008, the share of U.S. potash supply from imports increased from 80 to 85%. Canada's production and production capacity continue to increase. Projected U.S. consumption in 2030, based solely on historical trends, is estimated to be 5.05 mt in 2030 compared to 4.91 mt in 2001. However, if the 20.65 mt increase in K_2O removal in Table 7 was simply added to the 4.907 mt of K_2O consumed in 2001, total consumption in 2030 would be 25.6 mt, exceeding the combined capacity of U.S. and Canada.

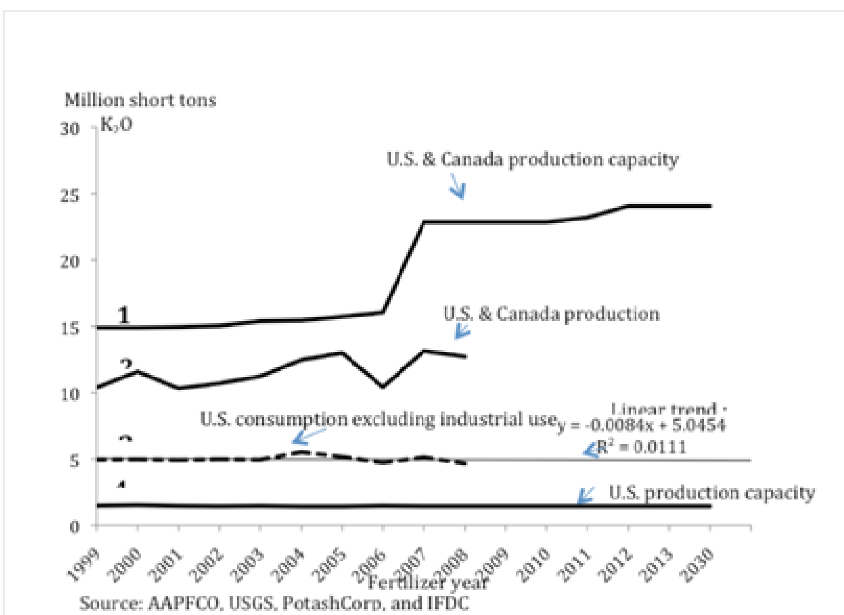

Figure 5. U.S. potash consumption and production capacity as well as U.S. and Canadian production and production capacity. Data sources: American Association of Plant Food Control Officials (AAPFCO), United States Geological Survey (USGS), PotashCorp, and the International Fertilizer Development Center (IFDC). The x in regression equations denotes the number of years since 1999.

It must be remembered that in Tables 5, 6, and 7, the increases in nutrient removal are coming from corn stover and perennial forages harvested as bioenergy feedstocks. Actual nutrient removal by corn stover has been shown to be much lower than published estimates. If perennial forages are analogous, K removal increases in 2030 would be well within projected, future production capacities for Canada.

End Products of Biofuel Production as Secondary Nutrient Sources

Sustainable nutrient management for biofuel production must consider the potential of biofuel production end products and byproducts as secondary nutrient sources. Effectively recycling nutrients from biofuel production facilities back into biomass production fields will reduce the need for supplemental fertilizers. As shown in Tables 5, 6, and 7, perennials and corn stover used as feedstocks for cellulosic ethanol production represent the largest increases in nutrient removal.

Cellulosic biomass contains cellulose, hemicelluloses, and lignin, as well as minerals, oils, proteins, and other potentially valuable compounds. During the pretreatment and fermentation processes, the cellulose and hemicelluloses are converted first to sugars, then to ethanol. Lignin and other compounds present in the original feedstock often remain relatively unchanged (Lynd, 1996). Rather than returning these materials directly to the land from which the feedstock was harvested, current cellulosic process designs call for capturing the protein for use in animal feed (depending on the feedstock), and burning the non-fermentable lignin to provide energy to support the operations of the ethanol plant (Huang at al., 2009). In some cases, excess electricity would be exported to the local power grid. Under this scenario, combustion residuals, such as fly ash, would be the likely end product returned to agricultural lands.

The value of combustion residuals as secondary nutrient sources is difficult to estimate. Little information is available on how the pretreatment and fermentation processes affect the combustion and emission characteristics of the lignin-rich residuals (Yang and Wyman, 2008). Up to this point, most of the studies addressing the chemical composition of combustion products have focused on biomass fuels or co-firing biomass materials with coal for power generation (Miles et al., 1996). Depending on the source material, the combustion ash often has significant amounts of silica, calcium, potassium, and water soluble alkali (Na_2O + K_2O). It may be that application of ash byproducts will help ease the demand for potash in the future.

As cellulosic ethanol plants move from testing to production, it will be important to determine how best to recapture nutrients for their recycling back to the cropland supplying the feedstocks.

Summary and Conclusions

The estimated one bdty biomass production needed to reach biofuel and bioenergy production goals will result in significant increases in quantities of nutrients removed from arable land. Estimates based on published nutrient removal rates indicate that increases could be 8.4 to 11.6 times the nutrient removal of the baseline year of 2001. Much of these projected increases come from harvests of corn stover and perennial forages. However, these nutrient removal estimates need to be tempered by improved estimates of removal, which could be much lower, if recently collected data for corn stover are a good indication. Translating nutrient removal increases into accurate predictions of nutrient demand is not straightforward. Disparities between nutrient removal and nutrient recommendations are at times significant, and future demand will likely be based more on the recommendations than the removals. Using increases in nutrient removal as a proxy for nutrient demand in 2030 indicates that domestic demand for N, P, and K will increase significantly, making the U.S. more reliant on N and K imports and consuming significantly more domestic P production. In all cases, greater U.S. consumption leaves less of the production capacity available for export to other countries. To help ease future demand and create a sustainable biofuel industry, nutrients will need to be recycled from production facilities back to the farmland producing their feedstocks to the extent possible. Until more is understood of cellulosic ethanol plants and their byproducts, it is not possible to estimate how much these secondary sources of nutrients will ease demand on the primary ones.

As part of the roadmap for the future, there is a pressing need to understand the nutrient uptake, partitioning, and loss of nutrients in corn stover and perennial species throughout the season, but especially at or near harvest. Harvest management will need to minimize, to the extent possible, the removal of nutrients from farmland to ensure primary resources remain viable in the future.

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Chapter 11

Economics of Feedstock Production, Harvest, Storage, and Transport

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Introduction

Generally, we lack well-developed and established technologies and research investments (knowledge) in producing, harvesting, storing, and transporting large quantities of herbaceous feedstock. Traditionally, there has been little incentive to produce or demand for crops with high biomass yields. Rather, other plant characteristics (e.g., energy content, protein content) were frequently higher valued than biomass. Given past demands for other higher-valued characteristics, we have not developed a supply chain for harvest, storage, and transport (HST) of low-value, low-density, herbaceous feedstock. The logistical challenges alone of using existing rural road and bridge networks will create numerous bottlenecks in storing and moving large quantities of bulky materials. Additionally, some rural areas will lack an adequate supply of relatively low-paid labor needed during the harvest window for such feedstock.

Another complicating factor in supplying biomass feedstock is that we have limited information on biomass producers' willingness to supply feedstock at alternative prices,especially given the risk and uncertainty involved in producing and marketing perennial biomass crops. So having a sense of what biomass producers would be willing to supply at alternative prices is important, especially to the biofuel producer needing adequate biomass feedstock supplies. Unlike traditional commodities (e.g., corn grain, soybeans) which have well-established markets and standardized quality criteria, most forms of herbaceous biomass do not. Also, producers frequently lack knowledge and experience growing biomass relative to grain and oilseed crops.

This white paper is designed to identify issues that need to be solved to provide an economic supply of feedstock to the conversion process. In the absence of this efficient supply system, what will feedstock cost for biofuel? The first section discusses various feedstocks from cropland, the cost components included in feedstock production, harvest, storage, and transport, and then derives estimates of total current costs of producing biomass feedstock and potential supplies of biomass feedstock by producing regions. This section also identifies some of the constraints to more competitive production of biomass feedstock. The second section addresses biomass supply logistics and harvest, storage, and transport (HST) technology in terms of present-day systems technologies, important linkages in an integrated supply system, and advancements made in recent years, as well as identifies obstacles to more efficient supply system logistics. The third section provides a sensitivity analysis of how cost reductions resulting from HST technology improvements may lower feedstock cost and make biomass feedstock a more economically competitive agricultural crop. The final section will provide a summary of results and implications of this analysis.

Biomass Feedstock Cost and Supply

Depending on the type of biomass, the breakeven costs of production consist of several components including establishment, maintenance, harvest, storage, transport, and land cost. The latter is the opportunity cost of using the land when land has an alternative use; that is, the cost is the foregone returns from that land in its best alternative use. When dedicated energy crops are grown on marginal land that is currently idle, there is likely to be a one-time cost of upgrading and converting the land to grow an energy crop. These conversion costs need to be included in the cost of the biomass. Some costs are fixed and do not vary with the yield of biomass (e.g. the cost of land), others are incurred annually, and for perennial crops, some costs are incurred only once over the life of the crop. Thus, the stand life of a perennial crop, the biomass yield per unit of land, and the growing season for the crop all potentially impact the cost per dry ton for biomass residues and dedicated energy crops. These factors are likely to differ across energy crops and across locations depending on climate, soil quality, and competing uses for land. The long term breakeven costs of using crop residues as feedstock includes the nutrient cost of replacement costs and the cost of harvesting, storage and transportation. These costs would also include a land opportunity cost, if it leads a landowner to switch from a more profitable tillage or rotation option to a less profitable one. We first briefly provide background information on the feedstocks considered, followed by a description and review of existing estimates for the factors that influence each of the production cost components.

Biomass Feedstock Background

Biomass feedstocks considered here include two types of crop residues (corn stover and wheat straw) and two herbaceous perennial crops (switchgrass and *Miscanthus*). Switchgrass is a warm season perennial grass with a stand life of ten years or more where production during the first two years is only a fraction of the production achieved during the remaining production years (Walsh, 2008; Kszos et al., 2002; Popp and Hogan, 2007; McLaughlin and Kszos, 2005; James et al., 2010; De la Torre Ugarte et al., 2003; Mooney et al., 2009) *Miscanthus* is a perennial rhizomatous grass with a stand length of fifteen or more years with maximum yield achieved between years two and five (Heaton et al., 2004; Atkinson, 2009; Clifton-Brown et al., 2001; James et al., 2010; De la Torre Ugarte et al., 2003). In this study, we will evaluate the sterile hybrid genotype *Miscanthus × giganteus*, a potential biofuel feedstock with a lifetime of 15 or more years. There are several varieties of switchgrass including the Cave-in-Rock cultivar, an upland variety well-suited for the upper Midwest, and Alamo and Kenlow, lowland varieties most suited for southern U.S. (Lemus and Parrish, 2009, Lewandowski, et al., 2003). The yields of these perennial grasses vary considerably across varieties and locations (Lemus and Parrish, 2009). Recent analysis of data from field trials across the U.S. shows that frequency distributions of yield for the upland and lowland varieties of switchgrass were unimodal, with mean (±SD) biomass yields of 8.7 ± 4.2 (3.9 ± 1.9 Dt/acre) and 12.9 ± 5.9 (5.75 ± 2.6 Dt/acre) metric tons dry matter per hectare (MT DM/ha) for the two varieties, respectively (Wullschlegera et al., 2010). This is consistent with estimates provided by Lemus and Parrish's (2009) review of literature which shows the annual yield of a lowland variety of switchgrass ranges between 11-16 MT DM/ ha (4.9-7.1 Dt/ ha) and is about 50% higher than an upland variety yield. Side-by-side field trials indicate that *Miscanthus* has relatively high yields in Illinois, more than twice those of switchgrass and higher than *Miscanthus* yields observed in Europe (Heaton, et al., 2008, Miguez, et al., 2008). The only *Miscanthus* yield estimates for other regions in the U.S. are currently from simulation models (Jain, et al., 2010). Simulated yields for switchgrass and *Miscanthus* find that the post-harvest (delivered) biomass yield of *Miscanthus* is about two times the yield of switchgrass in much of the rainfed U.S., with the exception of some of the northern states (e.g. Minnesota and Wisconsin) and southern states (e.g. Louisiana and Texas) where temperatures are either too low or not low enough, respectively, to support high yields of *Miscanthus* relative to switchgrass. In general, Atlantic states have high yields for *Miscanthus* and switchgrass, while western states have very low yields due to insufficient soil moisture. Furthermore, southern states have higher yields for *Miscanthus* and switchgrass compared to northern states. The simulated average delivered[1] yield of *Miscanthus* is highest in the Atlantic states at 31.6 MT DM/ha (14 Dt/acre) followed by the South at 30.2 MT DM/ha (13.5 Dt/ acre), Midwest at 23.8 MT DM/ha (10.6 Dt/acre), and finally the Plains at 19.8 MT DM/ha (8.8 Dt/acre). Corresponding estimates for average switchgrass yield are 16.4, 15.2, 10.7, and 11 MT DM/ha (7.3, 6.8, 4.8, and 4.9 Dt/acre) in these regions, respectively, (Chen, et al., 2010) as shown in Figure 1 (Chen, et al., 2010).[2]

The majority of switchgrass growth occurs during the warm summer months of June to August, whereas *Miscanthus* growth usually peaks between August and October. In the fall, perennial grasses undergo senescence and translocate nutrients from the above-ground plant canopy to the roots. Delaying harvest until after senescence reduces need for nutrient application in the subsequent year, reduces drying time, and improves the quality of the biomass. Yet, waiting to harvest until after senescence also decreases harvestable yield by 20-40% for *Miscanthus* and 15-20% for switchgrass (Jain, et al., 2010). The seasonality of biomass growth also influences the timing and number of harvests and therefore affects the duration of storage time and the amount of biomass loss during storage. All of these components influence the cost of harvesting and storage, as discussed below.

In the case of crop residues, the maximum biomass yield can be estimated from the corresponding grain yield. A grain-to-residue ratio of 1:1 for the amount of dry matter of crop grain to dry matter of crop residues (with 15% moisture) is consistently found in the literature (Sheehan et al., 2003; Wilcke and Wyatt, 2002; and Graham, Nelson and Sheehan, 2007). Due to the value of biomass returned to the soil as soil organic matter and protection against wind and water erosion, a fraction of the biomass is usually left on-field. Recommended stover removal rates depend on soil characteristics, climate, management practices (tillage), and other factors that determine the loss of soil organic matter and run-off. Assumed rates of removal range from 38% to 70% and Malcolm (2008) estimates that 50% of the residue can be removed from fields if no-till or conservation tillage is practiced and 30% can be removed if till or conventional tillage is used.[3] Using removal rates estimated by Malcolm (2008) and 2007 crop yields for corn and wheat, Chen et al. (2010) estimated that the average delivered yield for corn stover is the highest in Midwestern and Plain states at 4.0 MT/ha (1.8 t/ac) followed by the southern and western states at 3.3 and 3.2 MT/ha (1.5 and 1.4 t/ac), respectively. Atlantic states have the lowest corn stover yield at 2.8 MT/ha (1.25 t/ac). For wheat straw, delivered yield is highest in the West at 3.1 MT/ha (1.4 t/ac) followed by the Midwest at 2.3 MT/ha (1 t/ac) and less than 2 MT/ha (0.9 t/ac) in other regions. These yields are shown in Figure 1.

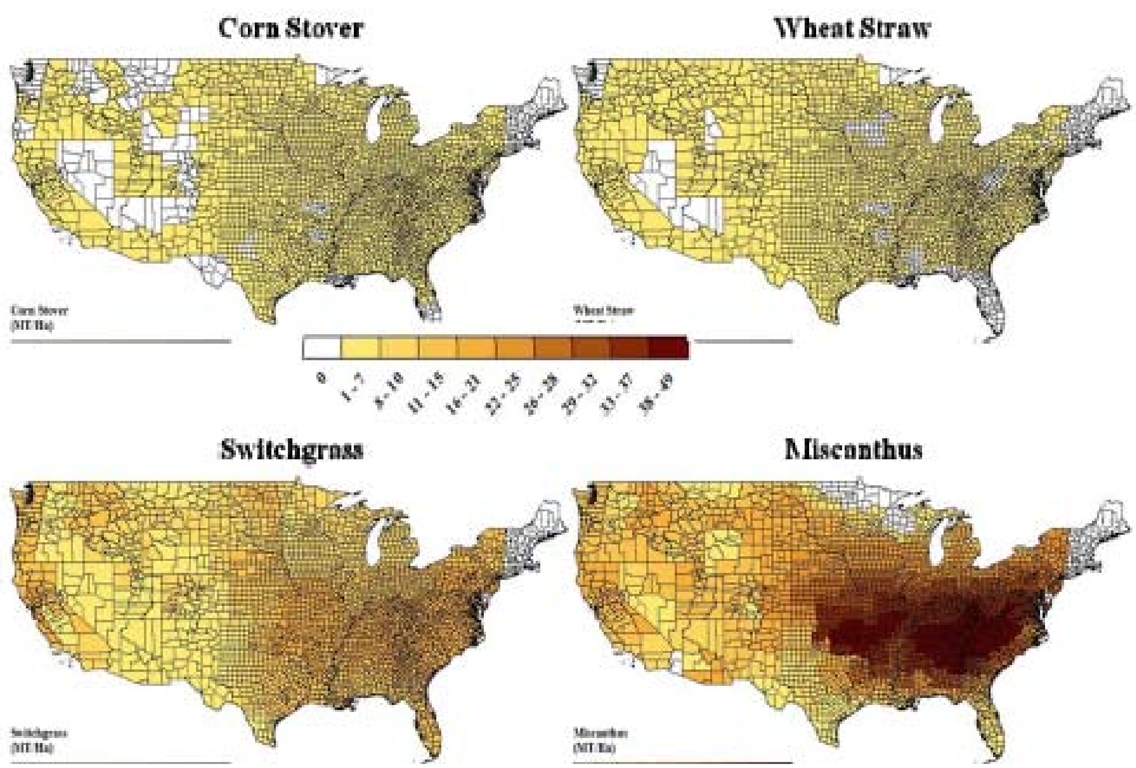

Figure 1. Delivered yields of Various Feedstocks (Metric Tons of Dry Matter per Hectare)

Establishment and Maintenance Costs

Perennial grass production costs differ over the lifetime of the plant, depending on the time period needed to achieve maximum harvestable yield. These costs include the cost of inputs, such as chemicals, fertilizers, and seeds, planting costs in the first year, potential second year replanting costs, and the cost of land. Fertilizer application rates, replanting probabilities, and second-year yields may differ across locations. Some input application rates could be dependent on yield and thus application rate could vary regionally.

Studies differ in their assumptions about the duration of the establishment phase for switchgrass and *Miscanthus* and the biomass yields that can be obtained in the first and second year. Most studies assume maximum yield is achieved in year three for switchgrass and maintained thereafter. The likelihood of reseeding in the second year could range between 15%-50% and could impose significant additional costs.

Input application rates differ across studies and sites and standardized recommendations are yet to be developed. Most studies assume no nitrogen is applied to switchgrass in the first year to prevent weeds. Application rates in subsequent years range from 67-112 kg/ha. Studies in Europe have shown that *Miscanthus* does not respond to N fertilization using annual application rates from 0 to 60 kg/ha (Jain et al., 2010; James et al., 2010). Similarly, field trials have not found a strong response from switchgrass or *Miscanthus* to applications of potassium (K), phosphorus (P), or calcium. Some studies, however, include applications of N, P, K, and lime to replenish soil reserves, especially on soils with lower fertility where application rates are assumed to depend on yield. There is considerable uncertainty about the cost of *Miscanthus* rhizomes since they are not yet commercially available for large scale plantations. For a large scale plantation, with 10,000-12,000 plugs/ ha, the costs of establishment (including labor, equipment, and chemicals) are expected to range between $3000 and $4000 per hectare ($1215-1620/acre) (Jain et al., 2010). This cost is expected to decrease substantially after commercial scale production begins.

Another key component of the cost of production is the cost of land. To the extent that the production of bioenergy crops diverts cropland from existing uses, the opportunity cost of that land is the foregone income from the most profitable alternative use of that land, such as corn and soybean production. Some studies also include the value of the corn stover that could be harvested from the field (James et al., 2010). These costs can be very high, particularly in the Midwest, and are estimated to range from $200-300 per hectare ($81-122/acre) in the South to $700-800 per hectare ($284-324/acre) in the Midwest, using 2007 prices. Jain et al. (2010) find that inclusion of a value for the stover raises the average breakeven price for switchgrass by 7% and 3% for *Miscanthus* across the Midwestern states. Yet, one of the benefits of perennial grasses is their ability to be productive on low quality land, as evidenced by switchgrass field experiments (Varvel et al., 2008). Production of bioenergy crops is therefore more likely to occur on marginal land with lower opportunity costs, such as currently idle cropland or cropland pasture (Khanna et al., 2010). In estimating county level costs, we assume that currently idle cropland or cropland pasture would yield the lowest returns from crop production in the county and is left idle because the cost of converting it for crop production is larger than potential returns. The opportunity cost of marginal land is estimated to range from $100-300 per hectare ($41-122/acre) across various rainfed regions in the U.S.

Several studies provide estimates of the nutrient application rates required to replace the N, P, and K removed from the field with the crop residue, with application increasing with biomass yield (Sheehan and Nelson, 2003; Wortmann et al., 2008). Production costs of crop residues could also include opportunity costs of land if the collection of residue leads to a change in rotation or tillage choices and a loss in profits from grain production. For example, the demand for crop residues could lead landowners to switch from a more profitable corn-soybean rotation with conventional tillage to no till and/or continuous corn rotation. The lost profits from this would be part of the breakeven cost of using the biomass from crop residues as a feedstock.

Harvesting Costs

Farm activities after establishment of an energy crop include mowing, raking, baling, and storage. There are several factors that are expected to influence these costs, including the size of the farm, the yield per hectare, the number of harvests, the timing of harvest, the harvesting horizon, and the method of storage. The harvesting operation is capital intensive and requires equipment such as a tractor, mower, rake, baler, and bale transporter. Other costs include labor and fuel. The large fixed cost component implies economies of scale if the harvesting equipment can be used over a larger acreage. For any given biomass yield level, harvesting costs per hectare fall as the hectares harvested annually increase. As yields increase, the fixed cost per ton falls but the speed at which the implements are operated changes and this reduces maximum capacity to harvest (in terms of annual harvested acres). Labor and fuel requirements for baling may also increase as tonnage increases (Jain et al., 2010; Thorsell et al., 2004). The least cost equipment choice may differ by farm size. For example, farms smaller than 200 hectares would find it costeffective to select round-baling instead of square-baling machines (Shastri et al., 2009).

Harvesting of switchgrass is optimal after senescence and during the September-December period while for *Miscanthus*, harvesting could occur between December and April. A single annual harvest is found to result in lower costs than two harvests a year for both switchgrass and *Miscanthus* (Aravindhakshan et al., 2010). A short (four month) harvest window requires considerable investment in harvest equipment. One approach to reduce harvesting costs is to extend the harvesting window and thereby spread the fixed costs of the harvest machines over more hectares and reduce the time that the harvested material must be stored. To maintain productivity, additional fertilizer applications would be needed for fields harvested prior to senescence and biomass yields would be lower for fields harvested later (Hwang et al., 2009). The harvesting window could also be extended by having a mix of different feedstocks, assuming a biorefinery can process a variety of feedstocks. Mapemba et al. (2008) consider the possibility of having an extended harvest system from June through February with wheat straw harvested in June and July, corn stover in September and October and perennial grasses from July through the following spring and found it possible to allocate harvest equipment in a way to reduce the capital investment in harvest machines by 50%. However, results are sensitive to assumptions about harvest days available which depend on the weather. Harvest days depend on both the condition of the soil (e.g. sufficiently dry soil to hold the weight of the harvest equipment) and the moisture content of the grass. A reduction in harvest days due to weather related constraints could limit the flexibility for scheduling harvest equipment optimally and may result in substantially higher harvesting costs.

Storage Costs

Biomass can be stored after harvest in several ways including on-farm open air, on-farm covered, or storage in a centralized covered facility. Open air storage could be unprotected on the ground or on crushed rock or covered by reusable tarp. The covered storage could be a pole frame structure with open sides on crushed rock or it could be an enclosed structure on crushed rock. The loss in biomass is highest when biomass is left unprotected and lowest in the enclosed structure. These losses depend on the number of days the biomass is stored and need to be weighed against the costs of installation, land, labor, and materials as well as the biomass quality that is needed by the bio-refinery. A centralized covered storage facility could be shared by many farms but would require producers to incur biomass handling and transportation costs to move the biomass from the farm. The optimal choice of storage facility is likely to depend on the volume of biomass and the length of time that it has to be stored, the price of biomass, the quality of biomass required, and the weather conditions within the region (Brummer et al., 2000; Duffy, 2007).

Transportation Costs

Most studies assume that biomass transportation from the farm to the refinery will be by truck. Transportation costs include the amortized capital cost of the truck, operating costs which include labor, fuel, maintenance, insurance, and repairs. Fuel costs depend on the distance travelled. Additionally, loading and unloading costs and waiting time for the driver also need to be factored in. Costs of transportation will vary across farms depending on their distance to the refinery and the collection area of the refinery. With high yielding feedstocks, a refinery can obtain its feedstock from a smaller collection area. In most studies, costs of transportation are estimated for a one-way distance from the farm to the refinery of less than 50 km, assuming that it will not be economical to transport biomass for longer distances (Atchison and Hettenhaus, 2003; Brechbill and Tyner, 2008a and 2008b; English et al., 2006; Khanna et al., 2008; Perlack and Turhollow, 2002; Taheripour and Tyner, 2008; Tiffany et al., 2006; Vadas et al., 2008). Estimated transportation cost per ton differs across studies, partially due to differences in the approach to estimating the cost of transportation. Some studies estimate the total transportation costs for a specific feedstock, biorefinery, and location while others take a more general approach and estimate transportation cost with two separate components, a distance fixed cost (e.g. staging, loading, and waiting cost per ton) and a distance variable cost per ton per km (or mile). In recent literature, transportation cost has been estimated to be around $5.60 per ton in Oklahoma (Aravindhakshan et al., 2010), $8.65 per ton in Iowa (Duffy, 2007), $15.60 per ton in Illinois (Shastri et al., 2009), and $14.00 per ton in the Midwest (Jain et al., 2010). For a summary of previous literature that separate the distance fixed cost and distance variable cost, see Miranowski and Rosburg (2010).

Total Costs of Production

Figure 2 provides the costs of producing *Miscanthus* and switchgrass under two alternative cost scenarios in the Midwest (based on Jain et al., 2010) and the costs of producing corn stover under alternative tillage and rotation choices in the Midwest. The cost of establishment is much higher for *Miscanthus* than for switchgrass while the cost of chemical inputs is higher for switchgrass than for *Miscanthus*. The chemical input cost ranges from 33-40% of total costs for *Miscanthus* and is only about 20-25% of total costs for switchgrass. The cost of harvesting is about 25-33% of total costs while the cost of storage and transportation account for another 20-33% of the cost. Due to the higher yield per hectare for *Miscanthus*, the share of land cost in the total cost is higher for switchgrass than for *Miscanthus*. It is about 16-18% of total cost for *Miscanthus* and 25-30% of the cost for switchgrass. The costs of dedicated energy crops will also vary with the lifetime of the crop. A reduction in the lifetime of *Miscanthus* from 15 years to 10 years would increase the breakeven price of *Miscanthus* by 11-15% while a 10% increase in bioenergy crop yields could reduce the breakeven price of *Miscanthus* and switchgrass by about 7% (Jain, et al., 2010). Total costs of production of corn stover are lower with no-till than with conventional till because the former allows a higher rate of residue collection without eroding soil quality. The cost of land due to a switch from a cornsoybean rotation to a continuous corn rotation is about 30% of the total cost, as shown in Figure 2. We assume here that conventional tillage and no-till are equally profitable. If they are not, then the switch from a corn-soybean rotation with conventional till to a continuous corn rotation with no-till will impose an opportunity cost of land.

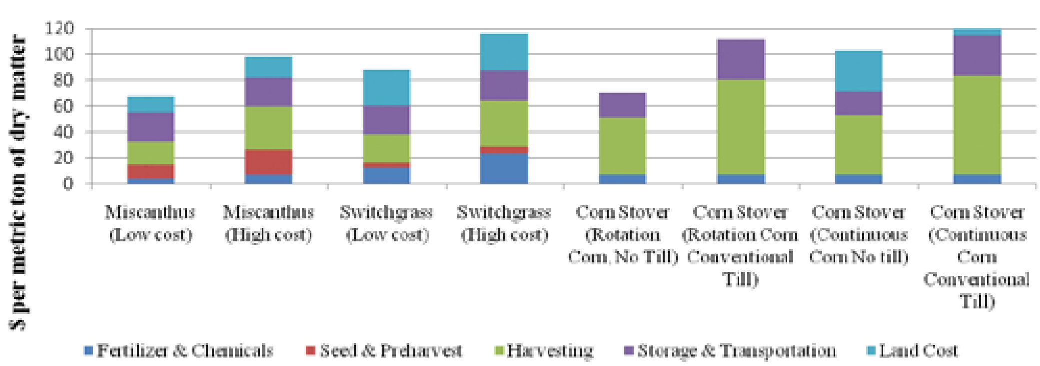

Figure 2. Cost of Production of Alternative Feedstocks.

The costs of feedstocks also vary across locations due to differences in yields per hectare and the cost of land across locations as shown in Figures 3a and 3b. In the low cost scenario, the cost of production of *Miscanthus* ranges from under $40 per MT to over $100 per MT, while switchgrass is between $50 and $95 per MT. Under the low cost scenario, *Miscanthus* has a lower cost of production compared to switchgrass in most states, except in the southern and northern regions where temperatures are either too cold or not cold enough for senescence to occur and for *Miscanthus* to be grown productivity. If, however, production conditions are more optimistic for switchgrass and not as optimistic for *Miscanthus*, so that we have a low cost scenario for switchgrass but a high cost scenario for *Miscanthus*, then switchgrass has a competitive advantage in almost all states in the rainfed U.S..

Figure 3b shows the costs of corn stover across different states for alternative rotation and tillage choices. In areas where corn-soybean rotations are the most profitable, the cost of corn stover is low if rotation corn is planted using no-till. Continuous corn with conventional tillage leads to the highest costs per ton of corn stover in most states. The lowest costs of corn stover (across states in Figure 3b) range from $57 per DMT with a corn-soybean rotation with no till to $90 per DMT with the same rotation but conventional till. Corresponding median value for these costs are $70 per DMT and $86 per DMT. The lowest costs of corn stover collection with continuous corn range from $60 with no-till to $96 per DMT with conventional till with median values higher than $100 per DMT.

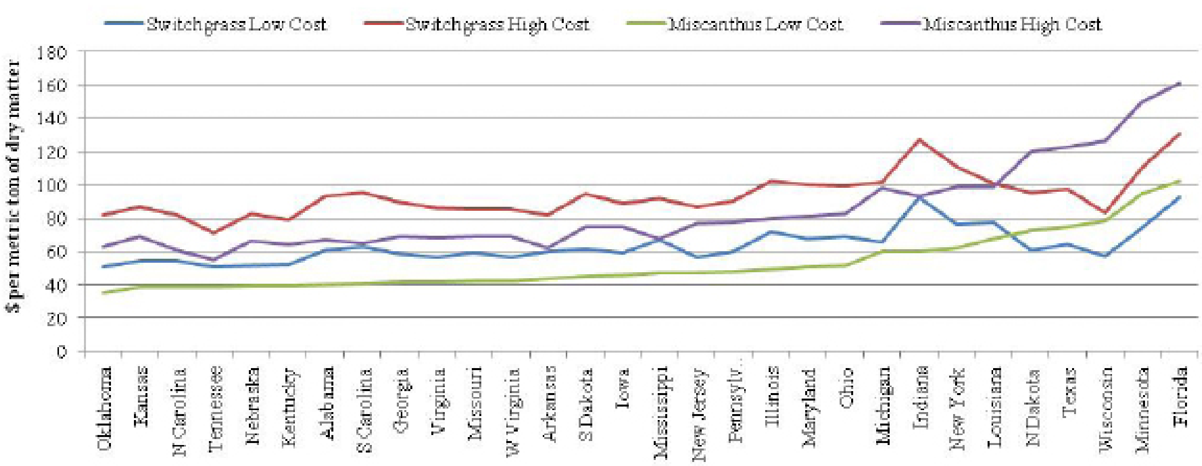

Figure 3a. Variability Across States in the Cost of Production of Miscanthus and Switchgrass.

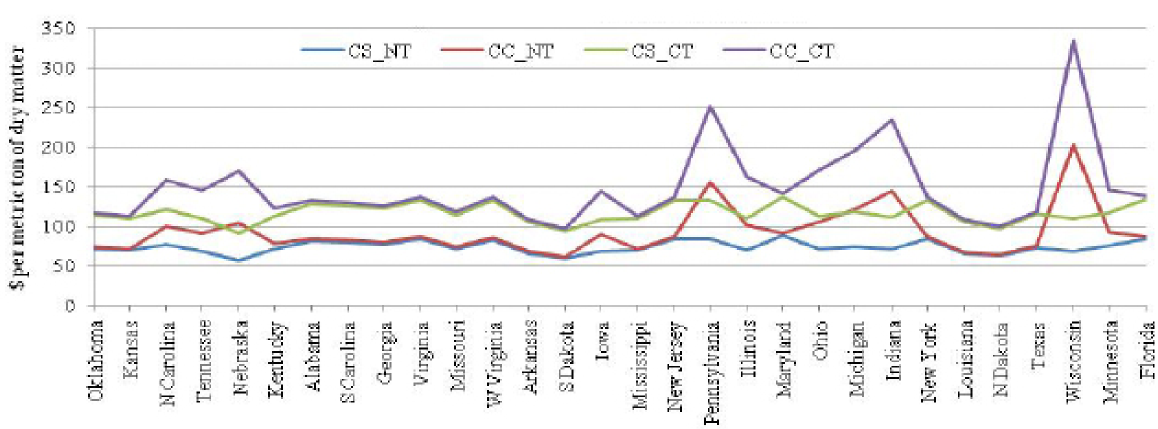

Figure 3B. Cost of Producing Corn Stover under Alternative Tillage and Rotation Choices.
CS_NT: Corn Soybean Rotation with No Till, CC-NT: Continuous Corn Rotation with No Till
CS-CT: Corn Soybean Rotation with Conventional Till, CC_ CT: Continuous Corn Rotation with Conventional Till

Khanna et al. (2010) use these production costs to develop biomass supply curves from crop residues and dedicated energy crops in order to determine the amount of biomass produced at given biomass prices. Results differ depending on assumptions about the costs of producing biomass, the yields of energy crops, and the harvest rates for crop residues, as well as with assumptions about the availability of marginal land. Their analysis shows that with low costs of production for both switchgrass and *Miscanthus* and availability of land in the Conservation Reserve Program for bioenergy crop production, there is potential to produce 250 MMT of biomass at a price of $40 per MT and about 900 MMT at a price of $140 per MT. Much of this supply would be met by *Miscanthus*, followed by corn stover (Figure 4a). If switchgrass yields were to double or if costs of production were low for switchgrass and high for *Miscanthus*, switchgrass would provide a larger share of biomass than *Miscanthus*, particularly at low biomass prices (Figure 4b).

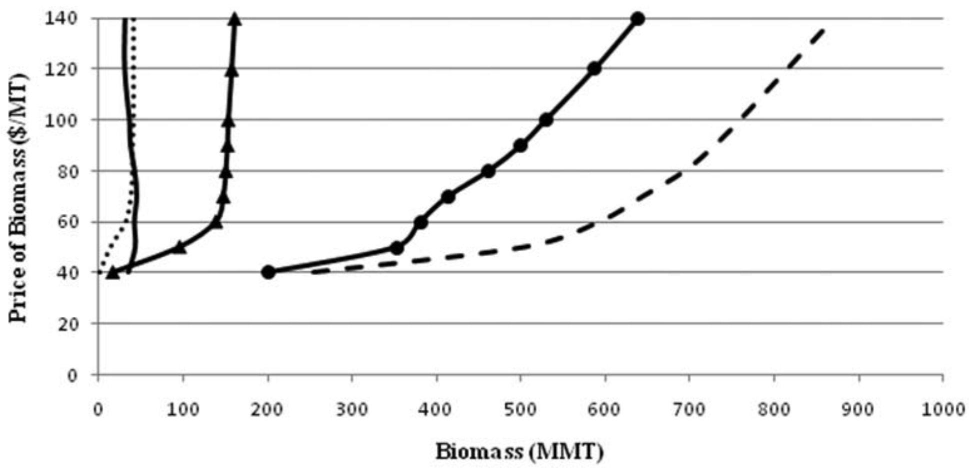

Figure 4a. Biomass Supply with Los Costs of Production Feedstocks

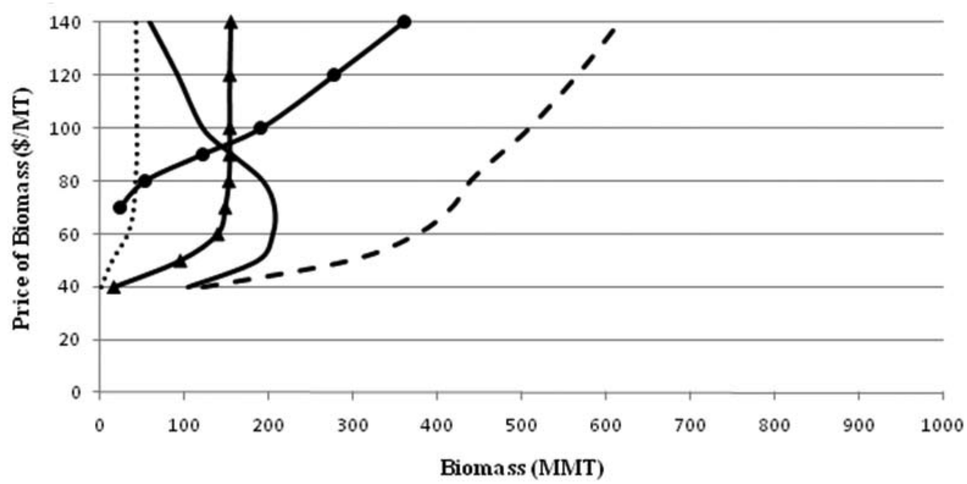

Figure 4b. Biomass Supply with Low Cost of Production of Switchgrass and High Costs of Production of Miscanthus.

Biomass Feedstock Supply Logistics Progression

This section focuses on developments in the integrated feedstock supply system and further technology improvements needed to improve the economics of the supply system and the added cost of producing the last unit of feedstock delivered to the biofuel processing plant. Alternatively, how can we further improve supply system logistics and the economics of biomass. The feedstock supply system encompasses all operations necessary to format and move biomass from the location of production (field or forest landing) to the biorefinery's conversion in-feed system. Figure 5 illustrates that feedstock supply logistics comprise elements from biomass harvest to conversion reactor handling and in-feed systems, but it is recognized that no part of the system is truly independent. As such, logistics designs are impacted by feedstock production systems and conversion processes. When considering final feedstock cost to the conversion process, the feedstock procurement costs (referred to as the “grower payment”) must also be included (Hess et al., 2009a). The grower payment is the cost value assigned to access a given quantity of biomass from the field or forest. It is not a farm gate or forest landing value, but is more representative of a cost of production (agriculture) or stumpage fee (forest).

From a logistics stand point, the grower payment defines the minimum price that a given quantity of resource can be drawn into the supply logistics system. While grower payments are difficult to assess for an emerging biorefining industry, they can be estimated by calculating production costs, sustainability constraints, and, in some cases, an incentive payment (Hess et al., 2009b). Hess et. al. (2009b) reported a U.S. average grower payment of $15.90/DM ton of removed corn stover (does not include costs of harvesting, moving material to storage, or any other logistic operations). This was a weighted average based on the number of corn acres within each region. Minimum grower payments are lowest in the Northern and Southern Plains and highest in the Pacific and Mountain states.

In addition to biomass availability at a given cost, biomass resource mix can significantly impact supply system designs. The variety of potential biomass resources results in equipment, costs, and logistics supply system designs that differ considerably from one design case to the next (Figure 5). As such, present day “Conventional” feedstock supply system designs are only replicable to the extent that other feedstock resources and local conditions are similar. These conventional designs tend to be vertically integrated with a specific conversion facility, and the supply system infrastructure and conversion facilities are dedicated to the predominant local feedstock species and formats. In the case of biorefineries that can receive more than one feedstock or feedstock format, a feedstock-receiving system is constructed for each feedstock type/format that the biorefinery will accept. The result is duplicate supply system infrastructures that are either under-used or, if fully used, require contracting and feedstock supply delivery schedules that balance the required throughput for each feedstock format. These designs do work today because they adapt to the local available biomass resources and facilitate producer participation by minimizing perturbations to their present operations and by reducing the investment risks associated with new and unproven supply system equipment.

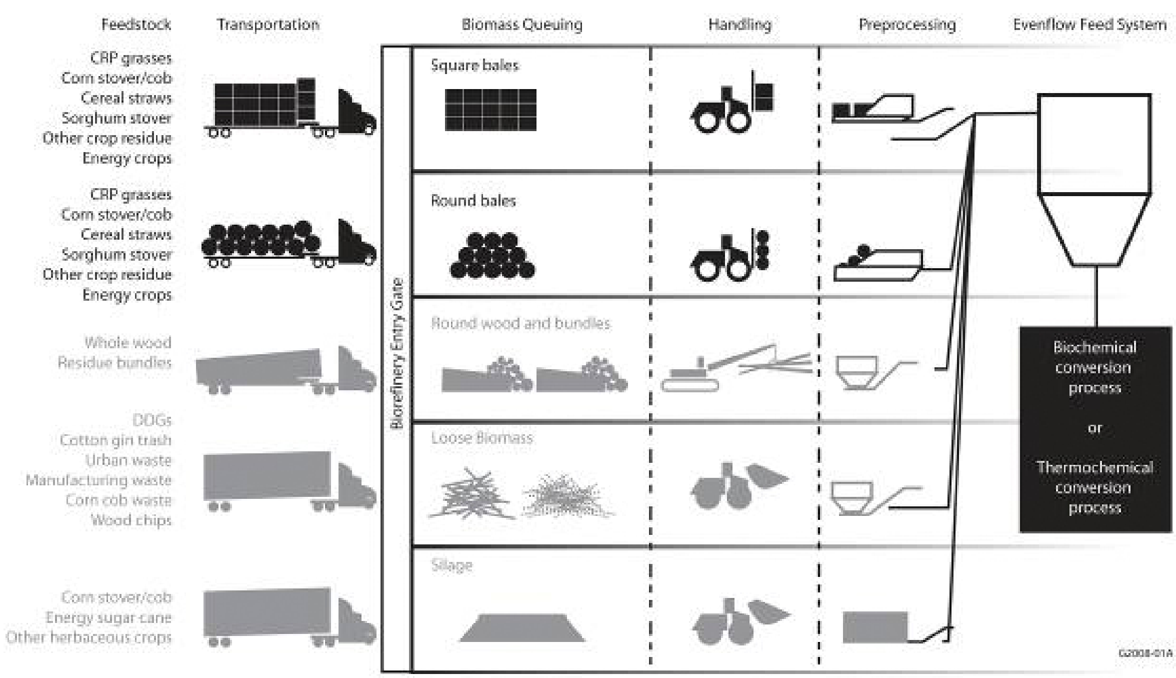

Figure 5. Conventional designs are tailored for each facility and respective feedstock 2 resource. No two are alike, and components are only replicable to the extent that feedstock 3 sources and local conditions are similar (Hess et al., 2009a).

The logistics of the feedstock supply system activities represent one of the largest barriers to the biofuels industry and can make up 40 to 60% of total ethanol production costs (Fales et al., 2007). By comparison, the feedstock logistics costs associated with corn-grain-based ethanol from a dry mill process range between 8% (2008$) and 27% (2002$), with changing energy costs as a key factor in the range (Hess et al., 2009a). Hess et al. (2009b) report harvest/collection, storage, handling/transport, and receiving/preprocessing unit operation costs for a corn stover conventional square bale supply system to be \$21.62±2.69, \$8.11±0.66, \$11.94±1.25, and \$13.74±1.31 respectively. Including a grower payment of \$15.90/DM ton, the final delivered feedstock cost to the in-feed of the conversion process is about \$71 per DM ton. The challenge is that these conventional biomass supply systems can only improve efficiency and cost savings to a point; they are unable to effectively overcome low bulk density and high moisture instability challenges without significant design changes (Hess et al., 2009b). A key finding of Hess et al. (2009b) was that with only incremental improvements and no technology changes, the Conventional Bale Stover supply system design was not able to achieve cost performance targets better than about \$49.00 per DM ton (with 2008$ and cost indices). A few of the key barriers to achieving greater supply system performance were low biomass bulk density, high field losses (which has the same impact as low yield), and material instability that resulted in high storage losses.

One strategy to address these logistic challenges is the gradual transition from existing biomass supply systems to an economic and reliable commodity-scale supply system that provides uniform, aerobically stable, quality-controlled feedstocks to biorefineries (Hess et al. 2009a). This uniform-format strategy takes advantage of the highly efficient, scalable, and economic bulk solids handling infrastructure that is used today for grain (Hess et al., 2009a). The Uniform-Format Supply System Design ("Uniform-Format") locates the preprocessing unit operation as early in the supply system as practically possible, creating a hub-and-spoke design that minimizes logistical issues with transporting and handling dispersed, low-density, often aerobically unstable biomass (Figure 6). The Uniform supply system formats biomass of various types (corn stover, switchgrass, etc.) and physical characteristics (bulk densities, moisture content, etc.) into a standardized format early in the supply chain. This uniform material format allows biomass to be handled as a commodity that can be bought and sold in a market, vastly increasing its availability to the biorefinery and enabling large-and small-scale facilities to operate with a continuous, consistent, and economic feedstock supply.

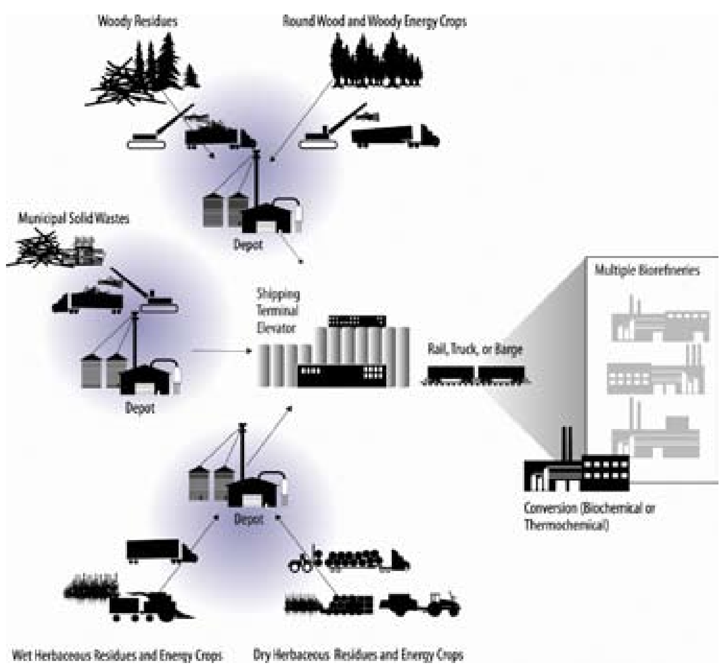

Figure 6. The Advanced Uniform-Format feedstock supply system (Advanced Uniform) design emulates the current grain commodity supply system, which manages crop diversity at the point of harvest and at the biomass depot/elevator, allowing subsequent supply system infrastructure to be similar for all biomass resources (Hess et al. 2009a).

Biomass commodities are storable, transportable, and have many end uses. Implementing a commodity-based feedstock supply system promotes cropping options beyond local markets, which in turn promotes crop diversity and enhances crop rotation practices.

The Uniform-Format design overcomes the physical and equipment barriers inherent in working with biomass. This is accomplished by increasing the material dry matter bulk density through size reduction, reducing moisture content through drying, improving equipment performance to minimize dry matter losses, and taking advantage of biomass material properties to facilitate material deconstruction. The Uniform-Format system produces a commodity product, reduces plant handling costs, and is conducive to long-term biomass supply sustainability required to meet the U.S. annual biofuel production goals of 60 billion gallons by 2030 (EISA 2007).

This commodity system increases crop production options by providing access to diverse local and nonlocal markets. This allows producers to grow crops in rotation without being bound to supply contracts and limited local demand. Increasing cropping options promotes enhanced sustainable crop rotation practices (Kitchen et al. 2005; Lerch et al. 2005; USDA-NRCS 2007; Williams et al. 2008; Yan et al. 2007).

Cost Sensitivity of Biomass Supply Logistics

What impacts would improvements in biomass supply logistics have on lowering HST and total cost components of supplying biomass? Evaluating the sensitivity of HST costs to specific logistical improvements is difficult, if not impossible, especially when considering the improvements as part of an integrated supply system. Instead, we will simply estimate the impacts of 10%, 25%, and 50% reductions in harvest, storage, and transportation cost components and their impact on total cost per dry ton biomass feedstock delivered to a biofuel processing plant. For this illustration, we use BIOBREAK, a biomass breakeven model designed to estimate all the costs incurred in delivering biomass to a commercial biofuel processing plant. Even though we are not using the same model and estimates used in other sections of this paper, comparable data sources and assumptions should provide similar results.

The Biofuel Breakeven model (BIOBREAK) is a flexible model (Miranowski and Rosburg, 2010a, 2010b) that estimates the long run breakeven price that biomass producers would be willing to accept for producing and delivering the last ton of feedstock to the biomass processing plant.[1] The model is used to evaluate the cost and feasibility of corn stover produced from continuous corn production (CC) or corn/soybean rotation in Midwest, switchgrass produced in Midwest ("MW": ND, SD, NE, KS, IA, IL, IN), South-Central ("SC": OK, TX, AR, LA) and Appalachian ("App": TN, KY, NC, VA, WV, PA) regions, *Miscanthus* in the Midwest and Appalachian regions, and wheat straw in the Pacific Northwest (WA, ID, OR), respectively. The biomass supplier's WTA or marginal cost for the last unit of delivered feedstock is equal to the total economic cost, including opportunity cost, which the supplier incurs in sustainably producing, harvesting, storing and transporting the biomass to the processing plant, minus government incentives received (G) (e.g. tax credits, production subsidies). Depending on the biomass feedstock, costs include establishment and seeding (C_{ES}), land rental/opportunity cost (C_{Opp}), harvest and maintenance (C_{HM}), nutrient replacement (C_{NR}), biomass storage (C_S), transportation fixed costs (DFC) and variable transportation costs calculated as the variable cost per mile (DVC) multiplied by the average hauling distance to the biorefinery (D).[2] Establishment and seeding cost and land/biomass opportunity cost are most commonly reported per acre and the biomass yield per acre (Y_B) is used to convert the per acre costs into per ton costs. Therefore, the total cost estimates provide the minimum amount the supplier would be willing to accept for the last dry ton of biomass delivered to the biorefinery and still breakeven in the long run.

The supplier breakeven values rely on Monte Carlo simulations, which permits parameter variability and parameter correlation and sensitivity testing not available in fixed parameter analyses. For this analysis, distributional assumptions for each parameter are based on actual research data updated to 2007 values and verified with industry information when available. Similar to results reported above, the biomass supplier's marginal cost or WTA for the last unit of biomass delivered to the biorefinery ranges between $70 per ton for wheat straw in the PNW to $130 per ton for switchgrass grown on high opportunity cost Midwest cropland. Table 1 provides the biomass supplier's WTA per ton for all ten feedstock/rotation/region combinations. Stover harvested from continuous corn is more expensive than from a corn/soybean rotation, because economies of reduced transportation costs are offset by reduced returns to CC. Midwest switchgrass and *Miscanthus* have higher WTA then results reported earlier because of the assumed used of high quality land with higher opportunity cost and lower yields relative to the Appalachian and South Central regions.

The supply logistics section above discusses current HST technology and supply systems and the need for continued improvement in supply logistics if these systems are to become economic. How sensitive are the results to supply logistics improvements in harvest, storage, and transportation cost components? Table 1 illustrates the sensitivity of the baseline costs to a 10%, 25%, and 50% reduction of harvest storage and transportation cost components for each of the feedstock /rotation/ region combinations. Because harvest costs constitute a larger share of total costs than storage or transportation, a 25% reduction in harvest costs alone would result in approximately a 10% reduction in total feedstock direct costs, or reduce the cost of CS corn stover from $85/ton to $76/ton or App *Miscanthus* from $102/ton to $91/ton. If the cost reduction in the harvest component of the supply system was due to improved feedstock densification and stabilization, then indirect cost reductions should also be realized in storage and transportation, further improving economic viability. Not only do comparable percentage cost reductions in storage and transportation have a more limited direct impact on total costs but they have far more limited indirect cost impacts because they are further downstream in the biomass supply logistics (or chain).

BIOBREAK Sensitivity to Harvest, Storage, and Transportation (% denotes reduction from Baseline)										
	Baseline	**Harvest**			**Transportation***			**Storage**		
		10%	**25%**	**50%**	**10%**	**25%**	**50%**	**10%**	**25%**	**50%**
Stover (CC)	$112	$109	$103	$92	$111	$109	$104	$112	$110	$108
Stover (CS)	$85	$83	$76	$66	$85	$81	$80	$85	$83	$81
SG (MW)	$130	$126	$119	$112	$128	$125	$121	$127	$125	$124
SG (App)	$96	$93	$88	$78	$94	$93	$89	$95	$94	$90
SG (SC)	$93	$90	$85	$76	$92	$90	$86	$93	$90	$88
Misc (MW)	$110	$107	$100	$89	$110	$107	$104	$110	$108	$105
Misc (App)	$102	$97	$91	$80	$100	$98	$95	$100	$99	$96
Wheat Straw	$70	$66	$61	$54	$68	$65	$59	$68	$67	$64
SG (MW_2)	$121	$118	$113	$104	$120	$118	$114	$121	$119	$116
Misc (MW_2)	$114	$112	$105	$93	$113	$111	$108	$114	$112	$108

Table 1. BIOBREAK Sensitivity to Harvest, Storage, and Transportation. * Note: Reduction in transportation cost is a reduction in the distance fixed cost and distance variable cost, while holding distance to refinery constant.

Results and Implications

In a market sense, the biofuel processor's willingness to pay or derived demand for the last ton of biomass delivered is less than the biomass producer's willingness to accept for or marginal cost of the last ton of biomass delivered to the processing plant. In the absence of government incentives (tax credits and biomass production subsidies) and the revised Renewable Fuel Standard mandates, no market will develop for most biomass feedstock. Biomass feedstock supplies remain relatively costly. Without substantial improvements in feedstock cultivars, production technologies, and very importantly, biomass feedstock supply logistics, the economics of the biomass will not sustain a biomass industry. If coupled with improved production technology, technological improvements that integrate efficiently into supply system logistics, such as improved density and stability, could significantly lower feedstock costs, improve biomass economics, and sustain an efficient biomass industry. There are additional economic gains if these technology improvements occur upstream (e.g., harvest technology) in the supply system logistics and indirectly reduce costs of storage and transport.

In the absence of improved production, processing, and HST technologies, government incentives and mandates and high oil prices may encourage the development of the biomass fuel industry, but the industry will not be sustained over the long run. Rather, further public and private investment in research, development, and biomass feedstock and fuel production is needed. Finally, this paper does not address a wide range risks and uncertainties surrounding the biomass industry and options for producer and processors for laying-off risk, or alternatively, what is the magnitude of the risk premium that it will take to induce someone to enter the industry. These are important economic and business finance issues that underlie biomass economics above and beyond the breakeven values that we present in this paper.

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[1] The complete model also includes the breakeven price that biomass processors would be willing to pay for the last dry ton of biomass feedstock delivered to the biofuel processing plant.
[2] The average hauling distance from the farm or storage area to the biorefinery is calculated as a function of the annual biorefinery biomass demand (BD), annual biomass yield (YB), and biomass density (B) using the formulation by French (1960) for a circular supply area with a square road grid.

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[1] Delivered yields incorporate losses during harvesting, storing and transporting.
[2] In contrast to these estimates, Aravindhakshan (2010) report higher yield for the switchgrass variety Alamo (15.87 MT/ha/year) than for *Miscanthus* (12.39 MT/ha/year) in Oklahoma field trials.
[3]Brechbill et al. (2008) and James et al. (2010) consider a removal rate of 38% of residue for corn stover.

Chapter 12

Balancing Feedstock Economics and Ecosystem Services

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Abstract

The purpose of this analysis is to examine the economic balance between production of cellulosic biofuel feedstocks and ecosystem services at the farm level. A literature review of the economics of ecosystem services, ecosystem service impacts of biofuel production, and economic factors influencing cellulosic biofuel production decisions at the farm level is provided as a broad overview. A case study on corn (Zea mays L.) stover harvest is used to illustrate a specific example of the balance between economic returns and the provision of ecosystem services as measured by changes in soil organic carbon (SOC). Case study results showed that SOC declined with increasing biomass harvest rates within each tillage system. However, harvest of corn stover for bioenergy with adoption of no-till (NT) could result in positive economic returns and increases in SOC relative to moldboard plow (MP) tillage systems without residue harvest, indicating a potential win-win scenario for economics and ecosystem services. Placing limits on crop residue harvest could further increase SOC, however at a cost to farm profitability. Results show that requiring 30% residue cover at planting would reduce net returns by $14.52 per acre.

Keywords: bioenergy, net returns, soil organic carbon, corn stover

Introduction

Agro-ecosystems provide a range of services; which, from an anthropocentric view, can be conceptualized as ecosystem services (de Groot et al., 2002). These ecosystem services have been categorized as: ‘provisioning’, ‘regulating’, ‘cultural’, and ‘supporting’ (Millennium Ecosystem Assessment, 2005). Provisioning services include the production of food, fiber, feed and fuel. Regulating services include functions that regulate climate, air, water, and earth surface processes such as greenhouse gas (GHG) balance, maintenance of the ozone layer, and regulation of hydrologic flows. Cultural services include aesthetic, spiritual, educational, and recreational benefits. Supporting services include nutrient cycling, soil formation, crop pollination, and natural pest control.

Ecosystem services at the farm level have been adversely affected by a number of factors related to biofuel production. The growing demand for energy, increasing energy costs, and the need to reduce reliance on fossil fuels and mitigate climate change are factors influencing the development and production of renewable fuels. Currently, corn grain is the primary feedstock for biofuel production in the U.S. and utilizes 24% of total U.S. corn grain production (RFA, 2009). The use of annual crops as biofuel feedstocks has resulted in an expansion of monocultural practices, putting pressure on land and water resources (Blanco-Canqui and Lal, 2009a; Spiertz and Ewert, 2009; Stonestrom et al., 2009). These pressures have resulted in government policy that promotes the use of alternative cellulosic biofuel feedstock sources (Spiertz and Ewert, 2009). The Renewable Fuel Standard (RFS) program under the Energy Independence and Energy Security Act of 2007 requires that biofuel production reach 36 billion gallons (to be blended into transportation fuel) by 2022 (US EPA, 2010). Of this requirement, 21 billion gallons are to be produced from "advanced biofuels" (US EPA, 2010), which include cellulosic sources such as crop residues (e.g., corn stover and wheat [*Triticum aestivum* L.] straw), woody crops (e.g., hybrid poplar [*Populus spp.*]), herbaceous crops (miscanthus [*Miscanthus x giganteus*] and switchgrass [*Panicum virgatum* L.]), and forest residues (Blanco-Canqui and Lal, 2009a; Wright, 1994). Beach and McCarl (2010) estimate that, in addition to 5.5 billion bushels of corn grain, it would take 52.7 million tons of corn stover and 86 million tons of switchgrass to meet the RFS. Thus, bio-energy production on agricultural lands is likely to have a significant impact on the ecosystem services provided by agro-ecosystems.

Crop residues have received significant attention as a low-cost cellulosic feedstock that can provide a value-added benefit and additional income stream to farmers, but the impact on ecosystem services must be taken into account. Corn stover has been recognized as an abundant cellulosic feedstock with significant potential (Graham et al., 2007; Wilhelm et al., 2004). Some of the adverse effects of removing crop residues include: soil organic carbon (SOC) loss (impacting GHG emissions); a decline in soil fertility and productivity (negative impact on nutrient cycle and nutrient losses); soil erosion; reduction of soil organism populations; reductions in water infiltration; and reductions in water quality (Anderson-Teixeira et al., 2009; Blanco-Canqui and Lal, 2009a; Kim et al., 2009; Melillo et al., 2009; Tarkalson et al., 2009). Blanco-Canqui (2010) estimated that removal of crop residue could potentially reduce SOC pools by 0.4 tons per acre per year. However, changes in tillage or crop rotation practices could mitigate these losses, and result in substantial reductions in fossil energy use and net greenhouse gas emissions (Sheehan et al., 2003). Soil organic carbon provides a strong proxy for measuring soil health and productivity (Lal, 1997; Vasques et al., 2010). Higher levels of SOC can improve soil stability, nutrient availability, microbial activity, soil and crop productivity, which improves off-site benefits including reductions in soil erosion, leaching of pesticides and nutrients into water bodies, and emissions of GHGs (Chan et al., 2002; Vasques et al., 2010; Wilhelm et al., 2004).

The purpose of this chapter is to examine the economic balance between the production of cellulosic biofuel feedstocks and ecosystem services at the farm level. Given the broad scope of this topic, a more focused discussion is provided concerning the use of corn stover, but attention is paid to other potential feedstocks. The broader link to the full range of ecosystem services mentioned above is made by providing a more focused analysis on the carbon impacts from biofuel feedstock production, but again this discussion is broadened to show the link between carbon and other ecosystem services. The tradeoff between biofuel feedstock production and ecosystem services is illustrated using a farm-level case-study examining the economics of harvesting corn stover and the subsequent impacts on SOC levels.

The remainder of the chapter is organized as follows. The following section provides a literature review of ecosystem service economics, effects of cellulosic biofuel feedstock production on ecosystem services, and factors influencing cellulosic biofuel feedstock production decisions at the farm level. This provides a broad overview of the interaction between economic factors, cellulosic feedstock production decisions, and provision of ecosystem services. Next, a farm-level case study examining the balance between production of biofuel feedstocks and ecosystem services is presented. The next section presents potential challenges and opportunities for cellulosic biofuel feedstock production at the farm level that may enhance or sustain ecosystem services. A final section provides concluding remarks.

Literature Review

Ecosystem Service Economics

From an economic perspective, the provision of ecosystem services by agricultural producers depends on the degree to which these services influence economic risks and returns at the farm level. A major challenge is that, even though management decisions are made at the farm level, this is not necessarily the spatial scale at which ecosystem services are generated or where benefits are realized (Gottfried et al., 1996; Lant et al., 2005; Fischer et al., 2009). Many of the benefits generated by farm-level decisions occur off-farm. In addition, most ecological services are public goods, resulting in a lack of markets for these services (Lant et al., 2005). Typically, farmers do not receive direct income in the marketplace from production of ecosystem services. Over time this has begun to change with the introduction of a number of limited regulated markets for these services, which include markets for carbon sequestration (e.g. European Union Trading Scheme, Chicago Climate Exchange), water quality, and biodiversity (Stanton et al., 2010).

Production of ecosystem services depends on the scale of analysis chosen and is often sensitive to location. From the perspective of climate change mitigation, the value of a ton of sequestered carbon is independent of where that ton is sequestered (Lant et al., 2005); although, the amount of carbon sequestered and the cost of sequestering carbon are sensitive to location. Also, if sequestering a ton of C changes the production of market products, this could affect market prices, resulting in changes in land use elsewhere, potentially offsetting some of the C emission reductions (Lubowski et al., 2006). In contrast, ecological services related to biodiversity and wildlife habitat, are greatly affected by the spatial pattern of vegetative cover (Gottfried et al., 1996). Similarly, the spatial pattern of landscapes affects the flow of nutrients or sediments in surface waters (Gottfried et al., 1996), so the geographical pattern of land uses as well as total allocation among land uses may be important (Lant et al., 2005). This can result in a nonlinear relationship between land use and ecosystem services produced, and may require coordination of management across multiple farms (Lant et al., 2005). These spatial dependencies are relevant to the ongoing debate on the relative advantages of intensification versus extensification for meeting agricultural production demands including meeting biofuel demands (Green et al., 2004; Jordan et al., 2007). With the 'intensification option' efforts are focused on increasing agricultural production on existing lands, allowing other lands to be dedicated to ecosystem service provision, while the 'extensification option' may spread production over a greater area, but focuses on farming in ways that enhance provision of ecosystem services on the farmed lands. The presence of spatial dependencies may mean that the economic optimum provision of ecosystem services may include a mix of the 'intensification option' and the 'extensification option', and that neither the intensive or extensive solution is strictly preferred (Hennessy and Lapan, 2010).

However, some benefits of ecosystem services do occur at the farm level. It has been argued that supporting services are intermediate services that serve as inputs to the production of the provisioning outputs of food, fuel, and fiber (Wossink and Swinton, 2007). As such, these services have economic value to the farmer tied to the impacts of these services on production of marketable farm goods, either as changes in purchased input costs or the value of productivity changes. Due to this 'jointness in production', if production of agricultural goods and ecosystem services are complements, producers may have economic incentives to provide these services, even if the ecological services are not directly marketable (Wossink and Swinton, 2007). These complementaries may also reduce incentives needed to entice greater provision of ecosystem services (Wossink and Swinton, 2007). Although, it is often believed that provision of ecosystem services will require economic tradeoffs, this illustrates the potential for win-win opportunities when ecosystem services are complementary to production of agricultural goods. Maintaining soil C may be an example where production of ecosystem services and agricultural goods are complementary.

Cellulosic Biofuel Feedstocks and Ecosystem Services

The impact from harvesting crop residues, perennial grasses and wood biomass as cellulosic biofuel feedstocks has been a significant source of multi-disciplinary research. A brief review of research findings on the potential impacts on other ecosystem services is provided in Table 1. While cellulosic biofuel feedstock production may provide an additional income stream for farmers and may reduce net greenhouse gas emissions, studies show adverse outcomes from residue removal may result. To sustain ecosystem services on the farm, some long-term studies have found that incorporating conservation practices (no-tillage, cover crops and crop nutrient management) into farming systems and limiting the quantity of residue removed may significantly reduce the effects from residue removal (Lafond et al., 2009; Hooker et al., 2005; Wilhelm et al., 2004).

Cellulosic Biomass Feedstock	Reported Impact from Biomass/Residue Removal	Source
Corn stover	Reduction of green house gas emissions	Sheehan et al., 2003; Adler et al., 2007
	Loss of SOC	Gabrielle and Gagnaire (2008); Anderson-Teixeira et al., (2009); Wilts et al. (2004); Allmaras et al. (2004); Blanco-Canqui and Lal (2009b)
	Reduction in soil aggregate stability	Blanco-Canqui et al. (2006b)
	Reductions in soil microbiology	Blanco-Canqui and Lal (2007)
	Soil compaction and soil erosion	Blanco-Canqui and Lal (2007); Mickelson et al. (2001)
	Decrease in soil water retention	Blanco-Canqui and Lal (2007)
	Nutrient removal (N, P, K)	Blanco-Canqui and Lal (2009b); Propheter and Staggenborg (2010)
	Decrease in cash crop yields	Wilhelm et al. (1986)
Wheat straw	Reduction of green house gas emissions	Dornburg et al. (2005)
	Loss of SOC	Saffih-Hdadi and Mary (2008); Cherebini and Ulgiati, (2010); Gabrielle and Gagnaire (2008)
	Reduction of soil aggregate stability	Black (1973)
	Nutrient removal (N,P,K)	Black (1973)
	Decrease in cash crop yields	Gabrielle and Gagnaire (2008)
Perennial grasses	Reduction of green house gas emissions	Schmer et al. (2008)
	Change in SOC -Increase or no change -Loss in SOC with excess removal	Tilman et al. (2006) Liebig et al. (2008); Skinner (2008)
	Nutrient removal (N,P,K)	Propheter and Staggenborg (2010)
Woody crops	Loss of SOC	Blanco-Canqui (2010)

Table 1. Reported effects of biomass harvesting and/or removal in the literature for alternative biofuel feedstock sources.

Much of the research has focused on crop residue removal. Crop residues left on the soil provide a variety of ecosystem services, namely nutrient cycling, soil carbon sequestration, improvement of soil physical properties, erosion control and crop productivity (Lal, 2008). Soil carbon is the predominantly studied factor. A positive relationship between residue returned to the soil, carbon sequestration and SOC pools has been established (Kong et al., 2005; Parton and Rasmussen, 1994; Paustian et al., 1992; Saffih-Hdadi and Mary, 2008). Hence, leaving crop residue in the soil results in higher SOC levels (Maskina et al., 1993; Wilhelm et al., 1986; Wilts et al., 2004), especially if accompanied with conservation practices (Allmaras et al., 2004). Another significant economic benefit of residue retention is higher potential cash crop yields, evidenced by improvements in soil properties as a result of higher SOC (Power et al., 1998). Higher levels of SOC can improve soil stability, nutrient availability, microbial activity, soil and crop productivity, as well (Chan et al., 2002; Vasques et al., 2010; Wilhelm et al., 2004).

Farmers' Willingness to Produce Biofuel Feedstocks and Biofuel Markets

The adoption process for biofuel crops and associated technologies is complex and risky. Agricultural producers are faced with the prospect of growing new and unfamiliar crops; harvesting crop residue from traditional crops with uncertain impacts on farm labor, equipment and soil resources; dealing with new crop and crop residue markets; and incorporating new technologies into their production systems (Rajagopal et al., 2007). A very limited number of studies have examined the adoption of alternative cellulosic biofuel feedstocks. Anand et al. (2008) examined the potential for harvesting winter cover crop residue (e.g. rye and wheat straw) in Alabama for cellulosic ethanol production. Bransby (1998), Hipple and Duffy (2002), and Jensen et al. (2007) have examined the adoption of switchgrass in Alabama, Iowa and Tennessee, respectively. Kelsey and Franke (2009) examined the potential for adoption of bio-energy crops in Oklahoma. The studies found that factors such as government programs, monetary incentives, education, irrigation, off-farm income, and conservation mindedness all had a significantly positive impact on adoption. On the other hand, factors such as farm size, land tenure arrangements, intense conservation behavior, risk, impacts on cash crop production practices, lack of bio-energy crop insurance, and lack of biofuel feedstock markets had a significantly negative impact on adoption. Of significance, is that the profitability of producing biofuel feedstocks versus other land-use alternatives was the most relevant factor impacting farmers' choices. Bransby (1998) reported that farmers would need $254 per acre of profit on average to plant switchgrass in Alabama, while farmers in Oklahoma indicated they would need an increase of $20 per acre to remove land from the Conservation Reserve Program to grow dedicated bio-energy crops (Kelsey and Franke, 2009). Anand et al. (2008) found that, for farmers willing to harvest cover crop residues as a cellulosic biofuel feedstock, the mean price that they would be willing to accept is $55 per dry ton. The availability of incentive programs, like the Biomass Crop Assistance Program (BCAP) can help improve the profitability of biofuel feedstock production, particularly for perennial feedstocks with high establishment costs (James and Swinton, 2009).

Bransby (1998), Jensen et al. (2007), and Kelsey and Franke (2009) all indicate that farmers may be willing to enter into long-term contracts for biofuel production. Long-term contracts are a likely necessity to ensure adequate feedstock supplies for both processors and bio-refineries. Investments into biofuel conversion facilities are not likely, unless feedstock supply can be assured in the long-term (Rajagopal et al., 2007). Larson et al. (2007) examined different contracting arrangements between processors and producers where biomass price, yield and production cost risk is born entirely or shared by both parties. Biomass price and revenue varies between alternative contracting arrangements. Larson et al. (2007) found that contracts that provide a guaranteed biomass price or guaranteed gross revenue per acre, where a portion of the price and/or yield risk is assumed by the processor, provided the highest guarantee of biomass production at prices ranging from $40 to $80 per dry ton. As per the law of supply, higher biomass prices resulted in greater production, with risk-averse farmers requiring a higher price to produce. Epplin et al. (2007) examined alternative contracting arrangements in Oklahoma related to land leases and production contracts for the supply of biomass to refineries. They found that contracting prices under either scenario would range from $48 to $67, which corresponded with actual contracting bids for switchgrass production in a Tennessee study (Clark et al., 2007). Other significant contracting components that will affect the adoption of these practices and that need further examination, include contractual components concerning timeframes, acreage commitments, timing of harvest, feedstock quality issues, biomass harvesting responsibilities (e.g. custom harvesting), technical assistance, nutrient replacement costs, water use and conservation, as well as environmental stewardship considerations (e.g. soil erosion) (Altman et al., 2007; Epplin et al., 2007; Glassner et al., 1998; Larson et al., 2007; Stricker et al., 2000). Many of these contractual considerations will affect the adoption of biofuel feedstock alternatives and need to be considered more closely to ensure farmers' willingness to supply cellulosic feedstocks in the long-term.

Case Study

This section of the chapter examines a case study that tries to balance cellulosic biofuel feedstock production with ecosystem services at the farm level. The purpose of the case study is to examine the economic and environmental feasibility of harvesting corn stover for ethanol production. The case study uses experimental data from a research farm in Morris, MN. A non-linear programming profit-maximization model was developed in Excel to determine optimal tillage practices and corn stover removal rates while giving consideration to environmental concerns, such as sustaining or improving soil quality and reducing soil erosion. Given the importance carbon plays in agro-ecosystems and the sustainability of a number of ecosystem services, SOC is used as a proxy for ecosystem service benefits provided by crop residues left on the soil surface.

Corn Stover as a Cellulosic Biofuel Feedstock

Corn stover has emerged as one of the potential major cellulosic biofuel feedstock sources for ethanol production in the U.S. (Wilhelm at el., 2004; Aden et al., 2002). Corn residue can provide as much as 1.7 times more carbon than residue produced by other crops such as barley, oats, sorghum, soybeans, sunflowers, and wheat (Allmaras et al., 2000). The harvesting of corn stover for biomass production may provide farmers an additional revenue generating source, but such an enterprise may result in both agronomic and environmental costs. These costs include: potential crop yield reductions, degradation in soil quality due to changes in SOC levels, and other adverse changes in soil properties (e.g. water infiltration, temperature, and nutrient balance) (Wilhelm et al., 2004). Wilhelm et al. (1986) showed that harvesting crop residues from the soil surface can result in lower corn yields due to lower soil organic matter content.

Though maintaining crop residues for soil and water conservation is important for sustainability purposes, there may be potential for partial corn stover removal as a biofuel feedstock enterprise, which may not significantly affect cash crop yields, and still help prevent soil erosion and maintain or increase soil organic matter (SOM) levels. Blanco-Canqui et al. (2006a) found an increase in corn stover removal rates may have a positive, negative or neutral effect on corn yield due to climate, soil topography, tillage system adopted, and agri-ecosystem characteristics.

The Farm Model

The farm model is based on a risk-neutral farmer, who is a profit maximizer, deciding whether or not to harvest corn stover as a new cellulosic biofuel feedstock enterprise. The farmer is assumed to grow two cash crops in a fixed two-year rotation (corn-soybean) and has the choice of applying different tillage practices (no-tillage, strip-till, chisel + disk, or moldboard plow). Table 2 provides an overview of the model including the farmer's objectives and the constraints the farmer is assumed to face.

Component	Functional Representation	Description
Farming Objective		
Maximize Profit	$\prod_j = \left[\sum_{i,j} D_{i,j}\left(Y_{i,j}p_i^c - w_{i,j}^c\right)\right] + \left[\begin{array}{l}(p^b b_j R) - (H^b + L^b b_j R + S^b b_j R \\ + T^b b_j R d + N_j^c + P_j^c + K_j^c + M_j^c)\end{array}\right]$	The profit function represents the net return from crop production plus the net return from harvesting corn stover as a cellulosic biofuel feedstock.
Model Constraints		
Yield Response	$Y_{i,j} = \alpha_{i,j} + \beta_{i,j}R \quad \forall (i,j)$	These functions estimate cash crop yield for corn and soybeans based on corn stover removal rates and tillage practice used.
Nutrient Accounting	$N_j^c = \phi_j + \sigma_j R \quad \forall j$ $C_j = \gamma_j + \delta_j R \quad \forall j$	These functions estimate the amount of N to maintain crop yields (to be replaced) and the loss of SOC.
Residue Retention	$R \le \eta_j$	This constraint limits the amount of corn stover that can be removed from the field.
Change in SOC	$C_j \ge 0 \quad \forall j$	This constraint requires that the change in SOC levels remain positive or at current levels.
Non-negativity	$R \ge 0$	Biomass removal rates cannot be negative.

Notation Used:

b_j = Amount (tons/acre) of corn stover produced using tillage *j;*
C_j = Annual average change in SOC in lbs/acre/year for tillage practice *j*
$D_{i,j}$ = Dummy variable indicating the choice of tillage practice *j* for crop *i*;
d = Distance to the refinery
H^b = Harvesting costs for corn stover ($/acre);
i = Crop Index: Soybean or corn;
j = Tillage Index: No tillage, strip-till, chisel + disk, or moldboard plow;
K_j^c = Cost of K application;
L^b = Loading costs of corn stover ($/ton);
M_j^c = Estimated cost of replacing lost carbon in soil;
N_j^c = Cost of additional N application to maintain yields;
p^b = Price ($) per unit for corn stover;
p_i^c = Price ($) per unit for crop *i*;
P_j^c = Cost of P application;
R = Percent corn stover removed per acre;
S^b = Storage costs of corn stover ($/ton);
T^b = Cost of transporting corn stover ($/ton/mile)
$w_{i,j}^c$ = Variable cost for producing cash crop *i* using tillage practice *j* ($/acre);
$Y_{i,j}$ = Yield per acre of crop *i* using tillage practice *j*;
η_j = Maximum permissible level of biomass that can be removed for tillage practice *j*;
α, β, φ, σ, γ and δ are estimable parameters.

Table 2. Farm Optimization Model

The farmer's overall objective is to maximize profit, which is the net return from crop production (given the rotation) plus the net return from harvesting corn stover for cellulosic ethanol production. It is assumed that the variable costs for a tillage practice are held constant except for fertilizers which may change with biomass removal. The fertilizer costs are captured in each tillage practice based upon the amount of biomass removed. Given that corn stover is a byproduct of the cash crop, it is assumed the farmer does not incur any direct production costs for growing corn stover. The farmer would incur costs associated with harvesting, moving, loading, storage and transporting of corn stover if it is sold as a biofuel feedstock and depending on potential contractual obligations with the processor or bio-refinery (Epplin et al., 2007). The cost of additional nitrogen (N), phosphorus (P), potassium (K) and estimated carbon replacement costs are tillage specific and are a function of the amount of the biomass removed and are discussed in detail in the next section. The inclusion of the cost of C in the objective function is to represent a cost for the loss in SOC.

The model has a number of constraints that incorporate the environmental objectives of the farmer to maintain SOC and incorporate impacts on cash crop yield and nutrient loss. Removing corn stover may result in lower crop yields due to lower soil productivity. These changes are modeled using crop yield response functions estimated using simulated data from the Environmental Policy Integrated Climate (EPIC) simulation model (Williams et al., 2006).

To maintain cash crop yields the farmer may need to replenish lost nutrients from the removal of crop biomass. Additional applications of N, P, and K would be required to compensate for the nutrients lost due to biomass removal. Application rates for supplemental N are dependent on the amount of residue removed and are estimated from the EPIC application rates based on the auto-fertilization option applying N to meet crop needs. Application rates for P and K were 1.58 lbs/ton of stover removed and 13.48 lbs/ton of stover removed (Hoskinson et al., 2007). These rates are comparable to rates used by Sheehan et al. (2003) of 1.6 lbs/ton and 15.2 lbs/ton of stover removed for P and K, respectively.

Farmers' net returns from biomass operations are dependent on the amount of biomass harvested. One may expect higher profits with higher biomass removal rates. However, various constraints affect the amount of biomass that can be harvested. Current harvesting technologies may not allow all the biomass to be harvested. Furthermore, farmers concerned about soil erosion may use conservation tillage practices that require at least 30% residue cover remain on the soil surface to meet conservation standards and various conservation programmatic requirements. Another related environmental constraint is sustaining or improving soil organic matter levels. Soil organic matter changes as measured by SOC changes in the model are assumed to be dependent upon the amount of biomass removed and are estimated using a response function. Again, the parameters for the SOC changes were estimated using EPIC simulation data. To maintain SOC levels, the change in SOC levels is constrained to be non-negative. For further detail concerning the nonlinear farm optimization model see Anand (2010).

Experimental Data

Crop yield data (see Table 3) were obtained from a tillage management study conducted at the USDA Agricultural Research Service Swan Lake Research Farm near Morris, MN. While the study design will be briefly described here, further details are available in Archer and Reicosky (2009). This seven year experiment (1997-2003) studied a corn-soybean rotation with eight tillage systems in a randomized complete block design with five replications. The plot size was 9.1 m wide (12 rows, 76 cm row spacing) by 27.4 m long. Tillage treatments included No-Till (NT), Moldboard Plow (MP), Chisel Plow (CP), and five strip till alternatives: Fall Residue Management (RM), Fall RM + Strip Till (ST), Spring RM, Spring RM + ST, and Fall RM + Subsoil. All crop and tillage treatments were present each year. Levels of herbicide application, fertilizer and seeding rates were kept the same for all practices (Archer and Reicosky, 2009). Planting and harvest dates for all practices were also kept the same. Of the eight tillage practices, this study focused on NT, MP, CP and ST to compare two conventional and two conservation tillage systems using yield data from the experiment. Experimental yield data were used in estimating production costs and in calibrating the model yields are described in the following sections.

