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Abstract

In this paper, we review some of the basic energy balance and climate change impact issues associated with biofuels. For both the basic energy and greenhouse gas balances of producing and using a range of fuels, and for the increasingly debated and important issues of non-greenhouse gas impacts such as land, fertilizer, and water use, we conclude that an improved framework for the analysis and evaluation of biofuels is needed. These new methodologies and data sets are needed on both physical and socioeconomic aspects of the life-cycle of biofuels. We detail some of components that could be used to build this methodology and highlight key areas for future research. We look at the history and potential impacts of building the resource base for biofuel research, as well as at some of the land-use and socioeconomic impacts of different feedstock-to-fuel pathways.

Introduction

The global industry producing biofuels—liquid transportation fuels from biomass that replace petroleum-based fuels—is growing rapidly. The rapid rise in biofuel production is driven by government mandates, regulation, and subsidies, as well as high petroleum prices. Globally, biofuel production is dominated by ethanol, with Brazil and the United States each producing about one third of the world total. Commercial production of fatty acid methyl ester (FAME, often identified simply as biodiesel) production began only after 1990 and is an order of magnitude smaller than ethanol production. Figure 1 illustrates the growth of the modern biofuel industry, highlighting the rapid evolution after the oil price shocks of 1973 and 1979 and the dramatic changes when oil prices have been above $25 per barrel.

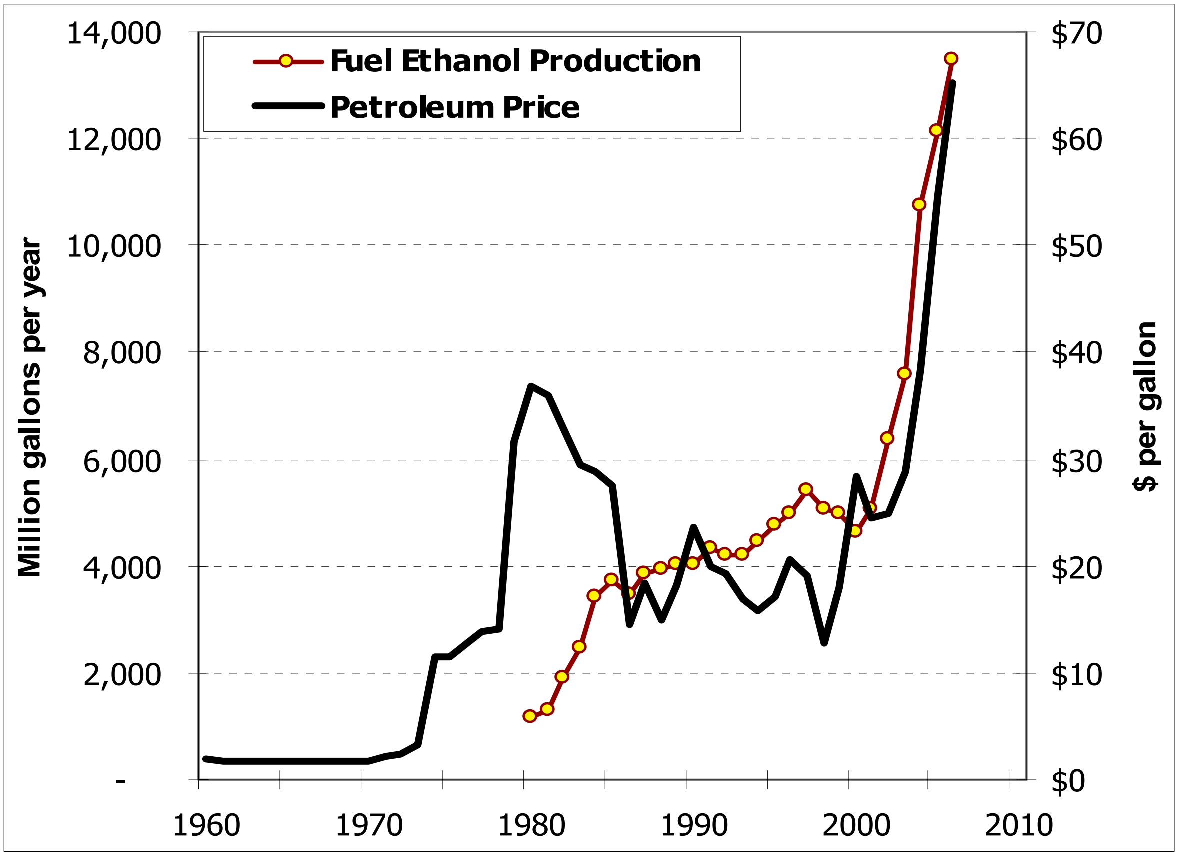

Figure 1: Worldwide fuel ethanol production and petroleum prices

Sources: Petroleum prices from (BP 2007) www.bp.com; Ethanol production is from the Renewable Fuels Association www.ethanolrfa.org where these data are cited as IEA. For ethanol production, the historical data series (1980-2004) does not match the data for more recent years, showing lower values for years that they overlap. The more recent values are shown here for 2004-2006.

Three common rationales exist for government policies to promote biofuels: 1) to support agriculture; 2) to reduce petroleum imports; and 3) to improve environmental quality (especially

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preventing global warming due to carbon dioxide emissions). In practice, however, current government biofuel policies tend to function most directly as agricultural support mechanisms, involving measures such as subsidies or mandates for the consumption of biofuels. By contrast, the environmental impacts of biofuels are often not measured, let alone used to determine the financial incentives or to guide government regulation. In addition, current biofuel feedstocks are fairly standard agricultural commodities (e.g. corn and soybeans) and current biofuel production processes are many years old. Yield maximization for a number of agricultural staple crops often involves high levels of fossil-fuel inputs, further complicating the mix of rationales for biofuel support programs. Ignoring the differential environmental effects of biofuels is thus unwise, for several reasons.

First, the biofuel industry is growing rapidly and is very profitable, in large part because of high world oil prices. Government policies to further subsidize, mandate, and otherwise promote biofuels are being implemented, and more are proposed. Given the large investments in research and capital that continue to flow into the biofuels sector, it is time to carefully assess the types and magnitudes of the incentives that could be employed to achieve high environmental performance. By engaging in this analysis, we can reward sustainable biofuel efforts, and avoid the very real possibility that the economy could be saddled with the legacy costs of shortsighted investments.

Second, biofuels are now being proposed, and often touted, as solutions to environmental problems, especially climate change. However biofuels can have a positive environmental impact relative to gasoline, or a negative one, depending on how the fuel is produced or grown, processed, and then used (Farrell, *et al*. 2006). For instance, corn-based ethanol, if distilled in a coal-fired facility, can have an greenhouse gas signature worse than that of gasoline (unless the coal plant has nontrivial SO_X emissions, which have a significant cooling effect), while cellulosic ethanol, produced using the unfermentable lignin fraction for process heat, or better yet a solar or wind-powered distillery, can be dramatically superior to gasoline (unless the biomass feedstocks ultimately displace wetlands or tropical forests) (Turner, Plevin *et al*. 2007). To distinguish these cases, and the myriad of other feedstock to fuel pathways, clear standards, guidelines, and models are needed.

Third, many new fuels, feedstocks, and processing technologies are now emerging, with numerous others under consideration or active research (see e.g. Lotero, Liu et al. 2005; Kalogo, Habibi et al. 2006; Kilman 2006; Lewandowski and Schmidt 2006; Mohan, Pittman et al. 2006; Tilman, Hill et al. 2006; Demirbas 2007; Gray 2007; Stephanopoulos 2007). These technologies are being developed as biofuel technologies per se; they are not simple adaptations of pre-exisiting agricultural production methods. If these developments can be managed to achieve high productivity while minimizing negative environmental and social impacts, the next generation of biofuels could avoid the disadvantageous properties of a number of current biofuels (e.g. low energy density, corrosiveness, poor performance at low temperatures, and others). A transparent set of data on what we wish biofuels to provide, as well as clear and accessible analytic tools to assess different fuels and pathways are both critical to efforts aimed at providing appropriate incentives for the commercialization of cleaner fuels.

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In this paper, we review some of the basic energy balance and climate change impact issues associated with biofuels. We conclude that an improved framework for the analysis and evaluation of biofuels is needed, and detail some of components that could be used to build this methodology. An important consideration here is how the land-use impacts of biofuels can be measured and used in decision-making. We also summarize and examine the history and potential impacts of biofuel research.

