

Growing Plants for Fuel: Predicting Effects on Water, Soil, and the Atmosphere

G. Philip Robertson, Stephen K. Hamilton, Stephen J. Del Grosso, and William J. Parton



Biofuels and Sustainability Reports

Biofuels, generally defined as liquid fuels derived from biological materials, can be made from plants, vegetable oils, forest products, or waste materials. The raw materials can be grown specifically for fuel purposes, or can be the residues or wastes of existing supply and consumption chains, such as agricultural residues or municipal garbage. In this series of reports, sponsored by the Energy Foundation, we explore the production and use of biofuels from an ecological perspective. Each report addresses one aspect of biofuel production. The report topics are biodiversity and land use; forestry; grasslands, rangelands, and agricultural systems; and biogeochemistry. A capstone issue will present a synthesis of the ecological dimensions of biofuel production.

These reports, which were reviewed by an Advisory Committee, are based upon scientific manuscripts initially presented at a conference in Washington, DC, on March 10, 2008 (see www.esa.org/biofuels). The conference was hosted by the Ecological Society of America (ESA) and sponsored by a consortium of other scientific organizations, non-governmental organizations, federal agencies, and the private sector. ESA also issued an official statement on the topic in January 2008, which can be found at:

<http://www.esa.org/pao/policyStatements/Statements/biofuel.php>

As innovations are made in the production and use of biofuels, ecologists worldwide will continue to actively monitor their impacts.

Cover photo credit: *Farming near Klingerstown, Pennsylvania. Photo by Scott Bauer, USDA-ARS.*

Inset: Switchgrass (Panicum virgatum) is harvested in Pennsylvania. Photo by Paul R. Adler, USDA-ARS.

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As society confronts dwindling supplies of fossil fuels to meet energy needs, alternative fuels from renewable resources are capturing the attention of farmers, conservationists, and policy makers. Gasoline blended with corn-based ethanol, one of several biofuels (liquid fuel derived from plant materials), is now sold in filling stations throughout the country. But the rush to ramp up corn ethanol production comes at a cost—to the atmosphere, to marine and freshwater ecosystems, to wildlife habitat, and to the supply of land available for food production. Cellulosic feedstocks, an energy source derived from plant matter such as woodchips, corn stalks, and switchgrass, are an alternative biofuel that may avoid many of the environmental pitfalls of grain-based biofuel crops.

In this issue we will look at both types of “bioenergy landscapes”—one agricultural system based on grains and the other on cellulose—and review what is known about their biogeochemical impacts—the effects on biological, chemical, physical, and geological processes in the natural environment. However, evaluating the costs and benefits of particular cropping systems requires looking at more than just the type of plant that is grown. What are the tradeoffs to society and the environment? How will production affect the ability of the ecosystem to filter water, control runoff and drainage, and provide other “ecosystem services” such as pest protection and climate stabilization? What is the land currently being used for? Will only one type of crop be grown, or will different crops be rotated and how often? Does the production involve tilling the soil?

Because interactions within ecosystems are so complex and results from comprehensive experimental studies of many bioenergy cropping systems are not yet available, mathematical models of ecosystem performance are a useful way to compare alternative systems. Ecosystem models allow us to examine factors such as growing conditions

and management practices and to project outcomes such as crop growth and nutrient loss over long time frames. We will examine the environmental outcomes of three alternative biofuel cropping systems to predict what the tradeoffs might be and how these outcomes might challenge our assumptions.

Demand for Agricultural Biofuels and the Growth of Corn Ethanol

In 2007, in an effort to move the country toward greater energy independence and security, Congress passed legislation that, among other provisions, mandates production of biofuels. The legislation requires that by 2022, production of biofuels be at least 36 billion gallons—15 billion gallons from grain-based ethanol and 21 billion from cellulosic or other non-grain-based sources. This seemingly large quantity is still only one-quarter of the amount of gasoline consumed in the United States in 2007, and by 2050 the demand for ethanol is expected to more than double, to 80 billion gallons.



Figure 1. Bales of corn stover collected from a Renewable Energy Assessment Project experiment near York, Nebraska. Stover is often left in place to protect soil, but it also has potential as a feedstock for cellulosic ethanol production.

