Biorenewable Energy: New Opportunities for Grassland Agriculture

Kenneth J. Moore
Iowa State University

Steven L. Fales
Iowa State University

Emily A. Heaton
Ceres , Inc.

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Biorenewable energy : new opportunities for grassland agriculture

Kenneth J . Moore and Steven L . Fales , Iowa State University , Ames , IA , USA
Emily A . Heaton , Ceres , Inc . , Thousand Oaks , CA , USA kjmoore@ iastate .edu

Key points : Biofuels represent a significant challenge and opportunity for grassland 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 . Low energy density of biomass will require high yield density to lower transportation costs . Corn and sorghum are crops that have high near-term potential as annual biomass crops . 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 .

Key words : Biomass , Bioenergy , Biofuels , Crops , Ethanol

Introduction Much of the world relies on petroleum and its derivatives as a primary source of energy . Demand continues to grow worldwide with the fastest growth in emerging economies such as China and India . Petroleum production is expected to peak in the first half of this century and it is clear that alternative sources and forms of energy will supplant it by the end of it (Duncan and Youngquist , 1999 ; Youngquist , 1999) .

Combustion of petroleum products releases CO_2 and other greenhouse gases into the atmosphere . This carbon previously had been sequestered for millions of years , and its relatively sudden release over a period of 100 to 200 years is causing a significant increase in atmospheric CO_2 concentration . Carbon dioxide levels have risen from a pre-industrial 280 ppm to a current (2008) level of over 380 ppm (Tans , 2008) . This increase has been related to a warming of the atmosphere and has been cited as the cause for global climate change . Anticipated consequences of global climate change include ice melting , sea level rising , erratic weather patterns , and a corresponding disruption of many human activities (IPCC , 2007ab) .

For these reasons , there is growing interest in developing alternative fuel sources that are renewable and carbon neutral in terms of net fixation/release rates , leading to a significant interest and investment in development of liquid fuels derived from agriculture (Farrell et al . , 2006) . In the U .S . , corn ethanol production is growing exponentially and is anticipated to reach 7.9 billion gallons in 2008 (Reuters , 2008) . Investment in corn ethanol plants in the U .S . has been underwritten to a large extent by federal subsidies in the form of a blenders credit paid to those who blend ethanol with gasoline . The large demand in corn grain for ethanol has raised concerns about impacts on food prices and the environment (Marshall and Greenhalgh , 2006) . However , corn ethanol can only meet a relatively small proportion of the demand for liquid transportation fuels . Even if the entire U .S . corn crop were processed into ethanol it would only account for approximately 12 to 15% of the 530 L annual U .S . consumption of gasoline (Perlack et al . , 2005) . Consequently , there is increasing interest in development of other renewable feedstocks for producing ethanol and other liquid fuels (Borgwardt , 1999) .

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 . Of particular interest to grassland agriculture , is the expectation that land currently enrolled in conservation programs and some pastureland would be converted to energy crop production . Much of this land is highly erosive and the only sustainable approach to managing it for bioenergy production would be the culture of perennial crops (Kort et al . , 1998) .

Energy from Cellulosic Biomass Conversion technologies The simplest and oldest method of biomass utilization for energy is direct combustion . Combustion of biomass either alone or in combination with another fuel such as coal , has shown good potential for heat and electric power production (van Loo and Koppejan , 2002) . The latter process , referred to as co-firing , is technically feasible although the economics will remain challenging as long as biomass remains significantly more expensive than coal . Currently , the primary emphasis with cellulosic biomass is as a feedstock for liquid transportation fuels . Two general approaches (platforms) are employed . The biochemical platform uses a combination of chemical and biological (enzyme) processes to extract carbohydrates from plant cell walls , followed by fermentation to ethanol and subsequent purification by distillation . Challenges with this approach have included the expense and efficiency of the enzymes , substrate specificity of the enzymes , and the need to remove lignin by pre-processing the biomass prior to hydrolysis . However , technological advances are being made in each of these areas , and it is likely that commercial scale cellulosic ethanol will be a reality within the next several years (U .S . DOE , 2006) .