Biofuel Production

Biofuels are produced in two distinct stages, feedstock production (or collection) and processing (sometimes called conversion or biorefining). Figure 2 shows biofuel production in the larger agricultural production system, and shows the major inputs and environmental concerns with each stage. It is helpful to think of biofuel "production pathways" that include feedstock production and processing of feedstock into fuel. Note that this figure does not include measures of sustainability of the production process,

On the left in Figure 2 is the feedstock phase, which includes crop production, agronomy, and processing. The center column covers processing, represented as a biorefinery. On the right are some of the important markets into which biofuels and their coproducts are sold. Biofuel production generally yields one or more coproducts, or may be a coproduct of some other, higher-valued process. As examples, animal feed is the key coproduct of corn ethanol, while biodiesel (FAME) is often thought of as a coproduct of the higher-valued soymeal. Ethanol production from sugar cane yields bagasse (residual plant fiber) that can be burned for heat or electricity production. Most of the markets into which biofuels and coproducts are sold involve considerable international trade.

Figure 2 illustrates the crucial concept that biofuel production affects many different markets, including markets for inputs (e.g., land and water) as well as markets for agricultural products and biofuel coproducts (e.g., food and animal feed). Note that some of these factors may be indirect, operating through market interactions rather than directly. It is vital to note – and to reflect in biofuel analyses – that the indirect impacts of biofuel production, and in particular the destruction of natural habitats (e.g. rainforests, savannah, or in some cases the exploitation of 'marginal' lands which are in active use, even at reduced productivity, by a range of communities, often poorer households and individuals) to expand agricultural land, may have larger environmental impacts than the direct effects. The indirect GHG emissions of biofuels produced from productive land that could otherwise support food production may be larger than the emissions from an equal amount of fossil fuels (Delucchi, 2006; Farrell, *et al*., 2006). Thus, indirect effects bring into question all current biofuel production pathways and many of those that are being developed. Attention to these issues is vital if biofuels are to become a significant component of sustainable energy and socioeconomic systems (Kammen, 2007).

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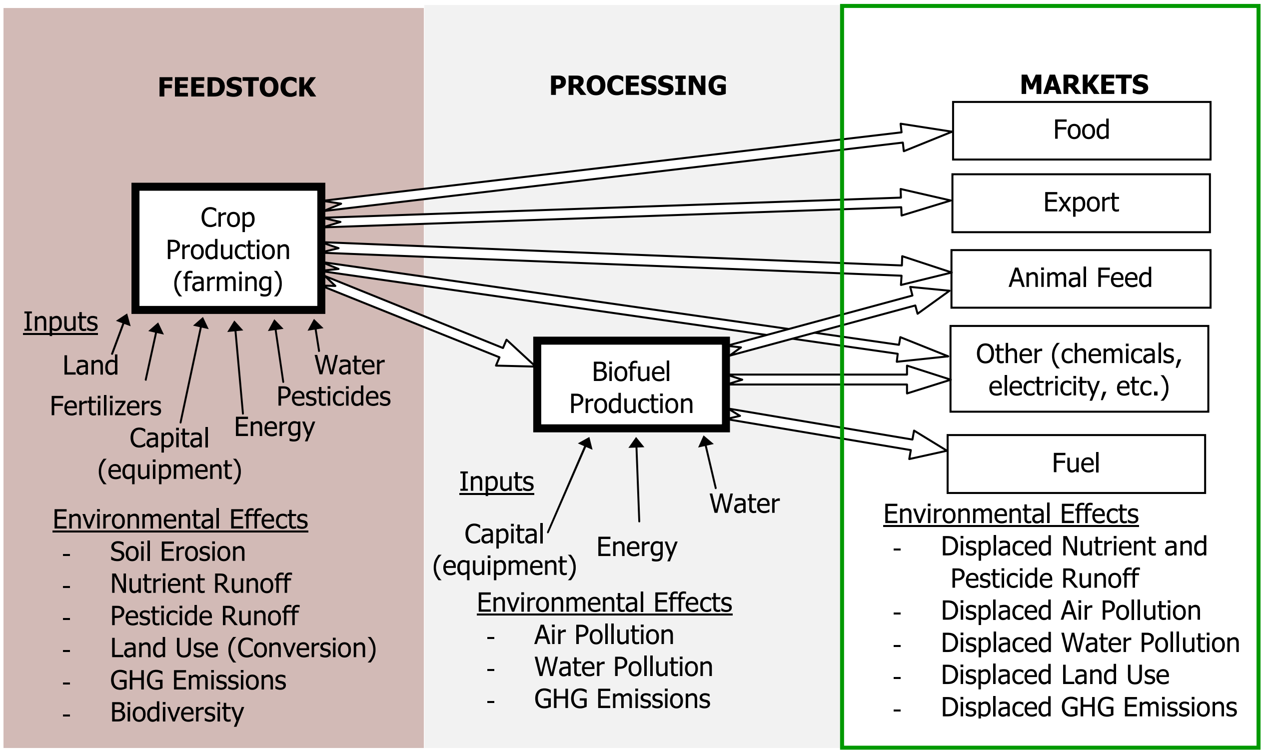

Figure 2: General Biofuel Pathway with Inputs and Environmental Impacts (simplified)

In addition to causing environmental effects, such as soil erosion and GHG emissions, biofuel production and use also *displaces* some environmental effects because they substitute in fuel and other markets for products that have their own environmental effects. The extent to which the coproducts of biofuel production displace other products and their environmental impacts (rather than stimulate additional consumption) depends on the elasticity of demand in the relevant markets (the more inelastic the demand, the greater the displacement), the way in which the coproducts affect supply curves, and other market and nonmarket (i.e., political and regulatory) factors.

These market interactions vary greatly by fuel and pathway, so any attempt to illustrate a comprehensive set of biofuel pathways and related markets would quickly become overwhelming. This is especially true because different production pathways will often involve competition and substitution among inputs and coproducts. Clarity in the assumed inputs and outputs of any such biofuel pathway is vital to developing a clear assessment of a particular fuel (Farrell, *et al.*, 2006). The largest volume biofuel production pathways today are sugarcane ethanol, corn ethanol, soy biodiesel, and palm biodiesel. (The latter two are both FAME.) In these production pathways, the key markets are for electricity and animal feed because these are where the coproducts tend to be sold.

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Life cycle assessment

Lifecycle assessment (LCA) is one technique used to evaluate the energy and global warming impacts of biofuels. In fact, use of LCA techniques is both a method, and a policy framework to evaluate biofuels. It permits an 'apples to apples' comparison of issues that include:

1) What is the net change in the world energy supply from increasing biofuel use by a given date; and
2) How much of the GHG emissions in the world should we attribute to a unit of biofuel produced.

Conceptually, a life cycle comprises all of the physical and economic processes involved directly or indirectly in the life of the product, from the recovery of raw materials used to make pieces of the product to recycling of the product at the end of its life. In practice, however, the life cycle studied in most LCA tools include the production of the fuel as well as its combustion, but typically ignore indirect effects or treat them poorly (Delucchi 2004).

The basic building block in LCA is a set of energy and material inputs associated with a particular output of interest for a particular stage in a life cycle, with emission factors attached to some of the inputs (Hendrickson, *et al*, 2006). A life cycle is then a particular combination of building blocks linked together, where the output of one block (or stage) is one of the inputs to another stage, and the output of the last stage is the product or quantity of interest. An LCA aggregates the emissions attached to the inputs over all of the linked stages, to produce an estimate of total emissions per unit of final product output from the life cycle (Jones, *et al*., 2007).

Consider, for example, the simplified depiction of the fuel life cycle shown in Figure 3. The fuel lifecycle begins with resource extraction (e.g. crude oil production and shipment), proceeds next to conversion processes that transform the resource to fuel (e.g. petroleum refining), and then storage, distribution, and dispensing. The final step is the use of the fuel in gasoline combustion. These steps are arranged linearly like a process flow diagram.

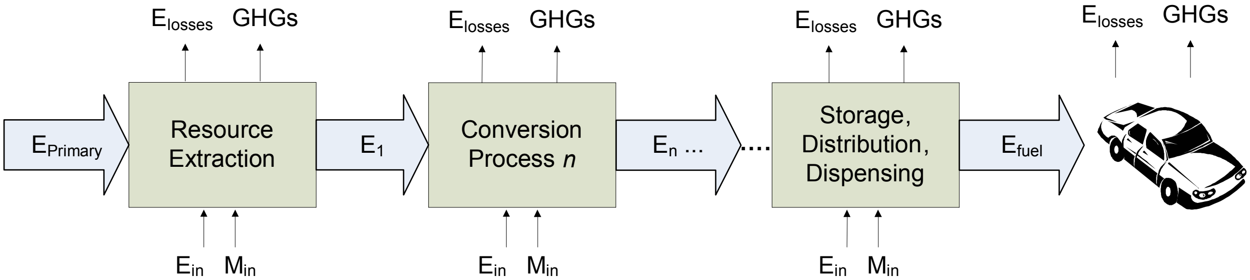

Figure 3: Traditional fuel life cycle analyses that exclude indirect effects

Each process in Figure 3 requires energy and material inputs (E_{in} and M_{in}), and each process has energy losses due to conversion efficiencies (E_{losses}), as well as greenhouse gas emissions (GHGs). Current LCA analyses roughly follow this approach, even though they can be quite

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complex. Some examples of this approach are the spreadsheet models GREET, LEM, and GHGenius, which is based on an early version of LEM. These models can be accessed or downloaded at:

GREET:	http://www.transportation.anl.gov/software/GREET/
LEM:	http://www.its.ucdavis.edu/people/faculty/delucchi/index.php#LifecycleEmissions
GHGenius:	http://www.nrcan.gc.ca/es/etb/ctfca/PDFs/GHGenius/gh_genius_pamphlet0405_e.html

These early-generation LCA models calculate the GHG effects of fuels by summing of the CO_2-equivalent emissions from a sequence of steps, with the emissions for each step calculated by multiplying the rate of use of some input by a GHG emissions factor associated with that input.

