Review

Next-generation biomass feedstocks for biofuel production

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Abstract

The development of second-generation biofuels - those that do not rely on grain crops as inputs - will require a diverse set of feedstocks that can be grown sustainably and processed cost-effectively. Here we review the outlook and challenges for meeting hoped-for production targets for such biofuels in the United States.

The importance of renewable biofuels in displacing fossil fuels within the transport sector in the United States is growing, especially in the light of concerns over energy security and global warming. The US federal government, as well as most governments worldwide, is strongly committed to displacing fossil fuels with renewable, potentially low carbon, biofuels produced from biomass. The primary motivation for these efforts is both to decrease reliance on fossil fuels, particularly imported fuels [1,2], and to address concerns over the contribution of fossil-fuel consumption by the transport sector to global warming [3,4]. The US federal government has therefore set a target of displacing 30% of current US gasoline (petrol and diesel) consumption within the transportation sector with biofuels by 2030. With total fossil fuel consumption within this sector currently running at levels of approximately 757 billion liters (200 billion gallons) per year [5], this requires the United States to develop a commercial infrastructure capable of producing approximately 227 billion liters (60 billion gallons) of biofuel per year on an energy-equivalent basis over this time frame. The European Union, China, Australia and New Zealand have also established similar targets for biofuel production.

Currently, the majority of biofuel production in the United States is in ethanol derived from starch- or grain-based feedstocks, such as corn (maize). Sugarcane is also a prime resource for biofuel production in Brazil [6] and other regions of the world. Reaching a production level of 24.6 billion liters (6.49 billion gallons) in 2007 [7], it is estimated that the maximum production levels of corn ethanol in the United States will reach approximately 57 billion liters (15 billion gallons) per year by 2015. This establishes an initial target of roughly 170 billion liters (45 billion gallons) of biofuel produced from non-grain and non-food sources in order to meet the overall biofuel target. These biofuels will be produced through the conversion of lignocellulosic biomass and are commonly referred to as second-generation biofuels. Those biomass feedstocks are not primarily composed of starches, but rather of the complex matrix of polysaccharides and lignin that forms plant cell walls. These lignocellulosic materials are inherently more difficult than grain-based materials to convert into fermentable sugars (Figure 1). The plant cell walls found within lignocellulosic biomass are a complex mixture of polysachharides, pectin and lignin. The polysaccharides are chemically linked to the lignin, and these complexes are very recalcitrant to processing and depolymerization into their respective monomers.

To meet these production targets, a robust and sustainable supply of the requisite feedstocks must be developed and established. A joint study by the US Departments of Energy and Agriculture, often referred to as the ‘Billion Ton Study’, determined that roughly 1.18 billion tonnes (1.3 billion tons) of non-grain biomass feedstocks could be produced on a renewable basis in the United States each year and dedicated to biofuel production [8]. These feedstocks are primarily distributed among forestry and agricultural resources (Figure 2). Assuming a conservative estimate of biofuel production at

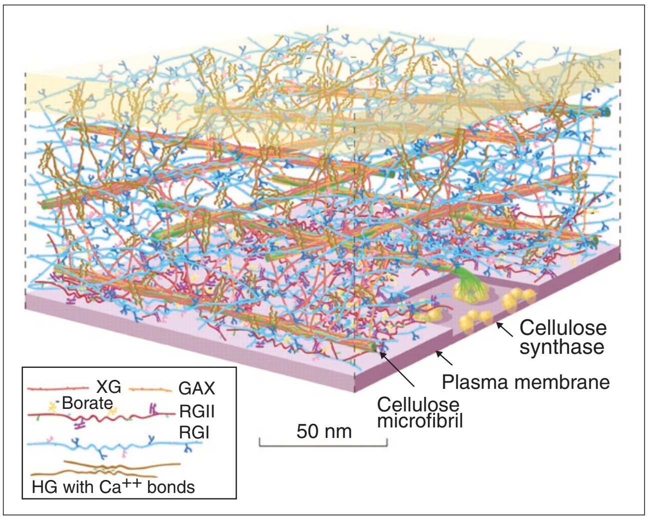

Figure 1
Schematic diagram depicting the chemical and structural complexities of the plant cell wall. Reproduced with permission from [24].