Photo by Wally Wilhelm, USDA-ARS

Photo by Stephen Ausmus, USDA-ARS



Figure 2. At the University of Minnesota-Morris Biomass Gasification Facility, researchers evaluate potential biomass feedstocks, including pressed corn stover.

How can US agriculture meet such a demand? Do we have enough available land, and what would such an expansion of the bioenergy landscape mean for the health of the planet? As farmers have shifted to producing more grain—mostly corn in the United States—for fuel instead of for food or animal feed, the price of corn has increased, in turn driving demand for even more production. Significantly increasing biofuel production can be achieved in only two ways: either by increasing the yield on existing farmland or by converting unfarmed land to biofuel agriculture.

There are a couple of strategies for growing corn more intensively on existing farms. For example, many corn farmers currently plant their lands in soybeans in alternate years. Should they plant soybeans less frequently, perhaps even shifting to continuous corn production, more agrochemicals will be needed because corn requires nitrogen fertilizer and more pesticides than soybeans. This would exacerbate the known environmental problems associated with large-scale agriculture—groundwater pollution, nutrient runoff, soil loss—and would also require the application of more petroleum-based fertilizer with its CO₂ costs. The second strategy, putting more land into corn production, has its own problems. Often land that is not now under production is not farmed because it is less suitable for intensive cropping—soils may be sloping or poorly drained or generally infertile. So putting more of this kind of land into intensive corn production will have even greater environmental cost because more chemicals are needed to overcome fertility limitations and these lands are often more vulnerable in any case to erosion and nutrient loss. Moreover, recent research has shown that landscapes with more corn and less soybean require more pesticide use on the soybeans because there are fewer biocontrol

insects available to control important soybean pests in these landscapes.

Some of the land not currently being farmed is enrolled in the Conservation Reserve Program (CRP), in which the federal government pays farmers to take highly erodible or environmentally sensitive land out of production. However, recent increases in corn prices have already encouraged some farmers to take their lands out of the CRP and put them back into production.

Biofuels from Cellulose

Assuming that production of grain-based ethanol can stay on course to provide the 15 billion gallons mandated by the Energy Independence and Security Act, could enough cellulosic material be grown to make up the rest of the projected 80 billion

gallons we will need by 2050? And even if there is enough available land on which to grow these alternative feedstocks, what would the biogeochemical repercussions be? Let's look at the question of feasibility first.

We can get a rough estimate of the total plant biomass needed to meet this ethanol demand by examining the yield from pilot refineries. If, as seem likely, technological advances allow ethanol yields at pilot refineries to be improved by 25% when fully commercialized, then about 600 million metric tons of biomass will be needed. About 40% of this might already be available in the form of municipal solid waste, industrial wood waste, and agricultural residues such as corn stalks and leaves, known as corn *stover*. The remaining biomass, about 350 million metric tons, would need to come from new plantings of cellulosic feedstock.

Switchgrass, a perennial prairie grass, is one of several promising cellulosic crops, and current switchgrass production rates suggest that about 47 million hectares, or about 115 million acres, would need to be devoted to cellulosic biofuel crops to meet this production goal. But finding this much land is a challenge. It represents about 25% of all the land currently cropped in the United States (178 million hectares or 436 million acres), and in any case, using this land would compete with current food production. Most rangeland is too arid to be this productive. However, growing biofuel crops on former cropland or pastureland, including the lands now in CRP, could be a significant part of the solution. The benefit of these lands is that they would not compete with existing food or forage production. Moreover – and leaving aside the question of whether some of these environmentally sensitive lands should be under production of any kind – using lands enrolled in CRP to grow perennial crops for biofuels might be a better alter-

Photo by Stephen Ausmus, USDA-ARS



Photo by Paul R. Adler, USDA-ARS

Figure 3. Left: Switchgrass (*Panicum virgatum*), a prairie grass native to North America. Right: Switchgrass is harvested to evaluate yield potential.

native than returning that environmentally vulnerable land to grain production. Whether there is indeed a sufficient land base available for this type of agriculture still needs to be determined.