Limitations of current LCA methods and tools

Current LCA methods have significant uncertainties and omissions (Delucchi 2004; Delucchi, 2006; Pennington, Potting *et al*. 2004; Rebitzer, Ekvall *et al*. 2004; Arons, *et al*, 2007). Several aspects of the areas of incompleteness and uncertainty are discussed below, including market-mediated effects, land use change, climate impacts of emissions, and uncertain and highly variable data. Research into improved LCA methods is a key component of the effort to understanding the energy and GHG implications of biofuels.

Market-mediated effects

Energy and environmental policies affect prices, which, in turn, affect consumption, and hence output, which then change emissions. Thus, GHG emissions are a function of market forces, and notably the intersection of global, not only national food and energy markets.

Many fuel production pathways result in multiple products, such as food, feed, or chemical coproducts. Conceptually, the best way to handle this in an LCA of GHG emissions is to include all of the emissions from the entire joint production process, and then model what happens to production and hence emissions in the markets affected by the output of all of the “coproducts” (all joint products other than the product of interest). This is the basis of what has been called the “displacement” or “system expansion” approach to estimating the emissions impacts of co-products[1]. However, most applications of this method assume that each unit of coproduct manufactured along with the biofuel causes one unit to *not* be manufactured elsewhere, “displacing” that other production, whereas in reality the degree of displacement is the dynamic result of market interactions, and generally will be less than one-for-one. As a result, LCAs that simply assume one-for-one displacement will overestimate the so-called “displacement credit.” Ideally, one would use an economic model to determine the effect of coproducts on their markets and the extent to which co-products displace other production. No LCA has such an economic model built into it, although LEM does have a single parameter that is meant to account for these market-mediated impacts of co-products (Delucchi, 2003).

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[1] In the context of biofuel LCAs, the displacement method was first clearly articulated and applied in DeLuchi (1991, 1993), and has been applied most comprehensively in Graboski (2002) and Kim and Dale (2002).

The same issue of joint production arises in petroleum refineries. A refinery turns crude oil into a broad slate of products, including numerous fuel products, petrochemicals, and asphalt. A change in demand for one product, such as gasoline, can affect the production and price of other products. One needs a model of refinery production costs and demand for all refinery products to estimate the equilibrium changes in output and consumption and finally emissions. No current generation LCA models incorporate this kind of analysis.

Land use change

Among the most important market-mediated effects of expanded biofuel production is land use change. An increase in the price of oil or a change in policy could result in expanded crop-based biofuel production, thereby displacing native ecosystems, existing agricultural production, or set-aside land. Changes in land use and vegetation can change physical parameters, such as albedo (reflectivity), evapotranspiration, and fluxes of sensible and latent heat, that directly affect the absorption and disposition of energy at the surface of the earth, and thereby affect local and regional temperatures (Marland, Pielke *et al*. 2003; Feddema, Oleson et al. 2005). Some of these effect are more important regionally than globally while global changes result in changes in carbon stocks (in the soil and biomass) as well as and N_20 and CH_4 emissions. The latter are not necessarily from land use "change", but result from fertilizer use and other forms of human managed land management (use). In addition, the replacement of native vegetation with biofuel feedstocks and the subsequent cultivation of the biomass can also significantly change the amount of carbon stored in biomass and soils, and thereby significantly change the amount of CO_2 removed from or emitted to the atmosphere compared with the assumed baseline.

By producing biofuels on a given plot of land, the demand for the product of the alternative land use is no longer met and over time new production would be required to meet at least some of that demand (prices will presumably increase, reducing consumption to some degree, although this effect is expected to be small because demand for food ultimately is very inelastic). This "displaced production" could lead to GHG emissions or other environmental impacts elsewhere, such as soil erosion or deforestation. Most current fuel life cycle models ignore (or treat too simply) changes in land use related biomass grown to make biofuels. An exception is LEM, which does have a detailed treatment of the climate impact of changes in carbon sequestration due to changes in land use (Delucchi, 2003, 2006).

Although there is wide consensus that these effects may be important, there is no well-accepted method for calculating the magnitude of these effects. Delucchi (2003, 2006) has proposed a method which estimates the present value of carbon emissions from land-use change over the life of a biofuels program, but this neither this nor any other method has been adopted by others.

Climate impacts of emissions

A critical area for further refinement of the models, and development of new analytic approaches is that of the impacts of other pollutants, as well as the choice of not only the Global Warming Potentials used for specific gasses, but also the analysis of non-constant carbon emission factors based on the dynamics of biofuel production, refining, and fuel end-use. Most fuel LCAs, for example, consider only three GHGs (CO_2, CH_4 and N_2O) and use the Global Warming Potentials (GWPs), developed by the IPCC, to convert non-CO_2 GHGs into CO_2 equivalents. The IPCC GWPs equate gases on the basis of their radiative forcing over a 100-year period, assuming an exponential decay of the gases (with multiple decay functions in the case of CO_2.)

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However, all air emissions, including CO, VOCs, NOx, SOx, NH_3, and aerosols, affect climate. LEM (Delucchi, 2003, 2003a, 2006) includes a treatment of the climate impact of a significant range of air emissions.

Moreover, the black-carbon (BC) component of aerosols has a very strong global warming effect (Menon, Hansen *et al.* 2002), and diesel engines are major sources of BC emissions. Very few LCAs include BC; with Delucchi (2003a, 2006) and Colella et al. (2005) recent exceptions. Stringent, health-based emissions standards for BC are now being implemented in the United States and Europe, but such standards do not exist (or are not enforced) in many other countries. This suggests that while BC emissions may become less important in some places in the future, they may be very significant elsewhere.

Not all LCA models treat emissions the same, even when they are included. For instance, GREET does not include N_2O emissions from atmospheric nitrogen fixed by soybeans, while LEM does, contributing to an almost order-of-magnitude greater estimate of GWI for soybean biodiesel (Delucchi, 2006).

Uncertain and variable data

In practice, *all* of the values entering into a life cycle GHG emissions calculation are uncertain. The emissions factors are generally more uncertain, as they usually represent temporally- or spatially-varying natural process, or are the result of an earlier LCA. Unfortunately, in many cases there are so few real emissions data that we may only know emissions to within a factor of two. For example, nitrous oxide emissions from vehicles might contribute as little as 3% or as much as 10% of simple, first-order fuel-cycle emissions. Field-monitoring studies are needed to validate not only current and future LCA models, but in the long-run, the GHG labels associated with fuels, such as will be needed in California and other locations that adopt Low Carbon Fuel Standards (Arons, *et al,* 2007; Brandt*, et al.*, 2007).

Usage rates for process inputs can also be highly uncertain, particularly in assessments of average impacts, such as the average GWI of ethanol produced in the US, which averages across a heterogeneous mix of facilities that use a variety of fuels at differing efficiencies. In many cases, input usage rates are based on unaudited, self-reported values from a self-selected subset of companies engaged in a given practice. Statistically meaningful probability distributions cannot be derived from these data (especially if our goal is to predict *future* fuel use, a point we will take up later). In other cases, input usage rates are inferred from related statistics. For example, on-farm energy use is not tracked in USDA statistical surveys of crop production; rather energy use is estimated from expenditures on fuels, based on assumptions about average fuel prices. Exactly how this process biases the resulting estimates is not clear.

An often poorly characterized source of emissions is the change in carbon sequestration in biomass and soils as a result of changes in land use related to the establishment of biomass used as a feedstock for biofuels. Generic data on the carbon contents of soils and plants are available, but there can be much variation about these generic means from site to site. The uncertainty inherent in carbon-storage factors related to land use can change life cycle CO_2-equivalent emissions by several percentage points.

