Environ. Sci. Technol. **2010,** *44,* 8385–8389

Biofuels Done Right: Land Efficient Animal Feeds Enable Large Environmental and Energy Benefits

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Received June 1, 2010. Revised manuscript received September 2, 2010. Accepted September 14, 2010.

There is an intense ongoing debate regarding the potential scale of biofuel production without creating adverse effects on food supply. We explore the possibility of three land-efficient technologies for producing food (actually animal feed), including leaf protein concentrates, pretreated forages, and double crops to increase the total amount of plant biomass available for biofuels. Using less than 30% of total U.S. cropland, pasture, and range, 400 billion liters of ethanol can be produced annually without decreasing domestic food production or agricultural exports. This approach also reduces U.S. greenhouse gas emissions by 670 Tg CO_2-equivalent per year, or over 10% of total U.S. annual emissions, while increasing soil fertility and promoting biodiversity. Thus we can replace a large fraction of U.S. petroleum consumption without indirect land use change.

Introduction

The potential for large scale biofuel production is widely believed to be limited by conflict with food needs (*1*), lack of available land (*2*), direct and indirect greenhouse gas (GHG) emissions (*3*), and other issues such as water use, biodiversity, etc. (*4*−*6*). These and many similar studies assume that biofuel production is imposed on an agricultural system *that does not otherwise change*. However, Tilman et al. point out that society cannot afford to miss out on the benefits of biofuels "done right" while not accepting the undesirable impacts of biofuels "done wrong" (*7*). Significant change is implied, even demanded, by this viewpoint. Our analysis explores potential changes in agriculture that utilize new technology and approaches to meet and reconcile what appear to be competing demands for food, biofuels, and environmental services.

We model the technical potential for changes in U.S. agriculture to meet the demand for large scale biofuel production using a combination of existing and emerging technologies. All current food provisioning services continue to be generated by the cropland now in use while maintaining soil fertility and simultaneously achieving large GHG reductions. Producing the same amount of food on current agricultural land eliminates the so-called indirect land use change (ILUC) effect. ILUC may occur when the supply of agricultural commodities is reduced by biofuel production, thereby catalyzing land use change with potentially large accompanying GHG releases (*3*).

Total US cropland is approximately 178 million hectares (ha), but we analyze only the 114 million ha of cropland used now to produce animal feed, corn ethanol, and exports. Cropland used for direct human consumption (including wheat, fruits and vegetables, and corn dedicated to corn starch, syrup, etc.), forests, grassland pasture, and rangeland are not considered. Thus, this analysis is not meant to determine an upper limit on U.S. biofuel production, but rather to provide an example of what is technically feasible.

Animal Feeds and Biofuels. Over 80% of total agricultural production in the United States is used to feed animals, not human beings directly, and most animal feed is produced for ruminants (cattle) (*8*), which are nutritionally versatile animals. Two land-efficient animal feed technologies are considered here: ammonia fiber expansion (AFEX) pretreatment to produce highly digestible (by ruminants) cellulosic biomass and leaf protein concentrate (LPC) production.

AFEX is an alkaline treatment for lignocellulosic materials that has been studied for use in biofuel production. During AFEX, concentrated ammonia is contacted with cellulosic biomass at moderate temperatures, resulting in greatly increased production of fermentable sugars by enzymatic hydrolysis (*9*). The process also increases the digestibility of cellulosic biomass for ruminant animals while increasing protein production in the animal rumen due to the addition of ammonia-based byproducts. Although extensive feed testing and commercial applications have not yet been introduced, AFEX-treated rice straw has been successfully included in dairy cattle diets (*10*), and tests with switchgrass and corn stover have shown increased cell wall digestibility when exposed to rumen microorganisms (*11*).

