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Review article

Environmental costs and benefits of transportation biofuel production from food- and lignocellulose-based energy crops. A review

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Abstract – Transportation biofuel production in the United States is currently dominated by ethanol from the grain of maize and, to a much lesser extent, biodiesel from soybeans. Although using these biofuels avoids many of the environmentally detrimental aspects of petroleum-based fossil fuels, biofuel production has its own environmental costs, largely related to fossil fuel use in converting crops to biofuels and crop cultivation itself, including ecological damages caused by nitrogen and phosphorus fertilizers, pesticides, and erosion. A new generation of biofuels derived from lignocellulosic sources offers greatly reduced environmental impacts while potentially avoiding conflicts between food and energy production. In particular, diverse mixtures of native prairie species offer biomass feedstocks that may yield greater net energy gains than monoculture energy crops when converted into biofuels, while also providing wildlife habitat and enriching degraded soils through carbon sequestration and nitrogen fixation. Ultimately, as demand for both food and energy rise in the coming decades, greater consideration will need to be given to how land can best be used for the greater benefit of society.

biodiesel / bioenergy / biomass / carbon / ethanol / greenhouse gas / maize / prairie

1. INTRODUCTION

Oil, coal, and natural gas currently supply around 90% of global energy use (Energy Information Administration, 2006). Rising energy prices, energy security concerns, long-run supply, climate change, environmental degradation, and impacts on human health are among the many concerns raised by this overwhelming reliance on fossil fuels (Ezzati et al., 2004; Schröter et al., 2005; Hansen et al., 2006; McMichael et al., 2006; Stern, 2006a,b). These problems have spawned efforts to develop renewable energy sources such as solar (Hoffert et al., 2002; Shinnar and Citro, 2006), wind (Lenzen and Munksgaard, 2002; Hoogwijk et al., 2004; Archer and Jacobson, 2005), hydrogen (Deluga et al., 2004; Jacobson et al., 2005), and biomass (Larson, 2000; Hamelinck and Faaij, 2006; Herrera, 2006). Although renewable energy sources have promise, three important questions need to be resolved before society can count on them as a sustainable energy supply. First, how much energy can renewable sources provide, and will this amount significantly reduce fossil fuel use while meeting rising energy demands to support a growing and increasingly affluent world population (Berndes et al., 2003; Hoogwijk et al., 2003; Meyers and Kent, 2003; Dorian et al., 2006; Sims et al., 2006; de Vries et al., 2007)? Second, can renewable energy be supplied at a reasonable cost? Third, to what degree will alternative energy sources reduce environmental damage relative to fossil fuel use (Chow et al., 2003; Keith et al., 2004)?

Here I explore one aspect of renewable energy, namely the environmental consequences of producing the biological materials used as feedstocks for the transportation biofuel industry in the United States. I focus this review on the possible benefits of transitioning biofuel production from crops traditionally cultivated for food to those developed as environmentally beneficial bioenergy sources. I first evaluate the current state of biofuel production by assessing various environmental aspects of the two predominant US biofuels, maize grain ethanol and soybean biodiesel. I then investigate the advantages that a second generation of transportation biofuels, derived primarily from lignocellulosic biomass, can provide over these first-generation food-based biofuels.

2. US BIOFUEL PRODUCTION FROM FOOD CROPS

In the following section, I explore the potential for the two dominant biofuels in the United States, maize grain ethanol and soybean biodiesel, to offset fossil fuel use, and then discuss various environmental impacts of their production and use.

2.1. The current state of us biofuel production

The United States transportation biofuel market is dominated by domestically-produced ethanol derived from the grain of maize (*Zea mays* ssp. *mays*) (Fig. 1). To produce

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Figure 1. Volunteer maize in a field of soybeans, indicative of the dominant crop rotation in the Midwest US. (Jason Hill).