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If the probability distributions for each of the usage rates and emissions factors and the correlations among them were well-defined, we could use standard statistical methods or Monte Carlo simulation to propagate uncertainty through the life cycle assessment model to understand the overall uncertainty of the result. However, in practice, many of the probability distributions are not known. Moreover, even if we had a complete and accurate sampling of current practice (say, with regards to fuel use at ethanol facilities), we could not readily use this information to predict future practice (in this case, fuel use at future ethanol facilities). In order to meaningfully apply probability distributions to the question of what will happen in the future, we have to build a model that has parameters (such as fuel costs) that themselves can be meaningfully characterized by objective probability distributions, and this does not now seem possible. What might be feasible, however, would be an investigation into the sensitivity of the LCA methods to uncertainty in various parameters in order to understand how to better understand the climate impacts of various transportation fuels. However, standard Monte Carlo techniques (and similar analyses) are unlikely to be useful at the current time.

Analytic Approaches to Modeling Land-use change

Land-use change has both local and global impacts. Further complicating the situation is that some land use changes associated with bioenergy crop production are direct and others are indirect. For example conversion from soybean to corn ethanol production in the US (direct change) will increase pressure to grow soybeans for food in the Amazon (indirect change) by an unknown amount. However, there is little data about indirect land use conversion effects, nor an agreed-upon approach to deal with them (Delucchi 2004, 2006; Tilman, Hill *et al*. 2006; Mathews, 2007).

Land use conversion effects associated with biofuel production are potentially significant, for both direct conversion for biofuel production and indirect effects mediated through commodity and land markets. Accurately including all of the indirect land uses changes associated with biofuel production would be very difficult. Between enormous data gaps, model uncertainty, deep uncertainties about future policies and prices, etcetera, the value of this exercise *as a prediction of a GWI that is meaningful in a regulatory context* may be questionable.

Furthermore, excluding global land use conversion effectively assigns a zero value to this effect, which we know to be a poor estimate. Instead, a policy-motivated LCFS could include a rough estimate of the portion of emissions from global land use conversion that is potentially attributable to crop-derived biofuels. While rough, such an estimate would send the correct signal about biofuels pathways that involve land use conversion.

As illustrated by the analysis in the LEM model, changes in carbon stocks related to deforestation and soil degradation are probably the most important factor associated with land use conversion affecting global climate (Delucchi, 2006). Estimates of the carbon emissions associated with global land use conversion exist in the literature on terrestrial carbon balances (Houghton 1999; Potter 1999; Schimel, House et al. 2001; Houghton 2003). Globally, the terrestrial ecosystem is a net sink for carbon (Schimel, House et al. 2001). However, land use conversion is estimated to have contributed between 0.6 and 2.5 gigatons of carbon annually (Gt C / yr) during the 1980's and between 0.8 and 2.4 gigatons of carbon annually (Gt C / yr) during the 1990's (Schimel, House et al. 2001). Because such estimates often rely on bottom-up aggregations of data on specific land use conversions, the particular contribution of crop-related land use conversions can be estimated. One such study attributes about 1.3 gigatons of carbon annually to crop-related land use conversion during the 1980's (Houghton 1999). Table 1 provides illustrative estimates that allow us to estimate emissions from land-use:

	Ethanol		
Feedstock (g CO_2e/kg)	*Corn*	*Grass*	*Wood*
Soil	96	48	45
Biomass	4	5	-31
Total	100	54	14
Fuel yield (L/Mg)	83	70	67
Energy content (MJ/L, HHV)	24	24	24
Emissions (g CO_2e/MJ)	51	32	9
Where we use 60 lbs/bushel for soy, 56 for corn, and 948.452 BTU/MJ			

Table 1: Illustrative land-use change calculations for various feedstocks.

The simple approach presented above yields values that push the GWI of most domestic crop-based biofuels above the GWI of gasoline. Although any attempt to calculate such values will be uncertain and open to debate, assigning zero emissions for global land use change clearly underestimates the effect. Hence, we believe a precautionary stance of assigning a non-zero value is appropriate because of the importance of providing signals and incentives to steer innovation and investment.

While inclusion of a simple land use conversion factor in biofuel GHG calculations used to label or regulate biofuels will yield more appropriate weightings between crop-based biofuels and other fuels, such regulation may not be the most appropriate mechanism to influence climatic change associated with land use conversion. Biofuel production is only a small portion of global land use (<5%), but as this percentage will increase it will have increasingly influence the entire land use system. Many of these changes will be indirect. A comprehensive regulatory scheme on land use change and climate change, operating independently of fuel-centered regulation, would minimize the negative climate effects associated with land use. However, no such regulation exists, and significant barriers may prevent implementing such regulations on a global scale.

If global efforts to curb deforestation and control climatic forcings associated with land use conversion are successful, the land use conversion charge outlined above will diminish. If, on the other hand, crop-based biofuels and a growing demand to feed a larger and more affluent global population increases pressure on forest and soil resources, then the land use conversion charge would increase. This charge should be updated periodically to reflect current conditions, though in practice, updates may be limited by data availability. The need to update these values as markets evolve creates some degree of unavoidable regulatory uncertainty, though the magnitude of the change for each update should stabilize after agreement has been reached on an appropriate methodology.

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Impacts of Land Conversion: An Initial framework

What happens to carbon emissions from soil and biomass due to land-use changes related to actions involving a particular biofuel or biofuel feedstock (e.g., corn ethanol)? A useful quantity that provides an answer to this question is grams of CO_2-equivalent emissions from land use change per BTU of biofuel produced. This quantity can be estimated as follows:

$$FLUCE_F = FEA_F \cdot \sum_L LUCE_{L \to L^*} \cdot LUC_{F:L \to L^*}$$

where:

$FLUCE_F$ = Land-use change emissions due to production of biofuel *F* (grams-CO_2-equivalent emissions per BTU of fuel *F* produced)
FEA_F = Areal energy production rate of biofuel *F* (BTUs of *F* produced per acre of land upon which the biomass feedstock for *F* is grown)
$LUCE_{L \to L^*}$ = Emissions per acre of land changed from type *L* to type *L** (grams CO_2-equivalent emissions per acre of land so changed)
$LUC_{F:L \to L^*}$ = fraction of an acre of land changed from type *L* to type *L** per acre of land upon which the biomass feedstock for *F* is grown
subscript L = land-use categories (e.g., tropical forest, temperate grassland)

The areal energy production rate, FEA, is reasonably well known. Data are available to estimate C emissions from soil and biomass due to land use change for different types of land uses (parameter LUCE), although there is a great deal of variability in the data pertaining to generic land-use types, on account of variability in climate, topography, soil characteristics, management techniques, and other factors that determine C sequestration and emissions. However, there is considerable difficulty in estimating how land uses change (parameter LUC), and it is on this parameter that we will focus.

Because it is likely that the set of values for LUC_F depend not only on the particular fuel *F* but also on the particular policy or action by which *F* is brought into production, it would be ideal to estimate LUC_F using a sophisticated model that includes detailed representations of agricultural economics, land uses, policies, trade, and other aspects. Models of this sort exist, and recently have been applied to precisely this question (see www.biofuelassessment.dtu.dk/). However, one reasonably may doubt that these models are yet sophisticated enough to provide reliable estimates of land-use changes related to biofuel production, given the complexity of global policies and markets for agriculture, energy, and land. If this is the case, one may propose simpler methods for estimating the relevant parameters in the equation given above, so long as the methods account for all of the relevant effects and emissions and are meant to represent reality, even if in a simplified way.

Thus, rather than attempt to actually model how specific land uses will change as a result of crop-specific policies, one may claim that because of the global interconnectedness of land and agricultural markets, it is likely that future crop-specific values do not deviate much from historical all-crop global averages. One can then use historical data to estimate global average

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values for LUCE and perhaps LUC, for all biomass (crops) and land-use types. For example, Houghton and Hackler (2001) provide estimates of emissions from land use change by type of change, and of historical changes in land use by land-use type. With these data, one can calculate a global, all-land-uses average per-acre emission rate from land-use change (parameter LUCE).

However, the calculation of a global all-crop, all-land-uses average value for LUC (acres of land changed per acre of land brought into production) is not necessarily straightforward. In the following we use an example to illustrate the interpretation and possible range of this parameter.

A farmer owns 11 acres of land. In the "no-biofuels" base case one acre is uncultivated grassland, and 10 acres are planted with corn at 100 bushels per acre, thus providing 1000 bushels to the market. In the biofuels scenario, the new demand for corn from a new biofuels plant causes the price of corn to rise, and the farmer contracts to provide an additional 100 bushels of corn per year to the new ethanol facility, while still supplying 1000 bushels to the non-biofuels market. Ignoring for now the effect of higher prices on corn demand, the farmer's range of choices in this biofuels scenario is defined by two bounds. First, he can simply grow the additional 100 bushels on what would have been his uncultivated acre of grassland (his 11th acre). In this case, the acre and 100 bushels of corn produced for the biofuel market has caused one acre of land-use change – the cultivation of the grassland – and LUC (acres of land use changed per acre of land brought into production to supply the biofuels market) therefore is 1.0.