High protein LPC products are generally produced by first pulping and then mechanically pressing fresh green plant matter to squeeze out a protein rich juice, which is then coagulated and dried (*12*). A fibrous material remains which is depleted in protein, but is still suitable for animal feed or biofuel production. This process has been studied for decades, and commercial scale facilities have been built (*13*). Currently, one commercial facility is in operation (Desialis, Paris, France). While most studies have focused on alfalfa as the feedstock, LPC production is suitable for any high-protein cellulosic biomass, including grasses.

We also consider aggressive double-cropping, thereby increasing the total biomass produced per ha. Double crops are typically winter annual grasses or legumes (e.g., winter wheat or clover) that are planted in autumn following the corn or soybean harvest. The double crop is harvested the next spring. Double crops take up nutrients that might otherwise cause environmental degradation and protect against wind and water erosion (*14*). In addition, root biomass from double crops enhances soil fertility (and sequesters carbon) by building soil organic matter (*15, 16*). Because of the soil protective effects of the double crop, much more corn stover can be removed, an important synergy for biofuels (*17*). The plant biomass made available by more land efficient feeds can then be used for biofuel production under the constraints noted above.

Not all land is suitable for double cropping (e.g., insufficient soil moisture to support the subsequent row crop). There are also potential drawbacks to double cropping, including potentially decreased grain yields (*18*), increased

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10.1021/es101864b

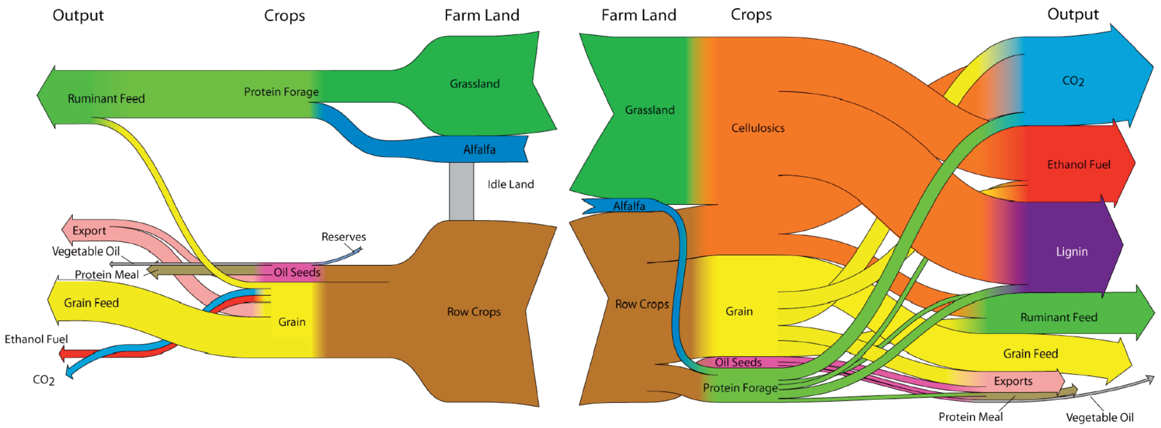

FIGURE 1. Annual mass flows from the current allocation of 114 million ha (left) versus a land efficient allocation (right) showing all major crops and outputs for the maximum ethanol production scenario. The CO_2 listed is biogenic carbon released during fermentation.

nitrogen fertilizer requirements, and increased potential of pests and diseases. Thus in our analysis, we limit double crops to a conservative value of one-third of all current corn and soybean land used for feed, exports, or ethanol (approximately 20 million ha). While double cropping is currently not extensively practiced, largely because there are few markets for these double crops, our analysis assumes that double crops are produced and harvested profitably. For maximum soil protection and organic matter conservation, we further assume no-till practice for corn and soybean production.