190 liters (50 gallons) per dry tonne, this would create an upper limit of biofuel production, albeit a highly optimistic one to be achieved over this time period, of 247 billion liters (65 billion gallons) per year.

Forestry resources

A recent report [9] reported that the amount of forestland, as of 2002, in the United States was roughly 303 million hectares (750 million acres). This represents one-third of the total land area of the nation. The majority of these lands are held by the forestry industry or other private interests. It is estimated that 204 million hectares (504 million acres) can be considered timberland and is capable of growing more than 1 cubic meter (35 cubic feet) of timber per hectare annually [9]. A significant portion of this land is not accessible to forestry equipment, however. In addition, there are approximately 68 million hectares (168 million acres) of forestland that the US Forest Service classifies as incapable of growing 1 cubic meter per hectare annually and is not considered as a viable biofuel feedstock growth area [9]. Current forest product manufacturing techniques produce large amounts of mill residues, known as secondary residues. These secondary residues account for approximately 50% of current biomass energy consumption in the United States, and will continue to play a vital role in producing biofuels. In total, the amount of harvested and consumed forestry resources in the United States - 127.8 million dry tonnes (142 million dry tons) - is considerably less than the available inventory. This excess capacity indicates that there is a significant amount of forestry resources - 331 million dry tonnes (368 million dry tons) - that could be dedicated to biofuel production on a sustainable basis (Figure 2).

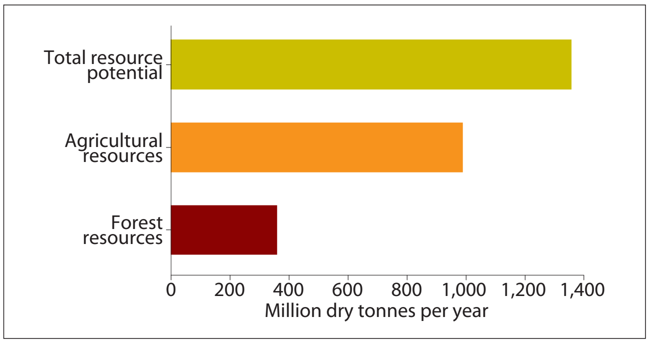

Figure 2
Estimates of biomass available for conversion into biofuels per year within the United States. Adapted from [8].

Some of the leading candidates that could be grown on these lands specifically for biofuel production are hybrid poplar, eucalyptus, loblolly pine, willow and silver maple. One hypothetical distribution of the forestry resources as a function of geography and climate within the United States is depicted in Figure 3. Poplar has several characteristics that make it an attractive candidate biofuel feedstock: it can be grown in several temperate climates as a short-rotation woody crop; it grows relatively rapidly at high density; it is a good plantation tree; and it has a fully sequenced genome. Poplar is considered as a model example of a short-rotation woody crop, and can produce 9 to 15.7 dry tonnes per hectare (4 to 7 dry tons per acre) annually over a 6- to 10-year rotation [10,11]. Willow and loblolly pine are also strong short-rotation woody crop candidates, as demonstrated in temperate-region plantations worldwide [12]. Eucalyptus, native to Australia but grown throughout the world, is another strong candidate for biofuel production. It has been grown and studied extensively in California and Florida, and appears to be amenable to high-density cultivation in plantation farms [13].

Another key aspect to forestry-resource management is the biomass turnover from leaf litter. This phenomenon is an annual process for deciduous trees, and occurs after leaf senescence, when most of the reserves have been remobilized except for cell-wall polysaccharides. In poplar, leaf biomass can represent 5-15% of the total aboveground biomass in a year, which looks insignificant. But this process occurs every year and can represent 25-60% equivalent of total yield (stems, bark, and branches at harvest). For example, a forest of poplar with 10 tonnes/hectare/year (4.4 tons/acre) productivity will have lost approximately 60 tonnes/hectare (26 tons/acre) of leaf biomass after 15 years of growth, and the final overall biomass recovered would be 150 tonnes/hectare (67 tons/acre), with an equivalent of 40% in leaf litter. Leaves present an additional advantage compared with stemwood, as they should be easier to process, because of the larger initial surface area. Finally, screening tree variants for enhanced starch remobilization during senescence could increase the sugar content of leaves.

