Intensive biofuel production and biodiversity loss: Is the LIHD model a viable solution?

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Introduction

Biofuels have often been considered renewable, carbon-neutral, “green” alternatives that could alleviate many of the environmental problems associated with fossil fuels. Increasingly, however, biofuels have been viewed with skepticism by scientists and others for their potential impacts on atmospheric carbon (McLaughlin and Walsh 1998, Hill 2007), world food prices (Runge and Senaur 2007), biodiversity (Hill 2007, Koh 2007), and rural culture (Widenoja 2007). There are many aspects of biofuel agriculture that one could consider, from subsidies and food prices to energy budgets and efficiency. For brevity, this paper will first review the potential impacts of biofuel expansion on biodiversity and habitat. The second part of the paper will give special attention low input, high diversity (LIHD) biofuel systems as a possible alternative to avoid some of the environmental problems caused by conventional biofuel production methods.

Biofuels and habitat loss

In his 2007 State of the Union address, President Bush announced his wish to replace 15% of gasoline with renewable fuels by 2017, creating a flurry among politicians and investors to push biofuel research and production (Lewis 2007). While this is perhaps a welcome deviation from the Bush administration’s unabated support of fossil fuels, biofuels are not without serious environmental problems. One fundamental concern is that there is simply not enough land area to grow biomass to meet the growing demand for biofuels. By one estimate, about 130 million hectares of biomass production would be needed to supply the United States with transportation fuel, which equivalent to the area of land occupied by all cropland in the late

1980's (Cook et al. 1991). Koh (2007) estimated that if 50% of the world's cultivated land area were converted to biomass for biodiesel, it would still fall 60% short of the world demand for biodiesel in 2050. Of course, these figures do not predict how or where the displaced food would be produced. Though few are advocating for a complete conversion to biofuels, there is no doubt that the increasing demand for biofuel production will cause serious land use conflicts between food production, biofuel production, and natural ecosystems.

There are three main classes of biofuels derived from herbaceous biomass: biodiesel, corn ethanol, and cellulosic ethanol. All types of biofuels share common ecological challenges, but each biofuel class also has unique features that complicate their usefulness and put biodiversity at risk.

Biodiesel

Biodiesel is largely derived from rapeseed, sunflower seed, oil palm, or soybean. Rapeseed is the source of 84% of the global market in biodiesel, but soybean and oil palm production is rapidly expanding. The United States currently is the largest producer of soybeans in the world, and soybeans account for the majority of the biodiesel production in the U.S. (Ash et al. 2006, EPA 2006). Competition with food crops and an increased interest in corn ethanol production in developed countries has pushed soybean production to the tropics, especially in Brazil and Southeast Asia where land is readily available and labor is cheaper (Koh 2007). Increased biodiesel production in these sensitive tropical areas has devastating consequences for biodiversity. In Brazil and Argentina, 91 million acres of forest and grassland have been converted to soybean production, driven largely by the demand for biodiesel in Brazil (Altieri and Holt-Gimenez 2007). In Indonesia, clearcutting for oil palm plantations has replaced illegal logging and fires as the leading cause of deforestation (Nellman et al. 2007). In Malaysia, 90%

of deforestation is attributed to clearing for biofuel production (Lewis 2007), and by 2022, it is estimated that 98% of the tropical rainforest in Indonesia and Malaysia will be gone. If the current rate of deforestation for oil palm plantations continues, the orangutan, not to mention countless less-well-known species, may become extinct as soon as 2012 (Williams 2007).

Corn Ethanol

Undoubtedly, corn ethanol has been one of the most-heralded types of biofuels in the developed world, but it has also received much criticism. One major problem with corn ethanol is that it is highly inefficient to produce. Corn ethanol production is in general greatly dependent on nonrenewable fuel inputs, yields only a small or even negative net gain of energy, and can result in a net increase of CO_2 emissions (Ulgiati 2001, DeWulf et al. 2005). Clearly, this exacerbates global warming, which is the very problem biofuels are trying to alleviate. The growth of corn ethanol also leads to socio-economic absurdities, such as the likelihood that Iowa will become a net corn importer by 2008 (Runge and Senaur 2007). Beyond inefficiency and social issues, the increased production of corn for ethanol also has a suite of problems related directly to habitat loss.