Tillage Practices	Soybean Yield (Bu/acre)	Corn Yield (Bu/acre)
Moldboard Plow	45.90	158.79
Fall residue mgmt and strip till	43.96	161.63
Chisel Plow	45.37	159.72
No-Till	44.09	157.27

Table 3. Average Crop Yields at Swan Lake Research Farm near Morris, MN. 1997-2003. Source: Archer and Reicosky, 2009.

EPIC Modeling and Response Function Estimation

Simulation modeling was conducted using the EPIC model (Williams et al., 2006) with the i_EPIC interface (Gassman et al., 2003). Soil input data were from the SSURGO database (Soil Survey Staff, 2010), and daily weather data were from the University of Minnesota West Central Research and Outreach Center in Morris, MN. Simulation was conducted for a period of 20 years using daily weather data for 1984 to 2003 for a Barnes loam soil (fine-loamy, mixed, superactive, frigid Calcic Hapludoll), which is a common soil type in western Minnesota as well as eastern North Dakota and northeastern South Dakota. The aforementioned tillage systems study was predominantly conducted on this soil type. Model parameters were calibrated so that simulated 1997-2003 average corn and soybean yields matched average observed yields from the above described experiment within a range of ±5% for each of the tillage treatments in the field study.

Modeled management practices in the EPIC model were based on the management practices used in four of the tillage system treatments from the field study: moldboard plow (MP), chisel plow (CP), fall residue manager + strip tillage (ST), and no-till (NT). Corn stover harvest (or removal) treatments were simulated for 10% increments ranging from 0 to 90% of the above ground biomass. Simulated yields were then calibrated using actual yields for a more accurate representation of field conditions. The EPIC simulation output included the crop yields, SOC changes (to a depth of 1.52 m), and amount of N application for each tillage practice to maintain crop yields. In addition, the same simulations were run without any supplemental N being applied to the cash crop to examine cash crop yield loss from residue removal.

EPIC model simulation results for SOC change as related to biomass harvest rate for each tillage system are shown in Figure 1. Response functions for yield, N fertilizer use, and SOC change (Table 4) as a function of biomass removal rate were estimated in Microsoft Excel using the simulated data obtained from the EPIC model. These response functions allow the economic model to optimize over a continuous range of biomass harvest rates from 0 to 100%. Statistical tests found that a linear relationship between the dependent variable and biomass removal rate provided the best fit. Response functions for SOC, soybean, corn and nitrogen for all four tillage practices are shown in Table 4.

	MP[1]	ST[1]	CP[1]	NT[1]
Nitrogen Supplement				
SOC	55.80-251.42R (R^2 =0.9984)	410.83-378.31R (R^2 =0.9999)	234.40-293.97R (R^2 =0.9985)	374.60-360.28R R^2 = (0.9913)
Soybean	45.91-0.09R (R^2 =0.9262)	43.93+0.42R (R^2 =0.9413)	45.36+0.09R (R^2 =0.8804)	44.03+0.34R (R^2 =0.8196)
Corn	158.81-0.15R (R^2 =0.8649)	161.84+0.39R (R^2 =0.6298)	159.70-0.03R (R^2 =0.0529)	157.34+0.46R (R^2 =0.8054)
Nitrogen	196.83+56.16R (R^2 =0.9994)	201.84+53.85R (R^2 =0.9997)	201.80+55.83R (R^2 =0.9995)	196.73+54.91R (R^2 =0.9997)
No Additional Nitrogen				
SOC	53.08-252.53R (R^2 =0.9992)	414.01-380.16R (R^2 =0.9999)	234.61-293.58R (R^2 =0.9985)	373.86-360.24R (R^2 =0.9917)
Soybean	45.91-0.09R (R^2 =0.9372)	43.93+0.42R R^2 = (0.9427)	45.36+.09R (R^2 =0.8679)	44.03+0.34R (R^2 =0.8215)
Corn	158.86-0.73R (R^2 =0.9936)	161.79-0.34R (R^2 =0.7660)	159.71-0.76R (R^2 =0.9721)	157.37-0.24R (R^2 =0.6907)

Table 4. Response Functions for Soil Organic Carbon (SOC), Soybean, Corn and Nitrogen for all Four Tillage Practices.
[1]MP:Moldboard Plow, ST:Strip Till, CP:Chisel Plow, NT:No-Till

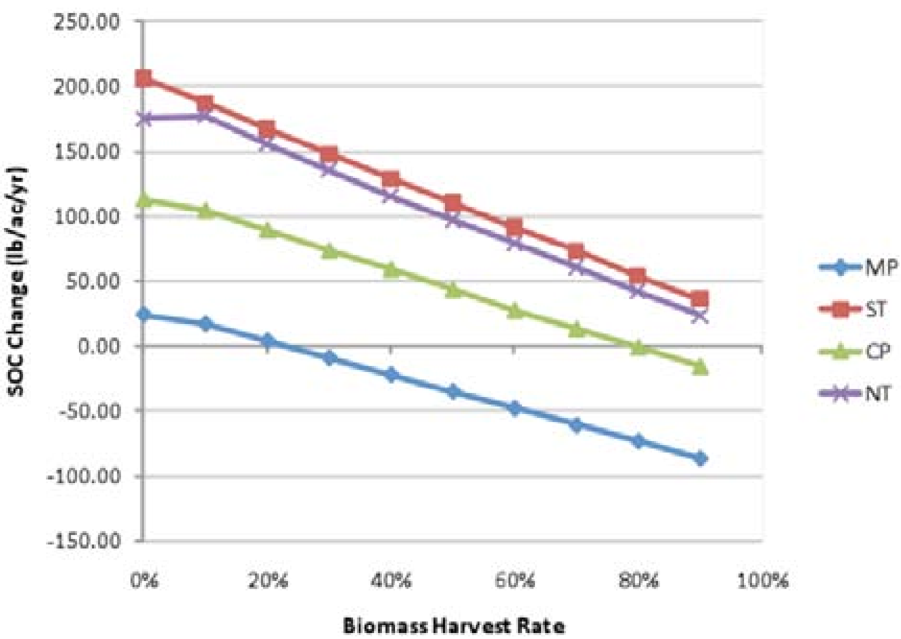

Figure 1. EPIC simulation results of annual SOC change as related to biomass harvest rate for moldboard plow (MP), strip-till (ST), chisel plow (CP), and no-till (NT) systems.

Economic and Conservation Data

Crop budgets were tabulated for all four tillage practices following Lazarus and Selley (2007) and Archer and Reicosky (2009) (see Table 5). Machinery costs were based upon Lazarus and Selley (2007) and costs for seeds, fertilizer and herbicides were the actual field costs. All costs are reported in 2008 prices. Annual prices for corn and soybean were five year averages (2003-2007) of the Minnesota price for each crop (USDA-NASS, 2010) and were $2.63bu/acre and $7.03bu/acre, respectively.

Costs for corn stover removal include harvesting (shredding, raking, baling, wrapping, moving), loading, storage and transportation. These costs were based upon Petrolia (2006) and are shown in Table 6. Prices for N ($0.49/lb), P ($0.58/lb) and K ($0.23/lb) were based on five year (2003-2007) average prices (USDA-NASS, 2010). Although the carbon lost due to biomass removal cannot be directly replenished, the costs for carbon replenishment were included in the model as an opportunity cost for reduced benefits due to lower SOC. Since, carbon prices vary widely amongst different sources, the base carbon price was assumed to be $0.01/lb. We later used a range of prices $0.01/lb to $0.20/lb in sensitivity analyses to reflect different pricing scenarios.

Tillage System	No-till	Moldboard Plow	Chisel Plow	Fall RM + Strip Till
Corn Production:				
Labor	6.89	11.34	9.77	8.67
Repairs	7.54	11.58	9.18	8.73
Diesel Fuel	6.51	13.62	10.39	10.29
Seed, Fertilizer, Herbicide	112.46	112.46	112.46	112.46
Interest	5.03	5.84	5.43	5.37
Depreciation	19.83	32.10	27.47	28.41
Drying Fuel	40.90	39.12	36.21	39.10
Total Operating Costs	199.17	226.06	210.91	213.05
Overhead	14.73	24.98	21.04	21.28
Total Cost	213.90	251.05	231.94	234.33
Soybean Production:				
Labor	6.32	12.04	10.46	8.10
Repairs	6.46	11.35	9.12	7.65
Fuel	5.76	13.89	11.23	9.52
Seed, Fertilizer, Herbicide	70.82	70.82	70.82	70.82
Interest	2.11	3.12	2.72	2.45
Depreciation	16.01	30.53	26.78	24.54
Drying Fuel	1.11	0.66	0.67	0.69
Total Operating costs	108.59	142.40	131.81	123.77
Overhead	12.16	24.54	21.59	18.67
Total Cost	**120.75**	**166.94**	**153.40**	**142.44**

Table 5. Cash Crop Cost Budgets for Corn and Soybean, 2008 ($ per acre). Source: Archer and Reicosky, 2009.

Operation	COST		
Shredding[1]	10.63	$/acre	
Raking[2]	6.80	$/acre	
Baling	12.67	$/acre	
Wrapping	4.60	$/ton	
Moving	4.57	$/ton	
Loading	3.10	$/ton	
Storage	7.31	$/ton	
Transportation	0.303	$/ton/mile	w/in 25 miles of plant
	0.198	$/ton/mile	26-100 miles from plant
	0.16	$/ton/mile	>100 miles from plant

Table 6. Biomass Costs for Corn Stover Removal. Source: Petrolia, 2006.

[1] Assumed this was done in conventional till (CT) regardless of whether biomass harvested.
For Strip Till (ST) it is assumed this would only be used if raking (>30% harvest).

[2] Assumed this would only be used for >30% harvest, otherwise could just bale the windrow.

Since farmers using conservation tillage practices (e.g. no-till) should maintain at least 30% ground cover to maintain eligibility for conservation payments, maximum permissible limits for biomass removal were calculated using the National Agronomy Manual (USDA-NRCS, 2002). Note that this limit would not apply if a producer did not wish to maintain eligibility for conservation payments, but we use this limit to illustrate the potential impact of maintaining conservation payment eligibility. For corn a 30% residue cover translates into 950 lbs/acre of residue weight to be left on the field. The total biomass available on the field in our experiments is 6,600 lbs/acre. For no-till, the adjustments for over winter decay (88% residue retention) and planter/no-till coulter usage (85% retention) were made, resulting in a maximum removal rate of 81%. For Strip till, adjustments for anhydrous application (80% retention), over winter decay (88% retention) and planter/no-till coulter usage (85% retention) were made resulting in a maximum removal rate of 76%. Limits on technically feasible harvest rates were not included in this analysis, so, for the conventional tillage practices, 100% removal was allowed. However, note that residue harvest rates are also limited indirectly in the model by the constraint that SOC changes be non-negative. This constraint will typically restrict maximum harvest rates within conventional tillage practices.

Contracting and Model Simulations

Various contract options between the farmer and a bio-refinery or intermediate processor in terms of farmer responsibilities for corn stover harvest are examined. Contracts are the likely market vehicle for emerging biomass markets and may be desired by both refineries and farmers to guard their investments. Refineries need a long-term sustainable supply, and farmers may require a strong commitment by bio-refineries to purchase their biomass. Five contractual cases based on farmer and bio-refinery responsibilities are examined. They include:

Case 1: Farmer is responsible for harvesting, loading, transport and storage costs (HLTS).

Case 2: Farmer is responsible for harvesting, loading and transport costs (HLT). No storage costs are incurred as farmer would transport the biomass as soon as it is harvested.

Case 3: Farmer is responsible for harvesting and loading (HL) and the refinery would be responsible for transport of biomass.

Case 4: Farmer is only responsible for harvesting (H). The refinery would load and transport it.

Case 5: Farmer is not responsible for any production costs (None). The refinery would harvest, load and transport the biomass.

Case 2 represents the base case for simulations. These cases represent potential contracting situations which may arise between farmers and bio-refineries for corn stover production (Epplin et al., 2007; Rajagopal et al., 2007). Model results under each case provide an examination of farm profitability under various contractual situations.

Simulations were then conducted to study the impact of changes in biomass prices and changes in carbon prices on farm profit. Variation in biomass prices would affect farmers' breakeven prices and their willingness to produce and sell biomass. A simulation with changes in carbon prices is also studied to see potential impacts of carbon replenishing costs although such technology doesn't presently exist. For all simulation runs, the distance to the refinery was assumed to be 50 miles. Following Sheehan et al., (2003) who stated that the corn stover prices should be in the range of $46 to $49 per dry ton for most refineries, we assumed an initial biomass selling price of $50 per dry ton. Sensitivity analysis was also conducted varying biomass selling price from $5 to $100 per dry ton, and calculating breakeven biomass selling price.

Results

Table 7 provides the results for the farm optimization model for Case 2 (the base case) at a biomass price of $50 per dry ton for all the tillage practices examined. In addition, the results are shown for the case when supplemental N is applied and is not applied, meaning the farmer may take a yield loss. The results show that the farmer would maximize profit by adopting no-till and harvesting 81% of the available corn stover. The farmer would earn a profit of $164.73/acre by not applying supplemental N and would make only $148.53/acre by adding supplemental N. Thus, given N prices used in the model, the farmer would be better off not applying supplemental N to his crops. That is, the yield loss and subsequent revenue loss from harvesting crop biomass is less than the cost of the supplemental N. Given these findings, the remainder of the results assume no additional supplemental N is used. Within each tillage system, the economic incentive is to remove the maximum amount of residue allowable while meeting minimum residue and SOC requirements.

Tillage System	**MP[1]**	**ST[1]**	**CP[1]**	**NT[1]**	**MP[1]**	**ST[1]**	**CP[1]**	**NT[1]**
	------ Nitrogen Supplement-------				--------No Additional Nitrogen ------			
% BM Removed	0.22	0.76	0.80	0.81	0.21	0.76	0.80	0.81
SOC (lb/acre)	0.00	121.62	0.00	84.03	0.00	123.38	0.00	83.32
Corn Profit ($/Acre)	35.04	46.59	44.57	52.24	33.91	45.98	43.98	50.47
Soybean Profit ($/Acre)	77.83	84.32	82.99	95.37	77.83	84.32	82.98	95.37
Biomass Profit ($/Acre)	0.08	2.21	12.30	1.83	2.68	18.06	23.28	18.89
Total Profit	**112.96**	**132.19**	**139.86**	**148.53**	**114.42**	**148.37**	**150.25**	**164.73**

Table 7. Comparison of Farm Profits under Different Tillage Practices.
[1]MP:Moldboard Plow, ST:Strip Till, CP:Chisel Plow, NT:No-Till

To examine the sensitivity of the results to the price of cellulosic biomass, this price was varied from $5 to $100 per dry ton for each of the contract cases described in the previous section. Results are shown in Figure 2. Farmers would break even at a price of $5.10 per dry ton if the refinery agreed to harvest, load and transport at its expense (case 5). If the farmer had to incur all these costs and store the biomass (case 1), the break-even price would increase to $43.20. If the farmer decided not to harvest any biomass, then profits would be $146.15 per acre. In each case, profits are maximized with no residue removal for prices below the break even, and at the maximum allowable removal rate (subject to minimum residue and SOC constraints) for prices above the break even. Assuming a biomass selling price of $50 per dry ton, a farmer’s profits would range between $155 and $205.65 depending upon the biomass harvesting production costs incurred by the farmer. Similarly, profits would range between $221.54 and $272.18 per acre if biomass prices increased to $100 per dry ton.

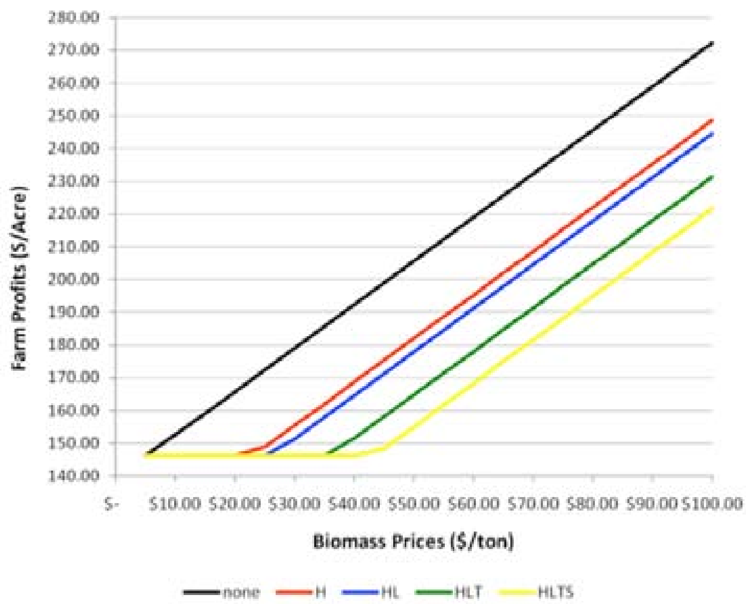

Figure 2. Change in farm profits with change in biomass prices.
None: Farmer is not responsible for harvesting, loading, transport and storage costs.
H: Farmer is responsible only for the harvesting costs.
HL: Farmer is responsible for harvesting and loading costs.
HLT: Farmer is responsible for harvesting, loading and transport costs.
HLTS: Farmer is responsible for harvesting, loading, transport and storage costs.

Replenishing lost carbon in the soil is not possible using fertilizers, unlike N, P and K, due to technological limitations. In addition, soil productivity and health are dependent on the level of carbon in the soil. Thus, removal of potential carbon from entering the soil can be captured as a cost. The model incorporates the cost of carbon as an opportunity cost of reduced soil benefits from corn stover harvest. It also has implications for climate change policy in terms of providing a dollar figure for sequestered carbon. Carbon prices were varied in simulations between $0.01/lb to $0.20/lb ($20 to $400/ton), and the cost of carbon losses relative to the no biomass harvest case were subtracted from net returns. Results show that farm profits would vary between $155 and $206 per acre for the five cases (Figure 3). Because SOC changes were a linear function of biomass removal, changing carbon prices did not lead to incremental changes in biomass harvest rates, but rather a switching point between maximum biomass harvest and no biomass harvest. The switch-over price at which a farmer would not harvest biomass due to the higher value of carbon in the soil for the five cases, HLTS, HLT, HL, H and none, would be $0.08, $0.14, $0.24, $0.26 and $0.42 respectively. Note that simulation model results showed SOC changes, and both corn and soybean yields were linear functions of residue removal rates (data not shown). As a result, net returns are linear in carbon prices, so profits are maximized by harvesting at the highest allowable rate for carbon prices below the switch-over price, with no residue harvest for carbon prices above the switch-over price.

Studying changes in profit by varying the biomass selling price can provide insight for policymakers and farmers when coupled with the impact of the percent of corn stover removed. Simulations were conducted to study changes in profit by varying the percent biomass removed from 0 to 100% and the biomass selling price from $0 per dry ton to $100 per dry ton. It was assumed that the farmer was responsible only for the shredding and the raking costs and all other production costs were paid by the refinery This has important policy implications as it allows calculations of farm payments using the biomass selling price.

A farmer using no-till could remove a maximum of 81% of the residue produced while complying with the conservation tillage requirements of maintaining 30% residue cover at planting. Assuming a biomass selling price of $50 per dry ton, the farmer would earn a profit of $199.64 per acre. If the farmer decided to harvest all corn stover, then the profits would increase to $214.16 per acre. Thus, the farmer would need to be supplied a subsidy of $14.52 per acre to maintain at least 30% residue cover with the biomass enterprise (Figure 4).

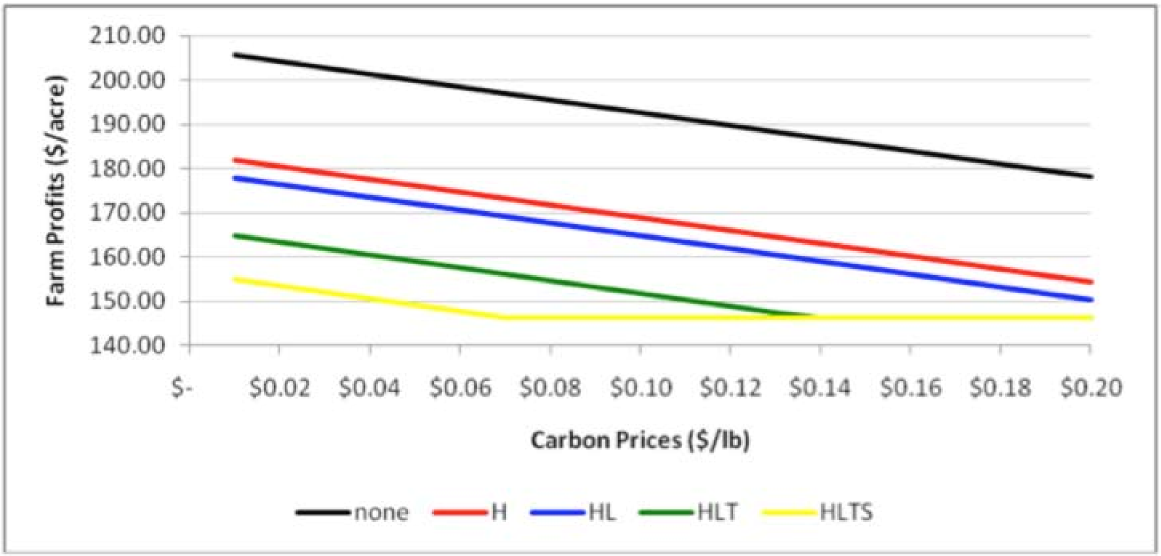

Figure 3. Change in farm profits with change in carbon prices.
None: Farmer is not responsible for harvesting, loading, transport and storage costs.
H: Farmer is responsible only for the harvesting costs.
HL: Farmer is responsible for harvesting and loading costs.
HLT: Farmer is responsible for harvesting, loading and transport costs.
HLTS: Farmer is responsible for harvesting, loading, transport and storage costs.

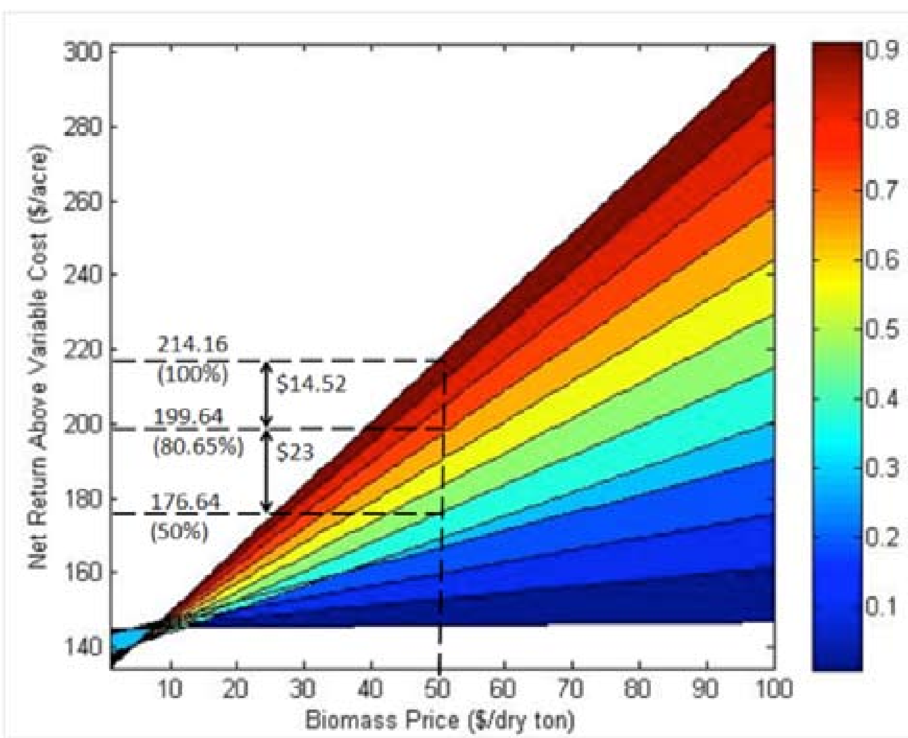

Figure 4. Response surface of farm profit versus biomass price showing removal rate contours for a case farm responsible for harvesting of the biomass for a no-till system.

The effect of limiting residue removal on economic returns has important implications when considering ecosystem services. The above example illustrates how conservation programs, such as the Environmental Quality Incentives Program, could provide support for ecosystems services related to conservation (e.g. soil erosion, nutrient leaching, etc.). While our analysis focused on soil carbon impacts, there could be other ecosystem service impacts from residue removal, such as increased erosion, increased nutrient and pesticide runoff, and decreased wildlife cover. This type of analysis can be pushed further, to examine a policy to maintain higher residue levels, perhaps to intensify the protection of these other ecosystem services. Consider the case where policy makers wish to cap the maximum allowable biomass removal at 50% in order to intensify soil conservation efforts. In this case, a profit maximizing farmer would require a subsidy of $23 per acre to compensate for voluntarily capping biomass removal at 50% (Figure 4).

Corn stover removal for ethanol production may prove to be a profitable enterprise for farmers. While SOC level declined with increasing biomass harvest rates, model results indicate the use of conservation tillage practices may provide an opportunity for farmers to profitably produce bioenergy feedstocks while increasing ecosystem services as measured by SOC relative to MP without biomass harvest. Placing limits on crop residue harvest amounts could further increase SOC; however these limits would tend to reduce farm profitability and might require incentives for voluntary adoption. The modeled potential for conservation tillage practices to allow for sustainable crop residue harvest will need to be confirmed by field research, particularly since impacts of conservation tillage practices on SOC are not incontrovertible (Baker et al., 2007).

Challenges and Opportunities

Factors other than net returns likely influence adoption. Our case example showed NT to by the most profitable tillage system with crop residue harvest. In addition, field research has indicated NT is more profitable than MP, and is competitive with CP without crop residue harvest (Archer and Reicosky, 2009), yet adoption of NT is limited in the study region. This may indicate that producers will be reluctant to adopt NT in production of biofeedstocks even if it will be more profitable.

While crop residue removal and carbon sequestration may be seen as incompatible, our case example shows it may be possible, with appropriate changes in tillage practices. Other research suggests that it is possible to balance both in integrated systems (Milder, et al., 2008). These integrated systems must take the multitude of ecosystem services into consideration to be sustainable (Mapemba et al., 2007). Thus, the goal is to develop integrated crop production systems that improve or sustain SOC levels. This can potentially be obtained through the integration of proper conservation practices, including: crop nutrient management (Allmaras, et al., 2004; Kaur et al., 2008; Lemke et al., 2010; Wilts, et al., 2004), soil amendments (Kelly et al., 1997), crop rotation (West and Post; 2002), conservation tillage (Hooker, 2005; Chan et al., 2002) and residue management (Abrahamson et al., 2009).

An alternative to the use of crop residues for bioenergy feedstock is the use of perennials such as switchgrass or miscanthus. It has been suggested that the use of perennials could help increase ecological services while meeting feedstock needs (Atwell et al., 2010; Jordan et al., 2007; Paine et al., 1996). Indeed, production and use of perennials as bioenergy feedstocks has been shown to decrease net GHG emissions (Adler et al., 2007; Schmer, et al., 2008; Tilman et al., 2006), and decrease erosion, N leaching and denitrification relative to annual crops (Vadas et al., 2008). However, a key factor is the direct and indirect effects on land use, as this has implications for global services such as net GHG emissions (Searchinger et al., 2008) or local services such as natural pest control services (Landis et al., 2008). If perennials are grown on existing cropland, this could result in forest or other sensitive lands being converted to crop production increasing GHG emissions on the newly converted lands (Searchinger et al., 2008). Also, it is difficult for perennial biomass crops to be economically competitive with annual crops on productive land (James et al., 2010); although, there are some cases where perennial/annual crop rotations may be viable (Vadas et al., 2008).

Many have suggested that perennial bioenergy crops (e.g. switchgrass or miscanthus) and/or short rotation woody crops be grown on sensitive, marginal, degraded, idle or abandoned lands (Blanco-Canqui, 2010; Campbell et al., 2008; Lemus and Lal, 2005; Paine et al., 1996; Tilman et al., 2006). Since these lands often have low productivity for annual crop production or are not currently used for crop production, using these lands for perennial biomass energy crops would reduce or eliminate the need to bring additional lands into annual crop production. Also, these are the lands where perennial biomass production is likely to be more economically produced (McLaughlin et al., 2002; Walsh et al., 2003).

Cover crops, such as small grains grown for conservation purposes, may provide another cellulosic biomass source as an alternative to crop residues (e.g. corn stover). While a portion of the cover crop residue (e.g. rye straw) would be harvested, the cover crop will still likely provide a myriad of conservation benefits, while still helping to maintain residue levels in conservation cropping systems. Cover crops can boost soil productivity as they increase SOC levels, improve water infiltration and reduce soil erosion (Reeves, 1994; Wilhelm et al., 2004). These benefits are primarily realized in the form of improved cash crop yields from improved soil productivity following the cover crop (Lotter et al.; 2003). Cover crops also play a role in improving weed suppression, nutrient cycling and cash crop yield stability (Creamer et al., 1996; Lotter et al., 2003; Snapp et al., 2005). The decision to grow heavy residue cover crops as a biofuel feedstock may be complicated by the reduction in conservation benefits resulting from biomass removal from the soil surface. Although these benefits may not be assigned a direct monetary value, it is necessary for the farmer to weigh the agronomic, economic and environmental benefits and costs, when considering growing a cover crop as a cellulosic biofuel feedstock source (Wilhelm et al., 2004). Additionally, the potential for growing high yielding cover crops may be limited in some regions due moisture and growing season limitations (Johnson et al., 1998; Unger and Vigil, 1998).

Anand (2010) and Anand et al. (2008) examined the willingness of farmers in Alabama to supply cover crop residue as a biofuel feedstock source. Fifty-seven percent of the farmers surveyed indicated they would be willing to produce a cover crop for biofuel production. The results provide some basis that farmers are willing to supply cover crops residues at the right price. Modeling results indicated that the minimum price farmers would be willing to accept for a dry ton of rye or wheat straw (when used as a cover crop) is $54.62, which is in line with other predicted market prices. They assume that the farmer would be responsible for harvesting and transporting the stover to the refinery.

Within all of these systems, moderate volumes of biomass may be harvested for biofuel production, differing on a site-by-site basis. The determination of the volumes and frequency of biomass or residue removal that is sustainable without adversely affecting SOC pools and ecosystem services is site specific and needs to be determined (Cherebini and Ulgiati, 2010; Lafond et al., 2009; Wilhelm et al., 2004).

While SOC may serve as a proxy for the provision of many ecosystem services, there are many other ecosystem services that were not included in the case example, many of which would be spatially dependent. This greatly complicates analysis that would lead to a full accounting of ecosystem services. In addition to the externality aspects of ecosystem services, this complexity and uncertainty in quantifying ecosystem services serves as a cause for market failure in the provision of these services (Yang et al., 2010). Hence, there is a need to improve our capacity to quantify impacts of our actions along with appropriate measures of uncertainty (Carpenter, et al., 2009).

Conclusion

Our case example showed the potential for corn stover to be harvested for bioenergy, providing both positive economic returns and increasing ecosystem services, as measured by changes in SOC, if tillage was switched from MP to NT. Our results also quantified economic incentives necessary to further increase provision of ecosystem services. However, the results were for a single site, with a single soil type. Changes in SOC are tied directly to the ecosystem services of climate regulation which is not sensitive to where C sequestration occurs. Changes in SOC have other potential ecosystem service effects which are sensitive to location (e.g. effects on water quality and quantity). In addition, bioenergy feedstock production can have impacts on a wide range of other ecosystem services. In evaluating potential for bioenergy production to increase provision of ecosystem services, it will be important to include multiple sites and multiple ecosystem services, and include spatially sensitive impacts.

Our case example analyzed net returns and ecosystem impacts for several contract alternatives. However, the analysis did not include uncertainty. Contract provisions will be particularly important under uncertainty, as will be potential impacts of bioenergy production on economic and ecosystem risks. This is an important area for future analysis as is inclusion of factors other than economics that may influence adoption of biofeedstock production alternatives.

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Chapter 13

Municipal Solid Waste as an Advanced Biofuels Feedstock – A Brief Summary of Technical, Regulatory, and Economic Considerations

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Abstract

Renewable energy technologies are being looked at as significant new sources to meet our current and future energy needs. Investments in research, development, and deployment of cellulosic biomass sources and conversion technologies for both power and transportation fuels are underway and will continue to grow. Some challenges include: securing cost- competitive reliable sources of quantities large enough to meet our energy needs; carrying capacity of infrastructures to harvest/ collect, sort, and pre- process biomass feedstocks and transport and store products; technologies capable of converting these into consumable cost- competitive energy products; and ensuring environmental and public health protection and benefits. Much attention is given to agriculturally derived feedstocks; however a diverse range of wastes, including municipal solid wastes (MSW), sewage sludge, food processing wastes and manures, also have potential to serve as advanced biofuels feedstock. These materials can be converted using a variety of technologies. Although they present some challenges, they also potentially present significant environmental and economic benefits for farmers, municipalities, and industries. This paper looks more closely at MSW as a potential feedstock, identifying a number of technical, economic, environmental, and public health questions for which future research, analysis, and demonstration are needed.

Introduction

The Energy Independence and Security Act mandated an increase of 36 billion gallons per year (BGY) of renewable fuels be blended into our transportation fuels by 2022. Cellulosic biomass sources are expected to provide 16 BGY (or 44%) of that total. Cellulosic feedstocks, including agricultural plant residues, wood, perennial grasses and other crops grown specifically for fuel production, and secondary materials derived from industrial processes such as sawdust and paper pulp, have the potential to be converted to biofuels. Another feedstock that has not been given as much attention is municipal solid waste. These oftentimes overlooked resources can be a reliable supplemental feedstock given their consistent generation and availability, and existing infrastructures of storage and transportation networks. Use of wastes can often translate into indirect environmental and economic benefits, having the potential to transform materials with high management costs into potentially high revenue-generating feedstocks. Municipal solid waste (MSW) and construction and demolition debris (CDD) diverted from landfills avoids generation of methane gases that would otherwise occur in a landfill. In the State of Maine, diverting post- recycled or non- reusable portions of waste has resulted in an 85- 90% reduction in landfilling needs, helping to extend the lifetime capacity of the landfill.[1] Use of MSW for energy products, including advanced biofuels, presents a number of potential benefits and co- mingling this continual source of feedstock may be a good supplement to other seasonally produced cellulosic feedstocks. This paper frames a number of technical, environmental, regulatory, and economic considerations in looking at the feasibility of MSW waste as an advanced biofuel feedstock for future research consideration.

A number of technical, economic, environmental, and social/political factors need to be considered in understanding benefits and challenges of using MSW. Technical considerations include regional reliability of wastes, characteristics of the waste, and compatibility with and efficiency of conversion technologies. Environmental performance, including air and water emissions, greenhouse gases, and waste generation can affect both costs and public acceptance. Economic factors include infrastructure costs to collect, transport, and convert wastes compared to infrastructure for other management options, such as recycling, waste- to- energy conversion, composting, and/or ultimate disposal; and comparative economics of its use for fuels versus power and/or other products.

State and national regulations and policies may also limit the use of wastes. Under EPA's recently promulgated Renewable Fuel Standard, advanced fuels must be derived from feedstocks that meet the definition of renewable biomass. Producers can use separated MSW (defined as material remaining after separation actions have been taken to remove recyclable paper, cardboard, plastics, rubber, textiles, metals, and glass) as feedstock to generate Renewable Identification Numbers (RINs) for their fuel.[2] In essence, this translates largely to yard and food wastes and construction and demolition wood debris.

Technical Considerations

Technical and economic feasibilities are often inter- dependent when considering feedstock/ conversion/energy product options. As a result, proof of concept, and cost- effective pilot scale demonstrations, and commercial scale implementation of feedstock/conversion pathways have, understandably, been priorities for research. However, it is important to characterize and understand other factors to operationalize feedstock production and use, including infrastructures needed to harvest, collect, process/pre- treat, and transport feedstock. Availability, reliability, composition, and density of feedstock supply will all affect technical and economic efficiencies. These considerations are briefly discussed for MSW as a potential supplemental feedstock.

Availability and Reliability of Feedstock

It is estimated that as much as 60 BGY of renewable fuels could be produced from a billion dry tons of biomass. The "Billion Ton Report," released in April 2005 by the U.S. Department of Energy and the U.S. Department of Agriculture, indicates a potential production of 1.36 billion tons of biomass per year, comprised of 428 million tons from annual crop residues, 368 million tons from forest residues and 377 million tons from 55 million acres of dedicated energy crops, along with grain and other miscellaneous sources.[3] (These estimates most likely will change once the revised DOE study, "Biomass as Feedstock for a Bioenergy and Bioproducts Industry: An Update to the Billion- Ton Annual Supply" is completed and published.[4]

Agricultural residues and energy crops vary geographically (Figure 1), are produced seasonally, and are dependent on a number of factors including precipitation, nutrients, and climate.[5] Seasonal availability of biomass requires periodic harvest and siting of land for longer- term storage of biomass for year round use.

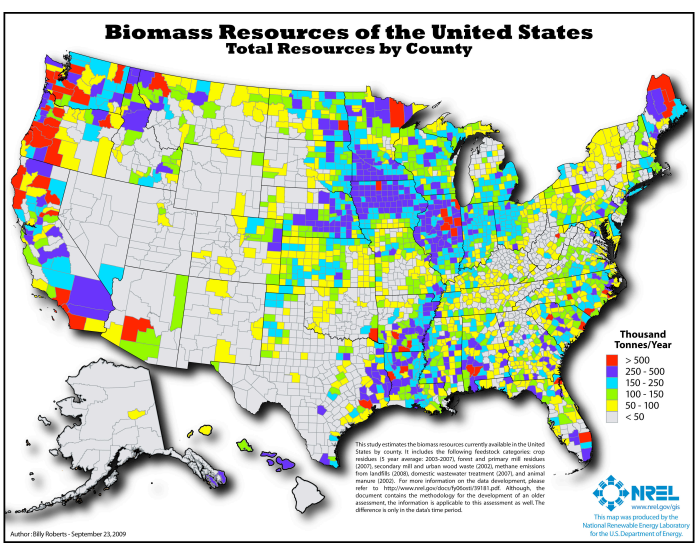

Figure 1. Biomass Resources of the United States; Total Resources by County, found at: http://www.nrel.gov/gis/images/map_biomass_total_us.jpg

In contrast, although waste generation rates, composition, and how they are managed also vary geographically, they are continually generated, regardless of environmental variables, and infrastructures are well established to collect, sort, and manage these materials.

BioCycle estimated that, in 2004, more than 509 Million Tons (MT) of municipal solid waste (MSW) was generated annually, with an estimated annual rate of 1.3 tons per capita.[6] EPA has estimated that in 2008, 251.3 MT of waste was generated. Although analyses and estimates of the amounts of waste and how it is managed vary, there are large quantities of waste available regionally.

However, not all this waste would be available or qualify as feedstocks for advanced biofuels, given other uses for these wastes and national policies. In 2008, the U.S. recycled 33.2% of its wastes and combusted 13% for power. Wastes that would otherwise be diverted to landfills may present the greatest opportunities for use as feedstocks. In 2008, 54% or 135 MT of all wastes generated were landfilled.[7] However, as mentioned above, only separated MSW free of recyclable paper, cardboard, plastics, rubber, textiles, metals, and glass will meet the renewable fuel standard. Therefore, infrastructure to separate recyclables and composition of the waste stream are critical. To date, much of the separated MSW that would be considered renewable biomass feedstock for advanced biofuels do not have high recycling rates relative to other biogenic wastes. (See Figure 2). Infrastructures for collecting these wastes and markets for these materials are not as well developed as markets for paper, plastic, glass, and metal wastes. Wood, wood packaging, food wastes, and yard wastes combined would amount to more than twice as much tonnage as paper and paper board biogenic wastes. Use of these wastes would help divert these wastes from the landfill helping to also preserve landfill capacity, while not diminishing recycling of other wastes for other purposes.

Availability of MSW for advanced biofuels will also depend on a number of other factors, including: BTU value, moisture, size of the waste; infrastructures to collect, sort, pre- treat, and transport the materials; distance between the source of materials and conversion facilities; how the waste is managed; and the economics of these different management options. Although economic fluctuations and population growth or decline influence the amount of MSW generated, (e.g., in some cities and towns waste generation varies based on tourist season population shifts), in general, generation rates for a particular region or county is and can be well measured and predictable. It is more difficult to develop national estimates, given discrepancies in definitions of types of wastes and the life cycle of those wastes, and inaccurate and/or inconsistent reporting by all local governments.

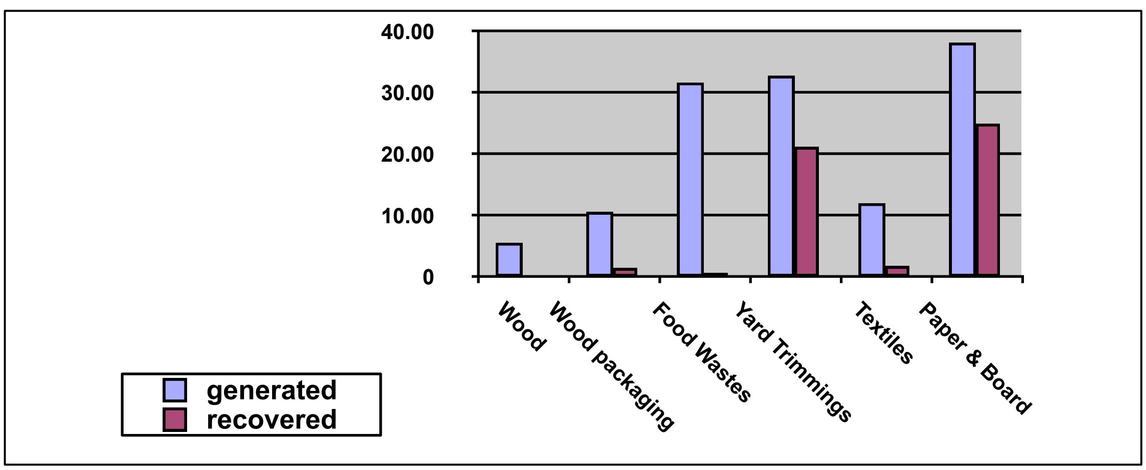

Figure 2. Generation and Recovery of Products in MSW, 2008 (Million Tons)

Source of data used for histogram: Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2008, p. 1, http://www.epa.gov/osw/nonhaz/municipal/pubs/msw2008rpt.pdf

In 2005, 167.8 Million Tons of total MSW was generated, having an average heat content of 11.73 Million BTU/Ton.[8,9] Of the total MSW generated, 105.58 Million Tons (63%) was biogenic (comprised of food wastes, wood, textiles, leather, yard trimmings, newsprint, paper, and containers and packaging).[10] This biogenic portion of waste contributed 56% of that heat content, containing 167 trillion BTU. [11]

Existing waste management trends will influence volumes of waste available for other purposes. Wastes can be recycled, combusted in Waste- to- Energy power facilities, converted to other energy products, composted, or landfilled. Depending on the price for recyclable materials, waste can be viewed as a commodity, or when landfilled, as a cost. Several studies have demonstrated that recycling materials is more beneficial in reducing life cycle greenhouse gases - by reducing demand on energy and material resources, and by diverting it from landfills - thereby reducing landfill methane gas generation. [12,13] It is a national policy to first encourage waste minimization, then reuse, recycling, and composting, followed by conversion to energy or landfilling. The National Recycling Coalition and U.S. EPA claim that a 32% recycling rate of MSW reduced the generation of 200 Million tons of GHGs, (about 3% of the nation's total carbon footprint).[14]

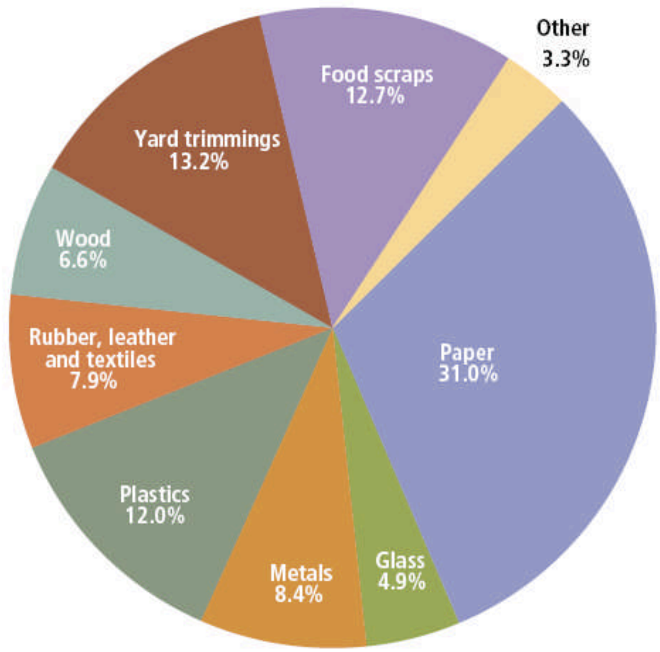

Figure 3. Total MSW Generation (by Material), 2008
250 Million Tons (Before Recycling).

EPA's Regulatory Impact Analysis in support of the Renewable Fuel Standard Program's Final Rule projected that in 2022, paper would comprise 24.5% of MSW, wood 5.6%, yard trimmings 12.8%, and food scraps 15.1%, with moisture content of 10%, 20%, 40%, and 70%, respectively.[15,16,17] Additionally, it estimated that only 8 million dry tons of construction and demolition debris (CDD) would be available for biofuels, based on population estimates and assumptions that 50% of this waste stream would be contaminated and un- useable. In total, of an estimated 44.5 million dry tons of MSW and CDD wood waste available, only 26 million dry tons would be used to produce 2.3 ethanol-equivalent billion gallons of fuel (assuming 90 gal/dry ton ethanol conversion yield for urban waste in 2022). [18]

Utilization and management of waste varies regionally, (Figure 4) and varies even more by state.[19] For example, in 2006, the State of Maine recycled as much as 32% of their wastes (increasing to 38% in 2008) and converted about 32% of their wastes to energy, landfilling 25% and exporting the remainder.[20,21] By contrast, in another region of the U.S., New Mexico only recycled 9% of its waste in 2006, landfilling 91%, with no waste- to- energy conversions.[22] In States with low recycling rates, opportunities may exist to use yard and food wastes and construction demolition wood debris as feedstocks. This new use could improve the economics of waste management and possibly increase recycling rates, in addition to energy use.

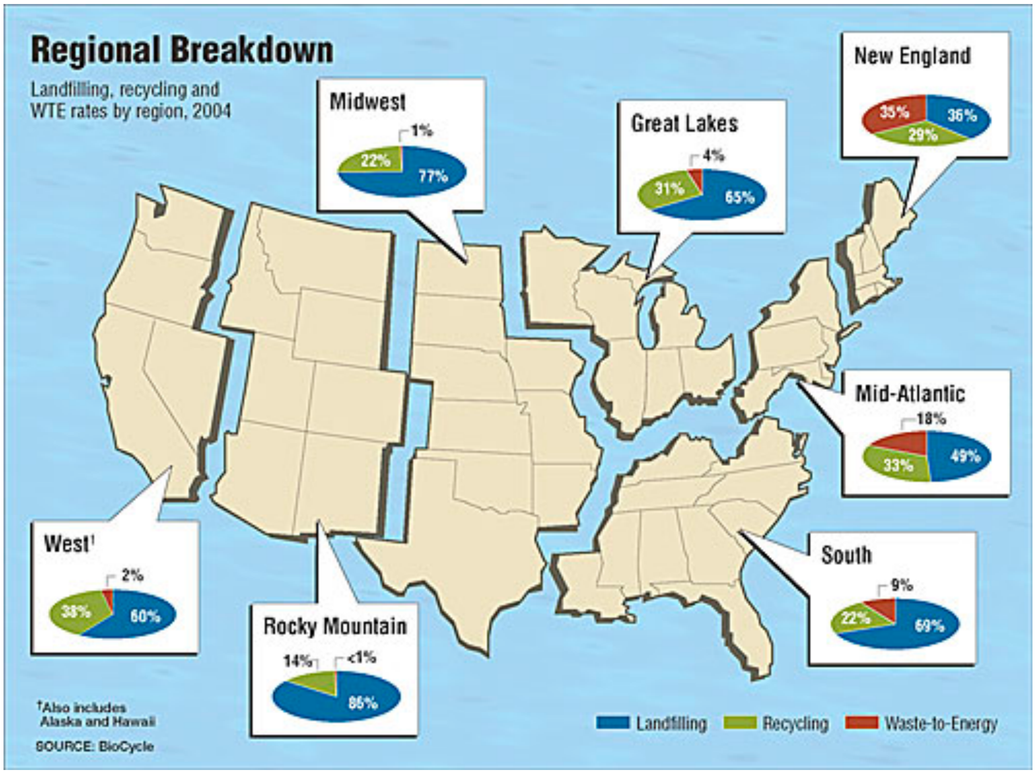

Figure 4. Source: BioCycle, April 2006, Vol. 47, No. 4, p. 26, found at:
http://www.jgpress.com/archives/_free/000848.html

Given variability of agricultural feedstocks, it may be advantageous to consider how waste is managed regionally and co- mingle plant derived biomass with other steadily generated feedstocks, such as MSW.

Availability Questions

- Does seasonal availability of plant derived feedstocks affect contracts and liabilities for suppliers and biorefineries?
- Are separated MSW streams (i.e., yard and food wastes and CDD) truly continual in supply?
- Would including a continual supply of separated MSW improve liabilities?
- Would farmers and farm owners be positively, negatively, or neutrally impacted by separated MSW being another feedstock source?
- How do biorefineries overcome the challenge of seasonal biomass availability? Does it affect their business and operational plans or their ability to secure funds from lending institutions?
- What controls can be devised to improve availability of separated MSW? Plant derived feedstock?

Composition of Feedstock

On average, a pound of MSW contains an average heating value of 5,100 BTUs.[23] However, in actuality, the amount of BTUs that can be extracted from a waste stream is dependent on the composition of the waste.

MSW is a heterogeneous mixture of materials from diverse sources. Depending on the composition of the mixture and whether and how it is separated, it will have varying biogenic content and heat value. Although there are great quantities of MSW available, only the biogenic portion (e.g., wood, yard trimmings, paper, and food wastes) would qualify as a renewable fuel source according to the amended Renewable Fuel Standard (RFS2). Biogenic wastes will vary in composition (i.e., volumes and sizes, energy, moisture, and chemical content). These characteristics will determine the energy input needed to process the wastes (e.g., collection, separation, densification, dewatering, shredding, etc.) and compatibility with conversion technologies, and will ultimately determine air and greenhouse gas life cycle emissions and net energy output.

The heat value of the waste would determine its value as a biofuel feedstock. Heat values vary considerably for different waste materials (see Table 1). The biogenic heat value of MSW has been consistently higher than the non- biogenic portion, but has decreased significantly (from about 67% in 1989 to 56% in 2005) as a result of plastics replacing paper in packaging and other consumer goods.[24] Of the biogenic portion, the largest percentage of BTUs comes from containers and packaging (16%). Other biogenic wastes contribute less BTU content to the waste stream (food waste contributing 8%, textiles 7%, wood 6%, paper 6%, news print 5%, and yard trimmings 4%).[25]

Plastics (which are not considered biogenic) contain the highest BTU content. Paper waste mixed with plastics would have a very high heat value, since plastics have BTU content ranging from16.5 Million BTU/ton to 38 Million BTU/ton (See Table 1), followed by paper wastes (which are biogenic). [26] Therefore, there has been some thought to co- mingle plastics with other biogenic wastes. However, there are several reasons not to co- mingle plastics with any biogentic wastes for energy production, particularly paper. First, paper has one of the highest recycling rates and economic values for use as recycled material. (Table 1). Second, there is a robust global market for recycling plastics, (55¢ - 89¢/lb). [27] Third, incineration of plastics in MSW, particularly at low oxygen levels, is associated with the generation of Polycyclic Aromatic Hydrocarbons (PAHs) emissions, which are carcinogenic, and will require stringent air pollution control devices.[28] Fourth, as previously discussed, under EPA's Renewable Fuel Standard Program, feedstocks containing plastics in a MSW stream will not be considered as a renewable biomass source.

It is preferable to continue recycling plastic and paper wastes. In 2008, Americans recycled about 61 million tons of wastes, composted 22.1 million tons, and combusted about 32 million tons (13%). Nationally, in 2008, the U.S. recycled and composted 1.5 pounds of the 4.5 pounds of waste generated per person per day and combusted (with energy recovery) or discarded the remaining 3 pounds per person per day. Given environmental, GHG, and economic benefits, increasing the recycling rate even further is a national goal.[29]

However, if post- recycling residual wastes have high biogenic and BTU content, they could be used as energy feedstocks. These residuals are typically landfilled, at a cost. Therefore, recycling infrastructures and use of waste as energy feedstock could be compatible. An analysis done by the County of Los Angeles Department of Public Works, and the Los Angeles County Solid Waste Management Committee's Alternative Technology Advisory Subcommittee outlined some of the key considerations in siting a facility and using existing infrastructure to use waste as an energy feedstock while not compromising recycling rates.30 Being able to divert at least 50% of the MRF residual away from the landfill was a critical factor.

Table 1. BTU Content and Generation, Recovery Rates for MSW

Materials	Million BTU/Ton	BTU/lb	MT generated in 2008	Recovered in 200822	Not Recovered in 2008	BTU Not Recovered
Plastics						
Polyethylene terepthalate (PET)	20.5	10,250	30.05 MT	2.12 MT (7.1%)	27.93 MT (92.9%)	712.2 M BTU (assuming an average 25.5 M BTU/ton)
High density polyethylene (HDPE)	19	9,500				
Polyvinyl chloride (PVC)	16.5	8,250				
Low density polyethylene/ Linear low density polyethylene (LDPE/LLDPE)	24.1	12,050				
Polypropylene (PP)	38	19,000				
Polystyrene (PS)	35.6	17,800				

Rubber	26.9	13,450	7.41 MT	1.06 MT (14.3%)	6.35 MT (85.7%)	131.1 M BTU (assuming an average 20.65 M BTU/ton)
Leather	14.4	7,200				
Textiles	13.8	6,900	12.37 MT	1.89 MT (15.3%) recovered	10.48 MT (84.7%)	144.6 M BTU
Wood	10	5,000	16.39 MT	1.58 MT (9.6 %) recovered	14.81 MT (90.4%)	148.1 M BTU
Food	5.2	2,600	31.79 MT	0.8 MT (2.5%) recovered	30.99 MT (97.5%)	161.2 M BTU
Yard Trimmings	6	3,000	32.9 MT	21.3 MT (64.7%) recovered	11.6 MT (35.3%)	69.6 M BTU
Newspaper	16	8,000	77.42 MT	42.94 MT (55.5%) recovered	34.48 MT (44.5%)	450.6 M BTU (assuming an average 13.07 M BTU/ton)
Corrugated Cardboard	16.5	8,250				
Mixed Paper	6.7	3,350				
Other	20.5	10,250				

Biogenic wastes have a lower heat value than plant derived cellulosic biomass and would most likely be suitable as a supplemental feedstock. DOE's Biomass Feedstock Composition and Property Database lists the BTU content per pound of all herbaceous feedstocks, by variety type. The Switchgrass variety Alamo shows a range of 7,927 BTU/lb to 8,223 BTU/lb (Table 2).31

Table 2.

BTU Content and Scenarios for Projected Switchgrass Production in Various Regions

Materials	Million BTU/Ton	BTU/lb	Region	Million Acres	Yield Scenario (Dry T/a) 2005	BTU Available	Yield Scenario (Dry T/a) 2020	BTU Available
Switchgrass	15.8	7,927 – 8,223 BTU/lb	North Central	200	4.8 960MT	15,168 M BTU	6.0	18,960 M BTU
			North East	36	4.3 154.8MT	2,445.8M BTU	5.3 190.8MT	3,014.6 M BTU
			South Central	64	5.9 377.6MT	5,966.1M BTU	7.4 473.6MT	7482.9 M BTU
			South East	22	6.9 151.8MT	2,398.4M BTU	8.6 189.2MT	2,989.4 M BTU

Composition of Waste Questions

- Given the BTU value and quantities of separated MSW, are they abundant and rich enough to consider as either an independent or supplemental feedstock?
- What are the thermal effects of co- mingling separated MSW with other plant derived biomass?
- Would some types of separated MSW be preferable over others?

Infrastructures

An optimal transportation radius for transporting biomass feedstock from field to a biorefinery is usually dependent on quantities available, mode of transport and infrastructure available, along with costs to harvest and transport it and price paid for the materials. Similar factors are considered for waste, however, hauling distances for wastes are influenced by a variety of factors, including local capacity to manage the waste, waste management contracts, inter- and intra- state transportation policies, and a hauler and waste management facility's ability to recover costs of hauling through tipping fees. Although these decisions may seem complex, infrastructures to collect, sort, process, manage, and treat MSW and transportation routes, collection, and transfer stations are, in most locations, already well established and operational in the U.S. Regulations and business plans for waste transport are also already well established and practiced.

Municipalities that have made significant investments in recycling infrastructure will strive to maximize recycling rates. Recycling infrastructures separate out recyclable material from non-recyclable either at the curb or separated at Materials Recovery Facilities (MRFs). Although modifications to these infrastructures may be needed to further sort or pre- process wastes (e.g., electricity interconnects, water supply, sewer, and increased transportation access), their existence greatly reduces the capital costs required for essential pre- sorting of wastes for use as energy feedstocks.[32]

However, as shown in Figure 4, above, some regions of the country landfill significant amounts of wastes rather than recycling them. Opportunities to use non- recycled waste could also exist if capital costs were available to increase infrastructures that could effectively separate out biogenic from non-biogenic wastes. Infrastructures to separate these wastes could additionally spur more recycling. Combined recycling and recovery of energy laden materials could present economic advantages to a community, under certain scenarios. Cost- sharing between a municipality, waste management company, and biofuels producer could, therefore, potentially help increase the use of waste for energy, while also, increasing recycling rates. A better understanding of the economic and business opportunities for this kind of arrangement is needed.

Wastes can be converted to power and heat, using combustion and thermochemical conversion technologies (e.g., gasification and pyrolysis), or converted to biofuels using thermochemical or biochemical processes (e.g., acid hydrolysis and fermentation). When waste is combusted to generate power, recyclable waste and non- combustible wastes are separated out, with the remaining combustible waste converted into "Refuse Derived Fuel (RDF)". RDF processing often includes further crushing, shredding, separation of non- combustibles, and pelletization of combustibles into a homogeneous fuel. According to an NREL study, "on average, 75%–85% of the weight of MSW is converted into RDF and approximately 80%–90% of the BTU value is retained. This leaves RDF with a higher heating value of 4,800–6,400 BTU/lb, which is approximately half of the BTU value of the same weight of coal.[33] Densification of this feedstock results in more homogeneous physical and chemical characteristics, lower pollutant emissions, and less oxygen required during combustion.[34]

Once separated, the pre- treatment requirements of separating and shredding wastes for combustion is somewhat similar to those needed for gasification or pyrolysis; however they differ significantly from the dilute acid, steam- explosion, and/or enzyme hydrolysis pretreatment used to break down the hemicelluloses and cellulose prior to the fermentation process. Separation, shredding, size reduction, removal of toxics, etc., for either process and acid and/or enzyme hydrolysis could occur both prior to and at the biorefinery.

Distances for transport of the wastes from collection and pre- processing to the biorefinery, availability of various modes of transport (trucks, rail, or barge), and costs will also be important considerations of whether wastes can be a viable feedstock. The throughput capacity of the facility to process the waste and delivery and production schedules will also affect location and the need for and availability of storage capacity. Co- locating separation facilities with biorefineries would eliminate transportation and storage costs but capital costs for a separation facility and costs to store and dispose of non- biogenic wastes would be incurred. A number of pilot demonstrations have entered into agreements with municipalities to co- locate separation facilities at or in close proximity to biorefineries. (See discussion under Conversion Technologies).

Long- term contracts between municipalities and the waste management sector for managing wastes are another essential component of the infrastructure for using wastes as feedstocks. Municipalities need assurances that capacity exists to manage their wastes, and waste management companies need waste flow assurances for long- term operational planning of land, equipment, labor and securing capital costs for expansions. These contracts ensure recycling, waste- to- energy conversions, composting and/or landfilling of a municipality's or region's wastes at a relatively stable tipping fee, and will be a critical factor in securing wastes as feedstocks.

Tipping fees vary considerably from state to state. In 2006, Massachusetts and New Jersey had the highest landfill tipping fees of $79 and $72 per ton, respectively, while Montana and Texas had the lowest, both at about $25/ton.[35] Tipping fees for waste- to- energy (WTE) are usually considerably higher in states that have WTE facilities.[36] Often, waste flow contracts involve importing wastes beyond the boundaries of the county or state in which a waste management facility is located or exporting wastes beyond where they were generated. States can be net importers or exporters of waste depending on infrastructures and economics.

It would be essential to understand how waste flows are secured and whether there is flexibility in existing contracts to divert some wastes for energy purposes. If wastes are imported from another state, it would be prudent to know whether that state was also considering waste as a potential energy source.

Infrastructure Questions

- Are existing infrastructures capable of pre- treating waste to the appropriate size for gasification, pyrolysis, or fermentation, or would this occur at the biorefinery?
- How will tipping fees and existing long- term contracts affect diversion of separated MSW for biofuels feedstocks?
- How do Renewable Portfolio Standards and competition for MSW as waste- to- energy feedstock and/or recycling impact use of separated MSW for biofuels feedstocks?
- Will states with extensive recycling infrastructure expand their capacity to increase markets for separated MSW as an advanced biofuels feedstock?
- Will states lacking recycling infrastructures use new markets for separated MSW as an opportunity to initiate recycling? What benefits and liabilities would occur?

All these factors will influence the feasibility of using these feedstocks for biofuels production, for producing power or being recycled into other products.

Economic analyses that consider a variety of scenarios and specific regional characteristics (types and volumes of wastes, available infrastructures and contracts, and distances) are needed to identify how to optimize transport and separation infrastructures.

Several transportation questions arise in considering use of wastes and co- mingling wastes with other biomass feedstocks.

- Would co- mingling of herbaceous feedstock and wastes affect decisions on optimal transportation distances?
- Would infrastructures to haul waste compete with infrastructures to haul herbaceous feedstocks?
- Would synchronization of delivery of feedstocks be needed? If not, what role would the biorefinery play in coordinating use and/or storing both these feedstocks?

Conversion Technologies

Biochemical, thermochemical, and chemical conversion platforms used to convert non- waste biofuel feedstocks can also be used to convert a variety of wastes, producing similar products. (See Table 3). All conversion methods require that the MSW be pre- shredded.

Table 3: Potential Waste Feedstocks for Biofuels

Waste Type	Processing Required	Conversion Technologies	Product(s)	Amount Generated in U.S. Per Year (Million Tons)
Biogenic portion of municipal solid waste, including food wastes	Separation of recyclables (metals, glass, plastics, paper) Shredding of biogenic portion of wastes	Hydrolysis & fermentation	Ethanol, butanol, and microbially- produced alternative fuels	~105.58
		Gasification	Syngas, ethanol, methanol, butanol biodiesel gasoline	
		Pyrolysis	Syngas, biodiesel, gasoline	
Food wastes, including waste oils and greases, food processing wastes	Collection prior to disposal	Transesterification	Biodiesel	

The biochemical and thermochemical platforms each rely on different catalysis systems. Biochemical conversions rely on biocatalysts, such as enzymes and microbes, as well as heat and chemicals to convert biomass to an intermediate sugar substrate that is then fermented to produce ethanol and other products. Thermochemical conversions rely on heat and/or physical catalysts that convert biomass to a gas or liquid, depending on the technology, and is then further converted to a fuel, power, or other chemical products.

Biochemical processes include anaerobic digestion and fermentation.

Anaerobic digestion of wastes uses microbes to convert wastes to methane and carbon dioxide in an oxygen free environment. This process requires that the MSW be shredded, inoculated, mixed with water, pulped, and fed into a reactor vessel. The composition of products is determined by the composition of feedstocks used and control of the process, (e.g., temperature, pH, oxygen, carbon/ nitrogen ratio, mixing, retention time). Size and consistency of the feedstock is an important variable, since decomposition and availability of the feedstock's organic materials is a critical first step in anaerobic digestion. Large polymers of organic materials are broken down through bacterial hydrolysis into smaller monomers of sugars and amino acids, followed by acidogenic bacteria further converting them into volatile fatty acids. Other acetogenic bacteria further convert these fatty acids into acetic acid, hydrogen, ammonia, and carbon dioxide, which are then converted by methogens to methane and carbon dioxide. The methane and carbon dioxide can further be used to produce energy products, including power and biofuels. This method is more suitable for high moisture content wastes, such as food wastes.[37]

Fermentation, in contrast, is an aerobic process. Various processes can be used to pretreat / deconstruct cellulose, including steam, enzymatic and/or acid hydrolysis. Dilute acids solubilize the hemicellulose and render the cellulose available for enzymatic hydrolysis and saccharification. Enzymatic hydrolysis converts cellulose to simple sugars such as hexose, pentose, and glucose, which is then used as a substrate for further fermentation by microbes to produce a variety of alcohols, including ethanol and butanol.

Pyrolysis and gasification are two thermochemical processes used to convert a variety of biomass feedstocks, including the non- fermentable lignin portion of cellulose, yielding diverse products that yield a variety of fuels, chemicals, and power.

Gasification requires that the waste feedstock be chipped or hammer milled to a particle size of 10- mm to 100- mm in diameter and have a lower moisture content similar to other biomass feedstocks, so that it can be auger- fed into the gasifier.[38] Processing refuse derived fuel helps to reduce the moisture content of MSW feedstock. Gasification occurs at higher temperatures (1,800ºF) with oxygen or air and catalysts. This process results in a syngas comprised of CO, H2, CO2, H2O, N2, and hydrocarbons, and small amounts of impurities (e.g., tars, sulfur, nitrogen oxides, particulates, and alkali metals). Gas cleanup is needed to remove followed by gas conditioning to remove hydrogen sulfide (H2S) and optimize the H2/CO ratio for fuel synthesis. The composition of the waste could influence the need for syngas cleanup. This syngas, which has a low to medium energy content, undergoes fuel synthesis either using catalysts or microbes. The choice of catalysts and the H2/CO ratio, or choice of subsequent fermentation of syngas by microbes, will determine the products to be produced. Diesel and alcohols (including methanol, propanol, butanol, and ethanol) can be produced through gasification, as well as other chemicals. Additionally syngas can be used for turbine power.

Heating values of waste feedstocks will vary based on both the moisture content of the waste, how it is pre- treated (e.g., densified), and the technology that it is converted in. Pacific Northwest National Labs (PNNL) compared the amount of MSW and/or RDF (densified and processed MSW fuel) that would be needed to get the same energy equivalent product output in a similar sized gasification unit as poplar wood biomass. "A 2,200 dry short ton per day biomass fed facility would require approximately 2,400 dry short tons per day of dry MSW or 2,300 dry short tons per day of dry RDF to supply the same quantity of stored energy to the gasifier." However, moisture content influences energy output as well. Considering that RDF has higher moisture content than conventional biomass and MSW has even significantly higher moisture content than conventional biomass, it was found that approximately 2,755 and 3,300 short tons per day of RDF and MSW, respectively, would be needed to supply the same quantity of stored energy to the gasifier as conventional biomass.[39]

The composition and contaminants in wastes will also affect catalysts during gasification of wastes. MSW can potentially contain sulfur, chlorine, fluoride, arsenic, phosphorous, mercury, and cadmium – which all can potentially interfere with catalysts used during gasification.[40]

Pyrolysis occurs in the absence of oxygen with or without catalysts, and at lower temperatures than gasification, and can result in diesel and gasoline fuels.

Esterification is a chemical process that can convert oil laden food wastes, such as waste greases, to biodiesel. There are several processes by which esterification can occur:

1. base catalyzed transesterification with alcohol
2. direct acid catalyzed esterification with methanol
3. conversion of oil to fatty acids followed by acid catalysis resulting in alkyl esters
4. glycerolysis

Basically, triglycerides are broken down into glycerol (glycerin) and free fatty acids (carboxylic acids). The free fatty acids are esterified using methanol, producing biodiesel and the by- product, glycerol. However, free fatty acids and glycerol can also react with each other to form glycerides. The above processes vary in controlling conditions for optimal yield of biodiesel and minimization of glycerides.

The source of feedstock has some effect on the quality of biodiesel produced, since the nature of the three long- chain fatty acids in triglycerides are determined by the fat or oil source. For that reason, biodiesel composition can vary considerably and therefore is tested to verify that it meets ASTM specifications and further registered with the U.S. EPA. Product quality and vehicle performance is best ensured when there is a complete transesterification reaction, and successful removal of any glycerin, catalyst, alcohol, and free fatty acids. The final biodiesel product is often analyzed for trace metals and pesticides, polycyclic aromatic hydrocarbons, chlorinated polycyclic hydrocarbons and aflatoxins.

Issues, such as throughput, feedstock characteristics, by- products, and environmental emissions will determine the economic feasibility of using certain technologies to convert certain feedstocks.

Land fill Methane Generation via Anaerobic Digestion - Besides diverting wastes prior to disposal, anaerobic digestion in existing landfills also generates methane. This biogas can be collected, and upgraded for use as a fuel in heavy duty vehicles. Roughly 58% of all landfills already have landfill gas (LFG) recovery operations in place.[41] However, there are mutliple limitations to this as a biofuels source, including the need to purify, store, and distribute the biogas, at a significant cost. Additionally, it is not certain that a sufficient number of vehicles would be available to use this biogas.

Although this paper focuses on MSW, a variety of other wastes can also be converted using these technologies. Manures and sewage sludges are most suitable for anaerobic digestion, given their high moisture content. Dewatering them for use in thermochemical processes, while feasible, would result in high energy inputs and high GHG outputs from pre- treatment.

A surprising number of biofuel facilities have partnered with either communities or waste management companies to use MSW to produce biofuels.

- Enerkem Mississippi Biofuels in Pontotoc, MS, is a facility that will sort, upstream recycle, and pre- treat MSW, construction and demolition wood, and agricultural and forest residues for thermochemical conversion to a syngas that will further be processed into 20 million gallons ethanol, plus methanol, and plastics, annually. The Enerkem and Three Rivers and Waste Management Authority partnership is constructing the facility using 2009 funding from the U.S. Department of Energy.
- Enerkem has also partnered with the largest ethanol producer in Canada, Greenfield Ethanol, to convert 100,000 metric tons of sorted MSW annually into 10 million gallons of ethanol using gasification, and is expected to be operational sometime in 2011.
- Masada OxyNol plans to hydrolyze and ferment 275,000 tons per year of sorted MSW to produce 9.5 million gallons per year of ethanol at their facility currently under construction in Middletown, NY
- Fulcrum BioEnergy is constructing a 10.5 million gallon per year commercial scale facility (Sierra Biofuels Plant) in Nevada. It plans to thermochemically convert post- recycled MSW to a syngas and further process it into ethanol.
- Agresti Biofuels LLC is planning to co- locate a facility adjacent to the Pike County, KY landfill where it will sort recyclables, cellulosic materials, and metals and use fermentation to convert the cellulose into ethanol.
- BlueFire Ethanol's process is designed to convert MSW wood and other agricultural residues into ethanol, using strong acid hydrolysis and fermentation. Plans include multiple plants with capacities up to 55 million gallons per year with the first facility located in Lancaster, CA.
- Taylor Biomass Energy plans to separate recyclables from 1,000 tons per day of MSW and thermochemically convert the 275 remaining tons to syngas followed by conversion to either ethanol or power.
- Coskata plans to have a 50 million to 100 million gallon ethanol plant up and running using integrated thermochemical and biochemical technology to convert wood chips and expand to MSW, tires, and other waste. Feedstock is first thermochemically converted to syngas and then feeds this syngas to anaerobic microbes to produce ethanol. Coskata has a bench scale pilot in Warrenville, IL and a larger 40,000 gallon per year operational pilot plant in Madison, PA, with plans for a commercial scale 50 Million gallon per year plant in 2011.
- Choren's gasification process followed by a Fischer- Tropsch process produces diesel using a wide variety of feedstocks, including biogenic wastes.
- POET has expanded beyond corn ethanol to cellulosic ethanol conversion technology with $80 million funding from DOE. This process is capable of using MSW, along with energy crops, stover, and wood chips. This 25 million gallons per year facility in Emmetsburg, Iowa will be operational in 2011, starting with corn cobs as feedstock but presumable expanding to other feedstocks, including wastes. POET is also looking into use of landfill methane in Sioux Falls, SD.
- Biogas Energy Project at the University of California at Davis has successfully converted eight tons of food waste per week in the San Francisco area and is licensed for use by Onsite Power Systems, Inc., in Davis.

Conversion Technology Questions

- How does using MSW affect conversion efficiencies, energy output, and environmental emissions and wastes? Are facilities that are using waste as a feedstock measuring these outcomes? Should they?
- Whether and when should MSW be used as an energy feedstock vs. recycling?
- What are the Life Cycle outcomes (for GHG and air emissions) associated with using waste as an energy feedstock vs. recycling?
- Do facilities and communities have common goals for optimizing economics, environmental, and social outcomes?
- Is anyone performing life cycle assessments for various feedstock/conversion technology/ energy products that include wastes or co- mingling wastes?
- How does composition of the wastes and operating conditions of the conversion technology affect air emissions?

Environmental Performance

Life cycle GHG emissions will vary based on the infrastructure used to collect, sort, manage, and convert wastes. U.S. EPA's Office of Research and Development has developed a life- cycle inventory database for North America and decision support tool (DST) for site- specific applications that includes GHG, other air and water emissions, and waste associated with MSW operations. This tool can compare quantitative life cycle assessments of GHG, other air, water, and waste emissions from various waste management infrastructures (e.g., non- sorted vs. sorted curb collection, square miles collected, fleet types, sorting facility types, and end- use of wastes) to determine optimal waste management options.[42] One comparison that has not been studied to date is the use of wastes as an energy source for biofuel production compared with other uses and management options.

Emissions from municipal waste combustors are well characterized and concerns have been raised about toxic emissions, such as dioxin, furans, mercury, lead, cadmium, and products of incomplete combustion. However, operational conditions of this technology are significantly different than pyrolysis and/or gasification. Gasification technologies operate at greater efficiencies than MSW combustors at lower oxygen levels and produce a variety of value added products beyond electricity, including liquid fuels and chemicals.[43]. Emissions from thermochemical conversion of MSW can include air pollutants, such as oxides of nitrogen and sulfur (NOx and SOx), hydrocarbons, carbon monoxide (CO), particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), and greenhouse gases such as CO2 and CH4. Studies have shown that PAH generation is influenced by temperatures in either the combustion or gasification zones of conversion technologies, post- combustion gas temperatures, residence times, and levels of oxygen.[44, 45, 46] Studies to characterize the differences between combustion, gasification, and pyrolysis are needed. The combustion process involves oxygen reacting with volatile products and char to form carbon dioxide and carbon monoxide. The gasification process occurs as the char reacts with carbon dioxide and steam to produce carbon monoxide and hydrogen. Pyrolysis occurs at lower oxygen levels. Understanding how these and other differences affect emissions from various wastes would be important to know for permitting facilities using wastes as feedstocks.

If pyrolysis and gasification technologies used only biogenic portions of the waste, it would be expected that volatile heavy metals and toxic emissions, such as dioxins and furans, would differ compared to waste combustion. Fugitive gas and dust emission levels would also vary with control strategies, operational practices and level of maintenance of a facility.

Organizations and communities have already equated gasification and pyrolysis to municipal solid waste combustion.[47] Characterization of air, water, and waste emissions from all MSW waste conversion technologies is needed to differentiate use of wastes for fuel from the stigma of MSW combustion technologies for improved public acceptance.

Environmental Performance Questions

- What research is already being conducted to characterize the environmental performance of various conversion technologies using different feedstocks and under varying operating conditions?

- What research is being conducted to compare environmental performance of using wastes as a biofuel feedstock vs. power vs. recycling vs. landfilling?
- What life cycle assessments are needed?
- Does waste as a feedstock result in significantly different environmental emissions?
- Are public concerns about thermochemical conversion units justified? What information and dialogue needs to occur to increase our common understanding of their performance, benefits, and concerns?

Regional and State Considerations of Wastes as Feedstock

Several States and regions have been assessing which feedstocks would be available for either direct use in biofuels or as an energy source to power a biorefinery.[48] Several States (e.g., Massachusetts[49,50], California[51], and Ohio[52,53]) have explored waste availability and its potential to meet regional energy needs either for power or transportation fuels. Further research is needed to understand the comparative impacts and benefits of various feedstock/conversion technology/product pathways for a variety of regionally specific goals, including GHG reductions, production of energy, air and water quality, natural resource conservation, jobs creation, and public health.

MSW is, in some instances, considered to be a renewable resource, and in others, not. Many States have qualified MSW as a renewable source for the purposes of State Renewable Portfolio Standards (RPSs), and the Energy Policy Act of 2005 includes MSW- derived electricity as a renewable energy resource, and EPA's Renewable Fuel Standard final rule defines the biogenic portion of separated MSW (i.e., after separating out recyclables) as renewable. The American Recovery and Reinvestment Act of 2009 includes MSW as qualifying to receive tax credits for renewable energy production, and most current legislation defines MSW as renewable.

Towns, counties, regions, and states vary on recycling rates and which wastes are recycled and/or recovered for energy. Construction demolition and debris (CDD), food wastes and yard wastes are often not recycled due to budget and infrastructure constraints.

Given that wastes will have varying GHG, air, water, and waste life cycle footprints, determined by a variety of geographic, economic, and technical factors, it would be advantageous to compare specific waste(s) to other available feedstocks to identify those yielding optimal outcomes, such as cost- effectiveness, minimal GHG emissions, and other optimal environmental, economic, and social outcomes, per BTU produced.

Regional and State Consideration Questions

- Is there a perceived new market for yard and food wastes and CDD as feedstock for biofuels?
- Will States increase recycling efforts of yard and food wastes and CDD?
- What would be critical considerations for states to increase recycling rates, including economic, political, environmental, social benefits and/or concerns?

Regulatory Considerations

Under EPA's recently promulgated Renewable Fuel Standard, advanced fuels must be derived from feedstocks that meet the definition of renewable biomass. Producers can use separated MSW (defined as material remaining after separation actions have been taken to remove recyclable paper, cardboard, plastics, rubber, textiles, metals, and glass) as feedstock to generate Renewable Identification Numbers (RINs) for their fuel.[54]

Renewable fuel producers must report and maintain records concerning the type and amount of feedstocks used for each batch of renewable fuel produced. Producers are required to quantify the portion of the final renewable fuel volume that qualifies as cellulosic biofuel for purposes of generating RINs, using a carbon- 14 dating test method that quantifies the fossil fuel portion of the final fuel and determines the remaining non- fossil fuel portion as cellulosic biofuel. Where the renewable portion of the fuel cannot be determined based on the relative energy content of the renewable biomass and fossil feedstock, the producer is required to determine the biogenic fraction of the renewable transportation fuel via ASTM D6866 (a method that tests the biobased content of solid, liquid, and gaseous samples using radiocarbon analysis).

For separated MSW streams to quality, they must be collected according to a plan submitted to and approved by U.S. EPA. This plan includes:

1. The location of the municipal waste facility from which the separated food and yard waste is collected.
2. Extent and nature of recycling that occurred prior to receipt of the waste material by the renewable fuel producer;
3. Identification of available recycling technology and practices that are appropriate for removing recycling materials from the waste stream by the fuel producer; and
4. Identification of the technology or practices selected for implementation by the fuel producer including an explanation for such selection, and reasons why other technologies or practices were not.

Regulatory Questions

- Does the requirement that only separated wastes, (not containing recyclable plastics and paper), be used for advanced biofuels feedstock affect whether yard and food wastes and CDD are used for biofuels?
- Does this policy create an unfair advantage for waste to be used for biofuels feedstocks compared to waste- to- energy conversion for power?
- Does the requirement spur new infrastructures for separation of yard and food wastes and CDD?
- Has a comprehensive life cycle analysis of emissions (toxics and GHG), resource inputs, and infrastructure needs been performed that would help identify optimal use of wastes for energy products?

Economic Considerations

Economics will determine the availability of waste as feedstocks compared with other uses. Economics will determine acceptable distances to haul wastes from point of generation to biorefinery, whether pre- treatment is feasible, and the scale of conversion operations. The gross energy value of the feedstock used and efficiencies of the conversion technology will also affect net energy and costs.

Economics of waste as a feedstock differs considerably from conventional biomass feedstocks. MSW disposal and conversion facilities charge a tipping fee that is determined by landfill owners and operators (which can be owned privately or by local governments), based on the cost to otherwise dispose, recycle, compost, or combust the waste; whereas, costs for conventional biomass vary based on market values. Tipping fees vary significantly depending on location. As mentioned earlier, local waste management capacity (for landfilling, recycling, composting, or combustion) and its ability to attract management of out- of- state waste will affect tipping fees and availability of MSW, both for local and out- of- state generated wastes. In 2004, tipping fees ranged from $24.06 per ton in the south to $70.06 per ton in the Northeast.[55]

Any processing of the MSW to produce a more manageable material will add cost to the overall conversion process, creating an economic trade- off between feed preparation costs and conversion technology capital and operating costs.