A second component of feasibility is the cost of ethanol production from cellulosic feedstock. Although the first cellulosic refinery is only now being built, financial incentives in the 2008 Farm Bill, along with an expectation that the prices of oil and grain will continue to rise, are likely to mean that the technology will soon be commercially viable.

Environmental Effects of Biofuel Production

Determining the environmental ramifications of growing crops for biofuels and producing ethanol from them is decidedly more complex. Of major environmental concern is how such crop production would affect our carbon footprint, nutrient and soil conservation, and water use. In the discussion below we will see that differences between cropping systems reflect not only how the plants are grown and harvested, but also the structure and physiology of the plants themselves.

Carbon Cycle and Greenhouse Gases

A major rationale behind the push for biofuels is not only that fossil fuels are non-renewable and largely imported, but also that, as a renewable resource, biofuels should be an environmentally better alternative—burning fuels made from plants will not contribute to greenhouse gas buildup, because when the plants regrow, they will take up CO₂ and thus offset any carbon released to the atmosphere during burning. In reality, however, the net contribution of biofuel agriculture to atmospheric warming depends on many factors, such

as what kinds of plants are grown, how much fuel and fertilizer are used to grow and harvest the plants and refine the ethanol, and whether the soil is tilled.

Conventionally produced grain-based ethanol has an overall carbon footprint much larger than ethanol from cellulosic crops. First, grain-based agriculture demands more fossil-fuel energy at every stage, from manufacturing the fertilizer that plants need, to planting and harvesting the crops, to powering the ethanol refining process. Second, growing corn and other grains usually, though not always, involves tilling the soil, which releases to the atmosphere as CO₂ the carbon that would otherwise become or remain stored in soil as organic matter. And even if the corn production involves no tilling, the soil cannot accumulate carbon if too much of the stover is removed to make biofuels.

Ethanol from cellulosic feedstock appears to be an attractive alternative to grain-based ethanol in terms of carbon emissions—the difference between how much carbon is released to the atmosphere (as the greenhouse gas CO₂) and how much is stored by plants. Cellulosic plants do not have high fertilizer requirements, and because they are perennial, cellulosic crops are not tilled. Their roots stay alive year-round and store significant amounts of carbon. And in the refinery, left-over lignin from cellulosic feedstocks can be used instead of fossil fuel to heat the fermenters and generate electricity to return to the power grid.

Nitrogen

Another contributor to atmospheric warming is nitrous oxide (N₂O), a much more potent greenhouse gas than CO₂. Nitrous oxide production stems from the application of nitrogen fertilizers, especially under certain soil conditions. Nitrogen that is not retained by the plants



Photo by Peggy Greb, USDA-ARS

Figure 4. Scientists inspect samples of water runoff that filtered through a switchgrass (*Panicum virgatum*) strip at the edge of a cottonfield.

finds its way into groundwater, streams, and marine systems through leaching and runoff, further contributing to N_2O production. And excess nitrogen can deplete aquatic systems of oxygen—effects on freshwater and coastal marine ecosystems are well known and sometimes dramatic, such as the “dead zone” in the Gulf of Mexico that in some years expands to 6,000 to 7,000 square miles. (See Dale *et al.* 2010 for further discussion of this issue.)

N_2O production in conventional grain-based systems can be twice that in perennial cropping systems. Grain crops need lots of nitrogen, which is why intensive agriculture uses lots of fertilizer. They are also not very efficient at retaining nitrogen, and in temperate climates, the lack of plant growth during much of the year means that much of the nitrogen applied is lost from the soil. In these grain-based systems it is possible to improve nutrient conservation by adjusting how and when fertilizer is used and by planting winter crops that can capture soil nitrogen that would otherwise be lost.

Nutrient loss appears to be less of a problem for most cellulosic cropping systems, partly because the perennial plants provide year-round cover and store nutrients

in their roots over the winter until they are ready to be used by new plant growth in the next growing season. In contrast, when corn and other grains are harvested, the relatively large amount of nitrogen they contain is removed from the system. If cellulosic crops are fertilized carefully, most if not all of the nitrogen added as fertilizer could be taken up by the established roots rather than escaping, though this has yet to be confirmed by long-term experiments.

