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Practical considerations in developing bioenergy crops

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Summary

Biofuels represent a significant challenge and opportunity for agriculture. Producing liquid fuels from cellulosic biomass affords a number of potential environmental benefits. Biofuels result in lower greenhouse gas emissions than fuels derived from petroleum. Growing perennial biomass crops reduces soil erosion and sequesters more carbon than annual crops grown for grain or biomass. Corn and sorghum are crops that have high near-term potential as annual biomass crops. Dedicated biomass crops with very high yields will produce more fuel per acre, helping to balance land for food and fuel. Switchgrass and Miscanthus are perennial species that have been broadly evaluated as potential biomass crops, but will benefit from further development for widespread use. New crops and cropping systems developed specifically for bioenergy production will be necessary to meet biofuel production targets. Bioenergy crops should be developed that use inputs efficiently, have high and stable productivity, have positive environment impact, and are compatible with existing cropping systems. Most importantly, biomass crop portfolios must be developed that allow for sustained energy supply throughout the year.

Introduction

The U.S. Departments of Agriculture (USDA) and Energy (DOE) released a feasibility study in which they evaluated the potential of cellulosic biomass for meeting a goal of replacing thirty percent of transportation fuels with ethanol derived from biomass by 2030 (Perlack et al., 2005). They estimated that this would require approximately one billion dry tons of feedstock to accomplish. They estimated present feedstock available from agricultural lands to be 194 million dry tons annually and evaluated alternative scenarios for increasing availability to the billion ton goal. Crop residues, such as corn stover, and dedicated energy crops are anticipated to be the largest sources, however a disproportionate amount of biomass is expected from a relatively small acreage devoted to dedicated biomass crops.

Major multi-national energy companies are now heavily investing in biomass energy for a variety of reasons including 1) pressure to reduce CO₂ emissions; 2) mandated requirements for green energy production and 3) increasing difficulty in extracting petroleum from the earth. Concomitantly, they have seen record profits as the price of oil increased over the past 2 years, causing ability and pressure to put money into renewable energy research and production. It is important to recognize that these companies are used to working with geologists to find the fuel they need; now they need to work with agronomists!

Growing biomass in conjunction with traditional food crops will require careful and intensive management. There is no way we will saturate demand for biomass from agriculture as we have traditionally done with food crops, and energy producers will require contracts for biomass.
delivered throughout the growing season. How will this be done? We suggest that it will be done by developing crop portfolios that allow expanded and more efficient use of the growing season. Further, it will be done in areas of the country that have the infrastructure for high-output production and distribution, i.e. the Midwest. It is just a matter of time, policy and of course, profit.

**Figure 1.** Example of a biomass crop portfolio to meet target feedstock tonnage throughout the year for a given region. Graphic courtesy of Ceres, Inc.

Biomass crops may create opportunities to diversify cropping systems and optimize landscape use based on spatial variation. In many crop producing regions, cropping systems are relatively simple, consisting of just a few monoculture crops grown in various sequences. Introduction of biomass crops into these rotations may produce positive rotation effects related to nutrient, moisture, and pest management. It may be possible to introduce perennial biomass crops into long-term rotations with annual grain or biomass crops to restore soil carbon balance and improve soil quality. By providing a market for cellulosic biomass, marginal land that is currently in row crop production could be diverted to perennial biomass crops that are more environmentally appropriate.

**Crop geography of biomass production**

The primary goal of biomass crop production is the capture and conversion of sunlight into chemical energy. The efficiency of this conversion depends on a number of factors some of which can be altered through management and others that cannot be managed. The potential production of any crop depends on climatic and edaphic factors associated with the region in which it is grown. Climatic factors such as precipitation, temperature and solar radiation determine where crop species can be grown and their potential yield within a given climatic region. Crop adaptation is limited by growing season, temperature and moisture stress, and in many cases, photoperiod (Nelson, 1996).
Soil quality also influences adaptation and yield potential of biomass crops. The inherent productivity of soil is affected by chemical, physical and biological properties which interact with climate to determine potential productivity of a site. Soils with physical limitations such as low water holding capacity, high bulk density, and poor drainage negatively influence plant growth. Soil fertility is also important, particularly with respect to plant nutrition and factors that adversely affect plant growth such as high and low pH, and accumulation of phytotoxic elements such as sodium and aluminum.