Economic Questions

Understanding all variables affecting economic feasibility is essential to determine whether MSW is a competitive feedstock. These include:

- Comparing tipping fees for wastes to be used for power vs. fuels vs. recycling vs. landfilling
- Comparing tipping fees for wastes as feedstock vs. market prices of conventional biomass
- Cost to use or expand existing infrastructures for hauling, sorting, processing, and storing
- What the net cost or cost- saving for recycling vs. using MSW as a biofuels feedstock is? What the determining factors are?
- Distances between supply, sorting infrastructures, and conversion technologies
- More detailed cost analyses for a variety of scenarios, including:
    - availability and costs of various types of wastes that considers collection and sorting

- costs to pre- treat wastes in either existing infrastructures or newly acquired infrastructures
- distances between waste generation, sorting and pre- treatment, and biofuel producers and costs of transport and storage infrastructures
- impact of these costs on tipping fees, if relevant
- comparison of these costs to using other biomass or co- mingling waste with other biomass.
- relationship between scale of facility and economics of tipping fees, if any, and
- identify minimum capacity of conversion technology below which the economics of using MSW is not viable.

Conclusion

Given the seasonal availability of plant derived feedstocks, and the continual supply and established infrastructure for MSW, it may be advantageous to consider use of separated MSW as an advanced biofuels feedstock.

However, a deeper understanding of the technical, economic, environmental, and social systems that generate and manage MSW is needed to identify which circumstances will result in the most sustainable arrangement. A sustainable outcome will include optimum economic gains, technical efficiencies, environmental protection, and social well- being where symbiosis exists between the biofuels system and other systems.

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Chapter 14

Biofuels and Bioenergy Production from Municipal Solid Waste Commingled with Agriculturally- Derived Biomass

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Abstract

The USDA in partnership with Salinas Valley Solid Waste Authority (SVSWA) and CR3, a technology holding company from Reno, NV, has introduced a biorefinery concept whereby agriculturally- derived biomass is commingled with municipal solid waste (MSW) to produce bioenergy. This team, which originally developed an autoclaving technology to pretreat MSW, has installed and operated a pilot- scale (2 T per batch) steam autoclave to evaluate its use for producing biofuels from waste biomass. Through this collaboration the SVSWA has arrived at the decision to commercialize autoclaving of their MSW with the intention of producing bioenergy from the cellulosic fraction from MSW. The autoclave has also been applied as a front- end technology to pretreat an array of different biomass feedstocks for energy production. Commingled feedstocks that have been test-autoclaved in this system include rice straw, wheat straw, grape pomace, olive industry waste, wax board, cardboard, food wastes, leafy vegetable wastes, and fast- food garbage. These streams were autoclaved and converted to bioenergy either alone and/or commingled with MSW. For each run the USDA research team provided data on the yields of methane production via anaerobic digestion versus ethanol yields via saccharification and fermentation; i.e., ethanol was produced from the isolated cellulose using typical commercial yeasts after dilute acid hydrolysis. In most cases results favored biomethane production as being more economically viable than ethanol production due to more efficient conversion and the scale of biomass availability. Specifically, the data from smaller scale operations generally point toward biogas production. The next step for the partnership is to demonstrate, at pilot scale, an anaerobic basin system developed at the USDA specifically for the purposes of producing biomethane from MSW commingled with agricultural wastes.

Introduction

The Renewable Fuel Standards set in 2007 mandated that 36 billion gallons of advanced biofuels be produced annually in the U.S. by 2022, with production of cellulosic ethanol to be established by 2010 as one source of this alternative fuel. The EPA has recently had to revise cellulosic ethanol targets in 2010 due to the reality that the industry lags behind schedule. Also, the scope of this mandate has been broadened to allow for alternative biofuels, beyond ethanol, to be considered as “ethanol equivalents”.

Herbaceous feedstocks have the potential to provide significant amounts of biomass to meet these mandated biofuels targets. In a report released by the US DOE and USDA in April 2005, commonly referred to as the “Billion Ton Report” (http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf) it was suggested that production of more than a billion dry tons of biomass per year is viable and would provide as much as 60 billion gallons of ethanol (or alternative fuels, perhaps). More specifically, the “Billion Ton Report” indicated a potential production of 1.36 billion tons of biomass per year, comprised of 428 million tons from annual crop residues, 368 million tons from forest residues and 377 million tons from 55 million acres of dedicated energy crops.

The Billion Ton Report provided the vision that a significant quantity of feedstock is available for future conversion to biofuels; however it did not lay out a plan for establishing the infrastructure for realizing this vision. Most traditional crops and most woody residue are only available on a seasonal basis in very specific regions. Significant breakthroughs must be realized to develop an infrastructure that will allow for sustainable growth of feedstock that then fits into a viable infrastructure for transportation, biomass pretreatment and conversion (T.L. Richard, Science, 329. no. 5993, pp. 793 – 796; 13 August 2010).

Utilizing agriculturally- derived biomass, with its seasonal availability, raises multiple issues that complicate infrastructure development, such as:

- Does the biomass change with age?
- Who handles transportation?
- Which party stores the feedstock, grower or biorefinery operator?
- Who takes on liability issues related to a guaranteed supply?
- Should the biorefinery operation be seasonal?
- What is the optimal transportation radius for supplying feedstock?
- Will lending agencies (bankers) provide the millions of dollars in funding needed for large scale biorefineries if the feedstock is variable?
- Will there be sufficient economic credits or incentives (carbon credits) if waste is diverted from landfills or sewage treatment facilities to produce bioenergy?

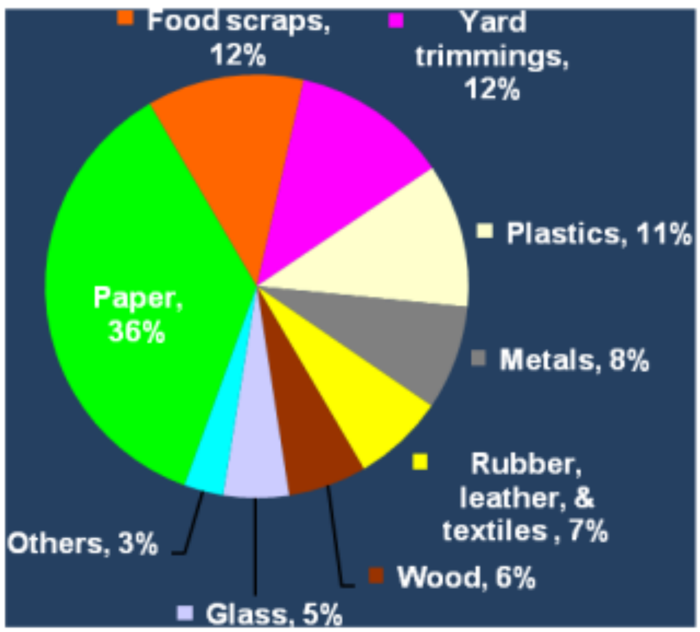

Figure 1: Composition of typical MSW in the U.S.

MSW as a Biofuels Feedstock

Utilizing MSW as a consistent feedstock provides answers to many of these infrastructure issues. For the most part, transportation routes, supply contracts, storage capacities, liability agreements, permitting rules, and cost structures are in place for MSW. As outlined in Figure 1, MSW is roughly 40% cellulose, much of it in the form of paper waste that has already been pulped and can be readily converted to sugars by hydrolysis. While MSW may be a viable feedstock for biofuels production, there is not enough biomass available to provide more than 10% of our U.S. domestic needs, at best. It is estimated that, in 2004, roughly 509 MM T of MSW was generated annually, with an estimated annual rate per capita of 1.3 tons[1]. At conservative conversion rates, this would result in less than 12 billion gallons of ethanol per year, less than 10% of the U.S. annual domestic gasoline usage of 138 billion gallons (http://americanfuels.blogspot.com/2010/04/2009- gasoline- consumption.html). The pulp fraction that can be fermented to ethanol represents only a small fraction (10- 20 %) of the total energy available in MSW, therefore the total impact of processing MSW cannot be measured simply by displacement of fossil fuel by ethanol. Dissolved organics derived primarily from food waste can be fermented to biomethane and used as a transportation fuel or green electricity, and the non- fermentable organic fraction (i.e., lignin) and non- biogenic (inorganic) fraction can be converted thermally to green electricity. As a result efficient use of this "waste" material can result in significant displacement of foreign oil and/or coal resulting in a significant savings in greenhouse gas emissions.

Commingled MSW with Agriculturally- Derived Biomass

Why commingle MSW with agriculturally- derived biomass for biorefinery development? In quick summary, MSW provides stability – both in consistency of supply and infrastructure development – while herbaceous feedstocks supply the potential for the quantities needed to meet our energy needs. MSW can be a reliable supplement to herbaceous feedstocks specifically because it is available on a daily basis through transportation networks that have been developed and optimized. Cellulosics from MSW after separation are comparable to commodity lignocellulosics and can be utilized to help jumpstart the cellulosic ethanol industry due to the relatively low cost of separation and the advantages related to locality and transportation. Availability is both consistent and predictable, with feedstock contracts usually held by single parties. Given these benefits, it is valuable to look more closely at initially utilizing this resource to start operation with the later potential of commingling MSW with herbaceous feedstocks, and identify what might be needed to assist operational application. This paper discusses a pilot study of commingling MSW with agriculturally- derived feedstocks for the production of either ethanol and/or biogas.

Case Study: Pilot- Scale Production of Bioenergy from Commingled MSW and Ag- Biomass

This section outlines technology to convert MSW and agriculturally- derived biomass to bioenergy at a pilot- scale operation in Salinas, California. Conversion is based on steam- processing biomass whereby unsorted incoming MSW, along with commingled biomass, is pressure cooked for ~30 minutes, and screened to separate the organic fraction from the remaining waste. Participating partners include researchers at the USDA, CR3 of Reno, NV, a technology holding company, and the Salinas Valley Solid Waste Authority (SVSWA). This team has installed a pilot scale MSW- autoclave to isolate uniformly the cellulosic fraction from MSW for biofuel research. The team has explored other technologies for end product development including a high- solids bioreactor system that can fully divert organic wastes into biomethane, as well as a pulp- washing operation that yields relatively clean cellulose for ethanol production or fiber sales in the secondary pulp market. Commercialization of the CR3 technology has been realized at facilities operated by Sterecycle, U.K, a licensing partner of CR3 that operates a 250 ton/day autoclave (see http://www.sterecycle.com/index.htm).

The key process toward this conversion is a two- ton/batch autoclave in which biomass is steam- processed at elevated pressure and temperature; a pretreatment process rendering output streams that are predictable and uniform. The autoclave developed and patented by CR3 consists of a horizontal rotary vessel with helical heating baffles that have been designed to externally heat the autoclave's contents, impart shear forces to the waste material, and facilitate breakdown (Figure 2, top left). This process converts MSW to a biomass source that is consistent on a daily basis, making it easy to augment this feedstock with agriculturally- derived biomass as it becomes available on a seasonal basis. MSW in Salinas has not been pre- sorted, although the SVSWA is active in its recycling efforts, therefore office paper, cans, bottles and boxes have been mainly segregated out of this waste stream. As such, this particular MSW stream (Figure 2, top right) is typically landfilled, and would be considered as a cost burden to most waste processors.

Figure 2. CR3 designed two- ton rotary autoclave operated by USDA at Salinas, CA showing (UL) the autoclave in the upright position for loading; (UR) loading of unsorted MSW; (LL) autoclaved MSW pulp commingled with different components of MSW pulp including unrecovered bottles and cans, and (LR) 3/8" screen accepts after trommelling containing a consistent high solids pulp that can be converted to bioenergy.

At the start of the process, MSW and commingled wastes are conveyed directly into the autoclave with only minor visual sorting; i.e., only large items such as durable goods – furniture, car batteries, appliances, etc. – are removed. The process consists of heating the vessel by the addition of direct steam with a corresponding pressure increase to 5 psig. Temperature is raised over a period of ~35 minutes to the operating temperature of 131oC (26 psig) via indirect heating oil, and the temperature is held constant for 30 minutes over which time the vessel is slowly rotated about the longitudinal axis. Rotation of the vessels results in (1) breakdown of the organic fraction into a moist pulp rich in cellulose; (2) cleaning and sterilization of non- organics (metals and glass) and "stiff" plastics, such as PET bottles; and (3) reduction in volume of the input waste material. At the end of the residence period, a flash- vacuum reduces the pressure to 10 psig and then the vessel is reheated to 24 psig over 10 min. The vessel is then evacuated to 0 psig and finally - 20" Hg via a jet eductor system.

Steam autoclaving is applied here to recover all of the waste cellulosic material contained in MSW (and commingled ag- derived biomass) that would not normally be recycled. The solids discharged from the autoclave are reduced in volume by as much as two- thirds relative to their original volume, and have the appearance of high consistency pulp fibers commingled with recyclable materials, pellets of plastics, and miscellaneous dirt. After autoclaving, the contents of the autoclave, which appear as a pulp material (Figure 2, lower left) are dropped into trommel screening system fitted with 3/8", 1/2", and 1" rotating screens. The organic fraction of autoclaved biomass is readily separated from the non- organics through simple size- sieving in a standard rotating trommel screen. Recovery of metals and high- melting plastics can be completed via this non- intrusive trommelling. The majority of the pulp fiber passes through the 3/8" screen and is overwhelmingly lignocellulosic in nature commingled with small debris and ash (Figure 2, lower right). In fact, the "accepts" from the 3/8" screen represents nearly 60 % of the material entering the autoclave (50 % of the volume), and after washing is arguably one of the least expensive sources of cellulosic pulp, which is then available for biorefinery development.

Advantages of this process are as follows:

- Autoclaving alone reduces the volume of the MSW stream by >60%, which implies significant landfill volume savings;
- Screening after autoclaving removes larger recyclable feedstocks, such as metals, glass and stiff plastics (PET bottles) not recovered during recycling protocols;
- Autoclaving and screening isolates organics such as food waste and a cellulose- rich pulp that is virtually the "cheapest" source of cellulose available for bioenergy conversion;
- Liquids isolated from this processing, along with much of the remaining solids, are rich in food waste and volatile solids for easy biological conversion to methane. This stream can be converted to methane via high- solids anaerobic fermentation very efficiently.

- The cellulosic- rich pulp can be converted to multiple biofuels including ethanol, methane, or "3rd generation" fuels as they become commercially viable.
- Biomass feedstocks can be readily commingled with cellulose isolated from MSW as they become available.
- The infrastructure is in place for collection and transportation of MSW.
- Two streams isolated from the MSW, the cellulose- rich pulp and the solubilized organic fraction can each be utilized to produce bioenergy. The USDA has worked with partners to provide data on converting MSW- derived cellulose to ethanol, showing yields of ~50 gals per ton of cleaned pulp using commercially available enzymes in a process that has yet to be optimized.

Rice Straw Conversion by Hot Water Treatment

The autoclave technology outlined for MSW pretreatment can also be utilized as a pretreatment system for non- cellulosic agricultural wastes. The USDA's efforts have focused on "green" techniques for pretreating biomass with strict directives to reduce water use and utilize all byproducts, such methane from solubilized organics stream. As a result, hot water pretreatment (HWP) was applied for enhancing the enzymatic hydrolysis of MSW and other biomass sources. HWP is referred to by multiple names including autohydrolysis, which explains the fundamental reaction mechanisms that occur as cellulose and hemicellulose are broken down and made more accessible to enzymes. Autohydrolysis is essentially subjecting the given substrate to high temperature (~200 oC) and high pressure (~300 psig). Although the pH is neutral at STP (standard temperature and pressure), acetyl groups from the hemicellulose are cleaved at higher temperature to produce acetic acid groups, dropping the pH slightly to ~4.5 and making the solution slightly acidic. These conditions at high temperature prove favorable for two mechanisms of cellulose hydrolysis.

Results of HWP experiments at different residence temperatures, varying between 190 and 230 oC and times from 10- 60 minutes are presented in Table 1. In this study, hydrolysis was performed using Celluclast 1.5 L and Novo 188 enzyme solutions (Novozyme) in 500 mL shake flasks at 55 oC. Ethanol production was achieved using an overnight seed culture of Ethanol Red yeast TM (Fermentis, France).

	Residence temp.(0C)	Residence time (min)	Severity Factor (R_o)	Cellulose Converted (%)	Cellulose to fermentation (t/1000 tpd basis)	Ethanol yield (gal/d)
Untreated	-	-	-	12	43	7,747
RS- 1	190	10	3.65	67.5	188	33,868
RS- 2	195	30	4.27	62.3	190	34,307
RS- 3	195	60	4.58	55.9	169	30,432
RS- 4	205	30	4.57	53.3	169	30,465
RS- 5	210	15	4.41	51.4	145	26,202
RS- 6	210	20	4.54	73.5	208	37,560
RS- 7	215	30	4.86	46.6	146	26,263
RS- 8	225	30	5.16	51.7	186	33,494
RS- 9	230	20	5.13	34.4	79	14,199

Table 1. Yields from enzyme hydrolysis and fermentation and estimations of the yields of ethanol from rice straw on a 1000 tpd OD basis.

These data show that autoclaving and/or varied HWP pretreatments can be applied to convert rice straw to ethanol at reasonable yields.

Autoclaving Commingled Streams: MSW with Agriculturally- Derived Biomass

The USDA has applied their autoclaving technology to an array of feedstocks as a pretreatment toward a consistent biorefinery operation. These include:

- Rice straw + MSW
- Raw waste / activated sludge
- Grape pomace
- Waxboard (beer box and lettuce boxes)
- Green/yard waste
- Commercial MSW

Biomethane Production

One life- cycle analysis published in Science (J.E. Campbell, et al. Science 324, 1055, 2009), concluded that converting biomass to electricity to run electric cars is more efficient than running cars on biomass converted to ethanol. Biomass- derived electricity produces an average 81% more transportation miles and 108% more emissions offsets per unit area cropland than cellulosic ethanol. The team in Salinas, (the USDA, CR3 and SVSWA) has carried out experiments comparing the conversion of these autoclaved commingled biomass streams into ethanol and biogas via anaerobic fermentation. Figure 3 depicts the biomethane production from a continuously stirred reactor (CSTR) fed a combination of commingled cellulosic MSW and rice straw at an organic loading rate of 1 kg/m3 d. The inoculant was the mixed liquor obtained at a municipal wastewater treatment facility and acclimated to cellulosic MSW.

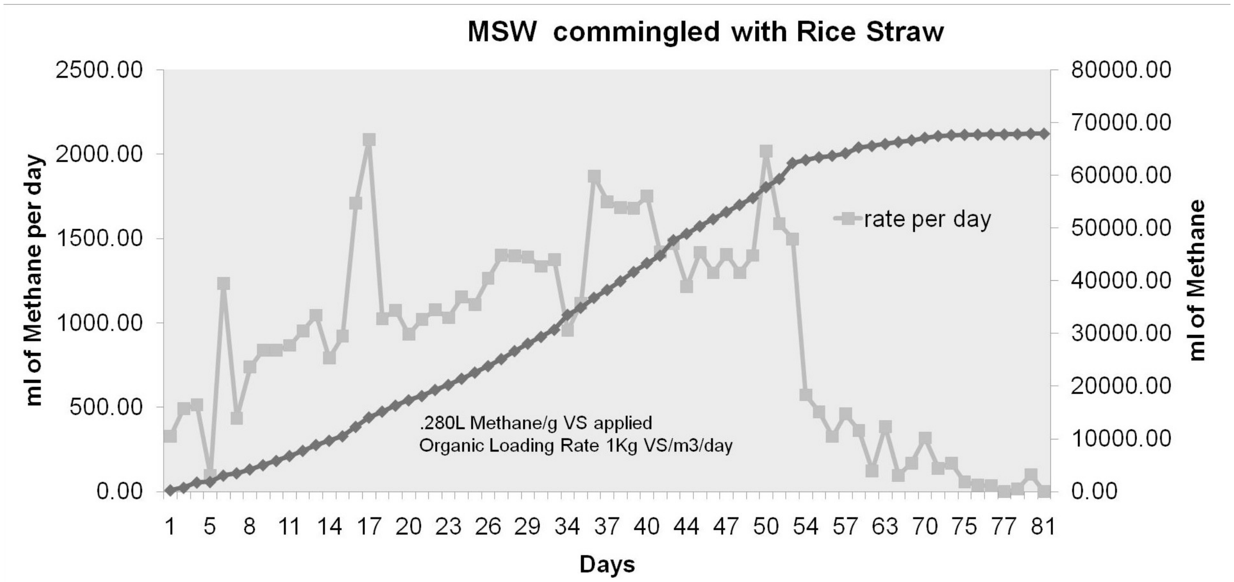

Figure 3. Methane production of autoclaved MSW commingled with rice straw using a high solids biogas reactor.

Research indicates that very high biomethane yields are available both from cellulosic MSW and biomass, however because of their nature (cellulose encrusted in lignin) longer retention times are required for their decomposition. Figure 4 shows the biomethane production from a 20 g plug feed of rice straw to the CSTR described above. Yields with the acclimated population have routinely been in the range of 385 mL CH4 per gram of biodegradable volatile solids (BVS).

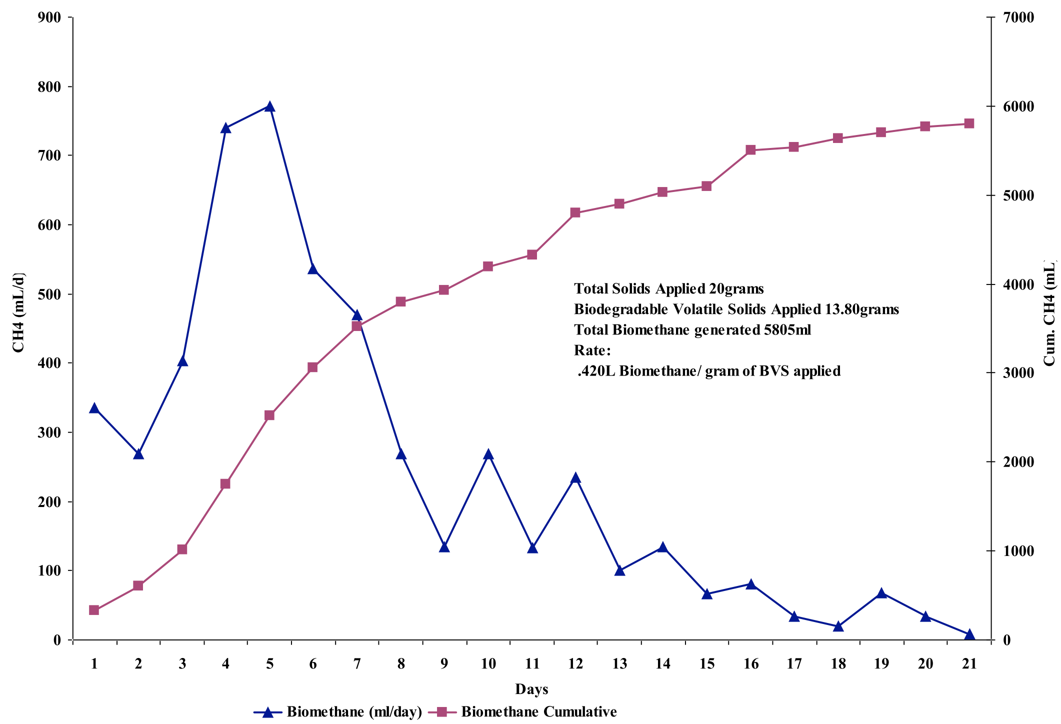

Figure 4: Biomethane production from a 20 g plug feed of rice straw to a CSTR

In order to maximize biomethane production from cellulosics, longer retention times are required as compared to food waste which is overwhelmingly the substrate utilized in this field. To minimize capital costs, high solids systems are highly preferable for cellulosic substrates. The USDA has developed a high solids system anaerobic system that embodies several advantages over current technologies employed for biogas production from MSW. The system depends on semi- continuous batch operation in which feedstock is fed at regular intervals while maintaining a hermetic seal to allow for anaerobic digestion of the reactor's contents during the feeding process.

The autoclave system yields 450- 500 lb of dry cellulosics per ton of incoming MSW at 40- 50 % solids. The pulp is to be diluted and fed continuously into high solids anaerobic digesters, with recycled permeate or gray water to obtain high solids (15- 20 %) fermentation conditions. Manure has a high nitrogen content and can be used to properly amend the carbon to nitrogen (C:N) ratio of the cellulosics; thus addition of manure or chicken litter to the basin is a desirable scenario to avoid chemical alteration of the C:N ratio. Laboratory experiments have determined that the entire fermentable fraction of the cellulosics (cellulose, hemicellulose) can be completely fermented within a 40 day time period. The method thus eliminates the cellulosics from MSW and reduces the time period for its destruction (which occurs naturally in a landfill) from 20- 50 years to 40- 120 days. Cellulosic residue such as rice straw can be shredded and commingled with the MSW pulp prior to feeding to allow for incorporation. The residuals from the basin represent a humic- like substance that can be used as an organic soil amendment (especially with enhanced C:N ratio) and can be used to restore nutrient poor soils. Metals analyses to this point have indicated that the soil amendment is well below EPA 503 regulations for compost.

This process is to be demonstrated at the SVSWA Crazy Horse Landfill and as the project that has been (described here) proves viable, SVSWA could scale to commercial for the production of biomethane. A preliminary study indicated that at 500 TPD incoming MSW the process would produce ample biogas to operate the facility, fuel the waste hauling fleet, and provide excess for sale to the surrounding community. As LNG or CNG, biomethane burns much cleaner than diesel, can displace those requirements for fossil fuel, and is a GHG negative (CO_2 saving) fuel alternative. Methane-derived fuels are amongst the lowest carbon fuels and life cycle analysis indicates that at 500 TPD incoming Salinas could avoid the emissions of 14,000 tons of CO_2 equivalent greenhouse gases over a 20 year operating period. Alternatively biogas can be utilized for green electricity production and can be used to displace coal providing a clean pathway to fueling electric cars.

Care has been taken to accommodate agricultural wastes into the feedstock. However, the economic viability of the system being developed in Salinas depends on the reliability of MSW production, with the existing infrastructure of the waste industry to create a platform feedstock. Agricultural wastes are only to be added if the transportation radius and collection mechanism are logical and if there is no other higher value use alternative. The system accepts both cellulosic and non-cellulosic agricultural wastes, making it a perfect fit for the Salinas Valley as the region produces 25,000 tons per year of processing waste and pre- packaged food products that have gone beyond shelf life. These materials are to be incorporated with the MSW feedstock with no modification and the autoclave will free their contents from the packaging. Cellulosic wastes, on the other hand, can be milled to reduce particle size and mixed with the high solids pulp prior to slurrying the feed to the anaerobic basins. Other wastes such as manure can be fed either directly or slurried with the cellulosic ag- wastes. As a result the anaerobic basins can be utilized to produce biomethane from a multitude of waste streams. Parallel basins that do not incorporate municipal wastes can be operated successfully and the residuals can be readily applied to food producing lands to return nutrients to the soil, completely integrating the farming community operations. This latter example of the basin's utility provides a sustainable option for producing energy in California's rice country. The pilot scale basin to be built in Salinas, CA will be in essence a prototype on- farm basin and will provide a good estimation of the economics of the system at this scale.

Biomethane yields achieved in the laboratory are in the range of 155 ethanol gallon equivalents (EGE) per ton of dry MSW pulp. Biomethane is scalable, has a reasonable capital investment, and thus is applicable on- farm and in rural communities as are predominately encountered in the U.S. Nationally biomethane could represent as a replacement fuel nearly 10 billion (EGE) annually based solely upon MSW. If produced locally from local waste materials including municipal wastes, biomethane will actually be a negative GHG emission fuel based upon well- to- wheel analysis. It is the USDA's mission to provide added value to existing agricultural operations, to open up pathways for new products, and to create jobs particularly in rural communities. Biomethane gas (BMG) can be produced in both rural and urban areas, it can be easily transported via pipeline to its ultimate destination for processing, and thus it can provide a distributed system capable of efficiently delivering energy from rural agricultural areas to urban centers with high energy demand.

If future biorefineries are to follow the trends shown by the corn- ethanol industry they require huge capital investments. The typical corn- ethanol facility increased from under 50 million gallons per year in 2004 to over 100MM gal/yr by 2006 [Todd Alexander and Marissa Leigh Alcala, Ethanol Producer Magazine, April 2006]. Moving cellulosic ethanol technology from the laboratory to a commercial- scale biorefinery is an expensive proposition and banks have appeared reluctant to fund these high- risk projects using first- of- a- kind technologies. With costs for moderate- scale demonstration plants ranging upwards of $80 million, and costs for significant commercial facilities (100 MM gal/yr) over $150 million, funding has proven problematic. To bridge this financing gap, the U.S. Department of Energy (DOE), along with the U.S. Department of Agriculture, have sponsored several granting programs; for example they announced that over $240 million in grants were awarded for nine small- scale cellulosic biorefinery projects in 2008, each ranging from $25 to $30 million. Despite this progress, ethanol from herbaceous feedstocks and/or waste has yet to prove commercially viable on a large scale for a host of reasons, including higher costs of enzymes (relative to corn- ethanol), low ethanol yields, and high separation costs as a result of low yields.

Ramping up cellulosic ethanol production will require major changes to grow, handle, transport and store the immense quantities of biomass - lignocellulosic feedstocks such as switchgrass, crop residues, forest wastes, and solid wastes - necessary to continually feed biorefineries and/or electric power generation stations. A recent article in Science (T.L. Richard, Science 329, 793, 2010) concludes that bioenergy from biomass has the potential to provide up to 60 percent of the world's primary energy, with estimates of a 50 percent reduction in greenhouse gas emissions by 2050. Such an exponential increase in bioenergy production in less than 40 years will need to be accompanied by a huge expansion of infrastructure.

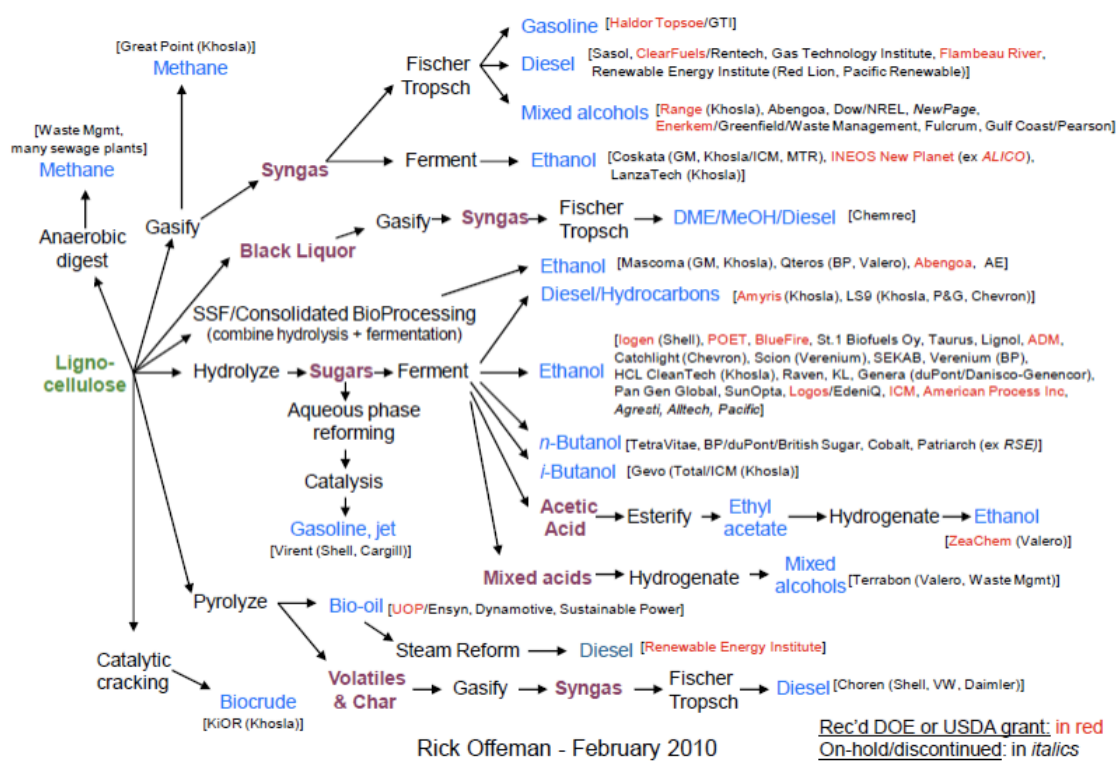

Figure 5. A listing of companies involved in biofuels production from lignocellulosic feedstock based on their processing methods.

Figure 5 is a listing of companies involved in biofuels production from lignocellulosic feedstock, outlining production of so- called 2nd and 3rd generation fuels in groups based upon their differing conversion technologies. Many promising technologies are represented within this listing. This figure neatly highlights the fact that all scenarios for biofuel production from biomass depend on providing the “cheapest” source of sustainable carbon on a consistent basis. Arguably, waste feedstocks are “cheap” sources of carbon, provided their pretreatment is appropriate for use within the processes outlined in Table 1. Rather than paying for feedstock, most waste treatment facilities are paid to “get rid of” waste, with typical tipping fees for MSW in the U.S. roughly $22- 40/ton.

Pulp isolated from MSW could feed virtually every one of these processes (2nd or 3rd generation fuels) since it is such a cost effective source of lignocellulose. Considering that ratepayers fund a tipping fee to landfill this waste, the cost of conversion, roughly $25 to $50/ton means that MSW can provide inexpensive biomass to this entire industry.

Summary

The uniform streams isolated from autoclaved MSW, either alone or commingled with agriculturally- derived biomass, have been converted to ethanol and biogas. It has been shown that MSW can be a platform feedstock for an integrated biorefinery to produce high yields of transportation fuel and/or methane depending on the needs of the local community. In one model scenario, we developed plans for an integrated biorefinery that utilizes three strategies; (1) biomethane production of volatile organics, (2) ethanol production via conversion of sugars derived from cellulose- rich pulp obtained from MSW, and (3) complete recycling of all metals and cans from the MSW with little additional labor. Large- scale commercial application of this specific autoclaving technology is being performed by Sterecycle, U.K, a licensee that operates a 250 ton/day autoclave (see http://www.sterecycle.com/index.htm).

The goal of this project is to establish the viability of a scaled- up system for effectively diverting the organic component of MSW from landfills and converting it to meaningful volumes of biomethane or ethanol. The first economic benefit of this process is diversion of nearly all of the organics from landfill operations. The second opportunity is resale of recycled metals and high- melting plastics obtained from autoclaved MSW after trommelling. The biggest economic driver for utilizing waste as a biomass source is the economic security of turning these societal costs into value- added products. Landfill costs (tipping fees) are increasing yearly, with costs surpassing $40/ton. Diversion of tipping fees adds financial security to economic risk assessment, since MSW in the proper situation is essentially available at the cost of pretreatment. Additional incentive is the recognition that tipping fees will likely get significantly higher with time due to relative scarcity of land and public sensitivity to landfills in their neighborhoods. As populations densities increase, tipping fees increase rapidly; for example tipping fees in Europe and Japan are significantly above $100/ton, with costs projected toward $200/ton by 2015.

In locales that cannot provide the amount of biomass required for an economical cellulosic ethanol plant, other technologies are possible. In rural communities, particularly those with low densities of agricultural residues (and, thus a large transportation radius), anaerobic digestion is potentially more attractive because it is not as dependent on scale. Biomethane from digestion can be sold to utility companies as natural gas, can run turbines for electricity production or can be liquefied and used as a transportation fuel. With a minor modification to the fuel system, liquefied biomethane can displace diesel in heavy duty vehicles and dramatically reduce their carbon foot- print. Swedish automobile manufacturers, led by Volvo, have begun marketing fleets of trucks that run on biomethane derived from an increasing number of filling stations that are connected to waste facilities (http://www.automotiveworld.com/news//80530- sweden- volvo- to- start- methane- diesel- tests- in-february).

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Chapter 15

Commercial Scale Corn Stover Harvests Using Field-Specific Erosion and Soil Organic Matter Targets

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Abstract

Corn stover,including the stalks, cobs, and leaves left over after a corn harvest, has the potential to provide farmers with an additional income stream and provide end users with a new source of feed or energy. However corn stover provides valuable services to the soil, reducing erosion and contributing to soil quality, which must be considered when harvesting stover. The Revised Universal Soil Loss Equation (RUSLE2) and Soil Conditioning Index (SCI), conservation tools which predict erosion and soil organic matter accumulation trends, can be used to estimate the amount of stover needed to meet management targets for these factors at the level of individual fields or even parts of fields. Target stover harvest rates can be estimated by subtracting the amount of stover that needs to be left in the field from the total amount of stover produced. The amount of stover that needs to be left in the field is determined on a field by field basis and varies depending on location, soil type, crop rotation and farming operations. This approach has been used to guide stover harvests of 3,200 dry tons per year near Cedar Rapids, Iowa in 2008 and 2009. Interviews with farmers were used as data inputs to create operation specific farm management models, soil survey data were used to identify average slope and predominant soil type for each field and revised corn and soybean harvest indices were used to estimate input residue rates. Field stover requirements varied from a low of 0.4 dry tons per acre for a flat field in continuous corn to more stover than would be produced by a 350 bushels per acre corn crop for several fields with average slopes over 4%. The average field stover requirement was 2.5 +/- 1.2 dry tons per acre for the 74 fields (8,800 ac) examined in 2008 and 2009. Corn stover was harvested as 0.46 dry ton large round bales using a “two pass” rake and baling system, a system with an average harvest rate of 1.7 +/- 0.6 dry tons per acre. Harvest was limited to areas of fields where harvest targets were within the harvest range of this system. Field operators were provided with field-specific target baling rates in the form of look up tables based on farmer reported corn grain yields. Stover was harvested at an average rate of 0.9 bales per acre below target, with 37 of 41 harvested fields baled at or below target. This study demonstrates that field specific stover retention rates can be estimated on a large scale and that current harvest equipment can be used to harvest corn stover at rates based on these estimates.

Introduction

As corn yields increase, the amount of stover produced also increases. Excessive stover can lead to additional management costs for farmers, who often use additional tillage passes to speed residue breakdown or reduce corn in their rotations. Stover harvests may offer farmers an additional revenue stream if excess residue can be harvested economically. Attractively priced corn stover may also facilitate the development of local feed or energy markets. However, stover provides valuable services to the soil. Compromising these services risks damage to the value and productivity of the field. Natural Resources Conservation Service (NRCS) Conservation Practice Standard 344 describes a number of factors that should be considered when removing residue, including water and wind erosion, accumulation of soil organic matter, water retention, chemical run off and wildlife habitat (NRCS, 2010a). Erosion and soil organic matter are the most frequently cited of these factors (Mann et al., 2002; Wilhelm et al., 2007; Blanco-Canquia and Lal, 2009; Johnson et al., 2010), with water retention becoming a concern in the western Corn Belt (Wortmann et al., 2008). The importance of each factor varies depending on local weather, soil type, field topography, farming operations and cropping history. Given this level of variability, generalizations about stover harvest rates, such as harvesting a certain percent or a flat rate, should be avoided. Rather, stover retention targets should be first estimated at the field or sub-field level. Stover harvest rates are the difference between the amount of stover needed to meet field-specific management targets, referred to here as the field stover requirement, and the total amount of stover produced by the corn crop.

Field stover requirements can be estimated using predictive conservation planning tools developed by the USDA. The Revised Universal Soil Loss Equation, version 2 (RUSLE2) provides a prediction of water erosion rates (USDA, 2008), the Wind Erosion Prediction System (WEPS) can be used to estimate wind erosion in areas where this is a factor (Wagner, 1996) and the Soil Conditioning Index (SCI) provides an estimate of trends in soil organic matter (NRCS, 2003). The NRCS does not have a National Conservation Practice Standard for crop residue removal, but the use of these tools has been suggested to estimate the effects of residue removal on soil quality (Andrews, 2006; Johnson et al., 2010). The tools are relatively simple to use, requiring knowledge of the location, slope and soil types of the fields considered for harvest and a history of field operations and residue inputs for the fields. These tools can be applied at the level of an entire field or subsections of the field.

Stover harvest operations can be matched to the fields where they are most appropriate by considering the range of removal rates possible with a set of harvest equipment, field stover requirements and the amount of stover produced. The rake and baling system used in this study had an average harvest rate of 1.7 +/- 0.6 dry tons per acre. Similar or higher harvest rates have been reported in other studies (Glassner et al., 1998; Hess et al., 2009) using similar equipment. Fields suitable for harvest with this system are those where the total amount of stover produced is at least equal to the field stover requirement plus the average harvest rate for the system.

Considerable attention has been given to the potential of corn stover as an energy source (Graham et al., 2007; Hess et al., 2009). However, the only documented large scale harvest operation (Glassner et al., 1998) was not a commercial success and concerns about damage to fields persist (Blanco-Canquia and Lal, 2009). Without both economic and environmental successes, corn stover harvests can not become a sustainable part of corn farming. Collectively the three companies working on this project, Archer Daniels Midland Company, John Deere & Company and Monsanto Company, have the experience in agronomics, field operations, processing and financial management required to sustainably harvest corn stover. In this paper we describe the methods we have used to determine corn stover harvest rates.

Results and methods

Corn stover harvests were carried out in Benton and Linn County Iowa in 2008 and 2009. The harvest was organized and overseen by a local co-coordinator with ties to the community. The project began with discussions with individual farmers, where their thoughts on harvest considerations and pricing were gathered. Following this, a project presentation and discussion was held with a larger group of farmers and other members of the community. Further discussions were held with individual farmers as they enrolled in the program. This level of community involvement helped ensure the success of the project and mitigated some concerns about unusual activities organized by three large corporations. Enrolled fields were fairly typical for the area, with an average size of 118 ac and silty clay loams as the predominant soil type (Table 1). Nearly all of the fields were either in a corn-soy (C-S) rotation or had been planted in corn for two or more years (C-C). Part of one field had been planted in alfalfa the preceding three years. Average corn yields exceeded 190 bu/ac both years. The major difference in fields between the years was average slope. In 2008 fields were enrolled in the program without any selection criteria. Over half of the fields (17) enrolled in 2008 had average slopes greater than 4% where large amounts of stover is needed to maintain erosion within management targets, and could not be harvested for stover. In 2009 fields were screened for low average slopes prior to enrollment with all but 3 of the enrolled fields expected to have harvest rates of over 1 dry ton/ac at average yields.

Year	Farmers	Fields	Area (ac)	Average size (ac)	Average slope	Major soil type	C-S/C-C rotation	Average corn yield (bu/ac)
2008	13	38	4807	126	4.1%	Silty clay loam	20/18	194
2009	11	36	3998	105	2.7%	Silty clay loam	25/11	191

Table 1. General characteristics of fields enrolled in the Cedar Rapids corn stover harvest program.

Field stover requirements were estimated for each field using the SCI within RUSLE2. These tools require two basic types of information: 1) A short history of farming operations, rotations and crop yields that can be obtained from the farmer or local agronomist and 2) field specific information that can be obtained from the Soil Survey Geographic (SSURGO) Database or Web Soil Survey (NRCS, 2010b, c). As part of the enrollment process, farmers were asked to participate in an interview where specific fields were identified and farm management information was collected. Enrolled fields were first identified in a plat book by the farmer. This information was used to select a satellite image and outline of the field, which was returned to the farmer for verification. Once the location and shape of the field was verified a distinctive field sign was placed at a field entrance specified by the farmer, with the GPS coordinates of the field sign recorded. Field crews used these signs to identify the correct fields prior to raking, baling or removing any bales from the field.

The interview process usually took over an hour, with most of the time spent covering the first field. Additional fields managed by the same farmer typically had very similar management histories, allowing the interview to proceed rapidly once an initial set of management practices was defined. Scheduling difficulties prevented face to face interviews with some farmers in both 2008 and 2009. These farmers were provided interview forms to fill out on their own. Data in the returned forms was quite sparse, requiring follow up telephone conversations to complete. Streamlining and automating data collection from the interview process is one of our current priorities. Two years of information was collected, starting immediately after harvest of the crop two years prior to the anticipated stover harvest (i.e. fall of 2006 for a 2008 stover harvest). All field operations occurring during this period were covered, including tillage, fertilizer applications, planting, spraying, harvests and yields. Specific equipment used and soil disturbance depths were recorded to allow matching of the farmer's descriptions to operation descriptions in RUSLE2. Additional information on fertilizer application rates, chemical applications and fuel use were collected as part of the interview to allow life cycle analysis (LCA) of the farming operations.

RUSLE2 requires information on soil type and slope. Field average slopes and predominant soil types were determined with information obtained from the Soil Survey Geographic (SSURGO) Database or Web Soil Survey (NRCS, 2010b, c). The soil type covering the largest area in the field was selected as input for RUSLE2. Nearly all of the soils in the program were silty clay loams. RUSLE2 output was relatively insensitive to changes in soil type within the range of soil types encountered. The use of field average slopes is a compromise between the limits of the harvest equipment and variable levels of stover required across different parts of the field. Raking crews were instructed to "stay off the slopes", avoiding parts of the field estimated to have 5% or greater slope. Tilt meters have been installed in raking tractors to help guide this in 2010. Slope lengths were estimated based on a slope length table provided by Dave Lightle, NRCS (Table 2). Contouring was assumed to run up and down the hills.

Slope (%)	Slope length (feet)
0.5	100
1.0	200
2.0	300
3.0	200
4.0	180
5.0	160
6.0	150

Table 2. Slope length estimates as a function of slope (D. Lightle).

Harvest index (HI) assumptions are used to estimate residue input rates in RUSLE2. The default values for corn are 0.50 (dry grain mass/(dry grain mass + dry stover mass)) and 0.42 for beans. These values likely overestimate residue input rates within the area of the study. Soy harvest index, a measurement that includes leaves shed during the season, has been reported as 0.47 and 0.45 over two years for maturity group II (Schapaugh and Wilcox, 1980). Corn harvest index at grain maturity was observed to vary based on grain yield (T. Barten, unpublished). A regression model based on these observations was used to estimate harvest index ($y = 0.0007x + 0.4168$, where x = corn yield in bushels per acre and y = HI) valid for 175-225 bushels per acre only), resulting in harvest index values ranging from 0.54 to 0.57. Actual corn and soy yield as reported by farmers were adjusted prior to input into RUSLE2 so that residue input values used in RUSLE2 better matched those of the farmers fields.

Field stover requirements were estimated within RUSLE2 by changing anticipated corn yield for the harvest season in 10 bushels per acre increments until either the erosion (ER) or organic matter (OM) sub-factors within the Soil Conditioning Index were at their lowest positive value. Slope and crop rotation were the largest factors affecting field stover requirements within the fields examined. Soil types were similar across fields and within rotation farm management was relatively similar across the participating farmers. This is illustrated in Table 3, where slope was varied within RUSLE2 for a specific, but typical field. At slopes of 2.0% and less the organic matter sub-factor was limiting, but at 2.5% and above the erosion sub-factor became limiting. The overall SCI score, which is a weighted sum of the OM and ER sub-factors plus a field operations sub-factor, reached a minimum of 0.4 just prior to the point at which erosion became the limiting sub-factor. When the ER factor is close to zero RUSLE2 estimates soil loss at 2.5 tons per acre. RUSLE2 predicts erosion based on sheet and rill erosion, but not ephemeral gully erosion which can be a significant factor in many fields (Casali et al., 2000). Still this value is about half of the soil loss tolerance or T factor for these fields. Soil formation rates in Iowa have been estimated at 4 to 5 tons per acre (Parsons et al., 1961; Hallberg et al., 1978), suggesting that this rate of soil loss can be considered sustainable. Wind erosion is not a significant factor in this part of Iowa and WEPS was not used. Field stover requirements were similar in C-S and C-C fields if stover was harvested in every year corn was planted. However, harvesting stover every other year in C-C fields allowed larger stover harvests due to the carry over in organic matter from the previous year's corn crop. This can lower stover harvest costs, but may not address farmer's residue management needs.

Field average slope (%)	Field stover requirement (dry tons/ac)	Corn grain yield required for 3 bale/ac harvest	SCI erosion sub-factor	SCI organic matter sub-factor	Soil loss (tons/ac)
0	2.0	170	0.92	0.04	0.2
0.5	2.0	170	0.77	0.04	0.6
1.0	2.0	170	0.59	0.04	1.0
1.5	2.0	170	0.38	0.04	1.6
2.0	2.0	170	0.14	0.04	2.2
2.5	2.2	175	0.03	0.10	2.5
3.0	3.3	235	0.01	0.26	2.5
3.5	3.3	235	0.03	0.48	2.5
4.0	3.8	260	0.03	0.64	2.5
4.5	4.3	290	0.03	0.81	2.5
5.0	4.8	315	0.03	0.97	2.5
5.5	5.1	330	0.01	1.10	2.5
6.0	5.5	350	0.01	1.20	2.5

Table 3. Field stover requirements for a soy-corn rotation (Field 2009-6-2) as a function of slope. Following a typical management practice for the area, soy was planted without tillage into corn residue in 2008 yielding 55 bushels per acre. A rolling harrow was used to prepare the seed bed prior to planting corn in 2009.

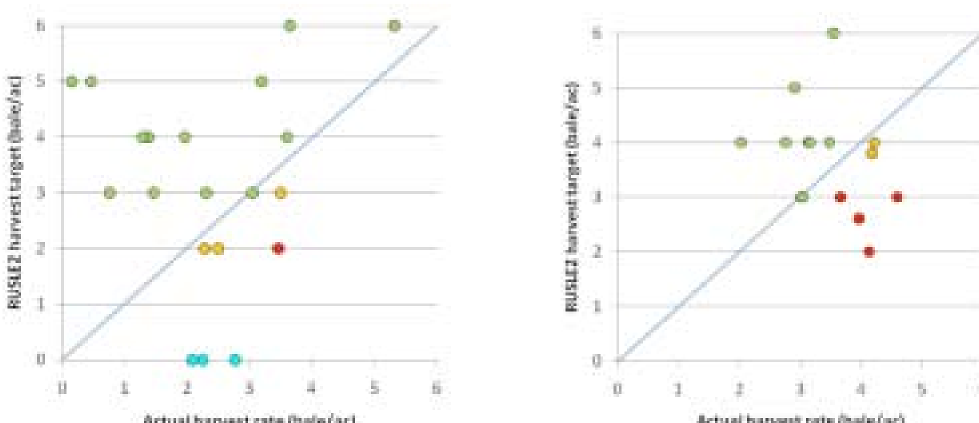
Target stover harvest rates were provided to field crews in a bound field book. A look up table, listing target baling rates based on farmer reported grain yield was prepared for each field. Target baling rates were determined assuming 1,100 lb fresh weight per bale and 16% moisture (0.46 dry tons/bale). The field stover requirement was converted from dry tons per acre to grain yield based on an assumed harvest index of 0.55. The amount of grain required to produce a bale's weight of stover (24 bushels per acre) was then added to the field stover requirement to produce a look up table with one bale increments. The field book also contained maps showing the location of the fields, contact numbers for the famer and other project members, field images with entrance points marked and any specific instructions from the farmers. Field stover requirements averaged 2.5 +/- 1.2 dry tons per acre across the 74 fields examined, with an average yield of 200 +/- 64 bushels per acre required to harvest stover at a rate of 3 bales/ac.

Corn stover was baled in a three step operation, often referred to as a "two pass" system. A 23' wheel rake (Kune SR112) was used to create windrows. Raking was done at an oblique angle to the corn rows, which evens out wear on the rake. No mowing or shredding was done prior to raking. Both of these operations can increase the amount of stover collected, but can also increase the percentage of higher moisture and ash content stalk bottoms collected and increase stover cover loss due to wind or rain. Large round bales were created using several different round balers, including John Deere 566, 567 and 568 balers and a Vermeer 605 M cornstalk special. Bales were removed from the field using a Bühler/Inland 2500 round bale carrier in 2009, an addition that greatly facilitated staging. Average baling rates were 1.2 +/- 0.5 and 1.7 +/- 0.6 dry tons per acre in 2008 and 2009 respectively. Stover removal rates, as a percent of total stover produced averaged 30 +/- 15% in 2008 and 47 +/- 18% in 2009. Harvesting at these rates leaves a large amount of stover on the field (Figure 1).

Figure 1. Raking and baling steps when collecting corn stover at target rates. Left: Corn stover was raked into windrows at an oblique angle to the corn rows. Right: Bales in the field prior to staging. Field stover requirement for this field was 2.6 dry tons per acre, target baling rate and actual baling rate were both 1.4 dry tons per acre (3.0 bales/ac).

The large majority of fields, 37 of 41, were harvested near or below target rates. Four fields were harvested at rates of more than 1 bale/ac over target rates (Figure 2). Field 2008-5-1, the most over harvested field, was harvested at a rate of 4 bales/ac but had a target rate of 2 bales/ac. In this field the OM sub-factor was -0.13, although the overall SCI score was 0.4 and erosion rate was estimated at 1.1 tons per acre. In 2008 many of the farmers were switching back and forth between corn and soy harvests, resulting in many of the larger corn fields being harvested for grain in two or three steps over several days or weeks. In several cases only parts of these fields were harvested for stover, resulting in field average baling rates of less than 2 bales/ac.

Interestingly, three fields were harvested in 2008 where estimates based on average slopes precluded stover harvest. These were irregular fields, where relatively small parts of the fields contained significant slopes. Following instructions to “stay off the slopes”, the field crew harvested only from the flatter part of these fields. Recalculation of target stover harvest rates, using only the flatter parts of the fields showed that the experienced field crew was correct and that these parts of the fields were harvestable. This approach, properly executed, has the potential of significantly increasing the number of fields that can have some stover removed.



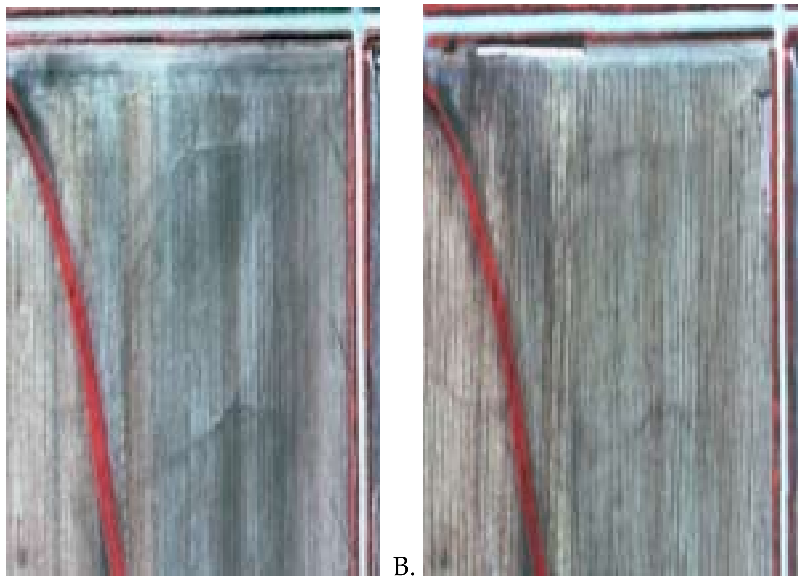
A. B.

Figure 2. Actual baling rates vs. target baling rates for 2008 (A) and 2009 (B). Fields indicated in green were harvested at or below target rates. Fields indicated in yellow were 0.5 bale/ac or less over target and those in red were over harvested by more than 0.5 bale/ac. The three fields, indicated in blue, with target rates of zero in 2008 were irregular fields containing both flatter and steeper areas. Partial harvests, limited to the flatter parts of the field were done in these fields. Also in 2008, several fields were not fully harvested due to scheduling conflicts as farmers switched back and forth between corn and beans . This resulted in field average harvest rates of < 2 bales/ac.

Only about 50% of the fields enrolled in the program were harvested each year. In 2008 this was primarily due to the enrollment of many fields with slopes that did not allow stover harvests. In 2009 an effort was made to enroll flatter fields, with lower anticipated field stover requirements. This effort was too successful, resulting in much more available stover than required for the project. For the 2010 season a running estimate of anticipated total stover harvest was maintained during enrollment based on farmer reported average slopes and crop rotation. Some over enrollment is required as not all fields will be able to be harvested due to weather and timing issues, but this estimation method should manage enrollment to better match project needs.

The amount of residue left in the field to meet the field stover requirements leaves the field completely covered (Figure 3). Aerial images of three fields were taken shortly after grain harvest and again shortly after stover harvest. A color infrared (CIR) image of one field is shown in Figure 4. Analysis of these images for Green Biomass Index (GBI), an indicator of residue cover (Paris et al., 2009), did not detect significant differences in residue cover after stover harvest.

Figure 3. Residue cover at 4 randomly selected spots with a field (2009-10-3) after stover harvest. A random sampling device (34" diameter sparkly hula hoop) was tossed from the bed of a pick up truck at different points in the field and photographed where it landed. Large amounts of residue can be seen after the harvest.



A. B.

Figure 4. Color Infrared images of a field (2009-3-1) shortly after grain harvest (A) and again shortly after stover harvest (B). No significant differences in residue coverage after stover harvest could be detected by image analysis in this or two other fields examined.

Nutrients lost from the field represent a cost to farmers that should be considered when harvesting stover. Macronutrients removed from the field in the stover were assessed by sampling a subset of bales from each field. Bales (n = 716) were sampled with an 18" x 0.75" "Penn State" Forage Probe (NASCO) driven by a gasoline powered drill. Samples were analyzed for phosphorus and potassium levels using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). Nitrogen was determined using a LECO FP-528 Nitrogen Analyzer. Sampling in 2008 was done between one week to two months of stover harvest. In 2009 sampling was done the day of stover harvest. Nitrogen, phosphorous and potassium levels varied by field and by year (Figure 5). Differences in sampling protocols, raking methods or the weather may have contributed to the nearly 2 fold difference in nutrient content observed across years. When averaged by field, average nutrient contents were: N 6.4 +/- 1.2, P_2O_5 0.26 +/- 0.06 and K_2O 4.0 +/- 0.73 lbs/bale. Correlations of nutrient levels were weak, with a K and P showing an R^2 of 0.71, N and P an R^2 of 0.58 and N and K an R^2 of 0.56. Fertilizer prices were very high at the end of 2008, but declined in 2009. The large annual variation in nutrient removal rates and prices lead to very large year-to-year change in the value of nutrients removed from the fields.

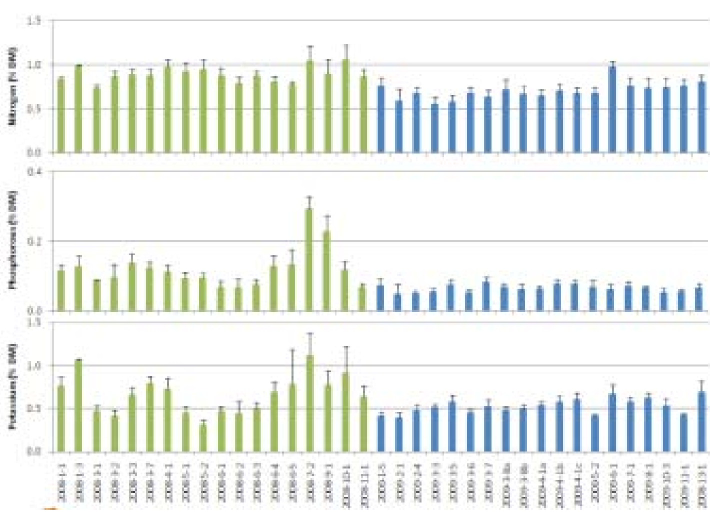


Figure 5. Macronutrient composition of corn stover bales. Elemental nitrogen, phosphorous and potassium content, expressed as a percent of dry matter were analyzed in a subset of bales harvested from each field. Composition varies by year and by field.

Discussion

Stover harvests rates and the risks or expenses this presents to farmers have been the subject of much debate. Here we show that conservation planning tools developed by the NRCS can be used to determine stover retention rates based on specific management targets for soil organic matter accumulation and erosion. The retention targets vary based on slope, soil types, location, cropping history and farm management. Management targets for erosion or soil organic matter accumulation may vary from farm to farm. In this study, an estimated soil loss rate of 2.5 tons ac^{-1} yr^{-1} was the maximum allowed. Soil organic matter is expected to increase, using a qualitative tool that predicts the direction of change in soil organic matter but not actual rates. As prediction tools improve, the specific tools used to predict the amount of stover needed to meet management targets will likely change over time. The important steps are determining specific management targets for the various factors affected by residue removal and developing specific stover retention targets consistent with these management targets.

We have also shown that fields can be harvested for corn stover with commercially available equipment at rates consistent with specific stover retention targets. Successfully harvesting stover and meeting retention requirements for stover involves matching fields to harvest operations. Field operations have specific average stover removal rates, with a relatively limited dynamic range. Fields can be harvested where the total amount of stover produced is greater than the amount of stover removed by the machinery used plus the amount of stover required by the field.

Field average slope and crop rotation were the best predictors of stover retention targets within the area of our harvest and could be used during field enrollment to approximate stover harvest rates. Partial field harvests, by avoiding steeper parts of the fields, allow more fields and area to be harvested for stover than if whole field averages are used to estimate retention targets. Currently this requires field operators to use their judgment or simple tools such as tilt meters to avoid slopes. Improved guidance systems or variable rate harvest machinery should improve farmer's ability to harvest stover and ensure that enough stover is left in the correct parts of fields to meet management targets.

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Chapter 16

Pyrolysis and Biochar-Opportunities for Distributed Production and Soil Quality Enhancement

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Introduction

The pyrolysis-biochar platform is fundamentally a vision for simultaneous production of renewable bioenergy, sequestration of large amounts of C in soils, and the enhancement of soil quality, water quality and agricultural productivity (Lehman et al., 2007; Laird 2008). Both pyrolysis and gasification are relatively simple, robust, and scalable technologies for transforming diverse biomass feedstocks into renewable energy products; heat, syngas, and/or bio-oil, which can displace some of the fossil fuels currently being used for industrial heat, power generation, and liquid transportation fuels. Pyrolysis and gasification are also generally amenable to distributed processing of biomass feedstocks, which may be critical for the economic viability of the emerging bioenergy industry (Wright et al., 2008).

Biomass is inherently a low density and often unstable material, which causes serious transportation and storage problems for large biorefineries. The capacity to store biomass on farm or in staging depots with just-in-time delivery of the biomass feedstock to a local processing facility would largely solve these transportation and storage problems. Furthermore, thermochemical plants capable of processing diverse sources of biomass will have the economic advantage of utilizing multiple and seasonal sources of feedstock and hence will have a larger and less expensive potential supply of feedstock than plants that are dependent on a single source of uniform high-quality feedstock. From an agronomic perspective, the loss of soil organic C and the associated degradation of soil quality will make the harvesting of biomass for any form of bioenergy production non-sustainable unless other sources of organic C are added to the soil to compensate for the biomass residue C that is removed. Processing biomass through a distributed network of relatively small pyrolysis plants and use of the biochar co-product of pyrolysis as a soil amendment appears to provide a simple and practical means of solving these problems (Figure 1). During pyrolysis most of the mineral nutrients that are present in biomass are concentrated into the biochar fraction, hence soil applications of biochar is a convenient means of recycling those nutrients to agricultural lands. Furthermore, given its high resistance to microbial attack (Granatstein et al., 2009), soil biochar applications offer the potential to stabilize some of the carbon fixed by terrestrial vegetation through photosynthesis, and appear to be a promising strategy for large scale, low cost carbon sequestration (Lehman et al., 2006; Wright et al., 2008; Laird et al., 2009; Mullen et al. 2010; Roberts et al., 2010).

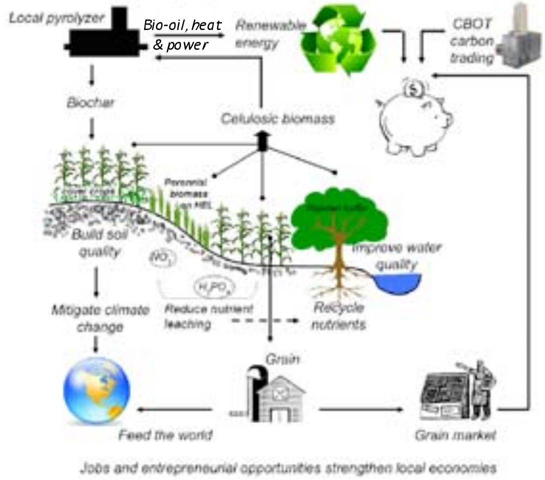

Figure 1: Landscape vision for integrated bioenergy-food production systems. In the vision food crops are grown on prime agricultural lands, perennial biomass crops are grow on highly erodible (HEL) land, woody biomass is grown in wet and frequently flooded areas adjacent to and expanding riparian buffers. Biomass harvested from diverse sources is processed in a local pyrolyzer producing renewable bioenergy and biochar. The biochar is returned to the soil recycling nutrients, enhancing soil quality, increasing agricultural productivity, and sequestering large amounts of carbon.

Production of Biochar

Almost any form of organic material can be pyrolyzed; however both energy conversion efficiency and the quality of the bio-oil, biochar and syngas co-products are dependent on the nature of the feedstock. In order to reduce energy loss, pyrolysis reactors should be fed materials with low moisture content (<10 percent moisture by mass). Lignocellulosic feedstocks with high content of alkalines (Na, K, Mg, Ca) typically result in high yields of biochar and relatively low yields of poor quality bio-oil. Feedstock rich in cellulose produce bio-oils rich in pyrolytic sugars, low molecular weight organic acids and water; whereas feedstocks high in lignin produce higher energy bio-oils enriched with mono-and oligo-phenols.

The diversity of feedstocks which can be processed by pyrolysis and the large number of design variables make it difficult to identify the optimum pyrolysis technology for a given situation. Some design criteria for pyrolysis reactor are shown in Table 1:

Final product targeted	Particle size	Reactor type	Heating rate	Operation mode	Heating method	Construction materials	Portability	Reactor position	Loading mode
Bio-oil Syngas Bio-char Heat	Trucks Chips Fine particles (Powder)	Fixed bed Moving beds Fluidized bed Circulating bed Ablative Auger	Slow Fast	Intermittent Batch Continuous	Direct contact of oxidant with the biomass Direct contact of biomass with a hot inert gas	Earth Brick Concrete Metals	Stationary Semi-portable Portable	Vertical Horizontal	Manual Mechanical With cars

Table 1: Criteria to select Pyrolysis Reactors

Slow Pyrolysis

The slow heating in the absence of oxygen to temperatures in excess of 400°C induces the thermal decomposition of lignocellulosic biomass producing approximately equal masses of syngas, bio-oil, and biochar. In traditional, charcoal kilns the syngas and the pyrolysis vapors (a multi-phase liquid formed by a decanted oil and pyrolygneous water when condensed) are vented to the atmosphere often creating serious air pollution hazards (Kammer et al., 2005). Biochar produced in traditional kilns is commonly commercialized as a fuel for domestic cooking and heating or used in the metallurgical industry. The world production of biochar in 2005 was more than 44 million tons (http://www.nationmaster.com/graph/ene_cha_pro_fro_cha_pla-energy-bio-char-production-from-plants).

Modern slow pyrolyzers either capture volatiles for use as source of chemicals or burn them directly to produce heat for coupled electricity generation or industrial processes (Figure 2). Slow pyrolyzers have several advantages relative to other thermochemical conversion technologies; the units tend to be small and inexpensive, they can accept diverse sources of feedstock, and the feedstock does not need to be finely ground. Slow pyrolyzers are, however, difficult to scale because heat transfer into coarse biomass is relatively slow, and hence the feedstock has a relatively long residence time in the reaction chamber. Slow pyrolyzers produce relatively more biochar and smaller amounts of usable energy products than other thermochemical conversion technologies. Slow pyrolyzers may also be optimized for the production of high-quality biochar, although that will depend on the, targeted application, nature of the feedstock as well as details of the thermochemical process. As such slow pyrolyzers appear to be best suited for supplying small amounts of heat and/or power to coupled facilities in remote locations, especially in regions with a high demand for biochar. The lack of commercial technologies to produce biochar and heat, the lack of grading standards for biochar for soil applications, the lack of technologies to modify the chemistry of biochar surfaces to address agronomical needs of targeted soils, and the lack of commercial stabilization, storage, handling and soil application technology for biochar is limiting the development of a slow pyrolysis industry.

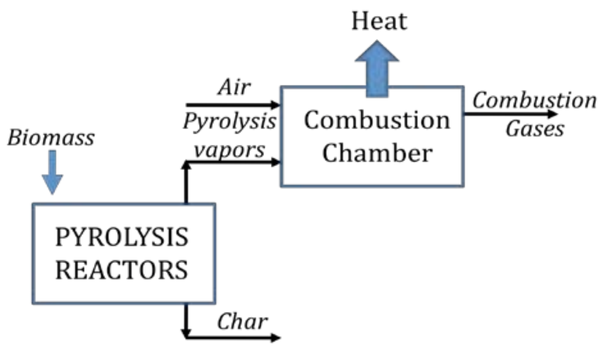

Figure 2: Pyrolysis scheme for the production of biochar and heat (Pelaez-Samaniego et al., 2008).

Fast Pyrolysis

During fast pyrolysis, biomass is rapidly (<1 s) heated to 400-700°C in the absence of oxygen. To achieve such rapid heating rates the particle size of the feedstock must generally be reduced to < 2 mm (Cummer and Brown, 2002), which requires significant amounts of energy. The primary energy product, bio-oil, is a dark brown liquid obtained by condensation of the pyrolysis vapor (Figure 3). Fast Pyrolysis yields 60-70 mass percent of the original biomass as bio-oil and 15-25 mass percent as biochar (Bridgwater et al. 1994, 2001; Czernik and Brigwater, 2004; Mohan et al., 2006). The overall energy recovery of fast pyrolysis depends critically on the moisture content of the biomass feedstock. For dry feedstock, reported energy recoveries in the bio-oil fraction are ~50 percent, and total energy recoveries (in the bio-oil and biochar) are ~75 percent relative to the energy content of the original biomass (Mullen et al., 2010). Once pyrolysis has converted the original biomass into a crude bio-oil, with an energy density of around 26,800 MJ/m^3, it can then be transported economically up to 500 km from the pyrolyzer to refineries where transportation fuels and chemicals can be produced taking advantage of the economies of scale (Bridgwater and Peacocke 2000; Granatstein et al., 2009; Mason et al. 2009; Huber 2008). Recent studies (Jones et al., 2009; Holmgren et al., 2008) demonstrated that at least 40 mass percent of fast pyrolysis oil can be converted into green gasoline and green diesel at a cost of 0.53 $ per L. Overall this approach could result in the production of 270 kg of green gasoline and green diesel and 150 kg of biochar per Mg (metric ton) of dry biomass. Fast pyrolyzers, based on fluidized and circulating bed reactors, are generally scalable but will need to operate at significantly larger scales than slow pyrolyzers to be economically viable. The economic viability of fast pyrolyzers will depend critically on the market for bio-oil; sale of the biochar co-product will provide a relatively small secondary source of revenue. The growth of a fast pyrolysis industry is currently limited by the lack of refineries able to convert bio-oils into transportation fuels and other high value products (Jones et al., 2009; Garcia-Perez et al., 2009).

Bio-oil consists of polar organic compounds (75-80 weight percent) and water (20-25 weight percent) and has a heating value about half that of petroleum based fuel oil (Bridgwater at al., 1999; Mullen et al., 2010). Bio-oil can be further refined to produce liquid transportation fuels. One approach is to gasify bio-oil and convert the syngas to methanol or to synthetic gasoline and diesel through Fischer-Tropsch (FT) catalytic reformation (Leibold et al., 2008). The gasification-FT process is currently employed on an industrial scale in South Africa and Malaysia to convert coal and natural gas to synthesis fuels. These FT refineries could be easily modified to use bio-oil as a feedstock. Another potentially more efficient approach that is still under development is hydro-treatment and catalytic cracking of bio-oil to produce drop-in liquid transportation fuels and various co-products. The U.S. Department of Energy (Jones et al., 2009) estimates that a 2000 ton per day integrated pyrolysis-hydrocracking refinery could produce gasoline and/or diesel fuels for a minimum price of $2.04 per gallon (in 2007 dollars). Bio-oil also can be burned directly in a furnace or boiler. The syngas co-product of fast pyrolysis can be used as a replacement for natural gas; however it is often burned in situ to dry the incoming biomass and power the pyrolyzer. Although biochar is a potential energy product that can replace pulverized coal, its application to soils has been proposed as a means of building soil quality and thereby making the harvesting of biomass for bioenergy production more sustainable (Lehmann, 2007; Laird, 2008).

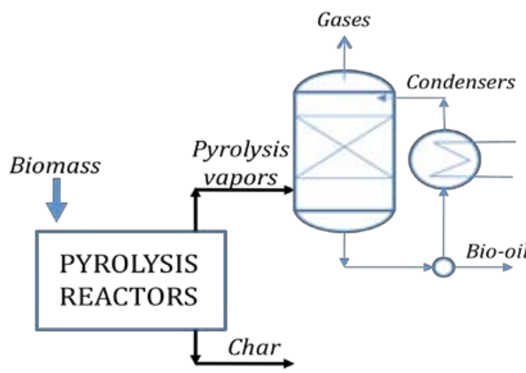

Figure 3: Pyrolysis scheme for the production of biochar, bio-oil and bio-gases (Pelaez-Samaniego et al., 2008).

Gasification

Gasification is the high-temperature (600-1400°C) partial combustion of biomass. Partial oxidation is achieved by allowing a small but carefully controlled amount of O_2 into the reaction chamber (15-28 percent of stoichiometric ratio). The primary products of gasification are CO, H_2, and CO_2. Part of the water vapor released during gasification is converted to H_2 by the slightly exothermic water-gas shift reaction ($H_2O + CO = H_2 + CO_2$) during gasification. Considerable heat is generated during gasification and can be used along with heat generated during the combustion of the syngas for power generation or as a source of process heat. The syngas after cleanup can also be used as feedstock for the production of synthetic fuels through FT catalytic reformation (Leibold et al., 2008); however FT reformation typically requires very large scale plants to be economical.

Although no biochar is produced in an ideal gasifier, where the biomass is completely converted to CO, H_2, CO_2 and ash, most existing gasification units actually end up producing small amounts of biochar (less than 10 mass percent). The ash co-product of an ideal biomass gasification reaction is a mixture of oxides, hydroxides and carbonates of the various inorganic metals that were present in the biomass feedstock, primarily Ca, Mg, K, and Si. Such gasification ashes are highly alkaline and may contain high concentrations of leachable polyaromatic hydrocarbons, which are potentially toxic high-temperature reaction products. As such, use of gasification ash as a soil amendment is potentially problematic. However, there is considerable flexibility in the design of gasification reactors. Some systems effectively couple pyrolysis of biomass with gasification of volatiles (Figure 4). Such systems may produce large amounts of high-quality biochar. Gasification of industrial wastes, municipal solid wastes and even biomass is already widely used. The production of usable biochar by gasification is still relatively novel.

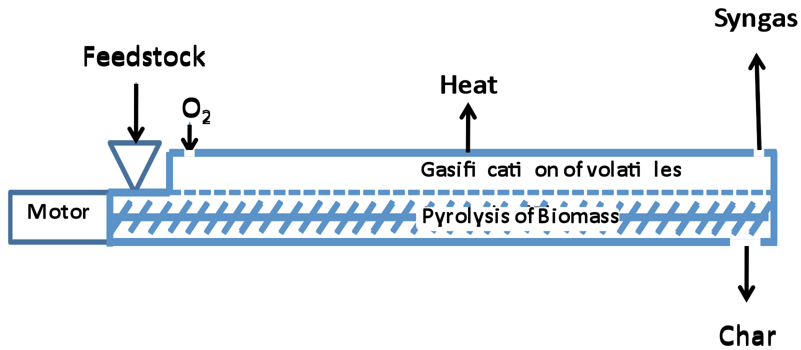

Figure 4: Auger based system that combines pyrolysis of biomass and gasification of volatiles.

Biochar Quality as a Soil Amendment

The definition of biochar quality is still in a state of flux as it depends to a large extent on the end purpose of the product. Feedstock quality, including concentrations of ash, which may include plant nutrients, lignin, cellulose, and hemicellulose, as well as the pyrolysis process and temperature all play a pivotal role in influencing the physical and chemical properties of the biochar co-product. If the biochar is burned, the caloric content, flash point, and ash content are key determinants of quality. If biochar is to be used as a filter material to remove organic or inorganic contaminants from an effluent stream then the adsorption capacity and hydraulic conductivity of the biochar will be critical for performance. If the biochar is used as a soil amendment, then the impact of biochar on soil quality, the ability of soils to retain plant available nutrients, water holding capacity, crop yields, and C-sequestration are just a few of the potential factors that will influence biochar quality. The template for quality suggested by researchers does not currently correlate individual biochars with performance for a potential application; however it does attempt to provide a common language. A standard group of characterization tests has been suggested as the biochar quality template (Lehmann and Joseph, 2009; McLaughlin et. al., 2009; Shinogi and Kanri, 2003). Shinogi and Kanri (2003) suggested a combination of physical (surface area, bulk density) and chemical properties (total carbon, total nitrogen, pH, fixed carbon, ash content, and volatile matter content) as indicators of biochar quality. As data bases become available with these and other biochar characteristics (cation exchange capacity, adsorbance), relationships between biochar properties and function for specific applications will become more apparent (Sohi et al., 2010). Current research is already making connections between these characteristics and their applications (Laird et. al., 2009). Many anticipate a time in the near future when quality standards are uniform throughout research, industry and the backyard community.

This presentation highlights the chemical and physical characteristics that are commonly used to define biochar quality and is not intended to be a comprehensive review. An excellent resource describing in detail biochar quality can be found in the book "Biochar Environmental Management: Science and Technology" edited by Lehmann and Joseph (2009).

Characteristics of Biochar

The char yield as well as, the chemical and physical characteristics of biochar depends on the nature of the feedstocks used (woody vs. herbaceous) and operating conditions and environment of the pyrolysis unit (low vs. high temperature, residence time; slow vs. fast pyrolysis, heating rate and feedstock preparation). The wide range of process parameters leads to the formation of biochar products that vary considerably in their elemental and ash composition, density, porosity, pore size distribution, surface area, surface chemical properties, water and ion adsorption and release, pH and uniformity of biochars' physical structure (Baldock and Smernik, 2002; Antal and Grønli, 2003; Downie et al., 2009; Krull et al., 2009; Chan and Xu, 2009). Joseph et al. (2009) has proposed a classification scheme based on these characteristics to describe the differences in the quality of biochar. We refer the reader to that review for specific details.

The biochar yield from the pyrolysis of biomass is influenced by the pyrolysis temperature, its lignin, cellulose, and hemicellulose content and to a lesser extent the extractive concentrations of the feedstock (McKay and Roberts, 1982; Antal and Grǿnli, 2003). Woody biomass with high lignin contents typically produce greater char yields than those derived from herbaceous feedstocks. A common feature among the various pyrolysis processes is that C content of the biochar product shows a consistent increase with increasing temperature (Antal and Grǿnli, 2003; Schnitzer et al., 2007; Zabaniotou et al., 2008; Joseph et al., 2009). Biochars with large amounts of poly-condensed aromatic structures are obtained by pyrolyzing feedstocks at temperatures between 400 and 600°C (Antal and Grǿnli, 2003; Amonette and Joseph, 2009). Temperatures above 500°C commonly produce chars with C contents greater than 80 percent, at temperatures between 400 and 500°C biochars have C contents that range from 60 to 80 percent and biochars produced at low temperatures (< 350°C) have C content that varies from 15 to 60 percent (Joseph et al., 2009). For a detailed description of the thermal degradation process (dehydration, pyrolysis, graphene formation and carbonization) that transforms biomass see Amonette and Joseph (2009) and Brown (2009).

In a recent study, Granatstein et al. (2009) found that the C content of biochars increased an average of 41 g C kg^{-1} for each 100°C rise in pyrolysis temperature (Figure 5).

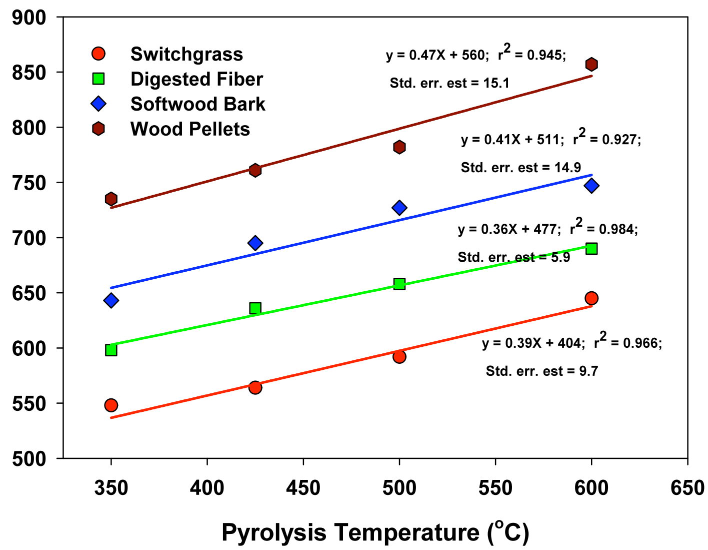

Figure 5. Relationship between pyrolysis temperature and the C concentration of the resulting biochar. From Granatstein et al., 2009.

Table 2 shows C, N and S concentrations of biochars as a function of pyrolysis temperature. A commercially available activated charcoal was included for comparison. Herbaceous feedstocks, switchgrass and anaerobic digested dairy manure fiber, pyrolyzed at 500°C had C contents of 60 and 66 percent respectively, as well as significantly higher N concentrations that were similar to the feedstock prior to pyrolysis. The woody feedstocks: bark-UGA, softwood bark and wood pellets had C contents above 70 percent with C:N ratios ranging from 200-600. The commercial activated charcoal derived from a hardwood had a C and N content of 87 percent, 0.47 percent, respectively. Nitrogen concentrations were > 2 percent for the herbaceous feedstocks and declined to <0.4 percent for the woody sources. The bark-UGA and softwood bark biochars originated from the same feedstock but were processed in different pyrolysis reactors.