Structure of the Modeling and Analysis. Animal feeding operations can be adapted to these new feeds, thereby freeing land for biofuel production. Three basic feed requirements—digestible energy (calories), protein, and rough fiber—are used to balance animal diets. Each feedstock or product contains a specific amount of these three components, and the products are combined to meet the nutritional requirements of domestic ruminant and nonruminant livestock (see Supporting Information (SI) for more information). In addition to animal feed, domestic vegetable oil production must also be balanced, and so a high oil canola is also included as a potential crop. This is because we expect LPCs to reduce soybean land, which would reduce the amount of vegetable oil generated as a coproduct of soybean meal.

The feedstocks used in this study include corn grain and stover (all the above-ground parts of the corn plant except the grain), soybean, canola, winter wheat as a double crop, alfalfa, and cellulosic biomass crops (CBCs). CBCs include any cellulosic perennial (e.g., switchgrass or Miscanthus), cellulosic annual (e.g., forage sorghum), or mixture of perennials and annuals (e.g., native prairie) that can be processed for animal feed or biofuel production (*19*). While switchgrass is used as the example CBC in this analysis, any relatively productive cellulosic crop might be used as long as it meets the specified ethanol yield and ruminant digestibility requirements.

All these potential uses of cropland were modeled using DAYCENT to determine their environmental impacts (*20*). The DAYCENT model simulates carbon and nitrogen dynamics given soil and weather data, thereby predicting soil organic carbon, plant biomass growth, and nitrogen related emissions. Each crop or crop rotation was simulated at nine different locations throughout the Midwest for a period of 60 years, and the results were averaged to estimate the environmental impact for each crop system. Environmental impacts modeled were carbon dioxide emissions, soil organic carbon change, nitrate leaching, and nitrous oxide production. Although ethanol was used in this analysis, other biofuels such as butanol or "green gasoline" can also be produced from cellulosic biomass. Assumed ethanol yields were 418 L/Mg grain (2.8 gallons/bushel) from corn (*21*) and 429 L/Mg fiber (*22*). Because the carbohydrate content varies significantly between the various cellulosic materials studied, cellulosic ethanol production potential is determined based on the fiber content rather than a constant amount per Mg biomass. In addition, the overall changes in GHG emissions (as CO_2 equivalents) resulting from changes in the agricultural sector and the transportation sector were determined. These changes included all emissions and sinks from the land, including growing, fertilizing, and harvesting the biomass, transportation to the processing facilities, and emissions from the biorefineries. All results are presented as GHG emission reductions, or the magnitude of United States' GHG emissions per year that are eliminated by the proposed changes in agriculture.

Using the above data, a nonlinear optimization model was constructed to determine either the maximum ethanol production or maximum GHG reduction available from this 114 million ha of land. Either ethanol production or GHG reduction is maximized by varying the amount of land dedicated to each type of crop as well as how each crop is used subject to constraints regarding animal feeding, export requirements, and biodiversity. Model outputs include how much crop land is used for each crop considered, net GHG reductions, biofuel production, soil organic carbon, and nitrate loss. Further information on this model is provided in the SI.

The purpose of this model is to determine the maximum amount of biofuel or maximum reduction in greenhouse gases without changing current food requirements in the United States. This model is limited in that it does not consider spatial parameters (such as variance in yields), temporal parameters (such as increasing population or crop yields), nor does it consider other policy or behavioral shifts such as changing human diets away from red meat consumption.

Results

Results of the analysis are summarized in Figure 1, which compares the current use of 114 million ha to produce food, feed, and some biofuels (left-hand side) with a more land efficient approach which uses that same acreage to generate an equal amount of food and animal feed while also providing much larger quantities of biofuels (right-hand side). More detailed information about the mass flows in these scenarios is presented in the supporting material.