Water Quality and Water Use

The quality of surface and groundwater can be degraded by soil erosion, by nutrient runoff into streams and lakes, and by nutrients leaching into groundwater. These conditions will be aggravated by heavy application of pesticides and fertilizers, which is common in intensively managed grain-based systems. In general, water quality degradation is likely to be less of a problem for most cellulosic biofuel crops, because of the ability of perennial plants, whose roots remain active year-round, to retain nutrients and prevent soil erosion. This would be especially true when the period between harvests is long, such as for trees. Not all cellulosic feedstocks are perennial plants, however, and in the case of corn stover, for example, nutrient loss and soil erosion could be exacerbated if too much biomass is removed.

How much water a system needs is a second consideration. One way to predict water demand of different cropping systems is to look at their different water use efficiencies—the ratio of crop biomass produced versus water lost from the system through evaporation and plant transpiration. Put another way, more efficient systems lose less available water to the atmosphere per unit of produced biomass. Perennial biofuel plants, with their deeper, better-established roots and longer growing seasons, generally use water more efficiently than do shallow-rooted annual crops. Determining the water needs of biofuel crops systems is tricky because climate exerts a strong influence. Moreover, it is not just the efficiency of the crop but also the total water use that can be important. Thus, even though water use efficiency of a certain type of crop may be high, if the crop is very productive—such as some grasses proposed for biofuel crops—the total water needed per acre will be high.

How a cropping system will influence the water balance at a landscape scale will depend not only on how much water is used by the crop but also on how it affects other factors such as soil erosion or runoff. This can be particularly important if the biofuel crop being planted is replacing a different kind of vegetation. Changing from native woody vegetation to intensively managed crops, for example, or planting woody vegetation on land that was not forested, can have consequences for soil erosion, stream flow, and groundwater recharge. Although cellulosic biofuel crops are not irrigated in

the United States now, large-scale irrigation could become profitable in the future as energy prices rise, and would have further repercussions for water use and water quality. Irrigation could also substantially enlarge a crop's carbon footprint because of the energy required to pump water from groundwater or surface reservoirs.

A final consideration for water use and water quality is that ethanol refineries require considerable amounts of water. Although newer refineries are more efficient, all refineries both use water and produce effluent containing salts and other pollutants that must be managed. (See Mitchell *et al.* 2010 for further discussion of water use and biofuel production.)

Modeling Biofuel Crop Systems

In an emerging field such as biofuel agriculture, it is difficult to predict environmental outcomes because results from comprehensive experimental studies are not yet available. In the meantime, it is possible to predict likely effects by using mathematical models derived from the study of similar ecosystems. These models represent the most important interactions within complex ecosystems and are used to predict plant growth, nutrient movement and loss, and soil carbon change, among other properties. And when the models are run for many places within a large geographic area, regional impacts can be assessed as well.

DAYCENT is one of several ecosystem models that are used to simulate greenhouse gas emissions and crop yields, and here we use it to explore three hypothetical systems: one is conventionally tilled cropland, a second is former cropland now in the Conservation Reserve Program, and a third is a restored or native prairie. We use the model to predict what happens when each of these systems is then used to produce different types of biofuel feedstocks over a ten-year period: corn-soybean, switchgrass, and prairie. These scenarios can be further refined to examine the effects of different managements. For example, we can add a no-till option for corn-soybean production, and in the restored prairie scenario we can also estimate the effects of adding nitrogen fertilizer.

Ecosystem Models

Organisms in ecosystems interact with each other and their physical environment in complex ways. Ecosystem models are representations of the ecosystem: mathematical equations or computer simulations are used to create virtual ecosystems in which these interactions result in specific outcomes. Modeling enables scientists and policy makers to predict how different components, or resources—from water, soil, and air to plants and animals—will respond to different types of changes.

The model allows us to predict changes in the carbon content of the soil, in nitrous oxide emissions, in plant growth, and in the net greenhouse gas balance of each system. The net greenhouse gas balance is measured in units of equivalent CO₂, or net CO₂ eq, which indicates the net change in total greenhouse gas emissions. This includes the contribution of CO₂ as well as the contribution of other greenhouse gases such as methane and N₂O, expressed in terms of how much CO₂ would be needed to produce an equivalent effect. Values of net CO₂ eq that are less than zero indicate net greenhouse gas mitigation, with the most favorable systems having the lowest values.