	Production	‡Biochar Characteristics					
Source	Temperature	C	N	S	C:N	C:S	pH
	°C	------------- $g\ kg^{-1}$ -------------					
Switchgrass	350	548 (1)† a	18.3 (0.2) a	1.3 (0.11) a	30	422	8.5 a
	425	554 (2) b	20.4 (0.2) b	1.4 (0.10) a	27	396	9.1 b
	500	592 (13) c	19.9 (0.7) ab	1.5 (0.26) a	30	395	9.4 c
	600	645 (26) d	20.6 (0.3) b	1.6 (0.40) a	31	403	9.4 c
Digested fiber	350	598 (2) a	22.3 (0.2) a	3.3 (0.21) a	27	181	8.3 a
	425	636 (3) b	23.0 (0.3) b	3.3 (0.16) a	28	193	9.1 b
	500	658 (10) c	22.3 (0.2) a	3.1 (0.22) a	30	212	9.3 c
	600	690 (5) d	21.7 (0.1) c	3.6 (0.04) b	32	192	9.3 c
Softwood bark	350	643 (1) a	3.3 (0.1) a	0.3 (0.08) a	195	2143	6.0 a
	425	695 (2) b	3.5 (0.3) a	0.3 (0.04) a	200	2317	7.2 b
	500	727 (17) c	3.5 (0.2) a	0.3 (0.20) a	208	2423	7.6 c
	600	717 (5) c	3.6 (0.1) a	0.3 (0.04) a	200	2390	8.4 d
Wood Pellets	350	735 (2) a	1.2 (0.2) a	0.8 (0.40) a	571	2000	6.0 a
	425	761 (4) b	1.1 (0.1) a	0.3 (0.04) a	692	2537	6.7 b
	500	782 (18) c	1.3 (0.2) a	0.7 (0.36) a	602	1117	7.2 c
	600	857 (2) d	1.5 (0.8) a	0.2 (0.04) a	571	4285	7.4 c
Peanut hull	500	706 (12)	17.4 (0.9)	0.6 (0.1)	41	1178	9.6 (0.1)
Bark-UGA	500	745 (4)	3.4 (0.3)	0.3 (0.1)	219	2483	7.6 (0.1)
Act. Char		873 (3)	4.7 (0.6)	7.6 (0.4)	186	115	9.6 (0.1)

Table 2. Selected characteristics of six biochars. Activated charcoal was included as a standard analysis and comparison to biochars. †Std. error of mean in parentheses. UGA-the bark was made using a pyrolyzer unit located at the University of Georgia, Athens. Statistical comparisons were not made among biochars. Values for a biochar within a column followed by the same letter are not significantly different at p = 0.05.

Previous studies of biochar production have shown that chars made from herbaceous feedstocks (switchgrass, digester fiber, peanut hulls) had lower carbon contents, higher nitrogen contents, and higher pH than chars made from woody feedstocks (Novak et al., 2009; Granatstein et al., 2009). The pH of biochar is dependent on the feedstock and pyrolysis temperature and is attributed to the chemical cracking of hemicellulose and cellulose during pyrolsis. Between 300 to 600°C organic acids and phenolic substances are created and alkali salts are formed that raise the pH of the biochar (Abe et al., 1998; Shinogi and Kanri, 2003). The higher pH of herbaceous biochars give them a greater liming impact per ton of biochar added to soil, increasing soil pH 0.5-1.0 pH units depending on soil type. Biochars produced from poultry litter have a pH range of 8.5-10.3 that is related to the concentration of Ca and Mg (Chan et al., 2008; Gaskin et al., 2008).

Elemental Characterization

Elemental analyses of many biochars are available in the literature; however, many of these data sets are incomplete, providing information for only a few elements which makes comparisons among biochars difficult (Baldock and Smernik, 2002; Glaser et al., 2002; Antal and Grønli, 2003; Gaskin et al., 2008; Novak et al., 2009; Chan and Xu, 2009). Much of the mineral content of the feedstock remains in the resulting biochar, where it is concentrated due to the loss of C, H and O during pyrolysis (Amonette and Joseph, 2009). Biochars produced from biosolids and manures are typically high in ash, for example, chicken-litter biochars can have greater than 45 percent mineral matter (Lima and Marshall, 2005).

There is considerable variation in the content of many elements especially N and P due to feedstock characteristics and range of production temperatures. Feedstocks typically high in N, P, K and S are sewage sludge, animal manures and biosolids. Elemental contents of the biochar produced reflect the concentration of elements in the feedstock. Herbaceous biomass and biochars derived from biosolids and manures have N, P, K and S contents greater than woody feedstocks. About half of the N and S are lost during pyrolysis as temperatures increase from 350 to 600°C. Significant N losses (60-80 percent) have been reported for biochars derived from sugar cane bagasse, rice husks, sewage sludge, and cattle manure (Shinogi and Kanri, 2003). The availability of the remaining N contained in biochar is considered limited. Bagreev et al. (2001) suggested that as the pyrolysis temperatures increase, N forms pyridine-like complexes that reduced availability. Cao and Harris (2010) suggested that the decrease in N concentration can be attributed to volatilization during heating and that some of the N-containing structures in the biochar (e.g., amino acids, amines, amino sugars) are condensed into recalcitrant forms. The residual nitrogen contained in biochar does not appear to be available. Bioavalibility of P in biochar depends substantially on soil pH, with little or no bioavailibilty in calcarious soils and higher bioavalibility in acidic soils.

Table 3 shows the elemental concentrations of six biochars as a function of production temperature (Granatstein et al., 2009). Ash contents were higher in the herbaceous than woody biochars, following the order of switchgrass > digested fiber > softwood bark > wood pellets. As production temperature increased so did the concentration of each element. Elemental concentrations were significantly higher for the herbaceous than woody chars. As an example, P concentrations were ~10 times greater in the switchgrass and digested fiber than softwood bark and wood pellet biochars. This trend was similar across all elements, except for Mn which was significantly greater in the softwood bark char. Altland et al. (2008) found consistently higher concentrations of Mn in tree barks in the range of 5 to 30 mg L^{-1}. Concentrations of B, Cu, and Zn were 2, 8, and 20 fold higher, respectively, than in the switchgrass char, that most likely resulted from mineral supplements in the dairy cattle feeds and the Cu foot baths used to treat hoof infections. Cao and Harris (2010) found similar elemental concentrations and trends in four types of dairy manure derived biochars; however, they did not measure Cu concentration.

Physical Characteristics

Pyrolysis temperature and feedstock composition have a significant influence on the physical characteristics related to pore structure, surface area and adsorption properties (Antal and Grønli, 2003; Downie et al., 2009; Amonette and Joseph, 2009). As pyrolysis temperatures increase, volatile compounds in the feedstock matrix are lost, surface area and ash increase but surface functional groups that provide exchange sites decrease (Guo and Rockstraw, 2007). Ligno-cellulose degradation begins at approximately 120°C, hemicelluloses are lost at 200-260°C, cellulose between 240 and 350°C and lignin is degraded at 280 to 350°C. The proportions of these fractions remaining along with the ash content influence the level of reactivity of the char and the development of shifts in physical structure that define the chars attributes (Downie et al., 2009). As pyrolysis temperatures increase the poly-condensation of C into aromatic rings provides a structure that enhances pore development and surface area of the biochar. Biochars with large amounts C in these condensed structures formed at high temperatures (400-700°C) generally have lower functional groups for generating surface charge and ion exchange due to decarboxylation, where low temperature chars contain significantly more C=O and C-H functional groups that promote nutrient retention (Glaser et al., 2002; Baldock and Smerink, 2002; Hammes et al., 2006). Novak et al. (2009) found that the surface charge of biochars was influenced by feedstock and temperature. At low temperatures a pecan shell derived biochar had a surface charge of 2.5 mmol H^+ eq g^{-1} where biochars produced above 500°C had no measurable surface charge. The micropores of biochar have been shown to contribute the most surface area to biochars which accounts for the high adsorptive capacity of high temperature biochars. For an in depth review of pore formation and function see Downie et al. (2009).

	Production	Elemental Composition										
Source	Temp.	Ash	P	K	S	Ca	Mg	Fe	B	Cu	Mn	Zn
	°C	------------------------ g kg^{-1} biochar ----------------------							------------ mg kg^{-1} biochar ---------			
Switchgrass	350	181.6 (9)	3.8 (0.12)	26.2 (1)	1.0 (0.04)	7.9 (0.22)	4.0 (0.12)	0.66 (0.2)	60.3 (3)	4.5 (0.2)	93.3 (2)	28.8 (6)
	425	203.8 (3)	4.3 (0.02)	32.2 (1)	1.2 (0.03)	8.2 (0.09)	4.4 (0.03)	0.55 (0.1)	60.5 (1)	6.0 (0.4)	104.0 (1)	29.5 (1)
	500	208.1 (8)	4.7 (0.14)	32.8 (2)	1.1 (0.02)	8.7 (0.41)	4.6 (0.29)	0.62 (0.1)	63.8 (2)	7.7 (1.3)	108.8 (3)	33.7 (2)
	600	268.3 (7)	5.5 (0.06)	39.8 (1)	1.2 (0.02)	11.6 (0.4)	5.7 (0.10)	0.65 (0.1)	61.5 (2)	8.0 (0.7)	136.0 (1)	33.5 (2)
Digested fiber	350	112.2 (6)	5.4 (0.28)	8.9 (1)	3.0 (0.19)	16.9 (1.4)	5.0 (0.29)	0.91 (0.06)	124.5 (7)	118.1 (5)	134.7 (6)	168.5 (9)
	425	146.2 (2)	6.9 (0.18)	11.1 (1)	2.8 (0.04)	22.4 (0.6)	6.5 (0.19)	1.20 (0.01)	145.2 (7)	153.2 (3)	172.0 (4)	217.2 (3)
	500	154.4 (1)	7.6 (0.32)	11.7 (1)	3.0 (0.02)	24.0 (0.5)	7.0 (0.22)	1.28 (0.02)	148.8 (4)	162.9 (5)	184.0 (4)	230.0 (5)
	600	166.3 (2)	8.2 (0.36)	12.6 (1)	3.4 (0.14)	24.9 (1.1)	7.7 (0.32)	1.51 (0.07)	162.4 (9)	184.1 (8)	200.0 (7)	252.1 (9)
Softwood bark	350	41.2 (3)	0.53 (0.06)	1.1 (0.1)	0.17 (0.01)	8.3 (0.4)	0.37 (0.03)	0.47 (0.05)	53.3 (3)	6.3 (0.5)	292.0 (6)	24.7 (2)
	425	46.5 (3)	0.35 (0.03)	1.0 (0.1)	0.22 (0.01)	10.4 (0.3)	0.49 (0.03)	0.80 (0.09)	55.2 (2)	6.7 (0.2)	309.3 (20)	38.8 (1)
	500	54.0 (2)	0.47 (0.03)	1.0 (0.1)	0.23 (0.01)	10.7 (0.1)	0.48 (0.02)	0.70 (0.03)	56.7 (8)	6.8 (0.7)	266.7 (25)	40.9 (2)
	600	81.2 (8)	0.74 (0.06)	1.6 (0.1)	0.31 (0.01)	17.2 (1.1)	0.73 (0.02)	0.93 (0.07)	56.3(3)	9.4 (0.2)	408.0 (14)	59.6 (3)
Wood Pellets	350	9.4 (2)	0.20 (0.01)	0.8 (0.1)	0.15 (0.01)	1.8 (0.02)	0.25 (0.01)	0.19 (0.1)	93.5 (5)	2.8 (0.2)	82.7 (2)	25.9 (1)
	425	11.2 (2)	0.21 (0.01)	0.9 (0.1)	0.16 (0.01)	1.9 (0.01)	0.27 (0.01)	0.16 (0.1)	99.7 (4)	3.6 (0.8)	88.0 (1)	28.0 (1)
	500	11.6 (1)	0.22 (0.03)	1.0 (0.1)	0.17 (0.02)	2.0 (0.03)	0.30 (0.04)	0.25 (0.1)	91.2 (5)	3.1 (0.2)	93.3 (13)	29.1 (3)
	600	7.5 (1)	0.27 (0.01)	1.4 (0.1)	0.17 (0.01)	2.4 (0.05)	0.35 (0.01)	0.19 (0.1)	83.3 (3)	3.5 (0.2)	110.7 (5)	31.2 (1)
Peanut hull	500	77.2 (8)	2.19 (0.03)	16.8 (1)	0.90 (0.1)	5.0 (0.02)	2.68 (0.03)	1.35 (0.1)	161.6 (9)	20.9 (0.1)	132.0 (1)	48.3 (4)
Bark-UGA	500	73.4 (2)	0.61 (0.04)	2.1 (0.1)	0.23 (0.1)	8.0 (0.42)	0.86 (0.05)	2.01 (0.7)	84.7 (9)	20.1 (0.4)	306.7 (18)	45.1 (1)
Act. Char	**1000**	**20.3 (3)**	**0.25 (0.01)**	**9.3 (0.3)**	**0.17 (0.01)**	**0.6 (0.04)**	**0.28 (0.01)**	**0.04 (0.0)**	**110.3 (9)**	**9.2 (0.4)**	**0**	**0.7 (1)**

Table 3. Elemental content of the six biochars used in the laboratory analyses. Activated charcoal was included as a standard analysis and comparison to biochars. From Granatstein et al. (2009). †Std. error of mean in parentheses. UGA-the bark was made using a pyrolyzer unit located at the University of Georgia, Athens. Statistical comparisons were not made among biochars. Values for a biochar within a column followed by the same letter are not significantly different at $p = 0.05$.

Modifying Biochar for Specific Applications

The use of biochars to adsorb N and P in soils and from waste water streams, and by increasing its cation/anion exchange capacity it is possible to add extra value to biochar and thus obtain higher market prices. Because biochars are significantly more stable than the fast and slow-cycling fractions of soil organic matter, the effects of biochar additions to soil can have significant long-term benefits on soil C sequestration (Lehmann et al., 2006; Lehmann, 2007). Any value added chemical processing treatment performed on the char to improve its nutrient adsorption capacity is going to increase production costs. However, the goal of a further processing treatment is to increase the economic value by creating a greater margin of return on the cost of production.

While biochar has a significant potential as a soil amendment, studies with freshly produced biochars have not been able to reproduce the effectiveness of the centuries old Terra Preta soils of the Amazon Basin (Granatstien et al., 2009). One possible reason is that when the biochar is left in the soil for long periods of time the surface of the char is slowly oxidized (Solomon et al., 2007). Treatment by ozone at room temperature has been shown to be an effective way to rapidly oxidize the surface of carbonaceous materials (Valdes et al., 2002; Chiang et al., 2002; Park and Jin, 2005). The oxidation process has been shown to lead to significant increases in the number of acidic surface oxygenated groups including carboxylic acid groups (Valdes, 2002, Chiang et al., 2002, Park et al., 2005). Carboxylic acid groups are essential for improving a biochars nutrient holding capacity, as well as polarizing the surface which may also increase water retention of the material.

A high proportion of carboxyl acids as well as other acidic oxygen groups may also provide biochar many of the desirable properties of humic acid which is an important component of soil organic matter. The relatively high concentration of acidic groups can allow the formation of chelates with metal ions and help to bind positively charged ions to the surface of the carbon. When the surface density of carboxylic acid groups is very high, chelates with metal ions can almost completely immobilize potentially toxic metal compounds. The results obtained by Valdes (2002) indicate that total acidic groups on activated carbons can reach at least 2 meq g^{-1} with half the acidic groups being carboxyl groups. Literature results pertaining to the ozonation of biochars are not readily available; however, preliminary results with biochars derived from softwood bark indicate that it is possible to readily generate at least 2 meq g^{-1} (Garcia-Perez, personal communication). Preliminary results also indicate that the pH at zero charge of ozonated biochars is considerably reduced. The acidic nature of oxidized biochars means that they may be well suited for retention of basic ions such as ammonium or other cation compounds (Kastner, 2009). Chiang et al. (2002) has shown a strong correlation between the quantity of ammonium adsorbed by the oxidized carbon and the concentration of acid groups on the surface.

The adsorption of phosphate ions will depend upon the concentration and accessibility of cations found in the ash. Effects of metal ion concentrations in fly ash have been the subject of significant research (Lu, et al., 2009; Agyei et al., 2000; 2002; Namasivayam and Sangeetha 2004; Oguz, 2005; Zhang, 2007; Xue et al., 2009). The use of fly ash has been considered for its potential to remove phosphate compounds from waste water. The application of this information to biochars for the removal of relatively low concentration phosphates is of interest, because of the desire to develop an adsorbent capable of removing both nitrogen and phosphorous compounds from waste streams. The addition of appropriate metal ions to the structure of the biomass should aid in creating additional basic sites on the char surface which will become positively charged in solution and attract anions to the surface.

Unlike the oxidation reactions which form chemically bonded surface groups on the carbon matrix, the metallic cations may need to be contained within the carbon matrix or held by chelates on the surface of the carbon structure to remain stable and not dissociate into the soil solution. The dissociation of certain metals can cause the loss of potentially marketable nutrients such as phosphates by the formation of insoluble salts with these metal ions, such as apatites with calcium ions (Lu et al., 2009).

Considerable effort has been made towards understanding the primary mechanism of phosphate removal. Lu (2009) showed that while the majority of phosphate removal appeared to be due to precipitation reactions, the data also suggested that a reasonable level of adsorption can be achieved on the ash. Not much attention has been given to the simultaneous removal of ammonium and phosphate; although the work by Zhang (2007) shows significant potential in this area. The use of Al and Fe to improve biochar phosphates adsorption is of considerable interest. This is especially important as both ions tend to create mildly acidic groups on the surface rather than the basic groups produced by ions such as calcium and sodium.

It has been reported that acidic functional groups on the surface of biochar can significantly increase nitrogen adsorption capacity. These acidic functional groups can be generated with oxidizing agents such as H_2O (steam) and CO_2 at high temperatures (300-700°C) or with ozone at room temperature (Chaing et al 2002, Valdes et al 2002). The development of low cost adsorbents such as: calcium carbonate, kaolinite, red mud, activated alumina, activated carbon from tamarind nut shell and bark, fly ash, and blast furnace slag, to remove phosphorous from aqueous streams has received increased attention in the last 10 years. In basic solutions (pH>7), biomass ashes with high contents of calcite are known to be efficient agents for the removal of phosphate. In acid conditions, aluminum and iron induce the precipitation of phosphates.

Impact of Biochar Applications on Soil Quality and Crop Productivity

Returning C to the soil in the form of biochar is an essential part of the integrated bioenergy-food production vision (Figure 1). Biochar applications to soils have been shown to enhance soil and water quality. Because of its high surface area and high surface charge density (Liang et al. 2006), biochar increases the ability of soils to retain nutrients and plant available water and reduces leaching of nutrients and agricultural chemicals (Laird et al., 2010a; Lehmann et al., 2003; Glaser at al., 2002). Soil biochar applications recycle most of the nutrients that are removed when biomass is harvested. Base cations (primarily Ca, Mg, and K) in biomass are transformed during pyrolysis into oxides, hydroxides, and carbonates (ash) that are mixed with the biochar. Due to the presence of these bases most biochars function as a liming agent when applied to soil. Biochar is a low density material that reduces soil bulk density (Laird et al., 2010b, Rogovska et al., 2010) and thereby increases water infiltration, root penetration, and soil aeration. Furthermore, biochar has been shown to increase soil aggregate stability (Glaser at al. 2002), although the mechanism for this effect is not yet clear (Brodowski et al., 2006).

Much of the interest on using biochar as soil amendment comes from studies of Amazonian soils where the presence of charcoal has led to significant improvements in soil quality and increases in crop yields. These changes have persisted for hundreds, if not thousands, of years (Lehmann, 2007; Novotony et al., 2007; Lehmann and Joseph, 2009). The application of charcoal can increase soil pH and decrease the Al concentration of acid soils which are often the limitations to growth in tropical soils (Cochrane and Sanchez, 1980; Mbagwu and Piccolo, 1997). Charcoal has been shown to be a soil conditioner in many tropical and subtropical soils increasing exchangeable bases, cation exchange capacity, and nutrient availability, decreased soil bulk density and improving water holding capacity (Laird et al., 2010b; Liang et al., 2006; Novak et al., 2009).

There are many positive reports on the effects of biochar on soil quality and crop productivity coming from studies involving highly degraded soils in the tropics. For example, increases in both corn grain (91 percent) and biomass (44 percent) yields were observed for charcoal kiln sites relative to control sites in Ghana (Oguntunde et al., 2004). Increased seed germination (30 percent), shoot heights (24 percent) and biomass production (13 percent) at charcoal kiln sites relative to undisturbed Alfisols and Ultisols in Zambia have also been observed (Chidumayo, 1994). In a carefully controlled study, Steiner et al. (2007) reported that biochar and fertilizer additions on highly weathered Central Amazonian soils significantly improved plant growth and doubled grain production relative to controls receiving fertilizer or biochar alone. Similar results were obtained by Major et. al. (2010) who reported 189 percent increase in aboveground biomass measured 5 months after application of 23 T acre^{-1} biochar to Typic Haplustox in Columbia.

From the available literature it is clear that incorporation of biochar into weathered tropical soils in the Amazon Rainforest and savannas of South America have generally had a very positive effect on soil fertility and crop productivity. The improvements in crop productivity were related to increased nutrient retention (Glaser et. al., 2002; Lehmann et.al., 2003); alleviation of Al toxicity in highly acidic soils due to presence of Ca and Mg oxides, hydroxides and carbonates (ash) mixed with the biochar (Steiner et. al., 2007); increased soil water permeability and plant water availability due to porous structure of biochar (Asai et. al., 2009); increased soil cation exchange capacity (Steiner et. al., 2007; Liang et al., 2006); enhanced cycling of P and S (DeLuca et.al., 2009); and neutralization of phytotoxic compounds in the soil (Steiner et.al., 2007). Moreover, biochar may indirectly influence plant growth by modify soil microbial communities. For example, biochar application to Typic Haplustox was shown to significantly increase biological N fixation by common beans (Rondon et al., 2007) and is hypothesized to be an excellent support material for Rhizobium inoculants (Pander et al., 1993). Comparisons between the bacterial composition of Amazonian Terra preta (Anthrosol with high content of charcoal) and adjusted pristine forest soils revealed 25 percent greater species richness on the Terra preta soils.

The above described-biochar induced increases in crop production occurred on highly weathered tropical soils where soil quality and nutrient availability are often limiting factors for crop productivity. For highly productive temperate region soils, by contrast, weather is commonly the most important factor limiting crop yields rather than soil quality. This led Galinato et al. (2010) to speculate that biochar applications to highly productive soils will have minimal effect on crop productivity. Data documenting the impact of biochar amendments on crop yields for temperate region soils are currently lacking.

The effect of biochar additions on nutrient availability and plant nutrient uptake is not entirely clear with reports showing both increasing and decreasing nutrient uptake in greenhouse experiments. Lehmann et al. (2003) argued that biochar might even limit soil N availability in N deficient soils due to the high C/N ratio of biochar, and therefore, biochar applications might reduce crop productivity at least temporarily. This is likely to be important only for biochars with high volatile matter content, as most of the fixed C in biochar is not biologically available. Foliar N concentrations of crops were shown to decrease in several studies when biochar was added to soils. For example, study done by Lehmann and colleagues (2003) observed a 70 percent increase in cowpea biomass production on highly weathered ferralsols amended with 10 percent (w/w) biochar compared to control with no biochar application. In this study application of biochar significantly increased soil pH (from 5.1 to 5.9); C content (from 40.0 to 159.4 g kg^{-1}); N content (from 3.2 to 4.0 g kg^{-1}); K content (from 28.1 to 258.3 mmolc kg^{-1}); and CEC (from 54.0 to 285.5 mmolc kg^{-1}). In another study, application of biochar without additional N fertilization resulted in reduced plant uptake of N and a decrease in rice grain yield (Asai et. al., 2009). The authors speculated that a portion of the C in the applied biochar was available for microbial decomposition and resulted in N immobilization in soils that were already severely N limited. Application of synthetic N and P fertilizer on the biochar amended soils, by contrast, brought a significant yield response which was attributed to reduced leaching and hence more efficient use of applied nutrients (Asai et. al., 2009). Several other studies have reported similar positive interactions between biochar and fertilizers additions (Chan et al., 2008; Kimetu et al., 2008; Van Zwieten et al., 2010).

Increasing rates of char amendments have led to reductions in soil nitrate production compared to un-amended soils, perhaps due to ammonium (NH_4^+) adsorption by the char inhibiting nitrification (Figure 6). Lehmann, et al., 2003 found that (NH_4^+) was adsorbed by charcoal with an increase in N uptake by rice. This effect suggests improved N conservation in soils and less off-site movement of nitrate due to leaching, as well as, a potential reduction in losses due to N_2O production.

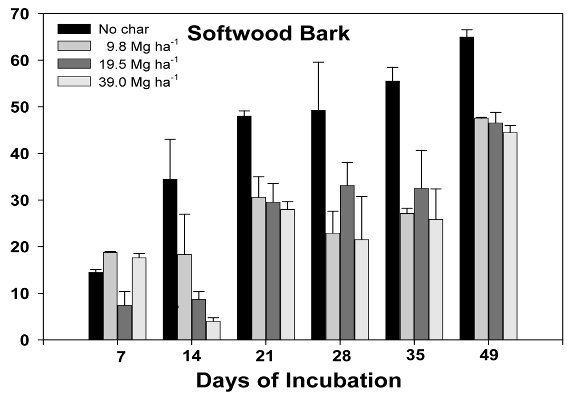

Figure 6. Soil N-mineralization rates for the Palouse silt loam incubated with biochar amendments. The biochar was made at the pyrolysis temperature of 500°C. From Granatstein et al., 2009.

The availability of other nutrients shows similar reductions in availability. Plant available P has been reported to be <13 percent of the total P in the biochar (Chan and Xu, 2009). In a preliminary investigation we found less than 3 percent (0.006 g P/kg char) of the P following a Na-bicarbonate extraction for available P, was released from a softwood biochar. In contrast, the availability of K from biochar is typically high (Lehman et al., 2003; Chan et al., 2008). Chan and Xu (2009) further report that few datasets are available that provides biochar micronutrient contents.

Ultimately the effects of biochar additions on soil quality and crop productivity will depend on quality of the biochar, which is influenced by characteristics of the feedstock and the pyrolitic conditions under which the biochar is produced. The importance of biochar quality was demonstrated by Deenik, et al., (2008) who showed significantly lower soybean plant growth for soils amended with a high volatile matter (35 percent) biochar and enhanced plant growth for soils amended with a low volatile matter (11 percent) biochar relative to controls receiving no biochar amendments. In this study, nitrogen uptake by soybeans in soils amended with biochar high in volatile matter was significantly lower, whereas N uptake increased with addition of biochar low in volatile matter (Deenik, et al., 2008).

The surface area of biochar may reach up to 400 m^2/g with much of this surface area in micro-and nano-pores, which have a higher capacity for adsorption of organic compounds compared to larger pores and flat surfaces (Elmer et al., 2009). Adsorption of organic contaminants and allelochemicals could substantially reduce phytotoxisity of these compounds. In a laboratory study, germination of corn seedlings in corn residue extract equilibrated with biochar increased early plant growth 300 percent compared to residue extract without the biochar treatment (Rogovska et al., 2010). On the other hand, adsorption of soil applied herbicides and insecticides by biochar may reduce the efficacy of these compounds for pest control (Yang et al., 2006) and the rate of their microbial degradation (Zhang et al., 2005). For example, application of biochar (1.0 percent by mass) significantly increased the half-life of chlorpyrifos, an organophosphate insecticide, from 12 to 43 days (Yu at al., 2009). Despite significant increase in half-life, plant uptake of chlorpyrifos in biochar amended soils deceased from 14.1 to 0.8 mg kg^{-1}.

Biochar may have a positive impact on plant resistance to disease due to its suppressive effect on soil pathogens (Matsubara et al., 2002), therefore indirectly increase crop productivity. Although the suppression effect of biochar on plant pathogens is not clearly understood, it is hypothesized that several mechanisms are involved: (i) stimulation of microbes which provide direct protection against pathogens via antibiosis, competition, or parasitism; (ii) promotion of plant growth by providing nutrients and improving nutrient solubilization and uptake; or (iii) induction of plant defense mechanisms against disease (Elad et al., 2010). Overall, the interest in biochar as soil amendment for carbon sequestration together with improved soil quality and crop production may be enhanced by its potential to minimize pesticide residues in crops and its role in increasing plant resistance to pathogens.

Impact of Biochar Additions on Soil C Sequestration

It is generally accepted that reducing atmospheric concentrations of CO_2 by permanently sequestering C in the soil could reduce the impact of climate-related damage. Increasing soil organic carbon (SOC) storage by conventional soil management practices such as conservation tillage, no-till, and perennial cropping systems can take many years and there is uncertainty about the C sequestration potential of these systems (Baker et. al., 2007; Denman et al., 2007). By contrast, application of biochar to agricultural soils is an immediate and easily quantifiable means of sequestering C and is rapidly emerging as a new management option that may merit high value C credits (McHenry, 2008; Glaser at al., 2009; Tenenbaum, 2009; Steinbeiss et. al., 2009).

Soils low in organic matter typically exhibit the greatest increase in C with the addition of any biochar. Figure 7 illustrates the relationship between the amount of C added as biochar on total soil C (predicted) and the amount of C measured in the soil after amendment. The straight line relationship indicates that virtually all of the added biochar was accounted for in the C analyses.

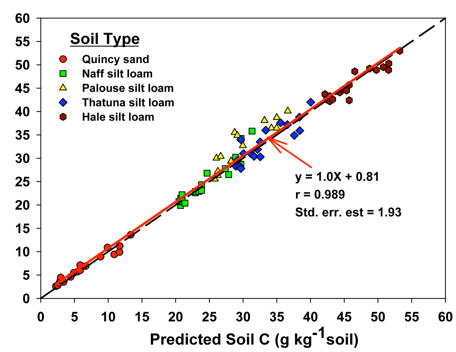

Figure 7. Comparison between the amount of C added in the bio-har amendments and the amount of C measured in the soil after amendment. From Granatstein et al., 2009.

Biochar is highly stable in soil environments and tends to accumulate in the stable soil organic matter fraction (Forbes et al., 2006). Radiocarbon dating of charcoal has indicated mean residence times up to 10,000 years in soils (Swift, 2001; Schmidt at al., 2002). Other studies have reported much shorter biochar half-lives ranging from <30 to several 100s of years (Bird et al., 1999; Steinbeiss et al., 2009; Hamer et al., 2004). A 3.2 year incubation study with ^{14}C-labeled biochar showed decomposition rates of 0.5 percent per year under optimal laboratory conditions, which led Kuzyakov et al. (2009) to suggest a half-life of biochar under natural soil conditions of about 1,400 years. The stability of biochar in soil environments depends on both the nature of the parent biological material and the extent of thermochemical alteration during pyrolysis. “Black-chars” produced by high temperature pyrolysis are believed to be biologically non-degradable and may persist in soils for millennia; whereas “brown-chars” produce at lower temperatures are biodegradable and persist in soils for shorter periods of time. However, abiotic decomposition of biochar through chemical oxidation, photooxidation, and solubilization also occurs, and C loss due to abiotic degradation may be 50 to 90 percent of that reported for biological degradation depending on charring temperature and volatile matter content of biochars (Zimmerman, 2010).

Uncertainty associated with degradation rates of different biochars and an apparent potential for some biochars to accelerate decomposition of biogenic soil organic matter complicates assessment of biochar as a carbon sequestration agent. During a 500-day soil-column incubation study, biochar consistently increased CO_2 emissions relative to unamended controls, with cumulative CO_2-C loss equivalent to 18-23 percent of biochar C applied (Rogovska et al., 2010). Mass balance analysis indicated biochar C recoveries ranging from 98 to 108 percent suggesting that little biochar C was mineralized during the incubation and that the evolved CO_2-C was primarily from SOM mineralization. Similarly, Wardle et al. (2008) reported that biochar appeared to accelerate decomposition of forest floor humus based on mass loss of litter bags filled with biochar, humus, and a 50:50 mix of humus and biochar. The stimulation of humus decomposition was attributed to increased nutrient retention by the biochar, which led to increased microbial activity and hence increased humus decomposition in litterbags containing both biochar and humus relative to litterbags containing only humus. In contrast, Kuzyakov at al. (2009) showed that biochar additions had no effect on SOC mineralization and CO_2 flux from soil and slightly reduced CO_2 flux from loess. They suggested that sorption of nutrients by biochar and nutrient immobilization by easily metabolized organic C limited nutrient availability and microbial activity in the loess systems. Spokas and Reicosky (2009) reported both increases and decreases in CO_2 emissions from soils amended with 16 different types of biochar, suggesting that biochar quality has a major influence on the interaction between biochar and soil organic matter.

Production of biomass crops for the sole purpose of producing biochar as a means to withdrawing CO_2 from the atmosphere might be technically feasible, but is not likely to be economically viable in the foreseeable future. Accrual of additional value through soil quality enhancement, increased crop yields, increased fertilizer and/or water use efficiency, and co-production of bioenergy appear to be necessary to economically justify the production of biochar for use as a soil amendment (Laird et al., 2009). Assuming sustainable production of 1.1 X 10^9 Mg biomass annually, the combined C credit for fossil fuel displacement and permanent biochar C sequestration is estimated to be 363 Tg per year, which corresponds to 10 percent of the average U.S. CO_2-C emissions (Laird, 2008).

The net effect of biochar on GHG emissions depends not only on the impact of biochar on the soil to which it is applied, but also on the macroeconomic impact of a pyrolysis-biochar industry on markets for food, feed, and fiber and any associate indirect land-use changes. Depending on those factors, the net values of GHG emissions can be negative (more CO_2 eq. reductions than emissions) or positive (Roberts et. al., 2010). Life cycle analysis of biochar produced from corn stover, yard waste, and switchgrass revealed that the yard waste system resulted in the largest reductions in GHG emissions (-885 kg CO_2 eq t^{-1} dry biomass), primary because of limited emissions associated with transportation, and no emissions associated with production and collection of the biomass. For the switchgrass system, on the other hand, the net GHG emissions were estimated to be positive (36kg CO_2 eg t^{-1} dry biomass) as a result of both direct and indirect land-use changes (Roberts et. al., 2010).

Adoption of new technology is often hindered by high startup costs, the need for market development, and unknown levels of risk associated with production costs. At this time, the greatest barriers to the viability of biochar as carbon sequestration tool are the high initial costs of designing, building and operating first generation biomass pyrolyzers with heat recovery and the lack of viable markets for biochar. The development of higher value engineered biochars able to play agronomical functions in targeted soils could also contribute to improve the economic viability of this technology. The value of carbon credits is currently too low to provide an incentive for farmers to apply biochar to their land and fossil fuels are still relatively inexpensive. In the future, however, dwindling global supplies of petroleum and concerns over global climate change may prompt changes in Federal policy that increase the value of both renewable energy and carbon credits and prompt wider use of biochar as soil amendment.

Problems and Hurdles to Adoption

Safety Issues

The production, transport and application of biochar has some safety concerns of which users should be aware, however if precautions are taken they are manageable. The primary concern for human and environmental risk is the particulate matter (PM). Biochar dust and vapor fall between the U.S.A Environmental Protection Agency (EPA) air quality standards of PM2.5 and PM10 (Blackwell et. al., 2009; EPA, 2006). These PM standards are associated with fine and ultra fine particles which can contain volatile compounds both organic and inorganic. During biomass pyrolysis several studies have shown production of acetic acid, furylaldehyde, methyl acetate and several other volatiles (Amonette and Joseph, 2009). Emissions of polycyclic aromatic hydrocarbons (PAH) have also been a concern, however results from the literature have been mixed as pyrolysis temperatures below 700°C are not a major contributor to PAHs (Verheijen et al., 2010; Garcia-Perez, 2008). Some of these contaminants could be eliminated if heat recovery systems are coupled with the pyrolysis reactor. When dealing with these issues of volatiles and PM sizes no biochar can be treated as equal; temperature, pyrolysis type and feedstock influence each biochar its characteristics. For example rice husk biochar can contain crystalline silica that could be carcinogenic (Blackwell, 2009). Exposure to the dust particles through inhalation appears to be the primary concern. MSDS sheets from Dynamotive's CQuest biochar suggest avoiding contact with eyes and use of an approved dust respirator be worn (Dynamotive, 2009). Verheijen et al. (2010) report that from the research the greatest concern for environmental pollutants and health concerns associated with biochar will come from small-scale pyrolysis units. In addition to volatiles, the dust can stay in the air and be spread through air currents causing air quality issues in surrounding areas. As the EPA reviews its air quality standards in 2011 surrounding the agricultural industry and the use of biochar becomes more widespread the dust portion of the equation will need to be further addressed. Production of bio-char pellets or briquettes should be considered as a way to reduce dust during bio-char production and transportation.

Outside of the health risks associated with the fine particles of biochar there is the added risk of fire hazard. The United Nations has recognized the hazard of spontaneous combustion for this material giving it a Class 4.2 rating for transportation. The classification arises because of the nature of small particles in closed spaces to ignite as with flour, grain elevator and coal dust (Giby et al., 2007). It is suspected that perhaps free-radicals are produced during pyrolysis attaching to the biochar surface may play a role fresh biochar combustion (Verheijen et al., 2009; Amonette and Joseph, 2009). In an attempt to counter act this hazard Blackwell et al. (2009) suggest several ideas such as wetting, covering, and adding retardant chemicals to the biochar, however industry needs to develop a standard in order to allow for safe cost efficient transport before biochar use can become large scale.

Application and Transportation

The transportation and application of biochar is still in the experimental process. In the above section we addressed some of the risk of biochar dust and it ability to stay suspended in air. This same issue currently is hindering the application and transportation of the material because of widespread loss of the biochar either in transport or application (Laird, www.biocharfarms.org). Several methods of remedy have been discussed including chemical binders, pelletizing, and material blending however no method is a current forerunner (Blackwell et al., 2009). Pelletizing the feedstock prior to pyrolysis may reduce dust during production and transportation. Simply putting biochar in large burlap bags during transportation has reduced biochar loss during transportation and application.

Methods of application for biochar in the field are currently being investigated and are dependent on the purpose, crop and form of biochar. Basic agronomy has addressed the application of fertilizers and provides a working base for application of biochars. Incorporation, banding, side-dressing, broadcast, foliar dusting, and liquid incorporation are all possibilities; however one must take into consideration the precautions already discussed about health, safety and loss. Blackwell et al. (2009) provides an excellent summary of these methods and the pros and cons. Following surface application biochar should be incorporated immediately to avoid subsequent loss to wind or surface runoff. Biochar can be incorporated by moldboard plow, chisel plow, disking, or roto-tillage. The incorporation method, however, will determine how deeply and how thoroughly the biochar is mixed with the soil. Incorporation with a liquid (manure effluent and water) may be difficult because biochar is often hydrophobic and therefore difficult to mix with water or liquid manure. In order for commercial growers to use this product a uniform method of effective application must be developed that is compatible with already available commercial application equipment. Until this is addressed application of biochar will remain at the small scale.

Economics

Any discussion about economic feasibility of the pyrolysis-biochar platform must include the cost of transportation, feedstock, energy (both used and supplied), production and application balanced by the value of the bioenergy and biochar co-products. Profitability will undoubtedly include economic and environmental tradeoffs. The economics of the pyrolysis-biochar platform will also depend on the predominant use of the technology. If C sequestration is valued above renewable energy then biochar production will increase and bio-oil production will decrease. If renewable energy production is the driving economic force; than more bio-oil or biopower and less biochar will be produced. Regardless of the predominant use, feedstock selection, transportation systems, pyrolysis plant design and operation, and product formulations will need to be optimized to maximize economic value and beneficial outcomes (Section 3.1-3.3).

An economic analysis was conducted by Washington State University (Granatstein et al., 2009) using forest thinnings as a biomass feedstock. Researchers concluded a stationary fast pyrolysis facility had the highest potential for profitability with a price of $87 per metric ton of biochar. However, a travelling portable unit could be feasible if located at stock piled sources of feedstock. Their economic assessment also concludes the profitability would increase with the development of local bio-oil refineries. They assess the maximum revenue for slow pyrolysis with energy as the primary usage to be $0.09296/kg and in fast pyrolysis $0.11848/kg of forest based feedstock (Granatstein et al., 2009). When addressing C sequestration and adding it into the equation Gaunt and Lehmann (2008) conclude that a slow pyrolysis unit will deliver net-negative emissions of greenhouse gases and if a facility is already profitable it can be assumed that revenue from C trading could make biochar production for soil application a worthy venture. These studies acknowledge feasibility needs to be addressed at a local level before full implementation.

Economic evaluation and feasibility are subject to future opportunities. As research continues the scope and use of biochar will start to become clearer. If unrealized markets in the area of nutrient recovery, water treatment, herbicide management and others develop the economics will follow.

Conclusions

The large amount of research related to biochar published in the last two years reflects growing optimism that the pyrolysis-biochar platform can be economically deployed on a large scale and in diverse settings and will simultaneously enhance energy security, build soil quality, increase agricultural productivity, sequester carbon, and provide opportunities for rural economic development. While the research published to-date is generally consistent with this optimistic scenario, the research has also shown the complexity of the pyrolysis-biochar platform. Different pyrolysis technologies and feedstocks will result in different quantities and qualities of bio-oil and biochar co-products. These differences are both problems in an emerging industry that lacks standards and regulations and opportunities for entrepreneurs to fill niche markets and develop value-added products. Bio-oil is not an ideal fuel because of acidity and high oxygen content; however it can be upgraded to produce drop-in liquid transportation fuels and various co-products. The co-production of bio-oil and biochar will only be viable when bio-oil refineries are developed. The co-production of biochar and heat seems the most likely short-term option for industrial development. Use of biochar as a soil amendment offers the opportunity to recycle nutrients, build soil quality and sequester carbon. To date little is known about the rate of char weathering in soils, which is important for the development of surface charge and the associate capacity of chars to enhance nutrient and water retention in soils. Biochar safety is a serious concern; however dust and fire hazards can be addressed through the development of stabilized agronomic biochar formulations. There is a need for significant research on a large scale to fully test the economic and environmental viability of the pyrolysis-biochar platform.

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Chapter 17

Development of Hybrid Poplar for Commercial Production in the United States: The Pacific Northwest and Minnesota Experience

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Introduction

The history of poplar culture in the United States dates back more than 100 years. Since those initial efforts great advances in the domestication of poplar have been made through contributions from many government and academic institutions and pioneering industrial companies. These efforts have led to the commercial developments we see today. While business conditions to date have restricted poplar cultivation to specific geographic locations, these developments have provided proof of concept to growing short-rotation trees using intensive agricultural techniques. As we look to the future and the great opportunity to develop a viable biomass energy feedstock supply, the poplar industry in the U.S. is well positioned to play a significant role in this commercial effort.

In this paper we profile two industrial programs that have achieved success in growing poplar for commercial purposes. We point out the essential elements that have made the GreenWood Resources and the Verso Paper programs viable. Both programs are anchored on strong science including breeding and tree improvement and silvicultural research. Finally, we identify the critical elements that need to be in place for this industry to further expand in the U.S.

History of Commercial Plantation Development-The Pacific Northwest Experience

Experience in planting poplar in the Pacific Northwest began in 1893 when the Willamette Pulp and Paper Company planted 400 hectares of P. trichocarpa in the vicinity of West Linn, Oregon over a twenty-year period, reportedly the first artificial regeneration program in the United States. Since that time over the last 45 years, the development of industrial poplar plantations in both the Pacific Northwest as well as the lower Mississippi River Valley has repeatedly occurred as a strategic response to constraints in the regional supply of hardwood fiber for premium grades of communication papers. Fully integrated paper companies-timberlands, pulp mills, paper machines, converting, and distribution and marketing departments-undertook the development of today’s industrial plantations and their underlying plant material assets.

Commercial development in the Pacific Northwest began when forecasted shortages in red alder (Alnus rubra) led to the establishment of poplar plantations as a replacement hardwood fiber supply. In 1982-1983, Crown Zellerbach Corporation began planting hybrid poplar in the lower Columbia River valley near Clatskanie, Oregon and in the mid Columbia River basin near Boardman, Oregon. Ultimately, James River Corporation acquired Crown Zellerbach's paper division and expanded the Clatskanie plantation to 4,500 hectares, while Boise Cascade and Potlatch Corporations took the lead from James River in the mid-Columbia River basin, independently establishing a combined total of 14,600 irrigated plantation hectares in the areas around Boardman Oregon and Wallula, Washington. By the mid 1990s, MacMillan Bloedel had added 3,200 plantation hectares in the Nooksack, Skagit, Snohomish, and Snoqualmie River valleys of northern Washington and in the Fraser Valley and on Vancouver Island in British Columbia.

Under James River's ownership from 1991 through 2000, the Clatskanie plantation produced approximately 30,000 dry metric tons annually for the refiner-ground wood operation at the Wauna, Oregon mill for the manufacture of high-bright specialty newsprint. Dependent on paper grade, fiber from the Clatskanie plantation accounted for up to 18% of the paper machine's pulp furnish and resulted in over $600,000 annual savings in bleaching costs. Coincident with Georgia Pacific Corporation acquisition of James River in 2001, the Clatskanie plantation was acquired by a timber investment organization under GreenWood Resources' management. At that point, the management at Clatskanie shifted to the production of saw logs and peeler logs in view of the continuing poor market for wood chips.

Boise Cascade's original strategic goal for its poplar program was to provide the entirety of the hardwood fiber required for the production of uncoated free sheet at the company's Wallula, Washington mill. Planting began in 1991 and the program has been harvesting up to of 100,000 dry metric tons annually since 1997. Coincident with Boise Cascade's 2004 sale of its paper and wood-products businesses to Madison Dearborn Partners, a private equity firm, approximately 3,600 hectares of Boise's poplar plantations were transferred to GreenWood Resources that are now grown primarily for saw logs. Today Boise Cascade manages approximately 4,000 hectares strategically located within 20 kilometers of the Wallula mill.

The Potlatch program started in 1994 as a response to declining wood flow from national forests and the need to increase fiber self-sufficiency at the Lewiston, Idaho mill. A 6,900-hectare plantation at Boardman, Oregon was sized to annually produce 170,000 dry metric tons to meet 25-30% of the fiber requirements of the Kraft pulp operation for paperboard manufacturing. Sustainable harvesting and chip production was targeted to commence in 2000. However in 1999, the company began to focus on diversified markets including higher-value saw logs and peeler logs with residual chips being sold to area pulp and paper mills. In 2007, GreenWood Resources acquired the Potlatch operation.

The former James River and Potlatch hybrid poplar plantation along with a portion of the Boise Cascade poplar estate are now consolidated under the GreenWood Tree Farm Fund. The fund owns approximately 15,000 hectares and saw-and planer mills and dry kilns capable of milling and drying 80 million board feet per year. The GreenWood Tree Farm Fund is the largest operator of poplar plantations in the Pacific Northwest.

Management Practices

Poplar plantations in the Pacific Northwest have been developed in two regions, the lower Columbia River floodplain and the mid-Columbia River basin. Annual precipitation along the lower Columbia River floodplain is 1,200 mm coming mostly in the fall through spring as rain but occasionally as snow. Temperatures are mild with occasional winter lows of -6°C while summer high temperatures rarely go above 30°C. In contrast, on the leeward side of the Cascades in the arid mid-Columbia River Basin annual rainfall is 300 mm falling mainly in the winter months due to the rain shadow effect of the Cascade Range. Drip irrigation is the prominent feature of plantation management. Summer high temperatures can reach over 38°C with regularity while winter low temperatures near -17°C are common. Soils in the area are sandy loams to fine sandy loams, low in organic matter, and range from 6.0 to 8.4 in pH.

Plantation establishment has mostly relied upon unrooted hardwood cuttings approximately 20 to 30 cm in length. These are produced from one-year-old sprouts grown in high-density nursery beds or from one-year-old branches pruned from two-year-old plantation trees. Plantations are established February through April by hand planting in pre-marked rows. Selected varieties are deployed to production fields as monoclonal blocks. Block sizes of 10 hectares are considered the ideal for simplifying planting, inventory, and salvage operations. Within-row spacing is gauged by individual tree planters or set by emitter spacing where drip irrigation is used. Poplar plantations in the Pacific Northwest have been managed at a density of 1,536 stems per hectare for six-to-eight year pulpwood rotations or at a density of 358 stems-per-hectare for 12 to 15 year sawlog rotations. A density of 3,587 stems-per-hectare for two or three year coppice rotations is anticipated for the production of bio-energy feedstock.

Site preparation techniques have been adapted from the intensive techniques used for agronomic and horticultural crops. Criteria for adequate site preparation include clean cultivation with tillage to a 30 to 50 cm depth, maximum clod size of 8 cm, and the elimination of subsoil compaction. Typically, pasture and annual crop fields are sprayed with a post-emergent herbicide in the year prior to planting followed by a series of heavy diskings to break the sod cover and incorporate organic matter in to the soil. Lighter diskings then follow in the fall to further reduce clod size and smooth the soil surface. Tree rows are marked by subsoiling. A soil-active herbicide is applied at this time and followed with pre-emergent herbicide applications during the winter. Site preparation techniques following harvesting additionally remove and harvest debris by removal by grinding operations. Rows are offset from the previous rotation and again marked by subsoilong. Stumps remaining from the previous rotation or their sprouts are treated with herbicides to eliminate coppicing. Pre-emergent and contact herbicide applications are made to established stands prior to budbreak. During the growing season and prior to the time of canopy closure, weed competition is held in check by mechanical cultivation featuring disking, chemical cultivation featuring hooded- tractor and back-pack sprayers, and hand weeding with hoes.

Plantations along the lower Columbia River floodplain have not exhibited nitrogen fertilizer responses likely due to the high organic matter content of the soil. Both nitrogen and phosphorus are applied to the inorganic soils in the mid Columbia River basin. Nitrogen application rates vary between 30 kg ha^{-1} yr^{-1} and 100 kg ha^{-1} yr^{-1} dependent on stand age. Phosphorous is added at a rate of 10 kg ha^{-1} yr^{-1} once during site preparation. Supplemental micronutrient applications are also commonly made. Plantations in the basin are also irrigated at rates between 300 and 1200 mm ha^{-1} yr^{-1} dependent on stand age. Conversely, plantations of the lower Columbia River floodplain are drained of excess water during the spring via a network of drainage ditches, tide gates, and pumping stations.

Lower Columbia River floodplain plantations are subject to infection by several leaf and shoot pathogens including, *Melampsora* leaf rust, *Venturia* shoot blight, and *Septoria* and *Marssonina* leaf spot. Control of these is addressed by varietal selection. Varietal selection is moderately effective in preventing deer browse and the planting of larger-sized whips is the primary management approach to reduce browsing. Girdling by field voles can potentially cause widespread mortality in lower Columbia River plantations; clean cultivation largely eliminates this problem. Varietal selection for resistance to wind throw following winter storms is a prominent feature of plantation management along the lower Columbia River floodplain. Varieties of the P. *deltoides* × P. *maximowiczii* taxon are especially resistant to wind throw. Insect infestations are a significant challenge to mid Columbia River basin plantations. These include both defoliators-*Chrysomela scripta* and *Hyphantria cunea*-and stem-borers, *Paranthrene tabaniformis* and *Cryptorhychus lapathi*. Systemic insecticides applied through the irrigation system and contact insecticides applied aerially. Applications of synthetic pheromones are effective in disrupting mating of some stem boring insects while the control of others relies on varietal selection.

Harvesting of pulpwood in the Pacific Northwest utilizes a feller-buncher to shear and bunch stems that are skidded to a landing in the field. There they are de-limbed and de-barked through a chain flail and then chipped and blown into a van for transport to area mills or port facilities where the chips are loaded onto river barges.

The GreenWood Resources Poplar Improvement Program

GreenWood Resources's poplar improvement work has originated in a variety of industrial pulp and paper operations each of which conducted poplar genetics research. These corporations included: (1) Crown Zellerbach, (2) James River, (3) Potlatch, (4) Boise Cascade, and (5) Westvaco. Many of these programs, in turn, had relied upon the tree improvement research and development efforts of both government and academic programs including the United States Forest Service Experimental Stations at Rhinelander, Wisconsin and Stoneville, Mississippi and the Universities of Minnesota, Washington, Mississippi State, Washington State, and Oklahoma State many of whom had benefited from project funding from the Departments of Energy and Agriculture. Varying portions of the five industrial programs were subsequently acquired as intellectual property assets by GreenWood Resources as it developed its poplar farming and marketing businesses over the period 2001 through 2007. The continuity of the past work extends from the breeding stock and plantation varieties in use today to the personnel that now continues the work within GreenWood's Tree Improvement Group. An abridged history of the GreenWood tree improvement program is presented in Table 1.

GreenWood's Pacific Northwest program has, since 1988, focused mainly on the first-generation of the *Populus ×generosa* taxon, a combination of *P. trichocarpa* from Oregon and Washington and *P. deltoides* from the upper midwest and southeastern United States and, secondarily, the *P. ×canadensis* inter-specific hybrid taxon, a cross between *P. deltoides* from the central and upper midwest and *P. nigra* from western Europe. The lower Mississippi River Valley program has focused exclusively on intra-specific *P. deltoides* breeding since 1989. In 1993, Pacific Northwest breeding efforts were broadened to include development of the *P. deltoides* × *P. maximowiczii* taxon using *P. deltoides* from the north central and southeastern regions and *P. maximowiczii*[1] from eastern Asia. Both the Pacific Northwest and Mississippi River Valley programs continue today. Additionally, exploratory hybridization is an ongoing effort in the search for more productive species combinations of which crosses involving the Asian species, *P. ciliata*, *P. simonii* and *P. yunnanensis* will figure prominently.

Year	Milestone Activity
1970s	United States Forest Service conducts large scale selection of *P. deltoides* phenotypes and establishes replicated clonal trials in Mississippi.
	Crown Zellerbach (CZ) establishes the Filter Managed Forest (FMF), a *P. deltoides* plantation near Vicksburg, Mississippi.
1981	University of Washington (UW) conducts breeding and testing of *P. ×generosa* hybrids in the Pacific Northwest.
	CZ begins poplar clone testing at Westport, Oregon.
1982	CZ begins planting local *P. trichocarpa* selections and UW hybrid poplars at the Lower Columbia River Tree Farm, Clatskanie, Oregon.
1983	CZ begins clone tests in the mid-Columbia Basin in Boardman, Oregon.
1986	CZ poplar programs sold to James River Corporation (JR).
1988	JR begins *P. ×generosa* hybridization program using superior *P. trichocarpa* phenotypes and select *P. deltoides* clones from FMF.
1989	*P. deltoides* 2nd gen breeding started by JR in support of FMF.
1990	JR sells Boardman research assets to Boise Cascade (BC).
	JR begins *P. trichocarpa* recurrent breeding program with the assemblage of a provenance collection from Oregon and Washington.
1991	BC begins poplar hybridization program for mid-Columbia Basin.
1993	JR establishes 2nd gen *P. deltoides* clone trials in Mississippi & Louisiana.
	Initiation of *P. deltoides* × *P. maximowiczii* breeding effort.
1994	First of four *P. trichocarpa* clone trials is established at Westport, Oregon.
	Potlach Corporation (PCH) begins poplar hybridization and clonal screening work at its Boardman Research Site.
1996	Westvaco (WV) restarts and intensifies *P. deltoides* breeding program.
2000	GreenWood Resources (GWR) acquires JR tree improvement assets.
	First Westport *P. trichocarpa* clone trial converted to breeding orchard.
2002	GWR begins contract *P. ×canadensis* breeding for PTC.
2005	GWR acquires BC tree improvement assets and begins development of *P. ×canadensis* taxon.
2007	GWR acquires PCH tree improvement assets
	GWR acquires a portion of the WV *P. deltoides* tree improvement assets.
	GWR signs tree improvement agreement with Alasia Franco Viva, Italy.

Table 1. History of the GreenWood Poplar Genetic Improvement Program.

History of Varietal Selection

In the Pacific Northwest, poplar varietal improvement was started by the University of Washington and Washington State University during the 1970s. Investigations revealed that the first inter-specific *P. ×generosa* generation outperformed biomass production of native *P. trichocarpa* as well as the second and backcross inter-specific generations.[2] Selected F_1 P. ×*generosa* and *P. deltoides* × *P. maximowiczii* clonal varieties are used along the lower Columbia River floodplain of western Oregon and Washington, while *P. ×canadensis* F_1 selections (e. g. 'NE367') are preferred on the leeward side of the Cascades in the shrub-steppe environment of the arid mid Columbia River basin. GreenWood's breeding programs is now the sole source of new F_1 inter-specific varietal selections as well as second-generation parental selections of *P. deltoides, P. nigra*, and *P. trichocarpa*.[3] Improvements are sought in yield, resistance to *Venturia* shoot blight, *Melampsora* leaf rust, and *Cryptorhynchus lapathi* stem borers, stem form, wood specific gravity, and wind firmness.

The longest term program managed by GreenWood Resources is its *P. ×generosa* breeding and varietal development effort of the Lower Columbia Tree Farm initiated in 1988. This project has served as a model for many of the other taxa under development. It has emphasized non-recurrent F_1 breeding on an annual basis, because of the good opportunity to expedite short-term improvement in plantation yields. Although breeding stock has been recruited from the same parental generation as the ones used in developing industry standards, gains nonetheless have been realized due to an increase in selection intensity that has accumulated throughout the period that hybrid populations were annually bred, tested, and selections made. Thus, the non-recurrent program has provided for continuous substitution of the lowest-ranking clones in the deployment pool as its genetic quality has been systematically upgraded yearly. The dynamic diversification and replacement of genotypes making up the deployment pool is also thought to have lessened the chance of plantation failures due to unforeseen biotic and abiotic events.

Yield Studies

Productivity of poplar plantations in the Pacific Northwest was initially reported as 20.9 MT ha^{-1} yr^{-1} (green basis) for unselected sources of *P. trichocarpa* managed under two year coppice rotations.[4] Further study showed that *P. trichocarpa* yields were maximized during the second two-year coppice or the third four-year coppice rotations at 8.9 and 9.7 MT ha^{-1} yr^{-1} (dry basis), respectively.[5] The first report of productivity in an inter-specific taxon included a comparative study of 50 native *P. trichocarpa* varieties and three newly-bred *P. ×generosa* selections.[6] Varieties were tested at a site in western Washington for four years in plots established at 1.2 × 1.2 m spacing. Yields of the 50 *P. trichocarpa* clones averaged 12.5 MT ha^{-1} yr^{-1} and varied between 5.2 and 23.1 MT ha^{-1} yr^{-1}. In comparison,the three *P. ×generosa* clones varied between 15.6 and 27.8 MT ha^{-1} yr^{-1} and averaged 23.6 MT ha^{-1} yr^{-1}. These productivity values were best considered as preliminary estimates because of the small-sized, 9-tree yield plots. Nonetheless, this research was instrumental in the pulp and paper industry's decision to undertake large-scale plantation developments. The following industrial studies conducted by GreenWood Resources provided estimates of productivity under commercial plantation conditions.

1987 Yield Analysis

The initial selections of *P. ×generosa* clones from the University of Washington program led to the commercialization of varieties '11-5' and '11-11' along the lower Columbia River floodplain by James River Corporation. James River continued to screen additional clones developed by the University of Washington in the mid 1980s, culminating in the selection of 11 new varieties that underwent yield verification tests in 1987.[7] This test involved four randomized complete blocks of 7 × 7 tree plots established at a 1.5 × 3.1 m spacing. Growth data were collected from the interior 5 × 5 plot following the sixth growing season and converted using varietal-specific weight equation 1 developed for a range of varieties. Mean annual biomass increments ranged from a low of 9.2 MT ha^{-1} yr^{-1} (variety 23-91) to a high of 19.3 MT ha^{-1} yr^{-1} (variety 49-177). The mean production level was 13.1 MT ha^{-1} yr^{-1}

Variety	Yield (MT ha^{-1} yr^{-1})
15-26	10
19-61	9.2
23-91	14.9
24-305	13.5
46-158	12.7
47-174	12.4
49-177	19.3
50-179	10.6
52-225	17.1
55-260	11.1
58-282	12.8

Table 3. 1987 Yield Verification Trial-Varietal Productivity Results.

1996 Yield Analysis

GreenWood Resources conducted an evaluation of its 1996 yield verification trial following the eleventh growing season. Originally planted for an eight year rotation for pulpwood production, the evaluation of the yield trial was scheduled for the eleventh year to coincide with the management for sawlog production.

The 1996 trial was established at 2.13 x 3.05 m spacing for an eight-year rotation. The evaluation included an assessment of varietal variation in per-hectare yield, stand survival, and leaf area index. The varieties in the yield trial had been bred over the period 1988-1991; as such they were the first proprietary clones to be tested and added to the University of Washington clones. These were planted in a verification trial located at Clatskanie, Oregon using four complete block replicates and 8 × 8, 64-tree plots. Stem diameter data were then collected in October 2006 from the interior 6 × 6 plot test trees.

Varietal yields converted to a per-hectare basis varied between a low value 6.9 MT ha^{-1} yr^{-1} (variety 117-91-1847) and a high value of 19.1 MT ha^{-1} yr^{-1} (variety 97-91-1315) after eleven growing seasons. (MAI after the 11th year was lower than that which would have been measured following the 8th year at the original 2.13 x 3.05 m spacing.) Yield averaged over all eight varieties was 12.9 MT ha^{-1} yr^{-1}.

Clone	Yield (MT ha^{-1} yr^{-1})
20-88-183	16.3
69-90-81	11.4
70-90-143	9.3
86-90-289	15.4
97-91-1315	19.1
117-91-1847	6.9
123-91-1903	12.9
131-91-1943	12.2

Table 5. 1996 Yield Verification Trial-Varietal Productivity Results

Poplar Biomass Production Economics for Non-irrigated Sites in the PNW

GreenWood Resources has been managing poplar plantations in the Lower Columbia River Basin of Oregon and Washington for more than 25 years. Through this operational experience GWR has verified costs of production and yields for various silvicultural activities and stand conditions. GWR has developed discounted cash flow models that contain management inputs necessary to achieve optimal production of biomass feedstock plantations on marginal agricultural soils typical of those in the Pacific Northwest. Table 6 shows a summary of a delivered cost analysis that was done on a biomass production system typical of non-irrigated coppice systems. A typical production system will feature five, three-year coppice cycles in a 15-year rotation. The first cycle is an establishment cycle where intensive weed control insures high survival and thus high future yields. At the end of the 15-year rotation the stumps are removed and a new more productive genotype is planted and the cycle renewed.

Expected Range of Delivered Prices	With Subsidies ($/BDT)	Without Subsidies ($/BDT)
Current Yields	60-85	70-100
Future Yields	50-70	55-80

Production Costs (average current)	% Cost
Land	27%
Establishment	9%
Crop Care & Management	28%
Harvest	24%
Transport	12%

**Range is based on land cost ($1000-2000/ac) and expected return (6-12%)*

Production Cost Assumptions

Acquisition Strategy	Purchase
Pre-BCAP IRR	10%
Yield (MAI-GT/ACRE)	14
Transport (avg haul-miles)	30
Perpetuity Value	8%

Table 6. Delivered cost analysis for non-irrigated, coppice biomass production systems.

The table shows a range of delivered prices per dry ton. The variance depends upon the production cost assumptions, availability of subsidies, and the impacts of future tree improvement efforts to increase yields. In this case, the land acquisition strategy is to purchase property for tree farm development. Establishment costs include site preparation, planting stock, and planting the trees. Crop care includes herbicide weed control, cultivation, fertilization, and crop protection. Harvest includes harvesting the trees, processing into chips, and transporting the chips to the roadside. Transport includes moving the product to the conversion facility. These results show that delivered costs for dedicated poplar biomass feedstock will range between U.S. $70-100 per bone dry ton using today's yields and no subsidies. The expectation is that tree improvement, production efficiencies, and advances in harvesting and processing technologies will significantly lower future delivered costs to the $U.S. 50-70 per bone dry ton range.

Hybridization and Varietal Development Process

GreenWood's hybridization and varietal development process is designed to take the minimum time within prudence to increase operational genetic gains per unit of time. The salient steps in the process are: (1) Controlled reproduction, (2) Field testing, and selection, (3) Verification, and (4) Multiplication. These are described below.

Controlled Reproduction

Controlled reproduction uses the current generation of parental breeding stock to create base populations for subsequent field testing and selection. Presently, all controlled crossing is conducted at the Westport Tree Improvement Center using procedures described by Stanton and Villar (1996).[8] Breeding stock is provided by arboreta at Westport, the Boardman Tree Farm, and the former Fitler Managed Forest including the Togo Island ownership.[9] Augmenting this supply is domestic exchange of *P. deltoides* and *P. nigra* reproductive materials with the Natural Resource Research Institute (University of Minnesota), Iowa State University, and Boise Cascade Corporation. International exchange of pollen and seed is accomplished with cooperators in Asia and Europe. International cooperators include: (1) Oji Paper, Japan (*P. maximowiczii*), (2) Liaoning Poplar Research Institute (*P. maximowiczii*), China, (3) Korean Forest Research Institute (*P. maximowiczii*) and (4) Alasia Franco Vivai, Italy (*P. deltoides* and *P. nigra*).

The controlled breeding procedure can be briefly described as follows. Dormant 0.9-1.2 m floral cuttings are collected from breeding orchards and stored at -2.2°C to meet chilling requirements the extent of which is dependent upon the provenance of the breeding stock. Staminate inflorescences are forced in water culture at temperatures varying between diurnal and nocturnal cycles. Pollen is extracted from ripened catkins and screened through 80 to 100 mesh sieves, dried over desiccant for 24 hours at room temperature, and refrigerated at 1.1°C until used within three to five weeks. *P. deltoides* female breeders are rooted in soil using a rooting hormone and warming of the soil to 24°C. *P. nigra* and *P. trichocarpa* breeders root readily without such assistance. Seed matures in one season, does not exhibit physiological dormancy, and germinates readily on mineral soil without stratification. The generally close crossing relationship between female *P. deltoides* selections and males of various *Tacamahaca* poplars (*P. trichocarpa, P. maximowiczii*, and *P. simonii*) exhibits a reproductive block in the reverse direction that necessitates the use of in vitro embryo rescue.

Field Evaluation

The experimental unit for field testing in the hybridization and varietal development program is the individual genotype replicated as a clonal propagule. Thus the size of research plots has the potential to be exceedingly large. Consequently, a multi-stage test protocol will be used to manage experimental clonal populations of potentially sizable numbers. Historically, the North American field testing program employed a three-stage testing program. The year following hybridization, each test population was introduced into a sequence of three field trials: (1) Stage-one seedling nursery testing, (2) Stage-two varietal screening, and (3) Stage-three clonal refinement. Each annual population was progressively narrowed to the best subset of genotypes as they passed through the test series with an increase in replication and plot size along with an increasing focus on traits of lower broad-sense heritability or ones more expensive to assess. The approach has been to evaluate each test population independently using the same set of check clones to identify the most productive and adaptable genotypes. As a final check prior to or coincident with operational use, newly selected clones were also established in replicated yield verification plots to substantiate genetic gain across a range of sites.

Poplar Development and Commercial Application in Minnesota

Research in the Upper Midwest on the intensive culture of hybrid poplar began in the mid-1970s through the pioneering efforts of Dave Dawson and the team of researchers at the USDA Forest Service, Forestry Sciences Laboratory at Rhinelander, Wisconsin. Work was done by Dave Dawson, Ed Hansen, Neil Nelson, Don Riemenschneider, Jud Isebrands, Jerry Zavitkovski and Dan Netzer in addition to many others. Research included evaluation of biomass yields, genetics, physiology and cultural practices such as plant spacing and weed control. This was seminal research that established the foundation for woody crops for fiber and energy in the region. Subsequent to this program, research began at other universities in the late 1970's as part of the DOE Biomass Feedstock Development Program administered at the Oak Ridge National Laboratory under contract to the DOE. While much of the USFS research was concentrated at the Harshaw experimental farm near Rhinelander, Wisconsin, studies expanded to other sites across the region and included clone tests, herbicide trials and yield studies. New research programs included, among others, those at the University of Minnesota, University of Wisconsin, Iowa State and Purdue.

The establishment of a research base in the Upper Midwest was critical to the eventual commercial application of poplar culture in Minnesota. Prior to the 1970s, little information was available on suitable hybrids, potential yields and management practices. The infrastructure of genetics tests, yield studies and plantation culture research produced information on clonal performance in the region, inputs necessary for successful plantation establishment and resulting wood yield. Without this established infrastructure, it is doubtful that a commercial program would have taken place. Research done by the USDA Forest Service and the University of Minnesota provided the foundation for selection of poplar hybrids that were suited to central Minnesota conditions and expected yield of those hybrids on moderately productive agricultural soils in the state. This document describes the process of genetic improvement that was done to facilitate the commercial production of poplar in the region and ongoing genetic improvement efforts. Also, a discussion of production economics and future research direction is included.

Commercial Application-Verso Paper, Sartell, MN

The expansion of the forest products industry in the late 1980s and early 1990s in Minnesota led to increased pulpwood harvests from a level of 1.3 million cords to 2.3 million cords. Higher harvest volumes and supply constraints led to a rapid increase in aspen stumpage price from approximately $15.00 to $60.00 per cord. In response to concerns over timber supply and price, Champion International began an evaluation in 1994 of the commercial application of poplar plantations to supply fiber to the paper mill at Sartell, Minnesota. For sake of clarity, this document will refer to the commercial program as the "Verso Paper" program. Verso Paper is the current owner of the mill at Sartell after sales of the plantation program and mill from Champion International to International Paper and ultimately to Verso Paper.

The Sartell mill is located in an agriculture-forested transitional zone and relatively high prices for wood delivered to the mill from existing forests were being paid due to very long hauls from the north in addition to high stumpage prices for aspen, the desired hardwood species. This mill was built in 1910 along the Mississippi River at a time when logs could be rafted to the location cheaply. The situation has changed with the bulk of wood raw material being delivered by truck or rail at a considerable cost. Although not extensive, the research base of clone tests and commercial-scale acreage of poplar that was established in the region was sufficient to demonstrate the concept of dedicated woody crops for fiber for the Sartell, MN mill. Plans for implementation of a commercial plantation program were formulated in 1995 and plantations began to be established in 1996. In order to begin this process, selection of genetic material with proven performance in the region was critical.

Genetic Improvement Research

Clone Testing

Prior to the mid-1990s, most genetic improvement work in woody crops in the region consisted of a series of clone tests using clones that were developed previously in other programs; notably the Oxford Paper program which began in the 1920s by Ernest Schreiner and was subsequently continued at the Northeast USDA-Forest Service station (hence the "NE ###" designation of many clones reported in yield and clone screening research done in the 1970s and 1980s). These clones were propagated and distributed to the various regions and some were used commercially for shelterbelts and plantations. Also, clones were being produced in Europe in Belgium, Germany and Italy and imported into the United States and Canada. Genetic resources from Canada were imported by Ed Hansen at the USFS-Rhinelander from a collection made by Louis Zsuffa at the University of Toronto in the early 1980s. This set of clones comprised of the older NE clones and newer European clones imported through Canada was the primary source of genetic material for testing in the early DOE-supported regional tests in Wisconsin (USFS-Rhinelander, Hansen, Netzer, Riemenschneider), Minnesota (University of Minnesota-NRRI and USFS-Rhinelander), Michigan (Don Dickmann at MSU) and Iowa (Iowa State-Rick Hall).

Clone tests were planted at multiple locations throughout the region in replicated studies. Trees were measured annually to assess growth rate and evaluated for susceptibility to Septoria canker, *Melampsora* leaf rust and *Marsonina* leaf spot. Of the more than 80 clones that were tested, only three clones, DN34, DN5 and NM6 (DN= *P. deltoides* X *P. nigra*, NM = *P. nigra* X *P. maximowiczii*) were found to be disease resistant and fast growing under Minnesota conditions. The prevalence of disease was found to be quite high with *Septoria* canker being the most severe disease issue. Most clones that were found to be highly susceptible to *Melampsora* leaf rust were eliminated from testing quickly due to premature defoliation and resulting interrupted bud-set in the fall which contributed to significant winter injury. Thus, only three clones were identified from this regional research program that showed promise to produce high yields over a reasonable rotation length. This result underscores the need for intensive regional field testing to determine long-term performance. Also, the fact that the number of acceptable clones was found to be a low percentage of the total clones tested indicated that testing poplar genetic material using a set of plant material with a wide geographic origin is not a particularly fruitful endeavor. The resulting set of acceptable clones was not genetically diverse and, although these clones served as a starting point for implementation, posed a risk to a long-term commercial venture.

Using the set of recommended clones, Champion International began a nursery propagation program to produce sufficient quantities of planting stock for large-scale commercial planting. The three clones that were propagated at the time were those identified in regional research; NM6, DN5 and DN34. A nursery was established in central Minnesota to produce quantities to allow planting of approximately 2,000 acres annually, roughly one million cuttings produced per year. Based on early commercial plantings of DN34, this clone was eliminated from the program due to slow growth early in the rotation and associated increased weed control costs. Thus there are currently only two hybrid poplar clones that exhibit all of the desirable commercial traits of adventitious rooting, rapid growth and disease resistance. Of these two, NM6 dominates the current commercial acreage due to a perceived problem with DN5 in terms of growth form (bole sweep). Obviously, genetics of woody crops are not diverse with only two clones currently of commercial interest. In light of the lack of a diverse pool of genotypes to choose from for commercial deployment, discussions began in 1995 among the forest products companies in the state and the University of Minnesota-Natural Resources Research Institute (UM Duluth-NRRI) to expand the genetic base through a breeding program at the UM-NRRI with the focus on producing new high-yielding poplar clones adapted to Minnesota conditions.

Poplar Clone Testing and Breeding in Minnesota-1996 to present

It was obvious from the first round of poplar clone trials that without further breeding, the likelihood of finding a wide array of poplar hybrids adapted to Minnesota conditions was very low. Very few additional clones were available from worldwide collections that weren't included in the first group of clone tests and options for expanded tests using promising plant materials were limited. This led to the conclusion that a breeding program targeted to the Upper Midwest was absolutely necessary if poplar culture were to continue as a commercially viable operation in the future. In the past, fundamental genetic improvement research was limited in the Lakes States with the exception of Carl Mohn's work at the University of Minnesota with his collection of open-pollinated native *P. deltoides* and limited breeding done by Don Riemenschneider and Dana Nelson at the UM, specifically, *P. deltoides* X *P. maximowiczii* crosses. Also, breeding efforts were begun at Iowa State by Rick Hall but funding was discontinued prematurely and clones were not propagated for extensive field testing. None of the newly-bred material at the University of Minnesota was extensively tested over a wide geographic area. Rather, this material was archived at several locations in Minnesota. Therefore, little concerted effort was ongoing in breeding or new clone testing in the region.

Through the ongoing relationship between the UMD-NRRI and the forest product industry in Minnesota, discussions took place to expand the poplar research program building on the existing foundation of yield trials and clone tests in the state. This effort began in 1996 through a jointly funded state-industry effort entitled the Minnesota Hybrid Poplar Research Cooperative (MHPRC). At the time, Champion International, Potlatch Corporation, Boise Cascade, Blandin Paper, Minnesota Power were industry members. Through the participation of the industry, the University of Minnesota-NRRI staff and USFS (Don Riemenschneider) developed a research plan to accelerate development of cottonwood and hybrid poplars for fiber and energy production. The unique relationship between the UM-NRRI and cooperating companies made it possible for the UM to plant acreages of research trials without the cost and obligation of long-term leasing of land and stand maintenance; both high-cost items to programs funded solely through public research grants. Access to a large climatically diverse land base is perhaps the single most important aspect of the UM-Minnesota program that has allowed us to establish a large research network in the region.

After a survey of available poplar material, the MHPRC began a renewed clone testing effort using the two sources of poplar material cited above; Carl Mohn's native cottonwood collection and the collection of *P. deltoides* X *P. maximowiczii* bred by Don Riemenschneider and Dana Nelson at the UM-Department of Forest Resources. Clones from these collections were propagated and replicated field tests were planted at many locations throughout Minnesota. This second round of clone screening research began in 1996 with trials planted at many locations ranging from extreme northern Minnesota (Birchdale, MN) to Waseca, Minnesota, a high-quality agricultural site located in south central Minnesota. Much of the effort was concentrated in central Minnesota due to the interest of Verso Paper in the area. All of these trials were planted on agricultural lands and managed using agronomic techniques commonly employed in intensively managed plantations in the region. Planting was done at an 8 foot by 8 foot spacing with aggressive weed control during the early years of plantation development prior to canopy closure. Clone screening trials have been planted annually since 1996 and have included sets of a wide range of plant material pre-existing the MHPRC as well as new hybrids generated through the MHPRC breeding program.

Figure 1 below shows a typical result of the second round of clone tests. This particular test was planted in 1997 in northwestern Minnesota and included 52 clones planted as three, two-tree replicates of each clone. This collection is derived in some form from *P. deltoides* in the region, either as pure-species clones or *P. deltoides* X *P. maximowiczii* hybrids with the female parent being native to the region. The two commercial clones identified through previous clone testing, NM6 and DN34, were included as commercial checks. The ten highest-yielding clones, based on diameter-squared, an index linearly related to total biomass, shows that the potential exists to significantly exceed the growth of the current commercial standards. The ratio of the average diameter-squared of the ten highest yielding clones to commercial standards was found to be 2.48 and 1.68 in the case of DN34 and NM6, respectively.

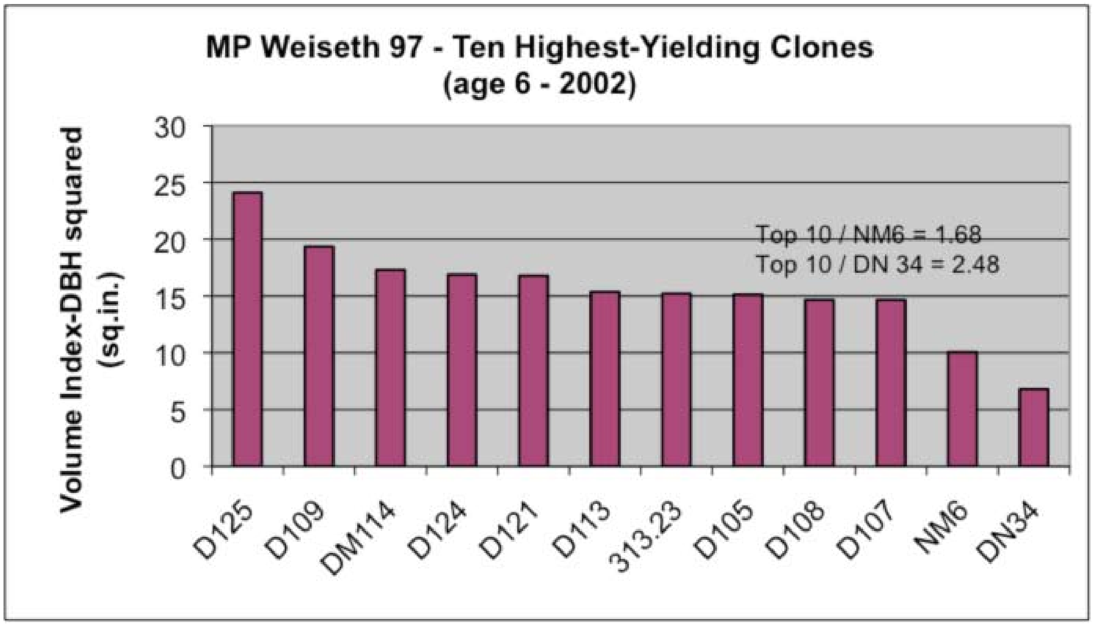

Figure 1. Growth of the ten highest-yielding poplar clones compared to the commercial clones NM6 and DN34 after six years in northwestern Minnesota.

Three important conclusions were drawn from this collection of clone tests. First, the growth potential of poplar genetic material native to the region was equal to or greater than the best commercial standards selected from collections available worldwide. Second, specific clones of pure-species *P. deltoides* selected from unimproved open-pollinated collections native to the region were capable of growing very fast. This was a surprising result and an important one as it demonstrated the potential gain that can be made using native resources as a foundation for breeding. Lastly, based on the set of clone tests in composite, a subset of clones demonstrated consistent performance with respect to growth rate, disease resistance and stem form across a wide range of sites (plasticity). Consistent performance of clones across a reasonable geographic range is absolutely critical to future commercial biomass production due to the fact that it is impractical to develop clones for very small sub-regions. Based on the results of these tests, those *P. deltoides* clones that exhibited plasticity across sites were used as the foundation of the early breeding that began in 1996.

Poplar Breeding and Field Testing

Breeding began in 1996 and has continued since that time. Having information on Eastern Cottonwood clones with proven performance in the region, we began a hybridization program using selected native *P. deltoides* as the female with *P. nigra, P. maximowiczii* and *P. trichocarpa* as pollen sources. Also, crossing within *P. deltoides* has been ongoing to improve the native resource for future breeding. Using the network of long-term clone tests and field trials of second-generation native *P. deltoides*, we are able to secure a sufficient supply of flowering branches of desired clones.

In the early years of breeding, pollen of *P. nigra, P. trichocarpa* and *P. maximowiczii* was obtained from collections maintained by the University of Toronto (Dr. Louis Zsuffa and Brenda VanStone-*P. nigra* and *P. maximowiczii*) and GreenWood Resources in Oregon (Dr. Brian Stanton -*P. trichocarpa*). Since that time, we have begun to assemble populations of *P. nigra* from Europe with over 2,600 clones in 34 families collected across a wide range of Europe from Turkey to Italy. This collection is being planted in longer-term breeding archives to provide genetically diverse collections with proven local adaptability. Also, this approach provides a degree of self-sufficiency with respect to both *P. deltoide*s and *P. nigra*, the principal components of the breeding program currently. At this time, we are able to procure a limited amount of *P. nigra* pollen from our flowering collections in Minnesota. Current breeding uses a combination of local sources of *P. nigra* as well as pollen from collections maintained by GreenWood Resources in Oregon. It is a goal of the ongoing research supported by the DOE-SunGrant Regional Biomass Feedstock Partnership to distribute this unique collection to other regions of the country for clone testing in various environments across the United States. Based on our experience in Minnesota, it appears that *P. nigra* has the potential to be a more plastic species than *P. deltoides* due to the fact that a high percentage of this collection have survived for several years under the relatively severe conditions of mid-continental winters of Minnesota. In light of this, we view the distribution of this *P. nigra* collection as an important component of a long-term national poplar improvement program. Collections of P. deltoides are available from institutions such as ArborGen LLC (Dr. Mike Cunningham) and Mississippi State University (Dr. Randy Rousseau) but flowering collections of *P. nigra* with proven regional performance are lacking.