However, at the other bound, the farmer can leave the grassland alone, and – specifically because of the *increase* in corn price – decide it is now worthwhile to spend the extra money needed to increase yield to 110 bushels per acre on the 10 acres (by applying more fertilizer or water, for instance) rather than cultivate the 11th acre (grassland) at 100 bushels/acre . In this scenario, he nominally uses 0.91 acres for the 100 bushels grown for the biofuel market, and the remaining 9.1 acres to supply the other 1000 bushels to the market. In this case, then, the 0.91 acres and 100 bushels of corn produced for biofuels have not resulted in *any* land use change (apart from the impacts of intensification per se), and LUC therefore is zero. Of course, the farmer may choose to do something in between.

Two points are important here. First, the yield increase in the second example must be due specifically to the increased demand for and price of corn, and not part of an ongoing increase in yields in the base case due to ongoing research and development and competitive pressure to increase outputs.

Second, our example so far does not account for the effect of price changes on demand. It may be, for example, that because of the higher price of corn, the farmer can sell only 990 bushels to the non-biofuels market, versus 1000 bushels in the no-biofuels base case. In this case, the farmer can use the now idled 0.1 of the 10 acres to produce 10 bushels of corn for the biofuels market, and then cultivate 0.9 of the 11th acre of grassland to produce the other 90 bushels of corn for the biofuels market. In this case, 1 acre of corn for ethanol brings into cultivation 0.9 acres of grassland, and LUC on account of this factor is 0.9/1.0 = 0.9.

As mentioned above, the inelasticity of demand for food suggests that the price-effect element of LUC (whereby higher prices due to biofuel demand suppress consumption in non-biofuels

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markets) is not likely to be significant., However, the yield intensification effect, whereby higher prices spur additional (beyond-baseline) increases in yield, is unknown. (For more discussion of the yield intensification effect, see Kløverpris *et al*. [2007]).

It is not clear if there is a simple way to estimate an all-crop, historical average value for LUC. The basic difficulty is that LUC depends ultimately on supply and demand functions, whereas what we observe are changes in consumption and production and changes in price. However, it may be possible to make serviceable estimates of LUC, based on inferences from observed consumption and price changes, without having to do general equilibrium modeling. More work in this area is needed.

Finally, we note two closely related, important methodological issues buried in the estimation of the parameter LUCE in the equation above. First, the period over which fuel production from an acre of land occurs is not the same as the period over which emissions from land-use change occurs. Second, whereas the annual fuel production from an acre reasonably can be assumed to be constant, annual emissions from land use change are not. One must make some transformations of one or the other stream in order to properly divide the emissions stream by the fuel production stream. Delucchi (2003) uses an annualization/present-value method to do this, but other methods may be possible

A comparison of recent biofuel analyses

The literature on biofuel LCAs contains conflicting studies, and in addition, published studies often employ differing units and system boundaries, making comparisons across studies difficult. As an example, we present in this section a comparison of six papers that evaluate the same biofuel production pathway, U.S. corn ethanol (Farrell *et al*. 2006). These studies all use current-generation LCA methods, and so ignore or treat poorly many important issues. Nonetheless, it is still useful to compare them to illustrate how such different results can come about.

The ERG Biofuel Analysis Meta-Model (EBAMM, available online at http://rael.berkeley.edu/ebamm) is a relatively simple, transparent tool for the comparison of biofuel production processes. EBAMM is available for free download and use. We used EBAMM to compare six published articles that illustrate the range of assumptions and data found for one biofuel, corn-based ethanol (Wang 2001; Graboski 2002; Patzek 2004; Shapouri, Duffield et al. 2004; Dias de Oliveira, Vaughan et al. 2005; Pimentel and Patzek 2005). Although the six articles have rather divergent results, the fundamental structure of their analyses is virtually identical. However, EBAMM is designed only to evaluate these six studies and thus ignores or treats poorly issues that these studies ignore or treat poorly, including especially land use change and end use technologies.

In addition, each study sheet calculates the coal, natural gas and petroleum energy consumed at each stage of production. This permits us to estimate the total primary energy required to produce ethanol. Similar calculations are performed in the study worksheets for net GHG emissions. These results are summarized in worksheets labeled “Petroleum” and “GHGs,” respectively.

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The *Cellulosic* case presented here is a preliminary estimate of a rapidly evolving technology designed to highlight the dramatic reductions in GHG emissions anticipated; it should not be taken as a definitive representation of the potential of this technology. In addition, other biofuel technologies are in active development, which are not addressed at all

While the six studies compared here are very similar, each uses slightly different system boundaries. To make the results commensurate, we adjusted all the studies so that they conformed to a consistent system boundary. Two parameters, caloric intake of farm workers and farm worker transportation, were deemed outside the system boundaries and were thus set to zero in the adjusted versions. (These factors are very small and the qualitative results would not change if they were included.) Six parameters were added if not reported: embodied energy in farm machinery, inputs packaging, embodied energy in capital equipment, process water, effluent restoration, and coproduct credit. Typical coproducts include distillers dried grains with solubles, corn gluten feed, and corn oil, which add value to ethanol production equivalent to \$0.10 - \$0.40 per liter of corn ethanol.

Two of the six studies stand out from the others because they report negative net energy values, and imply relatively high GHG emissions and petroleum inputs (Patzek 2004; Pimentel and Patzek 2005). The close evaluation required to replicate the net energy results showed that these two studies also stand apart from the others by assuming that ethanol coproducts (materials inevitably generated when ethanol is made, such as dried distillers grains with solubles, corn gluten feed, and corn oil) should not be credited with any of the input energy as a rough approximation of the impacts of soil erosion, and by including some input data that is old and unrepresentative of current processes or so poorly documented that its quality cannot be evaluated. (See Tables S2 and S3 in the Supplemental Online Material for Farrell, *et al.*, 2006, found at http://rael.berkeley.edu/ebamm).

Sensitivity analyses with EBAMM and elsewhere show that net energy calculations are most sensitive to assumptions about coproduct allocation (Kim and Dale 2002). Coproducts of ethanol have positive economic value and displace competing products that require energy to make. Therefore, increases in corn ethanol production to meet the requirements of EPACT 2005 will lead to more coproducts that displace whole corn and soybean meal in animal feed, and the energy thereby saved partly offsets the energy required for ethanol production (Delucchi 2004; Food and Agricultural Policy Research Institute 2005).

Producing one MJ of ethanol—for all pathways considered—requires far less petroleum than is required to produce one MJ of gasoline (Figure 4). However, the GHG metric illustrates that the environmental performance of ethanol varies greatly depending on production processes. However, single-factor metrics may be poor guides for policy. Using the petroleum intensity metric, the *Ethanol Today* case would be slightly preferred over the *Cellulosic* case (a petroleum input ratio of 0.06 compared to 0.08), however the *Ethanol Today* case results in greater GHG emissions than does *Cellulosic* (77 compared to 11), though both pathways have lower GHG emissions than gasoline. Indirect land use conversion tends to increase this disparity because it is more likely apply to corn-based ethanol than to cellulosic ethanol (especially if wastes or residues are used as the cellulosic feedstock).

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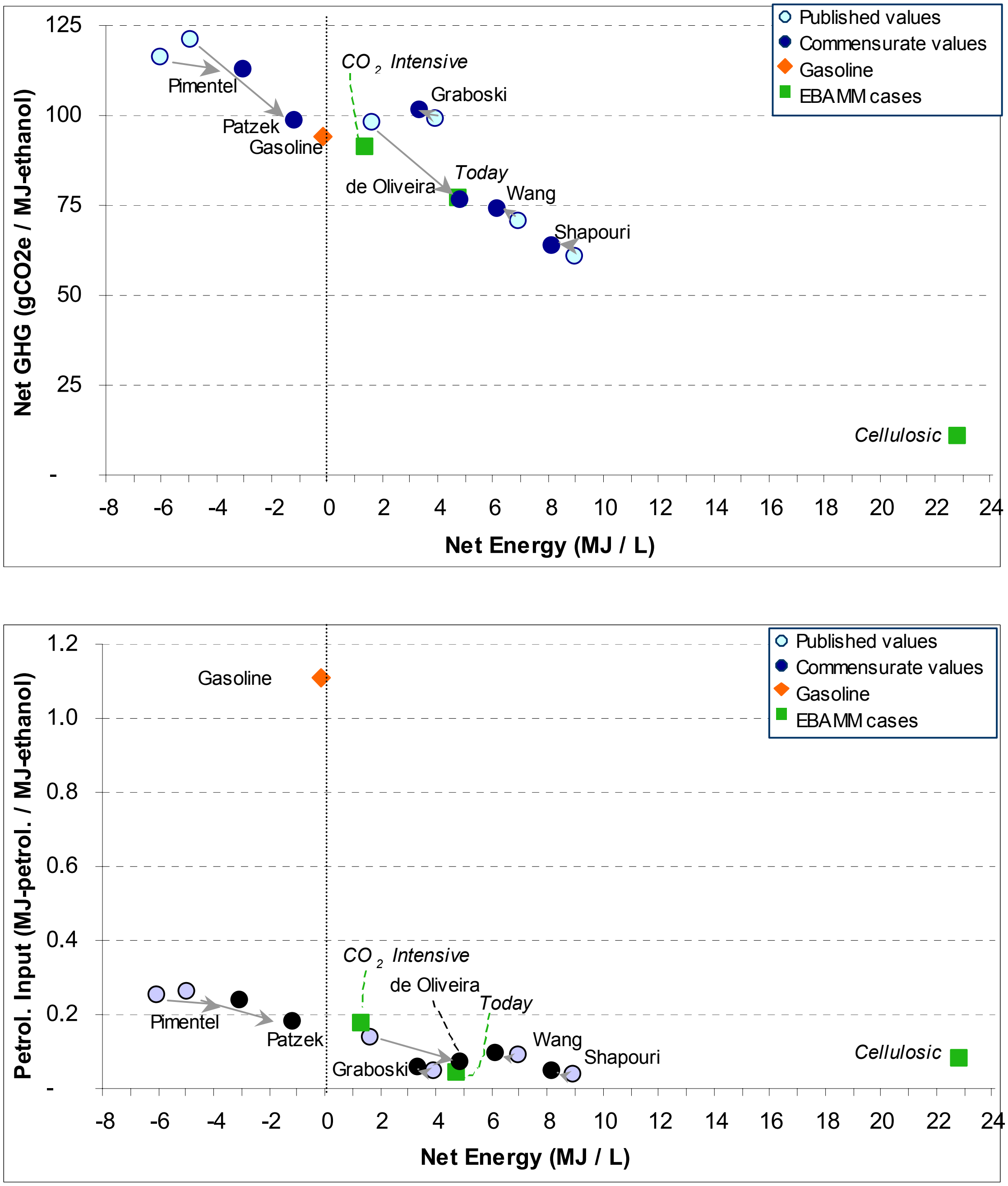