Cropland patterns shift significantly under this analysis. Oilseed acreage declines by approximately 30% compared to current usage while corn acreage expands and double

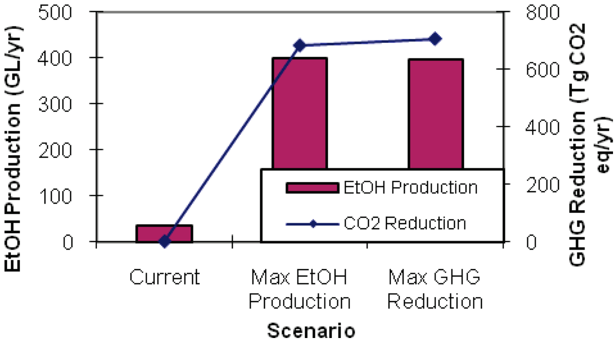

FIGURE 2. Ethanol production and GHG reductions from the current US agricultural system considered in this analysis (114 million ha), that same acreage configured for maximizing ethanol production, and that same acreage configured for maximizing GHG reductions.

crops are produced on one-third of corn plus oilseed land (recall that double crops do not require additional land). Alfalfa acreage decreases slightly and CBCs occupy about 45% of this cropland at an assumed yield of 13.7 Mg/ha (6.12 tons/acre) (*23, 24*). Thus U.S. crop land would be used quite differently if we were to use it more efficiently to produce the same amount of "food" (actually animal feeds) while also generating large amounts of biofuels and accomplishing significant GHG reductions.

Two different objectives are of the greatest importance: maximum biofuel production and maximum GHG reduction. According to our analysis, these two objectives harmonize well with each other and also with production of land efficient animal feeds. From Figure 2, the maximum ethanol production is 400 gigaliters per year (106 billion gallons/year), which is the energy equivalent of 80% of the gasoline derived from imported petroleum. Under this scenario GHGs are also reduced by 684 teragrams per year from current emission levels (compared to 6200 Tg/yr total United States emissions). Ethanol production from cellulosic materials also generates a lignin residue which is burned to provide electricity and steam for the biofuel processing facility (the "biorefinery"). Approximately 217 TWatt × hr of electricity (about 5% of total U.S. electricity consumption) is produced in excess of the electricity consumed in the biorefinery and is exported to the grid. (Corn ethanol production does not provide lignin or electricity.)

Maximum GHG reduction is 707 teragrams/year (approximately 11% of total U.S. GHG emissions), in which case ethanol production is reduced slightly to 397 gigaliters per year. These GHG reductions include about 110 teragrams/year of carbon sequestered as increased soil organic matter. Increased soil organic matter promotes soil fertility, and thereby the diversity of life sustained by the soil.

However, DAYCENT also predicts that nitrate releases may increase by 60% (an average of 13.3 kg/ha/yr compared to 8.3 kg/ha/yr) versus the current situation for these two scenarios. Nitrate leaching is currently a major contributor to hypoxia in the Gulf of Mexico (*4*), and thus reducing this leaching is critical for a sustainable bioeconomy. The increase in leaching is primarily due to the increase in corn production relative to soybean production as well as a slight increase due to the adoption of no-until agriculture, although the effect of no-until agriculture is arguable given the literature on this subject (*25*). Nitrate emissions from row crops increased 22% in this scenario, despite the increase in double cropping. Increased switchgrass production, which releases over 9 kg/ha/yr, contributes 27% of the total leaching, according to DAYCENT. Some candidate cellulosic biomass crops such as *Miscanthus* × *giganteus* have reported increased nitrogen use efficiencies (*26*) and might exhibit low nitrate emissions.

According to this analysis, expanded corn production is needed to support food, feed and biofuel production. But fertilizer nitrogen must then be used much more efficiently if we are to "do biofuels right" (*7*) and avoid additional environmental degradation. It is technically possible to change fertilizer use and farming practices to further reduce nitrate emissions (*4*). For example, controlled release fertilizers (CRFs) release nitrogen slowly into the soil, thus allowing the plant to fix a greater percentage of the nitrogen, and can decrease leaching by 50% (*27*). Landscapes can be designed to include buffer strips of deep-rooted perennial grasses surrounding corn fields to capture nitrogen in groundwater. Plants can also be bred or engineered for increased fertilizer use efficiency. Increased fertilizer use efficiency is therefore a potentially fruitful area for collaboration between farmers and farm organizations, biofuel producers, government agencies, and environmental groups. Changes in human nutritional choices to reduce the use of corn-fed animals would also decrease the bulk of nitrate emissions. We do not explore this possibility in our study.