The breeding program in the UM-NRRI in Minnesota has been active since 1996 and has conducted over 1,200 crosses and produced many thousands of potential new hybrids. Progeny resulting from these crosses are tested in large-scale field trials on Verso Paper lands. A typical field test is comprised of 30 families each having 30 individual full-sib clones per family with each clone being replicated three times for a total of 2,700 trees. Commercial check clones are included in these trials for comparison. Also, where possible, clones of the pure-species parents comprising the crosses being tested are included. In total, 900 clones (30 families X 30 individuals/family) are tested with these tests planted annually. Including new clones, commercial checks and parent clones, these trials include over 3,000 individual trees occupying seven acres and form the basis for the first stage of clone selection leading to commercial adoption. After selection of a reduced set of clones from the large-scale family tests, clone trials are planted on a greater number of sites across the intended range of site conditions. We continue to expand the network of clone tests in the region through the cooperation of universities and industry in neighboring states. The final stage leading to commercialization is yield trials. A limited number of clones are selected from the clone trial network for longer-term evaluation in closed-canopy, pure-clone blocks to evaluate biomass yield under conditions resembling commercial production acreage.

Due to the fact that the Minnesota program has been actively breeding since 1996, we have amassed an extensive system of family-field trials, clone tests and pure-species yield blocks with new clone identified for scale-up to commercial production. These clones are being propagated in nurseries managed by Verso Paper in central Minnesota and will be incorporated into commercial production over the next two years. Now that a “pipeline” of breeding, field trials and yield testing has been established, the potential exists to continually increase the genetic diversity of commercially acceptable clones and thereby, reduce production risk. Research being done under the DOE-funded SunGrant Regional Feedstocks Partnership is working to expand the model developed in Minnesota to a national scale through breeding, distribution of untruncated populations (seed collections without prior selection in any specific environment) and eventual field testing. This approach will eventually lead to regionally adapted clones having the desired commercial traits for bioenergy and fiber production.

Plantation Yield

One of the most important factors influencing the economics of biomass production is yield. We have established a series of yield tests across the state of Minnesota to assess the impact of soils, climate and genetics on yield. For our purposes, the value of interest is the total aboveground leafless biomass. For purposes of this discussion, yields are measured as total aboveground dry biomass (moisture free basis) included main stemwood, tops and branches. Also, we are assuming that plantations have been well maintained either in a commercial or a research setting. In most cases in our network of yield research plots, yield blocks are embedded within commercially managed plantations and, as such, reflect yields that can be expected under actual commercial management.

Our studies indicate that yield of hybrid poplar using superior clones such as DN5 and D124 on moderately productive agricultural sites in Minnesota is expected to be between 4.0 and 4.5 dry tons per acre per year. Data are needed on long-term growth characteristics of new clones. Behavior of clones at higher stand basal area later in the rotation is an important factor and has the potential to greatly affect the suitability of some clones to produce high biomass yields. Also, based on our research to date, the incremental stand basal area growth of the more productive clones ranges from 18 to 25 square feet per acre per year. This value can be used as the minimum expected baseline for closed-canopy stands of new candidate clones at mid-rotation.

Performance of clones vary considerably with DN34 being among the lowest yielding clones at all sites and as mentioned above, has been discontinued for use in commercial production. DN5 appears to be the most stable, high yielding clone across the range of sites in our studies. This underscores the potential variation among clones and the need to continue to improve genetics of poplar for production in the Lakes States. Clone NM6 is demonstrated to be a moderate- to high-yielding clone with stability across the range of sites. In commercial production, NM6 has been shown to yield 3.6 dry tons mean annual increment acre^{-1} year $^{-1}$ on moderately productive agricultural sites in central Minnesota (personal communication, Mike Young, Verso Paper).

Based on our experience to date, the average yield that can be expected in new plantations on land of average agricultural productivity in Minnesota is approximately 4.0 tons acre^{-1} year $^{-1}$. While data are not complete at this time, ongoing yield tests of a selected number of clones near Waseca, MN on high quality agricultural soils (180 bushel corn yield) show that yields of new clones will likely range from 5.0 to 5.5 dry tons increment acre^{-1} year $^{-1}$. The yield value of 4.0 dry tons acre^{-1} year $^{-1}$ is used as the starting point for economic analysis in the following section.

Poplar Production Economics and Agricultural Crop Profit

While yield is a critical part of biomass production, it is helpful to combine yield and production costs to provide a more complete picture of the economic feasibility of producing biomass energy through dedicated energy crops such as poplar. Through the cooperation of Verso Paper staff managing the large-scale industrial program, we have developed a cash-flow model that contains management inputs necessary to achieve optimal production on agricultural soils typical of those in Minnesota. Input on the management practice, frequency of application and other information such as herbicide rate applied were verified through discussion with Verso Paper staff. In order to provide some degree of "arms-length" from disclosure of industrial cost of production, we used a combination of published custom rate sheets for agricultural operations (Edwards, Iowa State 2010, https://www.extension.iastate.edu/store/ItemDetail.aspx?ProductID=1792) and contacts with agricultural contractors to fill in the cost data for each practice. Table 1 shows the cash flow model, practice and cost on a per-acre basis throughout the life of the plantation. We have assumed a single-harvest, twelve year rotation with one year added for site preparation and an average annual yield of four dry tons acre^{-1} year^{-1}. We then vary the stumpage price (direct revenue to the landowner) to estimate a breakeven production price using a real discount rate of four percent annually. As shown in the table below, the total discounted production cost is $450.00 per acre with the total yield held at 48 dry tons per acre at harvest. The breakeven price per dry ton at a 4% discount rate is estimated to be $15.63 per dry ton.

While breakeven prices for a specific production system provides some level of insight, a potentially more relevant question concerns alternate uses for the land and revenue to the landowner assuming competing crops. Thus, the appropriate question is; what does the stumpage value for poplar biomass have to be to provide the same profit as other crop options? To address this question, we used published production cost data from the FINBIN website, maintained by the University of Minnesota (http://www.finbin.umn.edu/). Using this information, the total direct (site prep, seed, planting, cultivation, herbicide, fertilizer, etc.) and indirect costs (buildings, machinery, interest, etc.) costs for selected crops was calculated. The total cost of corn production on owned land is reported to be $555 per acre including direct and indirect costs of $400 and $155, respectively. Assuming an average yield of 180 bushels per acre and a current market price of $4.41 per bushel, gross revenue minus expenses is $238.80 per acre. The stumpage price for poplar biomass after discounted annualized production costs of $37.54 ($450/12 year rotation) is $68.00 per dry ton. Assuming a harvest cost of $25.00 per dry ton and a transportation cost of $15.00 per dry ton (65 mile one-way haul), the estimated delivered cost of biomass would be $108.00 per dry ton. Conducting a similar analysis for wheat in Minnesota, the estimated stumpage price would have to be $50.00 per dry ton to produce the same revenue growing wheat. The delivered price for wheat-competitive biomass is estimated to be $90.00 per dry ton. While we do not advocate growing biomass in direct competition with major commodities, it is nevertheless instructive to understand the range of production cost for biomass assuming that energy crops are grown on some portion of the United States cropland base. It is important to highlight that of the 440 million acres of land classified as cropland in the United States, approximately 60 million acres is in the "cropland-as-pasture" category and an additional 40 million acres in the "idled lands" category. Thus, assuming that economic returns from these lands are 70% of wheat returns, the average stumpage value would be approximately $35.00 per dry ton or $75.00 delivered assuming a 65-mile one-way haul. Therefore, the likely range of delivered cost to a conversion facility would range from $70.00 to $100.00 per dry ton.

		Year of Operation												
Practice	Info Source	0	1	2	3	4	5	6	7	8	9	10	11	12
Burn-down Herbicide1	personal comm - Central Ag Services	13.5												
Primary Tillage2	Custom Rate – IA St – Edwards	14.1												
Secondary Tillage3	Custom Rate – IA St – Edwards	11.4												
Secondary Tillage3	Custom Rate – IA St. – Edwards		11.4											
Secondary Tillage3	Custom Rate – IA St. – Edwards		11.4											
Marking	AURI/UM - hybridpoplar.org		15											
Planting														
cuttings (450/acre @ $0.10)	personal comm - Jake Eaton - GWR, Mike Young, Verso		45											
planting (450/acre @ $0.05)	personal comm - Jake Eaton - GWR, Mike Young, Verso		22.5											
Pre-mergent Herbicide4	personal comm - Central Ag Services		43	43										
Cultivation	Custom Rate – IA St. – Edwards		9.3											
Cultivation	Custom Rate – IA St. – Edwards		9.3	9.3										
Cultivation	Custom Rate – IA St. – Edwards		9.3	9.3										
Cultivation	Custom Rate – IA St. – Edwards													
Post-Emerge Herbicide5	personal comm - Central Ag Services		43	43	43									
Fertilizer Application	personal comm - Central Ag Services							38.2		38.2		38.2		
Annual Sum of Costs		39	219.2	104.6	43	0	0	38.2	0	38.2	0	38.2	0	0
Revenue														750
Cash Flow		-39	-219.2	-104.6	-43	0	0	-38.2	0	-38.2	0	-38.2	0	750

Table 1. Cash flow model for a single-harvest, 12-year rotation poplar plantation in Minnesota.

Concluding Remarks, Research Needs, and Policy Considerations

Commercial production of poplar in the United States has been demonstrated to be viable both from a technical and economic perspective in specific regions of the U.S. Through research and practical experience, the production system of improved genetics, cultural practices and harvesting systems has been developed which has lead to high yields and feedstock acceptable for solid products, fiber and energy applications. However, the examples of commercial production are currently limited to two locations in the country with widely different climate and genetics. In order to begin the process of replicating the commercial success of woody crop production on a national scale, the following items are recommended for further research:

1 **Continued Breeding with Proven Parental Populations**-The wide geographic range of adaptability of cottonwood and related species and compatibility of these species in hybridization points to the potential to develop populations that are adapted to most locations in the U.S. Now that production systems have been developed for commercial production, further gains in yield are expected to come predominantly through genetic improvement. The experience in the Midwest and the Pacific Northwest has demonstrated the potential to increase yield through genetic improvement. In order to replicate this success, we recommend a national breeding program using proven genetic material from the various regions including the South, Mid-South, Midwest and Pacific Northwest. The resulting seed from crosses should be distributed to regional field-testing centers before having undergone a-priori screening in any specific environment. In this way, maximum genetic diversity is preserved and field tests from these populations will have the highest likelihood of identifying regionally appropriate hybrids for eventual commercial production.

2 **Regional Clone Trials**-Using products from the breeding program, a series of clone trials should be established within each region to identify field performance of a greatly reduced subset of clones. Prior experience has shown that a very small subset (1%) may ultimately prove to possess all of the traits of commercial interest. The location of these clone tests should be guided by some understanding of the likely target sites for bioenergy production.

3 **Yield Testing**-The final stage to commercialization involves testing of the candidate clones under closed-canopy conditions to move from relative performance (clone tests) to estimates of absolute biomass yield under conditions resembling commercial-scale plantings. These plots must be sufficiently large to minimize edge effects and allow estimation of biomass yield in the interior of a plantation.

4 **Fertilization Research**-Up to this point, fertilization response of poplar has been demonstrated to be highly variable depending on soils, cropping history, climate and genetic composition of the stand. Given the high financial and energy cost of fertilizers, particularly nitrogen, we recommend that research be done to identify those sites likely to produce economically and environmentally acceptable growth response. This avenue of research will likely be increasingly important as the geographic range of commercial production expands, particularly on the more heavily leached soils common in the Mid-South and South. Woody crops have the potential to be very efficient with respect to nutrient use and research is needed to quantify nutrient cycling and use at various locations.

5 **Coppice Production**-The bulk of commercial production at this time is limited to longer-rotation production for fiber, sawtimber and veneer logs on single-harvest rotations from seven to twelve years. However, as interest in dedicated woody energy crops increases, research in repeated-harvest, reduced-rotation (two to four year cutting cycles) coppice systems is needed. Subjects of importance include genetics, optimal planting density, yields, sustainability of production with repeated harvest and costs. While these systems have been demonstrated in specific locations, application of coppice systems should be demonstrated at multiple locations nationally.

6 **Harvest Technology**-Harvesting systems, such as the Case New Holland Biomass Harvester, are being developed that are capable of handling smaller diameter stems with high efficiency. In addition to chipping systems, integration of rapid harvesters with bundling of coppiced material is a potentially attractive option to allow long-term storage and air drying of biomass in bundles. Demonstration and evaluation of costs of harvesting of a variety of approaches should be done to identify trade-offs among the various harvesting systems.

In addition, there have been several recent policy rulings that have slowed the momentum of woody biomass feedstock development in the U.S.. Whether these rulings ultimately become the law of the land is unknown. However, they have raised the risk level for woody feedstock development and concurrently have resulted in the flight of investment capital away from these projects. Specifically, the following policies have affected development of the woody biomass production industry and will affect its large-scale commercialization in the near future.

7 **Renewable Fuel Standard (RFS) II-**Under the RFS II, a $1/gallon blender credit is given to producers using qualified RFS II feedstock. The standard as currently written, limits the production of biomass that can quality under the RFS II standard to tree plantations on non-federal land, and eliminates the opportunity to grow woody biomass on CRP, marginal agricultural or pasture lands for conversion into liquid fuels.

8 **GHG Emissions Tailoring Rule**-The rule states that CO2 emissions from biomass will be regulated in a similar manner to coal emissions. EPA was not willing to exempt biomass from this regulation and even small generators will come under this rule. This essentially rules that biomass is not carbon neutral and throws into doubt long-term policy support for biomass.

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[1]*Sensu lato*: Includes *P. cathayana, P. ussuriensis, P. suaveolens, and P. koreana*.

[2]Stettler, R. F., Fenn, R. C., Heilman, P. E., and Stanton, B. J. 1988. *Populus trichocarpa* × *Populus deltoides* hybrids for short rotation culture: Variation patterns and 4-year field performance. Canadian Journal of Forest Research 18: 745-753.

[3]Riemenschneider, D. E., Stanton, B. J., Vallee, G., and Perinet, P. 2001. Poplar breeding strategies. In Poplar Culture in North America. Part A. Chapter 2. *Edited by* D. I. Dickmann, J. G. Isebrands, J. E. Eckenwalder, and J. Richardson. NRC Research Press, National Research Council of Canada, Ottawa, ON K1A 0R6, Canada. pp. 43-76.

[4]Heilman, P. E., Peabody, D. V., DeBell, D. S., and Strand, D. F. 1972. A test of close-spaced, short rotation culture of black cottonwood. Canadian Journal of Forest Research 2: 456-459.

[5]Heilman, P. E. and Peabody, D. V. 1981. Effect of harvest cycle and spacing on productivity of black cottonwood in intensive culture. Canadian Journal of Forest Research. 11: 118-123.

[6]Heilman, P. C. and Stettler, R. F. 1985. Genetic variation and productivity of *Populus trichocarpa* and its hybrids. II. Biomass production in a 4-year plantation. Canadian Journal of Forest Research. 15: 384-388.

[7]Stanton, B.J., 1985. Clonal variation in Crown Zellerbach's cottonwood improvement program. Crown Zellerbach Forestry Research Division. Research Manuscript No. 70, 23 pp.

[8]Stanton, B.J. and Villar, M. 1996. Controlled reproduction of *Populus*. In Biology of *Populus* and its Implications for Management and Conservation. Part I Chapter 5. Edited by R.F. Stettler, H.D. Bradshaw, Jr., P.E. Heilman, and T.M. Hinckley. NRC Research Press, National Research Council of Canada, Ottawa, ON, Canada. pp. 113-138.

[9]*P. deltoides* clonal tests and breeding orchards at the former Fitler Managed Forest are located on lands that are under new ownership. Thus GreenWood has access only through 2012.

Chapter 18

Sustainable Solutions from Feedstock to Fuel for Advance Biofuel Production

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Environmentally and economically sustainable production of lignocellulosic ethanol for transportation fuel requires a feedstock-to-fuel approach that includes sustainable biorefinery design, delivering a reliable and cost-effective feedstock supply to the biorefinery gate and life cycle assessment (LCA) across the supply chain. In this paper, DuPont Danisco Cellulosic Ethanol (DDCE) and its collaborators from DuPont and Pioneer Hi-Bred, provide an overview of DDCE's progress in developing sustainable biorefinery systems and preparing for global commercial deployment.

Introduction

DuPont Danisco Cellulosic Ethanol (DDCE), a U.S.-based joint venture established in 2008, provides comprehensive solutions for production of fuel-grade ethanol from non-food plant material, including crop residues and dedicated energy crops. DuPont and Danisco jointly made an initial investment in DDCE of $140 million and an extensive intellectual property estate. The company earned early industry leadership by integrating and optimizing breakthrough biofuels technologies from its member companies and enacting a collaborative approach to create economic and environmental value for cellulosic ethanol.

DDCE is currently validating large-scale production of ethanol from corn cobs, corn stover, and switchgrass at its demonstration-scale biorefinery in Vonore, Tennessee. As the company prepares for commercial deployment, it is also establishing a commercially reliable and affordable supply of renewable lignocellulosic biomass through two projects: 1) a collaboration with the University of Tennessee and Genera Energy Biomass LLC to establish switchgrass crops and 2) an extensive corn stover harvest study in the U.S. Midwest. Both of these programs are described in more detail in this paper.

Section I-Sustainable, Renewable Motor Fuel

DDCE is working to deliver end-to-end solutions for cellulosic ethanol while demonstrating stewardship of farmland, ecosystems, and the communities where it does business.

DDCE's sustainability principles

- ▶ Deliver comprehensive cellulosic ethanol solutions with competitive social, economic, and environmental benefits
- ▶ Integrate sustainability into all business practices and decisions:
    - process design
    - site selection
    - feedstock supply
    - co-product management
- ▶ Assess environmental well-to-wheel impacts early and often to understand impacts of business and technology choices
- ▶ Engage stakeholders in dialogue on sustainability

Comprehensive Solutions for Efficient, Low-Cost Conversion

By integrating proprietary technologies from DuPont and Danisco, DDCE leverages the potential of cellulosic ethanol to meet the world's growing demands for renewable fuels. This includes reducing greenhouse gas emissions by 50 to more than 100 percent compared to gasoline.

DDCE's biorefinery design incorporates features for sustainable production such as water recycling, emissions reduction, and lignin product capture. DDCE's conversion system (see Figure 1) is a streamlined solution to the complex process of harnessing the energy content in the hemicellulose, cellulose and lignin components of plant materials. It comprises the following key process units: 1) substrate preparation 2) pre-treatment 3) saccharification (enzymatic hydrolysis) 4) fermentation 5) recovery and distillation.

The biorefinery includes onsite production of saccharification enzymes (to break the plant material into its component sugars) and ethanologen (low by-product fermentation) for economic, logistic and environmental advantages. Among these benefits is the ability to effectively and rapidly integrate bioprocessing performance upgrades. For example, DDCE's enzyme improvements have significantly reduced in-use enzyme costs for its biorefinery, decreasing the overall cost of manufacture. DDCE's integrated solution also features dual-sugar fermentation (C5/C6 sugars), based on *Zymomonas* mobilis technology developed by DuPont.

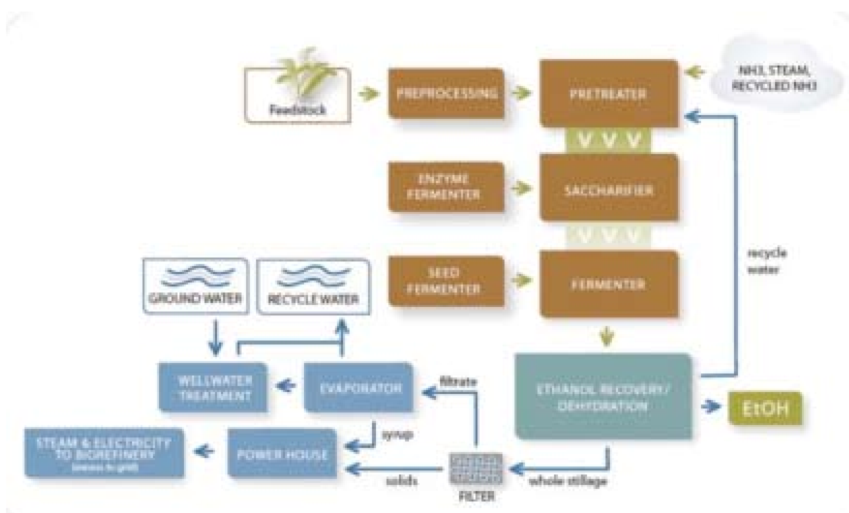

Figure 1: Schematic of DDCE's cellulosic ethanol process

Demonstration-Scale Biorefinery Sets a Global Precedent

DDCE designed, built, and operates a 250,000-gallon per year demonstration scale biorefinery in Vonore, TN which is one of the first cellulosic ethanol production plants in the world. The project is the result of collaboration between DDCE, the University of Tennessee and Genera Energy LLC. DDCE produces fuel-grade anhydrous ethanol at the biorefinery to generate data packages for validating process economics and environmental targets.

The Vonore facility, which began production in December of 2009, is an industrial prototype of DDCE's commercial plant design. It includes end-to-end production, a state-of-the-art Process Development Unit (PDU), and laboratory facilities. DDCE is using the demonstration data to design and license packages for biorefineries that will produce 25 to 100 million gallons of cellulosic ethanol per year.

DDCE is accelerating the commercial deployment of cellulosic ethanol through commercial plant project and licensing activities. The company will build a commercial scale biorefinery in the U.S. Midwest that will begin full-scale production of ethanol from corn stover. The next project will be a commercial switchgrass facility in the southeast U.S. These facilities will be centers of excellence and technological progress for the burgeoning cellulosic ethanol industry.

A typical commercial facility producing 50 million gallons of cellulosic ethanol per year will produce ethanol at less than $2 per gallon and those costs will decrease as the technology evolves. Feedstock costs are estimated to be between $45 and $60 per dry ton for corn stover. DDCE anticipates that, as subsidies sunset, it will be able to provide cellulosic ethanol at a price competitive with gasoline on energy parity.

Although DDCE is a forerunner in building and operating cellulosic ethanol facilities, its core business is licensing custom packages for safe, sustainable, low-cost production of fuel from biomass. As countries throughout the world strive to meet growing energy demands with renewable fuel, DDCE anticipates that a major portion of cellulosic ethanol will be produced using its licensed technology.

Section II-Projected Improvements in Biomass Production in the Next Decade

Rapid commercialization of DDCE technology on energy feedstock sources with potential volumes that supply relevant quantities of biofuel will ensure that we meet U.S. government blending goals, as set out in the Renewable Fuel Standards (RFS2).

Increasing Grain Yields and Trait Developments

Corn producers continue to value harvestable yield as the most important trait for productivity and profitability. Improvements in corn genetics, agronomic practices, and crop management to reduce stress (disease, insect, others) have led to tremendous gains in harvestable yield in corn. Improvements in corn genetics alone has led to a linear increase in grain yield of 74 kg/ha/yr (1.2 bu/acre/yr) during the period from 1934 to 1991 [Duvick 1997, 1999] (see Figure 2) and that rate of genetic gain is expected to double.

Both yield per acre and total corn production have roughly doubled between 1976 and 2009, but acreages planted and harvested have held nearly constant (see Figure 3). This means that increases in production are due almost solely to increased yield per acre. Put another way, since 1976 we have added the equivalent of nearly 70 million corn acres through gains in genetics, defensive traits, agronomic and management practices, and other improvements.

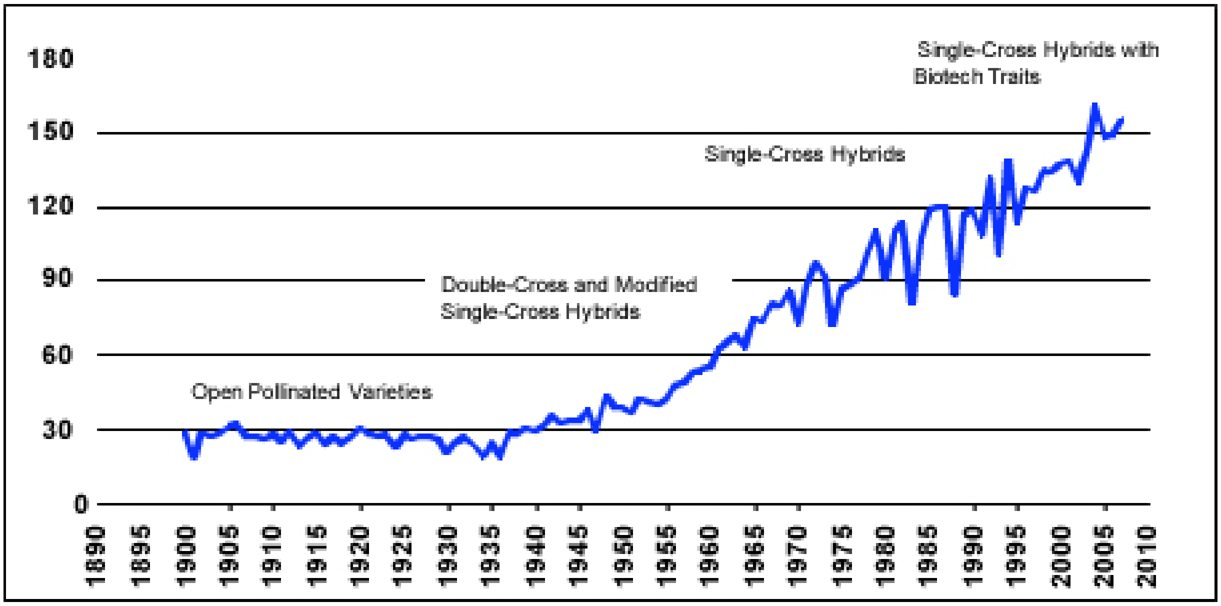

Figure 2: Historical U.S. Yield Improvement-Corn Bu/Ac

Year	Acres Planted	Acres Harvested	Yield per Acre	Total Harvest
	(million bushel)	(million)	harvested (bu)	(billion bu.)
1976	84.59	71.51	88.00	6.29
2009	86.48	79.62	164.90	13.13

Figure 3: Yield per acre and total corn production have roughly doubled between 1976 and 2009 (Source: USDA ERS Feed Grains Data; Yearbook Tables)

Researchers at Pioneer, a DuPont Company, are utilizing both transgenic and molecular breeding tools to positively impact overall corn yield. Compared to non-transgenic lines of corn, Pioneer expects a 10% improvement in harvestable yield with the next generation of seed corn products.

An increase in harvestable yield would come from a convergence of elite germplasms and key agronomic traits such as drought tolerance and nitrogen use efficiency. The introduction of transgenic yield traits combined with the broadest germplasm base in the industry will support Pioneer's commitment to bring a 40 percent yield increase in corn. Pioneer will continue to advance hybrids locally to deliver the best hybrid for each field and help growers succeed across diverse environments.

Impact on Biomass in Next Decade

Genetic gain of modern U.S. corn belt maize grain yields is not primarily a function of additional grain per plant (a change that would have a dramatic influence on harvest index; i.e. the ratio of economic yield [in this case corn grain] to total above ground biomass. It is a function of the number of plants per unit land area and the harvest index has remained relatively stable over time. Therefore as grain yields increase so will total biomass per unit land area (grain plus stover). Stover supply will increase as corn grain yields increase.

A recent literature survey by Lorenz et al (2010) investigated the feasibility of maintaining the current rate of genetic gain for grain yield while increasing the stover yield. The authors conclude that there is no evidence in the literature to preclude this despite the complex interactions of environment (especially light limitation), genetics (especially tropical germplasms), and crop management (planting density). However, in order to see additional breeding targets for stover yield, a stable, economically viable market for non-grain biomass will need to develop and DDCE is accelerating that market.

Section III-Feedstock Platforms

DDCE's feedstock platform has been developed using a rigorous review of economic, technical, and sustainability standards to select the optimal feedstocks for market development. These standards are used to assess a wide range of feedstocks. The ranking of feedstocks provides an indication of the potential to develop technology that can economically and sustainably convert a feedstock into renewable energy. Based on the results of this analysis, DDCE is pursuing corn stover as the first major feedstock platform to build-out its commercial design licensing package. The expectation is that technology advances derived from the corn residue platform will combine with increased policy support for dedicated energy crops and will open the door to further support expansion of feedstocks such as switchgrass and others.

Availability of Corn Residue Supply

The Billion Ton study conducted by the USDA and the U.S. Department of Energy (USDOE) revealed that there are an estimated 75 million dry tons of stover available for conversion into biofuels throughout the U.S. [Perlack, 2005]. Since that time, yields and acres associated with corn production have increased, which should provide further stover for renewable energy.

Corn stover is composed of about 70 percent cellulose and hemicellulose and 15 to 20 percent lignin. Cellulose and hemicellulose can be converted to ethanol and lignin can be used for biomass energy applications, such as boiler fuel for steam/electricity generation. DDCE is developing ways to efficiently collect, handle, and store biomass economically to improve processing technology and ensure biomass-to-cellulosic ethanol commercialization.

In general, the weight of stover is equivalent to the weight of grain [Sawyer, 2007]. This can vary depending on hybrid, growing conditions, production practices, and other variables. As one component of the experimental work in 2010, DDCE is evaluating grain and stover yields during harvest with partner farmers to gauge the impact of these factors on stover availability. Using a one-to-one ratio, a grain yield of 175 bushels (4.9 tons at 15% moisture) equates to a stover yield of 4.2 tons at dry weight. Similarly, a grain yield of 200 bushels (5.6 tons at 15% moisture) equates to a stover yield of 4.8 tons at dry weight (Figure 4). Other research has indicated that as yields increase, stover yields tend to drop slightly below the 1:1 ratio.

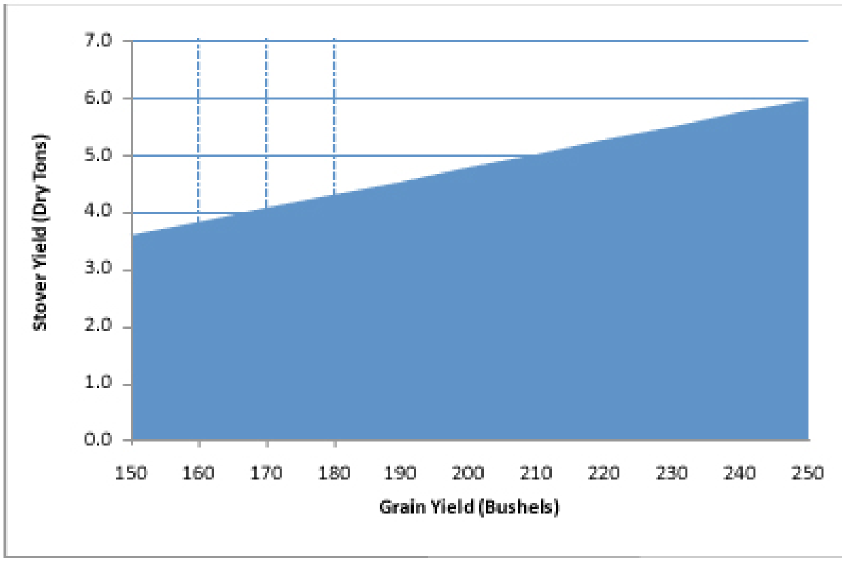

Figure 4: Estimate of stover tons/acre using 1:1 Ratio (Based on grain moisture of 15.5%)

Economic Cost of Supplying Corn Residues

A key assumption regarding biomass prices that should betested is the expectation that the value to the grower is static within a given collection boundary. Erickson and Tyner (2010) revealed that economic analysis on the breakeven price for cob collection for a given farmer varied significantly based on the size of the farm, corn yield, and capital costs of equipment to collect biomass. The authors noted that the challenges of creating cellulosic biofuels is not only technical advancement but an economic hurdle to secure an adequate supply of corn cobs at a given price that will be sustainable for a potential biorefinery and for farmers. While the equipment for corn stover collection may be different than corn cobs, the challenges of asset utilization, operational consistency, and value to growers will be major factors for any biomass user to consider in evaluating the structure of its business model to obtain feedstock for a biorefinery.

Agronomic Impact

Nutrient removal will vary, depending on factors such as amount of stover removed, the ration of leaves to stalks in the harvested fraction, the amount of precipitation prior to baling, farmer production practices, such as tillage methods, and other external factors such as land profile, soil type, and climatic conditions. It will be important for farmers to maintain disciplined soil testing and crop scouting programs that integrate the impacts of stover removal into their overall farm management plan.

Farmers need to utilize crop residues as a critical tool to maintain soil tilth, mitigate erosion, and promote environmental quality. However, some research indicates that stover removal can be a sustainable practice if it is managed appropriately. When looking at the best methods and amounts of stover to remove, some key factors for farmers to consider are:

1. Amount of stover available for harvest in different parts of the field
2. Nutrient balance
3. Soil organic matter
4. Soil erosion
5. Water and temperature dynamics
6. Compaction.

2010 Corn Stover Harvest Program

DDCE has been conducting an experimental stover collection program in several locations throughout the U.S. Corn Belt. The program involves partnering with America's farmers to economically and sustainably harvest stover and evaluate the impacts of storage conditions on the conversion of stover into cellulosic ethanol. During the harvest, DDCE will work closely with growers to support their economic goals and environmental stewardship principles. The DDCE Fall 2010 Experimental Feedstock Collection program involves:

- mutually beneficial contracts between DDCE and growers to collect stover
- professional custom stover harvesting managed by DDCE
- an extensive research program to evaluate areas, such as stover collection rates, field equipment and logistics, transport & storage, and agronomic impacts
- operational introduction to facilitate scale-up for a commercial project

DDCE works with farmers to create a long-term sustainable supply chain for corn stover that will benefit both growers and the emerging cellulosic ethanol industry.

Suitability of Switchgrass as a dedicated energy crop

Switchgrass has been shown to be a sustainable source of significant quantities of biomass for energy production. DDCE is working with the University of Tennessee and Genera Energy on a state-backed program to establish a reliable switchgrass supply chain while demonstrating the technology at the Vonore biorefinery.

Switchgrass in Tennessee yields between 6 and 12 tons of biomass per acre. It can be grown on marginal land not well-suited for food and feed crops, requires only minimal fertilizer and other chemicals, does not need irrigation, and can be harvested with existing farm equipment. Production of switchgrass as a dedicated energy crop has been demonstrated at a large scale in Tennessee as part of the comprehensive University of Tennessee Biofuels Initiative (UTBI).

Switchgrass can take two to three years to reach full production capacity. Once mature, the plant typically exceeds seven feet in height. With an extensive root system, it is often used for soil conservation, erosion control, and other environmental benefits. Switchgrass is a perennial plant and farmers can maintain switchgrass stands for a decade or more without replanting or observing diminishing yield. Some existing research stands have remained productive for more than 20 years after establishment. The state of Tennessee has done extensive studies to quantify the opportunity of a biofuels industry in the state.

University of Tennessee researchers (Ugarte, D., et. al, 2007) conducted extensive simulation analyses of the potential impacts on the agricultural sector of increasing the production of bioenergy crops and increasing the use of crop residue for bioenergy. Their research concluded that as the market for energy crops and biofuels develops, switchgrass production would be focused primarily in the Southeastern U.S., Texas, and Missouri, and provide feedstock for the production of over 2.8 billion gallons per year of cellulosic ethanol.

Harvest, Handling, Storage Systems

Switchgrass handling and storage are important variables in long term feedstock quality and bale integrity. Based on UT AgResearch studies and experiences with switchgrass production and handling, there are a number of producer management and handling and storage considerations to produce a high quality switchgrass product for energy feedstock uses.

The current recommendation for harvesting switchgrass is a system of harvesting once each year and a harvest window between a killing frost and shoot emergence in the spring. In Tennessee, this provides a harvest window generally between the end of October and the beginning of April.

Switchgrass costs

The large-scale 6,000 acre Switchgrass Farmer Incentive Program (SFIP) in Tennessee provides a current and relevant source of publicly available data regarding feedstock costs. In addition to considering costs and potential returns from planting switchgrass, farmers must also consider the costs and potential returns of alternative crops or enterprises. The land rental rate provides a measure of the comparable potential returns in an area.

While the cost to establish switchgrass requires a significant upfront cash investment in the first two years, the production cost decreases on a dry ton basis once the stand matures. DDCE and its collaborators are working on switchgrass supply models that enable viable and sustainable business outcomes at commercial scale.

Section IV-DDCE Life Cycle Assessment

Motivation for LCA

Life Cycle Assessment (LCA) is a holistic tool used to evaluate the environmental footprint of a product or process along the entire value chain. From the very early research and development stage of the cellulosic biorefinery project, starting in 2003, LCA was incorporated alongside process development to guide decision-makers to the most sustainable solutions. Now in 2010, as DDCE prepares for the commercialization phase, there are strong external drivers to apply LCA.

There are several emerging regulations and standards related to biofuels, all of which apply LCA methodologies to account for greenhouse gas (GHG) emissions. In the U.S., both the Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) released regulations related to GHG emission savings for biofuels in the form of the Renewable Fuel Standard (RFS) and a Low Carbon Fuel Standard (LCFS) respectively. The RFS requires cellulosic ethanol to be at least 60% lower than conventional gasoline in terms of well-to-wheel GHG emissions while CARB's LCFS rewards biofuels for GHG emission reductions vs. gasoline, but does not specify a certain savings requirement [US EPA, 2010], [CARB, 2009]. The well-to-wheel system for a transportation fuel includes upstream, on-site, and downstream processes, through combustion in a vehicle. U.S. state governments, for example in the Northeast and Mid-Atlantic states, are also contemplating a LCFS [Northeast, 2009]. European regulations such as the Renewable Transport Fuel Obligation (RTFO) in Great Britain and the European Renewable Energy Directive also encourage LCA methodologies since they could be highly influential in the U.S. [UK RTFO, 2007], [European, 2009]. All of these regulations apply LCA to calculate GHG emissions for transportation fuels.

Emerging sustainability standard-setting bodies such as the Council on Sustainable Biomass Production in the U.S. and the international Roundtable on Sustainable Biofuels also present external drivers for LCAs of DDCE products [CSBP, 2009], [RSB, 2009]. These organizations released voluntary sustainability standards related to biofuels, both of which incorporate LCA methodologies to calculate GHG emissions.

The intent of this LCA study is to compare DDCE cellulosic ethanol GHG emissions with other likely fuels in the marketplace and to determine if DDCE cellulosic ethanol will meet the GHG emissions savings requirement as mandated in the US EPA RFS2. A comprehensive ISO 14040 LCA report for DDCE is currently in progress. A small sub-set of what will be presented in the ISO report is included here. All results are preliminary, pending a full expert panel peer-review applying ISO 14040 requirements [ISO, 2006].

The Transportation Fuel System

DDCE GHG emission results can be compared to other relevant transportation fuels on an equivalent system boundary and functionality basis. For a fair comparison, each transportation fuel is studied on a well-to-wheel (WTW) basis. This includes upstream, on-site, and downstream processes, through combustion in a vehicle. The three broad steps feedstock production, biofuel production and vehicle use are explored in more detail below. The CO_2 sequestered in the biomass feedstock is eventually released back into the atmosphere as CO_2, through fermentation or combustion of the biomass co-products and the ethanol product. In the DDCE model, the CO_2 emissions sequestered and released are considered, but since they cancel each other out in the WTW analysis, they do not appear in the results charts.

There is currently a lack of consensus in the scientific community regarding the appropriate methodologies for taking into account indirect effects in a transportation fuel LCA. Therefore, it is appropriate that indirect effects such as indirect land use change not be included within the scope of the DDCE LCA at this time.

The fuel systems studied include the following life cycle stages:

- Feedstock production, including production of all farming inputs for cellulosic ethanol
- Feedstock transportation to the biorefinery
- Transformation of the feedstock into a fuel at the biorefinery
- Fuel transportation to a distribution center
- Fuel transportation to a refueling station
- Fuel combustion in a vehicle

Under the assumption that the conversion of fuel energy to vehicle propulsion is independent of the fuel type, an energy unit is the appropriate basis for comparing different transportation fuels. It is assumed that one megajoule (MJ) of ethanol is functionally equivalent to one MJ of gasoline.

Inputs to the DDCE Life Cycle Assessment

DDCE is currently validating production of ethanol from corn cobs, corn stover, and switchgrass at its Vonore, TN facility. For the purposes of this study, the product of the DDCE process is cellulosic ethanol from corn cobs. Other feedstocks will be evaluated at a later time.

At each step along the transportation fuel value chain, material and energy inputs are included. For example, at the farm where the corn cobs are produced, nitrogen-based fertilizers are applied to support a higher-yielding crop. The amount of nitrogen fertilizer used, as well as the environmental impacts associated with the production and usage of the fertilizer are quantified and tracked. Some DDCE system inputs are negligible. Cut-off rules are defined to determine which inputs are significant enough to include in the LCA. For the DDCE LCA, each material input that is more than one percent of the total mass going into the DDCE biorefinery is included in the DDCE LCA. (In order to be conservative in terms of inputs, the total mass calculation excludes the mass of the corn cob and water). Any input which accounts for less than this one percent is considered a minor input and is not included in the LCA.

Feedstock Farming

Researchers from Michigan State University (MSU) provided a rigorous, cradle-to-farm LCA model of corn grain, stover, and cob production for selected locations of the U.S. Corn Belt. It combines DAYCENT modeling results on carbon and nitrogen cycles in the soil with data on agro-chemical application and energy consumption at the farm (refer to Kim et al., 2009) for further details. Input data for the MSU models was collected at the county level, to the extent possible, and supplemented using data at state level or U.S. averages as necessary. Impacts associated with indirect land use change are not included in the DDCE LCA. Direct land use change effects, such as changes in soil organic carbon, are included. Other key inputs to the farming sub-system include fertilizers, fossil fuels used for farming equipment, herbicides and pesticides, and transportation of the feedstock to the cellulosic ethanol biorefinery.

It was determined in this study that, while corn stover removal causes a reduction in the soil organic carbon sequestration rate, it reduces nitrogen-related emissions from the soil. This change in nitrogen related emissions is shown in detail in Table 3 of the Kim et al., 2009 publication, where DAYCENT results are presented on a per hectare of land basis, with and without stover removal. Farming practices like planting winter cover crops and switching from conventional tillage to no-tillage could mitigate the effect stover removal has on the soil organic carbon sequestration rate. This study also emphasized the importance of using site-specific data whenever possible in order to improve the accuracy of an agricultural system LCA.

The Cellulosic Biorefinery

The main inputs to the DDCE biorefinery today are corn cobs, water, and various other process chemicals. Inclusion of process chemicals into the DDCE LCA was on the basis of the cut-off criteria, as described above. Some of the primary process chemicals include ammonia, sodium hydroxide, sulfuric acid, and glucose. The biorefinery creates ethanol from the corn cobs as well as two other biomass “co-products.” One of the co-products, called “syrup,” is a viscous liquid that is fed into an on-site boiler. The heat content of this biomass co-product is sufficient to generate all of the steam needed in the DDCE process. A small amount of extra steam is also produced which is assumed to be exported to a co-located user. Another biomass co-product called “lignin-rich filter cake”, or “LFC”, is assumed to be exported off-site to a local coal-fired power plant. It is expected that this LFC could displace a small (1-10%) amount of the fuel input to a typical pulverized coal-fired power plant (at roughly 450MW).

Ethanol Transportation, Distribution and Usage

Ethanol that is produced at the biorefinery must be transported to distribution centers and then further to the gas stations where it is ultimately used. At the present time, burdens associated with the blending of ethanol with gasoline are not included in the scope of the LCA since this minor operation is likely negligible compared to the rest of the supply chain. This blending operation is also omitted from GREET model simulations and RFS2 well-to-wheel analyses. GHG emissions for the transportation and distribution of the ethanol as reported in the Farrell et al. 2006 publication are used in the DDCE LCA [Farrell, 2006]. In this study, Farrell reported GHG emissions of 1.4 g CO_2 eq/MJ ethanol for transportation and distribution. This value is consistent with reported GHG emissions for the same steps in GREET 1.8c [ANL, 2010].

WTW GHG Emission Results

Shown in Figure 5 are the WTW GHG emission results for this DDCE cellulosic ethanol case, referred to as DDCE 2010. The direct 100 year global warming potentials (GWPs) were taken from Table 2.14 (errata) of the Intergovernmental Panel on Climate Change (IPCC) 2007 report [(IPCC, 2007)]. The net WTW GHG emissions shown are -17 g CO_2 eq/MJ of ethanol. This negative value indicates that the GHG credits associated with the steam and LFC export credits are greater than the burdens associated with all of the inputs used in the biorefinery. The GHG credits related to exported LFC and exported steam account for a significant portion of the overall GHG emissions for the DDCE 2010 case. LFC is a solid biomass co-product of the DDCE biorefinery, which can be used as fuel to produce heat or power.

The lignin is recovered at a moisture content suitable for burning in a solids boiler. It is assumed that the LFC is exported off-site and is used as a fuel in place of the solid fossil fuel coal. Since the heat or power facility receiving the LFC must be capable of handling solids, it is reasonable to assume that the conventional fossil fuel displaced by the LFC would be coal. Recent discussions between DDCE business leadership and potential customers and partners indicate that this co-product use scenario is viable. Using the system expansion approach, as recommended by the ISO 14044 LCA standard, a displacement credit corresponding to the equivalent amount of coal on a heat value basis is applied to the DDCE LCA. This results in the large GHG credit for exported LFC.

Similarly, the system expansion approach is used in the case of the excess steam generated at the biorefinery. It is assumed that the small amount of excess steam produced from the burning of the syrup is exported to a local user, thereby displacing steam from natural gas. Since the steam produced from the syrup co-product is more than enough needed by the DDCE biorefinery, there is no supplemental fossil fuel input needed for steam generation. Other significant contributors to GHG emissions include the electricity consumed at the biorefinery and emissions from corn production, including fuel and nitrogen fertilizer.

Some aspects of the biorefinery system, although they have been included in the LCA, do not contribute significantly to the WTW GHG emission results. These contributors include ethanol transport and distribution, direct emissions from the biorefinery, as well as the GHG emissions associated with ammonium sulfate, sodium hydroxide, sulfuric acid, enzymes, and glucose. Transportation of the biomass feedstock to the biorefinery also contributes only a small amount to the GHG emissions.

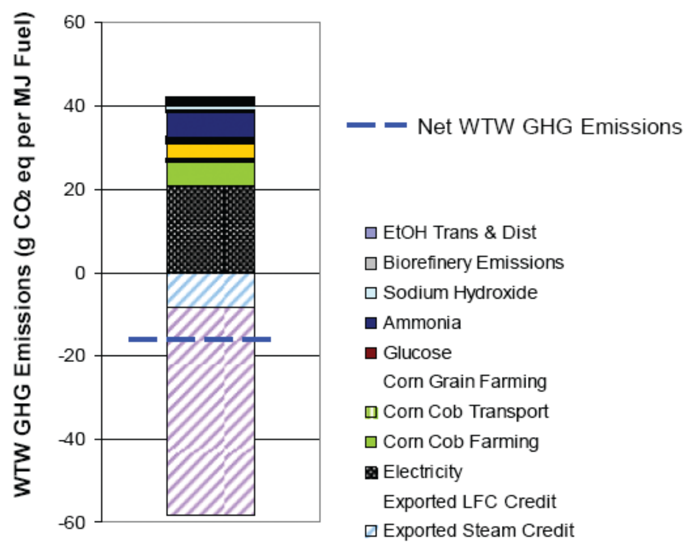

Figure 5: WTW GHG emission results for cellulosic ethanol in the DDCE 2010 case.

The following inputs are included in the total, but are not listed in the legend since their WTW GHG contributions are not visible on the graph: corn grain transport, sulfuric acid, enzymes and ammonium sulfate

Transportation Fuel Benchmarks

As described above, the primary goal of this DDCE LCA is to compare the WTW GHG results of the DDCE 2010 case with other fuels in the marketplace. Potential competitors to DDCE cellulosic ethanol include conventional gasoline, dry grind corn grain ethanol, and cellulosic ethanol from other suppliers. A broad search of the publicly available GHG emission data related to these fuels was completed. For the cellulosic ethanol benchmarks, corn stover and cob cases were considered the most relevant and will be discussed in the following sections.

Table 1 lists each benchmark with a brief case description, the as-reported WTW GHG value, and the data source reference. Figure 6 shows WTW GHG emissions for gasoline, dry grind corn grain ethanol, and stover or cob cellulosic ethanol, as reported by various sources.

Case # on Figure	Benchmark Case Source	WTW GHG emissions, g CO_2 eq/MJ, as reported	Reference Information
Fuel Category	**Gasoline**		
1	RFS2	93.1	US EPA, 2010
2	GREET US Gasoline	91.3	ANL, 2009
Fuel Category	**Dry Grind Corn Grain Ethanol**		
3	CA LCFS Midwest, dry mill, DDGS, NG	98.4	CARB, 2009
4	CA LCFS CA, dry mill, wet DGS, 80% NG and 20% biomass	77.4	CARB, 2009
5	RFS2- NG "Base Plant"	75.8	US EPA, 2010
6	GREET Dry Grind EtOH	65.3	ANL, 2009
7	NREL 2010	51.3	Hsu et al., 2010
8	RFS2-"Best Case"	49.3	US EPA, 2010
9	Liska et al.-"NE-CL Case"	30.6	Liska et al., 2009, closed loop facility with anaerobic digestion
Fuel Category	**Stove/Cob Cellulosic Ethanol**		
10	NREL 2010	41.1	Hsu et al., 2010
11	GREET Stover EtOH	7.3	ANL, 2009
12	Zeachem	5.5	http://www.zeachem.com/technology/LCA.php
13	Coskata	3.7	BIO World Congress 2010 presentation http://bio.org/worldcongress/applications/breakout2010/PrintSingle.aspx?pID=32&appID=5013
14	POET	-9.7	http://www.poet.com/discovery/releases/showRelease.asp?id=219
15	RFS2	-27.0	US EPA, 2010

Table 1: Benchmark case descriptions, WTW GHG emission values, and references for the data shown in Figure 6.

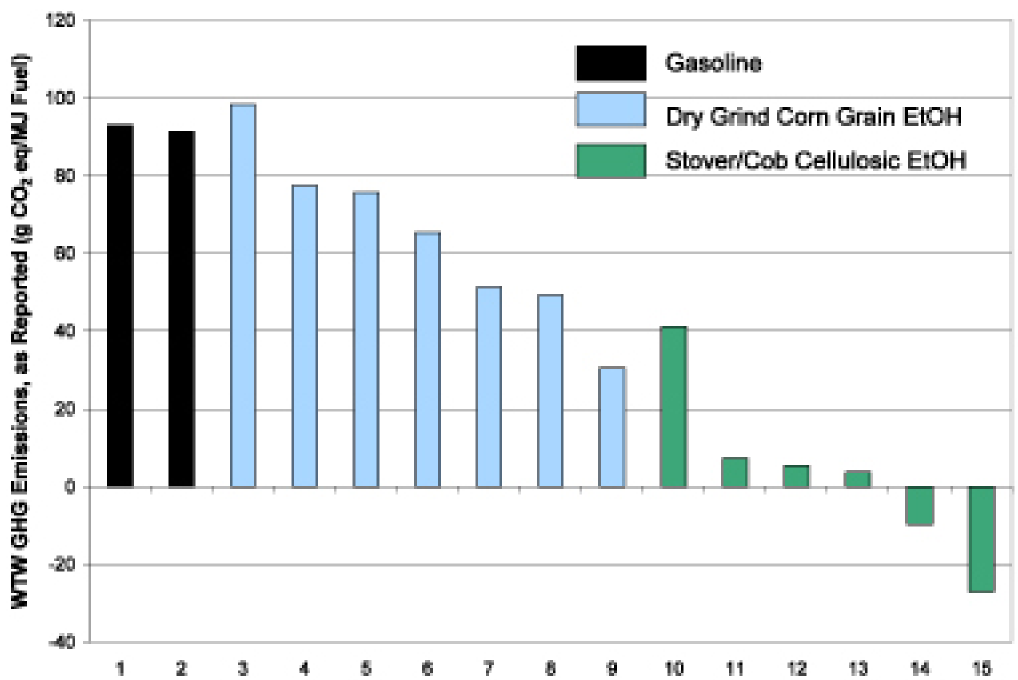

Figure 6: WTW GHG emission results for gasoline, dry grind corn grain ethanol, and stover or cob cellulosic ethanol benchmarks, as reported in literature and described in Table 1.

The two data sources included for conventional gasoline both report roughly the same WTW GHG emissions, at 92-93 g CO_2 eq/MJ. By contrast, there is a wide range of WTW GHG emission results reported by various sources for both dry grind ethanol and corn stover or cob ethanol. Out of the data sources reviewed for dry grind corn grain ethanol, the California Air Resources Board (CARB) reports the highest WTW GHG emissions, at 98.4 g CO_2 eq/MJ in case 3 and Liska et al. reports the most optimistic case at 30.6 g CO_2 eq/MJ in case 9. This wide range of results depends primarily on two factors: whether or not indirect effects are included, and if bioenergy or fossil energy is used at the biorefinery. For dry grind corn grain ethanol cases, including indirect effects will tend to increase the WTW GHG emission results while the use of bioenergy instead of fossil energy will decrease the WTW GHG emission results.

In the case of stover or cob cellulosic ethanol, information on potentially competing companies in the marketplace is publicly available. Both Zeachem and Coskata report WTW GHG emissions close to the results modeled by Argonne National Lab in the GREET tool at 7.3 g CO_2 eq/MJ. POET reports a net negative WTW GHG emission result of -9.7 g CO_2 eq/MJ for their cellulosic ethanol case. Hsu et al. reports the highest WTW GHG emission results out of all of the stover or cob cellulosic ethanol cases reviewed at 41.1 g CO_2 eq/MJ. The US EPA modeled the lowest WTW GHG emissions for stover ethanol at -27 g CO_2 eq/MJ. The inherent differences among the conversion technologies modeled and, with that, the generation and use of co-products is the primary reason for the wide range in GHG emissions reported for stover or cob cellulosic ethanol.

Benchmark Alignment for Comparison with DDCE Cellulosic Ethanol

The WTW GHG emission results of -17 g CO_2 eq/MJ for the DDCE 2010 case can be compared to the fifteen benchmark cases, as reported in literature. The DDCE 2010 case has the lowest WTW GHG emissions when compared to the gasoline, dry grind ethanol, and industry-reported cellulosic ethanol cases reviewed. Only the RFS2 stover ethanol case is better than DDCE in terms of WTW GHG emissions. However, it is dangerous to draw conclusions from comparisons of as-reported data from different data sources since differences among cases could be artifacts of differences in assumptions, background life cycle inventory data, and LCA methodologies. Therefore, for a fair comparison of different fuels, appropriate alignment of the cases must be completed. For the purposes of this study, alignment means to apply consistent life cycle inventory data to all input and output flows (as presented by the benchmarks) and to revise certain peripheral fuel system assumptions, without changing assumptions on the benchmark's core conversion process technology like yield and energy requirements. For example, if a benchmark case assumes the input of one kilowatt-hour (kWh) of electricity per kg of ethanol produced, the aligned case would still use this one kWh of electricity per kg of ethanol assumption, but would use the same electricity generation model that was used in the DDCE case, instead of the one from the benchmark case as reported.

However, it is impractical, if not impossible, to fully align all of the fifteen benchmark cases presented above, because many of these cases are not documented in sufficient transparency. In the special case of gasoline, it is appropriate to compare the DDCE case to the RFS2 conventional gasoline as reported, since this is the exact value which will be used for judging the GHG emission reduction capabilities of biofuels by the U.S. government. For the purposes of this paper, only one ethanol benchmark case is selected to align and compare with the DDCE 2010 case to demonstrate the affect of aligned assumptions on the final WTW results. The stover cellulosic ethanol case presented in the RFS2 study was selected to align for comparison with the DDCE 2010 case for the following reasons:

- The RFS2 stover ethanol case is the most challenging of all the data sources reviewed.
- The cases in RFS2 are documented in sufficient transparency to align them with the DDCE 2010 case.
- By using the RFS2 stover ethanol case, both benchmarks (conventional gasoline and cellulosic ethanol) come from the same data source.

The RFS2 stover ethanol case has by far the lowest WTW GHG emissions of the benchmarks reviewed, with a total of roughly -27 g CO_2 eq/MJ (a 129% reduction from conventional gasoline). Figure 7 shows the various contributors to the WTW GHG footprint for corn stover ethanol per the RFS2. Data for Figure 7 were obtained from docket EPA-HQ-OAR-2005-0161-3174[1].8.xls at www.regulations.gov [EPA, 2010].

The fuel production credit, which is the largest contributor, is primarily associated with the export of electricity produced from on-site biomass co-product streams. Domestic livestock and domestic land use change also contribute significantly to the WTW GHG footprint, while others such as tailpipe emissions and domestic rice methane are relatively small. The RFS2 claims that, in 2022, enzymatic corn stover ethanol biorefineries will export 3.6 kWh of electricity per gallon of ethanol produced. For each kWh of electricity exported, the RFS2 claims a displacement credit of 750 g of CO_2 eq. This emission factor for electricity is similar to the U.S.-average electrical grid of the years 2000-2010. The electricity export value could be seen as high when compared to GREET, which assumes an electricity export of merely 0.57 kWh per gallon of ethanol. Of course, as opposed to GREET which assumes a 2010 scenario, the RFS2 predicts a 2022 scenario, which would likely be more energy efficient, and therefore have more electricity available to export. It is important to note that greenhouse gas burdens associated with industrial chemicals used at the biorefinery, such as the ammonia that is used in the DDCE biorefinery, are not included in the RFS2 calculations.

To estimate the changes in the domestic agricultural sector and their associated emissions, the EPA used the Forestry and Agricultural Sector Optimization Model (FASOM). FASOM is a comprehensive forestry and agricultural sector model that tracks over 2,000 production possibilities for field crops, livestock, and biofuels for private lands in the contiguous United States. It accounts for changes in CO_2, methane, and N_2O from most agricultural activities and tracks carbon sequestration and carbon losses over time. Data generated from the FASOM model was combined with GREET lifecycle greenhouse gas emissions data to include upstream greenhouse gas emissions from farm inputs, [(US EPA, 2010)].

To estimate the domestic impacts of N_2O emissions from fertilizer application, the CENTURY and DAYCENT models were utilized. Both models simulate plant-soil systems and track fluxes of N_2O gasses. The model results for N_2O emissions from different crop and land use changes were combined with the FASOM model output to generate the overall domestic N_2O emissions, [(US EPA, 2010)].

Results from all of these models (FASOM, GREET, CENTURY and DAYCENT), which model both upstream greenhouse gas emissions from material and energy inputs to the farm as well as emissions from the farm (e.g. soil emissions/sequestration of CO_2 and N_2O and combustion of fuels on the farm) are included in the "Domestic Farm inputs and Fert N_2O" stacked bar.

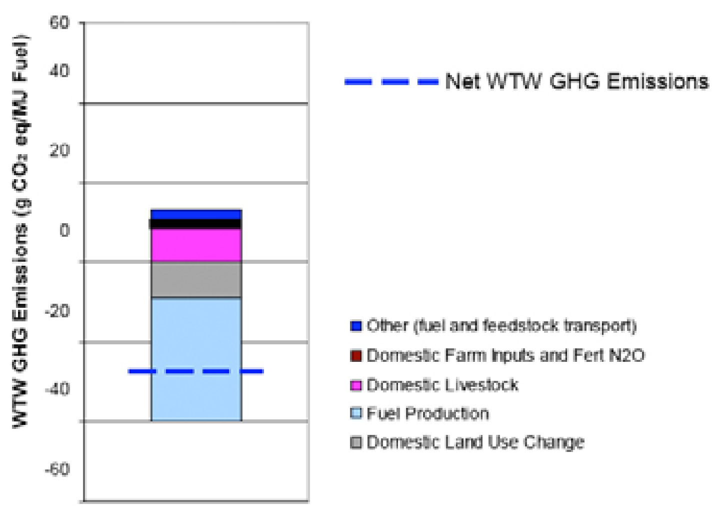

Figure 7: Detailed contributions to WTW GHG emissions for the stover ethanol in the RFS2.

The following inputs are included in the total, but are not listed in the legend since their WTW GHG contributions are not visible on the graph: tailpipe emissions and domestic rice methane.

Many of the contributors to the stover ethanol case in the RFS2 take into consideration indirect effects. These indirect effects, which can be seen in Figure 7 as the “boxed-in” contributors, are associated with how increases in biofuel production could have macroeconomic effects on other related value chains such as livestock and other agricultural products. The environmental burdens (or credits) associated with the increase or decrease in production in the “indirect” value chains (or product systems) are attributed to the biofuel supply chain.

For purposes of alignment with the DDCE 2010 case, the following modifications are made to the RFS2 case:

- Indirect effects are excluded (e.g. indirect land use change).
- Emission factors associated with inputs to the biorefinery are changed to be the same as the ones used for the DDCE 2010 case (e.g. electricity generation and biomass farming).
- The distance used for transport of corn stover from the farm to the biorefinery is aligned to be consistent with the distance used for the DDCE 2010 case (50 miles, one-way).
- GHG emissions associated with ethanol transportation and distribution from Farrell et al. are applied to the RFS2 stover ethanol case, to be consistent with the DDCE 2010 case.

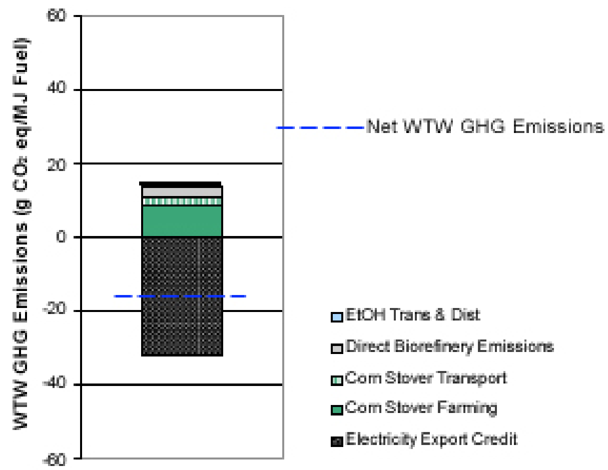

Figure 8: WTW GHG results for the aligned RFS2 stover cellulosic ethanol case.

Figure 8 shows the DDCE-aligned RFS2 results. There are five main contributors to the WTW GHG footprint for the stover cellulosic ethanol case; corn stover farming, transport of the stover to the biorefinery, electricity exports from the biorefinery, direct emissions at the biorefinery, and transportation and distribution of the ethanol fuel. The emission factors used for each of these contributors are the same as the emission factors used in the DDCE LCA results. The RFS2 cases no longer include GHG contributions associated with indirect effects. Direct effects (such as direct land use change, fertilizer use and soil emissions) are included within the scope of the DDCE LCA, and are incorporated into the emission factor for the stover farming.

After alignment, the RFS2 WTW GHG emissions increase from -27 g CO_2 eq/MJ to -17 g CO_2 eq/MJ. This increase can be explained by the removal of indirect effects. Since the majority of these indirect effects were credits, the removal of these contributions increased the WTW GHG footprint. The contributions directly associated with ethanol production at the biorefinery are in fact very similar before and after alignment-both contributing roughly -30 g CO_2 eq/MJ.

Comparison of the DDCE 2010 Case WTW GHG Results to the Aligned Benchmark

Shown in Figure 9 is the stover ethanol benchmark from the RFS2, aligned with the DDCE 2010 case LCA assumptions as described above, as well as the DDCE 2010 case and the original RFS2 conventional gasoline case. With alignment, the WTW GHG results for the RFS2 stover ethanol case and the DDCE 2010 case are both about -17 g CO_2 eq/MJ. According to the RFS2, a 60% reduction in WTW GHG emissions as compared with conventional gasoline is required to meet the "Cellulosic Biofuel" threshold. This reduction is indicated by the dashed line in 86. It can be seen from the graph that both the DDCE 2010 and RFS2 cases would meet this requirement since both show a WTW GHG emission reduction of about 118% from conventional gasoline.

For both cases, displacement credits associated with exports of co-products from the biorefinery have the largest relative contribution to the WTW GHG results. This aspect highlights the importance of these co-products to the overall sustainability of these biofuel production pathways.

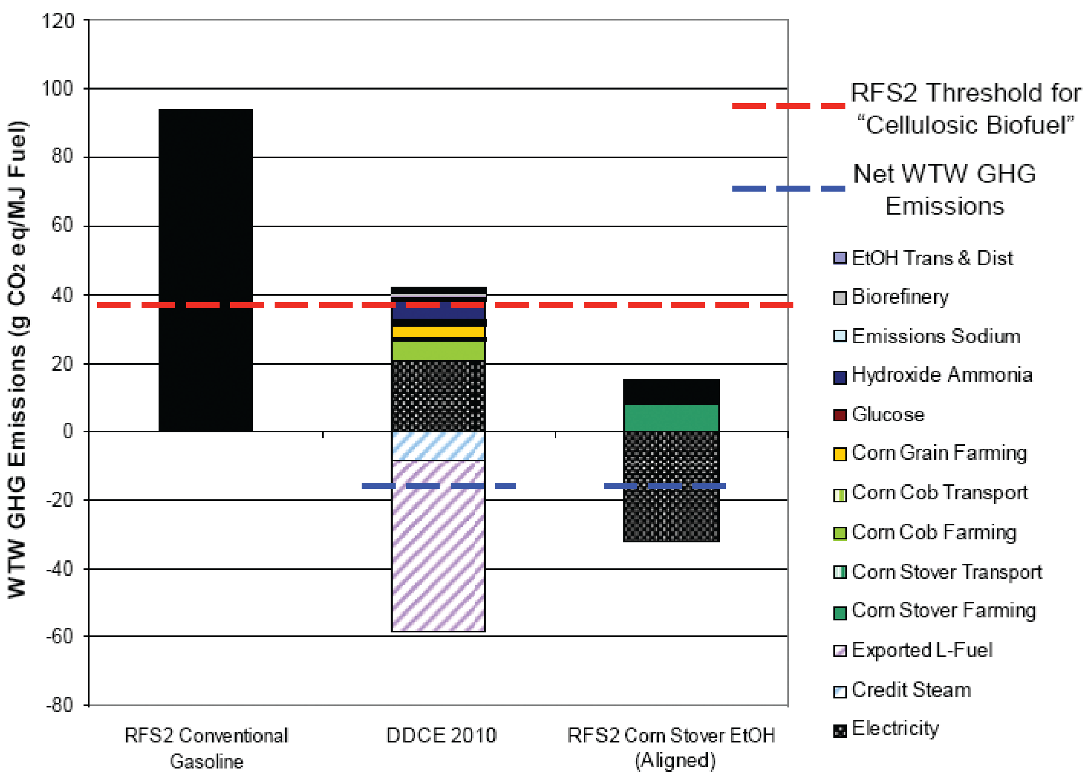

Figure 9: Comparison of the original RFS2 gasoline benchmark and the aligned RFS2 stover cellulosic ethanol benchmark with the DDCE 2010 case. The following inputs are included in the total but are not listed in the legend since their WTW GHG contributions are not visible on the graph: corn grain transport, sulfuric acid, enzymes and ammonium sulfate.

DDCE Participation in the Council on Sustainable Biomass Production (CSBP)

There are numerous considerations regarding the sustainability of a biofuel beyond GHG emissions. DDCE joined the Council on Sustainable Biomass Production (CSBP) in 2009 with the objectives to engage with stakeholders on the broad topic of sustainability and to participate in a collaborative effort to develop appropriate sustainability standards for biomass and bioenergy. As stated at www.cspb.org, "The Council on Sustainable Biomass Production (CSBP) is a multi-stakeholder organization established in 2007 to develop comprehensive voluntary sustainability standards for the production of biomass and its conversion to bioenergy." Current CSBP membership includes energy producers, biofuel producers, biomass producers, and non-governmental organizations. Representatives from government agencies, such as the Natural Resources Conservation Service, Forest Service, and the Agricultural Research Service within the U.S. Department of Agriculture (USDA) provide technical support for the CSBP.

A provisional standard is currently available for free download at www.csbp.org. The standard applies to non-food based feedstocks such as dedicated energy crops, crop residues, and native vegetation. A broad set of sustainability issues are addressed in the standard. The standard addresses climate change, biological diversity, water quantity and quality, soil quality, socio-economic well-being, and integrated resource management planning. During the 2010 growing season this standard was field tested by several biomass producers. DDCE is collaborating with the University of Tennessee Research Foundation, through its Genera Energy LLC, on feedstock production and cellulosic ethanol research. Genera Energy plans to participate in the field testing of the CSBP standard with its switchgrass production near Knoxville, TN.

Since joining CSBP, DDCE has taken a leadership role in the development of the GHG accounting methodology related to the sustainability principle on climate change. DDCE played a key role in facilitating a GHG accounting panel of experts. This panel met throughout the spring of 2010 in order to assist the CSBP in developing a GHG accounting methodology for biomass production. The resulting GHG accounting scheme was also field tested during the 2010 growing season.

Conclusions

The Renewable Fuel Standard-Energy Independence and Security Act has set the goal for the U.S. to produce 16 billion gallons of advanced cellulosic biofuels by 2022. This will require producing transportation fuel from multiple feedstocks, including herbaceous biomass such as switchgrass and crop residues such as corn stover, in an economically viable and sustainable manner. DDCE is making progress towards this goal by developing advanced biofuels from a diverse set of feedstocks including agricultural residues, dedicated energy crops, and eventually mixed feedstocks. The company takes a collaborative approach to create value from feedstock to fuel. This includes working with growers, researchers, environmental organizations, government, and industry. In the southeast U.S., DDCE has partnered with the University of Tennessee and Genera Energy LLC to establish a switchgrass supply chain and a demonstration-scale biorefinery. The company is also committed to working with growers to establish a corn stover supply chain and is conducting a comprehensive "Corn Stover Demo Harvest" in the Midwest that takes a scientifically rigorous approach to develop a cost-effective supply chain.

In the last 30 years, there has been a significant increase in corn grain yields due to gains in genetics, agronomic and management practices, and other improvements. This trend is expected to continue. With an increase in corn grain yields comes an increase in stover supply that will be critical to economically-viable commercial production.

Sustainable production is imperative. From the beginning of the cellulosic ethanol research program, there has been a strong internal driver to incorporate LCA and process development in order to guide decision-makers to the most sustainable solutions. Emerging sustainability standards and regulations now exist as external drivers for LCA. For the DDCE LCA, the DDCE 2010 case is compared to other potential transportation fuels in the market place on a well-to-wheel (WTW) basis. This includes upstream, on-site, and downstream processes through combustion in a vehicle. The WTW GHG emission results for the DDCE 2010 case are about the same as for the RFS2 corn stover ethanol case, once the cases are properly aligned. Compared to conventional gasoline, the DDCE 2010 case reduces GHG emissions by more than 100%. Hence the DDCE 2010 process would satisfy the 60% GHG savings requirement as defined by the RFS2.

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Chapter 19

Modeling Tools and Strategies for Developing Sustainable Feedstock Supplies

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Introduction

Assessing the feasibility of developing a strong biofuel industry around biomass feedstock requires a comprehensive evaluation of agronomic, environmental, social and economic factors. An encompassing assessment of the sustainability of biomass production as a feedstock for a developing bioenergy sector is complex due to the multiple dimensions involved in a complete evaluation of its social, technological and economic factors. The current trend of rising fossil fuel prices and observed climate change, and other adverse environmental and societal impacts of energy use make the exploration for more sustainable ways to use energy more important than ever (Kowalski et-al., 2009). According to Hill et-al. (2006) for biofuels derived from crops to be a viable alternative they should:

- provide a net energy gain,
- have environmental benefits,
- be economically competitive,
- be producible in large quantities and
- do not reduce food supplies.

Incorporating these multiple objectives into a single framework is challenging and requires tools and strategies to support decisions of stakeholders and policymakers. A fundamental component of such comprehensive assessments is the evaluation of the potential and attainable productivity of biofuel crops in different locations and growing conditions. Acquiring this type of information through field experimentation in herbaceous and woody crops, as well as in native forests and grasslands, is both expensive and time consuming, as it can take years of field trials to provide accurate estimates of potential production. An alternative science-based approach to estimate bioenergy crops productivity is to use biophysical or empirical simulation models. These models can provide estimates of average productivity and its inter-annual variability based on soil, weather, and bioenergy crops management databases that serve as inputs to the model.

To some extent the future of biofuels depends on technological breakthroughs which are difficult to predict, as technological advances might give an edge to particular renewable energy alternatives. Nonetheless, the current understanding is that transportation will continue to rely on liquid fuels in the coming decades and that a fraction of the liquid fuel supply will be based on oil, starch, and in particular ligno-cellulosic crops (Richard, 2010). Establishing a large scale biofuel industry requires a careful assessment of resources, logistic capabilities, and potential bottlenecks in the production chain before large investments are deployed in the field. Crops might play an important role supplying the feedstock for this demand of transportation fuels. Some of the more pressing questions are: Which crops to grow, where, and how to grow them? Also, what are the local and global consequences of growing crops for biofuel?

Approaching these questions can benefit greatly from modeling tools such as databases, computer simulation models and novel statistical approaches to integrate data and model inputs and outputs. Historically, crop research has focused on increasing seed yields of cereal and oilseed crops and much less attention has been given to improving yields of crops for total biomass. Recent interest in biomass crops has spurred research in developing annual grasses (e.g. sorghum), perennial rhizomatous grasses (e.g. switchgrass, Miscanthus, sugarcane, *Spartina*) and woody (e.g.willow, poplar) feedstocks that can be converted to liquid fuels using cellulose as the main substrate (Perlack et-al., 2005). In this chapter we will briefly review some of the candidate feedstocks for which our modeling efforts are relevant, describe data requirements (databases), biophysical models, and statistical tools to connect data and models and assess model performance.

Food-Based Biofuels

Currently, food crops are the main source of feedstock for biofuel. Grain maize is the main source of ethanol used mostly as an additive to conventional gasoline. However, it has been criticized mainly for competing with food production and having a low conversion efficiency to ethanol. This low conversion efficiency is in part a result of the large amounts of nitrogen (N) fertilizer needed to achieve high yields (Shapouri et al. 2002). Soybean oil is used for the production of biodiesel which seems to have a more favorable conversion efficiency and emissions reduction than ethanol production from maize grain (Hill et al., 2006). In addition to being food crops and having relatively low conversion efficiencies, the conversion of all U.S. maize grain and soybean oil into biofuels would only contribute to 12% and 6% of the U.S. gasoline and diesel demands, respectively, having even in that extreme case a low impact in the development of a significant alternative renewable energy (Hill et al., 2006).

Perennial Grasses

Perennial rhizomatous grasses have been put forward as dedicated biomass crops because of their many benefits which include high productivity, high water and nutrient use efficiency, nutrient recycling, long canopy duration and reduced agronomic inputs (e.g. fertilization and tillage) (Heaton et al., 2004b). These characteristics make them more suited for sustainable production of biomass than traditional crops grown for food production. Some of the species with great potential as biomass producers are: switchgrass (*Panicum virgatum*), *Miscanthus* × *giganteus*, and energycane (sugarcane bred for biomass production) (Somerville et al., 2010). Sugarcane is currently successfully used in Brazil for the production of ethanol (Nass et al., 2007) but there are concerns about its sustainability and the impact on deforestation of the Amazon and the Cerrado regions (Sawyer, 2008).

Woody Biomass

Worldwide 75% of current biofuel use is derived from wood and wood by-products (Food and Agriculture Organization (FAO), 2007). In many ways woody biomass is the oldest biofuel, having been burned directly or converted to charcoal for millennia. In more industrialized settings woody biomass is also utilized as a solid fuel for both on-site energy generation using from industrial waste (e.g. at sawmills and pulp plants) and in larger scale “cogeneration” electrical plants that use a mix of wood and fossil fuels.

The use of wood as a liquid biofuel feedstock is currently limited, yet wood has advantages as feedstock for cellulosic ethanol production due to its higher density than grass crops which can lead to greater transportation efficiency. Woody biofuels are also less sensitive to harvest time, potentially allowing a more stable fuel production that would buffer both the annual cycle of crop harvests and the inter-annual variability in crop yields. Worldwide there are large areas of marginal agricultural land that has been abandoned and allowed to regrow as forest. There are also large afforested areas where markets may favor liquid fuel production. Existing native and plantation forests could both be harvested directly for biofuel production and either regrown under their current land-use or converted to short-rotation coppice forestry. Coppice forestry is based on frequent harvesting and rapid regeneration by stump re-sprouting. Most research has focused on hybrid varieties of poplar (*Populus*) and willow (*Salix*) that have been selected for rapid regeneration. A survey of the scientific literature across all climates and clones suggests that poplar and willow can deliver mean annual yields in the range of 7.5 and 8.9 Mg ha^{-1} respectively with maximum reported annual yields of 40 and 38 Mg ha^{-1} respectively (Wang and Dietze *unpublished data*).

Biophysical Models

Computer simulation models play a critical role in the evaluation of potential biofuel crops. Unlike first generation biofuel crops, such as maize and soybean, which have been planted over large areas for many decades, most second generation crops have only been evaluated in a handful of field trials and in a comparatively short time span. This leads to a number of questions about how different crops will yield in different areas and what the long-term impacts on ecosystem services will be that can only be answered through the use of models.

Process-based simulation models are a cost-effective tool to assess the productivity and environmental benefit or impact of biofuel, forage, grain, and other mixed production systems. The successful application of these models requires a correct parameterization of crop, soil, and landscape properties, as well as a well defined initialization procedure. The quantification of the uncertainties associated with model-based extrapolation can be complex, and requires careful attention and interpretation. Models vary in the detail with which crop, soil and landscape-scale processes are treated and in the fundamental principles driving mass and energy flux in the system. These differences are briefly discussed for biomass accretion and nutrient cycling in the soil.

Biomass Accretion

There are two approaches used to simulate crop processes in cropping and ecosystem simulation models. Some modeling systems use a generic vegetation model (e.g. APEX-EPIC, C-Farm, CropSyst, DayCent, Ecosys, WIMOVAC), while others use a species-based model (e.g. APSIM, DSSAT). In the former a common framework is used to simulate all processes and different species or cultivars are represented by variations in the parameters. This confers substantial advantages in terms of algorithm development and re-use of code at run time, while facilitating the data collection for calibration and testing of the model. In the species-based approach, a different model is developed for each species and the parameters adjusted for each cultivar using so-called genetic coefficients.

Another dimension in which vegetation models vary is in the treatment of plant and population properties, with some models simulating growth and development of an individual plant (some species in the APSIM and DSSAT models) and others simulating these processes on a unit-area basis (most models). Most models mentioned in this chapter use a “top-down” approach for modeling crop processes, which means that the underlying mechanisms are modeled only one or two levels of resolution “below” the response variable of interest. The appropriateness of each approach is more related to the objective in the model application than with the approach itself. Large-scale or country-wide simulations that respond to climate and soil variables are likely more robust based on generic crop models (e.g. applications of EPIC in the Conservation Effects Assessment Project) while system biology studies may require a greater level of de-aggregation of physiological processes. The number of parameters of a model grows dramatically as the level of resolution increase, making the calibration difficult.

The algorithms to simulate growth vary for different models. Some models use a detailed, multi-layered canopy approach in which photosynthesis is simulated at multiple heights through the plant canopy on a sub-daily basis (typically hourly) and aggregated for the entire canopy (e.g. WIMOVAC). Some models fully couple photosynthesis, transpiration, and the other component of the energy balance (Grant, 1995; Kremer et al., 2008), while others simulate these processes somewhat independently (Sadras et al., 2005).

One approach that has been used in models to predict biomass production (Clifton-Brown et al., 2004) to simulate and analyze crop growth is to express biomass accumulation as the product of a resource captured and the efficiency with which it is converted to biomass. When the resources are radiation, water, or nutrients in general, the expression can be formalized as follows:

$$B = RUE \times fis \times St$$

$$B = TUE \times fis \times ET$$

$$B = XnUE \times Xn$$

where B is biomass produced (g m^{-2}), RUE is the radiation-use efficiency which is a crop/cultivar specific parameter (g MJ^{-1}), f_{is} is the fraction of the incident solar radiation intercepted by the canopy, S_t is total incoming solar radiation (MJ m^{-2}) in a given time interval, TUE is transpiration use efficiency (g B kg^{-1} H_2O), ET is the evapotranspiration, f_{is} is the fraction of ET which is crop transpiration (kg H_2O m^{-2}), and X_nUE is the use efficiency (kg B kg^{-1} X_n) of nutrient X_n (kg m^{-2}). The subject has been discussed and reviewed extensively for the radiation-based approach (Monteith, 1977; Sinclair and Muchow, 1999; Stöckle and Kemanian, 2009) and the transpiration based approach (Tanner, 1981; Tanner and Sinclair, 1983; Kemanian et al., 2005). As opposed to the original crop growth analysis proposed by Watson (1952), this framework targets the canopy instead of a representative leaf area section, and offers a robust framework for hypothesis-driven research (Sadras et al., 2005). Most simulation models using this "big leaf" approach for simulating growth apply the radiation-based approach (e.g. EPIC) while a more sophisticated dual approach is used in APSIM, C-Farm, and CropSyst in which the minimum of two estimations of growth is used, one based on transpiration and the other based on radiation interception. Stöckle and Kemanian (2009) have shown that the transpiration based approach is robust in most circumstances, being applicable without any calibration in different environments provided that transpiration is correctly simulated.

