Feedstocks for Lignocellulosic Biofuels
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PERSPECTIVE

Feedstocks for Lignocellulosic Biofuels

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In 2008, the world produced approximately 87 gigaliters of liquid biofuels, which is roughly equal to the volume of liquid fuel consumed by Germany that year. Essentially, all of this biofuel was produced from crops developed for food production, raising concerns about the net energy and greenhouse gas effects and potential competition between use of land for production of fuels, food, animal feed, fiber, and ecosystem services. The pending implementation of improved technologies to more effectively convert the nonedible parts of plants (lignocellulose) to liquid fuels opens diverse options to use biofuel feedstocks that reach beyond current crops and the land currently used for food and feed. However, there has been relatively little discussion of what types of plants may be useful as bioenergy crops.

For the purposes of examining this issue in a prospective context, we make the simplifying assumptions that technology will become available for converting to sugars most of the structural polysaccharides that comprise the bodies of plants, that all the sugars can be used for fuel production, and that the process energy required for the conversion of the sugars to fuels will be obtained from combustion of the other components of the biomass, mostly lignin. Thus, in a sugar-to-ethanol bioconversion process using current technology, a metric ton (MT) of switchgrass or poplar, for example, would be expected to yield about 310 liters of ethanol (*1*). Technical improvements may increase the amount to more than 380 liters. Although we refer here to cellulosic ethanol, bioconversion of sugars to butanol, alkanes, terpenes, or other prospective biofuels or other types of conversion technologies (*2*) are expected to result in similar amounts of fuels on an energy basis (*3*).

In terms of global grain or seed production, maize is the largest crop, producing about 820 million MT of grain (*4*) and a similar amount of stems and stripped cobs (stover) that is potentially available for fuel production. Conversion of half the maize stover in the United States to cellulosic ethanol would produce about 51 gigaliters of ethanol (GLE) (Table 1). Thus, the total amount of stover-based ethanol could approximately double the amount of ethanol produced from maize in the United States without expanded land use. However, there is concern that removal of even half the stover would exacerbate loss of soil carbon and erosion and would also require additional inputs of fertilizers to replace lost minerals (*5*). Because of the shortage of labor during harvest season and the costs associated with recovering stover or straw in a separate operation after grain harvest, the development of new farm implements that would allow simultaneous grain harvest and stover baling would probably be necessary to make widespread stover use practical. The low amount of stover, or residues from other crops, produced per hectare may impose relatively large costs for collection and transportation to refineries, reducing economic incentives to use stover (*6*).

Perennial plants that use C_4 photosynthesis, such as sugarcane, energy cane, elephant grass, switchgrass, and Miscanthus, have intrinsically high light, water, and nitrogen use efficiency as compared with that of C_3 species. Additionally, reduced tillage and perennial root systems add carbon to the soil and protect against erosion. The highest annual dry-matter production level for any vegetation is, for such C_4 grasses, 88 MT/ha/year for Napier Grass (*Pennisetum purpureum*) (Fig. 1) in El Salvador and 100 MT/ha/year for natural stands of *Echinochloa polystachya* on the Amazon floodplain (*7*). In the temperate zone, the perennial C_4 grass *Miscanthus x giganteus* (Fig. 1) has attracted considerable interest. It produced in England at 52°N a peak biomass of 30 MT/ha/year and harvestable biomass of 20 MT/ha/year, the highest recorded for a cool temperate climate (*8*). Seasonality leads to an annual cycle of senescence, in which perennial grasses such as Miscanthus mobilize mineral nutrients from the stem and leaves to the roots at the end of the growing season. Thus, harvest of biomass during the winter results in relatively low rates of removal of minerals (*9*). This, coupled with diazotrophic associations, may account for the observation that stands grown at Rothamsted, UK showed no response to added nitrogen during a 14-year period during which all biomass was removed each year (*10*, *11*). In side-by-side trials in central Illinois, unfertilized *M. x giganteus* produced 60% more biomass than a well-fertilized highly productive maize crop, and across the state, winter-harvestable yields averaged 30 MT/ha/year (*9*, *12*). Mechanistic models developed to project yields based on the extensive trials conducted in Europe, when applied to the United States, suggest that many locations east of the Mississippi could support average annual yields of over 30 MT/ha, with a considerable number of areas exceeding 40 MT/ha (Fig. 2) (*13*, *14*). We estimate that if Miscanthus were used as the only feedstock, less than half of the 14.2 Mha currently set aside for the Conservation Reserve Program would be required to deliver the 132 GLE/year mandate of the Energy Independence and Security Act of 2007 [supporting online material (SOM) text]. Similar opportunities may exist in Europe, if the potentially high yielding zones for *M. x giganteus* of Poland, Romania, Belarus, and the Ukraine are included (*15*). Higher yields per hectare are likely for miscanes (sugarcane–Miscanthus hybrids), energy canes, and napier grass in the southernmost U.S. states. A recent study estimated that more than 600 Mha of land worldwide has fallen out of agricultural production, mostly in the last 100 years (*16*). Some of this area appears suitable for production of such perennial grasses or other types of energy crops, but additional research is necessary to categorize the land with respect to potential for various types of energy crops. The lack of proximity to infrastructure of some underutilized land for the production and transportation of fuels may be a major limitation to its utilization in the foreseeable future.