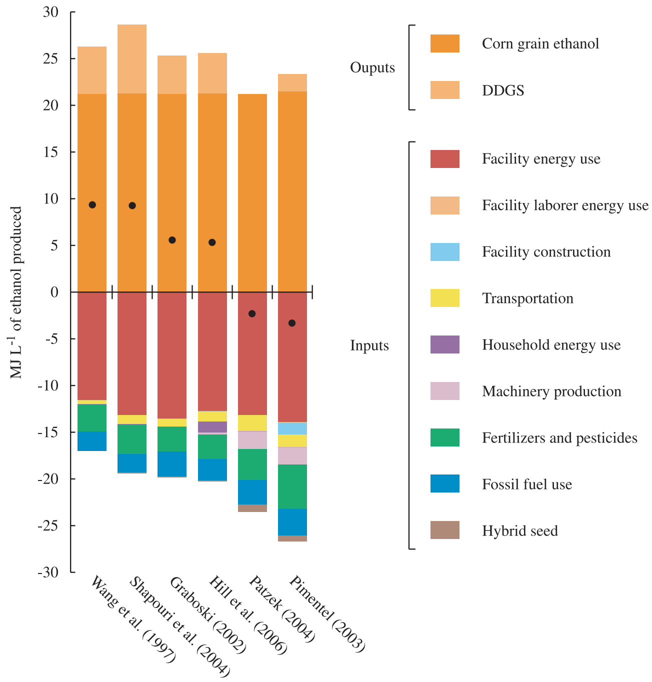

Figure 2. The net energy balance of maize grain ethanol as estimated by six recent studies, most recently by Hill et al. (2006). All eleven input and output categories are ordered as they are shown in the legend, but some are so small as to be imperceptible. Only the estimate of Hill et al. (2006) includes all eleven categories. The estimated net energy balance (the sum of the outputs minus the sum of the inputs) from each study is shown by the placement of a black dot.

ethanol, starch from maize kernels is broken down into sugars, which are then fermented and distilled. The remainder of the kernel is commonly processed into distiller's dry grain with solubles (DDGS), which serves as a high-quality animal feed (Spiehs et al., 2002; Lumpkins et al., 2004). The other major US transportation biofuel is soybean (*Glycine max*) biodiesel, which displaces petroleum diesel. In biodiesel production, soybeans are crushed to separate the oils from the meal, which is used primarily as a protein source in animal feed. The oils are then converted to biodiesel and glycerol via a transesterification reaction with the addition of catalysts and alcohol reagents (Van Gerpen, 2005; Haas et al., 2006; Meher et al., 2006).

Hill et al. (2006) examine the degree to which these two biofuels displace fossil fuels in the US transportation sector. In 2005, approximately 4.0×10^{10} kg of maize were used to produce 1.5×10^{10} L of ethanol in the US, and the oil from approximately 1.3×10^{9} kg of soybeans was used to generate 2.6×10^{8} L of biodiesel. In terms of each fuel's gross energy yield, these volumes of maize grain ethanol and soybean biodiesel have offset 1.7% and 0.1% of US gasoline and diesel use, respectively. Since fossil fuels are used both on farms and at conversion facilities to produce these biofuels, however, these gross energy values do not reflect the total "new energy" they contribute. The fossil energy invested in producing each of these biofuels must be subtracted from the gross energy yield to calculate the net energy yield. This fossil energy expenditure comes mainly from the petroleum diesel used to power farm equipment and tractor-trailers for transportation, the natural gas burned to provide process heat at the conversion facility, and the coal combusted to produce electricity. Maize and soybean production also require agrichemicals, barns, tractors, and other farm machinery that in turn require energy for their manufacture. Biofuel production requires the labor of farmers and factory workers who, with their families, consume energy in a variety of forms. Given current agricultural practices and biofuel industrial conversion standards, the production of both of these biofuels yields more energy than in the fossil fuels to produce them, with maize grain ethanol and soybean biodiesel yielding 25% and 93% more, respectively. Therefore, the US net energy offset in 2005 by producing maize grain ethanol was approximately 0.3% of gasoline use and 0.05% of diesel use from soybean biodiesel.

Whether maize grain ethanol returns more energy than is invested in its production has long been a source of debate, stretching back decades (Chambers et al., 1979). A comparison of recent, independent estimates of its net energy balance reveals two key areas of disagreement (Fig. 2). First, studies have varied the energy input boundaries for the life cycle of ethanol production, most notably in categories concerning energy expenditures to produce capital requirements such as farm equipment and conversion facilities. These input categories are rightfully included in net energy balance analyses because farm equipment is used directly in biofuel crop production and biofuel production facilities would not be built were it not for biofuel production itself. Second, there is variation in the estimates of the specific energy inputs themselves, both for widely-accepted categories and those less commonly included. Using current, well-supported, public data on farm inputs and ethanol production plant efficiencies resolves many of these discrepancies (Farrell et al., 2006; Hill et al., 2006).