The alternative to the "efficiency" based models are enzyme-kinetic models that calculate photosynthesis and transpiration based on a semi-mechanistic understanding of the effects of light, CO2, temperature, humidity, and nitrogen on leaf-level photosynthetic rates and stomatal conductance (Farqhuar et al 1980, Collatz et al 1992, Leuning 1995). Multi-layered coupled photosynthesis and transpiration models as those used in the Ecosys model (Grant, 1995), the model WIMOVAC (Humphries and Long, 1995) and that presented by Kremer et al. (2008). A recent study suggested that these multi-layered models perform better than efficiency based models, especially at short time intervals (Alton and Bodin, 2010).

Soil Carbon and Nutrient Cycling

One of the advantages of developing a bioenergy industry is the possibility of producing fuel while reducing the GHG emissions through direct reduction in emission and by offsetting fossil fuel usage. Therefore, simulating the components of the global warming potential of feedstock production systems is critical for a comprehensive assessment of the benefits and impact of bioenergy cropping systems.

Soil carbon cycling is an essential component of comprehensive agricultural and ecological models. Different approaches for simulation the soil carbon balance and its linkages with other nutrients have been discussed extensively elsewhere (Stewart et al., 2008) and a brief summary presented in Kemanian and Stöckle (2010) is used here to present examples of different models. Soil organic carbon is composed of an array of organo-mineral complexes whose turnover rates vary along a continuum from labile or fast turnover fractions to highly recalcitrant fractions. Representing this continuum has been a challenge for soil scientists and biological systems modelers. Early models of soil carbon (Cs) cycling consisted of one Cs pool and one residue pool (Henin and Dupuis, 1945). As basic knowledge on Cs dynamics expanded, new multi-compartment models represented explicitly the microbial pool and separated residues and Cs in several pools (Jenkinson and Rayner, 1977; McGill et al., 1981; Paul and N.G. Juma, 1981; Parton et al., 1988; Verberne et al., 1990; Coleman and Jenkinson, 2005). Other models represented mathematically the Cs turnover rate continuum (Ågren and Bosatta, 1987).

Multi-compartment models separate Cs in pools with different turnover rates. Each pool decomposes due to microbial attack at different rates assumed to depend on the chemical recalcitrance and physical protection of the organic matter fraction: the higher the recalcitrance and physical protection the lower the turnover rate. The carbon lost by a pool can have as destiny the atmosphere (CO_2 from microbial respiration), the microbial biomass pool, or another carbon pool through chemical reactions or physical aggregation. The transfer of carbon from one pool to another is accompanied by fluxes of other elements such as nitrogen and phosphorus. Six et-al. (2002) concluded after an extensive literature review that the success at matching measurable and modelable Cs pools has been minimal. Multi-compartment models such as the Century model (Parton et al., 1988) and Daycent (Del Grosso et al., 2005) have been widely used for assessing Cs evolution and variations of multi-compartment models have been incorporated in comprehensive cropping systems models (e.g. EPIC, Izaurralde et al., 2006; CropSyst, Stockle et al., 2003).

Another approach to accommodate the continuum of turnover rates of soil organic matter is to simulate a single pool of soil organic matter whose turnover rate varies with the size of the carbon pool. This approach is followed in the C-Farm model (Kemanian and Stöckle, 2010). In addition, the size of the organic carbon pool in relation to an assumed maximum carbon carrying capacity or carbon saturation level (Hassink and Whitmore, 1997; Six et al., 2002; Stewart et al., 2008). While this approach requires further testing the number of core parameters of the model is lower than that of multi-compartment models, the spin-up period for equilibrating organic matters pools is not needed, and the interpretation of outputs is straightforward.

Nitrous Oxide Emissions

The high temporal and spatial variability of nitrous oxide emissions from soil under agricultural management makes measurements at regional or national scales impractical (Giltrap et al., 2010). For this reason, there is an opportunity to use process-based models to assess nitrous oxide which are important components of improving the efficiency of cropping systems (minimizing N losses) and reducing their impact on greenhouse gases emissions. However, the variability of N_2O emissions makes modeling this process difficult in various ways. First, it requires an accurate spatial and temporal simulation of nitrate and oxygen content and heterotrophic respiration in soil. Second, there is large spatial variation in this process and the correct "average" condition for a field can be difficult to predict for different landscapes.

Nonetheless, a number of applications of simulation models to estimate nitrous oxide emission rates are presented in the literature. For example, Del Grosso et al. (2005) used the DAYCENT ecosystem model to estimate the nitrous oxide emissions for the main crops in the U.S. arguing that the combination of a process-based model that accounts for cropping system, soil type, climate and tillage and provide more informed decisions than a simple methodology which only considers an emission factor based on N applications. In the emission factor model, nitrous oxide emissions from cropping systems are mainly driven by fertilization events and there is no consideration to other processes that affect emissions such as fertilizer timing or application method. These authors suggest that converting the cropland area to no tillage can reduce, at the national scale, 20 percent of agricultural emissions of this greenhouse gas.

Another model that has been frequently used for simulation of nitrous oxide emissions is DNDC (Denitrification-Decomposition) (Li et al., 1992). Giltrap et al. (2010) reviewed the status of the model and the ability of the model to simulate GHG emissions under different ecosystems. They recognized that the model is a useful tool for modeling the environmental impact of agricultural practices and for improving our understanding of the underlying processes. Hsieh et al. (2005) used DNDC to simulate N_2O emissions from a fertilized humid grassland in Ireland and found that major emission events followed nitrogen applications and heavy rainfall. The measured annual emissions were 11.6 kg N ha^{-1} and the modeled prediction 15.4 kg N ha^{-1}, showing that the modeled captured the major emission events reasonably well. This study also indicated that emissions are predicted to increase up to 22.4 kg N ha^{-1} under the future climate scenario of the Hadley Center model output, holding other factors constant. Although this model was used here in a grazing system (not a biomass crop) it shows how biophysical models can be applied to better assess the long-term sustainability of cropping systems. Clearly, biomass crops that reduce or minimize external inputs such as N fertilizer will be both energetically more favorable as well as more likely to cause a smaller impact on future climate. In addition, reduced use of N fertilizer will make biomass crops more competitive economically with other alternative sources of energy.

Sustainability of Biomass Production

There have been several efforts at developing and testing biophysical models with the objective of simulating *M.* × *giganteus* and *P. virgatum* biomass production and evaluating the sustainability and economic feasibility of bioenergy crops. A recent study by Jain et al. (2010) integrated a biogeochemical model, a simple crop model (based on RUE and light interception) and an economic analysis to evaluate the feasibility and competitiveness of biomass crops *M.* × *giganteus* and *P. virgatum* with alternative row crops building upon the work of Khanna et al. (2008). In terms of productivity their model estimated that yields of *M.* × *giganteus* are largely driven by temperature and radiation in the Midwest with maximum peak yields of 7-48 Mg ha^{-1}. For switchgrass a similar pattern was found but average yields were about 3 times lower (10-16 Mg ha^{-1}-maximum of 40 Mg^{-1}). Under a low-cost scenario, *M.* × *giganteus* biomass was estimated to have a farm-gate cost between 34 and 80 \$ Mg^{-1} (58-131 under the high-cost scenario). The combination of predicted yields and economic considerations identified Missouri as a more competitive state for biomass crops.

A similar modeling approach was used by Heaton et al. (2004a) where a model based on RUE previously calibrated for Ireland (Clifton-brown et al., 2000) was used to predict potential biomass production for *M.* × *giganteus* in Illinois. As in the model used by Jain et al. (2010), these results are primarily driven by radiation and temperature and they suggested peak average yields between 27-44 Mg ha^{-1} for Illinois.

A different approach taken by Wullschleger et al. (2010) developed a database of *P. virgatum* productivity based on 39 field trials and estimated potential harvestable biomass based on a regression approach with maximum biomass yields projected in a corridor westward from the mid-Atlantic coast region to Kansas and Oklahoma. As opposed to Jain et al. (2010) who concentrated on the *P. virgatum* cultivar Cave-in-Rock, they evaluated a variety of lowland (southern and wetter habitats) and upland (mid and northern latitudes and drier habitats) *P. virgatum* cultivars.

Models that contain biogeochemical routines are suited for evaluating the potential for soil carbon sequestration and the fate of agricultural nitrogen. A subset of these (e.g. Century, DayCENT, CropSyst, C-Farm) are further able to evaluate trace gas emissions. As an example, Davis et al. (2009), using DayCent, evaluated the greenhouse gas emissions of *M. × giganteus*, corn, *P. virgatum* and native mixed species prairie. All of the perennial crops had lower net greenhouse gas emissions than corn. These authors found *M. × giganteus* to be a sink for GHG emissions in contrast to the net positive GHG emissions from corn, *P. virgatum* and mixed prairie. *M. × giganteus* also had a higher potential for building soil organic carbon than the other feedstocks. In addition, this study suggested that *M. × giganteus* is capable of fixing substantial amounts of atmospheric N, since this was a requirement for balancing the N budget in the DayCent models and potential N-fixing activity was measured in the rhizomes and rhizosphere of *M. × giganteus* in Illinois (Davis et al., 2009). Further research is needed to confirm the potential of biomass crops with substantial N fixing potential that can reduce the need for external fertilizer inputs.

One of the main concerns of the use of highly productive grasses for biofuel production is their accompanied increase in water use and its effects on the hydrologic cycle. Models that have hydrology sub-models are able to address questions about the potential impacts of biofuel crops on stream flow and nutrient run-off. Vanloocke et al. (2010) used Agro-IBIS to study the potential impact of growing M. × giganteus in the Midwestern U.S. Their simulations suggested that if *M. × giganteus* were to be grown in 10% of the land as suggested by Heaton et al. (2008) little impact will occur to the hydrological cycle. Only when simulating a replacement of current vegetation with 50% (or greater) of *M. × giganteus* noticeable changes were detected in the overall hydrological cycle of the Midwestern U.S. with an increase of 40-160 mm per year in total evapotranspiration. This higher ET under *M. × giganteus* is mainly a result of the longer growing season of *M. × giganteus* compared to annual crops such as corn and soybean. However, this small impact on the hydrological cycle can have major effects on climate as the area devoted to highly productive biomass crops is expanded.

Models that have a land surface model are designed to capture the full energy and mass balance of the ecosystem at a fast time scale. This enables these models to be coupled with atmospheric models and thus address questions about the potential atmospheric feedbacks that could result from large-scale biofuel crop deployment. These feedbacks could include changes in air temperature and precipitation patterns. This is an active area of research and integrated models capable of producing robust forecasts are under development.

The Ecosystem Demography model (ED) is a physiologically-based plant growth model that was originally formulated to model forest ecosystem dynamics (Medvigy et al., 2009). ED is being applied to evaluate woody biofuel crops such as hybrid poplar as well as to evaluate the potential use of native forest and other novel tree species (Wang and Dietze, *in prep*). ED has also been reformulated to represent perennial grasses and in particular is leveraging its representation of community dynamics to address the use of native grasslands and polycultures.

Databases

There are a number of datasets that play a critical role as drivers of biofuel crop models as well as in their parameterization, calibration, and validation. Below we highlight some of these resources. For drivers we focus on the availability of data related to weather and soils, while for model testing we focus on databases that compile site-level yield data and species-level ecophysiological data. There are a number of other resources that are commonly used to test plant and ecosystem models in other contexts but which are not yet utilized extensively by biofuel modelers, generally because there is a limitation of data due to the small spatial scales and short histories for many second generation crops. These include remote sensing, eddy-covariance, and USDA county-level data on crop and forest production. As research matures, and biofuel crops are planted on larger scales, modelers are encouraged to look more broadly to these and other emerging data sets.

Biofuel Trait and Yield Database

The Biofuel Ecophysiological Trait and Yield Database (BETY-db, http://ebi-forecast.igb.uiuc.edu/) was created in order to compile the available field data about proposed "second generation" biofuel crops. There are two categories of data currently represented in the database: information on the productivity of different species and cultivars at different sites and "trait" information on the characteristics of different species. These data are also associated with detailed information on treatments that have been applied (e.g. different levels of N addition) and different management operations (e.g. dates of planting and harvest). Both types of data can be queried in a number of ways, for example by species or by location using a Google map interface. In the context of modeling biofuel crops the trait database is intended primarily to produce initial estimates for model parameters. Existing utilities in BETY-db have been designed to estimate the probability distributions of each trait based on a meta-analytical model (LeBauer et al *in prep*). Yield data across many sites are also critical for model validation. Beyond model applications, the database is intended to promote data sharing and cross-site syntheses. For example, a meta-analysis of the switchgrass data from this database suggested that perennial grasses grown with legumes may have comparable yields and lower inputs than fertilized monocultures (Wang et al., 2010). Similarly, analyses of trait data may be useful for pre-screening potential species or cultivars based on comparison to the traits of current crops. Finally, the spatial query in the database is intended to allow land managers and extension agents evaluate what yields have actually been achieved in a given region by different crops.

Meteorological Data

A crucial component needed for evaluating which crops to grow for bioenergy and where and how to grow them is the weather and climate data for a particular region. In order to make regional-scale projections of biofuel crops all models require estimates of climate that reflect the differences among regions. Furthermore, most models are dynamic and thus need detailed weather data with high temporal and spatial resolution. The critical variables are precipitation, temperature, yet most models also require or render better results when humidity, atmospheric pressure, and wind speed are also available. Carbon dioxide concentration is also needed by enzyme-kinetic photosynthesis models. Land surface sub-models, which explicitly calculate the overall energy balance, will typically need to be able to resolve the sub-daily cycles of these variables. A number of models that run at hourly time intervals are capable of using daily meteorological records and simulate hourly conditions based on typical patterns of temperature and radiation daily fluctuations (Campbell and Norman, 1998). The hourly fluctuations of precipitation, wind speed and relative humidity are harder to simulate realistically based on daily summaries and these are often considered uniform or simulated stochastically using appropriate algorithms.

Another variable of interest is solar radiation, with models varying from those that just require an overall light level to those that need radiation broken up by different spectral bands (e.g. photosynthetically active radiation, near infra-red, and long-wave infra-red) or into direct and diffuse radiation versus indirect or diffuse radiation. Since meteorological stations are not laid out on a well-defined grid, modelers rely on data products that have been interpolated either statistically or, more often, via data assimilation in atmospheric models. Weather databases can generally be divided by their spatial and temporal resolution. Below we will describe some of the data products available at a state-by-state level, nationwide, and globally.

Statewide

The Iowa Environmental Mesonet (http://mesonet.agron.iastate.edu/) is an example of weather data that are synthesized from 7 different observing networks and represents an outstanding effort at integrating meteorological variables for different purposes. Hourly (or even every minute) data from ASOS (Automated Surface Observing Systems) and AWOS (Automated Weather Observing System) can be obtained from the Iowa Environmental Mesonet from a convenient interface (http://mesonet.agron.iastate.edu/request/asos/1min.phtml). For Illinois, there is another weather database managed by the Illinois State Water Survey (http://www.isws.illinois.edu/data/climatedb/ and http://www.isws.illinois.edu/warm/datatype.asp). These weather databases are suitable for use in most computer simulation models that typically run at daily or hourly time intervals.

U.S. Nationwide

At the national scale there are a number of data products available, however there is a strong trade-off among data products in terms of spatial vs. temporal resolution. The PRISM database (Parameter-elevation Regressions on Independent Slopes Model) has the greatest spatial resolution (a grid of 800-m) but has the coarsest temporal resolution (monthly). At the other extreme, NARR, the product with the highest temporal resolution (3 hrs) also has the coarsest spatial resolution (32-km). This trade-off in part reflects the fact that there is only a finite amount of information in the network of weather stations. It also reflects a switch between statistical and atmospheric models, the latter possessing computational constraints in reducing their spatial resolution but inherently operating at high temporal resolution.

PRISM-http://www.prism.oregonstate.edu/

PRISM uses meteorological station "point" data and a digital elevation model (DEM) to generate fine-scale (800m) gridded estimates of climate parameters on a month-by-month basis (Daly et al., 1994). PRISM is designed specifically to capture the small-scale topographic variability in climate, using a DEM and a windowing technique to group stations onto individual topographic facets. PRISM develops a weighted precipitation/elevation (P/E) regression function to predict precipitation at the elevation of each cell using data from nearby stations, with greater weight given to stations with location, elevation, and topographic positioning (e.g. aspect) similar to that of the grid cell. In a model comparison, PRISM exhibited superior performance to various methods of kriging, and has been successfully applied to the entire United States (Daly et al. 1994).

Daymet-http://www.daymet.org

Daymet is a semi-mechanistic statistical model conceptually similar to PRISM that generates daily surfaces of seven variables: daily mean, minimum, and maximum temperature, precipitation, humidity, radiation, and day length (Thornton and Running, 1999). The Daymet data set spans 1980-2003 and has a 1km resolution. Data are downloadable either as time-series at point locations or climatological maps. Daily radiation is generated based on algorithms that produce adequate monthly averages but that show less variation than station or satellite based daily radiation measurements.

NARR-http://nomads.ncdc.noaa.gov/

The North American Regional Reanalysis (NARR) is an atmospheric-model data-assimilation product from NOAA that covers all of North America and parts of the Atlantic Ocean, Pacific Ocean, Central America and the Eurasian arctic. Historical climate data that has been assimilated through atmospheric models is typically referred to as "reanalysis" products and a number of other reanalysis data sets are available on a global scale and will be discussed below. The NARR has a spatial resolution of approximately 32 km and a 3 hour temporal resolution and spans the time period from 1979 to the present. Because the NARR is processed through an atmospheric model there are a large number of output variables available that include both the state of the land surface and the atmosphere.

Global

At a global scale there is a diversity of different products available. In terms of raw weather station data and statistically interpolated products we briefly describe three sources: CRU, LocClim, and Worldclim. The CRU dataset is a product of the Climate Research Unit at the University of East Anglia (http://www.cru.uea.ac.uk/cru/data/availability/) which provides gridded surface temperature datasets over the past 150 years and has played a critical role in diagnosing spatial patterns of climate change. LocClim (http://www.fao.org/sd/locclim/srv/locclim.home) is a UN FAO tool used to estimate eight different climate variables: Average, minimum, and maximum temperatures, precipitation, light, humidity, wind speed, and potential evapotranspiration. Estimates are available at monthly, 10-day, and daily time intervals. The grid resolution in LocClim is not predetermined; the utility performs interpolation on-the-fly based on latitude, longitude, and elevation. The underlying dataset in LocClim is the FAOCLIM data set of 28800 met stations. WorldClim is a high-resolution (1km) global gridded data set of average climate for 1950-2000 (Hijmans et al., 2005) for 23 climate variables: mean, minimum, and maximum temperature, precipitation, and 19 bioclimatic indicators. The same algorithm has also been used to produce climate maps for IPCC climate change scenarios (2020, 2050, and 2080 under the A2A and B2A emissions scenarios) and for the mid-Holocene (6000BP), last glacial maximum (21,000BP), and last interglacial (130,000BP).

In addition to statistically gridded data sets, there are also a few key global “reanalysis” data sets. The most commonly used are the ECMWF (European Centre for Medium-Range Weather Forcasts) “ERA-40” (Uppala et al 2005, http://data.ecmwf.int/data/) and the NCEP (National Center for Environmental Prediction) “Reanalysis 2” (Kanamitsu et al. (2002), http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html). Both these data products have a 2.5 degree resolution and a 6 hour time step. The ERA-40 covers 1957-2001 with a newer ERA-Interim product covering 1989-2009 while the NCEP covers 1979-2008 with a newer “Twentieth Century” product covering 1871-2008 (Compo et al., 2010). There is also a reanalysis from the Princeton Land Surface Hydrology Research Group (LSHRG, Sheffield et al 2006)) that attempts to correct biases in the NCEP reanalysis based on a number of satellite and surface data compilations, such as CRU, and which appears to have the least biased radiation (Ricciuto pers com). This data set is available at 3-hr and monthly time steps and a 1.0 degree resolution.

Soil Databases

Another important component for estimating biomass productivity and ecosystem services of biomass production are soil characteristics. For a specific location, soil properties can be measured directly, but soil sampling and analysis is typically time consuming and costly; and for large regions prohibitive. Assessing sustainability of biomass production at a regional level requires incorporating soil information and here we describe the main sources of soil data on a national and global scale.

SSURGO

The Soil Survey Geographic (SSURGO) database is available for selected counties and areas throughout the United States and its territories. In SSURGO mapping scales generally range from 1:12,000 to 1:63,360 and this is the most detailed level of soil mapping done by the Natural Resources Conservation Service (NRCS). Maps are derived from point observation and conceptual models of soil formation (Soil Survey Staff, 2009). This database is linked to a National Soil Information System (NASIS) attribute database which provides the relative extent of the component soils and their properties for each map unit. The SSURGO map units consist of 1 to 3 components each (Figure 1). The database consists of two main components, a GIS polygon map of different soil map units and a set of attribute tables that describe different soil properties for those map units, often with attributes varying with depth. For the purpose of biomass production modeling, examples of information that can be queried from the database are: soil texture, soil organic matter, pH, available water capacity, soil reaction, and electrical conductivity.

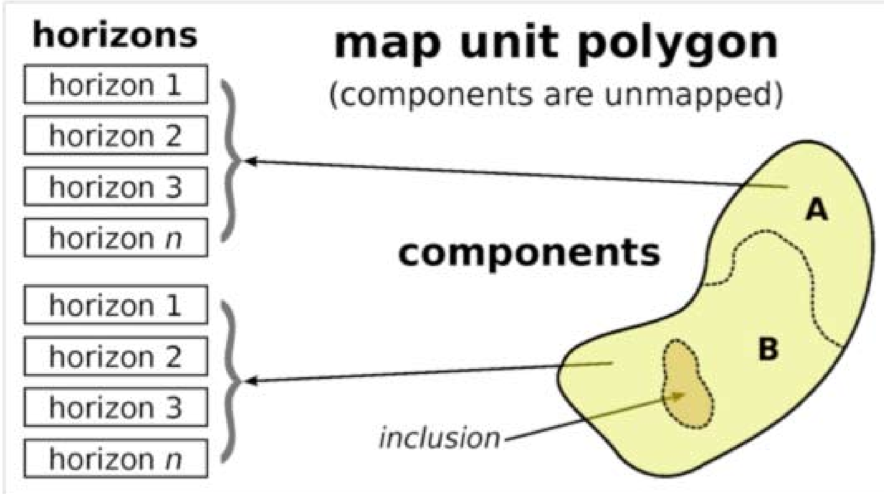

Figure 1: Structural diagram of USDA-NRCS digital soil survey data. Spatial data repre-sent map unit polygons, usually consisting of multiple un-mapped components. The complex hierarchy of map unit ⟶ component ⟶ horizon data is encoded through a series of 1-to-many tabular relationships. Reproduced with permission from Beaudette, 2008.

The database provides basic information from where the soil profile input required for the model has to be derived. This is not a simple task as the input, for instance the layering of the soil profile, is more detailed than the original information and the correlation between variables has to be conserved. Soil organic matter estimates for the profile and the distribution with depth has to be scrutinized carefully as using the raw data carelessly will most likely result in poor outputs. Pedotransfer functions are customarily used to predict soil properties from basic textural data (e.g. Saxton and Rawls, 2006).

STATSGO2

For larger scale simulations (i.e. national scale) the U.S. General Soil Map, known as STATSGO2, consists of general soil association units, which is generalized soil information interpreted from detailed soil survey data and inferred from natural conditions where soil information is absent. It was developed by the National Cooperative Soil Survey and it consists of a broad-based inventory of soils and non-soil areas that occur in a repeatable pattern on the landscape and that can be cartographically shown at the approximate scale of 1:250,000.

The design of STATSGO is very similar to SURGO. The tabular data contain estimated data on the physical and chemical soil properties, soil interpretations, and static and dynamic metadata. Most tabular data exist in the database as a range of soil properties, depicting the range for the geographic extent of the map unit. In addition to low and high values for most data, a representative value is also included for these soil properties. This indicates that working at this scale there is a source of uncertainty that has to be taken into account, since the magnitude of the variability in soil variables of interest can be substantial.

Using the Soil Databases

The simplest way to access the data from the soil databases is the Web Soil Survey (http://websoilsurvey.nrcs.usda.gov/app/) which is an interactive web application that allows access to maps and soil characteristics and attributes.

Data for soil survey contains a tabular and spatial component. The spatial component is a vector file (ESRI shape file) with the “map unit” key as the main information. The tabular data contains four general classes of information: 1) chemical and physical data (pH, CEC, particle size distribution, etc.), 2) morphologic data (horizonation, etc.), 3) taxonomic data and 4) interpretations for land use and engineering. The vast number of decisions made based on soil surveys reflect the inherent value of this information (Beaudette, 2008).

An example application of the STATSGO2 database is the rasterized calculation of available water capacity, using a 32 by 32 km grid over the conterminous U.S. (Figure 2). The available water capacity of a soil is a crucial variable in estimating the potential biomass productivity of different regions.

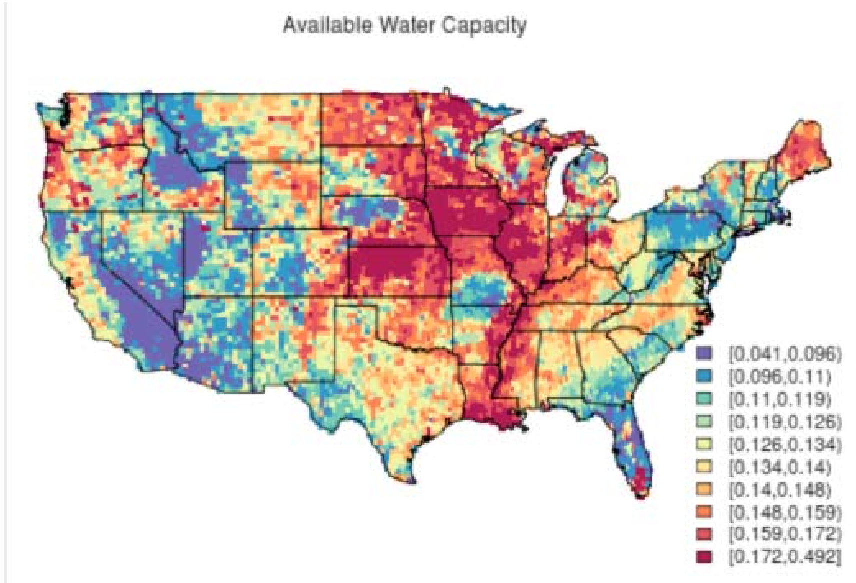

Figure 2: Available water capacity (proportion) based on a 32 by 32km grid over the conterminous U.S. This map was produced by rasterizing the STATSGO2 and performing a weighted average over different horizon depths and the proportionate contribution of soil components.

Global Scale Soils Data

At a global scale it is difficult to compile all the different national soils maps that use different resolutions, classifications, and sampling methods. Fortunately the U.N. Food and Agriculture Organization does provide a global-scale soils map (http://www.fao.org/nr/land/soils/en/). This map is fairly coarse in resolution, but does provide information on soil texture and soil depth that is required to drive the soil moisture sub-models of most vegetation models. To our knowledge there is not a global scale map of soil carbon stores, soil nutrients, or other soil biogeochemical rates or properties, though model-based estimates of some of these do exist as part of climate change research (IPCC, http://www.ipcc-data.org/).

Land Use Databases

Other databases of importance are those providing information about land cover. This is useful when performing detailed landscape-level assessments of the impact of crops, trees or other large scale practices. One example is the national land cover database from the Multi-Resolution Land Characteristics Consortium (MRLC, www.mrlc.gov). This is available for the 50 U.S. states and it provides classification of land on a 30 by 30m resolution that can be used to plan where biomass crops might be deployed at a more detailed level. One disadvantage is that the latest version is from 2001 and many changes might have occurred to land use since then. Examples of land classification are: open water, grassland, cropland, mixed forest, etc. Another useful database is the USDA-NASS Cropland Data Layer (CDL) which contains crop specific information. The CDL Program annually focuses on producing digital categorized geo-referenced output products using imagery from the Resourcesat-1 AWIFS and the Landsat 5 TM satellites (http://www.nass.usda.gov/research/Cropland/SARS1a.htm). At a global scale the MODIS satellites provide an annual 500m land cover estimate from 2001 to the present (http://modis-land.gsfc.nasa.gov/). These maps provide up-to-date land cover information and can be useful for both modeling outside the U.S. and for assessing land cover change.

Model Assessment

Models are only as good as the data that go into building them and thus model assessment is a critical activity. We can conceptually break assessment down into two phases, training and testing. Activities in the training phase are focused on using data to estimate model parameters while the testing phase is focused on confronting the model with independent data.

There are a number of different approaches used during the training phase and we will conceptually break them down into what we call parameterization and calibration, though these labels are not universally used and not all techniques fit nicely into these definitions. By parameterization we refer to the process of setting model parameters where there is a direct mapping of field or experimental data to a specific parameter or set of parameters. This definition is distinct from usages found in other fields, such as atmospheric science, where most model parameters are known physical constants and parameterization instead refers to the choice of a functional form for modeling a process statistically rather than mechanistically. Examples of this could range from 1:1 mappings between parameters and data, such as the C:N ratio of a tissue or the specific leaf area of a leaf, to parameters that are fit statistically but still have a direct link to data, such as the estimation of photosynthetic parameters from an A/Ci curve or an exponential decay rate from a litter bag experiment. Parameterization has traditionally occurred by reference to the scientific literature or using expert opinion to fix parameter values. In the past it has often been difficult for the non-expert to see where specific model parameters have come from, which has been known to engender distrust of models. Some of the disadvantages of traditional parameterization are that error distributions associated with parameters have rarely been reported and there has been a bit of subjectivity in choices about why parameter values from one study were chosen over another. Newer meta-analytical techniques aim to get around this because they allow parameters to be constrained based on the combined weight of multiple studies and provide a formal estimate of parameter uncertainty that can be used for error propagation (LeBauer et al in prep).

In contrast to parameterization, where there is a direct mapping between data and parameters, we use the term calibration to deal with the situation where the connection between data and parameters is often less direct but more holistic. In general during calibration we are comparing a model output to data, for example the comparison between predicted and observed yield. Yield is not determined by a single parameter but is influenced by many different parameters in many different processes. Another important distinction between parameterization and calibration is that the whole model has to be run in calibration while in parameterization we only need to know the biological meaning of a parameter or a single functional relationship. Because of this, calibration methods end up being much more computationally intensive. However, there are a few advantages of calibration. First, it allows the estimation the overall error variance of the model. Second, it potentially allows for the estimation of covariances between parameters, which can often be substantial and tend to reduce the overall model uncertainty. Third, calibration allows one to estimate model parameters that are difficult or impossible to measure directly in the field, for example, carbon allocation (Miguez, 2009).

There are a number of statistical methods available that can be used during calibration. In general it is best to base calibration on objective criteria rather than simply "tuning" the model-manually adjusting free parameters to make the model match the data. The statistical approaches to calibration have sometimes been referred to as "inverse modeling" because it is the reverse of "forward" modeling where a model is run forward given a set of known parameters in order to produce an unknown output. Instead in inverse modeling the desired output is known (i.e. data) and the goal is to figure out what parameters produce the required outputs. We will discuss three approaches to calibration: minimization of an objective function, maximization of a likelihood, and estimation of the posterior parameter distribution. In the first approach the modeler must specify some function that they would like to minimize. Traditionally, the mean squared error (MSE), the sum of squares error (SSE) or other function that expresses the mismatch between the model and the data, which will be minimized.

$$SSE=\sum_{i}(O_i-S_i)^2$$

$$MSE=\frac{1}{n}\sum_{i}^{n}(O_i-S_i)^2$$

Where O_i is the observed data, S_i is the simulated data and n is the total number of observations.

Given the complexity of vegetation models analytical solutions to these minimizations typically do not exist and one uses a numerical optimization algorithm (Bolker, 2008). The second approach, maximum likelihood, is similar to the objective function approach except that instead of minimizing an objective function one is instead calculating the probability that a certain parameter set would have produced the observed data. This probability statement is referred to as the likelihood function and the goal is usually to find the most likely parameter values, i.e. those that maximize the likelihood function. As with objective functions, likelihood functions are usually evaluated using numerical optimization. The most common choice of probability distributions is to assume that error is normally distributed, in which case the maximum likelihood solution is equivalent to the sum of squares objective function, which is likewise the most commonly chosen objective function (Givens and Hoeting, 2005).

An example in the context of biomass crops where the objective was to produce reliable estimates of switchgrass productivity used a combination of parameters derived from the literature and optimization using a numerical algorithm minimizing the mean sum of squares of the error function (Di Vittorio, et al. 2010). While the authors were able to obtain several parameters directly from the literature, they identified 5 parameters which needed to be optimized based on data. These parameters were mostly related to root and carbon dynamic processes which are seldom measured in detail in individual studies. This effort at identifying uncertainty in parameters and evaluating the robustness of model simulations is crucial for the generation of robust forecasts of feedstock availability.

The third alternative for calibration, estimation of the posterior parameter distribution, is also based on probability theory, just like maximum likelihood, but instead employs Bayes' Theorem in order to estimate the full probability distribution of a parameter (Gelman et al., 2004). Bayesian methods are popular because most often what we are actually interested in is the probability of the model parameters not the probability of the data, which is calculated in maximum likelihood. Furthermore, because these methods provide a whole probability distribution for the parameter, rather than a single optimum value, they more directly capture and propagate model uncertainty. Bayesian posterior parameter distributions are usually estimated by Markov Chain-Monte Carlo (MCMC) numerical techniques, which tend to be more computationally demanding than numerical optimization (Brooks, 1998).

Before proceeding on to model testing we also wanted to briefly touch on data assimilation methods, which have received a lot of attention in the modeling literature lately. The exact definition of data assimilation varies from discipline to discipline and many modelers refer to techniques that we would lump under calibration as data assimilation. Traditionally in atmospheric science, where data assimilation has seen the greatest use, the technique referred strictly to methods for estimating the value of a model's state variables from data, rather than estimating model parameters. Data assimilation can further be broken down into off-line methods, where all the data are available, and on-line methods, where data assimilation is being performed in real time and each new data point arrives in order with analyses being updated at each time point. Wikle and Berliner (2007) give a good overview of both classical and Bayesian approaches to data assimilation while Lewis et al. (2006) provided a detailed treatment of these methods.

Finally, after the model training phase models then often undergo a testing phase, which is sometimes also referred to as model validation or model verification. Typically some portion of the data collected is withheld during the training phase for use in the testing phase, since the aim is to provide an independent test of model performance rather than testing the model against the same data that was used for calibration. During testing model parameters are either fixed to the values estimated during the training phase or, if Bayesian methods were used, are sampled from their posterior distributions. In the latter it is customary to run the model many times to generate an "ensemble" estimate of model uncertainty. While modelers often refer to this phase a model validation, technically we can never assess if the model is valid in all situations, and indeed all models will be wrong under some conditions (Oreskes et al 1994). Rather we are attempting to discern under which conditions the model is reliable and which it is not.

A major challenge in modeling efforts is to integrate databases, field experiments, biophysical models while using optimization and sensitivity analysis techniques. A strategy for simulating productivity and assessing sustainability of biomass feedstocks is to integrate databases, biophysical models and statistical approaches. Miguez et al (2009) developed *M. × giganteus* harvestable biomass projections by integrating weather data from North American Regional Reanalysis, the U.S. general soil map (STATSGO2) and a biophysical model (Figure 3). A recent example of data and model integration, specifically targeted to evaluating the sustainability and productivity of biofuel crop systems was presented by Zhang et al. (2010). Within their spatially explicit framework, they integrated weather data from NARR, the EPIC biophysical model, the SSURGO soil database, Land use, hydrological unit and political boundaries into a homogeneous spatial modeling unit. Using an optimization algorithm they were able to develop a set of optimal solutions that represents a compromise between N losses, energy production and greenhouse gas emissions.

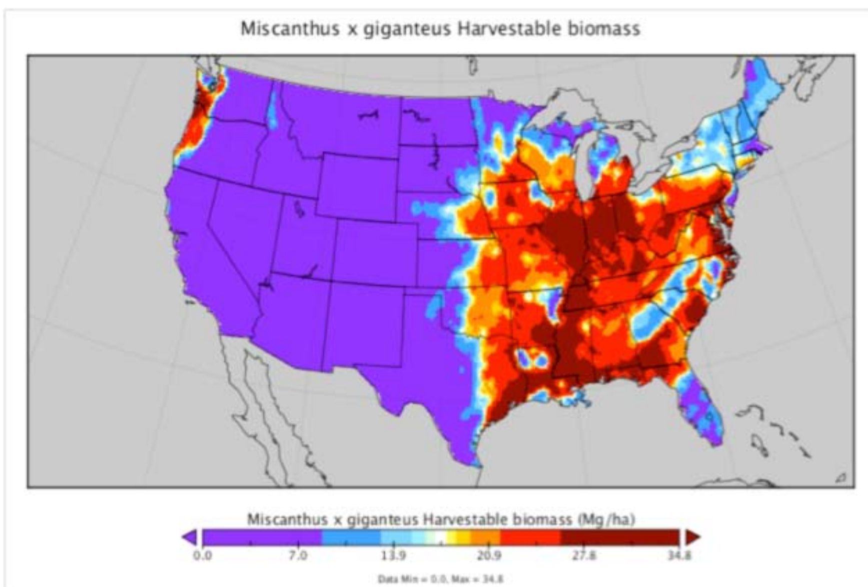

Figure 3: M. × giganteus simulated harvestable biomass production for the U.S. integrating weather (NARR) and soil (STATSGO2) databases.

Conclusions

In this chapter we outlined the characteristic of existing models and databases that are useful for regional assessments of productivity and sustainability of biomass feedstocks along with a summary of statistical approaches for model training and testing.

An ideal framework would provide seamless access to databases required for model development or adaptation. It is of utmost importance that these databases are maintained and quality control criteria are used. The databases can later be used in testing the model simulations as well and this does not need to be a static process, but rather a continuous process in which models are developed, tested and refined.

Ultimately, the objectives of a particular application dictate the appropriate balance among model complexity, data availability, and desired outcome. In this context, simulation models are a powerful component of systems for multi-criteria assessment of the productivity and impacts of biofuel feedstock production.

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Chapter 20

Are Local, State, and Federal Government Bioenergy Efforts Synchronized?

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Introduction

Perhaps the most important question policymakers and stakeholders are asking today is whether local, state and the federal government policies are synchronized with regard to incentivizing and regulating bioenergy. Unfortunately, the answer is an unequivocal "no." One must only look at several websites[3] that have emerged in recent years to track bioenergy statutes and rules to discover that governments in the U.S. have enacted a plethora of regulations and incentives that influence the development of biomass-based electricity, heat, transportation fuels, and biobased products. The U.S. Department of Energy has compiled a list, detailed in Table 1, of individual references to technology and other fuel incentive programs:

	Biodiesel	Ethanol	Methane (CNG)	Propane (LPG)	Hydrogen (fuel cells)	Vehicles[1]	Fuel Economy	Other[2]
Federal	31	29	25	25	27	38	13	19
State	408	399	334	266	254	473	55	171
Total	439	428	359	291	271	514	68	190

Table 1. Count of federal and state programs providing incentives for Biofuels. [1] Electric vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles. [2] Includes aftermarket conversion incentives, idle reduction technologies, and emerging fuel types and additional technologies. Source: U.S. DOE.

Although the overall number depicted in Table 1 is somewhat inflated by duplicate listings among the categories,[4] and does not include localities, the point remains that the landscape of bioenergy policies is highly populated and extremely varied. If the federal government or a regional collaboration of states, therefore, seek a more coordinated, integrated policy framework for bioenergy development-which will play a critical role in decreasing compliance costs for the nascent industry-they almost certainly will have to reconcile laws and regulations that may have conflicting or overlapping provisions. Although President Obama established in early 2009 a Biofuels Interagency Working Group (BIWG) to coordinate federal interagency policy on biofuels development and infrastructure policy,[5] the role of states and localities in the BIWG process to create more coordinated policy is not clear. While scholars have critiqued elements of federal, state and local policies, academia has not issued to date any comprehensive study assessing how these diverse programs may interact to promote or inhibit biofuel development and use. Indeed, this may be impossible given the number of programs, regulations and unforeseeable consequences. Although a review of all these competing or complementary regulations is beyond the scope of this paper, it will highlight the most important federal and state programs.

Federal Legislation

The Renewable Fuel Standard (RFS)

Use of crops and crop residues for biofuels has developed rapidly in the U.S. since federal energy bills emphasizing biomass were passed by Congress in 2005 (The Energy Policy Act)[6] and 2007 (The Energy Independence and Security Act (EISA).[7] These bills provide volumetric targets for blending of biomass-based transportation fuels, and subsidies for the domestic manufacture of ethanol and biodiesel, with the objectives of promoting rural development, reducing foreign energy dependence, and decreasing the greenhouse gas footprint (GHG) of transportation fuels. The mandate, set in statute and by implementing regulations,[8] calls for 36 billion gallons per year (bgy) of total renewable fuels by 2022 (of which corn ethanol can constitute up to fifteen billion gallons), 1 bgy of biodiesel (primarily soybean oil and other fats, oils and greases (FOGs) by 2012, and another twenty-one bgy from advanced (non-corn starch) biofuels by 2022, 16 billion of which derived from cellulosic sources. Advanced Biofuels also include ethanol made from sugarcane, whether domestic or imported.

EISA has incentivized substantial investment in corn-based ethanol, particularly in the upper Midwest where the majority of corn is produced. Corn starch-based ethanol production capacity will reach the 15 bgy EISA cap within the next few years.[9] These investments provide an incentive to maintain policies favorable to corn ethanol production and use, including those in the 2008 Farm Bill.[10] But there are inconsistencies, practical and political difficulties in implementing the RFS mandate.

Type	GHG Savings	2009	2022
Cellulosic	60%	---	16.0
Biomass diesel	50%	0.5	1.0
Advanced	50%	0.6	21.0
Corn Grain	20%	10.0	15.0
Totals		11.1	36.0

Table 2. Federal renewable fuel standard, mandated alternative fuel volumes.[11] Corn grain meets the 20 percent GHG reduction requirement for a fuel to be classified as "renewable."

For example, the mandated amount currently produced or anticipated equals or exceeds current and projected demand for ethanol as a component of gasoline in the U.S., at the current blending percentage maximum of 10 percent of gasoline. This limitation is referred to as the blend wall, and unless the percentage of ethanol allowed in motor fuels is increased, current and projected capacity mandated at the federal level argues against investment in further ethanol production, mandated or not, simply because there will be no market for it. Stricter federal fuel economy standards may also limit the amount of fuel needed, lowering demand.[12] EPA recently finalized a rule increasing the blend limit to 15 percent,[13] although this almost certainly will not end the debate surrounding further increasing blending allowances under the Clean Air Act.

An additional complication for biofuel suppliers is that, under the RFS, EPA has the authority to suspend the annual mandated requirements for advanced and cellulosic fuels if supplies do not appear likely to be met domestically. This was propsed in 2011 for cellulosic biofuels as it is apparent that there will be insufficient stocks to meet the mandate of 500 million gallons in 2012.[14] EPA is proposing an overall volume range between 3.45 and 12.9 million gallons. In addition, blenders can purchase renewable energy credits (tracked through renewable identification numbers, or "RINs") for a default price if the price of ethanol is too high. These provisions were included in laws and regulations to protect fuel consumers from high prices, but introduce uncertainty for potential biofuel developers and investors.

There are also minimum standards for the greenhouse gas savings required of mandated biofuels in federal legislation (Table 2). Generally, corn ethanol capacity in place or planned at the time of EISA's enactment is unaffected by GHG requirements due to grandfathering provisions. Calculations for GHG intensity of those fuels not exempted must include, in addition to direct emissions, estimates of terrestrial carbon losses due to land conversion elsewhere in the world resulting from crop diversion for biofuels. These are the so-called market-mediated effects or "indirect land use effects" (ILUC). US-EPA uses the FASOM model (McCarl, 1995) to assess domestic land use change, and the FAPRI model (CARD, 2010) to estimate global economic effects on land. Other jurisdictions like the State of California rely on different models/methods (e.g., GTAP) (Tyner, et al. 2010) to calculate these values. These differences are discussed in greater detail below.

Other Federal Programs

Tariffs, Taxes and Tax Credits

The U.S. currently imposes a 2.5 percent ad valorem tax and a secondary import tariff on most imported ethanol equal to $0.54 per gallon. The amount has fluctuated over the last several years.[15] The purpose of this tariff has been to stimulate the development of a domestic ethanol-based biofuel industry. In response to pressure from Brazil, as well as federal budgetary constraints, Congress will likely remove the tariff in 2011. There is also a tax credit for all ethanol blended in the United States, whether domestic or imported, of $0.45 a gallon. Biodiesel producers enjoy similar tax incentives through the end of 2011.

Production Subsidies, Grants, and Loans

There are many different grant and loan programs for facility development, as summarized at the U.S. DOE website cited above (Table 1). Potentially the most important subsidy from a crop production perspective is the USDA Farm Service Administration's (FSA) Biomass Crop Assistance Program (BCAP). FSA implemented BCAP throughout the later part of 2009 and early 2010, only to be halted pending finalization of a formal implementing rule. In late October 2010, the Commodity Credit Corporation (CCC) issued the final rule, with immediate resumption of implementation.[16] The program consists of two parts. First is a matching payment of up to $45 for the price received by eligible material owners (EMOs) for the collection, harvest, storage and transportation of eligible biomass to qualified conversion facilities for use as heat, power, bio-based products, or biofuels. Sourcing biomass for the matching payment from forests, whether public or private, is limited to prevent damage to sensitive environments. Also, no matching payments will be made for Title I crops, yard/food/animal wastes, municipal solid wastes, or algae. The second part of BCAP, referred to as the establishment and annual payments program or "project areas" program, will pay up to 75 percent of the costs of establishment, and annual payments, within the estimated 32 project areas designated by FSA for the production of eligible crops on eligible private lands. As of writing, FSA has awarded one project area for mixed species of perennial grasses, and one for giant miscanthus. All BCAP-subsidized material must be produced according to a conservation or forest stewardship plan or the equivalent, and the regulation limits growing of invasive or potentially invasive species. Many aspects of the final rule will require CCC and its advisors to provide further guidance (e.g., qualification of new crops and eligible practices), highlighting the importance of government regulators moving forward in establishing a viable and sustainable production system. The BCAP Final Rule is not entirely consistent with RFS, as RFS excludes biomass from federal forest lands categorically. Categorical exclusions of biomass sourced from state forests, or even federal forests, may not apply to individual state's biofuel feedstock programs, however.

GHG Programs

Since the Obama Administration came to office in 2009, on the heels of the U.S. Supreme Court's landmark decision in *Massachusetts, et al., v. EPA*,[17] EPA has pursued ambitiously regulatory programs to reduce GHG emissions from mobile and stationary sources. In the absence of omnibus federal legislation, EPA has finalized rules under existing Clean Air Act (CAA) provisions including a stationary source "tailoring" rule.[18] EPA has delayed for three years a determination whether biomass combustion will be treated as carbon neutral under the program.[19] Policymakers must consider how to reconcile the GHG accounting and "other" sustainability aspects of energy biomass feedstocks between the RFS, BCAP, and the CAA.

California

Of all the states, California has adopted the broadest and most aggressive state-level energy policies in the U.S. to date, including both mandates and other directed development of alternative energy and transportation fuels. The ambitiously named Global Warming Solutions Act (commonly known as Assembly Bill 32, or "A.B., 32") requires the state to reduce per capita carbon dioxide (CO_2) emissions over the next 40 year period from approximately 14 tons CO_2 equivalent (CO_2e) to 1.4, which equates to approximately a 90 percent reduction (CARB, 2008). Many strategies for GHG reductions through biofuels use fall under the A.B. 32 umbrella. The main ones are highlighted below.

The Low Carbon Fuel Standard

Under the auspices of A.B. 32's mandate, the Air Resources Board (ARB) has implemented a low carbon fuel standard (LCFS) (CARB, 2010; Sperling and Yeh, 2009) that mandates an overall reduction in the GHG intensity of transportation fuels by 10 percent in 2020, with increases in the incremental percent reduction progressively as the target date is neared. The rules governing the LCFS differ in important ways from the federal RFS, thereby presenting fuel blenders with differing standards for compliance at the state and federal level.

One of the significant ways CA policy differs from federal policy is its regulation of corn starch-derived ethanol, particularly with regard to GHG intensity calculations. As stated previously, both the RFS and LCFS specify minimum levels of GHG/carbon intensity reduction. To estimate GHG levels, both EPA and ARB deploy life cycle assessment (LCA), which is mandated under both schemes, and indeed at some level by most sustainability standards related to biofuels (van Dam et al., 2008; Endres, 2010). LCA is used to estimate the net GHG reduction, if any, from biofuel production and use, compared to conventional petroleum fuels. This involves calculating total GHG savings and emissions involved in the complete biofuel cycle from crop production to end use. The LCA model most commonly used in the U.S. for direct emission is the GREET model (Wang et al., 2010). Two California resource agencies, ARB and the Energy Commission (CEC) have adopted a modified version of GREET called CA-GREET. US-EPA also uses the GREET model (US-EPA, 2010). Even the most careful LCAs, however, involve assumptions and decisions about qualitative criteria used in making quantitative assessments (Zah et al., 2008). LCAs cannot anticipate future conditions and technical advances, and therefore are best used for purposes of comparison rather than for setting absolute standards. Better transparency and ease of use of LCA models is needed to legitimize them as a basis for important public policy decisions (Liska and Cassman, 2008). Different LCA methods and assumptions result in different GHG estimates (Liska et al., 2009; Plevin, 2009; Liska and Cassman, 2009). These differences may be large enough to influence biofuel marketing decisions, and even investments.

The factors included or left out of LCA calculations can lead to strikingly different assessments about the value of biofuels. Similarly, the boundaries assumed for the calculation of life-cycle effects also influence results. Most initial calculations about the GHG reduction benefits of biofuels were based on direct emission calculations from field to tank. Searchinger et al.(2008), however, argue that previous LCA calculations showing positive GHG effects from the use of crop based biofuels (Farrell et al, 2006) become significantly negative if indirect effects related to market effects on land conversion are considered. Stated briefly, Searchinger et al's hypothesis is that using staple commodities like corn or soybeans for biofuels in one part of the world will lead to an increased use of land in other parts of the world to replace the lost food crops. Converting forest land to farmland in places like Brazil releases such large amounts of carbon into the atmosphere that the positive effects of crop based biofuel use on GHG reduction are reversed. In effect, they argue that it is essential to broaden the boundary conditions of LCA calculations about biofuel crop production to include the entire worldwide system of agricultural markets and use the global atmosphere as the system's boundary. They estimate that the use of corn ethanol would result in a net increase of 104 g CO_2eq per MJ of ethanol. This change results from including carbon loss from land conversion in remote regions, otherwise known as market-mediated effects or indirect land use change (ILUC).

Adopting this argument, the most recent calculations reported by staff at CARB have reduced Searchinger et al's estimate to 30 g CO_2eq per MJ (CARB, 2009). Other recent estimates lower it further to as low as 13 g CO_2eq per MJ, nearly a tenfold lower estimate than Searchinger et al's original estimate (Tyner et al., 2010). Adding CARB's estimate for the generic lifecycle CO_2e costs for corn ethanol makes most corn ethanol equivalent to gasoline in its GHG effects on the atmosphere, rendering it useless in helping fuel blenders to meet the LCFS. EPA's LCA for the RFS, on the other hand, including ILUC, has placed corn ethanol above the 20 percent renewable fuel threshold (US-EPA, 2010). California's fuel demand equals approximately 10 percent of domestic use, so this difference between federal and California policy is not inconsequential.

The method chosen by CARB to assess the indirect or market-mediated effects of corn ethanol and other crop-based biofuels is based on the use of the Global Trade Analysis Project (GTAP) model.[20] GTAP is a computable global equilibrium (CGE) model developed at Purdue University to estimate the indirect carbon cost by inferring land change elsewhere in the United States and internationally. While no claim is made about land change in any specific location, GTAP uses data on land values and crop production from around the world, together with estimates of most significant international economic sectors, to analyze world food markets subjected to pressure from the use of corn for ethanol in the United States, or other crop uses for fuel. All other factors are held constant. One of the mechanisms for market adjustment required by the model structurally when crop production in the United States is altered is change in land allocated for crop production. These estimates of land use inferred from the GTAP CGE model are combined with estimates of the carbon content of terrestrial biomass and soil carbon on affected acres to estimate carbon losses from changes in land use.

ILUC calculation, whether using the FASOM (EPA) or GTAP (CA) LCA models, has been subject to criticism. For example, some skeptics claim that regulators used the GTAP model to bias the LCFS against crop-based biofuels using inaccurate estimates of what happens in the "real world" (Liska and Perin, 2009; Kline et al., 2009; Babcock, 2009). This includes the inability of the model to account for new technologies, and even failure to predict accurately induced land change in the U.S. (Babcock, 2009; Glauber, 2009). Others claim that it is poor policy for agencies to pick preferred technologies at such early stages in the development of biomass-based fuels. A record of this vigorous and interesting debate is available at the CARB website.[21] California is currently evaluating its use of the GTAP model using an expert work group. While EPA (2009) is mandated to calculate ILUC effects for biofuels, it does not use GTAP for the RFP reportedly because of significant current limitations in its ability to estimate indirect land use change. Instead, EPA uses a different set of models and approaches in combination (US EPA, 2010). Again, this will result in different estimates for these values for the same fuel.

CARB also has convened a sustainability work group to develop "other" sustainability criteria for fuels qualifying for the LCFS, including soil and water quality, and biodiversity.[22] For forest biomass, agencies involved in A.B. 32 activities have convened the Interagency Forestry Working Group to develop standards.[23] The two working groups coordinate their activities to a certain extent.

The Renewable Electricity Standard

CARB is in the process of implementing Executive Order S-21-09, which mandates 33 percent renewables in California's electricity supply by 2020. While the effort was delayed in the summer of 2010 in anticipation of legislative action.

Alternative and Renewable Fuel and Vehicle Technology Program

Assembly Bill 118 (A.B. 118) created the Alternative and Renewable Fuel and Technology Program[24] to establish a coordinated investment program for alternative fuels and transportation policy. This multi-million dollar investment program is funded by taxpayers to promote alternative fuel and vehicle development and use in California, and includes investment in both biofuel technologies and vehicle technologies. CEC has developed a set of sustainability standards that, in part, guide funding decisions.[25] It is yet to be seen whether LCFS and A.B. 118 sustainability standards, as well as any standards developed for the cap and trade program, infra, will be coordinated.

The Cap and Trade Proposed Regulation

CARB proposed a final cap and trade regulation in October 2010.[26] The RES and LCFS GHG reductions are calculated as part of the cap contained in the new program.[27] The use of biomass as an energy feedstock as a compliance strategy for capped entities is contemplated by the proposed regulation. Also, standards have been and are being developed for valuing the GHG reduction value of domestic and foreign offset projects used for C & T program compliance. It remains to be seen how California will reconcile its existing, or any newly developed energy-biomass-specific standard, with international norms and rules of sustainable forestry management. Also, policymakers will be confronted with the paucity of scientific consensus on how to measure carbon flux in a valuation system for offsets.

In sum, although pursued under an umbrella GHG statute, the focus of California's renewable biomass-related programs is not completely consistent. Each agency has differing fundamental responsibilities, administrative processes, and even cultures. The governor has mandated a multi-agency workgroup to help integrate state level biomass energy programs but with limited success.[28] These circumstances illustrate how administrative obstacles may inhibit well-intentioned environmental regulations and development of flexible reactions to quickly evolving problems and scientific knowledge.

This issue is not limited to California. For example, EPA and USDA use different estimates for the amount of land available in the important "cropland-pasture" category of land used to determine the sustainability effects of biofuels mandates. Specifically, the amount of U.S. land eligible for inclusion for biomass production for biofuels is defined by EPA as equal to 402 million acres. USDA (2010) finds that there are more cropland-pasture acres (36 million) than reported by EPA (20 million) in the RIA (US EPA, 2010). The land qualifying for biomass production varies accordingly by state and under full use, some states may have less eligible landscape area than might otherwise be used if EPA's more restrictive estimate is used.

Other State Incentives

Most current state laws and incentives are summarized by state at the US DOE and the Database of State Incentives for Renewable Energy (DSIRE, www.dsireusa.org) websites discussed above.

Multi-state organizations

The Western Governors Association (http://www.westgov.org/) has begun to implement an effort to harmonize rules and regulations governing biomass energy and alternative fuels in that region, though without specific effect to date. As noted on the website, the western states have adopted differing targets and timetables for GHG emission reduction from the energy and transportation sectors. Each state agrees broadly on the need to develop and use alternative Biofuels, but specific biomass resources vary widely across the region and each state has differing environmental, economic, social and political issues that make adopting comprehensive policies across the region difficult. Some of the more obvious measures these states seek to adopt in common is the use of fuel taxes and state vehicle purchases to promote higher blends of ethanol use. Siting and permitting difficulties are noted for many of the states. (http://www.westgov.org/index.php?option=com_content&view=article&id=126&Itemid=67). A number of policy statements about Biofuels and other biomass energy sources can be found at the website.

The Northeastern States (New England plus New York and New Jersey) have developed a 501c(3) organization called NESCAUM (http://www.nescaum.org/), to help states in that region coordinate public policies required by the federal Clean Air Act, and also now including Biofuels and other transportation and energy related issues. The NESCAUM states have developed a memorandum of understanding to jointly adopt transportation fuel standards following the principles of a low carbon fuel standard, based at least in part on the one adopted in California (http://www.nescaum.org/topics/low-carbon-fuels). NESCAUM is mindful of the need to accommodate other biofuel and biomass energy policies and asserts this need as a principle (http://www.nescaum.org/topics/low-carbon-fuels).

Sustainability Standards

Sustainability standards are needed to protect landscapes from strictly economic pressures for the use of biomass. A large number of different sustainability standards are being developed or have been adopted to guide or regulate the production, use and trade of biofuels or biofuel feedstocks (van Dam et al., 2008; Yeh et al., 2010, Endres 2010, RSB, 2011). A common feature is to protect against the degradation of landscapes and exploitation of politically vulnerable, poor populations in the process of producing and using biofuels. Some policies are voluntary, while others result from laws or other governmental regulations. There is some similarity of intent among all these groups and standards, but also differences. Reconciling differing or somewhat incongruent standards across regulatory and jurisdictional standards has not been achieved. Doing so will be challenging because sustainability standards often combine technical, measurable issues with values (Kaffka, 2009). Conflicting standards create uncertainty and will inhibit trade in biofuels and overall economic development of the biofuel sector. Adaptation and innovation will characterize any set of sustainability standards that successfully protect landscapes used for biomass production.

Synchronization of Federal, State and Local Efforts

Even this brief summary of select biofuel laws, regulations, and incentives in the U.S. reveals a complex mixture of efforts to stimulate and guide sustainable biofuel development and use in the United States and internationally. The U.S. federal system of governance results in different approaches to alternative transportation fuels that are not harmonized. There are some efforts to create comparable regulations at the state level, particularly expanding the use of a LCFS similar to the one adopted in California, and development of regional GHG cap and trade regimes. However, these efforts have not gained much traction to date. Even at a single level of government, there are conflicting data, visions, programs and in some cases laws that will have as yet unforeseeable consequences. Fuel blenders and other biofuel businesses must navigate this uncertain and complex set of circumstances. The existence of all these programs provides both incentives and disincentives to the development of sustainable biofuel supplies.

The potential for conflicting laws and regulations, operating across different levels of governance or in different countries, is inherently chaotic. It can impede the development of useful biofuels, and such is likely the status quo condition. A biomass energy roadmap must include some means of identifying important conflicts among diverse regulations. Some means of net benefit analysis among incongruent regulations and weighing of conflicting public policy goals is needed but not available.

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[3] The U.S. Department of Energy (DOE) lists many federal and state incentive, tax and regulatory programs at a helpful website (http://www.afdc.energy.gov/afdc/laws/). Also, DOE, in conjunction with the N.C. Solar Center, N.C. State University, and the Interstate Renewable Energy Council, maintains a database of state and federal incentives and policies (http://www.dsireusa.org/).

[4] A single law or regulation may include more than one bioenergy provision such as a combination of

incentives, technology mandates, and other regulations.
[5] Presidential Documents, Biofuels and Rural Economic Development, 74 Fed. Reg. 21531-21532 (May 7, 2009).
[6] The Energy Policy Act of 2005, Pub. L. No. 109-58, 119 Stat 594 (Aug. 8, 2005).
[7] The Energy Independence and Security Act of 2007, Pub. L. No. 110-140, 121 Stat. 1492 (Dec. 19, 2007).
[8] The U.S. Environmental Protection Agency, Regulation of Fuel and Fuel Additives; Changes to Renewable Fuel Standard Program; Final Rule, 75 Fed. Reg. 14674 (Mar. 26, 2010) [hereinafter RFS2 Final Rule].
[9] RFA (2010), Climate of Opportunity, 2010 Ethanol Outlook Report http://www.ethanolrfa.org/page/-/objects/pdf/outlook/RFAoutlook2010_fin.pdf?nocdn=1.
[10] The Food, Conservation, and Energy Act of 2008, Pub. L. No. 110-246, §9008(e), 122 Stat. 1651, 2089 (2008).
[11] Cellulosic includes: (1) crop residues such as corn stover, wheat straw, rice straw, citrus residue and others; (2) forest material including eligible forest thinnings and solid residue remaining from forest production; (3) annual cover crops planted on existing crop land such as winter cover crops; (4) separated food and yard waste including biogenic waste from food processing; (5) perennial grasses including switchgrass and Miscanthus. Cellulosics must achieve a 60 percent GHG savings over petroleum-based fuels. Advanced biofuels include renewable fuel from qualifying feed stocks other than ethanol derived from corn starch, with at least 20 percent lower GHG intensity than petroleum fuels (includes ethanol Brazilian from sugarcane).
[12] National Highway Transportation Safety Agency, CAFÉ Overview-Frequently Asked Questions, http://icsw.nhtsa.gov/cars/rules/CAFE/overview.htm.
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[27] Id. Appendix E.

[28] Ruhl and Salzman note in their article Massive Problems in the Administrative State: Strategies for Whittling Away, 98 Cal L. Rev. 59-120 (2010), that a similar multi-agency coordination effort for water resources by CalFed did not meet expectations.

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Chapter 21

Climate Change: What To Expect and How Will It Affect Feedstock Production Options?

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Abstract
Climate change has been occurring and the expectation is that the rate of change will increase over the next 50 years. Increases in temperature, especially, minimum temperatures, along with a projected increase in extreme temperature events will increase the rate of vegetative plant growth and decrease the length of the reproductive period. There will be shifts in precipitation patterns during the season with a projection that the summer period will become drier over most of the United States leading to the potential for more drought occurrences in agricultural regions. Variations in temperature and precipitation are the major factors causing variation in yields among years. Examination of past maize production in Iowa and Georgia show there has been a steady increase in production; however, in the period from 1970 to 1995 in Iowa, along with the remainder of the Corn Belt, there were variations in stover and grain production by as much as 30% from the trend line. Variations due to weather were more scattered in the Georgia data. The implications, based on the increased variation in temperature and precipitation, are for more variation in agricultural production leading to more uncertainty in the reliability of biofuel supplies. Agricultural management systems will have to be developed to decrease the risk of agricultural production to climate variation in order to maintain a reliable food, feed, and fuel supply.

Introduction
Climate change over the next 30 to 50 years will place new stresses on agricultural production because of the increasing temperatures, increased variability in precipitation, enhanced potential for more extreme storms, and more differences within the growing season. There have been several assessments of the potential scenarios for climate change and Meehl et al. (2007) summarized that on a global basis "it is very likely that heat waves will be more intense, more frequent and longer lasting in a future warmer climate. Cold episodes are projected to decrease significantly in a future warmer climate. Almost everywhere, daily minimum temperatures are projected to increase faster than daily maximum temperatures, leading to a decrease in diurnal temperature range. Decreases in frost days are projected to occur almost everywhere in the middle and high latitudes, with a comparable increase in growing season length." In terms of precipitation, they stated that "For a future warmer climate, the current generation of models indicates that precipitation generally increases in the areas of regional tropical precipitation maxima (such as the monsoon regimes) and over the tropical Pacific in particular, with general decreases in the subtropics, and increases at high latitudes as a consequence of a general intensification of the global hydrological cycle. Globally averaged mean water vapor, evaporation and precipitation are projected to increase" (Meehl et al., 2007). These summaries point out the expected global change in temperature and precipitation. Across North America there are expected changes in climate mirroring the worldwide changes. These have been summarized recently by Karl et al. (2009) where temperature and precipitation patterns across the United States for the next 50 years show a warming trend for most of the United States of 1.5 to 2.0°C and a slight increase in precipitation over

most of the United States. Their projections of an increase in the number of days which the temperature will be higher than the climatic normals by 5°C (heat-waves) will impact agricultural systems. They also project an increase in warm nights, defined as occurring when the minimum temperature is above the 90^{th} percentile of the climatological distribution for the day (Tebaldi et al., 2006; Karl et al., 2009). Coupled with these changes is the decrease in the number of frost days by 10% in the eastern half of the U.S. and an increase in the length of the growing season by over 10 days. Karl et al. (2009) showed that precipitation events would change in frequency and intensity with a projected increase in spring precipitation, particularly in the Northeast and Midwest of the United States, and a decline in the Southwestern U.S.. The increase in extreme temperature events, warm nights, and more variable precipitation will impact agriculture and agricultural production. A trend for warmer winters will affect perennial crops and weeds, and also expand the potential habitable range of some insect and disease pests. Although there is uncertainty about the absolute magnitude of the changes over the next 50 years, there is general agreement that CO_2 levels will increase to near 450 μmol mol^{-1} (ppm), temperatures will increase by 0.8 to 1.0°C, and precipitation will become more variable as defined in the IPCC AR4 analysis (IPCC, 2007). Changes in temperature have caused longer growing seasons and directly impacted phenological phases (Schwartz et al., 2006; Wolfe et al., 2005, Xiao et al., 2008; Karl et al., 2009). There are changes occurring in climate and these will directly and indirectly affect plant growth and ultimately biofuel production. In this paper we summarize some of the potential scenarios in climate change and relate these to plant production in order to demonstrate the impact of climate change on biofuel production.

Climate Change Scenarios

Across the United States there will not be one singular climate trend over the next 40-50 years. There will be regional differences induced by the combinations of landforms and circulation patterns. Temperatures across North America are expected to increase; however, the largest increases are expected in the northern latitudes above 50°N with more moderate increases in the remainder of North America (Christensen et al., 2007). The projected rise in mean temperature for the mid-continent regions by 2050 is 2.0°C with an uncertainty range of ±1.0°C. In the northern latitudes there would be more warming during the winter months, while throughout the mid-continent regions less seasonal variation will be evident (Christensen et al., 2007). Across the mid-latitudes, there will be a greater increase in the nighttime minimum temperatures than the daytime maximum temperatures. One aspect important to agriculture is the projected increase in the number of days with high temperatures, defined as those days that are significantly above the average temperature, because of the impact on plant stress from the rapid change in evaporative demand on the plant. This latter aspect has implications for plant growth and development. Meehl et al. (2004) showed a decrease in the number of frost days in the year, with the largest decrease in the spring compared to the fall. There would be regional differences in these patterns because of the impact of local factors, e.g., regional atmospheric circulation patterns and pressure systems (Meehl et al., 2004). There is an increase in the number of days within the year that will exceed 32.0°C based on the use of model simulations using lower emission scenarios and if CO_2 rises more rapidly, then projected temperature increases may also be higher.

Precipitation patterns across North America have shown regional variability over the past 50 years as shown in Figure 1. The Pacific and intermountain Northwest and Southeast U.S. have experienced declines in annual precipitation, while throughout the remainder of the U.S. there has been increased variation even within individual states (e.g. Iowa). A critical part of the climate puzzle is the seasonal variation in precipitation and there have been shifts in the seasonal patterns with the expectation of further increases in seasonal variation. Projections for precipitation across North America for the period from 2080 to 2099 show a large continuance in the variation in the seasonal patterns of precipitation (Karl et al., 2009). Throughout the U.S. and into Southern Canada there is an expected decrease in summer precipitation, while winter and spring precipitation for the upper portion of the U.S. and Canada show an increase (Figure 2). In the southern portion of the U.S. into Mexico a large decrease in winter and fall precipitation is expected to occur (Figure 2). These regional differences in precipitation will impact soil water availability in rainfed agriculture, especially with the decrease in summer precipitation over the U.S. and the agricultural region of Canada.

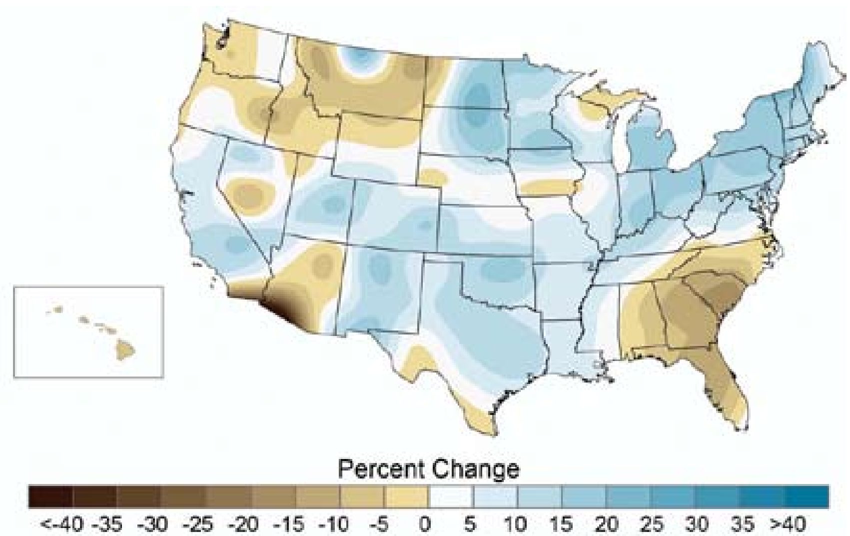

Figure 1. Changes in annual precipitation over the United States from 1958 to 2008. (Adapted from Karl et al., 2009).

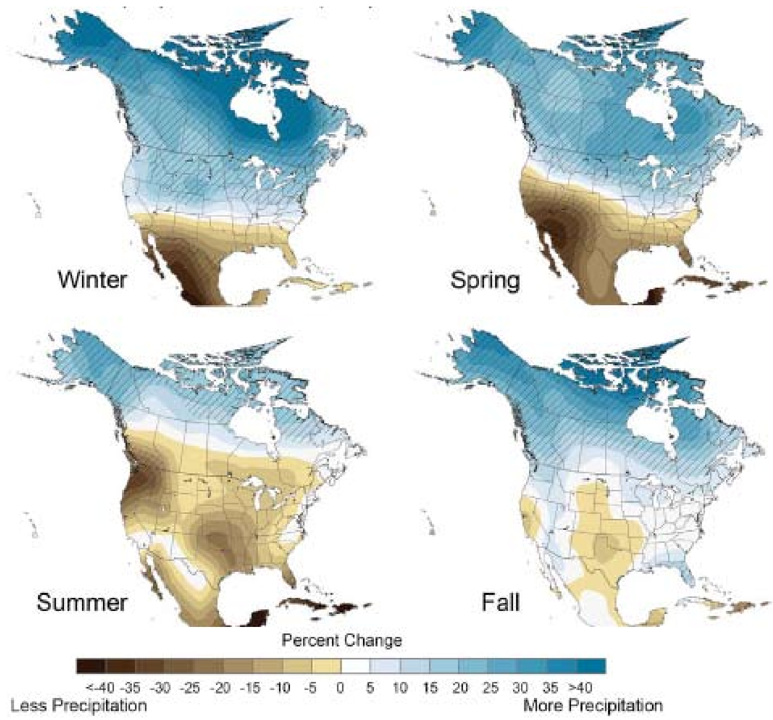

Figure 2. Projected regional changes in precipitation across North America for the period of 2080 to 2099. (Adapted from Karl et al., 2009).

One important aspect of climate change with significance for agriculture is the potential impact, not only on the mean values of temperature and precipitation, but also on the frequency and severity of meteorological events within the growing season. Mearns et al. (1984) showed that relatively small changes in mean temperature can lead to large increases in the frequency of extreme events. Mearns et al. (1995) observed that in the Central Plains, a frequency decrease was the major change along with change in intensity. Gutowski et al. (2007) found that high intensity precipitation would constitute a larger fraction of the total precipitation under scenarios of global warming. These observations were found to be evident for all regions and seasons. Rind et al. (1990) suggested that both drought and floods may intensify with climate change. The change in probability of drought may increase more than would be expected due a reduction in mean precipitation and conversely, increases in floods or extremely wet portions of the year may be larger than expected from the increase in mean precipitation. Shifts in the intensity of storms have implications for availability of soil water to the crop because intense storms often lead to runoff rather than infiltration into the soil. The probability of drought will increase because the reduction in rainfall will be linked with an increase in potential evapotranspiration, which will exaggerate the effect of a reduction in precipitation. This characteristic of climate change has to be considered in evaluation of the potential impacts on agriculture or agro-ecosystems. Wang (2005) observed, based on the use of 15 global climate models, in the primary agricultural areas of the world there would be potential drought occurring over the next 50-100 years. The only consistent wet areas predicted from this ensemble of models were the northern middle and high latitudes and this was limited to the non-growing season period. This is similar to the analysis of Tao et al. (2003) for China in which they found that rainfed crops in the north China Plain and northeast China would have challenges induced by soil moisture deficit and decreases in precipitation. Kim (2005) observed that future trends in precipitation induced by warming would lead to increased cold-season precipitation and increase the rainfall-portion of total precipitation in Sierra Nevada river basins in the western U.S.. Dai (2006) evaluated the impact of surface air temperature, dew point temperature, and air pressure from around the world on specific humidity and relative humidity. He found that the spatial patterns of specific humidity were controlled by surface temperature. This change in specific humidity will impact the water vapor of the atmosphere and have a large impact on the potential evapotranspiration of agricultural areas. There are assumptions that increasing temperatures would benefit plant growth; however, a recent report by Zhao and Running (2010) suggest positive temperature effects were offset by the occurrence of drought during the 2000-2009 period. This decade was selected because it has been the warmest in recorded history with the concurrent expectation for an increase in the global net primary productivity. What was observed in the analysis was actually a decrease in net primary productivity because of the large-scale droughts around the world. One of their conclusions central to the discussion about climate impacts on biofuel production is increasing trends for drought around the world could intensify competition between food demand and biofuel production (Zhao and Running, 2010). The shifting precipitation patterns leading to increased uncertainty in soil water supplies, especially during the growing season, could impose a major limitation on plant growth and potential harvestable yield.

An overlooked component in the climate change discussion and important to plant growth is solar radiation. The projections regarding changes in precipitation in water vapor and cloud cover will increase contributing to a decrease in incoming solar radiation. Stanhill and Cohen (2001) evaluated the change in solar radiation and found for the past 50 years a reduction of 2.7% per decade with the current totals now being reduced 20 W m^{-2} reducing the daily total solar radiation values over the past 10 years across the central United States to 25.5 MJ m^{-2} day^{-1} from 26.3 MJ m^{-2} day^{-1}. They referred to this phenomenon as “global dimming.” Changes in solar radiation would directly impact crop water balance and evapotranspiration of crops with less effect on crop productivity because of other factors limiting productivity (e.g., water, temperature, nutrients, and mutual shading within canopies). Evaluation of the impacts of a changing climate on plant production has to include an evaluation of a number of factors affecting plant growth.

Climate Impacts on Plant Growth

Climate change will directly impact plant growth and the effects of CO_2 and temperature have been summarized by Hatfield et al. (2008). There are some general statements which can be made about the climate change impacts. Rising CO_2 levels in the atmosphere will increase plant growth of C_3 species, while the effect in C_4 species will be rather small with the expectation that increasing CO_2 will also cause plants to become more water use efficient. This latter response will help offset some of the potential limitations caused by the increased probability of drought during the growing season. The improvement in water use efficiency is a direct result from reduced stomatal conductance and reduced transpiration relative to CO_2 uptake. An example of an experiment designed to evaluate this effect was reported by Bernacchi et al. (2007). They observed water use from soybean at elevated CO_2 levels in the free air carbon dioxide enrichment (FACE) plots with adequate soil water was less compared to control plots at ambient CO_2. When the control plots exhausted their water supply water use declined. However, in the elevated-CO_2 plots the stomata remained open for an additional six days and the plants continued to transpire. This allowed these plants to continue to photosynthesize and grow, while the control plants ceased growth. Under rain-fed agriculture, which often experiences periods of water deficit, the net impact of elevated concentrations of CO_2 would be to enable conservation of soil water, buffering crop growth during periods of abiotic stress. This would enhance potential production even under periods of moderate drought, which would enable continued production of biofuels and overall would be a positive impact of rising CO_2 levels.

Rising temperatures will impact plant growth at multiple levels during the growing season. The review and synthesis by Hatfield et al. (2008) summarized the temperature responses for the major crop species and among these crops, maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L.) have potential as biofuel crops because of their large amount of grain or biomass residue. Each crop species responds differently to temperature throughout their life cycles with the vegetative period of growth having a higher temperature optimum than the reproductive stage. For example, in maize the maximum is at 37.0°C and minimum temperature is 8.0°C with an optimum near 34.0°C, while in the reproductive stage the minimum remains at 8.0°C and the optimum decreases to 22.0°C. Sorghum has very similar temperature responses as maize with an optimum reproductive temperature of 25.0°C. Exposure to higher temperatures during vegetative growth causes growth to progress at its fastest rate. Above the optimum, growth rates slow and cease when plants are exposed to their maximum temperature. Vegetative development (node and leaf appearance rate) will accelerate as temperatures increase up to the species optimum temperature. The projected increase in temperatures over the next 30-50 years will cause more rapid rate of plant development (Brown et al., 2000, Hatfield et al., 2008). In both maize and sorghum, exposure to higher temperatures will cause faster rate of development and this doesn't translate into maximum production because shorter life cycle creates smaller plants, shortened reproductive duration, and reduced yield potential because of reduced light interception during the growing season. Yields will be impacted when temperatures fall below or above specific thresholds at critical times during development.

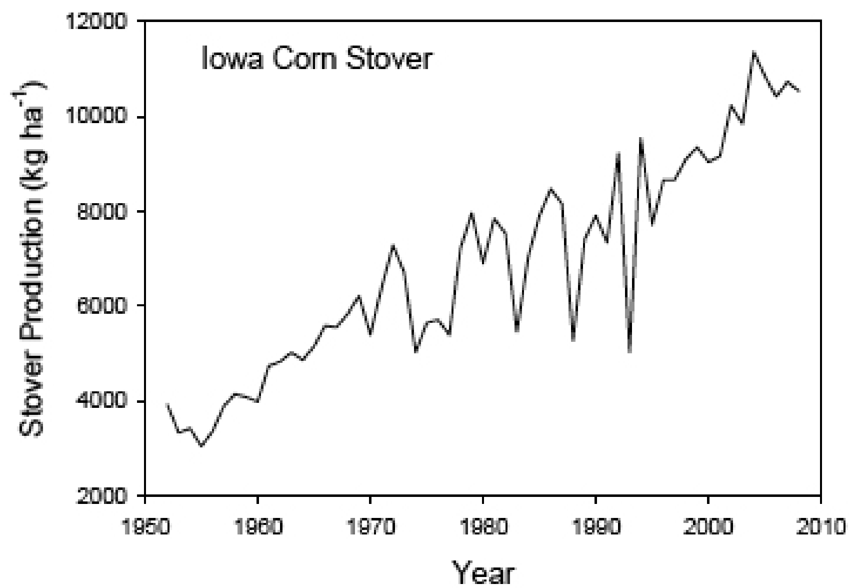

Figure 3. Variation in corn stover production derived from annual corn grain yields across Iowa from 1950-2008. (Grain yield data extracted from NASS Quickstats, www.nass.usda.gov).