A favorable reduction in net CO₂ eq can be achieved by several means, but especially by increasing the amount of carbon stored in the soil and by decreasing the release of N₂O. Generally, but not always, higher plant growth will increase the amount of carbon returned to the soil as organic matter from fallen leaves, stems, and crop residue as well as from decaying roots. But soil tillage can offset this increase by speeding up decomposition, thus reducing carbon storage. And application of nitrogen fertilizer can lead to substantial N₂O loss. From an environmental perspective, then, positive model outcomes would include increased soil carbon, decreased N₂O emissions, and, ultimately, more negative values of equivalent CO₂ (meaning the systems consume more greenhouse gases than they release).

What the Model Tells Us

In the scenario that begins with conventionally tilled cropland, conversion to a perennial grass provides the most biogeochemical benefit. Because carbon is stored in roots and there is no annual tillage to promote soil carbon loss, soil carbon accumulates at high rates in the switchgrass scenario and at almost as high a rate in no-till corn (Figure 5, left-hand bars). N₂O emissions are also lowest under switchgrass management in this scenario (Figure 5, second group of bars from the left). Combining the effects of soil carbon change together with N₂O emissions and with other, minor sources of greenhouse gas burden (not shown in Figure 5) leads to a negative net greenhouse gas balance for switchgrass (Figure 5, third set of bars), or net greenhouse gas mitigation. No-till long-rotation corn also substantially lowered the greenhouse gas footprint as compared to the same crop rotation under conventional tillage, but while productivity of the no-till corn was higher than that for switchgrass (Figure 5, rightmost bars), the net greenhouse gas balance for switchgrass was better owing largely to N₂O differences.

Not surprisingly, results differ in the second model scenario, when the land being converted is cropland that has been idled for conservation for 20 years (Figure 6). Production shoots up dramatically for both the conven-

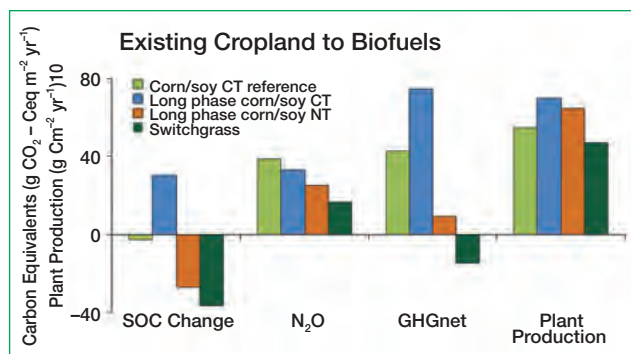


Figure 5. Model predictions of soil carbon change, N₂O emissions, net greenhouse gas (GHG) balance (GHGnet), and above-ground plant growth for conversion of existing corn-soybean conventionally tilled farmland in central Iowa converted to different cropping schemes. The y-axis measures annual GHG production in grams of equivalent CO₂ per square meter (see text); and plant growth is measured in grams of carbon per square meter. Colored bars indicate, respectively, the existing (reference) production system, a long-phase corn-soybean rotation (4 years of corn followed by 1 year of soybean) conventionally tilled (CT), a long-phase corn-soybean no till (NT), and switchgrass production systems. Net GHG change includes changes in soil organic carbon (SOC change), direct and indirect N₂O emissions, and CO₂ emissions associated with production and application of N fertilizer. Negative values indicate net GHG mitigation.

tional and no-till corn-soybean scenarios because of the high corn yields that result in part from improved soil fertility, and increases by 50% for switchgrass because of the added nitrogen fertilizer. Although none of the cropping systems have a net greenhouse gas balance better than that of the original conservation land, and none are negative, the switchgrass scenario is again substantially better than others. Switchgrass cultivation also provides the most favorable net greenhouse gas balance when former CRP land is converted to biofuel crops, but