Several environmental benefits come from replacing fossil fuels with maize grain ethanol and soybean biodiesel. Displacing petroleum-derived transportation fuels with biofuels avoids the negative effects of oil drilling, refining, and combustion. Further, the CO_2 released when combusting plant-derived biofuels was removed from the atmosphere during crop growth whereas burning fossil fuels introduces "new" CO_2 into the atmosphere, thus contributing to global warming. Therefore, a biofuel produced from crops grown with conventional farming practices, which lead to essentially no soil carbon sequestration (Robertson et al., 2000), would be carbon neutral were it not for the fossil fuels combusted in biofuel production. Even if carbon neutral, however, biofuel production may not be global climate change neutral. Biofuel production from maize and soybeans may increase emissions of nitrous oxide (N_2O), a potent greenhouse gas, from maize and soybean croplands. Under current farm and biofuel industry production standards, maize grain ethanol releases approximately 12% fewer greenhouse gases than gasoline, while soybean biodiesel releases approximately 41% less greenhouse gases than diesel because of lower farm and conversion facility fossil energy requirements (Hill et al., 2006). Farrell et al. (2006) reported a similar 18% savings for maize grain ethanol while noting that shifting conversion facility fossil fuel use from natural gas, as is commonly used, to coal would lead maize grain ethanol to be a net source that is approximately 2% greater than gasoline. These estimates assume that the cropland used to produce these biofuels is in equilibrium for carbon loss and gain. Converting land from any use that has a net sequestration of carbon (e.g., intact ecosystems or certain lands in conservation reserve) to crop production for biofuels would decrease this greenhouse gas savings and might cause the biofuel to release more greenhouse gases than the fossil fuel it replaced.

Biofuel production can introduce other negative environmental consequences that do not occur with fossil fuel production, namely those directly associated with crop production and conversion of these crops to biofuels. Here, the environmental effects of maize and soybean production are rightfully ascribed to the biofuels derived from them. Typical cultivation practices employed in major maize and soybean producing states use 7 g and 0.1 g of nitrogen (N) fertilizer per MJ of energy gained in producing maize grain ethanol and soybean biodiesel, respectively (Hill et al., 2006). Similarly, 2.6 g and 0.2 g of phosphorus (P) fertilizer are applied per MJ of energy gained in producing maize grain ethanol and soybean biodiesel, respectively. Eutrophication from N and P of agricultural origin moving to surface and ground water (Powers, 2005) leads to loss of diversity (Carpenter et al., 1998; Suding et al., 2005), changes in aquatic ecosystem structure and function (Smith et al., 1999), drinking water contamination (Socolow, 1999), and water quality degradation including the anoxic zone in the Gulf of Mexico (McIsaac et al., 2002; Dodds, 2006). In addition to these fertilizers, 0.1 g and 0.01 g of pesticides are applied per MJ of energy gained in producing maize grain ethanol and soybean biodiesel, respectively. For maize, approximately 36% of this amount is atrazine, 23% acetochlor, 16% metolachlor, and 8% glyphosate, and around 82% of pesticide application to soybeans is glyphosate (United States Department of Agriculture, 2003 and 2005). Also, both maize and soybean farming cause erosion and sedimentation (Johnson et al., 2006). Water availability is also of concern both for crop irrigation in drier climates and for converting feedstock conversion to biofuel (Berndes, 2002; Oki and Kanae, 2006).

2.2. Impacts of increasing us biofuel production

Both maize grain ethanol and soybean biodiesel are currently used primarily as fuel additives rather than as biofuels themselves. When blended at low levels with gasoline or diesel, ethanol serves as an oxygenate, helping engines meet the emission requirements of the US Clean Air Act of 1990 (Fernandez and Keller, 2000; Hansen et al., 2005). Maize grain ethanol production is growing rapidly due to state mandates for replacing methyl *tert*-butyl ether (MTBE), a gasoline oxygenate that pollutes groundwaters, federal production subsidies and incentives (e.g., a \$0.14/L federal volumetric ethanol excise tax credit), and a tariff on importing ethanol from foreign sources (\$0.14/L). Biodiesel blended into diesel substantially reduces tailpipe emissions of many criteria pollutants including carbon monoxide (CO), oxides of sulphur (SO_X), hydrocarbons (HC), and particulate matter (PM) (Wang et al., 2000; Nabi et al., 2006).