One of the largest current sources of biofuels is Brazilian sugarcane. In 2009, production for fuel on about 4.6 Mha (*4*) resulted in about 27 GLE plus 2 GW of net electricity from combustion of bagasse (*17*). The Brazilian light-duty fleet is mostly composed of flex-fuel vehicles, so this production replaced about 40% of the gasoline used in Brazil (*18*). The Brazilian government recently announced that expansion of the crop would be limited to 63.5 Mha (*19*). This land could be made available, without the clearing of natural ecosystems, by means of a slight increase in the low stocking density on the estimated 237 Mha of cattle ranching (*18*). Assuming that expansion of the amount of the crop used for nonfuel purposes continues at historical rates, approximately 60 Mha could eventually be available for fuel production (SOM text). If changes in fuel production technologies enabled the use of the polysaccharide component of bagasse to produce a liquid fuel, in addition to the fuel produced from sugar we estimate that Brazil could produce up to ~800 GLE (SOM text) or

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equivalent amounts of other liquid fuels (*3*). On an energy basis, this would be equivalent to approximately 14% of the current world transportation fuel demand of 4900 Gl in 2006. Many other regions of the world are also well suited to sugarcane production or formerly produced sugarcane on land that has been abandoned. Thus, the total amount of fuel that may be produced from sugarcane worldwide could eventually be a very substantial proportion of global transportation fuels.

Approximately 18% of the terrestrial surface is semi-arid (200 to 800 mm of rainfall and an average growing season temperature >21°C) and prone to drought (*20*). Thus, a potential opportunity for production of biomass for fuels from land that is water-limited is the use of species with high efficiencies of water use and drought resistance, such as various *Agave* species that thrive under arid and semi-arid conditions (Fig. 1). *Agave* spp. use a type of photosynthesis called Crassulacean acid metabolism (CAM) that strongly reduces the amount of water transpired by absorbing CO_2 during the cold desert night and then internally assimilating this into sugars through photosynthesis during the warmer days. By opening their stomata at night, they lose far less water than they would during the day. Thus, *Agave* spp. have a water-use efficiency that may be as much as six times greater than that of C_3 species, such as wheat (*21*). Several *Agave* species have been cultivated on approximately 500,000 ha for production of sisal coarse fibers (*A. sisalana* and *A. fourcroydes*) or alcoholic beverages (*A. tequilana* and *A. salmiana*), so agronomic practices are well established. Somewhat surprisingly, some *Agave* spp. have been reported to exhibit high harvested biomass yields on semi-arid land when harvested on 5- to 6-year cycles. For instance, *A. desertii* grown with 430 mm of rainfall in California yielded 7 dry MT/ha/year, and *A. salmiana* grown with 320 mm of rainfall in Mexico yielded 10 dry MT/ha/year (*22*). *A. sisalana* production fields in Tanzania provided annual harvests of leaves of 58 wet MT/ha/year (*23*). Much of the land that has fallen out of agricultural production worldwide is semi-arid (*16*), and it appears that the amount of land that may be available for cultivation of *Agave* species is vast.

Woody biomass can be harvested sustainably for lumber and paper and may therefore provide biofuel feedstock for some regions. Approximately 89 to 107 Mha of land that were formerly in agriculture globally are now in forests and urban areas (*16*). Although there are large tracts of such forest land that are now mature ecosystems valued for biological diversity, recreation, and carbon sequestration, there are more recently abandoned lands that have lower ecosystem service values and could be used for plantation biomass crops. For example, some areas of the southeastern United States that were formerly managed as pine plantations have not yet succeeded to other uses. The continuing trend to electronic media and paper recycling may reduce the demand for pulp woods and thus presents an opportunity to reallocate woody biomass for energy. Additionally, the U.S. Forest Service confronts a challenge to manage excess wood residues that increase fire risks. The encroachment of the pine bark beetle has led to widespread mortality of trees, which will require their removal to reduce the risk of fueling catastrophic forest fires. Wood resources thus provide regionally specific opportunities for sustainably harvested biomass feedstocks. For perspective, the biomass that is harvested annually in the Northern Hemisphere for wood products has an energy content equivalent to approximately 107% of the liquid fuel consumption in the United States (*24*). Wood is a renewable resource that could contribute to lignocellulosic feedstocks if managed carefully. In order to maximize the amount of woody biomass produced per hectare, the best practice appears to be to coppice harvesting (Fig. 1.), in which the plants are cut near ground level after the end of the growing season every 3 to 5 years, depending on the species and the growing conditions (*25*). The plants rapidly regenerate shoots from the rootstock without any intervention. Thus, this approach minimizes losses of mineral nutrients, soil erosion, and organic carbon emissions and the investment of photosynthate in regrowing the roots. Harvesting in the winter at long intervals also appears to enhance biodiversity in the stands as compared with that of annual crops. Some tree species that appear to be suitable for coppice production have nitrogen-fixing symbionts and mycorhizzal associations that may help to minimize inputs (*25*).