Figure 4 (top) Net energy and net greenhouse gases for gasoline, six studies, and three cases. (bottom) Net energy and petroleum inputs for the same. In these figures, hollow triangles are reported data that include incommensurate assumptions, while solid triangles are adjusted values that use identical system boundaries. Conventional Gasoline is shown as orange circles and *EBAMM Scenarios* are shown as green squares. Indirect GHG emissions due to land use change is not included in these calculations, and could increase corn-based ethanol emissions significantly. This figure first appeared in (Farrell, *et al*. 2006).

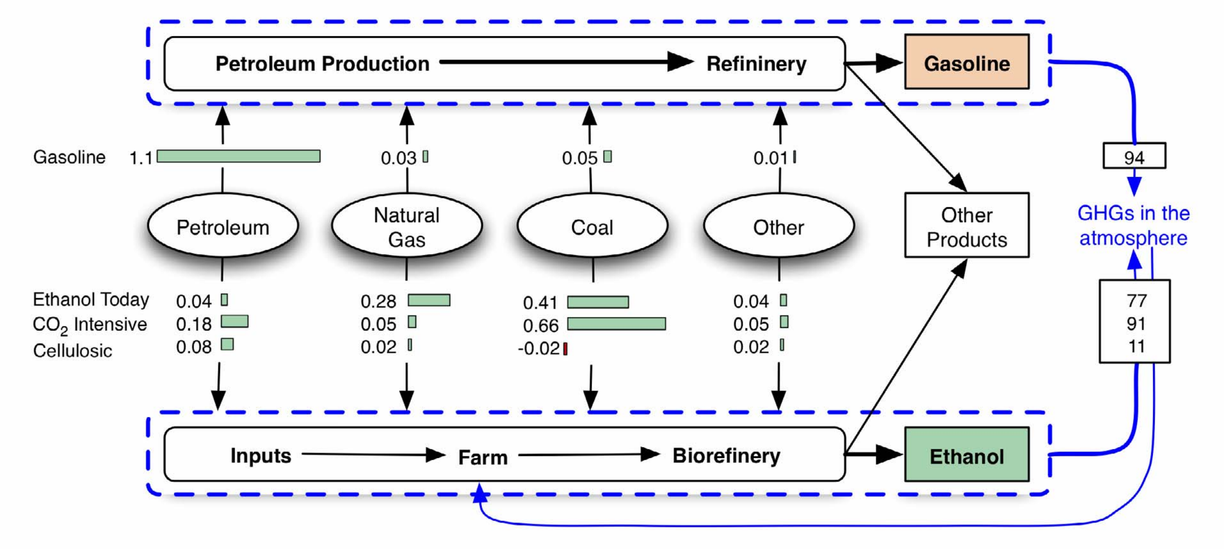

Figure 5. Alternative metrics for evaluating ethanol based on the intensity of primary energy inputs (MJ) per MJ of fuel and of net greenhouse gas emissions (kgCO_2-equivalent) per MJ of fuel. For gasoline both petroleum feedstock and petroleum energy inputs are included. "Other" includes nuclear and hydro electricity generation. Relative to gasoline, ethanol produced today is much less petroleum intensive, but much more natural gas and coal intensive. Production of ethanol from lignite-fired biorefineries located far from where the corn is grown results in ethanol with a high coal intensity and a moderate petroleum intensity. Cellulosic ethanol is expected to have an extremely low intensity for all fossil fuels and a slightly negative coal intensity due to electricity sales that would displace coal. Indirect GHG emissions due to land use change are not included in these calculations, and could increase corn-based ethanol emissions significantly. This figure first appeared in (Farrell, *et al.* 2006).

GHG emissions due to indirect land use change are assigned to those biofuels produced from feedstocks grown on arable land that competes for food production. These preliminary and primarily illustrative values are shown in Table 1 above. By considering indirect land use in this way, ethanol produced from corn in a coal-fired dry mill has *higher* GHG emissions than gasoline. The "Low Input Biofuel" under consideration is E85, containing ethanol produced from a mixed prairie grass system, described by Tilman *et al.* (2006). The large negative GHG emissions in this case are based on the assumption that grasses that require very little input (e.g. fertilizer) are grown on degraded lands that are unsuitable for food production.

In this case carbon is stored by the grasses in their roots and in the soil. This carbon can be sequestered in this way for long periods of time, but is vulnerable to release should that land ever be turned over to conventional agriculture. This technology is not yet proven and is somewhat controversial. It also has relatively low yield per unit area, because the inputs are so low, however, the amount of degraded land available for such cultivation may be large. However, it should be noted that the benefits of this scenario derive from the presumption that the degraded land would otherwise have remained degraded. This is not necessarily a reasonable assumption, because it is always possible to actively restore degraded land to some other "natural" state that stores even more carbon than does a managed mixed prairie grass system[2]. In any event, research

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[2] In this vein, Marland and Schlamadinger (1995) have pointed out that "biofuels systems require a large resource commitment (land) and a greenhouse-gas assessment should consider the opportunity for using the land in other ways to minimize net greenhouse-gas emissions" (p. 1136).

into the technical and commercial feasibility of this approach, and its potential application in ways that would not place additional pressure for the conversion of natural ecosystems to biofuel crops is a very important area of research.

Note that carbon storage in roots and soil may also be feasible for other biomass production systems, including possibly switchgrass (*Panicum virgatum*) and miscanthus (*Miscanthus x giganteus*). These species may be more productive then collections of prairie grasses, and therefore may be more profitable than the system proposed by Tilman *et ai*, 2006 while still having very good GHG profiles. There are currently significant biotechnology research and development efforts underway to improve such species, potentially setting up a competition between semi-natural biofuel production and production through the large-scale cultivation of genetically modified monocrops. Understanding how to evaluate the relative costs and benefits of such systems is also important research task.

Note also that the only differences between the two corn-based ethanol cases depicted are in biomass processing; all the other stages are identical in the two cases. A better understanding of the range of potential GHG emissions associated with feedstock production, and perhaps reductions in these emissions, might show even greater variation.

Biofuel Market Development

Growth of global demand for biofuels (Figure 1) has so far resulted in large increases in the scale of production of ethanol and FAME biodiesel. One indicator of the magnitude of this increase in demand for biofuels is its impact on prices in large, established agricultural commodity markets. Consider as an example, changes in U.S. corn markets during the development of the ethanol industry (Figure 6). Since 1980, average corn prices in the United States have exceeded three dollars per bushel only five times, including last year and the forecast for this year. Note that in the three prior cases—in 1980, 1983, and 1995—high prices for corn, accompanied substantial declines in production. In contrast, in 2006 and 2007 (forecast) high production is expected to accompany high prices. Indeed, both average corn prices and total corn production for 2007 are forecasted to set new records. The additional demand for corn by ethanol producers is raising corn prices because the incremental corn production involves higher production costs due to increased competition with other uses for land, expansion to less productive land, and the need to employ more expensive production methods. Because corn is a globally traded commodity and the corn market affects other agricultural commodities such as sugar and animal feed, high prices for corn will tend to increase the prices for other crops. Over the last several years, the increased demand for corn by ethanol producers has risen faster than total U.S. corn production, contributing to a decline in corn exports and increase in the cost of animal feed.