Because yield density of available ethanol feedstock will likely be a major criterion in considering the location of biorefineries, it is reasonable to assume that they will be located in regions where biomass production potential per unit area is relatively high. These areas are generally characterized by adequate precipitation for crop production, a moderate to long growing season, and soils capable of sustaining a high level of productivity. Within the U.S., the highest biomass producing areas are located in the humid temperate and subtropical regions which extends east from about 98° W longitude. Other considerations of likely importance will be the existence of current cropping systems that are compatible with biomass production and agricultural and transportation infrastructure.

### Dedicated bioenergy crops

What are the species that will be used to provide bioenergy feedstock and to what degree will they vary by production region? This section will review some key grasses in use as early energy crop species while the next explores trait considerations in the development of new dedicated energy crops.

**Table 1. Basic information on early and developing grass energy crops species in the United States.**

<table>
<thead>
<tr>
<th>Crop</th>
<th>Establishment method</th>
<th>Life cycle</th>
<th>Established agronomics</th>
<th>Established U.S. markets</th>
<th>Typical biomass yield (t DM/ha)^1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>Seed</td>
<td>Annual</td>
<td>Yes</td>
<td>Food, grain ethanol</td>
<td>11 – 22</td>
</tr>
<tr>
<td>Sorghum</td>
<td>Seed</td>
<td>Annual</td>
<td>Yes</td>
<td>Food, feed</td>
<td>15 – 27</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>Seed</td>
<td>Perennial</td>
<td>No</td>
<td>Forage</td>
<td>7 – 22</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>Rhizomes</td>
<td>Perennial</td>
<td>No</td>
<td>Not developed</td>
<td>22 – 34</td>
</tr>
</tbody>
</table>

^1(Bean et al., 2006, Pyter et al., 2007, Schmer et al., 2008)

**Annual grasses**

**Corn (Zea mays L.)**

As mentioned previously, the dominate biofuel at present is grain ethanol from corn grown intensively on an increasing number of acres in the U.S. (NASS, 2007). Corn grain is a logical first biofuel feedstock since it has long been used for production of food grade ethanol around the world, and has established economic and agronomic infrastructure. Modern corn hybrids are the product of more than a century of dedicated crop breeding and are dramatically different from their wild progenitors (Jauhar, 2006). Corn has been bred to respond strongly to inputs of irrigation and fertilizer, as well as coupled with dedicated pest management regimes, leading to unprecedented grain yields.
Because corn has been purpose bred as a food crop, it is not surprising that it is not optimized as an energy crop. The economic and energetic inputs that have been acceptable or tolerable in food crops come under heavy scrutiny if applied to energy crops as they reduce the net energy produced in the biofuel while increasing both the carbon footprint and production cost of the feedstock. New efforts are now underway to breed corn varieties that require fewer inputs, as well as those that are dual purpose food/biofuel varieties, relying on increased fermentable sugars in the grain and a higher fraction of stover that can be converted to ethanol via cellulosic conversion pathways.

Despite the concerns over using corn for food vs. fuel and the environmental impact of continuous corn production on U.S. cropland, it is one of the few existing crops today that is readily available and can be immediately deployed for ethanol production (Table 1). There is little doubt that corn will remain an integral component of the energy crop species portfolio for the foreseeable future.

**Sorghum (Sorghum bicolor (L) Moench)**

Sorghum is an early annual biomass crop that seems to combine the domesticated advantages of corn with the low-input benefits of perennial grasses. Like corn it has established markets and a well-developed portfolio of crop management tools. Both crops were domesticated by early agrarian societies and have been adapted to a broad range of production environments. Sorghum is traditionally used in areas considered marginal for corn production and is known for its low input requirements, particularly of nitrogen fertilizer and water. This makes it an attractive candidate as an environmentally, energetically and economically favorable alternative annual biofuel feedstock, especially in areas of the U.S. outside of the Corn Belt.

Of the different types of sorghum crops, sweet sorghum and forage sorghum have gained most attention as cellulosic biomass feedstocks. Sweet sorghum has the attraction of high ethanol yields possible from both fermentable sugars and stover biomass. New lines of forage sorghum that may be considered inferior for livestock production have such high biomass yields as to recommend them for development into cellulosic feedstock varieties. Particularly proraising in this regard are the photoperiod sensitive varieties that require day length cues to switch from vegetative to reproductive growth. When grown in higher latitudes, these varieties do not receive such a cue and will keep producing vegetative biomass until low temperatures terminate growth for the season.