Both maize and soybean prices rose in 2006 as a result of increased biofuel demand, with prices for maize doubling between 2005 and the beginning of 2007. As demand for alternative fuels continues to rise, competition between using these crops for food and fuel purposes will become more pronounced. Currently, about 50% of the US maize crop is used to feed livestock, while the remainder is processed for human consumption, exported, or fermented into ethanol (United States Department of Agriculture, 2006). Likewise, 90% of domestically-produced soybean meal is used for livestock feed (United States Census Bureau, 2006a), and soybean oil constitutes 80% of US fat and oil consumption (United States Census Bureau, 2006b). As a consequence of increased ethanol demand, more acreage is expected to be planted to maize at the expense of other crops, namely soybeans (FAPRI, 2006). However, changing the two-year maize and soybean rotation that is predominant in the US Midwest to continuous maize not only increases total fertilizer and pesticide use, but also decreases soil quality and yield (Karlen et al., 2006). Still, utilizing even substantial portions of US maize and soybean production would have but a minor effect on domestic energy markets. Devoting all US maize and soybean production to ethanol and biodiesel production would yield just 12% and 6% of US gasoline and diesel demand in terms of gross energy, respectively, with net energy gains of just 2.4% and 2.9% (Hill et al., 2006).

3. MAXIMIZING THE ENVIRONMENTAL BENEFITS OF CURRENT BIOFUELS

Both government mandates for biofuel use and development of a domestic biofuel production industry based on maize grain ethanol and soybean biodiesel have established these two biofuels as the dominant renewable transportation alternatives in the near-term. Efforts at various stages of their production and use can be made to maximize their environmental performance.

The environmental performance of current biofuels can be augmented by utilizing more sustainable crop production practices that increase resource use efficiency and integrate enlightened management practices (Tilman et al., 2002; Cook, 2006). These include reduced or no-till cultivation (West and Post, 2002; Kim and Dale, 2005a; Grandy et al., 2006), organic (Drinkwater et al., 1998; Kramer et al., 2006) and more efficient (Matson et al., 1998; Crews and Peoples, 2005) fertilization, and the use of cover crops (Kim and Dale, 2005b). Although it has not been firmly established, applying conservation tillage to agricultural lands currently farmed under conventional tillage may sequester carbon in soils (West and Marland, 2002; Johnson et al., 2005), perhaps leading to one of seven "stabilization wedges" needed to stabilize atmospheric CO_2 emissions if adopted on a global basis (Pacala and Socolow, 2004). Reduced erosion and decreased farm fossil fuel use for soybean farming in recent years (i.e., between the major biodiesel life cycle analyses of Sheehan et al. (1998) and Hill et al. (2006)) is largely due to fewer passes over land with farm implements and greater adoption of reduced tillage practices, in part attributable to widespread planting of soybeans genetically modified for glyphosate resistance (Cerdeira and Duke, 2006). This transition to glyphosate-dominated soybean herbicide use is also associated with lower environmental damage from pesticide toxicity (Nelson and Bullock, 2003), although many long-term ecological consequences of genetically modified organisms are as yet unrealized (Andow, 2003).

Other biofuel feedstocks include waste cooking oils and fats (Zhang et al., 2003; Cvengroŝ and Cvengroŝová, 2004) and residues from forest industries (Parikka, 2004). Crop waste (i.e., that lost during handling, storage, and transport between farms and households) and agricultural residues (i.e., the crop biomass remaining after the consumable portion is removed) also provide attractive raw materials for biofuel production (Gallagher et al., 2003; Kim and Dale, 2004). While using crop waste has the benefit of avoiding the conflict between food and fuel uses for the crops themselves, using agricultural residues with sensitivity to environmental concerns maximizes the use of additional products generated via high-input, intensive farming. In the Midwest US, residual maize stover can be harvested and combusted directly or converted to ethanol (Aden et al., 2002; Hoskinson et al., 2006) in a process akin to fermenting the sugars in sugarcane to ethanol while burning the residual bagasse to supply process heat and electricity (Borrero et al., 2003; De Olivera et al., 2005; Botha and von Blottnitz, 2006). Stover removal may reduce soil organic carbon storage, reduce productivity, and increase soil erosion, however (Linden et al., 2000; Hooker et al., 2005; Dolan et al., 2006; Johnson et al., 2006), thus requiring careful consideration of stover removal rates (Wilhelm et al., 2004). Using stover as a valuable coproduct of maize production also raises the possibility of tapping extant maize genetic diversity for desirable energy characters such as higher cellulose fractions or a perennial habit (Cox et al., 2006). Even if breeding for such characteristics leads to some degree of grain yield loss, such hybrids may prove economically viable depending on stover prices in a biofuel market.