We performed multiple sensitivity analyses to better understand the system performance, one of which is shown in Figure 3. This figure shows how predicted ethanol production and GHG emission reductions respond to changes (25% increase or decrease) in four key system variables: animal feed consumption, yield of CBCs, export demands, and acreage placed in cover crops. For example, a 25% increase in animal feed consumption would reduce the amount of ethanol produced by 18% and would also reduce GHG emissions savings by about 26%. In contrast, higher CBC yields increase both the amount of ethanol produced and the GHG emissions savings. Increasing CBC yield is the most important variable analyzed here for its ability to reduce overall GHG emissions. For each of these four variables, those changes which increase ethanol production also decrease GHG emissions.

In addition to the above changes in variables, we identified several alternative scenarios, as listed in Table 1. Further analyses are present in the SI. Only the scenarios that limited nitrate emissions greatly changed the results presented here; all other scenarios maintained ethanol production to at least 80% of the base case values. Nitrate emissions can be decreased to less than one-fifth the current level, but in this scenario only 76 gigaliters of ethanol are produced. If current tillage practices are used rather than no-until, then the reduction in carbon emissions decreases by 11%, but overall US emissions are still reduced by 608 Tg/yr. Due to the uncertainty in implementing AFEX-treated feeds, we also considered the case in which this technology was eliminated. In this case, ethanol production was reduced by 7% compared to the base case. Leaf protein concentrate technology is not as important in this study, as ethanol production only decreases 5% and the reduction in GHG emissions actually improves slightly if no leaf protein concentrate is used. If corn yields decrease 15% due to double crop implementation, then ethanol yields decrease to 382 gigaliters/year. While these values are lower than our base case, they still demonstrate a high degree of compatibility between biofuel production, greenhouse gas reductions, and land efficient animal feed production. Overall, ethanol production and GHG reduction results are very robust to changes in system parameters.

Discussion

Large scale biofuel production can be successfully reconciled with food production while also accomplishing significant GHG reductions and promoting biodiversity. Producing the same amount of food on *existing land* eliminates the indirect land use change (ILUC) effect associated with increased GHG

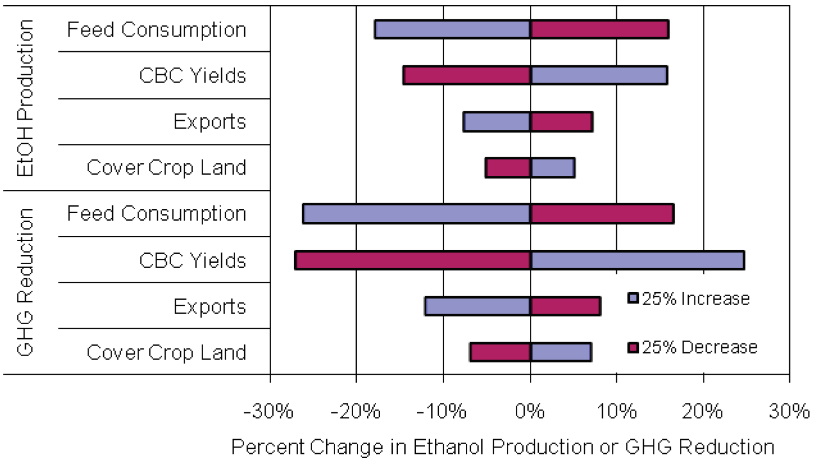

FIGURE 3. Effects of changes in four system variables (consumption of animal feed, yield of cellulosic biomass crops, U.S. grain and soybean exports, and land that includes double crops) on the ethanol production and GHG reduction achieved for the maximum ethanol scenario. Variables are increased (blue bars) or decreased (red bars) by 25%. The % change in ethanol production and GHG reduction are compared to the base case maximum ethanol scenario presented in Figure 2.