A major advantage of sorghum for an early biomass feedstock is its established presence as a crop in the U.S., and the familiarity of farmers with its successful production. That said, sorghum produced for cellulosic biomass will likely require different agronomic management practices than growers are accustomed to using for grain, sugar or forage production, and these practices are only beginning to be researched. The need for cellulosic biomass to be dry, for example, will likely influence harvest time and method, and maximizing tons per acre instead of optimizing forage quality and quantity might change fertility recommendations.

**Perennial grasses**

**Switchgrass (Panicum virgatum L.)**

A perennial grass native to much of North America, switchgrass is probably the best known
cellulosic biomass crop in the U.S., thanks in part to its specific mention in a U.S. State of the Union address (Bush, 2007). A major component of prairie ecosystems, switchgrass has long been used as a warm-season forage and later as a conservation tool for erosion control. Because of its ability to produce biomass more consistently than many other native U.S. species over multiple locations and years, and its favorable environmental qualities, switchgrass was identified as a leading candidate for bioenergy production (McLaughlin & Kszos, 2005, Parrish & Fike, 2005). The U.S. Dept. of Energy began investigating it as a model bioenergy species through a variety of research programs over 20 years ago (DOE, 2006). While more developed than many other species now being investigated as energy crops, switchgrass is still far from a completely domesticated crop. It is only the recent and exponentially growing interest in renewable energy from plant biomass that has forced the recent proliferation of switchgrass improvement efforts.

There are several characteristics that lend switchgrass to cellulosic biomass production, some of which have been alluded to previously. It is perhaps fair to say that just as sorghum represents an annual species that already combines the convenient attributes of a widely used domesticated crop with the low-inputs and high yields of an energy crop, switchgrass represents a perennial species with similar, but less developed capability. It already has the capacity for use in modern production agriculture on a large scale, coupled with moderate biomass yields and promising genetic variation for improvement (Missaoui et al., 2005, Taliaferro, 2002). Seed is currently available for purchase in the U.S., planting and harvesting can be done with conventional forage equipment, and some herbicides have been labeled for use in switchgrass (Nyoka et al., 2007). The environmental benefits of switchgrass on soil, water and habitat quality are well documented (Giuliano and Daves, 2002, Ichizen et al., 2005, Lemus and Lal, 2005, Lin et al., 2005). As a perennial, planting is required only once, and if properly managed, a switchgrass stand can be maintained for an indefinite period with low input demands (Parrish and Fike, 2005).

It is technically feasible to grow switchgrass with success, but production for bioenergy is not yet optimized. Further, no real economic or agronomic crop support infrastructure yet exists for it or any other dedicated energy crop. Switchgrass has traditionally been grown on only limited acreage in the U.S., and the majority of U.S. farmers are as of yet unfamiliar with its management (Jensen et al., 2007). Improving the agronomic and economic management of switchgrass for bioenergy has been a major focus of U.S. research, with the goal of informing grower practices. Recent evidence indicates this strategy may be working. Schmer et al. (2008) found that field scale production and grower familiarity dramatically enhanced crop productivity, leading to yields of biomass and energy over 90% greater than those found at the research plot scale for LIHD plantings (see Intensive vs. extensive biomass production, above).

Most switchgrass varieties used today have undergone only a few breeding cycles or have been simply increased from wild populations. There is wide genetic variability to be exploited in switchgrass and dedicated breeding programs have made rapid improvements through traditional and molecular approaches (Bouton, 2002, Taliaferro, 2002, Vogel et al., 2002).

**Giant Miscanthus (Miscanthus x giganteus).**

Another perennial grass under development as a cellulosic biomass crop is the sterile hybrid Miscanthus x giganteus, often referred to as Giant Miscanthus. A relative newcomer to U.S. energy crop considerations, Giant Miscanthus has been investigated in Europe in the much same way as switchgrass has been in North America. Likely a product of hybridization between
Japanese *M. sacchariflorus* and *M. sinensis*, this triploid is not capable of producing fertile seed and is typically planted using rhizome cuttings (Hodkinson *et al.*, 2002, Lewandowski *et al.*, 2000, Nixon *et al.*, 2001). Giant Miscanthus was advanced as an energy crop in the EU in part because this sterility, coupled with a non-spreading growth habit, mitigated risk of weediness or pollen outcrossing with compatible species. Following years of testing in multi-location trials around the EU, Giant Miscanthus was shown to produce consistently high biomass across a range of conditions with minimal inputs, and at temperatures and latitudes beyond the normal growing range of warm season grasses (Jones & Walsh, 2001). When evaluated in the U.S., Giant Miscanthus produced record yields, on average 2-4 times more biomass than switchgrass (Heaton, 2006, Heaton *et al.*, 2008).