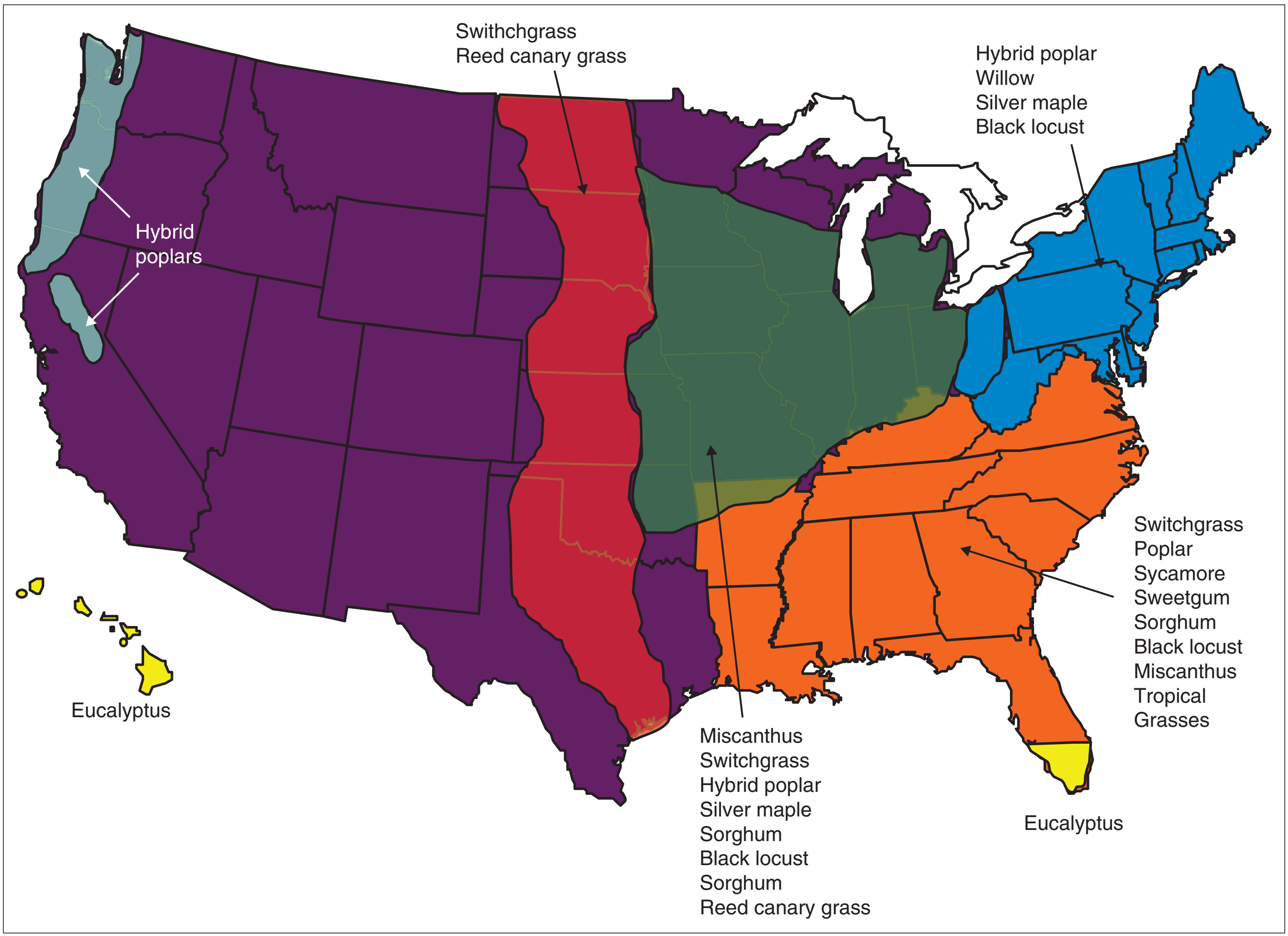

Figure 3
Map of the potential feedstocks for conversion into biofuels that could be grown in different regions of the United States. Source: Department of Energy and Oak Ridge National Laboratory.