Although both maize grain ethanol and soybean biodiesel are valuable biofuel additives, neither can do much to displace fossil fuels, and devoting any amount of these crops to biofuels has a disproportionately large effect on food markets. Given that current biofuel production is limited and that which is available comes at a considerable environmental price (De Oliveira et al., 2005), it is prudent to consider how biofuels can best be integrated into transportation fuel supplies. For example, Kim and Dale (2006) conclude that, under biofuel supply constraints and current vehicle fuel efficiencies, ethanol used in an E10 blend (10% ethanol and 90% gasoline by volume) provides greater environmental benefits in criteria pollutant release than an E85 blend (85% ethanol and 15% gasoline by volume). Similarly, the potential for soybean biodiesel to displace diesel use is limited, but diesel blends with as little as 1–2% biodiesel provide essential lubricity lost by the removal of sulphur in ultra-low sulphur diesel formulations (Hu et al., 2005; Knothe and Steidley, 2005). Blending available biofuel stocks at low levels into conventional fuels might maximize their environmental benefits, therefore, especially in light of current supply constraints.

Employing less intensive cropping methods, using agricultural wastes and residues, and properly integrating biofuels into conventional supplies as fuel additives rather than fuel substitutes serve to minimize the negative environmental consequences of current biofuel production. However, making biofuels that will be both environmentally superior to fossil fuels and displace significant quantities of fossil fuel use will require exploration of plant resources other than those that have been domesticated and bred primarily for their food, feed, or forage value. In doing so, there even is the prospect of utilizing and improving degraded and marginal lands on which food crop production is neither economically viable nor environmentally sound.

4. ALTERNATE US BIOFUEL FEEDSTOCK PRODUCTION METHODS

Growing recognition of the limited ability of food crop-based biofuels to offset fossil fuel use has increased awareness that a variety of new energy feedstocks will be needed if plant-based biofuels are to make any sort of significant impact on alleviating domestic reliance upon conventional transportation fuels. Increased attention is being given to lignocellulosic biomass as the preferred feedstock for the second generation of biofuels (Schubert, 2006). In the following section, I provide a brief overview of how lignocellulosic biomass can be used to supply transportation energy, the various energy crops that are being developed, and the potential for these biofuels to offset fossil fuel use. I follow this with more detailed consideration of how diverse mixtures of native prairie species in US grasslands can provide a sustainable supply of biofuel feedstock while simultaneously improving degraded lands and providing habitat for wildlife.

4.1. Biofuels from lignocellulosic biomass

Lignocellulosic biomass, which consists of the cellulose, hemicellulose, and lignin compounds found in plant cell walls that comprise the bulk of herbaceous and woody vegetative tissues (McKendry, 2002), provides a valuable and versatile feedstock for the production of a variety of biofuels (Huber et al., 2006). It can be combusted directly to provide electricity, itself an emerging transportation fuel, and process heat (Mann and Spath, 2001; Demirbaž, 2003; Robinson et al., 2003; Mani et al., 2006; Qin et al., 2006). Biomass can also be converted to ethanol through enzymatic hydrolysis of the cellulosic fractions into sugars (Foyle et al., 2006) followed by fermentation of these sugars as in maize grain ethanol production, with the lignin fractions being burned to provide heat and electricity (Lynd et al., 1991; Wyman, 1999; Lynd et al., 2002; Hamelinck et al., 2005). Biomass can also be gasified to produce hydrogen (Zhang et al., 2004; Kumabe et al., 2007 Ptasinski et al., 2007), electricity, synthetic hydrocarbons such as gasoline and diesel through subsequent Fischer-Tropsch synthesis (Spath and Dayton, 2003; Wang et al., 2005; Zwart and Boerrigter, 2005), or other biofuels such as dimethyl ether (Semelsberger et al., 2006). Other valuable products may also be generated in such "biorefinery" streams (Wyman, 2003; Montgomery, 2004; Ragauskas et al., 2006). New technologies for producing biofuels from biomass are rapidly emerging, including the development of engineered yeast for increased ethanol yields (Alper et al., 2006), utilization of new microorganisms for ethanol production (Seo et al., 2005), pretreatments for cellulosic digestion (Mosier et al., 2005), fuel cells for converting sugars directly to electricity (Chaudhuri and Lovley, 2003), and catalysts for more efficient conversion of biomass to syngas (Salge et al., 2006).