One of the critical phenological stages for high temperature impacts is the reproductive stage because of the effect on pollen viability, fertilization, and grain or fruit formation. Yield potential will be affected by chronic exposures to high temperatures during the pollination stage of initial grain or fruit set. Temperature extremes during the reproductive stage of development can produce some of the largest impacts on crop production. The projection for increased high temperature extremes during the growing season will potentially impact yield from a three-fold effect. The first effect will be due to temperature stress alone causing reduced pollen viability and potential grain set and this coupled with reduced growth will lead to decreased yield. If we assume that harvest index (grain/stover production) is fairly constant then a reduction in vegetative growth will translate into reduced grain yield. The second effect would be exposure to high temperature extremes during the pollen stage limiting the potential grain set. The final effect from warming temperature, especially during the reproductive stage, is to decrease the length of grain-filling period through a more rapid grain-fill leading to smaller grain-size. The projected increase in minimum temperatures (Karl et al., 2009) will cause the grain-filling period to be shortened (Hatfield et al., 2008). An example of the evaluation of the temperature effect on maize yields is given by Muchow et al. (1990) who reported highest grain yields were from locations with relatively cool growing season mean temperatures (18.0 to 19.8°C at Grand Junction, CO), compared to warmer sites, e.g., Champaign, IL (21.5 to 24.0°C), or warm tropical sites (26.3 to 28.9°C). In a later study across a greater range of sites, Lobell and Field (2007) evaluated the effects of temperature and rainfall using records from 1961-2002 and found an 8.3% yield reduction per 1.0°C rise in temperature. Runge (1968) observed maize yields were responsive to interactions of daily maximum temperature and rainfall 25 days prior and 15 days after anthesis. He found interactions between temperature and rainfall when rainfall was low (zero to 44 mm per 8 days), yield was reduced by 1.2 to 3.2% per 1.0°C rise. Conversely, when temperatures were warm (Tmax of 35°C), yield was reduced 9% per 25.4 mm decline in rainfall. In sorghum, maximum dry matter production and grain yield has been observed at 27.0(day)/22.0(night)°C compared to exposure to temperatures 3.0 or 6.0°C lower or 3.0 or 6.0°C warmer (Downs, 1972). Duration of grain filling decreases as temperature increases and reduces grain yield (Chowdury and Wardlaw, 1978; Prasad et al., 2006). In a recent analysis of temperature effects on maize, soybean [*Glycine max* (L.) Merr.] and cotton (*Gossypium hirsutum* L.), Schlenker and Roberts (2009) found temperatures above 29.0°C in maize reduced yields and the slope of yield decline above this temperature value was greater than the increase in yield observed up to this temperature threshold. They projected for these three crops a 30-46% decrease in yield for the slowest warming scenario and a 63-82% decrease under a more rapidly warming scenario. Kucharik and Serbin (2008) evaluated temperature and precipitation impacts on corn and soybean production in Wisconsin and concluded that for each additional degree of warming during the summer months corn yields would decrease by 13% and soybean by 16%. In their analysis they observed that potential increases in precipitation could offset the negative temperature impacts. These values are much larger than those projected by Hatfield et al. (2008); however, they show the potential implications of warming on crop production. Projected changes in both temperature and precipitation leading to more extreme events during the growing season will create a situation in which crop yields and also biomass production will decrease in C_4 crops like maize and sorghum. The interactions of temperature and precipitation on plant growth and exposure to conditions outside of the optimum temperature range and decreased soil water availability will combine to have a negative impact on growth and grain yield.

Implications of Climate Change on Biofuel Production

Climate impacts crop production and as an example, maize biomass production is presented for Iowa and Georgia and sorghum for silage production in Kansas to demonstrate variation in production over time. Data on corn stover production were derived from the statewide average grain yields available from the National Agricultural Statistics Service (NASS at www.nass.usda.gov/Quickstats) and converted to stover yield assuming a harvest index of 0.5. Hatfield (2010) demonstrated that these observations provide a valuable source of information to evaluate the effects of climate on crop production. In the Iowa data, there are some important observations emerging from the records typical of the Corn Belt (Figure 3). First, there is a continual upward trend in stover production with amounts more than doubling over the past 60 years and the expectation for continued increases in the future. Second, there is a period in the record from 1970 through 1995 exhibiting large variation among years with the variation related to more variation in annual rainfall during this period. The projected climate scenarios for the next 40-50 years are not different than this period with more variable precipitation and inter-annual variation within the growing season. As shown in Figure 2 there is a projected decrease in summer precipitation across most of the United States which will increase the potential likelihood of drought occurrences. These projections are confirmed by a recent analysis of Mishra and Cherkauer (2010) and their findings that maize yields were correlated with meteorological drought and maximum daily temperature during the grain filling period. With the re-emergence of variation in growing season precipitation coupled with the increasing temperatures, leading to greater water use by the crop, then the expectation across the Corn Belt will be enhanced variation in corn grain and stover production among years.

Analysis of corn production trends from Georgia, typical of the Southeastern United States, show similar patterns to those in Iowa (Figure 4). There has been a steady progression upwards in corn grain and stover production and these values represent a combination of irrigated and rainfed production systems. Production levels are lower in Georgia than in Iowa; however, the effect of climate on stover yields exists throughout the entire record due mainly to precipitation variation during the growing season (Figure 4). In both states, decreases in precipitation during the June-August period below the normal amounts were the most significant in affecting production. Decreases in stover production often exceed 30% from the trend line for the record. This same magnitude of reduction is found in the Iowa data as well indicating climate impacts cause significant reductions in corn production. Sorghum for silage production data for Kansas were selected as being representative of a forage crop and there was a large variation in these production values over time (Figure 5). There are some significant differences in the yield trends lines for the sorghum data compared to the corn. First, there is no increasing trend in yields over the 60 years of data. Second, the variation in production among years shows over a 30% decrease in yield with one-third of the years showing a negative yield response. Precipitation is more variable in Kansas compared to either Iowa or Georgia; however, the magnitude of this variation may be indicative of the potential increasing variation in precipitation under future climate scenarios. Climate variation does affect production and the observations by Hatfield (2010) and Zhao and Running (2010) reveal that variation in growing season precipitation is the primary variable affecting production. The projections for increased variation in annual precipitation and overall declines in the growing season precipitation amounts will further exaggerate annual variation in production.

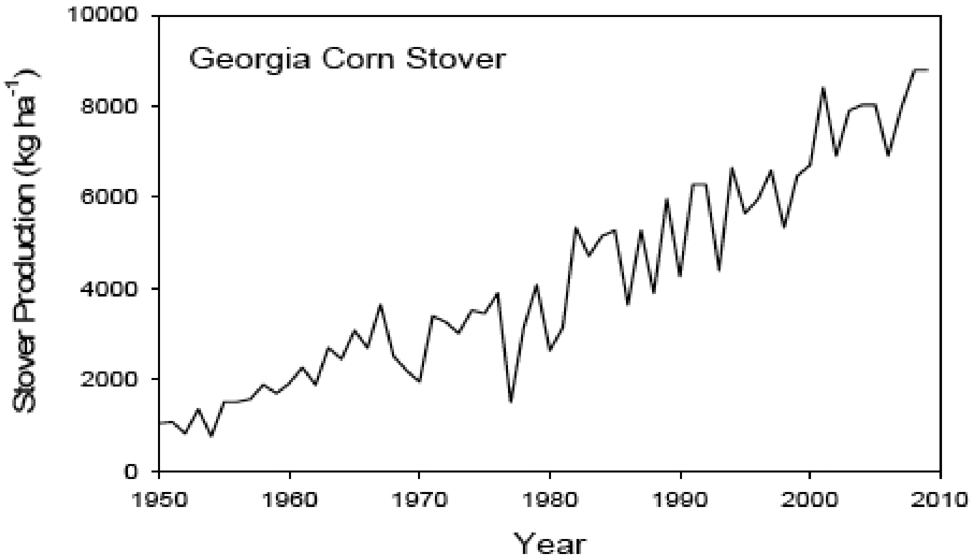

Figure 4. Variation in corn stover production derived from annual corn grain yields across Georgia from 1950-2008. (Grain yield data extracted from NASS Quickstats, www.nass.usda.gov).

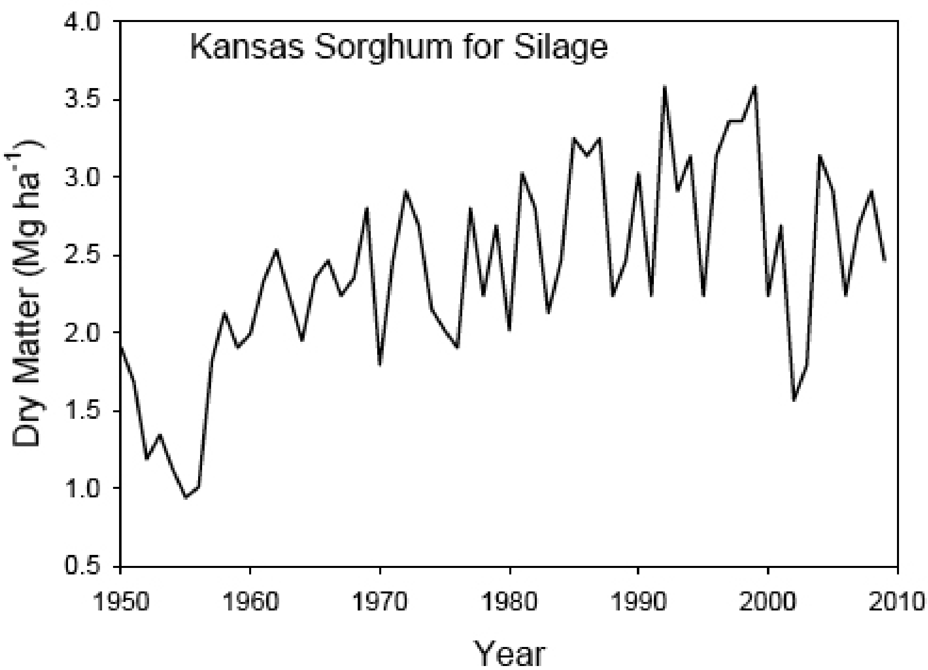

Figure 5. Variation in sorghum for silage production for Kansas from 1950-2009. (Production data extracted from NASS Quickstats, www.nass.usda.gov).

Two other crops are considered as potential energy crops, Switchgrass (*Panicum virgatum* L.) and Miscanthus (*Miscanthus* x giganteus). Both of these are warm season perennial grass species with higher optimum temperatures than corn. Beale and Long (1995) evaluated the response of Miscanthus to more northern latitudes and cooler climates and found the growth was not affected. This would suggest that this crop would be highly adapted to a wide range of climates. Brown et al. (2000) used the erosion productivity impact calculator (EPIC) model to simulate the impact of changing climate on switchgrass, corn, sorghum, winter wheat, and soybean and found that increasing temperatures decreased yields of all crops except switchgrass. They observed the warmer temperatures increased heat stress on the grain crops and hastened crop maturity; however, for switchgrass the lengthening of the growing season and reduced cold stress contributed to the positive response to a warming climate. There are no long-term data sets available to evaluate the impacts of variable precipitation on Miscanthus or switchgrass and some evaluations on water use conducted in Illinois demonstrate water use was higher for both of these crops compared to maize (Hickman et al., 2010). VanLoocke et al. (2010) observed that Miscanthus had a higher water use rate and depleted soil water more than maize. Both of these studies show that water use by these two crops are higher than the traditional grain crops in the Midwest and variation in precipitation would create variations in production. However, given the higher water use rates the impact of increased variation in precipitation may create larger inter-annual variations in production compared to the corn and sorghum production data shown in Figures 3, 4, and 5.

Production of annual and perennial crops offers a potential source of biofuels; however, increased variability in climate over the next 50 years will increase the variability in annual production. This variation will lead to uncertainty in the supply of biomass for energy and also continue to create a situation of the food versus fuel debate in the most appropriate use of the land resources. There are potential adaptation strategies which could be implemented to alleviate some of the potential negative impacts including alteration in planting date, shifting cultivars, greater mix of genetic material to reduce risk, implementation of soil management practices which enhance water conservation and availability to the growing crop, and shifts in the mix of species to take advantage of the warming climate. These have be evaluated for these production systems, but, the information exists from research on dryland farming systems and research conducted during the 1960-1980's in terms in increasing production in water-limited and more arid climates. The future is not bleak; however, there are some challenges to be addressed to ensure we have an adequate balance of food, feed, fiber, and fuel.

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Chapter 22

The National Biofuels Strategy – Importance of Sustainable Feedstock Production Systems in Region-based Supply Chains

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Abstract

Region-based production systems are needed to produce the feedstocks that will be turned into the biofuels required to meet Federal mandated targets. Executive and Legislative actions have put into motion significant government responses designed to advance the development and production of domestic biofuels and other biobased products. Thirty-six billion gallons of biofuels must be blended with U.S. transportation fuels by 2022. With more than 13 of the 15 billion gallons of corn grain ethanol presently being produced, careful planning for the expansion of a biomass sector must be done now because the land and financial resources required to produce the next 21 billion gallons of advanced biofuels are significant – 27 million acres of dedicated feedstock crops and $168 billion to build the needed biorefineries. This paper discusses *Growing America's Fuel*, the U.S. Government strategy to increase the production of biofuels and provide new opportunities for farm, forest, and rural community economic development, and the need for sustainable biomass production supported by the development and growth of fully integrated regional systems that produce biofuels, biopower, and other biobased products. Specific attention is given to the need for understanding expanded advanced biofuel production in a context of multifunctional landscapes, addressing uncertainties of expanded production up-front, using regionalized feedstock strategies, recognizing natural biophysical realities of production limits, the need for continued production efficiency improvement, and policy dynamics. American farms and forests have the capacity to support expanded biofuels production, but care will be needed to produce biomass and other feedstocks in ways that consider the multiple economic, environmental, and social benefits that our rural lands and communities provide so that truly sustainable systems are deployed.

Introduction

Recent Executive and Legislative actions have put into motion significant Federal Government responses designed to advance the development and production of domestic biofuels and other biobased products. The May 5, 2009 Presidential memorandum Biofuels and Rural Economic Development[1] instructed the Secretary of Agriculture to work in concert with the Secretary of the Department of Energy (DOE) and Administrator of the Environmental Protection Agency (EPA) to form the Biofuels Interagency Working Group (IWG) and come up with a comprehensive plan to accelerate U.S. biofuels production. This action was driven by the Energy Independence and Security Act of 2007 (EISA)[2] that expanded the Renewable Fuel Standard [2] (RFS2) by requiring that U.S. transportation fuels contain 36 billion gallons by 2022.[3] With conventional biofuels from corn grain ethanol capped at 15 billion gallons, at least 21 billion gallons will need to be derived from cellulosic and other biobased materials to meet RFS2 requirements.[4] The magnitude of biomass and other dedicated feedstock production needed to achieve this level poses significant technological and financial challenges, and the creation of what amounts to an entirely new agricultural and forestry sector.

Considering where the U.S. is presently and where the country will need to be to meet the RFS2 mandates, the President's Biofuels IWG released its first report, *Growing America's Fuel*, on February 3, 2010 that provided the U.S. Government strategy to increase the production of biofuels.[5] The report pointed out that the present U.S. approach to biofuel development has not put the country on a trajectory to reach the legislative goals that have been set by RFS2. Even though many bioenergy projects have been funded by federal agencies over the past 10 years, there was not an explicit management plan in place across government that pulls together all of the pieces needed for achieving the required targets. Also, critical parts of the required supply chains related to the feedstock supply have received relatively less attention compared to investment into the development of conversion technologies. Critical components of the supply chain that need attention are development of superior performing biomass crops and purpose-grown woody species suited to different growing environments across the country; identification of optimal region-based systems to sustainably produce biomass while at the same time meeting other food, feed, and fiber needs; development of technologies that produce biofuels compatible with the existing transportation fuels infrastructure – particularly those used by sectors that cannot utilize ethanol; and support for development and demonstration projects that bridge the gap between promising innovations and commercial deployment.

With this in mind, *Growing America's Fuel* outlines a transformational management approach for the development of renewable biofuels production by placing an emphasis on outcomes, with clear definition of the roles and responsibilities of agencies across government and using a complete supply chain systems approach. From the sustainable production and management of biomass on farms and in forests, to the transportation and delivery of feedstocks to state-of-the-art biorefinery operations where they are converted into advanced fuels, to their distribution and use by consumers – this effort is designed to strategically unleash the creativity and skills of people in government, university laboratories, garages of aspiring entrepreneurs, and the research and development facilities of the private sector[6] to help create wealth in rural areas, provide opportunities for new industries and jobs, lower greenhouse gas emissions, and reduce our nation's dependency on foreign oil.[7]

The recent economic crisis has set back deployment of first-of-a-kind advanced biorefineries by two or more years. The actions outlined above are needed to reduce financial risks and build investor confidence so the pace needed to achieve our biofuel production goals is put back on track – an approach that is being utilized worldwide to help expand the emerging biofuels sector.[8]

Discussion

The Federal Biofuels Strategy

The purpose of the U.S. Government strategy outlined in *Growing America's Fuel* is to accelerate the commercial development of an advanced biofuel industry – drop-in fuels that can directly replace petroleum-based fuels. Key features of the strategy include utilization of government agencies' core mission competencies; the use of robust public-private partnerships; and working backwards from targets using supply chain systems approaches that are appropriate for utilizing the available natural, human capital, and industrial resources of different regions of the country - an asset-based sustainable development approach building upon the resources available in local communities. The plan is designed to allow all regions of the U.S. to contribute towards achieving the RFS2 goal of 36 billion gallons of biofuels by 2022. The plan also recognizes that policy and institutional barriers need to be overcome,[9] and streamlined processes put into place to help move promising new innovations rapidly from the proof-of-concept stage, through pilot demonstration, and into commercial use. A small high-level management group was identified as needed and established to address policy issues, set timelines, and monitor progress towards completion of clearly defined deliverables.

The plan builds upon the past investments and successes of different agencies but has designated lead-agency responsibilities and accountability for each supply chain segment based on core mission competencies. Combined with high-level management, this approach helps to better ensure that the work done on specific components by different agencies is complementary to the specifications of entire supply chains with their end-product requirements. Without this whole-system perspective, including coordination and feedback from each supply chain component, the limited resources that are available may be directed to component efforts that themselves are good but which may not lead to ultimate highest impact,[10] commercial production of advanced biofuels and achieving the legislated U.S. transportation fuel blending targets.

With advanced biofuels as the desired end-product, the strategy therefore identifies DOE as having primary leadership for the development of new biofuel conversion technologies and basic long-term discovery science. The USDA has research leadership responsibility for the development and sustainable production of dedicated biomass crops and purpose-grown wood species that can be incorporated into existing agriculture and forest-based systems, with delivery of research accomplishments expected in relatively short timeframes of five years or less. Expertise is provided for regulatory and policy analyses by the EPA and the USDA Office of Energy Policy and New Uses (OEPNU). Roles have also been identified for expanding efforts in outreach extension technology transfer, workforce development, commercial biorefinery construction, and all other aspects of supply chain segments by the coordinated contributions of USDA, DOE, and other federal departments including the Department of Transportation (DOT) and Department of Defense (DoD). Formal structures for new partnerships with business development and investment communities have also been formed to help commercialize promising technologies.[11]

Significant coordination across government agencies is needed to implement the *Growing America's Fuel* strategy, so institutions such as the Biomass Research and Development Board (BRDB)[12] and its Technical Advisory Committee provide direction and charge agency policy and technical staff to coordinate Federal activities that promote development and adoption of biobased fuels and other biobased products. The current BRDB is co-chaired by the Under Secretary of USDA Rural Development and the DOE Under Secretary of Science, with principal participation by the USDA Under Secretary of Research, Education, and Economics and the DOE Under Secretary of Energy, along with representatives from the Department of Interior, EPA, DoD, National Science Foundation (NSF), White House Office of Science and Technology Policy (OSTP), and DOT with observers from the Office of Management and Budget (OMB).

Growing America's Fuel provides direction to departments and their agencies for setting priorities and use of existing and new resources. As an example, with assignment of responsibility of the feedstock supply component to USDA, not only has greater coordination been needed to align various service agencies' programs – those who provide service programs that benefit the public (a detailed description of those that apply to biofuels is given below), but also has required input from USDA science and policy analysis agencies to support the procedures and programs that are delivered. In response, the USDA Bioenergy Science Team (BEST) has been established that is made up of representatives from all USDA agencies with science programs [Agricultural Marketing Service (AMS), ARS, Economic Research Service (ERS), Forest Service Research and Development (FS), National Agricultural Statistics Service (NASS), NIFA, and OEPNU] to provide a clearing-house for science and technology consultation. In addition, the Energy Council Coordinating Committee (ECCC)[13] provides linkages among all USDA mission area programs – both service and science agencies.

The *Growing America's Fuel*s plan has also been used as the basis for implementing the new regional USDA Biomass Research Centers (BRC) being co-administered by the ARS and FS.[14] The purpose of the centers is to provide a coordinated, region-based research focus designed with relatively short-term deliverables to help accelerate the commercial production of biomass and other dedicated biofuel feedstocks. The centers provide a focused long-term leadership structure for coordination of biomass research across the country, providing a national perspective that compliments other USDA agency efforts designed to help as many U.S. regions as possible participate in the emerging biofuels and other biobased products economy. Similarly, the recent call for applications by the NIFA for the Agriculture and Food Research Initiative (AFRI), Sustainable Bioenergy Challenge Area, Regional Approaches to Sustainable Bioenergy Systems[15] and certain aspects of the Biomass Research and Development Initiative, Title IX Grant Program (9008)[16] that is jointly funded and administered by

NIFA and the DOE Office of Biomass Research Programs were developed with guidance from the plan, and are complementary with the objectives of the USDA BRC. The AFRI Sustainable Bioenergy Challenge, in particular, takes a regional systems approach that not only focuses on research but also strongly supports and integrates education (workforce development) and outreach (extension and technology transfer), as well as analysis across the supply chain to facilitate the development of sustainable bioenergy systems. The plan also influences other bioenergy research supported by the DOE Office of Science and USDA NIFA Plant Feedstock Genomics for Bioenergy program,[17] as well as the DOE Advanced Research Projects Agency • Energy (ARPA•e) Biomass Energy Projects program.[18]

The plan recognizes the role of the federal government has its limits and requires significant commercialization efforts with private business. Robust partnerships are needed not only among federal agencies but also with state agencies, land grant and other universities, private sector industries and financial investors, non-government organizations and foundations, tribal nations, and international entities. Participation by all partners is needed to synergize resources and investments and complete the needed supply chain components and operations for region-based biofuel production across the country.

The needs for development of region-based supply chains go beyond feedstock production system research. Specific federal support is available to assist commercialization efforts through the USDA and DOE Small Business Innovation Grants (SBIR)[19 20] and USDA and DOE commercialization grants and loan guarantee programs that support pilot-scale demonstration, larger-scaled technology from proven pilot-scaled demonstrations, and commercial-scaled and full-scale sized facilities, as well as multiple deployed commercial facilities. For example, the USDA Rural Development (RD) administers many programs for the production of biofuels through the 2008 Farm Bill Energy Title IX Sections 9003, 9005 and 9007 programs, as well as the Business and Industry Guaranteed Loan Program (B&I Program) that can be used to finance commercial first-of-a-kind scaled and full-scale projects.[21] Similar commercial development programs are available through the DOE Office of Energy Efficiency and Renewable Energy (EERE).[22]

In addition to conversion technology development and biorefinery deployment, a concurrent coordinated whole supply chain effort is needed to help ensure that sustainable supplies of feedstocks will be available to meet the needs of what will be a rapidly emerging biobased economy. In the past, the feedstock needs of the biofuels supply chain have not received as much attention or investment as the technologies needed to convert biobased materials into biofuels – as well as linking the production of appropriate feedstocks to specific conversion technologies. The research and commercialization programs mentioned above can be utilized to help begin to establish linkages between feedstock supplies and new conversion technologies to accelerate commercial deployment by plant material sales companies, farmers, foresters, biorefinery operators, and others involved in advanced biofuels production. So even though feedstock producer risks still remain one of the key challenges for the commercial deployment of sustainable bioenergy producing systems, efforts are underway to understand and mitigate the economic risk to farmers and land managers who may consider producing dedicated energy feedstock crops, instead of traditional products produced from crop rotations or timber stands that may have lower economic returns.

Importance of Sustainable Feedstock Production

Scope of the challenge. Presently, more than 13 of the 15-billion gallons of ethanol from corn grain starch allowed blended with petroleum under RFS2 are being produced at 203 biorefineries in the U.S.,[23] with nearly the required biorefinery nameplate capacity already constructed or planned for construction to produce 15-billion gallons. When the RFS2 cap is reached, around 40% of the U.S. corn grain crop will be used for ethanol production.[24] Beyond corn grain ethanol, advanced biofuel biorefineries will be needed to produce the additional 21-billion gallons needed to reach the 36-billion gallon mandate. These advanced biofuel facilities are mostly in the planning or pilot demonstration phases of development, and the milestone targets under RFS2 are already behind schedule.[25] The USDA reports the investment required for more than 500 new biorefineries needed to produce the 21 billion gallons of advanced biofuels is approximately $168 billion.[26]

In addition to the pace of development and deployment of conversion technologies for advanced biofuel production, what has not been fully recognized is that the expansion of an advanced biofuels industry will also require creation of an entirely new feedstock sector. The biomass and other dedicated feedstocks needed to produce biofuels, biopower, and the raw industrial materials for biobased products will have to be supported by existing agricultural and forestry lands that already produce products for established markets. The agricultural land area required to annually support the feedstock needs could exceed 27 million acres – an area approximately equal to the present area of corn and soybean production in Iowa[27] – and this does not include the agriculture and forestland areas that will provide residues from crops and timber harvest. Fortunately, the needed amounts of feedstocks, the lands for feedstock production, and the biorefinery facilities to produce the biofuels will not appear overnight – scaling up will take time. Also, demands from farm and forest lands may be relieved by more intensive production of purpose-grown wood, algae production, and utilization of animal manure and municipal solid wastes that could be utilized as feedstocks for the production of advanced biofuels.

Scaling up advanced biofuel production will require consideration of factors that can directly influence feedstock supply to individual biorefineries, as well as macro-supply considerations at larger regional and national scales. It is likely that impacts of expanded advanced biofuel production will not be as great for the first 30, 40, or 50 new biorefineries that are initially built, as with the next 300, 400, or 500 facilities that are built.

It is anticipated that expanded production of biomass and other dedicated feedstock crops and purpose-grown wood will affect virtually every aspect of agriculture and forestry – ranging from domestic demand and exports of commodities, to prices, and the allocation of acreage among the crops and timber that are grown.[28] This applies to both local economies that are directly affected by the placement of new biorefineries within their range of influence, as well as regional and nation-scale economies that respond to this new sector – particularly with greatly expanded production.

Address uncertainties up-front. The *Growing America's Fuel* plan specifies that economic, environmental, and social aspects of sustainability be addressed up-front as the advanced biofuel sector expands. Regional feedstock production systems should be designed, implemented, and monitored in ways that lead to management practices that reduce disruption to the existing food, feed, and fiber markets; maintain or even enhance the quality of soil, air, and water natural resources, while at the same time preserve or restore the function of closely associated natural ecosystems; and provide new economic opportunities that benefit land owners and rural communities, as well as the expanded biofuels industry. With these specifications in mind, all regional supply chain components should be considered together to ensure that the resulting systems are productive, profitable, and done with good stewardship of all available resources, including both natural and human capital – an operational perspective of sustainability.

Domestic and international shifts have already occurred across agriculture in response to the growth of the corn grain starch ethanol industry, and changes will likely continue for many years as new advanced biofuels markets expand. Lessons learned from the ethanol biofuels industry,[29] including collateral changes to commodity markets,[30] should be considered and applied as the new advanced biofuels industry becomes established and contributes greater amounts to the transportation fuels market.

There is a wide range of predictions concerning the impacts an expanded biofuel sector will have on existing markets.[31] [32] [33] [34] However, since biomass-based supply chains for advanced biofuels have only just begun to emerge, real-time changes to the conditions of farms and forests, communities, surrounding lands, new biorefinery operations, and markets should be carefully monitored. This will require new applications of existing quantitative methodologies and development of new approaches to track changes in biophysical and socio-economic indicators at appropriate spatial scales, across landscapes, and throughout entire supply chains.

Never before have we known more about the relationships between anthropogenic actions and their impacts on the world around us and had the computational power to describe not just what is happening, but also the ability to attempt to predict alternative futures. Application of system analysis methods with careful monitoring of and adjustment to the development of the structure, conduct, and performance of the new markets could help alleviate conflicts and smooth the transition from a petroleum-based economy to a new bioeconomy. Establishment of key indicators of system conditions combined with modeling approaches, when validated with site-specific information, could help identify problems and be used to suggest changes that support the sustainable development of the emerging industry as it expands.

Recent advances using high-speed computing have linked biophysical and economic models in ways that allow integrated analyses of the impacts of management on environmental and economic factors,[35] and provide opportunities to design systems based on optimized multiple objective and policy alternatives, including social dimensions. Integrated analyses are important because individual supply chain components may not capture important feedbacks and interactions.[36] Integrated analyses may be used to identify the most sustainable options to manage agricultural and forest landscapes, and provide details about the potential tradeoffs that should be considered across regions and competing sectors.[37]

For optimal biofuel supply chains to emerge – ones that benefit all system participants – up-stream biomass supply components cannot be developed without down-stream market signals including cost points and feedstock quality specifications of the biorefineries. Similarly, given options for choosing among down-stream technology adoption, up-stream signals from farms and rural communities need to be included in technologic-economic decision frameworks to provide the most robust opportunities for farm and rural community economic development.[38]

Developing Sustainable Systems – Additional Considerations

Expanded multifunctional landscape approach. Even though the lack of commercial-scale biorefineries is a chief limiter to the immediate creation of widely distributed dedicated biomass and other feedstock markets, the eventual success of advanced biofuels production will not depend alone on the success of conversion technologies or any other individual supply chain component – the aggregation and synergies of all components together will determine ultimate success of future advanced biofuel systems. The optimal ways to develop and produce biomass and other feedstocks will have to be done within a context of complete supply chains that are defined by specific product targets, and considering the multiple economic, environmental, and social services that rural landscapes and their associated communities provide.[39]

Rural lands are already called upon to provide ecosystems services including clean air and water, wildlife habitat, and support for biodiversity; income to farmers, foresters, and their rural communities; high quality, nutritious, abundant, and safe food products; as well a fiber and wood products. In addition to these uses, working lands are now expected to provide the feedstocks to produce biofuel, biopower, and additional biobased consumer products.

The use of corn grain by ethanol biorefineries has also resulted in the production of dried distillers grains (DDG), a coproduct of biofuels production, has been utilized by livestock sector as a feed supplement. So even when lands utilized for crop production or grazing shift to feedstock production to supply biorefineries, the expected production of coproducts produced by biorefineries can be used as livestock feed to off-set some of the impacts. Likewise, feedstocks may be designed to also produce constituents for use in industrial processes and manufacturing. As a consequence, along with the creation of new markets, existing commodity markets, farm and forest income, government payments, and food and wood product prices are likely to change.[40]

Consideration will need to be given to carbon sequestration, validation of environmental credits such as carbon for trading, as well as maintaining limits within the feedstock supply side contributions for meeting biofuel GHG reduction targets under RFS2. As biomass and other dedicated feedstocks are integrated into existing systems, labor, time, and logistical constraints will have to be considered as new operations are introduced into farm or forest annual management operation cycles[41] – these could have significant effects on the quality of rural life, both positive and negative.

All of these factors provide an opportunity for greater use of systems architecture[42] that leads to better designed systems, particularly in a period of uncertainty. New systems should be developed with an on-going understanding of how multi-functional landscapes respond, and with consideration for what could be the most sustainable options to utilize greater portions of farms and forests for biomass production. Ultimately, integrated education and extension activities that address strategic components of the whole supply chain will be needed to assure that a well-trained diverse workforce is available, and to help provide the information decision makers need to meet their production and management goals. Such programs can be delivered by traditional agriculture educational institutions[43 44] or non-government organizations.[45]

Regionalized feedstock strategies. No one kind of dedicated bioenergy crop or purpose-grown wood species will be able to provide all of the required biomass needed to meet or exceed RFS2 targets, so different species options will need to be available depending on the needs of the biorefineries and local production conditions. There are many kinds and sources of feedstocks that can be converted into biofuels. It is important that the limitations to performance of different feedstocks be considered within a context of regional adaptation, and in comparison to the productivity of other feedstocks at the same time – preference and previous investment decisions should give way to longer-term pragmatism. To develop high-performance supply chains that result in sustainable biofuel production, choices will need to be made and efforts concentrated for the best use of the regional resources that are available.

Toward this end, *Growing America's Fuel* recognizes a suite of five classes of dedicated agricultural and forestry feedstocks. The examples are not inclusive of all species that fit these classes, and it needs to be recognized that some feedstocks are not as productive as others, even when grown under their optimal conditions. The classes of feedstocks include: (1) energy cane, a high biomass form of sugarcane that is optimized for sugar and cellulose content; (2) woody biomass – purpose-grown wood species such as poplar, residues left after timber harvest, and harvest of diseased and insect damaged trees;[46] (3) perennial grasses – e.g., switchgrass, Miscanthus, and native prairie species; (4) biomass sorghum (including sweet sorghum); and (5) oil producing crops – e.g., industrial canola, Camelina, soybean, and algae. These five classes are in addition to corn grain starch and crop residues – e.g., corn stover and cereal straw, but do not include other potential sources of feedstocks with significant potential, such as municipal solid waste, waste vegetable oil and tallow, and animal manure – different combinations of which are recognized by DOE and EPA.

Using the five classes of feedstocks, USDA developed regional feedstock production scenarios to determine whether the agricultural and forest resources base was available to meet RFS2 mandates.[47] State-level estimates for biomass and dedicated feedstock production were based on NASS 2007 Census of Agriculture data. It was estimated that a portion of the acreage of higher-risk crops grown in different states could be replaced with dedicated feedstock crops, with the assumption a competitive cost-point could be achieved to displace less profitable, higher risk crops that were already grown in those states. The estimated acres of dedicated biomass crop were then considered as a portion of the total cropland and pasture areas reported by NASS in the region.

The estimated areas of feedstock production utilized in any region ranged from 0.2-12 percent of total crop and pastureland production areas. Planned commercial biorefinery operations in the southeast U.S. and Inner Mongolia, China have set similar limits on percentages of arable farmland to be used for feedstock production to supply their biorefineries and thus minimize the adverse impacts of feedstock production on agricultural enterprise diversity.[48] As more commercial biorefineries come into production, direct observations will be possible to determine the actual impacts expanded biofuels production have on competing land uses.

By selecting a range of feedstocks that are adapted to the wide range of growing conditions across the country, a diversity of supply chains can emerge so that many rural areas will have the opportunity to participate in the production of biofuels – whether already producing feedstocks that contribute to existing biofuels or biopower production, or not. This approach also encourages the use of feedstocks best suited to different U.S. regions, and takes advantage of the geographically diverse natural, business, and workforce resources within the regions. It can be assumed that utilizing a diversity of feedstocks reduces resource pressure on any one area, and provides greater resilience to changing markets, drought, pests, and other production risks.

Realities of biophysical production limits. As global challenges from increasing constraints on world resources are faced,[49] and the most sustainable options to move forward identified,[50] it will be increasingly important to recognize how certain natural biophysical forces drive our ability to utilize resources and produce products. The natural capacity of lands to produce biomass is largely regulated by the natural amounts of sunlight, temperature, and precipitation received and distributed throughout the year – and offset by respiration, is referred to as net primary production (NPP).[51] Tropical regions of the world have the greatest NPP to fix carbon per unit of area. Because the amount of natural NPP in Brazil is more than twice that of the southeastern U.S., the Brazilians can generally produce greater amounts of biofuels per acre per unit of input than the U.S. Net primary production will be a significant factor influencing the long-term capacity and economic competitiveness of different regions to economically produce and harvest the feedstocks needed to meet the biofuels goals of the nation.

In the U.S., semi-tropical Hawaii and the southeast region of continental North America have the greatest NPP.[52,53] Net primary production generally decreases in the U.S. as latitude increases – due to limited production season-length; and generally west of the 100° W meridian – due to limited water availability. The productivity within any region can be enhanced by the addition of external inputs to the production system such as irrigation water and fertilizers – but these are provided at the costs of additional financial, energy, and available water resources. Competition for supplementary inputs, or products produced with those inputs, may limit their availability for use in the future production of feedstocks and ultimately biofuels (e.g., water for use in greater valued agricultural products, industrial purposes, ecosystem health, or human consumption).

Estimates for the amounts of biofuel that can be produced in different U.S. regions indicate that a majority of production will come from the southeastern and central-eastern states (50 and 43 percent, respectively).[54] Although only five-percent of the total U.S. biofuels production will be met by agricultural and forest feedstock production from the western half of the U.S., the region has a significant immediate role to play in the production of lipids that can be converted to advanced biofuels. Existing available transesterification or hydrotreating / hydroreformation technologies have been tested and are currently being certified for commercial use. Also, even though the contribution to the total U.S. need for biofuels may be limited in the western U.S. compared to the Southeastern and Central-East regions, localized production of biofuels could make significant economic contributions within rural communities, on farms, and in forests by reducing the costs of purchased fuels from distant sources and providing new sources of diversified income - especially in regions geographically and logistically isolated from sources of fuel supplies outside the region (e.g. Pacific Northwest).

Continued production improvement. Improving production efficiency through genetic improvement historically has been a proven strategy to increase agricultural output with both positive and negative consequences. Genetic improvement of dedicated feedstocks is needed to increase production per unit of land area, reduce production costs for growers and transaction costs for purchasers of feedstocks, and reduce pressure to utilize competing lands that are needed for the production of other agricultural and forest-based products. Genetic improvement and increased yields can also help maintain ecosystem services from a limited land resources base. Genetic improvement that reduces the costs of purchased inputs, most of which require additional energy to manufacture or deliver, will help reduce the ultimate costs of biofuels and increase their competitiveness with petroleum-based fuels. Yield increases can be expected as has been demonstrated for corn[55] and sugarcane.[56] As the production of biomass and other dedicated feedstocks expands, it will be important to track production input use and other production statistics over time to be assured that specific improvement strategies are working and that high-cost purchased inputs are justified, particularly in light of recent analyses showing that some net genetic gains for existing crops may have reached plateaus on average in certain regions.[57]

When utilizing cellulosic residues for biofuel production after corn grain harvest, continued genetic improvements for yield will also be necessary to ensure that enough residue is available within an economic logistics distance to supply biofuel refineries, and just as importantly to see to it that enough is returned to fields so soil carbon levels and soil quality can be maintained.[58] Soil quality must be maintained to allow continued expression of crop yield potential from genetic improvement.[59,60] The importance of crop and forest residues needed to maintain soil productivity reduces the amount of residues available for biofuel use[61] below earlier estimates.[62] Such stringent estimates are not meant to hinder the utilization of residues or dedicated biomass and other bioenergy feedstocks. Stringent estimates are needed to recognize the biophysical limitations that need to be considered and to ensure that biorefineries are fiscally viable so a sustainable industry emerges that can meet the needs for biofuels now, as well as for future generations.

Integrating conversion technologies and feedstock supplies. The supply of agriculture and forest-based feedstocks to biorefineries introduces new complexities to the production of fuels that relatively static-sourced petroleum-based fuels do not. The initial time required to scale up local feedstock production to match the operational needs of new biorefineries will have to be considered, as well as the synchronization of that supply with the start-up time of the biorefinery. It is estimated that the time to build the feedstock production infrastructure and multiply feedstock materials to match biorefinery input specifications may require four years to accomplish, compared to two years for facility construction.

Additional considerations will have to be given to how weather variability affects not only risks to feedstock production and grower income, but also risks associated with the dependable delivery of feedstock to the biorefinery. The feedstock supplier and biorefinery are linked financially and logistically through geography. Some excess production capacity within the economic feedstock management area of the biorefinery or a backup source of feedstock will be required to maintain biorefinery schedules regardless of periodic interruptions in supply due to factors such as drought.[63] Trade-off strategies that consider when to supplement fresh-supplied feedstocks from production fields with stored or concentrated feedstocks (bio-oils) will need to be determined. The impacts of inclement weather on just-in-time delivery of seasonal and annual feedstocks need to be included in the strategies.

Production strategies are being conceived to extend the feedstock supply period to biorefineries so the length of time a plant operates during a year is greater than when supplied a single feedstock. For example, ethanol facilities in Brazil and Argentina envision extending seasonal operations of biorefineries that use sugarcane as the feedstock by planting sweet sorghum in other fields within the supply radius to extend operations by two months in the period before sugarcane harvest. Sweet sorghum not only diversifies the feedstocks used by the biorefinery, but it also provides a rotation crop to help improve the performance of the sugar cane production system.

Policy dynamics. Policy makers view biofuels and the production of other biobased products as a route to rural economic development and creation of rural economic wealth.[64] As a result, policies have been implemented to provide incentives to reduce risks and encourage investment in commercial biofuel production.[65] The expansion of biomass and other dedicated feedstocks production to support biofuels supply chain development will impact many aspects of existing agriculture and forestry. With this context, it is important to look at how the structure of U.S. agriculture evolved during the twentieth century – much the result of policy.

Programs developed in the past primarily directed resources to boost farm productivity and the use of conservation practices. Resulting changes to agriculture were characterized by increases in farm size and decreases in farm enterprise diversity, greater use of mechanization, increased productivity, fewer numbers of active farmers, population migration away from rural areas, increased use of purchased inputs, and increased exports. Farm policies including government payments also had significant impacts on land ownership, land rental costs, distribution of payment benefits, and production.[66] As a result of increased production and low commodity prices, new food products were developed that helped make processed food and pre-packaged meal products affordable, and a smaller portion of consumer income used to purchase food.[67]

With the decline in the portion of the population involved directly in agriculture and forestry, consumer preferences also changed the direction of production and policies. Continued changes in consumer food preferences have influenced the kinds of agricultural products that are penetrating the market, including high-value commodities and special-use products. Such preferences are affecting demand relating to the scale of livestock and specialty crop operations.[68] At the same time, public interest in the environment has influenced the direction of agricultural to address water and air quality and wildlife and landscape protection – values that are driven by non-farm populations that are far from rural communities.[69] The impacts consumer and market demand will have on the direction of biofuels development are not known. Certain sectors such as air transportation that require advanced biofuels may create new supply chains to meet their needs, while legislated standards may continue to drive broader ground transportation fuel use sector development.

USDA programs have historically helped reduce or shift risks and provide incentives so operators may change what and how they produce. Programs now being applied to biofuels supply chain components are intended to build capacity until more profitable and predictable markets for new biomass and dedicated feedstocks develop. By lowering risks, producers may be more receptive to growing biofuel feedstocks because they will have assured markets for their product. Just as programs have been created to help reduce investor uncertainty and provide incentives for the construction of new biorefineries,[70] uncertainty affects grower confidence to plant and grow the feedstocks needed to supply new biorefineries.

There are multiple USDA programs to help reduce risk and instill confidence to make investments in the production of dedicated feedstock crops and purpose-grown wood. The USDA Farm Service Agency (FSA) offers the Noninsured Crop Disaster Assistance Program (NAP)[71] to reduce production risks faced by producers of commercial crops or other agricultural commodities (including biomass) that are not otherwise insurable through normal commercial or USDA Risk Management Agency insurance tools. The NAP reduces financial losses that occur when natural disasters cause a catastrophic loss of production or when producers are prevented from planting an eligible crop. The FSA Conservation Loan (CL) program[72] provides farmers access to credit to implement conservation practices approved by the Natural Resources Conservation Service (NRCS) such as those to reduce soil erosion, improve water quality, and promote sustainable agricultural practices. The FSA Biomass Crop Assistance Program (BCAP) provides financial assistance to producers or entities that deliver eligible biomass materials to facilities that produce heat, power, biobased products, or biofuels. The BCAP program assists with collection, harvest, storage, and transportation costs associated with the delivery of eligible feedstock materials to qualified conversion facilities.[73]

The results of implemented policies can have unforeseen consequences. Increasing use of biomass for biopower generation has begun to create new supply chains that require biomass to offset carbon emissions in coal-burning facilities and overseas markets, but this has created new challenges to existing industries that utilize wood wastes when the profits from sales to new power markets are greater than when used in traditional markets. Initial USDA regulations for implementing the BCAP provided a shift in market profitability that led to a movement of sawmill residues away from traditional product markets such as particleboard to biopower.[74] More market adjustments can be expected to occur as production and utilization of dedicated biomass crops and purpose-grown wood becomes more widespread.

Lowered risk to incent feedstock production does not need to be the sole domain of public agency programs. Private business can also help reduce grower risks by providing long-term contracts with price guarantees for feedstocks production. Such actions by biorefineries and other downstream users helps ensure adequate supplies of feedstock will be produced and delivered to maintain operations, that in turn leads to additional investment in processing facilities.

More research is needed to understand the roles and interactions the private sector and public policy will have in creating sustainable supply chains, particularly as actual advanced biofuels facilities come into full-scale production. A whole-system perspective is needed for technology development to help accelerate advanced biofuels development forward. Similarly, given the limited public resources that are available, a coordination of public efforts combining science and service agencies programs is needed to help identify and create the needed components that will make up sustainable supply chains.

Conclusions

Growing America's Fuel provides an integrated strategy supporting the development and growth of region-based systems for the sustainable production of biofuels, biopower, and biobased products. This regional approach provides the opportunity to support the participation and economic development of as many rural areas as possible. It is within this context that the agricultural and forest-based bioenergy sector is being encouraged to emerge, with an expectation that consumer interest in biofuels could greatly influence the market signal, and thus the demand for biofuels.

The plan recognizes that increased attention must be given to the development of entire supply chains. However, unlike conventional crop production and forest management systems, the kinds of biomass and other dedicated feedstocks that are produced must fit within the needs of the biorefineries that deliver biofuels certified for specific end-user needs. There is an opportunity to design entirely new agricultural and forestry sectors that can dependably produce and deliver the supplies of the biomass and other dedicated feedstocks that will be needed, and doing so with economic, social, and environmental costs and benefits in mind from the beginning, so that truly sustainable biofuels are produced and available now, as well as for future generations.

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Chapter 23

Where To From Here?

Douglas L. Karlen

The goals for this workshop and the subsequent regional roadmaps were to provide a science-based background and forward-looking strategies that would enable agriculture to help solve our nation's bioenergy challenges by ensuring sustainable feedstock supplies for advanced biofuels. The background chapters formed the basis for the workshop presentations, while the six regional roadmaps show how agriculture can provide region-based strategies to solve complex problems. None of the strategies are individually optimal for all geographic regions.

Agriculture has tremendous potential to help solve America's energy challenges, but soil, water, and air resources cannot be managed using rigid engineering practices or designs. Natural resources are living and dynamic-changing in response to natural and human-induced stresses. Identification of the six U.S. regions delineated in the workshop was based on participant input. The teams preparing each roadmap were self-selected and represent both technical-and experiential-based knowledge that is unique for each region. Yet there are some common principles within each roadmap that provide guidance for those seeking to work with agriculture to solve bioenergy and other complex problems. Key points from each roadmap include:

1. Regional Diversity
   - a. The Southeast included 11 states and most of the U.S. Piedmont and Coastal Plain. It has the highest net primary productivity (NPP) of any region and is capable of producing almost any feedstock.
   - b. The West has many unique features including the Desert Southwest, Pacific Northwest, Rocky Mountains, Pacific Islands, California, and Alaska, each with different natural and cultural resources that interact to influence bioenergy development.
   - c. The Northeast roadmap covered 12 states and the District of Columbia and accounts for about 21% of the U.S. population on only 6% of the nation's total landmass. Its unique features include having significant amounts of standing biomass suitable for advanced biofuel production and large urban areas with high demand for liquid fuels.
   - d. The Mid-South region included Arkansas, Western Alabama, Louisiana, Mississippi, Southern Missouri, Tennessee, Eastern and Central Texas, and Eastern Oklahoma. It has: 1) a semi-tropical climate with east-west rainfall and north-south temperature and growing degree unit (GDU) gradients, 2) sufficient rainfall and GDUs for many bioenergy crops, although seasonal weather patterns can be extremely variable, and 3) a large amount of marginal land, numerous scattered and diverse agricultural production systems, and a large number of small land holdings.
   - e. The Great Plains is a national leader in the production of livestock, ethanol, and cotton, and has a cultural history of producing herbaceous perennials as well as a diverse supply of crop residues. It is poised with an available workforce as well as an agricultural and transportation infrastructure that can move rapidly from the research scale to full-scale functional systems as part of the U.S. bioeconomy. Water availability for feedstock production and biofuel processing is a significant limiting factor in this region.

f. The Upper Midwest included Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, Northern Missouri, and Wisconsin. It is an area characterized by highly productive Mollisols that were predominately formed under prairie conditions and Alfisols that formed under forested conditions. Midwest crop and animal production opportunities are significant. The challenge will be balancing regional feed and food production, natural resource protection, and advanced biofuel production.

2. Critical Perspectives

a. The potential for western U.S. feedstock development is generally under-estimated because many crop residues, available forest resources, and dedicated energy crops are widely distributed and often only available in small quantities in any given area.

b. Variation in both national and state policy definitions of feedstock often exclude some types and sources of forest biomass prevalent in the West.

c. Perennial forages were identified as the most viable advanced biofuel feedstock for the Great Plains region.

d. Standardized guidelines for risk assessment may be needed in all regions before growers produce any bioenergy feedstock. If the risk is too great, producers will continue growing their current crops.

e. One of the greatest advantages for sorghum in the Mid-South is that it has a very mature seed industry that can readily provide sufficient material for widespread production.

f. The diverse rural Northeast landscape will prevent any single feedstock from dominating the market. Successful biomass supply chains for advanced biofuel production should use a hub and spoke distribution system, similar to current grain-handling systems, rather than centralized mega-refineries. The hub and spoke distribution system may also work well at the national level.

g. The Southeast is expected to continue receiving relatively high amounts of rainfall making transport and processing plant location critical for feedstock selection. Although rainfall may be significant, many Southeast soils have low water holding potential. Soil conditions and irregularity of rainfall frequency dictate that drought-tolerant species will be selected over those that cannot sustain themselves under these conditions.

3. Research & Development Needs

a. To ensure sustainable feedstock supplies, region-specific studies will require consideration of invasiveness, conversion efficiencies, environmental effects, residue removal, nutrient and water use efficiency, and land use conversion.

b. Current biophysical, economic, and life cycle models being used to estimate potential feedstock supplies will need regional parameterization.

c. Feedstock development, establishment, production (including harvest, storage, and transport), economics, ecosystem service assessment and monitoring, life-cycle assessments, and factors influencing producer adoption should be quantified collaboratively with feedstock producers by establishing long-term research sites.

d. Genetic diversity among woody species needs to be understood and utilized more completely to increase biomass supply.

e. Region-specific net primary production (NPP) and carbon mapping studies are needed for all potential feedstock sources.

f. Optimal conversion platforms need to be identified for all potential feedstock sources.

g. All dimensions of sustainability need to be defined with an agreed upon set of standards.

h. Production efficiency, in terms of energy content per unit of production, needs to be determined for each feedstock using available conversion technology.

i. Information needs to be developed and rapidly exchanged between producers and industry through collaborative research, extension, and education efforts.

j. Multi-state, regional consortiums of decision makers, scientists, non-government organizations (NGOs), producers, and consumers should be fostered to develop policies, breakdown barriers, create markets, and encourage development and adoption of sustainable bioenergy systems.

In summary, as we move forward to develop sustainable feedstock supplies for advanced biofuels, it will become increasingly important to recognize the diversity within agriculture and forestry resources. We must also strive to work with the natural resources base rather than attempting to control or overcome it. There is no single feedstock that will be desired or most effective for any region, or the nation as a whole. Understanding and utilizing feedstock diversity and its linkage to conversion technologies may be the key to the future solutions. Indeed, agriculture and forestry can contribute to sustainable solutions for America's energy challenges.

Sustainable Alternative Fuel Feedstock Opportunities, Challenges and Roadmaps for Six U.S. Regions

Proceedings of the Sustainable Feedstocks for Advance Biofuels Workshop

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Regional Roadmaps

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Chapter 24

Upper Midwest Regional Roadmap

Upper Midwest Biomass Sustainability Plan

The Upper Midwest comprises the states of Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, Missouri, and Wisconsin. The area is characterized by highly productive Mollisols, which were formed under predominately prairie conditions and Alfisols which were formed under forested conditions. The opportunities that exist for this region to produce biomass are phenomenal. The challenges in maintaining the region's food production and natural resource protection are real and must be considered in all aspects of moving the country towards advanced biofuels.

Logistics

Contributed by Bill Berguson

Issues related to the logistics of biomass procurement are important and have the potential to affect price, location, and risk associated with biofuels production. Logistics issues involve the production, harvesting, handling, transport, and storage of biomass materials to ensure a consistent year- round supply of biomass to conversion facilities. Several factors can affect the logistics of biomass procurement. The type of biomass material and whether it is agricultural residues or biomass produced through dedicated energy crops can affect feedstock logistics. Agricultural residues such as corn stover or wheat straw are obviously collected at or very near the time of harvesting the grain crop and, as such, have the potential to interfere with the grain harvest particularly during those periods of difficult weather conditions. Desynchronizing harvest timing can be accomplished using a mix of residues and purpose- grown energy crops, both woody and herbaceous, which would provide greater flexibility in timing of harvest. Also, storage issues are of concern. Moisture content of biomass material such as wheat straw and herbaceous biomass must be below a threshold to ensure that self- heating and fire risk is minimized. A mix of woody and herbaceous biomass may be important to allow greater flexibility in harvest timing and storage.

Advances in harvesting technology are needed to produce biomass in the preferred form (bales, chips, bundles) having the desired characteristics (moisture content, ash content, low nutrient content) that contribute to efficient production and processing. Transportation logistics such as highway infrastructure and truck availability are important considerations. While some logistics issues are relatively straightforward and technology is relatively advanced, additional research and development is needed to resolve logistics issues associated with biomass procurement for the future U.S. biofuels industry.

Nutrient Supply and Use

Contributed by Scott Murrell

Nutrients are resources that require well- informed management to ensure their availability in the future. Both short and long- term objectives must be met with their use. Short term objectives include efficient use of nutrients; meeting quality and quantity requirements of biomass feedstocks for renewable energy industries; limiting nutrient losses to the environment; and creating profitability in all parts of the production and end- use chains. Long- term objectives are to improve and maintain the productivity of soils, improve or preserve environmental quality, and ensure nutrient resources are available far into the future.

It must be recognized that the Upper Midwest is characterized by weather and landscape variability that creates significant nutrient management challenges. A roadmap for future nutrient management will need to consider the following questions for each feedstock under consideration:

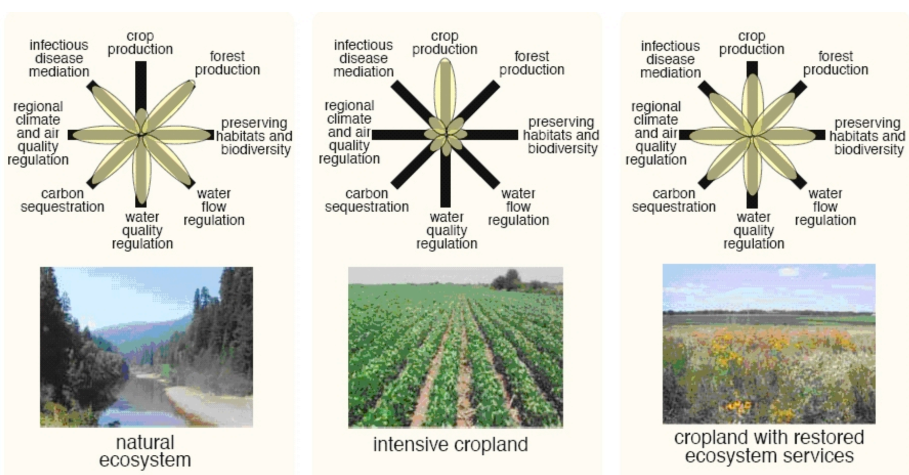
- What nutrient sources, rates, application timings, and placement methods are needed to realize short and long- term objectives for biomass feedstock production?
- How do management practices need to be configured on a site- specific basis to address weather variability as well as variability within fields and landscapes?
- To what extent can a biomass production and manufacturing system recycle nutrients to avoid stressing nutrient resources?
- How will nutrient use in the U.S. affect nutrient imports, exports, and global supplies?

The role of science in future nutrient management will be to define important factors to consider, the magnitude of their potential impacts, and the probability that their affects will be felt in a production system for a given set of circumstances.

Ecosystem Services

Contributed by Michael Jawson and Evan DeLucia

Ecosystem services are defined as the benefits provided by ecosystems (UN Millennium Assessment, 2005) or as the benefits that humans derive from ecosystems. These include provisioning services such as food, water, timber, and fiber; regulating services that affect climate, floods, disease, wastes, and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling. Maintaining sustainability requires that the primary ecosystem service provided by a particular land use, such as biofuels production, cannot eliminate other ecosystem services to such an extent that they are not available to future generations. That is, a balance must be maintained among the ecosystem services as shown in the figure below. While ecosystem services represent a conceptual advancement in the management of natural, cultural, and other resources, there are a number of issues that still need to be addressed for this concept to be more fully utilized within the biofuels production arena and more broadly across all applicable situations. Among these is the identification of the critical ecosystem services for a particular situation and how they will be monetized. Monetization will require societal and specific interest group values to be explicitly addressed. Addressing these knowledge gaps is necessary to more fully utilize ecosystem services as a guiding principal. However, even without full characterization of ecosystem services, they still are a necessary element of a roadmap to sustainable biofuel production.



Source: http://es.epa.gov/ncer/rfa/2009/2009_star_ecosystem_services.html, (April 3, 2009)

Note: Modification of these diagrams is needed for biofuel production.

Productivity Optimization

Contributed by Mike Edgerton

Highly productive systems are required for agriculture to provide us with sustainable supplies of food, energy, and environmental services. Where production is not able to keep pace with demand, short-term needs drive the use of unsustainable practices that ultimately end with the exhaustion of soil and other natural resources (Montgomery, 2007). The growth of bioenergy markets and increased awareness of environmental services is placing new demands on agriculture, increasing the importance of productivity in agriculture.

Improvements in farm productivity historically have come about as new agricultural technologies are developed (Troyer, 2006) and adopted by farmers (Griliches, 1960). Technological improvements have come from both improvements in genetics and advances in agronomy (Duvick, 2005), which can act synergistically and allow, as examples, earlier planting dates (Kucharik, 2008) or higher plant populations (Hammer et al., 2009). As farmers gain experience with new technologies they balance risks and costs to optimize their operations (Babcock, 1992), reducing the gap between crop yield potential and actual yields (Lobell et al., 2009). Efforts to increase productivity must therefore encompass agronomic improvements, genetic improvements and the supply of realistic production costs and risk information to farmers.

Bioenergy feedstocks in the upper Midwest have different needs, ranging from education and knowledge transfer to longer term questions requiring additional research. Woody feedstocks, with established agronomic practices, may be grown outside of their current range requiring transfer of knowledge and skills to a new set of farmers. Harvest of corn stover requires both education on best management practices and also new research to better understand the effects of residue removal on soil properties and nutrient dynamics. Perennial grasses, while not totally new crops, have the least established management practices and will benefit from research on establishment, nutrient management, pest and disease control, harvest methods, and many other management issues. Integration of the different crops is hypothesized to improve productivity of food, energy, and environmental services. However, estimates of benefits is largely based on theoretical approaches (e.g. Nassauer and Corry, 2004) and direct study of integrated landscapes is needed to validate the economic and environmental assumptions used in landscape design models.

Productivity of all of the bioenergy feedstocks in the region can be increased by genetic improvements. Rates of improvement and investment in breeding programs will depend on the species, as an example, woody crops have longer cycle times than annual crops. Genetic improvement of the more profitable crops occurs largely in the private sector (Bliss, 2006) with important contributions such as improved disease resistance coming from the public sector (Meyer et al., 2009). There is some speculative investment in private sector grass breeding programs but significant public investment is needed for less established biomass feedstocks. Private sector breeding programs use integrated testing, genotyping, and data analysis tools to maximize returns from investments the programs. In contrast, many public domain breeding programs are fragmented, with individual programs independently developing genotyping and data management platforms (Dubcovsky, 2004). This fragmentation reduces genetic rate of gain and hinders data exchange and learning across breeding experiments. Productivity in most bioenergy feedstocks can be improved by the development of a coordinated public genotyping and data analysis platform that works across all feedstocks and breeding programs

Uncertainties around bioenergy and environmental services markets are barriers to the development of these markets. Simple questions, such as feedstock specifications for bioenergy applications have not be answered and cannot be answered until the tradeoffs between upstream costs to produce feedstock and downstream costs to a processing operation have been answered. Realistic yield expectations and annual yield variations, particularly for newer crops on "marginal" land, are not well understood. Similarly, the value of different environmental services or the quantity of services obtained from different landscape management options are not well understood. The development of "small" scale (~ 50,000 dry tons/year), profitable, or breakeven bioenergy programs operating in niche markets with higher energy costs, such as university power plants, could provide a laboratory in which many of these questions could be answered.

Increased productivity, increasing returns from each cultivated acre, allows choices between food, energy, and environmental services. Productivity in all three areas can be increased by investing in agronomics, genetics, and farmer education. The establishment of actual working bioenergy operations on local levels can provide important laboratories where new ideas can be tested and data on costs, yields, and environmental impacts can be collected and bioenergy production can begin moving down the learning curve.

Food – Feed – Fiber – Fuel Balance/Competition

Contributed by Gary Feyereisen

Agricultural land is a finite resource. Increasing production of biofuels raises the question of how this resource should be allocated for food, feed, fiber, and fuel. Some shifting of land use has already occurred. In Iowa, corn area has been increasing, at the expense of soybeans, for the past decade by about 200,000 acres per year. Using an increasing fraction of the corn and soybean crops for biofuel production has the potential to reduce grain available for feed, export, or other uses, placing upward pressure on food prices domestically and internationally. Government policy, through farm subsidies, crop insurance programs, export credits, import tariffs, production quotas, biofuel mandates, conservation programs, and other market manipulations, directly and indirectly affects resource allocation across food, feed, fiber and fuel uses, making this a public conversation.

Multipurpose crops, such as corn or soy, which can produce biofuels, food, and feed, maintain the flexibility to reallocate across end uses in the event of a short crop. In contrast, perennial cellulose crops can only be used for energy production or possibly as cattle feed. Because conversion to perennial crops requires significant capital investment and multiple growing seasons, lands in perennial crop production are unlikely to be available for food or feed production for several years. Locating perennial cellulose crops on land less suited to row crop production can reduce the drawbacks of long- term land commitment and offers potential benefits such as increased erosion protection, improved water quality, and wild life habitat.

Corn and soy are the primary biofuel feedstocks in the Upper Midwest region today. However, crop residues, perennial grasses, woody products, and other oilseeds may all become important feedstocks in the future. Crop residues, provided they are harvested without negative impact on soil and the environment, may have the least impact on grain production. Some competition could exist where crop residues are used for animal feed or bedding. Cover crops or double cropping may increase crop residue harvests. All of the other bioenergy feedstocks will have some effect on land available for feed production. Perennial grasses, including crops such as Miscanthus, could compete with grain production if grown on high quality crop land. However, high biomass yields may mitigate this and some grasses offer flexibility as forages. Establishment of woody crops such as hybrid poplar or willow is a decades- long venture; thus, the permanence of this strategy and displacement of other land uses requires deliberate consideration. Use of oilseed crops for biofuels will add pressure to vegetable oil markets, a factor compounded by the relatively low yield per acre of oilseeds. Displacement of soybean acres with another oil seed that yields more oil per acre may mitigate this, but may also have an impact on protein supply. The appropriate biofuel feedstock for a given region or locality will be driven by the unique combination of climate, soils, alternative land uses, and market opportunities. Creative use of the various biofuel feedstocks within the landscape is needed in order to increase overall harvest without significantly degrading the environment.

Policy

Contributed by Marilyn Buford

Policies are generally considered to be stated principles that guide decisions made to achieve rational outcomes. Policy application often occurs in the context of complex systems, such as governments and economies, and policies that do not consider the universe of critical factors influencing the outcomes can have counterintuitive and counterproductive effects. While numerous questions regarding biofuels and bioenergy are debated from local to national to international levels, there is general agreement that to some degree, bioenergy and bioproducts can help meet energy security, environmental quality, and economic opportunity goals.

Bioenergy and bioproduct policies operate at the nexus of national security, environmental quality, and economic opportunity. As such, analyses must consider these important objectives and calculate relative costs and benefits of alternatives across that nexus. For example, a lifecycle analysis comparing biofuels to conventional petroleum- derived transportation fuels that ignores the greenhouse gas emissions associated with related military operations, such as sea lane security, is likely seriously flawed (Moran and Russell 2008, Liska and Perrin 2009, Liska and Perrin 2010).

Science and scientists do not make policy but research results and their interpretation and limitations inform policy makers and influence policy. Research that leads to new feedstocks, novel and effective management and production systems, efficient conversion systems, and quantifying the relative costs and benefits of alternative energy systems is critically important in reaching renewable energy goals and in informing policy development and application. It is also critically important to understand the connections and interactions between agriculture policy, natural resource policy, and energy policy, and how these policies might be effectively integrated to reach national goals.

Summary

Contributed by Newell Kitchen

On a region- by- region basis, nowhere in the U.S. has the landscape been so completely enlisted into feed grain crop production than the region represented by the Upper Midwest. National maps showing where corn and soybean crops are annually grown demonstrate all the necessary elements are in place to productively and efficiently grow these two crops foundational to the modern human food supply due to highly productive soils, ideal growing seasons with generally sufficient water without supplemental irrigation, well- developed storage and transportation systems that capitalize on major river ways, extensive agribusinesses providing crop inputs and equipment sales and maintenance services, and two centuries of human experience managing the landscape. While production of these feed grains is extremely successful here, the mono- culture, annual crop system has also disrupted important landscape ecosystem functions resulting in major environmental challenges. Federal, state, and local governments continue to spend millions on educational programs and conservation practices addressing these issues and yet many environmental issues persist.

Now crop production has a growing demand with biofuels. The same factors found to make the Upper Midwest so productive for feed grain production are also projected to be essential for developing a sustainable biofuel feedstock production system. Thus the question often asked is “How will humanity respond to the projected demand for bioenergy feedstock crops to help power modern societies in a world also increasing in food demand?” Simply stated, can both food and biofuel production systems coexist? While market pull will ultimately shape how the Upper Midwest landscape is managed in the future, the convergence of food and biofuel production needs creates a unique opportunity to optimize crop production systems. The working hypothesis of this chapter is that by integrating food and biofuel production within the landscape, productivity can be improved over the current monoculture feed-grain system and will simultaneously promote greater landscape ecosystem services. The guiding principle for accomplishing this will be diversification. Greater diversity is needed with: 1) crop selection (e.g., grain crops, oil crops, herbaceous perennials, woody crops); 2) placement of crops to match soil and landscape resources; 3) crop genetics developed and marketed with landscape performance criteria included; 4) critical inputs necessary in highly productive crop management systems (e.g., use and reuse of nutrients), and 4) delivering and processing of plant products into feed and fuel commodities.

Reference for Ecosystem Services Section

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Chapter 25

Northeast Regional Roadmap

2030 Bioenergy vision for Northeast region

Regional overview and working hypotheses

The Northeast region includes twelve states (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and West Virginia), as well as the District of Columbia. Altogether, this region accounts for ~21% of the US population, with ~6% of the nation's total landmass (~7.5% of continental US; http://quickfacts.census.gov/qfd/index.html). Petroleum consumption in 2008 for the Northeast was a little over 17% of the US total (http://www.eia.doe.gov/state/), indicating that per capita petroleum consumption - particularly for transportation fuel - is somewhat less than other regions. However, many Northeast states are notable for significantly higher usage of petroleum- based home heating oil during winter months as compared to other regions.

The six New England states and New York consumed 2.09 quadrillion BTUs of thermal energy in 2007 for space heating, hot water, and industrial heat, representing 38.7% of all energy consumed in these states for electricity, transportation and thermal needs (BTEC 2010). Over 95% of these thermal needs are met by fossil fuels, predominantly natural gas, heating oil, and propane. With consumption of about 5 billion gallons annually (4 billion gallons in residential systems and about 1 billion gallons in commercial units), the Northeastern U.S. is one of the world's largest markets for heating oil. Heating oil represents 54 percent of total demand for #2 distillate oil in the Northeast, compared to 38 percent for highway diesel. The northeast U.S. consumes 86% of all the distillate oil used for heating applications in the U.S. This is one of the only regions in the U.S. and one of the few regions in the world that depends so heavily on oil for thermal needs.

According to recent projections by the USDA (2010), the Northeast region is expected to account for approximately 420 million gallons per year (MGY) of advanced biofuel production by 2022. This would be equivalent to 2% of the 21 billion gallons per year (BGY) national advanced biofuel target for 2022 as defined by the revised Renewable Fuel Standard (RFS2) established by the 2007 Energy Independence and Security Act. Such a modest biofuel projection for the Northeast should be interpreted with some caution. First, USDA's (2010) regional boundaries were drawn according to assumed similarities in dominant feedstocks, which resulted in the inclusion of a somewhat different set of states than those defined here. In particular, Michigan was included by USDA (2010) in the Northeast region, while Delaware, Maryland, and Pennsylvania were instead placed in the Central East region. Secondly, more local analyses have indicated that there may be the potential for significantly higher advanced biofuels production in the Northeast than suggested by the USDA. For example, the recent renewable fuels roadmap produced in NY indicates that between 500 - 1,449 MGY of sustainably produced lignocellulosic advanced biofuels could be profitably produced in the State of New York alone by 2020 (Wonjar et al. 2010). The upper end of this estimate is 3.5 times the USDA estimate for the entire Northeast U.S. A spatial overview of total available biomass estimates (including urban and landfill waste streams) made by the National Renewable Energy Laboratory for Northeast counties is shown in Figure 1, while biomass estimates that exclude these waste streams are shown in Figure 2. (NOTE: The authors expect that the yields indicated in Figures 1 and 2 are significantly underestimated for all sources, particularly woody biomass from forests in the Northeast region and perennial grasses on the coastal plain.)

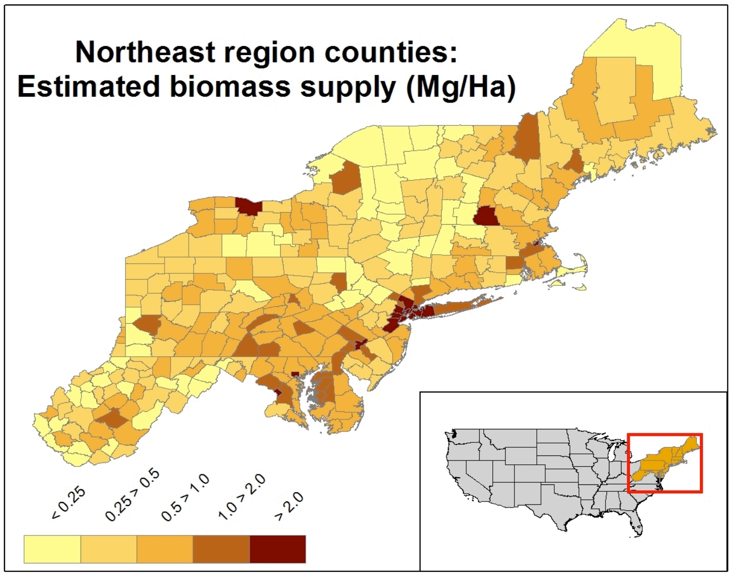

Figure 1. Data adapted from Milbrandt (2005)

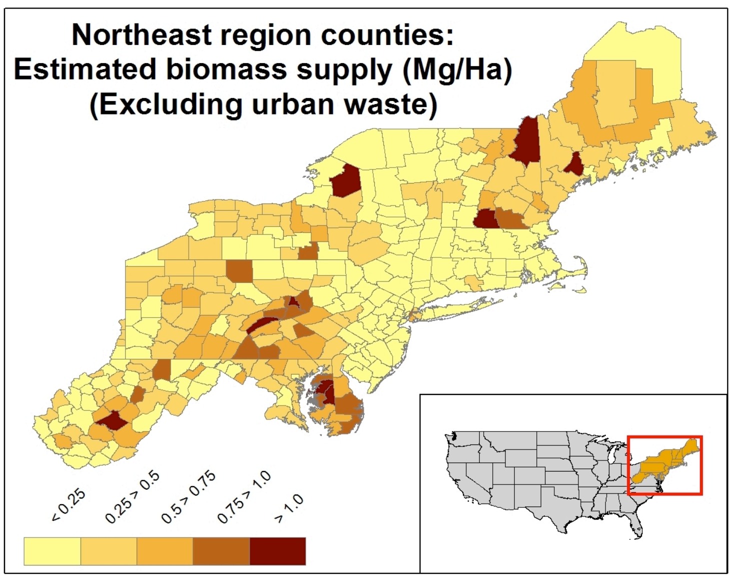

Figure 2. Data adapted from Milbrandt (2005)

Because the Northeast contains both significant amounts of standing biomass suitable for advanced biofuel production and large urban areas that have significant demands for liquid fuels, our working hypothesis is that the regional road map should not be constrained by the assumption that the USDA (2010) projections of modest biofuel production in the Northeast will necessarily hold true. However, our panel largely agreed with USDA's (2010) suggestion that two of the most promising sources for near- term bioenergy production in the Northeast region are likely the high volumes of low value wood found on existing forestry lands and waste biomass from urban areas. It was also noted that longer term scale up of the bioenergy industry will undoubtedly require extensive cultivation of perennial grasses and short rotation woody crops, particularly on marginal lands. While use of crop residues, particularly corn stover, may also play some role in bioenergy production for the Northeast, there was consensus among the group that the scale of residue utilization in this region is likely limited by large extant demands for this material from both the dairy industry and well- established soil conservation protocols. Moreover, a major increase in corn acreage for production of either grain- based ethanol or stover- based advanced cellulosic biofuels is not foreseen by our group as a likely scenario for the Northeast. As an example of the region the NY Renewable Fuels Roadmap indicated that between 9.4 and 14.6 million oven- dry tonne (odt) per year of biomass could be sustainably produced in NY in addition to all the current food and fiber production (Wonjar et al. 2010). About half of the biomass is from forest resources and the next largest source is perennial energy crop. Crop residues and waste grease contribute less than 15 percent of the total potential supply.

What this overall vision entails is continued maintenance of the diverse landscape that currently prevails in the rural Northeast, with no one feedstock or perennial or annual energy crop becoming dominant in the region. Such a vision further argues for the development of a biomass supply chain and advanced biofuel production sector that is distributed across the landscape, rather than one that is necessarily centralized into “mega- refineries” (i.e., producing in excess of 60 MGY of biofuel; Gray et al. 2010). This distributed production system would be characterized by numerous collection facilities in which a wide diversity of raw biomass would be delivered from across local landscapes (i.e., < 10 miles of transport distance), and then pre- processed into biomass products standardized for use in the bioenergy sector. Following the pre- processing stage, the standardized products would then be efficiently transported to biofuel refineries and/or other bioenergy usages by means of rail, barge, and/or long- haul trucking. This type of distributed production system is also sometimes referred to as the “hub and spoke” model (Figure 3). Carolan et al. (2007) proposed a hub and spoke system for cellulosic ethanol production in Michigan and concluded it likely to result in lower minimum ethanol selling prices because of lower feedstock and by- product transportation costs, higher returns to scale, better capacity utilization, and cross- subsidization from other value added products. Also, they suggest the system could reduce the number of contracts for a biorefinery with feedstock producers and improve contracting efficiency.

The hub and spoke system could have multiple other benefits that would contribute to a local, diversified sustainable landscape. It could encourage local investment in pre- processing facilities and generate rural jobs and local economic development. This system would contribute to the use of multiple feedstocks and a commoditized bioenergy feedstock development that would encourage diverse feedstock in the landscape. Feed or other co- products could be developed as value added product streams that could be utilized in these rural communities. Nutrients extracted from the feedstock could be recycled to fields and forests, maintaining soil productivity and avoiding the concentration of nutrients observed in concentrated animal feeding systems. Ideally, this system could enhance the biodiversity already present in this region and help to stimulate economic development in the rural areas of the northeast where it is most needed.

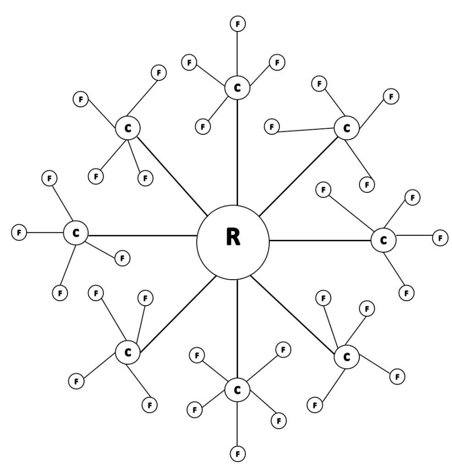

Figure 3: Hub and Spoke Framework for Biomass Transport and Processing

F = Forest / Farm biomass source; C = Biomass collection facility; R = Refinery

Northeast roadmap (Summarized in Figure 4)

Phase 1 goals: 2010 - 2015

Our group identified several issues as critical for the near- term emergence of a sustainable bioenergy and advanced biofuels sector - based upon the distributed hub and spoke model - in the Northeast region. Perhaps most essential is the establishment of industry specifications that guide the pre-processing of biomass products for compatibility with their final intended usages, including advanced biofuel refineries, co- firing in electrical power plant, pellets for home heating, and other applications (see, e.g., Hess et al. 2009; Miranowski et al. in these proceedings). Such specifications are particularly necessary for the Northeast, where a diversity of feedstock types will be utilized. The group also agreed that a simplification and rationalization of the regulatory and policy structure is needed to provide the appropriate signals for development of the biomass industry. This point about the need for better policy guidance was also noted in the keynote presentation by Jody Endres, in a submitted paper by Steve Kaffka, and by several regional break out groups during the course of the workshop.

Use of biomass products - particularly low value material from forests and perennial energy crops - as a substitute for home heating oil is regarded as a clear near- term opportunity for developing the transport and logistics infrastructure required for the longer term scale- up of biofuel production in the Northeast. Reducing home heating oil use with biomass substitution is notable for having the desirable effect of displacing the use of imported petroleum, which is a major rationale for the long- term drive toward lignocellulosic advanced biofuels production. However, unlike lignocellulosic advanced biofuels, conversion of biomass into thermal heat energy has the further advantage of not requiring major technological breakthroughs for short- term implementation, although some retrofits to home furnaces and fireplaces would be necessary (see, e.g., Biomass Thermal Energy Council [BTEC] 2010). With the appropriate policy incentives, the home heating market could provide an immediate opportunity for the biomass supply chain to begin taking shape, thereby promoting development of market efficiencies required for larger scale production of advanced liquid fuels. Replacing 19% of this heating oil demand with biomass in high efficiency furnaces produced in the U.S. would replace about 1.14 billion gallons of heating oil annually, create over 140,000 jobs in the region and reinvest about $4.5 billion into the economies of the region (BTEC 2010). This represents a unique opportunity for biomass and will create additional markets for this material in addition the developing biofuels market.

Another near- term opportunity was identified with regard to the current practice of importing large amounts of corn grain - for both animal feed and, increasingly, feedstock for corn- based ethanol facilities - from the Midwest by rail. Woody biomass from the Northeast could potentially be processed into a form that is appropriate for powering Midwest ethanol facilities, and exported by use of rail cars that currently leave the Northeast region with little to no return cargo. Substitution of woody biomass for fossil fuel sources that currently power many Midwest ethanol facilities would improve both the fossil energy return and greenhouse gas profiles for first generation biofuels, and thus may be a pathway that is worthwhile of explicit policy incentives.

As these biomass markets emerge over the next five year time horizon, intensive research and development of dedicated feedstock cultivars - such as switchgrass, hybrid poplar, shrub willow and other high productivity species - should continue in preparation for the next phase of the bioenergy economy. Integral parts of this research effort should include development of cultivars and cropping strategies for increased yield, disease- resistance, improvement of in- field harvesting systems, and defining appropriate farm- scale best management practices (BMPs) for conservation of soil and water resources. Ongoing efforts by the Natural Resources Conservation Service (NRCS) to include energy production in resource assessments are considered a crucial tool for partnering with landowners who are poised to establish bioenergy feedstock cropping systems.

Phase 2 goals: 2015 - 2020

Following the initial development phases, a major expansion of the bioenergy economy for the Northeast is envisioned during the latter part of this decade. This expansion will include extensive plantings of herbaceous perennials and short rotation woody crops on marginal lands, both of which will be used as primary feedstocks for advanced biofuel refineries and combined heat and power facilities that are distributed across the landscape.

As the bioenergy market begins entering this more intensive phase, it will be critical to continue field monitoring of feedstock landscapes to ensure that BMPs are effectively achieving intended conservation goals. Adaptive adjustment of BMPs to reflect the findings of monitoring studies should be anticipated during the scale- up period. In addition, careful attention will need to be paid to the nutrient concentration issues associated with refineries and power facilities. Efficient return of concentrated nutrients back to the wider landscape should be considered a major sustainability priority. Such nutrient recycling not only can help avoid eutrophication problems at refinery sites, but also is an investment towards maintaining long- term environmental productivity while reducing the need for imported fertilizers. Ongoing research and marketing of useful co- products associated with the biomass production chain will also be critical for ensuring the economic sustainability of the bioenergy system.

Phase 3 goals: 2020 - 2030

Rapid expansion of the bioenergy economy should continue through the 2020s, with the maturation of the sector bringing increased efficiencies through all aspects of the supply chain. By 2020, it is expected that bioenergy should be economically competitive with fossil fuel- based fuels, particularly if market price signals are established for the purpose of reducing fossil- based carbon emissions.

Large- scale emergence of high productivity algal feedstocks could also occur during this time- frame, bringing the potential for intensification, market up- scaling, and co- product values for biomass that currently are difficult to bound. In the Northeast, the most obvious opportunities for algal culture are co- siting with electric generation facilities and wastewater treatment (including biofuel refineries), although other applications and technologies that could be suitable for the region cannot be ruled out.

Ongoing attention to sustainability criteria will remain critical as the bioenergy industry expands and matures, particularly as new feedstocks and technologies are introduced into the market. Accurate greenhouse gas accounting, maintenance of soil and water resources, and risk assessments for ensuring new feedstock species do not pose high invasive threats before introduction into the landscape are among the issues that will almost certainly remain important through 2030 and beyond.