Agricultural resources

Agriculture is the third largest use of land in the United States, estimated at 182-184 million hectares (448-455 million acres) [8,14]. It was recently reported that approximately 141 million hectares (349 million acres) of land are actively farmed to grow crops, with an additional 16 million hectares (39 million acres) of idle cropland [8]. These idle croplands include those that have been placed in the Conservation Reserve Program (CRP). Other uses include 27 million hectares (67 million acres) for pasture [15]. A significant area of cropland, 25 million hectares (62 million acres), uses no-till cultivation to reduce soil erosion and maintain soil nutrients, whereas another 20 million hectares (50 million acres) of cropland use a conservation tillage system. When these factors are taken into account, it is estimated that there are 175 million dry tonnes (194 million dry tons) of agricultural resources available for biofuel production with no changes in farming practice. This estimate includes 102 million dry tonnes (113 million dry tons) of crop residues (68 million dry tonnes (75 million dry tons) of which are corn stover), 54 million dry tonnes (60 million dry tons) of animal manures and residues, 13.5 million dry tonnes (15 million dry tons) of grain (starch) used for ethanol production, and 5.4 million dry tonnes (6 million dry tons) of corn fiber [8].

Given these baseline numbers, it is possible to project scenarios by which these agricultural resources could expand to produce a more significant resource available for conversion into biofuels. This was the approach taken in the Billion Ton Study to evaluate different scenarios for increased biomass production [8]. One of the mid-21st-century scenarios presented in the report that did not include massive land-use changes assumed an increase in corn yields of 25-50%, as well as smaller yield increases for wheat, sorghum, soybeans, rice and cotton. The cropland acreage for each was held constant, but it was assumed that collection of residues increased to between 60% and 75% while maintaining no-till and conservation tillage practices. Another 67.5 million dry tonnes (75 million dry tons) was projected to be available through manure and other residues and wastes. Finally, 15-25 million dry tonnes (17-28 million dry tons) were assumed to be grown on 50% of the available CRP land. This scenario resulted in the annual production of 537 million dry tonnes (597 million dry tons) under high-yield improvements and 381 million dry tonnes (423 million dry tons) per year under moderate-yield improvements, with two-thirds to three-quarters of the total biomass in the form of crop residues.

A more aggressive scenario projects the additional growth of dedicated perennial crops within this portfolio of agricultural resources, accompanied by significant changes in land use [8]. Examples of these perennial crops include herbaceous species, such as switchgrass [16,17], miscanthus [18,19] and sorghum [20,21], that can be grown in various regions of the United States (Figure 3). Each of these grasses has advantages and disadvantages that must be carefully considered, but all hold promise as viable energy crops that could significantly increase the amount of biomass available for conversion into biofuel when implemented appropriately. The inclusion of these perennial crops within agricultural resource lands or CRP land is projected to result in 14 or 22 million hectares (35 or 55 million acres) associated with moderate (11 dry tonnes per hectare; 5 dry tons per acre) and high (18 dry tonnes per hectare; 8 dry tons per acre) yields, respectively [8]. With a high percentage of these perennial crops dedicated to biofuel production, this scenario projects that 523 to 898 million dry tonnes (581 to 998 million dry tons) of biomass could be produced at moderate and high yields, respectively. Crop residues remain the most significant component (50%) of the available biomass, with perennial crops contributing 30-40%.

Genetics and feedstock improvement

In addition to growing currently available feedstocks on available land to produce biofuels, the realization of dedicated energy crops with enhanced characteristics would represent a significant step forward. The genetic sequences of a few key biomass feedstocks are already known, such as poplar [22], and there are more in the sequencing pipeline. This genetic information gives scientists the knowledge required to develop strategies for engineering plants with far superior characteristics, such as diminished recalcitrance to conversion [23].

There have been several recent examples where genetic engineering has been used to modify the composition of the plant in order to hypothetically reduce the cost associated with the conversion process. The presence of lignin in plant cell walls [24] impedes the hydrolysis of polysaccharides to simple sugars. Lignin and lignin by-products can also inhibit the microbes that carry out fermentation, decreasing biofuel yield. Both of these factors drive up the cost of biofuel production. Recent advances in the understanding of lignin composition, biosynthesis, and regulation have set the stage for designer lignins in dedicated energy crops. Recent studies on lignin degradation that occurs in the environment may provide a new means of identifying key microbes and enzymes that can efficiently remove lignin from dedicated bioenergy crops [25]. Other examples include modifying lignin biosynthesis in plants in order to make the plant more readily broken down in the biorefinery [26], adjusting the types of lignin present in plants, and adjusting the ratio between polysaccharides and lignin [27].