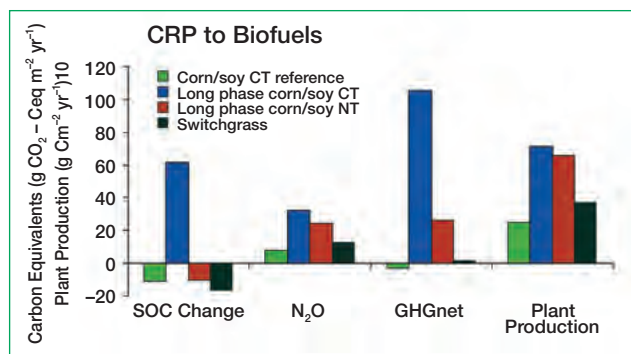


Figure 6. Model predictions of soil carbon change, N₂O emissions, net GHG balance (GHGnet), and above-ground plant growth (ANPP) for conversion of Conservation Reserve Program (CRP) farmland in central Iowa to different cropping schemes. The first bar in the graph represents the reference CRP system. See Figure 5 legend for further explanation.

it is not net negative as in the prior scenario, largely because soil carbon does not accumulate very quickly under land that has already accumulated carbon while fallowed in conservation grasses. On the other hand, the switchgrass system does not lose carbon, as happens when CRP land is plowed and planted to corn, resulting in an enormous net greenhouse gas cost—almost twice that as when converting from former cropland—because of soil carbon loss to CO₂ on plowing. If no-tilled, however, the corn-soybean rotation can accumulate almost as much carbon as switchgrass in this scenario. However, because a corn-soybean crop needs more nitrogen fertilizer, even a no-tilled corn-soybean system has a less beneficial net greenhouse gas balance than switchgrass.

The third model scenario involves harvesting unburned restored prairie for cellulosic biomass (Figure 7), which appears to result in net greenhouse gas production unless the prairie is fertilized. This is because harvested prairie is predicted to lose soil carbon—less above-ground residue is returned to the soil than in grazed prairie that is burned every four years. Plant productivity in harvested prairie slowly declines as more nitrogen is removed in the harvested biomass than would have been removed by grazing and burning. Fertilization improves the greenhouse gas balance because it stimulates carbon accumulation in roots as it stimulates aboveground plant growth. And although there is an N₂O cost to fertilization, it is minor because fertilizer requirements are low.

Outcomes of ecosystem conversion clearly are affected by a complex interaction of many factors, beginning with how the land use would change. Choices that are beneficial from a climate perspective in one setting—a particular choice of crop, perhaps, or the use of fertilizer—may not be in another. Increasing N₂O emissions may be a tradeoff for a greater capacity to increase storage of carbon in the soil. Nonetheless, such changes are not likely to be seen immediately.

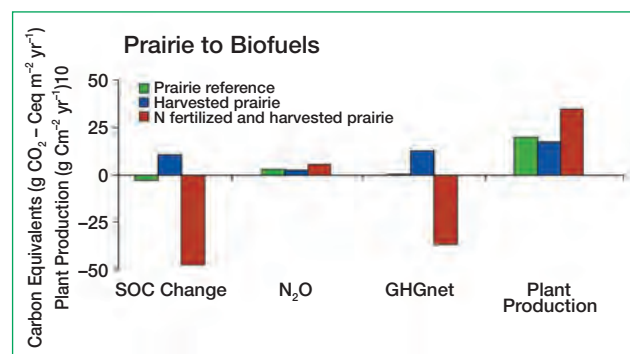


Figure 7. Model predictions of soil carbon change, N₂O emissions, net GHG balance (GHGnet), and plant growth (ANPP) for conversion of restored or native prairie in eastern Kansas to different cropping schemes. From left to right, bars represent the existing (reference) prairie system, harvested prairie, and fertilized harvested prairie. See Figure 5 legend for further explanation.

Also important to note is that beneficial increases in soil carbon that might accompany land conversion may not be sustained at such high rates decades later as the system comes to equilibrium with the new vegetation and management regimen. Ten years, the time period in our modeling exercise, represents the period during which maximum change in carbon soil content would occur following a change in cropping system. This time period must be factored into any decisions about the possible benefits of different types of land conversion for biofuel production, because at some point soil carbon accumulation will slow substantially.

Simulations are valuable for what they reveal about likely tradeoffs and varying outcomes of different management scenarios, and they underscore the importance of taking a systems approach when planning landscape management for biofuels production.

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