Of the crops discussed here, Giant Miscanthus is probably least compatible with the existing production agriculture infrastructure in the U.S. Digging, sorting, transporting and planting rhizomes dramatically increases planting costs over traditional seed based crops. This cost is partially offset by the higher biomass yields from Giant Miscanthus and the low annual production costs. Like switchgrass, Giant Miscanthus has long stand lifetimes, low input requirements and well documented environmental benefits (Schneckenberger and Kuzyakov, 2007, Semere and Slater, 2007a, Semere and Slater, 2007b). In England the crop is commercially used in electricity production through co-firing with coal, and here a successful agricultural industry has developed, supported by economic incentive packages and federal research. This has led planted acreage to increase by approximately 300% every year since the support programs began (DEFRA, 2006).

Though Giant Miscanthus is sterile and cannot be selectively improved in the same way as switchgrass, the Miscanthus genus has much genetic variation to exploit through traditional and molecular breeding, and in fact this has been done for the crop’s cousin, sugarcane (Amalraj & Balasundaram, 2006). Miscanthus research in the U.S. and the EU now emphasizes crop breeding and development of commercially viable agronomic practices.

**Biomass crop ideotype**

Development of crops bred specifically for cellulosic biomass is in its infancy. Which plants are naturally best suited to biomass production? We have already discussed some early leading energy crops and alluded to factors favoring their success in this regard. It must be realized, however, that crops used at this early stage are as likely to be promoted from luck or legacy as they are from merit. However, we are now at a time when genomic understanding enables plant breeding at an unprecedented rate and the outcomes of the Green Revolution may be weighed with the perspective of time, thus we have the opportunity to design a sea change in global agriculture. A careful consideration of crop traits useful to biomass feedstock production from first principles seems prudent. Factors that should be evaluated in that analysis are outlined here.

Generally, an ideal biomass crop must be characterized by the resource efficient conversion of sunlight energy into usable carbohydrate energy.

**Efficiency:** Biomass crops must store as much carbon per unit input of water, fertilizer, light, heat, etc. as possible to allow them to be cheaply and sustainably produced. Grasses with the C4 photosynthetic pathway have inherent efficiencies that lend them to cellulosic biomass production; perennials in this group have added benefits over annuals in providing ecosystem
services (Long, 1994, Samson et al., 2005).

Productivity: High yield density (unit biomass/unit land area) is required to a) make harvest and transport economically viable; b) allow biorefineries to realize economies of scale; and c) reduce opportunity costs from competing land uses.

Flexibility: Biomass feedstock must be available upon demand and therefore available in sufficient and changeable quantities year round. Crop mixtures comprising different life cycles and maturity times must be developed to support this demand and minimize need for storage or drying.

Stability: Energy security will depend on a stable supply of feedstock within and between growing years. Crops and crop mixtures must minimize risk of yield loss from pests, disease or weather.

Sustainability: In a carbon-conscience and resource constrained future, biomass crops must have a favorable environment impact, including both a positive greenhouse gas and energy balance. Ecosystem services such as carbon sequestration, water and nutrient cycling and wildlife habitat will add value and utility to the system.

Compatibility: To meet mounting demand, biomass crops must be adopted and scaled up rapidly. This necessitates new crops be developed and introduced in tandem with agronomic practices that make them easily incorporated into the existing agricultural infrastructure in the U.S.

Future research needs and challenges

Replacing a significant proportion of transportation energy with cellulosic biofuels will require development of highly productive energy crops. The crops described above represent near-term alternatives and will require significant improvements in biomass productivity to remain viable as energy crops in the future.

A rational long-term approach will be required to develop alternative, high-yielding biomass crops specifically designed for energy and industrial uses. A significant research effort is needed to identify alternative plant species that produce higher biomass yields and have desirable biomass traits, develop cultivated varieties of alternative species through genomics and plant breeding approaches, and develop appropriate crop management practices and systems for producing dedicated energy crops.

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