Corn ethanol production is growing rapidly in the United States. The rising demand for corn ethanol has caused an increase in corn prices, from around $2 per bushel in 2005 to up to $4 a bushel in 2007 (Widenoja 2007). This dramatic increase in corn prices, in addition to prompting a cascade of food-affordability problems in Mexico and other areas, has also created less incentive for farmers to participate in the Conservation Reserve Program and other federal conservation measures. Currently, the USDA is accepting no new signups for the CRP, and may allow farmers to terminate their CRP contracts early for the expressed purpose of producing more corn (Ringleman 2007). In Iowa alone, up to 500,000 acres of CRP land, or one-quarter of the total, will likely be farmed in 2008 due to the increased market value of corn (Widenoja 2007). The loss of habitat patches and corridors in heavily farmed regions such as Iowa could pose a serious threat to regional biodiversity.

To boost production for ethanol, corn is increasingly being grown without rotation with another crop (often soybean), leading to greater soil erosion and a heightened dependence on chemical fertilizers (Hill 2007). Even without further intensification, corn production is generally more reliant on pesticide and fertilizer inputs and contributes more to soil erosion than other biofuel crops. Runoff from cornfields often contains high levels of sediment, nutrients, and chemical pesticides, all of which have well-known detrimental effects on aquatic biodiversity. Retaining CRP land can mitigate some of the problems associated with polluted runoff, especially when located around streams and waterways (Mulkey et al. 2006). However, since increasing corn prices act as an incentive to cultivate CRP lands, the future of maintaining terrestrial and aquatic ecosystem health in corn-producing areas is doubtful.

Cellulosic Ethanol

Cellulosic ethanol is derived from the structural tissue of an array of plant materials including corn stover, sugarcane, woodchips, willow (*Salix sp.*), and switchgrass (*Panicum virgatum*). In the United States, perennial grasses, especially switchgrass, have received the most attention and research for their ability to produce high yields quickly and sequester carbon in the soil. From an energetics perspective, cellulosic ethanol from perennial grasses is up to 15 times more efficient to produce than corn ethanol, resulting in a net reduction of atmospheric CO_2 (McLaughlin and Walsh 1998). Perennial grasses also cycle and store nitrogen and other nutrients efficiently, reducing the need for inorganic fertilizers (Anex et al. 2007). The extensive root systems of many grasses, including switchgrass, have been utilized in CRP lands to reduce runoff and soil erosion generated from intensive agricultural production, mitigating the damage to aquatic ecosystems (Mulkey et al. 2006).

Despite the benefits of switchgrass and other sources of cellulosic ethanol, these systems are subject to the same land use constraints of all other biofuel types. Additionally, fertilizer use can be minimized by using native perennial grasses, but annually removing aboveground biomass from the system necessitates the use of at least some fertilizer (Mulkey et al. 2006). Monocultures of switchgrass or other grasses provide few niches for natural predators that feed on crop pests, so chemical pesticides are often applied. The desire for weed-free stands of grasses also encourages the use of chemical pesticides.

Although perennial grasses have been planted on CRP land for erosion control and wildlife habitat, the harvesting of biomass every year, or even twice a year, severely reduces the habitat value to birds, arthropods, and other wildlife (Bies 2006). Patches or strips of grasses could be left unharvested each year, although small patches of monospecific grass may provide only marginal habitat value. Alternately, biomass could be harvested in late fall to avoid some impacts to wildlife, but decomposition and physical matting of the grass may create problems with harvesting. It is also unclear how cutting and removing the biomass will affect nutrient cycling and carbon sequestration (McLaughlin and Walsh 1998, Mulkey et al. 2006).

Switchgrass has received most of the attention for cellulosic ethanol production, but other perennial grasses such as big bluestem (*Andropogon gerardii*) and reed canary grass (*Phalaris arundinacea*) are being investigated for their biofuel potential (Hill 2007). These species utilize nutrients efficiently, grow rapidly, and have few pests or diseases, all traits that are trademark characteristics of invasive species (Raghu et al. 2007). Though all native to the United States, switchgrass, big bluestem, and reed canary grass are relatively aggressive species with a high potential for becoming invasive if introduced to new areas. Reed canary grass in particular has caused major setbacks in wet prairie restoration projects across the U.S. (Adams and Galatowitsch 2006), and big bluestem and switchgrass are readily capable of reducing grassland biodiversity without careful management (Wedin and Tilman 1990, Smith et al. 2004). If natural invasive potential is not enough to cause concern, very fast-growing varieties of switchgrass are being bred for ethanol production, essentially increasing its capacity for invasion (Altieri and Holt-Gimenez 2007). The next step in modern agricultural "improvement" is genetic modification, which could further exacerbate the problem of invasiveness. New fast-growing, highly productive varieties of switchgrass or other biomass crops, whether modified genetically or by artificial selection, may have a competitive advantage over native genotypes.