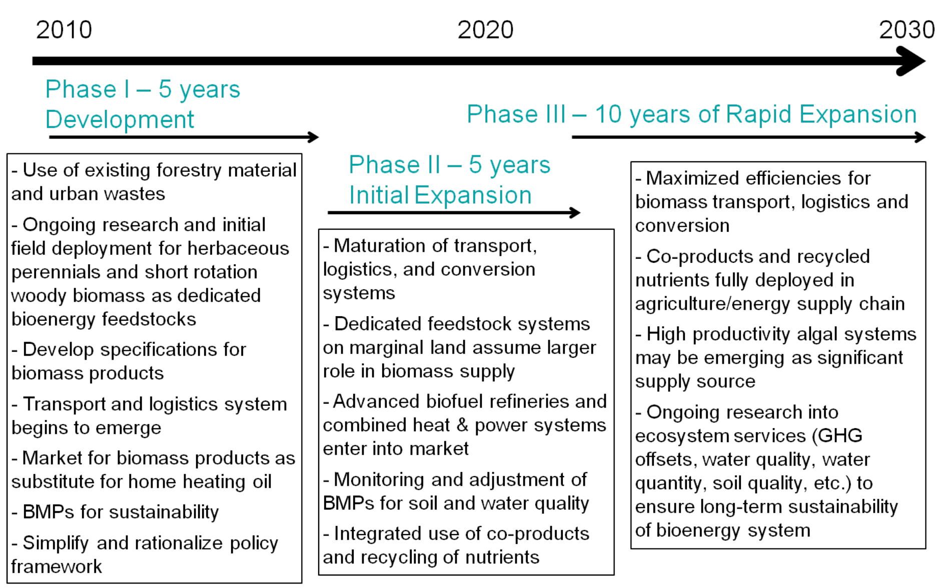

Figure 4: Summary of Northeast Bioenergy Roadmap for 2030

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Chapter 26

West of the Rockies Regional Roadmap

Our objective is to outline a roadmap for sustainable bioenergy production in the western United States.The West is characterized by wide variation in climate, productivity, distribution and abundance of feedstocks, and soil and water resources, which determines the ability to produce bioenergy. It is also characterized by densely populated coastal and inland cities and extensive sparsely populated regions. These conditions provide unique opportunities and challenges for bioenergy development.

The West has many unique physiographic features including the Desert Southwest, Pacific Northwest, Rocky Mountain Region, Pacific Islands, California and Alaska. Each area has different natural and cultural resources that interact to influence bioenergy development. The Desert Southwest has high solar radiation, but water is scarce and population centers are concentrated. The Pacific Northwest has abundant precipitation along the coast coupled with semiarid to arid inland areas. Woody biomass is available at higher elevations where precipitation is greater. Grain production, with its accompanying straw as a potential feedstock, is concentrated in the interior Palouse. The Rocky Mountain States have both woody and herbaceous agricultural biomass scattered widely throughout the area. In contrast, the Pacific Island areas are very isolated with biomass and climate conditions that strongly favor small scale energy production. California, with new and impending policies, has a wide range of natural, agricultural, and demographic conditions that make it a proving ground for local and national energy development. Finally, Alaska has a low population density and vast amounts of woody biomass, most of which is inaccessible with current infrastructure.

A common finding throughout the West is that significant land areas are devoted to timber and/or grazing. There is also a very high proportion of land that is under federal, state, or tribal jurisdiction making it subject to policies that are unique to the West. Finally, fire management across these areas is an important and strategic objective.

Western agriculture is highly dependent on irrigation water derived primarily from snow pack driven runoff. The most productive and strategically located areas are these irrigated lands. Managing water resources and effects of projected climate change are therefore important for animal, crop, energy, and human needs. Concentrated human population centers along coastal areas and concentrated animal feeding operations such as dairies and feedlots present opportunities for using solid waste as as bioenergy feedstocks.

The natural, cultural and human resource diversity of the West, coupled with a mix of widely dispersed and concentrated feedstocks provide platforms for both large and small- scale energy production facilities using appropriate but diverse technologies.

We have these six recommendations:

Feedstock Development

The potential for Western U.S. feedstock development is often underestimated because the materials are widely distributed. Key resources include woody biomass from forest lands, crop residues from cereal and grass seed production (Figure 1), municipal solid waste in large population centers (Figure2), minor concentrations of prunings from commercial orchards, and manures or other by- product streams from existing timber and agricultural industries. These feedstock sources are highly diverse and may be widely dispersed. Because of their complexity, distribution and relationship to population centers, a critical focus for the West should be on integrated or multi- feedstock biorefineries with logistics being the key for development. Research and development activities should be focused on flexible, mobile processes to accommodate feedstocks that are disbursed and on concentrated energy production near major populations centers.

Synchronization and Harmonization of Policy

The diversity and complexity of Western bioenergy systems makes synchronization and harmonization of policy and development of sustainability guidelines very challenging. Variations in feedstock definitions in both national and state policies often exclude some types of biomass prevalent in the West. For example, the US EPA Renewable Fuel Standard (RFS2) "Renewable Biomass" definition restricts the use of fiber from federal lands, which accounts for more than 50 percent of the land area in many western states (Figure 3). Better coordination of federal and state bioenergy policies would significantly improve resource use and management, as well as communication and cooperation among Tribal, County, State and Federal Agencies that create regulations, administrate rules, issue permits or manage western lands. To achieve this goal, current policy definitions, conflicts, and restrictions need to be reconciled and optimized across all jurisdictions unique in the West.

Modeling Western Regions

Current biophysical, economic, and life cycle models that are being used to estimate potential biomass supplies and sustainability impacts are not parameterized correctly for Western conditions. National and local data sets generally are more complete and of greater reliability in the Midwest and Eastern U.S. Policies based on these data and corresponding simulations do not accurately address bioenergy potential in the West. Current and developing models should be validated using western data sets where possible. The range in reliability and completeness of data from various data sets should also be taken in to account when validating models. Thus, more data collection and evaluation are necessary in the West. Developing more complete data sets for this region should be an immediate goal.

Fire Management and Bioenergy Development

Public lands and National forests are disproportionately located in the Western Region (Figure 3). Such lands are managed for various resource objectives and governed by national and regional policy. This influences the availability of biomass for bioenergy production. It also influences access to power transmission lines and conversion facilities. One major resource objective in the West is management of catastrophic fires that threaten the conservation values of public lands, and lead to increased greenhouse gas emissions and climate change. The complexity of Federal, Tribal and State land ownership presents unique biorefinery siting challenges. Nonetheless, interest in woody biomass from forest land has increased because of the threat of catastrophic fire and the potential to serve as a bioenergy feedstock. Currently, logistics and economics may not support the cost of energy production based on energy production alone, but many challenges in getting woody biomass from the forest to processors might be overcome by combining energy production with several other ecological and economic benefits of biomass removal. Biomass removal and utilization projects should integrate habitat restoration, stand improvement, reduction in wildfire potential, improvement in rural economies, and energy production as part of their design criteria. Existing equipment, contractors, and other idle infrastructure associated with the timber industry may be resources that can be converted to combined energy and woody biomass removal systems that serve multiple ecosystem objectives.

Irrigation and Water Issues

Water is a very critical resource in the West. Because of limited precipitation over much of the region, the West is dependent on surface water derived primarily from snow packs in upper elevations. A significant amount of land in the region is irrigated (Figure 4). With water these areas are highly productive and can provide various feedstock sources for bioenergy production. Irrigated lands are usually reserved for producing food crops, but in the West food and fuel do not have to be in conflict. Crop rotation, water availability, and differences in seasonal water use influence how irrigated lands are managed. Annual and perennial bioenergy crops and harvest of food crop residues can fit in to existing irrigated cropping systems. Integration of bioenergy production into irrigated land should be explored using an agricultural systems approach. Irrigated lands of the West can provide food as well as energy crops if existing water resources are managed holistically.

The effect of climate change is very important in the West. Changes in climate are expected to result in a progressively smaller snowpack and earlier runoff. Many current energy and irrigation storage systems have insufficient volume to accommodate these changes in annual flow. Earlier runoff will most likely reduce water availability during the summer and increase hydropower production at a time of year when it is least needed and less valuable. Improved and additional water storage capacity may be required to meet climate change induced seasonal distribution and supply of water.

Research Questions

Development of a bioenergy economy tailored to the West should consider all of the factors discussed above. The market mechanisms needed to jump start bioenergy production will be different in the West than in other parts of the U.S. Regionally specific research on the sustainability of various feedstocks including: invasiveness, conversion efficiencies, environmental effects, residue removal, nutrient and water use efficiencies, and land use conversion effects is needed. The West already plays a unique, dominant role in specialty crop development and production and is well suited to pursuing the development of specialty crops for bioenergy production. It is commonly stated that “marginal” lands will be utilized to meet bioenergy needs. Large areas of the West include saline and alkali soils and face frequent drought and/or extreme cold or heat. Marginal lands such as these will require research to economically and sustainably produce biomass feedstock, but they should not be overlooked.

The wide array of feedstock sources, with both dispersed and concentrated distributions in the West, and interrelationships between feedstock supply and conversion technologies will dictate the operation size and business model that can be used in a given area. Large amounts of concentrated biomass favor large scale technologies such as gasification, while widely dispersed biomass favors small scale technology. Research is therefore needed to address multiple energy platforms and collection infrastructures throughout the West. Systems to utilize widely dispersed woody biomass, specialty crops, crop residues and dedicated energy crops all need to be pursued.

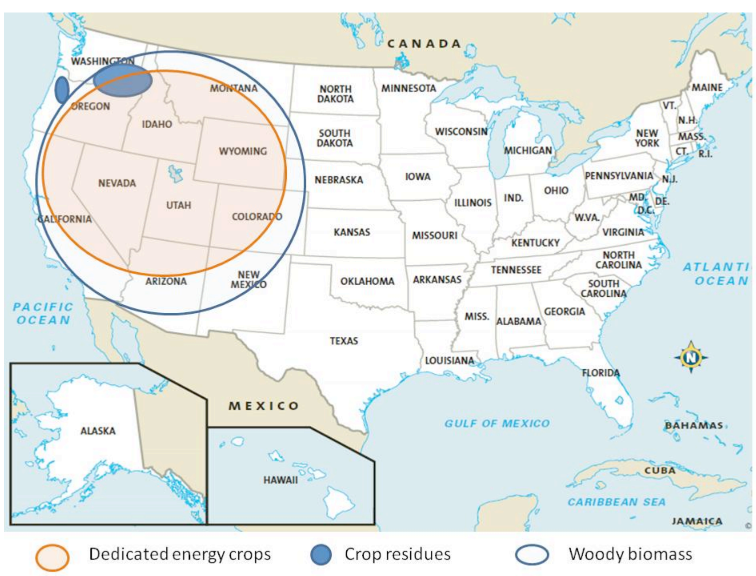

Figure 1. Feedstock distribution in the West.

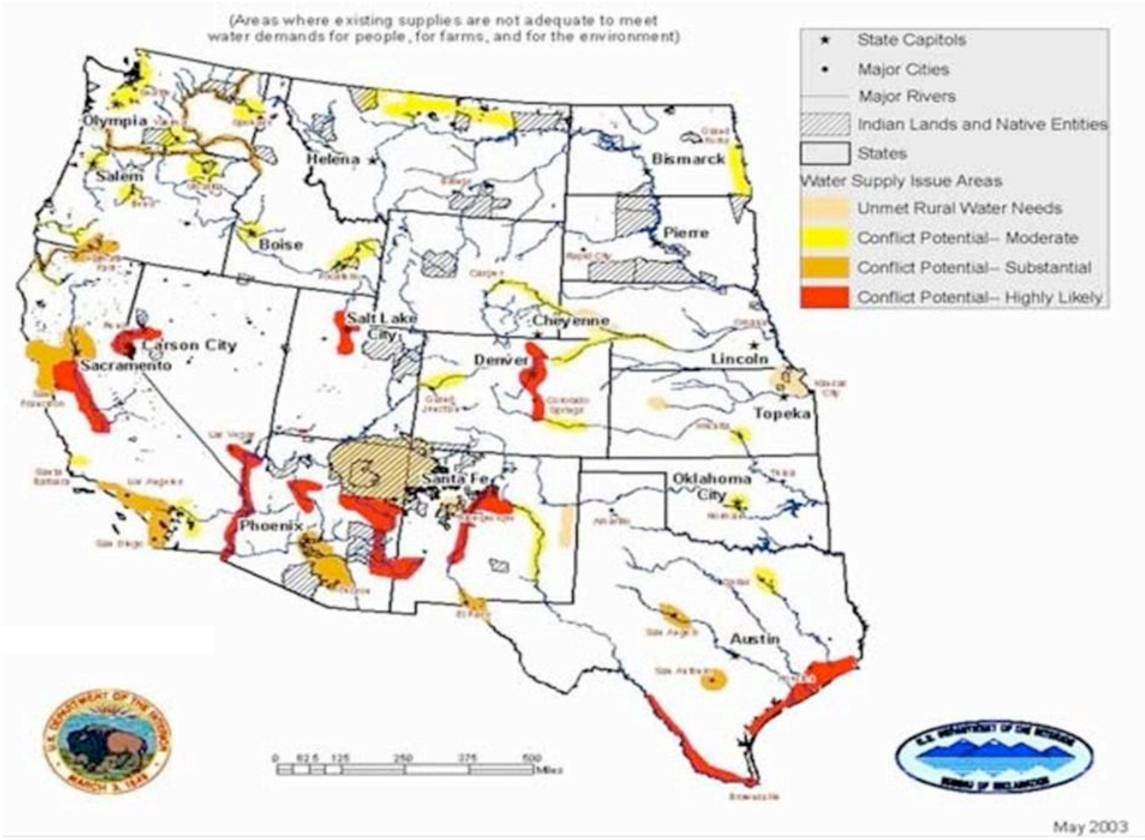

Figure 2. Population distribution

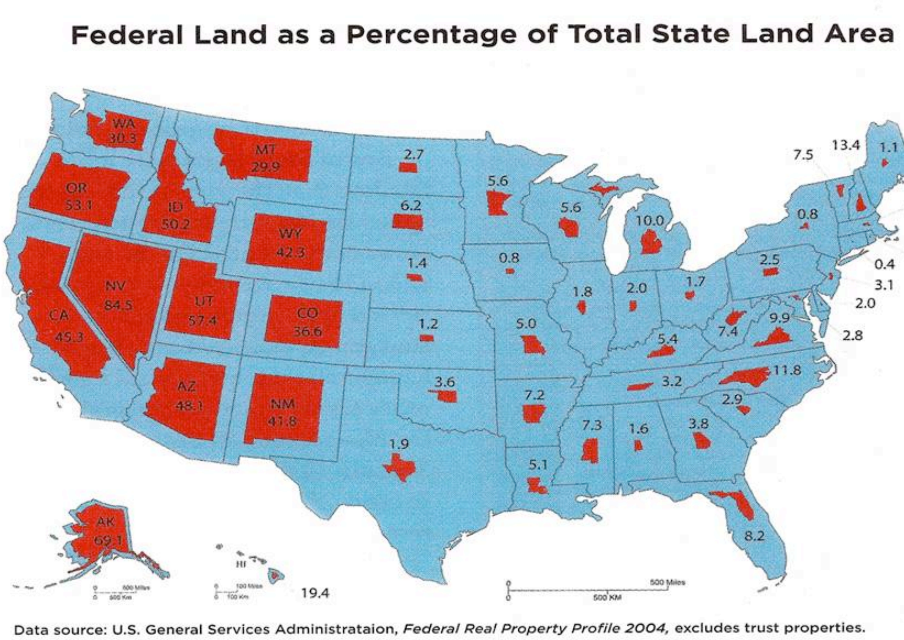

Figure 3. Public land ownership in the West

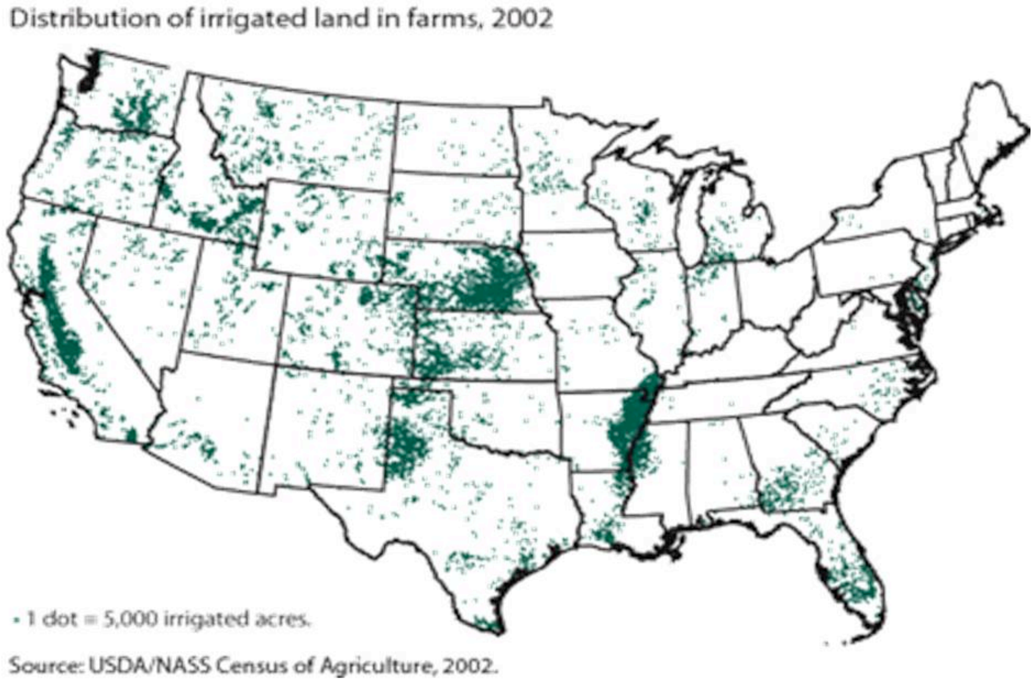

Figure 4. Distribution of irrigated land in the US

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- Marcia Patton- Mallory, US Forest Service,
- Jody Endres, University of Illinois,

Chapter 27

Great Plains Regional Roadmap

Section I. Broad Overview Issues

Net Primary Productivity (NPP)

Based on the regional NPP, several advanced biofuel feedstock sources were identified for this region. The top three feedstock sources included:

- Switchgrass
- Mixed species, natural grasslands, cool- and warm- season, less agriculturally managed
- Seeded polycultures (native and introduced species; distinguished from native by seeding)

Other sources of biofuel feedstock might include:

- Wheat straw residues
- Corn stover
- Big bluestem
- Prairie cordgrass
- Alfalfa
- Short- rotation woody
- Other leguminous shrubs
- Annual cover crops (rye, triticale, turnips, etc.)
- Sorghum
- Miscanthus
- Jerusalem artichoke (tuberous starch conversion to ethanol)
- Sugarbeet
- Brassicas
- Sunflower
- Animal manure
- Mesquite, juniper – land clearing

The following characteristics make these aforementioned feedstocks the most suitable:

- Net primary productivity
- Sustainability based on net ecosystem exchange
- Producer acceptance
- Economics
- Long- term ecological sustainability
- Water constraints / availability
- Dedicated crops and associated residues
- Availability of land for biofuel activity (e.g. Sandhills, old alfalfa systems)
- Sustainable production trumps NPP; Producer acceptance/adoption/profit trumps NPP

Availability of feedstock sources is variable. At least initially, the following sources could be considered immediately available: (1) crop residues, (2) animal manure from feedlots, and (3) managed, mixed species (Conservation Reserve Program [CRP]) vegetation. Once advanced biofuel systems are well developed, it is envisioned that the following sources would be substantial in a subsequent phase: (1)

native polycultures, (2) purposely grown polycultures, and (3) crop residues. Crop residues would be immediately available from maize and other residues but continual removal of N with harvested residues (and the need to fertilize at higher rates) could be a drain on natural resources unless some of the N is recycled and returned to fields that are being harvested. Removing crop residues without recycling nutrients, particularly N, cannot be suggested as a sustainable practice. Other feedstock sources would be available, but this would depend on the conversion technology and business model proposed.

Research and development questions that must be answered to ensure sustainable supplies of feedstock sources include the following issues:

- Water use efficiency
- No- till production under irrigation
- Contract development (supply processing plants within local regions)
- Perennial systems (establishment, new crops, costs, agronomy, support systems, harvesting, optimum mixtures)
- Genetic improvement
- Long- term issues remain to be defined (long- term impacts on soil resources, ecosystem services; field- scale work needed; watershed- scale; landscape ecology)
- Availability and quality of aggregators and conversion facilities
- Quality characteristics of feedstock (divergent even within switchgrass)
- Influence of seasonal supply of feedstock on potential business models
- How to densify feedstocks and related issues of handling
- Desired feedstock specificity will determine type of feedstock made available (i.e. mixtures vs. managed single species)
- Feedstock characterization linked to conversion type; continual interaction will be needed
- Residues vs. dedicated grass energy crops are similar, but unrelated to woody species
- Types of biomass, particle size, etc. suggests standards will be needed; may need intermediate aggregator to supply the conversion facility
- Market still needed for processing feedstocks
- Water availability for non- traditional crops with irrigation
- Equipment is generally available for harvesting

Some further discussion points with regard to NPP were: (1) NPP may not be the key determinant of where advanced biofuel feedstocks are produced, (2) we should not assume that marginal lands will automatically be available for biofuel production because producers can use this land for other activities such as grazing, and (3) land use capability of marginal lands may have serious limitations (rocky, highly erodible, accessibility, etc.). These factors may or may not influence current land use but they could create the need for greater incentives in the future.

Water availability

Irrigation of bioenergy- based perennial grass crops is not likely due to economic inefficiency and other competing uses for water. Issues needing further research include:

- Drought tolerance
- Residue management of irrigated crops may require harvest of residues
- Switchgrass planted in center- pivot irrigation corners (non- irrigated areas)
- Genetic improvement of switchgrass
- Fall vs. spring harvest of switchgrass has issues on dry matter and compositional effects

Combination facilities with different conversion platforms are envisioned for the Great Plains region. Existing starch- based ethanol conversion facilities will likely have the resources to more easily convert to alternative platforms. Some issues to consider are:

- Existing industry base in the region (density per acre)
- Aggregation of feedstock needed for facilities to start up

- Unknown future of which planned facilities will be cellulosic in the Great Plains vs. grain ethanol; some facilities are in demonstration phase at locations throughout the U.S.
- Co- location of different conversion facilities makes sense (grain and cellulosic ethanol)
- Integration of co- products is needed

Water supply regulations will likely limit sustainable supplies of many of the suggested feedstock sources for the region. The following water resource considerations are seen as most limiting for sustainable feedstock production in this region:

- If corn irrigation is limited, then decline of irrigated corn will reduce crop residue supply
- Perennial grass crops will improve water- use efficiency at the landscape level
- Unknown issues of water availability for industry to develop processing plants (Water supplied by rainfall indicates need for boundaries on water needed by processing plants.)

Section II. Feedstock Specific Issues

Based on information presented at the workshop regarding crop residues, herbaceous perennials, woody species, lipid- based oilseeds and algal feedstock sources, perennial forage feedstocks were identified as the single, most viable advanced biofuel feedstock for the Great Plains region. Woody feedstocks were questioned as a possibility for riparian zones, but state- level Natural Resources Departments are not encouraging their use. Additionally, the region is marginally suited for woody utilization but circumstances might change depending on decisions in other geographic regions. It might be reasonable to expect co- location of an algae plant with a coal processing plant, particularly as a waste- reduction strategy. Such an application would have to be considered a niche at this point in time.

The existing knowledge base regarding advanced biofuel feedstock sources, availability, and management is limited. Crop residue utilization is site- specific to irrigated corn with no tillage. There are issues with other crops in maintaining soil organic C. We don't have the information and tools needed to get site- specific advice on how much residue must remain. There is a great need to draw information from modeling efforts including the USDA- ARS Energy Assessment Project (REAP) and the John Deere – Archer- Daniels- Midland - Monsanto (DAM) stover removal project to identify sustainable, site- specific residue removal rates.

Research and development is needed to address the following issues in this region:

- Getting the biofuel market in place will drive the in- the- field planting of herbaceous perennials for biofuel production
- Research will be near completion to be able to provide recommendations and implementation for herbaceous perennial biofuel systems

Section III. Potential Limiting Factors

Workshop presentations on potential limiting factors for advanced biofuel systems raised the following issues relevant to the Great Plains region:

- Timing of feedstock availability will determine supply stream
- Source of energy from livestock manure, utilization in coal- fired energy plants, using byproduct as enriched fertilizer source
- Coal- fired energy plants can be supplemented with biomass sources
- Power energy – limitations on energy distribution; need plants next
- Liquid vs. power vs. electrical – does not necessarily change the roadmap
- Heat generation – pellets (switchgrass biomass, small- scale now, but intent to get large- scale bulk delivery to boiler plants)
- Cotton gin residues
- Cotton seed oil; meal used for animal feed

For advanced biofuel feedstock systems in the Great Plains, the following nutrient supply and management issues are of greatest concern:

- Water
- Nitrogen sources have a value, so no cheap source except for feedlot manure
- Still a need to recycle nutrients
- Phosphorus is needed for corn and alfalfa, but may not be needed or is available for grassland areas; Need to better understand the P response in various herbaceous perennials
- Concentration of N via digestion of animal manure prior to energy conversion
- Don't know enough about micronutrient requirements of herbaceous perennials
- Understanding of microbial ecology (associative N fixers, heterotrophs, mycorrhizal associations) under herbaceous perennials is lacking
- Rooting depth and distribution of herbaceous perennials is extensive and creates a different environment for nutrient extraction

The production, harvest, storage, and/or transportation factors of greatest concern in the region are:

- Need to get sufficient density of feedstock available
- Can mobile processing units be developed? Mobile pyrolysis unit in TX
- Idaho National Lab has mobile densification unit (product that can be processed) – glued from lignin in feedstock itself; alfalfa pellets glued with pellet
- Cost- effective densification
- Torrefaction, slow pyrolysis, fast pyrolysis for creating different stabilities of feedstock – unknown needs by industry
- Climate determines storage loss

Challenges related to balancing economics and ecosystem services are numerous and we anticipate the following issues to limit sustainable feedstock supplies:

- Nutrient cycling needs to be tightened with utilization
- Harvesting of CRP fields could reduce biological diversity, pheasant populations
- Harvest timing important for wildlife
- Need for riparian zones remaining unharvested
- Every other year harvest a possibility to keep wildlife habitat
- Managed harvest concentrates predation
- Buffers will be important for maintaining habitat – incentives needed
- Values on ecosystem services need to be established
- Sustainability standards will be important
- Monetary support for ecosystem services necessary; agriculture does not need to support the entire ecosystem; government incentive or support required
- Need to know net global warming potential (C balance) of each biofuel scenario
- Wetland management with prairie cordgrass unknown, but possible benefits
- Will overall farm profitability be increased?
- Rural economic development by contracting services for harvest, transport, storage

Section IV. Considerations for Future Development

The Great Plains region has unique capabilities to help meet the demands for food, feed, fiber, and fuel production in the new bioeconomy. The region is a national leader in the production of livestock, ethanol, and cotton, and has a cultural history of producing herbaceous perennials as well as a diverse supply of crop residues. Soils and climate in much of the region are well- suited to dryland production of annual and perennial biomass feedstocks. Additionally, an adequate supply of marginally productive cropland and CRP are available and can be affordably converted to herbaceous perennials to provide a consistent and sustainable feedstock supply that will minimize impact on food production. More than 20 years of research on establishment and management of herbaceous perennials has been conducted in the region, with long- term and farm- scale research having been conducted on production, harvest and storage management, potential ethanol yield, production economics, energetics, and ecosystem services such as carbon sequestration. An attribute throughout the region is proximity to existing starch- based ethanol plants, electric power generation facilities, and agricultural processing facilities, which would be synergistic with biomass energy production. The Great Plains is poised with an available workforce and agricultural and transportation infrastructure to rapidly move from the research scale to the full-scale functional aspects of the new bioeconomy.

Advantages of advanced biofuel systems in the Great Plains:

- Better drying conditions in this low rainfall region
- Land prices reasonable
- History of producing the feedstocks
- No- till is well accepted
- Adequate precipitation to get adequate yields
- Available land mass
- Cost of production relatively low in some areas
- Magnitude of CRP lands
- Appropriate soils for herbaceous perennials

Continued needs for the region, include:

- Research is needed on feedstock development, rapid and economical establishment, sustainable feedstock production, economics, ecosystem services, life- cycle assessments, factors that influence producer adoption such as net returns to farmers, and establishing long-term agricultural research sites with farmer collaboration
- Conditions are at the ethanol blend wall, so there are no incentives to commercialize cellulosic feedstocks
- Implementation of the Biomass Crop Assistance Program (BCAP) or similar policies to mitigate risk is needed, similar to federal crop insurance for biomass feedstocks
- Conflicting policies need to be resolved, such as the US EPA maximum achievable control technology (MACT) regulations vs. renewable energy incentives
- Collaborations should be incentivized across the supply chain to promote commercialization
- Movement is needed from research and demonstration to commercialization

Workshop participants for this region:

- Larry Tieszen, USDA- EROS
- Vance Owens, South Dakota State University
- Rob Mitchell, USDA- ARS
- Robin Jenkins, Dupont
- Tom Gerik, Texas A&M Agrilife
- Alan Franzluebbers, USDA- ARS
- John Ferrell, US- DOE- Office of Biomass Program
- Jim Doolittle, South Dakota State University
- Norman B. Bliss, USGS- EROS, Sioux Falls SD
- David Archer, USDA- ARS

Chapter 28

Southeast Regional Roadmap

Introduction

The southeastern United States, an area including twelve states (AL, DE, FL, GA, KY, MD, MS, NC, SC, TN, VA, and WV) and most of the Piedmont and Atlantic coastal plain region of the U.S. is expected to provide 10.47 billion gallons or 49.8% percent of the country's advanced biofuels by 2020 (USDA, 2010). The Southeast has the highest net primary productivity of any region and is capable of producing almost any feedstock. To meet USDA's production goals, considerable advances in feedstock production, infrastructure, and processing platforms will be required. Substantial investment, outreach and education, research and development will also be essential. This document is intended to serve as a roadmap to identify some of the critical research, infrastructure, outreach, and policy needs in the southeastern United States

Feedstocks

The Southeast has the highest net primary productivity of any region in the U.S. (Figure 1). The climate can support diverse feedstock production through the entire year. There is a substantial inventory of standing woody biomass that is expected to be a primary feedstock for the region initially (Figure 2). This feedstock would be supplemented with other woody biomass grown for energy including pine, poplar, sweet gum and sycamore as these are expected to grow quickly throughout most of the region. As biomass processing capabilities develop, grasses such as Miscanthus, Arundo, Bermuda, and switchgrass will be cultivated initially on marginal or unused land and then perhaps in rotations with other cash crops. The southern portions of the region are the only areas in the country that can grow sugar/energy cane which is also expected to be a feedstock due to its high productivity. Some traditional crops like soybeans, sorghum, sugar beets, and sweet potatoes may also be contributing feedstock. Crop residues and animal manures may be used but will probably play a bigger role in improving soil quality and fertility. While we expect that algal feedstocks and crop residue may not offer as great of opportunity in the Southeast as some other regions, opportunities may still exist. Municipal solid waste may also be a legitimate feedstock in the Southeast due to expected continued growth of Piedmont and coastal population centers. The proximity to end users of electricity or fuels is also an advantage due to cost savings from reduced transmission losses. Smaller power plants will begin using more biomass to produce local, green energy that may compete for feedstocks that is also suitable for liquid biofuel production.

Figure 1. Net Primary Production (gC/m2/year). From Izaurralde et al., 2005.

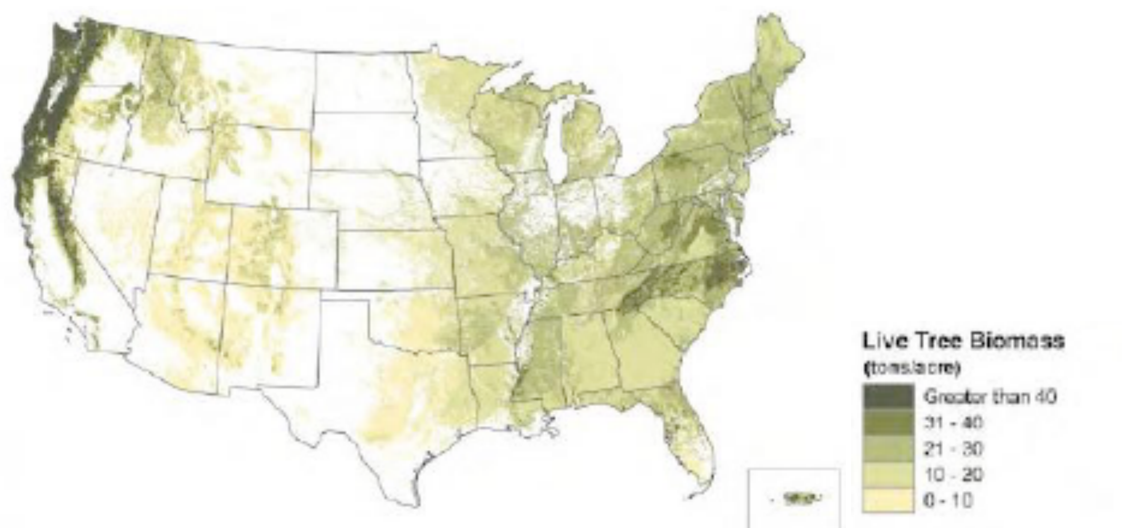


Figure 2. Live tree biomass in the U.S. From Smith et al., 2009

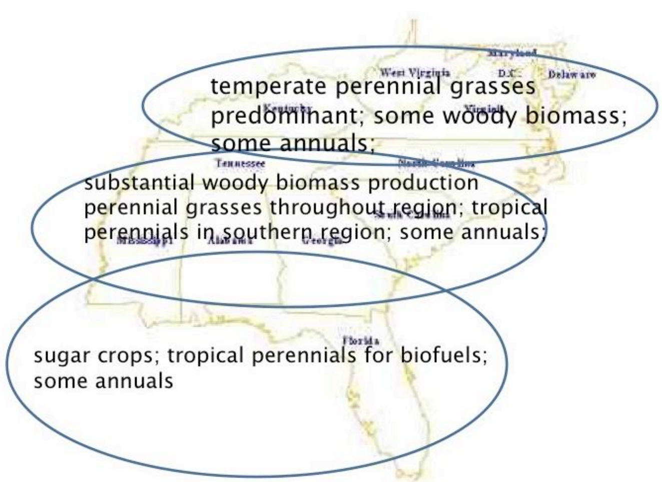


Figure 3. Expected distribution of feedstocks in the southeastern United States.

There are some limitations for feedstock production in the southeastern United States. Water requirements for producing feedstocks are a primary concern. While irrigation may be necessary to establish some feedstocks, water quantity issues and the need to keep input costs low will probably demand that most feedstocks not require irrigation. Urban and ecosystem demands for water will continue to grow and the bioenergy industry will not compete well with these demands in the Southeast. Since the Southeast is expected to continue to receive relatively high amounts of rainfall, the distribution of this rainfall will be critical to feedstock selection. Feedstocks that can tolerate droughts on soils with low water holding potential will be selected over those that cannot sustain themselves in these conditions. In addition, water quality will be a critical issue. Maintaining soil organic matter and residues to prevent soil erosion and limiting nutrient additions will be important for protecting water quality.

Fertility requirements of the feedstocks will also be a critical decision factor. The coastal plain and Piedmont regions of the Southeast have soils with low natural fertility and soil organic matter. Residues are needed to build soil carbon levels and to control runoff and soil erosion. Fertility requirements are expected to come primarily through byproducts such as poultry litter, manures, and co- products of bioenergy production. The invasiveness of feedstocks will also be a consideration as the Southeast has had numerous examples of invasive plants in the region. Producers will need a good understanding of productivity per acre, conversion technology availability and cost, convertibility or energy content (BTU density), and ability to sustain long term production and yields to make informed decisions on feedstock production.

The following research and development questions must be answered to ensure sustainable supplies of these feedstock sources in the Southeast:

- Research is needed to assess the production efficiency in terms of energy content per unit of production based on available conversion technology for each of the feedstocks that can be grown in the Southeast.
- We need a better understanding of the invasive characteristics that may be associated with these feedstocks.
- Climate change impacts on production of various feedstocks.
- Determine feedstock specific parameters for water quality/quantity issues. What are the water footprints of the various feedstocks including both production and processing.
- Bioenergy feedstocks should encourage development of new technologies for appropriate irrigation. This may be low cost technology to assist with crop establishment or technology that can be deployed with much lower cost and less water losses.
- Research on rainfall/runoff capture to supplement crop growth during drought.
- Data is needed on the water and nutrient use efficiency for each feedstock so that informed decisions can be made.
- Research on how to convert land and the environmental impacts of a feedstock.
- Research on determination of sustainable woody residue biomass removal rates.
- Soil limitations and suitability of the feedstock for southeastern soils. Many of the results from other regions with better soils may not be applicable here. Are yield forecasts realistic and stable considering several studies are showing reduced yields after a few years for southeastern conditions and are they similar for marginal vs prime land?

Infrastructure, Processing and Conversion Platforms

The Southeast can supply a wide variety of feedstocks which support a wide variety of conversion platforms. Thermo- chemical conversion is well suited for our existing woody biomass and will most likely be the dominant platform of choice in the near future. With appropriate policy incentives production of significant portion of local electricity will be supported by biofuels in the not too distant future. Feedstocks are available for biochemical conversion as well. Free sugar production from sugar/ energy canes and sweet sorghum is being used for direct fermentation to ethanol and other renewables in portions of the Southeast. Some of the forage and tall grasses will lend themselves as feedstock for cellulosic conversion via biochemical processes as they become more economically viable. Oil producing crops will lead to conversion to drop- in fuels for aviation or other needs. As feedstock availability ramps up, we would expect other conversion platforms to enter the Southeast. Production and delivery systems will need to be developed as feedstock demand increases and changes.

The following research and development questions related to infrastructure, logistics and processing must be answered for an economically sustainable renewable fuel industry in the Southeast:

- Research and development is required to match conversion processes with the most appropriate feedstock species and plant parts.
- Research to determine the effects of genetic and phenotypic variability on conversion technologies and development of fast and efficient methods to assess feedstock variability.
- Research and demonstration on the uses of byproducts and co- products of biofuel production.
- Research positive and negative environmental effects of feedstock production and the use of by- products and co- products from conversion facilities.
- Research is needed on feedstock harvest and handling logistics - especially related to moisture content and drying processes.
- Economic models will need to developed for the assessment of feedstock production, harvesting, preprocessing, delivery and conversion to renewable energy or fuels.

Education and Policy needs

There are currently no major limiting factors for production; however, changes in forest land ownership, urbanization of the Southeast, and relatively smaller farm sizes could limit sustainable feedstock supplies. The Southeast will need mechanisms to preserve farm lands, to maintain feedstock supplies while dealing with a large number of land owners, and to overcome transportation and handling costs associated with moving biomass to local processing facilities.

While the existing knowledge base in the Southeast regarding biofuel feedstock sources, availability, and management requirements is probably sufficient to develop a sustainable supply of feedstocks for thermo- chemical conversion, it is not adequate to overcome the risks associated with advanced biofuel production. There are many unanswered questions that would facilitate more rapid development. Changing land use patterns lead to questions about how the industry will develop with guaranteed supplies to warrant large initial investments. Crop choices are made based on economic returns data that includes all production inputs and costs as well as potential revenue. Much of this data is currently unavailable for biofuel feedstocks. Water issues will be critical as stated earlier for both feedstock production and conversion. On some potential feedstocks like energy cane that is harvested over a few months of the year, development of co- crops like sorghum may be important for establishing a sustainable supply.

Politics and economics may play a greater role than science in feedstock selection. Land use planning must be developed to accommodate this. There should be a strong increase the retention of local resources in rural economies for:

- Fuels in the region, not exported internationally
- Electricity feedstocks, not exported to coal states

The Tennessee Model for establishing a statewide vision and effort should be considered as a possible course for developing a market for biofuels in the Southeast.

Summary and Roadmap Forward

In the southeastern United States, existing forest resources will be the predominant short term bioenergy feedstocks followed by expansion to short rotation woody biomass, perennial grasses, and annual crops. These feedstocks will support a variety of conversion platforms initially including co-firing for energy and liquid fuel production. As these initial ventures support rural development and demonstrate success, trends such as long- term contracted production systems; grower participation in downstream processing and the development of farmer coops will emerge. Logistics companies, similar to existing wood logistics companies, will also emerge offering new opportunities in rural environments. As the infrastructure improves, production of advanced biofuels readily incorporated in liquid transportation fuel system will begin to develop. This will be aided by the development of State and Federal policy to stimulate the markets for these advanced biofuels. Marginal and underused lands will be the primary lands converted and harvest removal rates will take into account soil protection and not compromise soil health.

Key Recommendations:

- Research on the "sustainability" of various feedstocks: Invasiveness, conversion efficiencies, environmental effects, residue removal, nutrient and water use efficiencies, land use conversion effects etc.

- Information needs to be developed and rapidly exchanged between producers and industry through collaborative research, extension, and education efforts.

- Establish interstate consortiums (e.g. Chesapeake Bay, Tennessee Model) of decision makers, scientists, NGOs, etc. to develop/influence policy, breakdown barriers, create markets, encourage adoption and develop sustainable bioenergy.

- Conduct an analysis of needs for liquid fuel and power requirements in the region to determine number and type of facilities which can be supported sustainably.

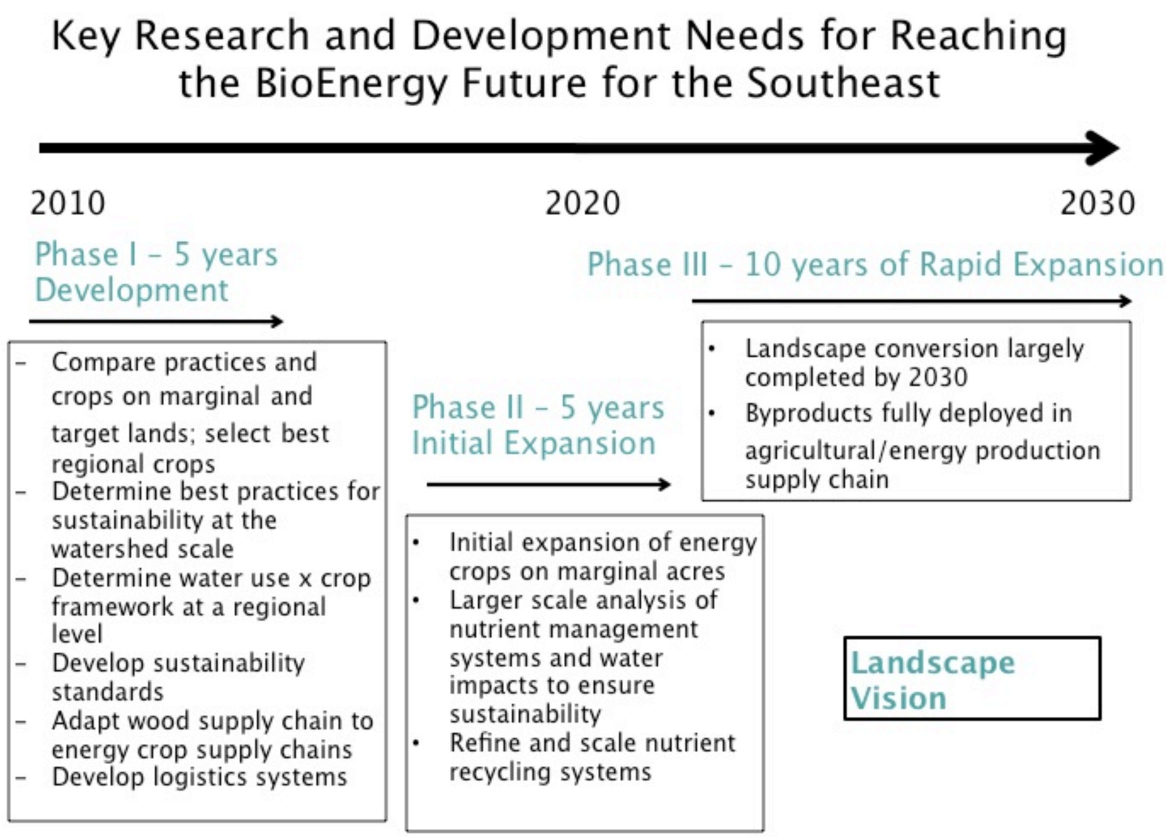
- Coordinate a comprehensive approach to decisions for feedstock handling and logistics.

- Encourage land use planning to facilitate the coupling of feedstock production and conversion.

- Develop and evaluate case studies to determine attributes of successful bioenergy systems.

References:

USDA. 2010. A USDA Regional Roadmap to Meeting the Biofuels Goals of the Renewable Fuels Standard by 2022. United States Department of Agriculture, Washington


Key Research and Development Needs for Reaching the BioEnergy Future for the Southeast
2010
2020
2030
Phase I – 5 years Development
– Compare practices and crops on marginal and target lands; select best regional crops
– Determine best practices for sustainability at the watershed scale
– Determine water use x crop framework at a regional level
– Develop sustainability standards
– Adapt wood supply chain to energy crop supply chains
– Develop logistics systems
Phase II – 5 years Initial Expansion
• Initial expansion of energy crops on marginal acres
• Larger scale analysis of nutrient management systems and water impacts to ensure sustainability
• Refine and scale nutrient recycling systems
Phase III – 10 years of Rapid Expansion
• Landscape conversion largely completed by 2030
• Byproducts fully deployed in agricultural/energy production supply chain
Landscape Vision

Workshop participants for this region:

- Mark Risse, University of Georgia
- Chere Peterson, SWCS
- Elena Berger, Georgia Tech
- Dan Szeezil, Carbon Solutions Group
- Tim Strickland, USDA- ARS, Tifton, GA
- Tomas Persson, University of Georgia, Griffin
- Ping Huang, Auburn University
- Carla Shoemaker, Auburn University
- Marcia Ernst, Ernst Conservation Seeds
- Laurence Eaton, Oak Ridge National Lab
- Bharat Singh, Fort Valley State University
- Peter Chanin, White Technology
- Bill Anderson, USDA- ARS, Tifton, GA
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Chapter 29

Mid- South Regional Roadmap

A Roadmap for Sustainable Advanced Biofuel Feedstock Production in the Mid- South

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Introduction

The Energy Independence and Security Act of 2007 is aimed at decreasing US dependence on non-renewable fossil fuel energy sources and requires increased production of alternative fuels to 36 billion gallons by 2022 (Rahall et al., 2007). Because Congress has capped the production of corn- based ethanol production at 15 billion gallons, the remainder of the 36 billion gallons will be comprised of advanced biofuels derived largely from lignocellulosic feedstock (Service 2010; Figure 1). Lignocellulosic bioethanol production has become an attractive alternative to using non- structural carbohydrate (starch and soluble sugars) sources for ethanol production (Sivakumar et al., 2010; Waltz, 2008) for various reasons. One reason is that the majority of carbon fixed by photosynthetic organisms is incorporated into the cellulosic components of plant cell walls, thereby representing an abundant feedstock for bioenergy conversion (Sivakumar et al., 2010). Another advantage of using lignocellulosic bioenergy production is that biofuels can be produced from abundant, non- food sources such as corn stover, various grasses, and woody biomass without competing with the production of important food crops (Sivakumar et al., 2010; Waltz, 2008). As a result, a number of crops have been studied for their potential use as dedicated bioenergy feedstock, including grasses such as Miscanthus (Fischer et al., 2005), sorghum (Rooney et al., 2007; Venuto and Kindiger, 2008; Wang et al., 2008), and switchgrass (Schmer et al., 2008) and short rotation woody species such as willow and poplar (Fischer et al., 2005; Aylott et al., 2008).

Although various studies exist that deal with the production of lignocellulosic feedstocks (e.g. Fischer et al., 2005; Aylott et al., 2007; Venuto and Kindiger, 2008), a number of aspects of bioenergy feedstock production (feedstock choice, natural resource availability, available infrastructure, etc.) are strongly influenced by the region in which the feedstock is produced and processed. Given the need for regional specificity, this consensus document was developed as an outcome of the Soil and Water Conservation Society (SWCS) workshop entitled "Sustainable Feedstocks for Advanced Biofuels: A workshop to create regionally specific roadmaps for feedstock supply chains."

Mid- South Characteristics

For regional discussion purposes, the Mid- South region included Arkansas, Western Alabama, Louisiana, Mississippi, Southern Missouri, Tennessee, Eastern and Central Texas, and Eastern Oklahoma. Some general characteristics of the region were provided by workshop participants and included: 1) a semi- tropical climate with a gradient of increasing rainfall from the west to the east, 2) a gradient of increasing temperature and growing degree days from north to south, 3) adequate rainfall, temperature, and growing season length for the production of most bioenergy crops, 4) a large amount of marginal land and fiber crop land that would not compete with food production, 5) a high number of livestock production systems that could serve as potential fertilizer sources and/or alternative uses of bioenergy crops, 6) extremely variable weather conditions (hurricanes, temperature, rainfall extremes, etc.), 7) a large number of scattered and diverse agricultural production systems, and 8) a large number of small holdings.

General Feedstock Production Issues

There are a number of key factors to consider when selecting an appropriate bioenergy feedstock for a given region.

1. The crop utilized must be amenable to biorefinery processing (i.e. have a suitable biofuel conversion efficiency and conversion platform; Yuan et al., 2008).
2. The bioenergy feedstock should not compete strongly with food production, and there must be a balance between crop land use and marginal land use for growing dedicated bioenergy crops to meet food and fuel demands simultaneously (Sivakumar et al., 2010).
3. Production of a given feedstock should not damage the environment or unsustainably deplete natural resources (Sivakumar et al., 2010).
4. Multipurpose crops (i.e. grazing and biofuel feedstock) will be important in reducing risk and increasing whole- farm productivity (Rinehart, 2006).
5. Private forested land could be a very important component of the bioenergy feedstock supply. We need to consider forested land if we want to meet fast- approaching bioenergy demands (Perlack et al., 2005).
6. Growing dedicated bioenergy crops has to be profitable (James et al., 2010).
7. Regardless of the crop, there must be a consistent supply for the biorefineries. Therefore, the given feedstock must produce sufficiently high biomass levels in order to meet the demand (James et al., 2010).

Most Promising Bioenergy Feedstock Sources

A number of crops were proposed as promising bioenergy feedstock sources for the Mid- South region and included 1) sugar/energy cane, 2) switchgrass, 3) Miscanthus, 4) sorghum (both forage sorghum and sweet sorghum), 5) cotton, 6) woody crops, 7) perennial legumes, 8) annual legumes, 9) cover crops, 10) grasses (cool and warm season), and 11) agroforestry systems that would include woody crops and perennials or annuals from the previous list. Each session participant cast votes for the three crops they thought were the most promising feedstock options for the Mid- South. The most promising crops (with the number of votes in parenthesis) were:

- Woody Crops (12)
- Sorghum (9)
- Switchgrass (8)
- Sugar/Energy Cane (5)
- Grasses (4)
- Miscanthus (2)
- Cover Crops (1)
- Perennial Legumes (1)

Woody crops, sorghum, and switchgrass, the top three in the list, were discussed in subsequent regional breakout sessions.

<u>Woody Crops</u>

Characteristics Making Woody Crops a Suitable Feedstock

There are a number of factors making woody crops an attractive potential feedstock for bioenergy production in the Mid- South region of the U.S. For example, the infrastructure is already in place for woody crop production in the Mid- South (Kline and Coleman, 2010) and a substantial silviculture knowledge base currently exists in the southern U.S. (Kline and Coleman, 2010) where 130, 000 km2 of loblolly pine plantations are routinely managed for large- scale timber production (Munsell and Fox, 2010). Due to a favorable climate for biomass production, woody crops have high growth rates and large biomass yields in the southern U.S. Loblolly pine growth rates have been reported in excess of 22.4 Mg ha- 1 y- 1 on a green weight basis (Munsell and Fox, 2010), and a wide harvest window (year-round) is available (Hinchee et al., 2009). However, harvest during the dormant season may be preferable to increase total production over long periods of time. Genetic diversity among woody species provides substantial potential for genetic improvement to increase biomass yields and wider adaptability of some species (Hinchee et al., 2009). As a result, woody crops could provide a consistent feedstock supply to the biorefineries.

It is also important to consider the environmental benefits of using woody crop species as a potential bioenergy feedstock source. Managing woody crops for the production of both wood products (lumber, furniture, etc.) and bioenergy feedstock improves environmental quality through long- term carbon storage in wood products, lower fossil fuel- derived carbon emissions when woody crops are used for bioenergy production (Van Deusen 2010; Figure 2), and lower rates of NOx and SO_2 emission during combustion due to the low nitrogen and sulfur content of woody tissues (Demirbas, 2003). Some woody crop species (i.e. loblolly pine) have low water and fertilizer requirements; however, these are species-specific characteristics, and some woody crop species (i.e. cottonwood) are highly sensitive to drought and require larger fertilizer inputs (Kline and Coleman, 2010).

Because woody crop feedstock can be derived from any number of naturally occurring species that can be grown for multiple purposes (i.e. pulpwood, lumber, bioenergy), the farmer will have fewer risks associated with the production of woody biomass than with a single- use dedicated bioenergy crop. Also, the energy costs associated densification and transport of low density biomass feedstock sources would not be a major concern due to the high energy density of woody tissues. Woody crops (e.g. loblolly pine) are also less likely to compete with food crops because some species grow well on land not typically suitable for food crop production. Additionally, woody crops are candidates for either thermochemical or biochemical conversion processes and woody biomass can be successfully co- fired with coal at electricity- generating power plants to reduce the emission of atmospheric pollutants (Demirbas, 2003).

Water Resource Considerations for Woody Crop Production:

Water availability is a major factor to consider when choosing potential bioenergy feedstock candidates. Because bioenergy crops needing irrigation water would be in greater competition with industry and municipalities for water use, water use efficiency will be an important trait for any crop grown as a bioenergy feedstock source. In regional breakout sessions, it was suggested that crops not needing irrigation water at all during the growing season might be most appropriate (rain- fed crops). Although some woody crop species do not require irrigation (loblolly pine), other species (i.e. willow, cottonwood) naturally occur on wet sites and may actually be less water use efficient and more susceptible to drought (Kline and Coleman, 2010). Additionally, farmers will need to know how irrigation affects biomass production for woody crop species. If yield can be substantially increased with irrigation, farmers will likely employ irrigation to improve the productivity and profitability of their operation.

Research and Development

The top areas identified by workshop participants as areas with the greatest research and development needs were the following: 1) Risk Assessment: For growers to accept a given crop for bioenergy feedstock production, they will need some sort of assessment of risk. If risk is too great, farmers may continue to utilize traditional production systems. For example, the cost associated with producing short rotation woody biomass as a bioenergy feedstock is currently unknown, and needs to be more precisely defined for different species that would be appropriate in the Mid- South. 2) Net primary productivity and carbon mapping for different woody crop species throughout the Mid- South will be needed. 3) Conversion platforms: More research is needed to identify the most suitable conversion platforms for a range of species. For example, some species will be amenable to biochemical conversion processes, whereas others might be more amenable to thermochemical methods (i.e. pyrolysis). 4) Because a substantial amount of genetic diversity and the potential for hybridization is available for some tree species, additional research will be needed to improve the productivity or adaptability of various woody crop species. 5) Because other forms of alternative energy could compete with biofuel production, additional research will be needed to estimate the potential for disruptive technologies to limit the demand for advanced biofuel feedstock. 6) The efficacy of woody crops as bioenergy feedstock sources needs to be compared with other potential bioenergy feedstock sources (i.e. annual and perennial grasses). For example, the amount of land required to produce a given tonnage of bioenergy feedstock from woody crops should be compared with the amount of land that would be required to obtain equivalent biomass production from other species. 7) The impacts of policy changes and tax laws on potential bioenergy feedstock production need to be assessed. 8) Supply chain analysis will be critical for determining the sustainability of feedstock production within the Mid- South region. 9) Because the infrastructure does not currently exist in the Mid- South for the production and processing of bioenergy feedstock, most of the logistic issues associated with the production, harvesting, transportation, and processing of short rotation woody crops for advanced biofuel production remain to be investigated. 10) Industry needs should be more clearly expressed to producers. Producers must know the type of feedstock required, the amounts that will be needed, when the feedstock will be needed, and where it will need to be transported. 11) Additional research is needed to identify best management practices for short- rotation woody crop production, including the potential for intercropping with short rotation woody crops and the fertilizer regime required for sustainable production of various species of short rotation woody crops.

Sorghum

Characteristics Making Sorghum a Suitable Feedstock

Sorghum is a very flexible annual crop that has tremendous potential as a bioenergy crop, particularly within our region. Sorghum is grown world- wide and is reported to the fifth most grown crop in the world. It is currently grown throughout the South as an animal feed (grain sorghum), as a forage (forage sorghum, sorghum- sudan), for bioenergy (grain sorghum), and for syrup production (sweet sorghum). Sweet sorghum contains significant amounts of sugar which can readily be converted directly into ethanol (Cundiff and Vaughn, 1987).

Within our region, sorghum has many advantages. One of the greatest advantages is that is an annual crop which can easily be integrated into an existing production system requiring only one season for planting and harvesting. High biomass production is possible with this annual system with production routinely exceeding 15- 20 tons/acre (Hallam et al., 2001). Producers would still have substantial flexibility to change varieties and/or crops on an annual basis as different prices or needs arise. Long-term commitment would not be necessary to raise this crop. As growers become familiar with bioenergy crops, many may want to try sorghum as a first attempt before committing long- term to grow crops for a biorefinery. Many of the other crops discussed in this paper require more than 3- 5 years for adequate production to sustain a biorefinery.

As an annual crop, sorghum also has an advantage that allows it to be grown during summer months in a relatively short season. This short season production could be augmented with the production of a cover crop that could additionally produce significant biomass. Some research has shown rye cover crops to yield 5- 6 tons/acre which could be harvested for bioenergy or could be retained for improved soil quality. One significant advantage of a cover crop that would be harvested for bioenergy purposes is that it could be used in the spring reducing the amount of sorghum that would need to be stored from the previous season. The lack of need for long- term storage for sorghum would be desirable as the bioenergy crop degrades over time, particularly when stored outside.

Also providing for increased flexibility is that some varieties of sorghum could be harvested multiple times, again reducing the time necessary for long- term storage (Pederson and Toy, 1997). Even though extra harvests could be costly, the advantages of reducing storage time and improvements in quality could well offset the negatives.

Sorghum could also fit well within small farm production systems which are prevalent within this growing region. Many small farms grow cattle which would function well with excess production of sorghum being used for cattle feed (Ademosum et al., 1968). Other animal production systems could also fit well alongside sorghum production with increasing numbers of sheep and goats being produced regionally.

The areas where sorghum could grow are widespread with reasonable climate, soils, water, and nutrients being required. Climate is usually tropical or sub- tropical for maximum production with this region mostly fitting within this description. Even though surface water is abundant within the region, increasing urban expansion pressures mostly require that agricultural crops be rainfed with minimal irrigation other than perhaps during stand establishment. Sorghum's water requirement is less than that of corn and is able to resist drought conditions for substantial periods of time. Nutrient requirements are also reduced from corn with lesser amounts of nitrogen being required for maximum production (Rooney, 2007).

One of the greatest advantages of this crop is that it is a very mature seed industry that can readily provide sufficient seed for widespread production. However, increased emphasis on various aspects of this material could readily improve the genetics allowing for increased drought and disease resistance, improved yields, reduced nutrient use, and improved palatability for animals. Genetic variation still exists within this crop as evidenced by plants with widely varying heights that are present in many grain and forage sorghum fields.

Sweet sorghum, in particular, lends itself to small- scale production using readily available technology that has been used for many years for conversion to ethanol (Cundiff and Vaughn, 1987). Residual material remaining after sugar has been removed could be used for animal feed which in turn would support animal production facilities.

Water Resource Considerations for Sorghum Production:

Although sorghum is a drought tolerant species, sorghum needs 30 inches of rainfall to get the maximum yield. In areas where this much rainfall is available, sorghum could be grown without irrigation, but in areas with less rainfall, farmers would likely irrigate sorghum to produce as much biomass as they can (improve profitability).

Research and Development

Although sorghum is a well- established crop with abundant seed available, much research remains to be done, especially for bioenergy purposes. Production practices need to be developed to allow this annual crop to be grown using conservation practices, particularly with cover crops and perhaps using legumes to offset nitrogen requirements.

Maintaining maximum yields of sorghum will require agronomic research in the various climatic regions of the South. Many of the technologies that should be evaluated include: fertilization (split applications and amounts), rotations with non- grassy crops to reduce disease pressures, and determination of appropriate plant populations.

Improved harvesting methods should also be developed that can adequately handle the extremely large plants and reduce time required to dry before storage. Improved crimping technologies should be developed to allow disruption of the membranes for quick drying without excessive energy requirements. In addition, machinery may need to be developed to assist with harvesting practices when plants have excessively lodged due to the large plants and high winds. Further assisting with reduction of lodging, is the need to evaluate different planting and fertilization patterns to reduce this problem.

Appropriate storage practices should also be determined for sorghum. Currently, baling is the choice often selected by researchers for storage of this bioenergy crop. However, the crop is often harvested when moisture contents are in excess of 40% and baling should not occur until drying has reduced the moisture content to less than 20%. Enhancing drying capability and allowing sorghum to quickly be baled would enhance our ability to store a high quality product.

Switchgrass

Characteristics Making Switchgrass a Suitable Feedstock

A number of characteristics make switchgrass suitable as a potential bioenergy feedstock in the Mid-South. Switchgrass is a native, perennial species that does not require reestablishment every year and would not raise concerns over invasiveness in the Mid- South; there are known methods for establishing a stand; switchgrass does not need to be irrigated and requires little or no N fertilization, resulting in decreased yearly input costs; switchgrass is a multipurpose crop that can be used as a cellulosic ethanol feedstock and as a nutritious source of livestock forage if properly managed; switchgrass is relatively easy to terminate and harvest; switchgrass is a multipurpose crop that can be used as a feedstock for cellulosic ethanol production and as a nutritious source of livestock forage if properly managed; switchgrass has high ethanol yields per unit biomass; mixed culture of switchgrass with other native perennial grasses also supports biodiversity and provides wildlife habitat; because it is widely adapted, there is a broad range of availability across the Mid- South where switchgrass can be grown; government funded research programs already exist for switchgrass production; improved switchgrass varieties produce high yields with low inputs (Mitchell et al., 2008; Rinehart 2006; Schmer et al., 2008).

Water Resource Considerations for Switchgrass Production:

Switchgrass grows well in regions receiving 15 to 30 or more inches of precipitation per year (Rinehart, 2006). Where switchgrass is grown, it is not typically irrigated, and water use efficiency is one of the major factors making switchgrass a promising bioenergy crop. However, growers would be growing switchgrass for high biomass yields and will need to know if irrigation would increase yields. If irrigation can increase yields and financial return then it may be used in some years and in some areas of the Mid- South.

Research and Development

Stand establishment is a major obstacle in switchgrass production. For example, seed germination can be inhibited by low soil moisture, incorrect planting depth (switchgrass requires a depth of ¼ to ½ inches), and seed dormancy (stratification step may be needed). Additionally, poor seedling vigor and strong competition from weeds are major issues limiting switchgrass establishment (Rinehart, 2006). More research is needed to improve seed germination, seedling viability, and weed control methods for improved stand establishment in switchgrass. Following the establishment phase, producers will need to have fertilization recommendations in order to obtain optimal biomass productivity.

Although switchgrass can be harvested using traditional equipment for hay harvesting (Rinehart, 2006), producers need to know if it is more feasible to have multiple harvests per year or a single harvest at the end of the season. More research and development is needed into using switchgrass as a multipurpose crop (grazing and bioenergy feedstock). Farmers may be able to improve profitability if they can use the same crop as a forage source early in the season, and remove cattle in time to produce a sufficient biomass crop by the end of the season. Storage capacity will also be a concern when harvesting large amounts of plant biomass.

Broad Issues

Conversion Platforms

Multiple conversion platforms could be employed for any one of the feedstock choices listed above. However, more research and development are needed to establish which conversion platforms are best suited for a specific feedstock source. The lignin content of plant tissues is expected to have a major impact on the conversion platform utilized and the biofuel conversion efficiency. Boateng et al. (2008) reported that lignin content was positively correlated with production of pyrolysis products, whereas biochemical conversion was negatively influenced by higher lignin concentrations in alfalfa. Consequently, feedstocks containing high lignin concentrations (woody crops) may be more amenable to thermochemical conversion platforms, whereas other species with relatively low lignin concentrations (i.e. switchgrass and sorghum) may be better suited to biochemical conversion platforms. Additionally, high concentrations of secondary chemicals in the tissues of some crop species (i.e. pine) are known to inhibit biochemical conversion processes and would likely necessitate the use of thermochemical conversion methods (Kline and Coleman, 2010).

Harvest and Logistic Issues

Most efforts have been devoted to using existing harvesting equipment for bioenergy crops. Due to their widespread usage and similarities of plant materials, existing hay equipment is a most natural selection for cutting, baling, and transporting bioenergy crops (Nordh and Dimitriou, 2003; Thorsell et al., 2004). If current technology machines could be used, small farmers may be able to make a positive contribution to bioenergy production. However, significant differences may require differing machines for additional purposes. These more complicated machines may then require specialized harvesting technology which could be owned by cooperatives, bioenergy refineries, or custom harvesting specialists who move through a region and harvest all crops before moving on to another region, much like custom wheat harvesters in the Midwest.

Currently, most bioenergy crops are cut during the fall of the year when nutrients have senesced back to the rootstock; however, additional advantages may be offered until well in the spring (Hadders and Ollson, 1997). One criterion that is usually used to determine cutting height is the height that the plants can be cut without damaging tires which pass through the field over the cut stalks. Cutting plants too short can leave sharp, strong, stalks that can easily penetrate rubber tires. However, cutting too high can leave excessive amounts of crops in the field and unnecessarily reduce harvested biomass.

Depending upon the crop and variety, bioenergy crops may be cut when dry or wet. If cut dry, they are likely to be baled immediately and either stored or transported to a holding facility where they are stored prior to being used in a biorefinery (Thorsell et al., 2004). Preferable shapes for baling are either large round bales or large square bales which adequately shed water for outdoor storage. Additional research is currently being conducted to determine if large bales can be densified which would reduce both storage and transportation cost.

If crops are cut before they are adequately dried for baling, they are often conditioned by fracturing the membranes of the stalk with crimping rollers (Sokhansanj and Hess, 2009). This assists with infield drying that allows the moisture to escape and the materials to be baled without danger of spoilage. Typically, the overall moisture content of the material should be near 15% or spoilage or combustion can occur. During the infield drying, the materials may need to be turned and/or spread to accelerate drying from sun and wind. Fortunately, much of the South has limited rainfall during the fall of the year when most bioenergy crops will be harvested. This limited rainfall should contribute to allowing adequate drying to occur for most bioenergy crops.

As mentioned earlier, bioenergy crops differ in several ways from traditional hay crops. First, the amounts are usually much greater with biomass levels easily surpassing maximum hay production. This can directly impact the machinery necessary for cutting and crimping the biomass. These larger biomass amounts will require heavier, more costly, and complicated harvesting equipment. Additional power will be required to operate the equipment unless harvesting speed is reduced, which is not desirable. Another difference not often considered is that these large bioenergy crops may tend to lodge more often requiring additional equipment or power. High winds which often occur during the late summer and early fall of the year in this region, can flatten bioenergy crops thus complicating their harvest. Additional research may be necessary to determine methods of preventing wind damage.

Some bioenergy crops that will be processed for sugar will be harvested while wet and quickly processed to obtain the sugar solution (Cundiff and Vaughn, 1987). Machines especially designed for harvesting of sweet sorghum can be used to harvest whole stalks which can then be processed (Rains et al. 1990). Spoilage can occur if the plants are not quickly processed after harvest (Eiland et al., 1987).

Transportation cost is often considered to be a limiting factor with the relatively light weight biomass requiring excessive costs to be transported from field to refinery (Sokhansanj and Hess, 2009). Intermediate handling of biomass would be required to move the biomass to the edge of the field, to a regional temporary staging area, and then on to the refinery. Of particular significance is the estimated time of handling multiple bales at each location which could easily exceed 30 minutes. Crews working 24 hours/day could function much like in the cotton industry where modules are tagged and moved to the gin on an as needed basis. However, the amount of biomass necessary to constantly operate a moderate- size refinery is quite large and will likely require continuous movement of materials.

Lifecycle, Modeling, and Policy Issues

Lifecycle

Lifecycle assessments are very local and farm to farm assessments will likely give substantially different results even within a relatively small geographic region. It might be possible to use an average of multiple data points for a wide range of systems to estimate the impact of cropping systems and management strategies on lifecycle assessments. Additionally, it will be important to estimate the impact of transitioning from a given production system to a dedicated bioenergy cropping system on lifecycle assessments.

Models

Models exist in different scales: field scale, water shed scale, etc. There is a need to be able to convert from small- scale, model- generated data to extrapolate to larger scale areas. Because there is no comprehensive model to look at all sustainability issues, an integrated series of models will be essential in allowing researchers to evaluate numerous sustainability issues, including productivity/profitability and issues associated with environmental sustainability. Regardless of the model used, the model assumptions must be validated; however, only limited data is available for select bioenergy crops. More data will be needed on the production of a wide range of feedstock sources under various soil and environmental conditions throughout the Mid- South region. Access to existing data (older data) needs to be improved. This would decrease the need for expensive field tests to be conducted when the data already exists. Because site specific yield differences can exist even within a field, data points are needed from large- acreage model validation studies to improve model parameterization. Because model insensitivity to environmental extremes (i.e. drought and heat stress) can result in discrepancies between simulated and actual yields, more data is needed to accurately and quantitatively predict the impact of environmental extremes on biomass production for a number of bioenergy crops. Ultimately, the existing knowledge base for bioenergy crops needs to be improved in order for models to be valid.

Policies

Laws influence cooperatives and largely determine farmer adoption of a given feedstock production system. Water rights are a serious concern in some areas of the Mid- South, and would limit the production of bioenergy crops requiring irrigation in those regions. Laws intended to improve environmental quality will influence the amount of biomass that can be produced and the amount of biomass that can be utilized for bioenergy purposes. For example, laws that limit fertilizer application rates (NPK) to prevent nonpoint source pollution and improve water quality may require lower fertilization rates than those needed for optimal biomass production. Because different feedstocks will contain varying concentrations of mercury, nitrogen, and sulfur, regulations to limit the emission of atmospheric pollutants such as mercury vapor, NOx, and SO2 will govern the amount of thermal energy that can be generated from a given feedstock. Additionally, policies implemented to limit ash toxicity and other forms of environmental pollution will largely determine waste handling procedures at biorefineries. Finally, permitting complications may represent a major limitation to the production of advanced biofuel feedstock. If people in charge of permitting in a given county do not have an expert on- site who knows what a given reactor or other specialized equipment does, they will likely not approve it.

Climate Change and Global Realities

Climate Change

Reports on the effect of global climate change on crop yield have proposed substantial losses in productivity under the global surface temperature increases projected to result by the end of the 21st century (Peng et al., 2004). For example, Peng et al. (2004) reported that every 1°C increase in mean minimum temperature (above the optimum) resulted in a 10% decline in rice yields. Although these findings are cause for concern, even more concerning than changes in average temperature or precipitation are climatic extremes predicted to result under a changing global climate (i.e. record high temperatures, excessively long periods of drought or flooding, greater frequency and intensity of severe weather events). Breeding bioenergy crops for yield stability under variable climatic conditions will be essential. In regions of the Mid- South where high winds and heavy rains typically associated with severe weather conditions are common, shorter plants less susceptible to lodging (Berry et al. 2000) might be most appropriate. In regions where drought becomes a major concern, farmers will probably need to consider on- site water storage and to employ partial root zone drying as an irrigation strategy to improve water use efficiency (White and Raine, 2009). Despite some of the limitations associated with crop modeling discussed previously, more robust crop models will be needed to predict the potential impact of global climate change on the productivity of a range of potential bioenergy crops throughout the Mid- South.

Global Realities

Fluctuations in oil prices strongly influence the utilization of alternative fuels on a global scale. When oil prices are high, interest in renewable energy and investments in renewable energy research and development are at their peak, whereas low oil prices strongly limit the development and adoption of alternative energy technologies (Kyle, 2008). Additionally, labor availability is a substantial limitation to sustainable bioenergy feedstock and advanced biofuel production because fewer young people are engaging in agriculture, and many young people are moving away from rural communities for other employment (Gale, 2003). Rural development will be essential in stemming the urban migration and creating jobs in rural communities. It will also be essential that increased production of bioenergy crops does not significantly constrain global food supply (Sivakumar et al., 2010). Regarding sustainability, farmers may produce feedstock in a sustainable manner by judiciously using available resources; minimizing energy inputs and greenhouse gas emissions; and limiting environmental contamination, but they have no control over the practices employed at other points in the supply chain. Improving sustainability on a supply chain scale will be essential for sustainable bioenergy feedstock production. Finally, given the U.S. Navy's recent interest in using bio- based jet fuel and diesel to power its planes and ships (Biello, 2009) and the role of Wal- Mart, the world's largest retailer, in promoting sustainable agriculture and renewable energy (Clifford, 2010), it is likely that these two entities could have considerable influence on renewable energy policy in the U.S.

Top Issues & Recommendations for the Mid- South

Policy Issues and Potential Actions

- Government Incentives: Risk is a substantial constraint to the production of feedstock for advanced biofuel production. Farmers need to know there is going to be a market for their feedstock; companies need to know there is a consistent supply. We need a coherent government policy to promote biofuel production. USDA programs to offer incentives to both groups (tax breaks, loan guarantees, etc.) will be needed to get this started. There is also an abundance of small farms in the Mid- South that should be protected (>90% of all farms in the U.S. are considered small). A mandate needs to be established requiring that a certain percentage of the material being supplied to the refineries is coming from small farms.
- State Cooperative Laws: Producers and processors need to interact in order for feedstock production to take place. In Tennessee, millions of dollars have been invested into biorefinery development and addressing feedstock production issues, including crop growth, harvesting, storage, and transport (Charles, 2007). A major driving force for this is that Tennessee, along with other states, has new laws governing cooperatives. Cooperatives in some states now have more contract authority. They can make deals and accept outside money to set up demonstration facilities. New cooperative laws are needed that give state cooperatives contract authority and allow them to accept money from non- members.

Facilitation

- USDA and State University extension infrastructure exists in the U.S. and will be essential in providing farmers with recommendations on sustainable bioenergy feedstock production, and in educating farmers on the available programs and incentives available to them. There must be some on- the- ground face- to- face interaction between farmers and extension agents to show producers that sustainable biofuel feedstock production can be a profitable enterprise.

Research and Development

- Environmental sustainability will be essential for long- term production of biofuel feedstocks. Sustainability needs to be more uniformly defined with an agreed upon set of standards.
- Lands must be targeted that will not take away from the food supply. Government incentive could possibly limit biofuel production on good lands. Although some production on good food production lands will occur, the US government will probably need to control food prices. In order for any government action to take place, marginal land needs to be more clearly defined. Currently, definitions of marginal lands vary depending upon the production system employed (e.g. trees may be highly productive on lands that would be considered marginal for grain crop production).
- Biorefinery logistics: Farmers will probably need biomass collection points in each county that could then feed into a centrally located large- scale biorefinery.

Mid- South Characteristics Contributing to Sustainable Feedstock Production

- Existing rural electric cooperatives could provide a good model. Co- firing biomass with coal could be a possible market for bioenergy feedstock, where electric companies could include a portion of “green” energy with an added premium or credit associated with the use of renewable energy.
- The Mid- South has the capabilities to produce high tonnage, where land areas previously unused could contribute to biomass production.
- We will not need to compete with food production since the Mid- South already has sufficient acreages of marginal lands.
- We have an established petroleum infrastructure and distribution system that we could tap into and use.

Future Concerns

- Petroleum, wind energy, solar power, and natural gas compete strongly with alternative biofuels, and wind energy and solar power could function as major disruptive technologies that limit the demand for advanced biofuels.

Timeline

Phase I: Completed by 2014

- The knowledge base must be improved by addressing both general and feedstock specific research and development concerns.
- Policy must change in order to facilitate research and development. Government incentives along with changes in laws governing cooperatives will be essential to build a useable knowledge base.
- Operation of demonstration farms and processing facilities should begin within this time frame.

Phase II: Completed by 2018

- The necessary infrastructure should be in place at this time with additional refineries being added to the landscape as production expands.
- Farmers begin including bioenergy feedstock into their existing agricultural production systems using soil and water conservation practices.
- Economically feasible production of advanced biofuels is already under way at this time.

Phase III: Completed by 2022

- Period of rapid expansion for both producers and processors.
- Marginal lands and some of the private forested lands have been largely converted into bioenergy feedstock production areas by the end of this phase.

Workshop participants for this region:

- John Snider, USDA- ARS
- Pradip Das, Monsanto
- John Read, USDA- ARS
- John Reilley, USDA- NRCS
- Paul White, USDA- ARS
- Corey Radtke, Shell Global Solutions
- Steve Thomas, U.S. DOE
- James H Purdue, USDA- FS
- Ray Huhnke, Oklahoma State University
- Chris Jonas, DuPont (DDCE)
- Guorong Zhang, Tennessee State University
- Solomon Haile, Tennessee State University
- Jason de Koff, Tennessee State University
- Tom Gerik, Texas A&M
- Alexandre Rocatelli, University of Arkansas
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- Joseph Molnar, Auburn University

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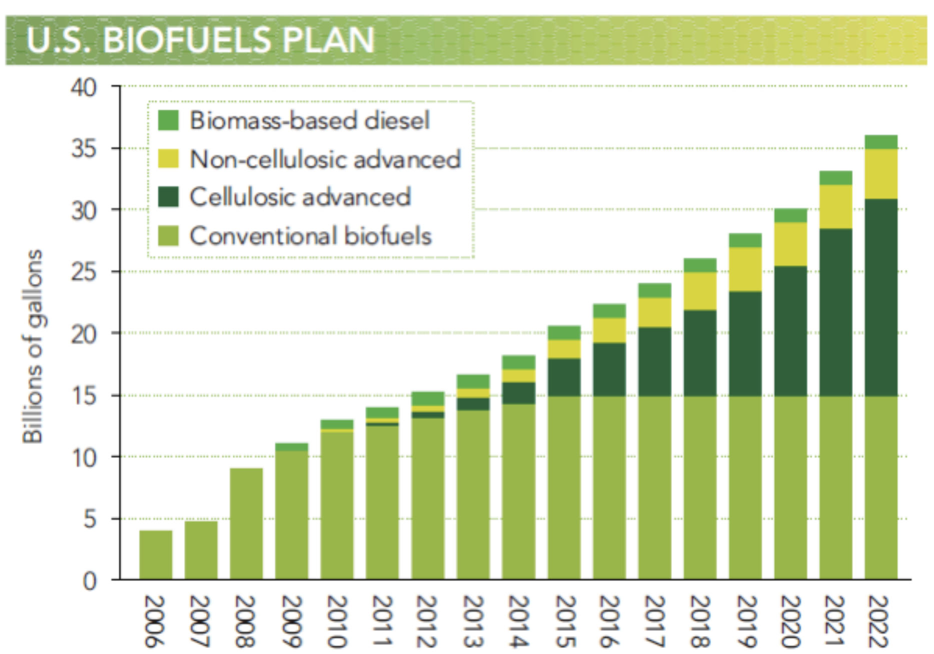

Figure 1. Projected U.S. biofuel production as outlined in the Energy Independence and Security Act of 2007 (Service 2010).

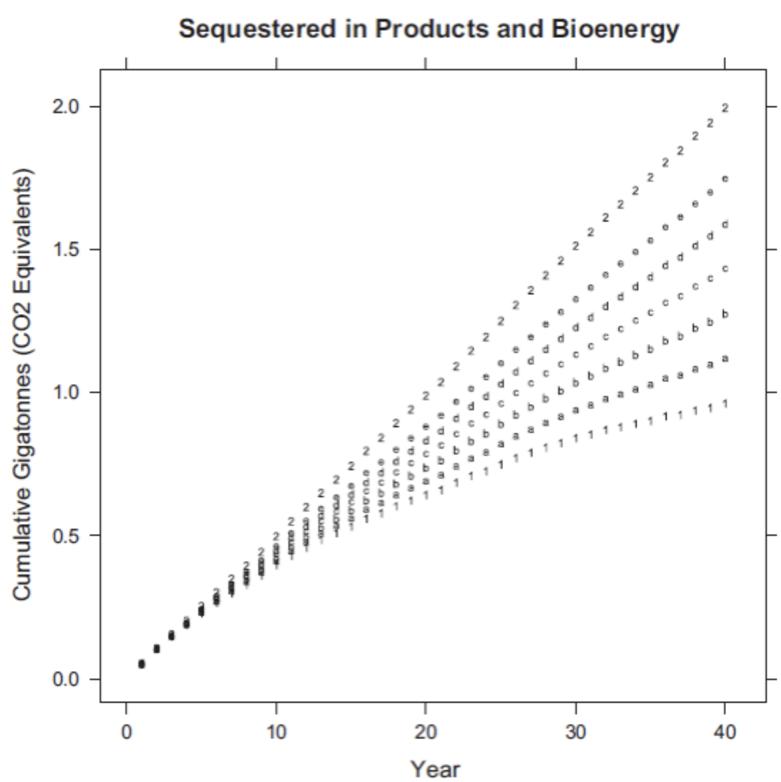

Figure 2. Cumulative sequestration (gigatonnes of CO_2 equivalent) in products and bioenergy.
Reference curves for 10 and 50 year half lives with zero percent going to bioenergy are coded with 1s and 2s.
The remaining curves have the half life for products fixed at 10 years, while the percentage of the harvest going to bioenergy varies.
Bioenergy percentages are coded as: a = 10, b = 20, c = 30, d = 40, e = 50 (Van Deusen et al. 2010).

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