Fig. 1. Examples of some potential bioenergy crops. (**A**) *M. x gigantaeus* in Illinois. (**B**) Modern high production line of 5-year-old *A. tequiliana* in Mexico. Picture is courtesy of Dr. M. C. Alejandro Velázquez Loera, Universidad Autónoma Chapingo, D. F. Mexico. (**C**) One-year-old stand of Napier grass (*Pennisetum purpureum* Schumach.) in Florida. Picture is courtesy of B. Conway, BP. (**D**) Two-year-old willow coppice from 8-year-old roots in England (in third regeneration cycle).

Table 1. Estimated productivity, rainfall, and nitrogen requirements of current or potential bioenergy crops (see SOM for data sources).

Crop	Average productivity (MT ha^{-1} $year^{-1}$)	Ethanol yield (liter ha^{-1})	Seasonal water requirements (cm $year^{-1}$)	Tolerance to drought	Nitrogen requirements (kg ha^{-1} $year^{-1}$)
Corn		3800 (total)	50–80	low	90–120
Grain	7	2900			
Stover	3	900			
Sugarcane	80 (wet)	9950 (total)	150–250	moderate	0–100
Sugar	11	6900			
Bagasse	10	3000			
Miscanthus	15–40	4600–12,400	75–120	low	0–15
Poplar	5–11	1500–3400	70–105	moderate	0–50
Agave spp.	10–34	3000–10,500	30–80	high	0–12

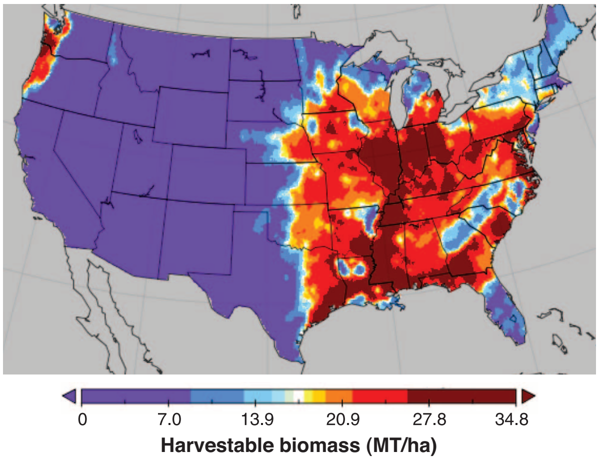

Fig. 2. Projected annual average harvestable yield of *M. x giganteus* in the third year after planting based on weather data for each of the past 30 years, and soil moisture and soil depth gridded across the 48 contiguous states. [Figure courtesy of Fernando Miguez and Germán Bollero using a model parameterized as described previously (*13*)] Projections agreed closely with prior measurements (*12*). After planting, annual average harvestable yields would be expected to increase for the first 3 years and then remain more or less constant for several further years (*10*, *27*). In contrast to maize, projected yields are higher to the south and east of the cornbelt.

The ability to produce lignocellulosic fuels sustainably is of paramount importance. Because the use of groundwater for irrigation is generally not sustainable, we envision that the type of energy crop grown in a given region will be primarily related to water-use efficiency (Table 1). Thus, relatively water-inefficient C_3 species such as poplar will be grown only where rainfall is abundant. Water-efficient C_4 grasses such as sugarcane, switchgrass, and Miscanthus will be grown where rainfall is not in excess, and highly water-efficient CAM plants such as *Agave* spp. will be grown in arid regions. In regard to soil quality, several hundred years of experience with sugarcane production and recent studies of the effects of sugarcane cultivation on soil carbon indicate that the crop can be grown sustainably (*26*). The available evidence also suggests that perennial grasses and trees can be produced sustainably and can improve terrestrial carbon sequestration. Because it is inevitable that some mineral nutrients will be removed when biomass is harvested, it will be essential to recycle mineral nutrients, which are not consumed in the production of biofuels, from biomass-processing facilities back onto the land. Because species diversity supports ecosystem health, and in order to maximize tolerance to both biotic and abiotic stresses, it will be desirable to use genetically diverse, or species diverse, plantations of energy crops. Long-term research concerning the agroecology practices that maximize net biomass productivity, sustainability goals, and environmental benefits in different types of biomass cropping systems is needed to identify the best management practices and varieties and the implications of allocation of land to production of lignocellulosic fuels. Importantly, by focusing on the use of dedicated energy crops—rather than on repurposing food and feed crops—it should be possible to overcome many of the problematic constraints associated with our narrow dependence on a relatively small number of food crops and to develop agroecosystems for fuel production that are compatible with contemporary environmental goals.

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Supporting Online Material

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