Demand for ethanol feedstock has greatly exceeded expectations. The United States Department of Agriculture's Economic Research Service reports that corn acreage for 2007 increased by 11% to 87 million acres. Only two years ago the *high* forecast for 2008 acreage was less than this total. Many recent forecasts for U.S. ethanol include a *doubling* of production over the next 4 – 6 years. The U. S Department of Agriculture central case forecast is typical:

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> Corn used to produce ethanol in the United States continues strong expansion through 2009/10, with slower growth in subsequent years. By the end of the projections, ethanol production exceeds 12 billion gallons per year, using more than 4.3 billion bushels of corn. The projected large increase in ethanol production reflects the Energy Policy Act of 2005, the elimination of use of MTBE as a gasoline additive, ongoing ethanol plant construction, and economic incentives provided by continued high oil prices (U.S. Department of Agriculture 2007).

These forecasts run significantly in excess of the mandated levels of 7.5 billion gallons by 2012, as required by the Renewable Fuel Program of the U. S. Energy Policy Act of 2005. This anticipated overshooting of the target indicates that some combination of expectations about future oil prices and the fuel additive requirements is the primary driver of growth.

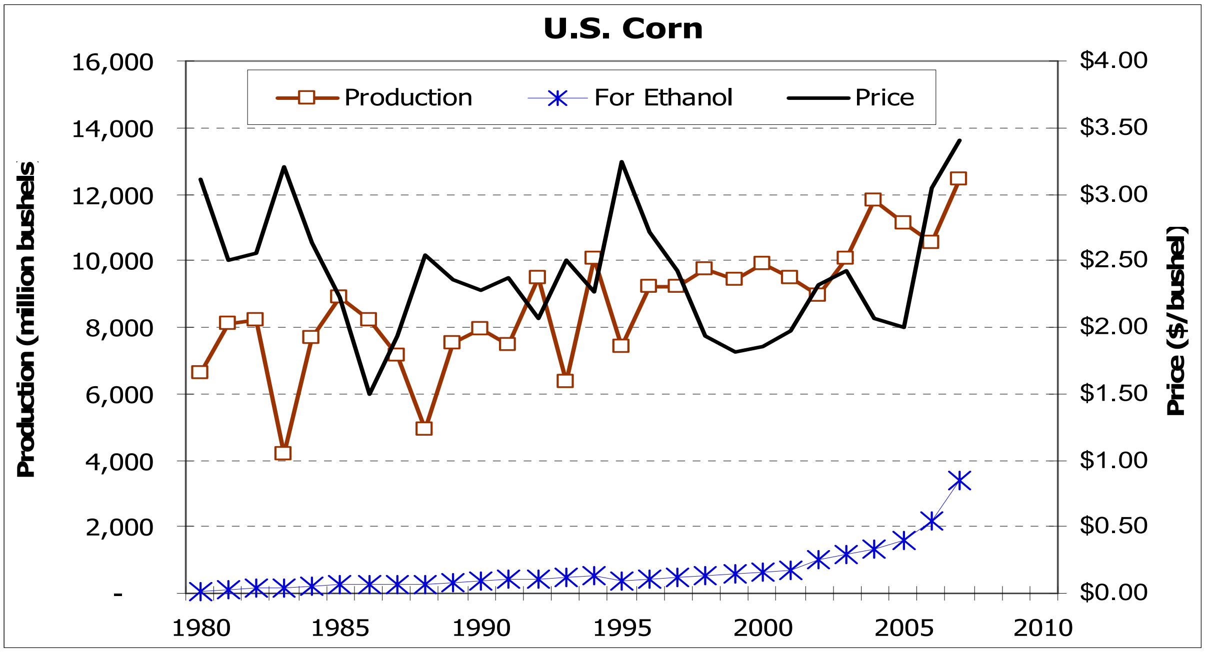

Figure 6: U.S. corn production (left scale) and prices (right scale)
Source: U.S. Department of Agriculture,
http://www.ers.usda.gov/data/feedgrains/FeedGrainsQueriable.aspx

This rapid growth in output using current ethanol production technologies is unlikely to continue over the longer term due to the rapid development of biofuels with superior properties, and very significant concerns about the cost and environmental implications of current biofuel feedstock production (Biofuelwatch 2007). It is not clear how biofuel markets will develop after 2010, but a framework for assessing the potential biofuel output, greenhouse gas impacts, land-use changes, and socioeconomic impacts, will be required to assess the costs and benefits of the wide range of biofuel strategies that will be proposed and considered in the coming years.

In the last few years, a range of funding mechanisms has emerged to advance science and develop technologies that would significantly impact the biofuel feedstocks and pathways that are available to the market. These new investments are notable on several dimensions. First, they involve substantial funds that dwarf earlier programs--they involve hundreds of millions of dollars. Second, each investor has committed to a long-term program—time horizons for

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funding is in the 5 to 10 year range. Third, both the private and public sectors are committing these funds. And crucially, in terms of who is performing the research, the parties involved in each initiative have established linkages among multiple universities, government laboratories, as well as both mature and entrepreneurial firms at the outset. The involvement of this diverse set of actors is promising because it addresses obstacles to the transfer of technical knowledge in the innovation process--from early-stage research to commercial products.

The Returns on Research and Development: Examples of Past Efforts

The potential for initiatives like these, and the others that are, and will spring up globally, to make important, promising, and likely also challenging innovations in the entire pathway from laboratory-based crop design, to biofuel agronomy, to feedstock handling, to fuel production and infrastructure design is significant. Figure 7 documents the research and development spending history, and the patenting levels, in five energy areas over the past forty years (Kammen and Nemet, 2005). In four of the five areas funding and patenting are highly correlated, and in the fifth, nuclear fission a correlation exists, but the effective moratorium on reactor construction in the United States has likely led to some distortions technological evolution of the field.

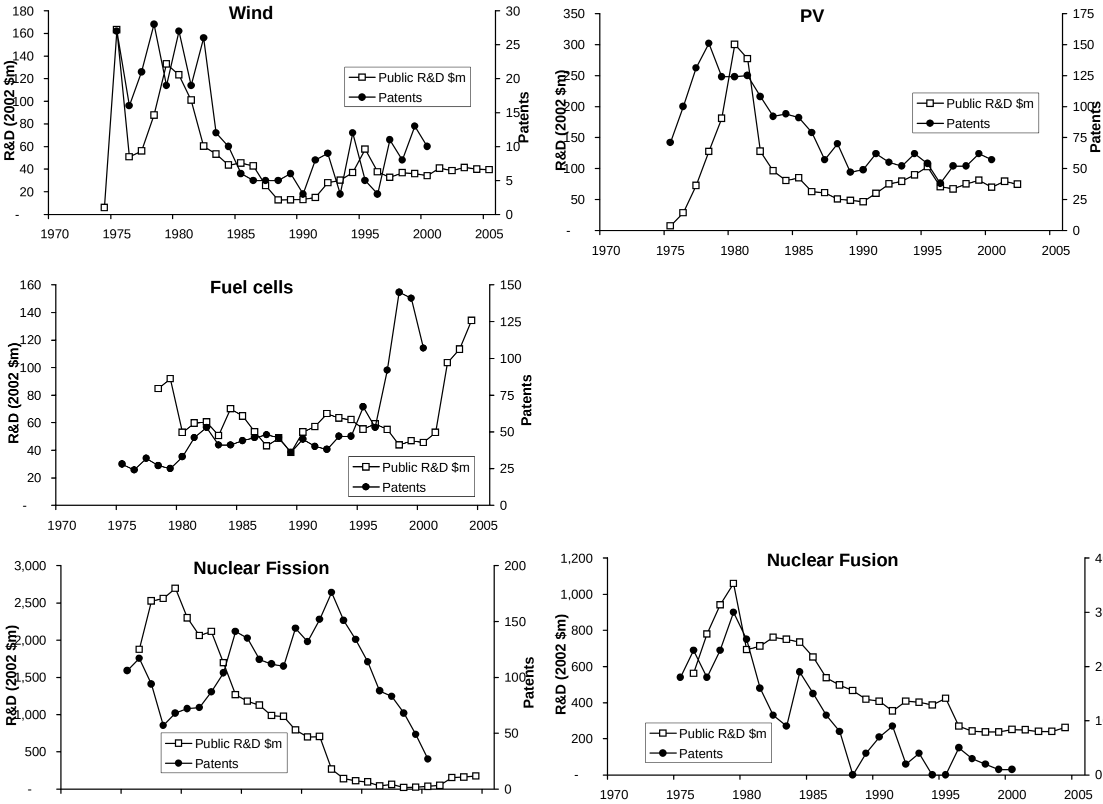

Figure 7. Patenting provides a measure of the outcomes of the innovation process. We use records of successful U.S. patent applications as a proxy for the intensity of innovative activity and find strong correlations between public R&D and patenting across a variety of energy

technologies. Since the early 1980s, all three indicators—public sector R&D, private sector R&D, and patenting—exhibit consistently negative trends. The data include only U.S. patents issued to U.S. inventors. Patents are dated by their year of application to remove the effects of the lag between application and approval (Source: Margolis and Kammen, 1999; Kammen and Nemet, 2005; Nemet and Kammen, 2007).