Various plant species are currently used or are being developed for biomass production. Unlike maize and soybeans, which are annuals, lignocellulosic bioenergy crops are typically perennials, including both woody species such as willows (*Salix* spp.) (Volk et al., 2004; Keoleian and Volk, 2005; Volk et al., 2006), poplars (*Populus* spp.) (Husain et al., 1998; Tuskan et al., 2006), and other hardwoods (Geyer, 2006), and herbaceous species such as switchgrass (*Panicum virgatum*) (Parrish and Fike, 2005; Samson et al., 2005; Fike et al., 2006), big bluestem (*Andropogon gerardii*) (Hallam et al., 2001), reed canarygrass (*Phalaris arundinacea*) (Lewandowski et al., 2003), and Miscanthus (*Miscanthus* spp.) (Clifton-Brown et al., 2004; Heaton et al., 2004). Of these, switchgrass has received particular attention, having been chosen by the US Department of Energy's Bioenergy Feedstock Development Program as a model energy crop due to its high biomass yields, broad geographic range, efficient nutrient utilization, low erosion potential, carbon sequestration capability, and reduced fossil fuel input requirements relative to annual crops. (McLaughlin and Walsh, 1998; McLaughlin and Kszos, 2005).

Lignocellulosic biomass can be produced with significant environmental advantages over food-based crops, but it is not without potential problems. Particular care must be taken when selecting species for use as biofuel crops, for example, as many of the traits leading to the success of bioenergy crops, such as C_4 photosynthesis, long canopy duration, lack of pests and diseases, and rapid spring growth, are also associated with invasiveness potential (Raghu et al., 2006). Many lignocellulosic crops can be grown with low agrichemical and fossil fuel inputs, but intensive cropping practices may also be employed with high or even excessive fertilizer and pesticide inputs (Fike et al., 2006; Parrish and Fike, 2005). Converting land from annual crop production into stands of perennial grasses in the Conservation Reserve Program (CRP) has restored the ability of these soils to sequester carbon (Gebhart et al., 1994), but although carbon can also be sequestered in switchgrass stands managed for maximizing biomass production with high levels of nitrogen fertilization (Frank et al., 2004; Liebig et al., 2005), release of N_2O into the atmosphere may significantly offset the greenhouse gas mitigation potential of such lands (Conant et al., 2005). The spatial pattern of lignocellulosic crop production can also have a large impact on wildlife habitat and biodiversity preservation (Cook et al., 1991; Leemans et al., 1996; Green et al., 2005).

Even though the current contribution of lignocellulosic biofuels from both crop residues and dedicated energy crops to the US transportation energy supply is negligible, the potential exists for them to rival or surpass crop-based biofuels. Perlack et al. (2005) recently estimated that 6.8×10^{10} kg of maize stover can currently be sustainably harvested in the US. Assuming a demonstrated ethanol yield of 0.255 L per kg of biomass (Sheehan et al., 2004), this would provide 1.7×10^{10} L of ethanol, slightly greater than 2005 US ethanol production from maize grain, plus an additional electrical energy equivalent of 1.6×10^9 L of ethanol to be sold back to the grid. This would provide enough energy to offset 2.2% of US gasoline use, and assuming an average net energy balance ratio of 5 for lignocellulosic ethanol production (Hammerschlag, 2006), the net contribution would be 1.8%, greater than current the net contribution of maize grain ethanol (0.3%). According to Milbrandt (2005), planting every acre of land currently in the CRP into switchgrass would yield approximately 7.6×10^{10} kg of biomass. This would provide approximately 1.9×10^{10} L of ethanol and 1.8×10^9 L of ethanol energy equivalent electricity, or enough to offset 2.5% of gasoline use with a net contribution of 2.0%. In addition to greater net energy gains than maize grain ethanol, both maize stover ethanol and ethanol from switchgrass grown on lands not currently in production would have the benefit of avoiding competition with food markets for biofuel feedstocks.

Figure 3. Blackeyed Susan (*Rudbeckia hirta*), wild bergamot (*Monarda fistulosa*), and big bluestem (*Andropogon gerardii*) in a diverse restored prairie in Minnesota, USA. (Clarence Lehman).

Figure 4. An aerial view of the biodiversity experiment at Cedar Creek Natural History Area in Bethel, Minnesota, USA, reported in Tilman et al. (2006). The 9 m × 9 m plots are planted to either 1, 2, 4, 8, or 16 species randomly drawn from a set of native prairie plants. (David Tilman).