Another area where genetic engineering could produce dramatic positive results is the development of perennial feedstocks that can reach high energy densities over a short time with minimal fertilization and water consumption. By combining the known targeted climates and soil types present in the available CRP and marginal lands with tailored feedstocks, it may be possible to develop grasses and short-rotation woody crops that maximize carbon and nitrogen fixation within these ecosystems. This would ensure that the optimal greenhouse gas emission profiles from the perspective of the overall carbon and nitrogen lifecycles are achieved in biofuels produced using these feedstocks [28].

In addition to modifying the intrinsic polysaccharide/lignin composition and central metabolism of the feedstock itself, other research groups are attempting to express enzymes directly within plants that are capable of breaking down cellulose into glucose. These enzymes are called cellulases, and supplying them to the production process represents one of the largest costs in biofuel production [29]. Expressing and localizing cellulases within the plant could potentially eliminate the need for producing the cellulase offline at the biorefinery. Researchers have successfully expressed the gene encoding the catalytic domain of one cellulase into *Arabidopsis*, tobacco and potato [30].

Challenges for the future

Numerous challenges must be addressed for feedstock production to reach established targets. Some of the main challenges are associated with developing a vast amount of acreage within the United States dedicated to feedstock growth for biofuel conversion, and include ensuring sustainability, reducing cost and devising responsible land-use change policies [31-33]. In regard to agricultural residues, care must be taken to ensure that removal of the residues from the fields does not negatively impact any other interlinked parameter, such as silage and other established beneficial farming practices. The development of specialized harvesting equipment for these residues also needs to be addressed if gains in production are to be realized.

As dedicated non-food energy crops, most probably in the form of grasses and short-rotation woody crops, become widespread and grown on marginal lands or CRP, land-management practices and crop selection controls must be established in order to minimize any indirect carbon or nitrogen emissions from the soil as a result of changes in land use [34-36]. This is especially true for nitrogen-related emissions, as they pose a greater risk to the environment as a more potent greenhouse gas [37]. Water consumption and recycling during crop growth and conversion must also be addressed, not only at the local biorefinery level, but also from a systems perspective that takes into account federal, state, county and city water resource management issues and water rights in order to minimize any negative impacts on an already strained resource [38,39].

Other concerns that must also be addressed are the development of the necessary infrastructure for harvesting, collecting, processing, and distributing large volumes of biofuels [40]. Corn ethanol facilities are typically located near corn and soybean acreage in the Midwest, and it is expected that next-generation cellulosic biorefineries will adapt a similar model of proximity to high-density growth areas in order to reduce costs associated with feedstock transportation [41]. This strategy will therefore require a means to distribute the biofuels from the points of production in the Midwest to the primary points of consumption in the populous West and East coasts. Additional complications are the blending of biofuels and their distribution within existing pipelines [42]. Because of the relative hydrophilic nature of ethanol compared with gasoline and diesel, it can easily become contaminated with water and could potentially dissolve residues that have been deposited over time in pipelines and fuel tanks [43]. Ethanol will therefore have to be distributed using ethanol-compatible pipelines, railroad cars and tanker trucks. Finally, the issues that surround the deployment of genetically engineered crops, such as biocontainment of transgenes and potential invasive species contamination, must be fully addressed before these transgenic crops can be considered to be a viable option [44].

In conclusion, the role of sustainable, cost-effective, and scalable feedstock production is one of the most pressing needs in the realization of a biofuels industry capable of replacing a significant portion of the fossil-fuel consumption of the United States. It is important to recognize that different feedstocks will need to be grown in different regions to meet the tonnage required. This diversification in the supply chain should be considered a strength and not a weakness, as the numerous possible feedstock and environmental combinations should be able to maximize productivity and sustainability while minimizing cost. Although enough hypothetical biomass seems to be available to meet biofuel production targets, significant hurdles remain before those numbers can become a cost-effective and environmentally beneficial reality. Genetic engineering and synthetic biology can be used to produce feedstocks with the desired traits, especially when leveraged with existing expertise within the plant biology and agronomy communities.

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