The recent dramatic increase in interest in the biofuel sector – including dramatic increases in production of ethanol (Farrell, *et al.,* 2006) – as well as significant private sector interest in a diverse range of biofuels, provides a call for analysis similar to Figure 7 in the biofuel area. Previous studies (e.g. Evenson and Waggoner, 1979) have shown a strong relationship between effort – both funding and market opportunity, and innovation in the biofuel sector. Unlike our previous work in energy, where few public sector funding avenues exist (e.g. primarily the U. S. Department of Energy), multiple funding sources may exist for biofuel/bioproducts research, and we consider this note to be a first pass, not suitable yet for policy use as has been made of our prior work (Margolis and Kammen, 1999; Kammen and Nemet, 2005). Our goal is to begin the assessment here, and to examine next possible other funding sources, patenting/implementation uses of the sources of support in order to draw a clearer picture of what we might expect from dramatic increases in biofuel development and deployment.

As an example of a private-sector funded initiative, the University of California Berkeley, along with partners the Lawrence Berkeley National Laboratory and the University of Illinois at Urbana Champaign have formed the Energy Biosciences Institute (http://www.ebiweb.org/). EBI is supported by a 10 year, $500 million commitment from BP, and is envisioned to focus on a wide range of biofuel analysis and production pathways, with the fast growing C4 plant, *Miscanthus Giganticus* (elephant grass) seen as a promising initial crop for investigation.

In the public sector, the U.S. Department of Energy has committed $375m over five years to establish three "Bioenergy Research Centers." Based at the Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, and the University of Wisconsin, the centers will engage in research on cellulosic ethanol and other biofuels as part of the federal goal to reduce U.S. gasoline consumption by 20 percent within 10 years.

Among this group, the Joint Bioenergy Institute (JBEI) at Lawrence Berkeley Lab (http://jbei.lbl.gov) will focus its scientific effort in three key areas: feedstock production, deconstruction, and fuels synthesis. JBEI will employ an opportunistic "start-up company" approach, partnering with industry, to develop new science and technologies that address the most challenging steps in industrial bioenergy processing. Crosscutting technologies in computational tools, systems and synthetic biology tools, and advanced imaging will be applied in a multi-pronged approach for biomass-to-biofuel solutions in addition to discovery-driven benefits for biohydrogen research, solar-to-fuel initiatives, and broader DOE programs.

The venture capital industry, which typically expects a financial return after three to seven years, has recently begun to invest heavily in entrepreneurial biofuels firms. In aggregate, the industry invested over $800m in biofuels companies in 2006, after investing only $20m in 2005, and less than a million dollars in 2004 (Makower and Pernick, et al., 2007).

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Investments like these have great potential to generate important innovations in the entire pathway from laboratory-based crop design, to biofuel agronomy, to feedstock handling, to fuel production and infrastructure design.

While these large, long-term, and collaborative investments are encouraging, they still only represent an input to the innovation process. Ultimately, the benefits of improved biofuels to the agricultural sector, environmental quality, and petroleum import reduction will depend on the effectiveness of the outputs of these efforts. Previous studies (e.g. Evenson and Waggoner, 1979) have shown a strong relationship between effort – both funding and market opportunity-- and innovation outputs in the biofuel sector. Similarly, other work has found a strong link between R&D investment and innovation, as measured by patenting activity (Margolis and Kammen 1999; Kammen and Nemet 2005). With the diverse variety of new funding sources that has emerged in only the past 12 months and the array of devices and processes involved in the production of biofuels that is described above, measurement is less straightforward. Still, on a first look, the relationship between investment and output in biofuels appears well correlated over the past three decades. We compared patenting activity in the field of bio-energy[3] to federal R&D investment (Figure 7). While there is year-to-year volatility in patenting activity, the general trend in patenting activity appears to be well correlated with that of federal R&D spending. This analysis represents a preliminary assessment. Subsequently, we will examine the wider spectrum of funding sources which has only emerged recently, as well as the characteristics of how these sources are used and how the outcomes are patented to draw a clearer picture of what we might expect from dramatic increases in biofuel development and deployment.

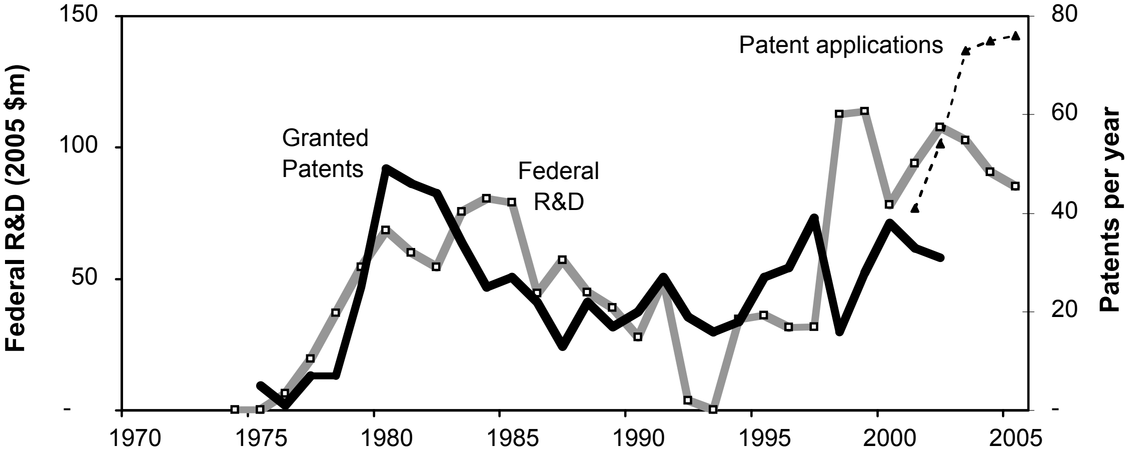

Figure 7. A preliminary assessment of U.S. Bio-energy patents and federal R&D. Black solid line shows the number of patents that were ultimately granted by the year they were applied for (right axis). Dashed black line shows applications for patents in recent years (right axis). Gray line shows federal R&D funding (left axis). While the number of patent search categories is significantly larger in the agricultural sector than in energy, we focused the patent searches on combinations of feedstock and fuel search strings. Using the U.S. Patent and Trademark Office Bibliographic database as our data source (www.uspto.gov) we searched the abstracts of granted

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[3] Our definition of "bio-energy" includes the use of biological material to produce electricity and transportation fuels. The search terms used in the patents search reflect this definition.

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patents to capture the keywords: "biofuels," "biodiesel," "biomass gasification", "biomass energy", "ethanol for energy production", "cellulosic ethanol" (Nemet 2007; Nemet and Kammen, 2007; Nemet and Kammen, 2007a).

Already a number of new crops, including switchgrass, palm oil, cedar, willow, and other fast growing tree species, as well as municipal solid waste and algae, are being touted and explored as potential biofuel feedstocks. In addition, a wide range of output fuels, are envisioned, in addition to the commonly cited examples of biodiesel and ethanol gasoline blends. In this rapidly evolving biofuel research and deployment field, a set of evaluation tools for both the potential return on research investment, as well as means to assess the energy benefits and greenhouse gas impacts of emerging fuels are critically needed.

Conclusions

The first, most obvious, and most critical aspect of the biofuel economy today is that it is in dramatic flux and evolution. The existence and character of the global biofuel industry is strongly the result of policy interventionsmotivated and justified largely as a means of agricultural support, but with increasingconcern about environmental effects. These forces are not necessarily in alignment. If this situation persists, we are likely to see increasing tensions between policies, and problems developing in the valuation of biofuels versus other forms of energy sources, as well as over biofuels as they relate to land-use, land spared for nature, and the lives of the poor.

To address this clash of policies, views, economic valuations and environmental goals, a clear set of evaluation methodologies, and high-quality, open access to data will be required. A vital first step is the design, public access, and dialog over the models and tools used to assess the impacts, costs, and benefits of biofuels. Methodologically, several approaches now exist to examine the energy content and the greenhoue gas impact or biofuels. These approaches are already becoming policy tools through low-carbon fuel standards, and renewable fuel obligations (quotas). A vital next step is to evolve the models to not only reflect carbon, but ecological and cultural sustainability for rich and poor countries and communities alike.

Acknowledgments

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