Low-Input High-Diversity (LIHD) biofuels

Cellulosic ethanol is perhaps the most environmentally benign form of biofuel agriculture because of its energetic efficiency and the use of native, perennial grasses. Some of the ecological problems associated with cellulosic ethanol production can be alleviated if nonrenewable energy and chemical inputs could be decreased and the species diversity of the system could be increased. The idea that perennial grasses grown in a polyculture can produce energy for human use is not new, as prairie-like agroecosystems have been researched by Wes Jackson and others at the Land Institute for many years (Jackson 2002). However, the idea that biofuel systems could mimic natural ecosystems was formally introduced by ecologist David Tilman and colleagues in 2006. The low-input high-diversity (LIHD) model described by Tilman et al. (2006) offers an agroecological framework that could be useful for reducing biodiversity loss associated with biofuel production.

By planting, harvesting, and monitoring grassland plots of varying diversity (1, 2, 4, 8, or 16 species) over a 10 year period, Tilman et al. (2006) showed that the plots with highest diversity produced significantly more usable energy per hectare than less diverse plots, and also produced more energy than corn ethanol or soybean biodiesel. Eighteen species from several functional groups were used in the study, including C4 grasses, C3 grasses, forbs, legumes, and woody species. All species were native to grasslands in the study area, although *Poa pratensis* is an aggressive cultivar that is frequently undesired in natural prairies. The diverse plots were designed to mimic a native tallgrass prairie, one of the most exploited and fragmented ecosystem types in North America.

No fertilizers or pesticides were used to manage the plots, which significantly reduced fossil fuel inputs and completely eliminated negative environmental effects of excess nutrients and chemical toxins. The total energetic input into the system was about 15 times lower than needed for corn ethanol and about 4 times lower than soybean biodiesel, representing a significant decrease in carbon emissions. Additionally, over the 10 years of the study, the most diverse plots (containing 16 species) sequestered 31 times the carbon than did the monocultures, although the authors admitted that difference may narrow in the future as root growth in the diverse systems slows. The combination of low energy input and high carbon storage makes the diverse systems strongly carbon-negative. If LIHD could be adopted on a large scale, it would be much more effective at combating global warming than conventional biofuels. Clearly, this has benefits for biodiversity on a global scale.

Moreover, the plots in the study were situated on degraded, abandoned, nutrient-poor agricultural land. If LIHD biofuel production could be successful on exhausted farmland, the pressure to grow biofuels at the expense food crops or natural ecosystems would be reduced.

Where ecologically appropriate, LIHD systems could be established in lieu of CRP land, providing both ecosystem services and economic benefits to the farmer.

From the perspective from biodiversity, LIHD is a hopeful proposal because it addresses the problem of biofuels on at least two levels. First, LIHD systems would directly increase the diversity in abandoned or marginal agricultural land by recreating a historically important plant community, which in turn would attract an array of associated biodiversity. Considering that less than 1% of the original tallgrass prairie is left intact in North America (Samson and Knopf 1994), there is a clear need for restoration and expansion of remaining areas. Secondly, LIHD would increase the quality of the agricultural matrix, that is, it would facilitate migration between existing habitat fragments, thereby lowering the risk of extinction (Vandermeer and Perfecto 2006). Even if LIHD systems fall short of completely reflecting the diversity and function of native tallgrass prairies, they could be quite valuable for reducing extinction in the historical tallgrass prairie region and in surrounding areas with mixed forest, savanna, and prairie.

Limitations of LIHD systems

The LIHD concept described by Tilman et al. (2006) is a significant ideological advance which may resolve some of the problems of biodiversity loss and habitat destruction associated with conventional biofuels. Despite these benefits, the LIDH model has several problems that threaten its usefulness as a viable alternative to conventional biofuel systems.[*]

First, LIHD prairies are likely to thrive best in areas where tallgrass prairies existed historically, that is, in central North America where mollisols are the dominant soil type.