TABLE 1. Ethanol Production and GHG Reduction for Several Alternate Scenarios and Compared to the Base Case Scenario

	ethanol production		GHG reduction	
	GL/yr	% of base[a]	Tg/yr	% of base[a]
base case - maximum ethanol	400		684	
current tillage practices[b]	397	99%	608	89%
minimum nitrate emissions	76	19%	86	13%
same nitrate emissions	323	81%	445	65%
no AFEX feed present	371	93%	698	102%
no LPC feed present	380	95%	702	103%
reduced corn yields with double crop	382	96%	652	95%
no maximum row crop constraint	495	124%	611	89%

[a] Magnitude of ethanol production of GHG reduction relative to the base case, maximum ethanol scenario. [b] The scenario that includes current tillage practices is optimized for maximum GHG reductions. All other scenarios maximize ethanol production.

emissions of biofuels. We believe our analysis is conservative in that it under predicts potential GHG reductions and biofuel production. For example, our analysis does not deal with (i) changing dietary trends which might reduce the need for animal feeds, (ii) more efficient use of grassland pasture and range, (iii) utilization of cellulosic residues other than corn stover, (iv) higher CBC yields, (v) more use of double crops beyond the one-third limit imposed in our analysis, or (vi) any biomass derived from forests. Each of these factors would likely increase biofuel production and further reduce GHG emissions while also reducing pressure on agricultural land. Except for possible increases in nitrate emissions, environmental services such as enhanced biodiversity, increased soil organic matter, and reduced GHG emissions are well-served by the approaches outlined here.

Our analysis deals only with the technical potential of these changes. Multiple drivers would be required to actually produce these changes. The most important driver would be if these changes in land use patterns were shown to be economically attractive to farmers, livestock producers, and the biofuel industry. Thus much more exploration of the technology and economics of combined food/feed/fuel systems is required. Continued policy emphasis and incentives tied to improving the environmental performance of biofuels as well as animal feed production would also tend to drive desired changes. Combining double crops with increased corn stover harvest is a key driver because of the large amounts of cellulosic biomass made available with concurrent improvements in several environmental parameters. Thus policies that encourage the use of double crops in biofuel systems could have large, positive effects. These policies would need to be accompanied by other policies that minimize nitrogen emissions for the maximum environmental benefits.

As noted, the technologies that provide most of the benefit to food and biofuel production are extensive double cropping and large scale production of diverse cellulosic crops appropriate to different regions of the country. These are not exotic, expensive, or high risk technologies. Considering their large benefits to energy security and climate security, extensive double cropping and production of diverse cellulosic crops deserve more study for widespread application in integrated biofuel and animal feeding systems than they have received to date.

The U.S. is the world's largest petroleum user and also a significant exporter of agricultural commodities. Our analysis shows that the U.S. can produce very large amounts of biofuels, maintain domestic food supplies, continue our contribution to international food supplies, increase soil fertility, and significantly reduce GHGs. If so, then integrating biofuel production with animal feed production may also be a pathway available to many other countries. Resolving the apparent "food versus fuel" conflict seems to be more a matter of making the right choices rather than hard resource and technical constraints. If we so choose, we can quite readily adapt our agricultural system to produce food, animal feed, and sustainable biofuels.

Acknowledgments

This work was funded by DOE Great Lakes Bioenergy Research Center (www.greatlakesbioenergy.org) supported by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, through Cooperative Agreement DEFC02-07ER64494. Support was also provided by the Michigan Agricultural Experiment Station and by General Motors Corporation.

Supporting Information Available

A detailed description of the model used and several sensitivity analyses. This material is available free of charge via the Internet at http://pubs.acs.org.

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ES101864B