An alternative approach to generating liquid biofuels is thermochemical processing. This platform employs elevated temperatures (> 500°C) and restricted oxygen either to gasify the material or liquefy it to a bio-oil, depending on the specific processing conditions used (Huber et al., 2006). The advantage to this approach is that pre-processing to remove lignin is not necessary, and that the system is compatible with a host of organic materials of differing chemical composition. The resulting gas (syngas) can be converted to a variety of products, including fuels, through either catalytic or microbial fermentation. Bio-oil has properties similar to petroleum, and after post-processing clean-up to remove caustic substances and residual water, it can be converted to a variety of materials, including gasoline and diesel fuel (Huber et al., 2006).

Energetics of biofuels Much has been written on the energetics of producing energy from biomass. Substantial energy is invested in the production of any crop and it is reasonable to expect that the ratio of usable energy produced is greater than that used in the process. A major challenge in fairly assessing the energy balance for biofuel production is determining the appropriate boundaries of the system. Some of the most widely publicized studies on net energy balance" for ethanol (e.g., Pimentel, 2003; Pimentel and Patzek, 2005) claim that it takes about 70% more energy to grow corn for ethanol than is contained in the ethanol. However, these analyses are based on relatively old production data and do not take into account the energy value of the animal feed co-product of making ethanol. Current estimates find corn grain ethanol has an energy balance of 1.34 (Wang et al., 2007). That is, for every fossil fuel unit of energy input, 1.34 units of energy are captured in the ethanol. Although positive, this is a relatively modest gain, due mostly to the intensive inputs required to produce corn grain including machinery, fertilizers, and transportation costs. As the industry matures, it is expected that the ratio will become increasingly positive over time due to efficiency increases all along the value chain (CAST, 2007).

The energetics of energy produced from cellulosic biomass are significantly more favorable than that produced from grain because of lower inputs to feedstock production. Estimates of efficiency for cellulosic ethanol range from 2.6 to 5.0 and the ratio of energy produced to that expended for biomass is anticipated to improve with refinements in conversion technologies, as well as improvements in feedstock production, harvest, and transportation logistics (Schmer et al., 2008).

Environmental benefits of biomass Among the potential environmental benefits of biofuels, reduction in greenhouse-gas emissions is most often touted. The benefit varies greatly among biomass crops, cropping systems and conversion technologies, with perennial cropping systems yielding the most benefit. Most biofuels result in release of less greenhouse gases than petroleum-derived fuels. However, there are concerns that diverting cropland from food production to bioenergy production may actually increase green-house gas emissions on a global scale due to conversion of native grasslands and forests to food and bioenergy crops (Farrell et al., 2006; Hill et al., 2006; Scharlemann and Laurance, 2008; Schemer et al., 2008).

In addition to having lower carbon emissions, perennial bioenergy crops have many other positive environmental benefits compared with annual row crops. By providing continuous ground cover, perennial grasses protect the soil from erosion by wind and water. Runoff is much less from perennial than annual crops so movement of sediment and dissolved agrichemicals in surface water is greatly reduced. However, use of cover crops and reduced tillage for production of annual biomass crops would mitigate some of their negative effects relative to perennial biomass crops (Kort et al., 1998; Sheehan et al., 2004).

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.

Biomass from Grasslands

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).

Within much of continental U.S., precipitation decreases in a gradient from east to west and limits most dryland crop production to areas with humid climates east of 98° W longitude (Baron and Belanger, 2007). To the west, precipitation received is generally less than potential evapotranspiration and irrigation or other moisture management strategies are required to produce maximum crop yields. Solar radiation, day length, and length of the growing season vary with latitude. At higher latitudes, the growing season is shorter and seasonal fluctuations in day length are greater (Casler et al., 2004). The ability to tolerate low winter temperatures further limits the adaptation of perennial species (Vogel et al., 2002).

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.