[*] Discrepancies in the research methodology and conclusions of Tilman et al. (2006) have been raised by Russelle et al. (2007) and Cassman (2007), and past studies by the Tilman group have been criticized for failing to actually show any link between diversity and ecosystem function. However, this section considers LIHD as a broad concept, assumes it *is* ecologically feasible, and is not a direct critique of Tilman et al. (2006) per se.

Mollisols also occur in large regions of Eurasia and in Patagonia in South America (USDA Global Soil Regions Map, 2005), and those also may be appropriate areas for LIHD biofuel production. In North America and central Eurasia, however, most of those soils have been dominated by conventional corn, wheat, or barley production. There is simply not enough abandoned agricultural land in these areas to support widespread LIHD. By a generous estimate, even if all the abandoned agricultural land in the world were converted to LIHD production, it would produce only enough energy to replace 13% of global petroleum consumption (Tilman et al. 2006), and realistic estimates may be much lower (Russelle et al. 2007). Thus, if LIHD systems were to be widely adopted in the future as the most economically- and ecologically-sound alternative energy source, it would still result in significant displacement of food crops and natural ecosystems.

It is also unclear if the results of the study, which took place in Minnesota, could be extrapolated to other parts of the world (Russelle et al. 2007). If increasing native biodiversity is a goal of LIHD, at the very least, new systems composed of locally native species would have to be developed for each region of the world. In forested areas that are threatened by conventional biofuel expansion, woody LIHD systems (i.e., agroforests) would have to be developed, because grasslands would not meaningfully address biodiversity loss either from a habitat fragment or matrix perspective. Developing new systems for different regions could be a major challenge to the widespread adoption of LIHD, requiring knowledge and expertise of local ecosystems and a great deal of research. This would be difficult to carry out in part because it directly contrasts the predominant industrial model of uniformity, efficiency, and commodification of the modern agricultural process.

One of the advantages of LIHD systems is that they can be established on severely degraded land with low nutrient content. While it is true that tallgrass prairies can be established and restored on marginal land, the challenges of doing so may prohibit LIHD systems from being successful. Common problems of prairie re-creation and restoration may be further complicated by managing LIHD systems for biofuel production. For example, degraded fields can be so dominated by persistent invasive species such as spotted knapweed (*Centuarea maculosa*), Kentucky bluegrass (*Poa pratensis*), and orchard grass (*Dactylis glomerata*) that increasing native diversity is nearly impossible (Blumenthal et al. 2003, Biondini 2007). Many sub-dominant prairie species, important for overall diversity, have conservative establishment characteristics that limit their ability to compete with invasives (Kleijn 2003). To reduce the dominance of invasives, harvest of the biomass should occur in early or mid summer, before many invasives go to seed. However, the greatest biomass, and thus the most energy, is available after the summer growing season.

Furthermore, prairie re-establishment projects are often reliant on native propagules that have survived in the seedbank (Glass 1989), but in previously farmed areas, the seedbank may be destroyed by decades of tilling. Prairies created from seed can take several years for the plant community to stabilize, and the diversity after that time is often less than what was present in the original seed mix (Piper and Pimm 2002). Also, it may be unreasonable to expect farmers to establish LIHD systems and then wait several years before they reap any economic benefit. Finally, the supply of genotypically native seeds of the common warm-season grasses (such as *Andropogon gerardii*, *Schizachyrium scoparium* and *Sorghastrum nutans*), and especially rarer species, is small and unpredictable, and seeds are time-consuming to collect and process

(Apfelbaum et al. 1997). There simply may not be enough seed available to plant LIHD systems on a large scale.

Once established, native prairies must be carefully managed to maintain diversity, but new challenges arise if the biomass is removed annually, as in the case of biofuel systems. For example, diversity decreases in most cases when aboveground biomass is removed by annual burning (Gibson et al. 1993). Whereas some nutrients remain for uptake after a fire, annual harvesting leaves few above-ground nutrients available for next years' growth, complicating nutrient cycles and leaving the sustainability of annually-harvested LIHD systems in question (Van Dyke et al. 2004, Mulkey et al. 2006, Russelle 2007). Since the ecology of prairie re-creation and restoration is complex, farmers can not be expected to take up this task without extensive training, a task which extension services and other agricultural assistance programs are not equipped to do.