4.2. The promise of prairies

Energy crops, both food-based and lignocellulosic, are typically cultivated as monocultures, but enhanced environmental, energetic, and economic benefits may be realized by growing biomass in polycultures (Fig. 3). Tilman et al. (2006) recently demonstrated the value of biodiversity in biofuel production from grassland biomass (Fig. 4). They reported that annual production of native prairie plant biomass increased with species diversity, with plots planted to sixteen species yielding 238% more aboveground biomass than plots planted to a single species on average. Not only did more diverse plots become increasingly more productive over time relative to less diverse plots, but they also provided greater stability in year-to-year yield. Even though this experiment was conducted on degraded land, converting the biomass from the highly diverse plots to ethanol would generate a net energy gain of 17.8 GJ ha^{-1}, comparable to the average yield of 18.9 GJ ha^{-1} for maize grain ethanol produced on fertile farmland (Fig. 5A). In addition, whereas maize grain ethanol yields 25% more fossil energy than invested in its production, producing ethanol from the highly diverse prairie biomass harvested in this experiment would yield 440% more.

The environmental benefits of prairie biofuels are numerous. Unlike maize and soybeans, a prairie requires little or no fertilizer inputs. Nitrogen, which is cycled more efficiently in prairies than in cultivated maize cropland (Brye et al., 2001), can be supplied by native legumes. Phosphorus and other nutrients would need to be supplied only at low levels due to both efficient use in prairie plants and translocation of many elements to root systems late in the season before aboveground biomass is harvested (Fig. 5B). Unlike maize and soybean cropland, an established prairie requires no herbicide or insecticide application as it resists invasion from plants, pathogens, and herbivorous insects (Fig. 5C). This encourages diverse ecosystems, reduces input costs, and provides a valuable form of insurance to farmers (Heal et al., 2004). Harvesting a prairie also mimics natural burning, which is necessary for keeping out invading woody species, which can reduce soil carbon storage (Jackson et al., 2002). A prairie can provide habitat for wildlife, and biomass harvest can be timed to occur only after birds have fledged (Murray et al., 2003; Roth et al., 2005; Semere and Slater, 2007). Restoring prairie for biofuel use can produce a valuable energy feedstock while offering valuable ecosystem services (Clergue et al., 2005; Foley et al., 2005). These ecosystem services include pollinator habitat for service to nearby crop fields (Greenleaf and Kremen, 2006) and mitigation of agricultural runoff from traditional farming by reducing flow volumes and increasing nutrient use opportunity (Huggins et al., 2001), akin to similar services provided by wetlands (Hey et al., 2005).

One of the most vital ecosystem services provided by a diverse prairie is its ability to serve as a substantial carbon sink, reducing atmospheric carbon and improving degraded land. Approximately 1/3 of the total prairie plant biomass is above ground and available for harvesting each year, but the other 2/3 below ground continues to grow, sequestering carbon and supporting a rhizosphere that also decreases atmospheric carbon (Six et al., 2006). In total, about 4.4 Mg ha^{-1} yr^{-1} of CO_2 are sequestered each year in the Cedar Creek prairie, far exceeding the 0.3 Mg ha^{-1} yr^{-1} of CO_2 released when combusting the fossil fuels used to produce biofuels from the aboveground biomass. Therefore, as the carbon released when combusting

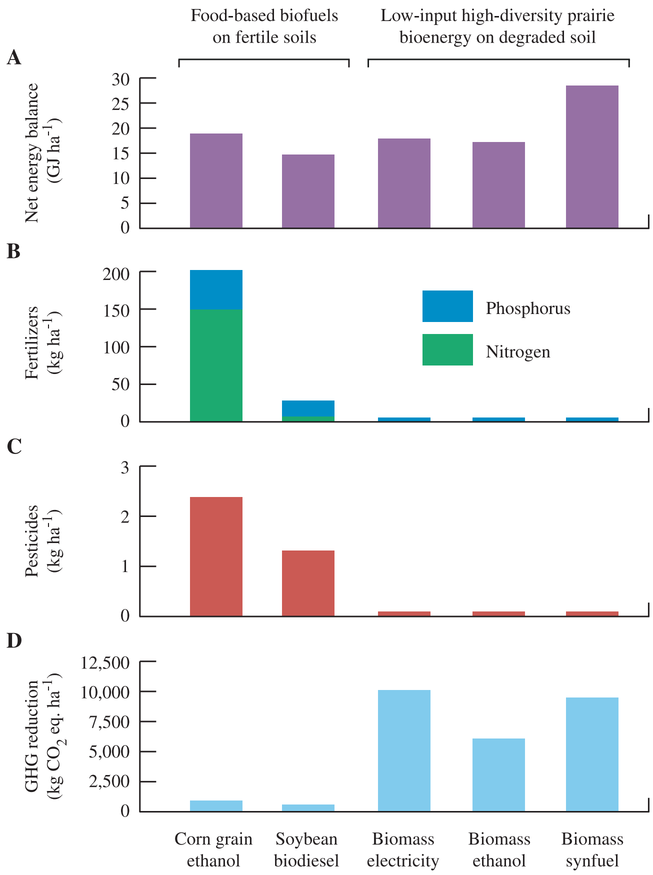

Figure 5. Comparison of energetic and environmental aspects of biofuels produced from food-based crops and low agricultural input, highly diverse prairie biomass. Biofuels produced from biomass include electricity, ethanol, and synfuel hydrocarbons. Greenhouse gas (GHG) reductions are estimated relative to the fossil fuels that each of the biofuels displaces. Adapted from Tilman et al. (2006).