Intensive vs. extensive biomass production Production practices used in grassland agriculture lie along a continuum between those that are extremely intensive and those that are more broadly extensive (Moore and Jung, 2001). In the most intensive systems the environment is substantially manipulated to optimize production of a single species. Nutrients, water and other inputs are provided to create an environment that maximizes yield. Competition from other plant species and negative influences of insects and diseases are controlled by application of pesticides. Corn silage and alfalfa are examples of forage crops that are often intensively managed. On the other end of the spectrum are extensive rangeland systems where vegetation management, if practiced at all, involves fostering growth of a plant community that is better adapted to the environment. In these systems, cultural practices including defoliation management, controlled burning, and reseeding are the primary management tools used to manage productivity (Moore and Jung, 2001).

The use of extensively managed grasslands for biomass production has been advocated as a more sustainable alternative to dedicated energy crops grown in monoculture. Grasslands managed in this way have been referred to as Low Input High Diversity (LIHD) production systems (Tilman et al., 2006). As the term suggests, these systems are not intensively managed and are characterized by relatively high plant species diversity. They are generally located on marginal or degraded agricultural land (Tilman et al., 2006), but may also include natural grasslands (Wallace and Palmer, 2007). The putative benefits of harvesting biomass from extensively managed grasslands include greater carbon sequestration, reduced use of fertilizers and pesticides, no tillage, less soil erosion, and less displacement of food production (Tilman et al., 2006; Wallace and Palmer, 2007).

Certainly the potential benefits of using LIHD systems for biomass production merit further investigation and discussion. However, there are several potential problems in their widespread use as a feedstock for bioenergy production (Russelle et al., 2007). The most relevant of these is the comparatively low yield produced on an area basis. Because biomass has a relatively low bulk density, it is considerably more expensive to transport than more energy dense fuels such as coal. Transportation cost represents a significant fraction of the delivered cost of feedstock to a biorefinery (Perlack and Turhollow, 2003). The delivered cost of a feedstock is inversely related to the distance it must be transported to the point of use. For example, the land area required to support a biorefinery processing 5,000 t per day 300 days per year would be 3,750 km^2 for a LIHD grassland system producing 4.0 dry t/ha each year. The average one-way hauling distance would be 34.5 km assuming no transport or storage losses and contiguous availability. Compare this to a dedicated energy crop yielding ten times that amount of biomass. In this latter case, the area required to supply the biorefinery would be 375 km^2 and the average hauling distance would be 10.9 km. Obviously other factors such as land available for biomass production and the transportation infrastructure available will affect transportation cost, but the point is that it is a major component of feedstock cost. Highe yield density is not currently possible with LIHD systems, thus economics and logistics favor the use of High Input Low Diversity systems all other factors being equal, which they admittedly they are not.

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

Crop	Establishment Method	Life Cycle	Established Agronomics	Established U.S. Markets	Typical Biomass Yield (t DM / ha)[1]
Corn	Seed	Annual	Yes	Food, grain ethanol	11-22
Sorghum	Seed	Annual	Yes	Food, feed	15-27
Switchgrass	Seed	Perennial	No	Forage	7-22
Miscanthus	Rhizomes	Perennial	No	Not developed	22-34

[1] (Bean et al., 2006; NASS, 2007; Pyter et al., 2007; Schmer et al., 2008)

There are other considerations that further limit the potential of LIHD of contributing significantly to biofuel production , at least in the U .S . According to statistics cited by Russele et al . (2007) , there are only 6 .1 million ha of land classified as idle cropland in the U .S . , much of it located in regions where precipitation is limiting to plant growth . The same is true for natural grasslands in the U .S . Most undisturbed native grasslands are located in subhumid and drier areas where moisture is limiting to biomass production . Additionally , infrastructure such as roads and utilities are less developed than in humid temperate regions where dedicated energy crops are most likely to be grown .

Dedicated bioenergy crops It is clear that grassland agriculture will play a pivotal role in supplying feedstock for cellulosic biofuel , independent of the type of fuel and where it is produced . What is less clear are the species that will be used to provide that feedstock and the degree to which they will 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 .

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 (see Energetics of biofuels , above) . 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 promising 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 it s favorable environmental qualities , switchgrass was identified as a leading candidate for bioenergy production (McLaughlin and Kszos, 2005; Parrish and 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 (U.S. 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). 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 and 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 and 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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