The LIHD concept faces similar problems of cellulosic ethanol when it comes to the invasive potential of some of the species used. Although LIHD is an ecological approach to biofuel production, seed companies would surely try to sell farmers new, fast-growing, high-yielding varieties of certain species. This would likely entail moving more of a plant's biomass from the root system to the above-ground portions, limiting carbon sequestration and changing nutrient cycles in the soil. Worse, using "improved" varieties could limit genetic diversity in the LIHD field and in surrounding populations of genotypically native species. For nearly every major agricultural system in the developed world, the alteration and distribution of seeds has become controlled by a few large corporations such as Syngenta and Monsanto, which have close financial relationships with other members of the agro-petro-industrial complex. While these corporations are not necessarily anti-environmental, they are profit-seeking businesses with a poor history of encouraging sustainable agriculture and biodiversity conservation. Their involvement with LIHD could undermine some of the ecological benefits of diverse biofuel systems.

Also of concern is that the technology for converting multi-species cellulosic biomass into fuel is in its infancy (Houghton et al. 2006). Assuming an efficient way to process multi-species biomass is discovered in the future, it is likely that processing plants would only be able to convert one kind of LIHD makeup at a time. That is, plants may not have the technological flexibility to process multi-species biomass of different species composition and relative abundance. The lack of uniformity in LIHD systems could be a major problem, even with plant material produced within a single field. For example, soil patches with high nitrogen may yield few legumes, while areas with slightly less nitrogen may have a greater abundance of legumes (Piper 1994). These affects would be amplified as the spatial scale increases. Temporal variations in species composition caused by changes in yearly weather patterns, invasion, and other unplanned disturbances could also compound efforts to produce ethanol from multi-species biomass. Even if the micro-scale and temporal problems were resolved in the future, either one type of LIHD system would be cultivated across a large region regardless of the native biota, or a series of small, local processing plants would need to be set up to accommodate different species mixes appropriate for each location. Given the current agro-industrial economic system and the scale at which biofuels are needed to be grown to meet fuel demands, the latter situation is unlikely.

This leads to the conclusion that LIHD systems are subject to a paradox of scale. On one hand, LIHD systems require expertise and local knowledge to successfully establish and manage, and because of this, like other high-diversity agroecosystems, LIHD would work better at a small scale. However, in order for LIHD or any biofuel system to meaningfully alleviate our dependence on fossil fuels, a vast amount of land must be converted. In today's agro-industrial economy, it is much easier to establish large, monospecific fields maintained with pesticides and fertilizers than it is to carefully manage a high diversity tallgrass prairie. The paradox is this: LIHD, almost by definition, can not work on a large scale, but biofuels, due to their high demand, must.

Conclusion

It is clear that conventional biofuel systems often complicate the problems they intend to solve, and pose a significant threat to global biodiversity. Biodiesel production is a major contributor to unprecedented rates of deforestation in large parts of the tropics. Corn ethanol, with its heavy dependence on fossil fuel inputs and high rates of soil erosion and polluted runoff, is perhaps the most wasteful and ineffective alternative energy source in use today. Switchgrass and other cellulosic ethanol sources are more environmentally sound, but still rely on pesticide and fertilizer inputs and are subject to the same land use conflicts as other biofuels. With the demand for renewable fuels increasing, a different approach must be taken. The low-input high-diversity concept presented by Tilman and others is a pioneering step in the right direction, but ultimately falls short of a workable solution.

Clearly LIHD is not a dead-end proposition, and more research must be done to determine the ecological, technical, economic, and political feasibility of LIHD biofuel systems. Energy could be diverted from research on biofuel systems that will almost certainly be unsustainable over the long term, such as corn ethanol. One important area of research is to apply the LIHD concept to tallgrass prairies with different species compositions, and even to completely different ecosystem types such as forests. It would also be beneficial to make processing plants flexible as to what species mix and proportions they can use to make ethanol. Perhaps paramount is the need for research to increase the efficiency of the conversion process in order to get the most energy out per unit of biomass. Increasing efficiency would reduce the amount of land needed to produce biofuels, resulting in less competition with food crops and less ecosystem destruction. Even if efficiency increases, it is hard to imagine that there will ever be enough productive land available to heavily rely on biofuels, LIHD or otherwise. Biofuels must be combined with robust, truly renewable energy sources that are not agriculturally based to lessen the impact on global biodiversity.

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