the biofuel was initially sequestered from the atmosphere in the aboveground biomass itself, biofuels from prairie grasses are “carbon negative” (Fig. 5D). On the other hand, with respect to atmospheric carbon, both maize grain ethanol and soybean biodiesel are “carbon positive”, creating a net release of greenhouse gases, albeit less than fossil fuels they displace. Intensive farming has led to massive carbon loss in soils (Huggins et al., 1998), and the ability of diverse prairies to sequester carbon and build soils (McLauchlan et al., 2006) can restore fertile land and increase its value (Daily, 1995; Lal, 2004).

Implementing large-scale biofuel production from diverse prairie biomass will require consideration of various practical and economic factors. First, supplies of both native grass and forb seed are limited, and quantities sufficient to plant available lands will take many growing seasons to produce. Second, various technical aspects of utilizing biomass of diverse species for biofuel production are unknown, although recent studies have considered both the digestibility (Weimer and Springer, 2006) and combustion (Florine et al., 2006) of diverse grasses. Third, as with all lignocellulosic biomass sources, development of an infrastructure for transporting biomass to biofuel production facilities will be critical (Atchison and Hettenhaus, 2004; Kumar and Sokhansanj, 2006; Morrow et al., 2006). Fourth, a subsidy and incentive policy will be needed to foster adoption of lignocellulosic biomass, much as was done to encourage, and is still required for, the current generation of food-based biofuels (Tyson, 2005). Such a policy might allow for harvesting prairie biomass for biofuels production on land in set-aside programs (e.g., CRP and CSP lands) while still receiving subsidy payments. Any such policy could be tailored to encourage management practices benefiting environmental concerns (Walsh et al., 2003) and outdoor recreation (Sullivan et al., 2004). A US carbon trading market that rewards farmers for conservation-friendly practices might also provide sufficient monetary incentive for prairie biomass farming (McLaughlin et al., 2002; Schneider and McCarl, 2003; Kurkalova et al., 2004).

The demonstrated potential for producing biofuels from diverse mixtures of prairie species raises many related questions. How, for example, do interactions among species compositions and management practices affect both productivity and ecosystem services in grasslands (Camill et al., 2004; Guo, 2006), especially when restored and managed specifically for biofuel production? What are the relative benefits of planting fertile farmland to prairie rather than food crops for biofuel production? Can prairie biomass production strategies be combined with grazing opportunities for mutual benefit? How will grassland productivity respond to global warming (De Broeck et al., 2006)? With the positive relationship between biodiversity and ecosystem productivity now firmly established (Hooper et al., 2005; Cardinale et al., 2006), are other native flora also suitable for biofuel production while maintaining a healthy, functioning ecosystem?

5. CONCLUSION

The shift to automobiles and airplanes marked the end of the era when transportation biofuel consisted mainly of the hay fed to horses, the ordinary diets of pedestrians, and wood used to power many steamboats and locomotives. As petroleum began to meet our transportation energy needs, agricultural practices focused more on those crops consumed by humans or fed to livestock and poultry. The recent surge in interest for using biological material to offset petroleum use has wed together food and transportation energy concerns once again. This presents both challenges and opportunities. Conflict over using crops such as maize and soybeans for food and biofuels will increase as demands for both end products rise in the future. Demand for agricultural products may very well be the major cause of future nonclimatic global change (Tilman et al., 2001). In the near term, gains in conservation and efficiency can have much greater effect on slowing climate change than even radical shifts in agricultural practices (Jackson and Schlesinger, 2004). In the long term, this linking together of food and fuel markets in a time of increasing awareness of the benefits of sustainability will allow us to reevaluate current land use and implement strategies that lead to truly sustainable food and biofuel supplies (Robertson et al., 2004; Robertson and Swinton, 2005; Reijinders, 2006). The actual benefits of this shift will be realized more fully when biofuel production no longer relies upon fitting our energy production into our current agricultural system but rather adapting our agricultural practices in an environmentally sensitive manner to supply both our food and energy needs.

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