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LIFECYCLE ANALYSES OF BIOFUELS

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OVERVIEW

This manuscript on lifecycle analysis (LCA) of biofuels for transportation has three major parts:

I. An analysis of greenhouse-gas emissions from biofuels, estimated using the Lifecycle Emissions Model (LEM).

II. A review of recent LCAs of biofuels.

III. A comprehensive conceptual framework for doing LCAs of biofuels.

I. ANALYSIS OF GREENHOUSE-GAS EMISSIONS FROM BIOFUELS

The LEM analysis of lifecycle GHG emissions from biofuels is organized as follows:

- A short overview of the Lifecycle Emissions Model (LEM).
- Brief, general descriptions of the basic technical processes as they are represented in the LEM.
- Estimates of CO_2-equivalent GHG emissions from biofuels at three different levels of aggregation: at the level of the farm (e.g., land-use and cultivation emissions per hectare); for the whole upstream fuel lifecycle (also known as "well-to-tank"), and for the entire fuel and vehicle-use lifecycle (in grams/mile; sometimes called "well-to-wheel," but in this case also including the vehicle lifecycle). These will be produced for selected biofuel and other pathways in the LEM.
- The ratio of process energy inputs to fuel outputs, for selected fuelcycles.
- Emissions of individual pollutants by stage, for selected fuelcycles.
- A brief, general discussion of the differences in LEM results by country and year.
- A brief discussion of the differences between using the CO_2-equivalency factors (CEFs) in the LEM and the "Global Warming Potentials" (GWPs) of the Intergovernmental Panel on Climate Change (IPCC).

The analysis of lifecycle GHG emissions from biofuels was performed using the Lifecycle Emissions Model (LEM). The LEM has been developed over a number of years by Dr. Delucchi and colleagues. Complete documentation of the LEM is available on Dr. Delucchi's web page.

For economy of presentation, the main results of the lifecycle analysis (LCA) of biofuels and vehicles are reported for the U. S. for the year 2010, using LEM CEFs. As mentioned above, we do present and discuss some results for different years and different countries, for the IPCC GWPs as opposed to the LEM CEFs.

Overview of the LEM

The LEM uses lifecycle analysis (LCA) to estimate energy use, criteria air-pollutant emissions, and CO_2-equivalent greenhouse-gas emissions from a wide range of energy and material lifecycles. It includes lifecycles for passenger transport modes, freight transport modes, electricity, materials, heating and cooling, and more. For transport modes, it represents the lifecycle of fuels, vehicles, materials, and infrastructure. It calculates energy use and lifecycle emissions of all regulated air pollutants plus so-called greenhouse gases. It includes input data for up to 30 countries, for the years 1970 to 2050, and is fully specified for the U. S.

For motor vehicles, the LEM calculates lifecycle emissions for a variety of combinations of end-use fuel (e.g., methanol), fuel feedstocks (e.g., coal), and vehicle types (e.g., fuel-cell vehicle). For light-duty vehicles, the fuel and feedstock combinations included in the LEM are shown in Table 0.

TABLE 0. FUEL, FEEDSTOCK, AND VEHICLE COMBINATIONS IN THE LEM

Fuel --> ↓ Feedstock	*Gasoline*	*Diesel*	*Methanol*	*Ethanol*	*Methane (CNG, LNG)*	*Propane (LPG)*	*Hydrogen (CH2) (LH2)*	*Electric*
Petroleum	**ICEV, FCV**	**ICEV**				**ICEV**		**BPEV**
Coal	**ICEV**	**ICEV**	**ICEV, FCV**				**FCV**	**BPEV**
Natural gas		**ICEV**	**ICEV, FCV**		**ICEV**	**ICEV**	**ICEV, FCV**	**BPEV**
Wood or grass			**ICEV, FCV**	**ICEV, FCV**	**ICEV**		**FCV**	**BPEV**
Soybeans		**ICEV**						
Corn				**ICEV**				
Solar power							**ICEV, FCV**	**BPEV**
Nuclear power							**ICEV, FCV**	**BPEV**

Notes: ICEV = internal-combustion-engine vehicle; FCV = fuel-cell vehicle; BPEV = battery-powered electric vehicle.

The LEM has similar but fewer combinations for heavy-duty vehicles (HDVs), mini-cars, and motor scooters.

As indicated in Table 0, the LEM includes the following biofuel lifecycles:

- corn to ethanol
- soybeans to biodiesel
- switchgrass to ethanol
- wood to ethanol
- wood to methanol
- wood to synthetic natural gas
- switchgrass to hydrogen

Fuel, material, vehicle, and infrastructure lifecycles in the LEM

The LEM estimates the use of energy, and emissions of greenhouse gases and urban air pollutants, for the complete lifecycle of fuels, materials, vehicles, and infrastructure for the transportation modes listed above. For fuels and electricity, these lifecycles are constructed as follows:

- **end use**: the use of a finished fuel product, such as gasoline, electricity, or heating oil, by consumers.
- **dispensing of fuels**: pumping of liquid fuels, and compression or liquefaction of gaseous transportation fuels.
- **fuel distribution and storage**: the transport of a finished fuel product to end users and the operation of bulk-service facilities. For example, the shipment of gasoline by truck to a service station.
- **fuel production**: the transformation of a primary resource, such as crude oil or coal, to a finished fuel product or energy carrier, such as gasoline or electricity.
- **feedstock transport**: the transport of a primary resource to a fuel production facility. For example, the transport of crude oil from the wellhead to a petroleum refinery. A complete country-by-country accounting of imports of crude oil and petroleum products by country is included in the LEM.
- **feedstock production**: the production of a primary resource, such as crude oil, coal, or biomass. Based on primary survey data at energy-mining and recovery operations, or survey or estimated data for agricultural operations.

For materials, the lifecycle is:

- crude-ore **recovery** and finished-material **manufacture**: the recovery and transport of crude ores used to make finished materials and the manufacture of finished materials from raw materials.

- the **transport** of finished materials to end users.

For vehicles, the lifecycle is:

- **materials use**: see the "lifecycle of materials".

- **vehicle assembly**: assembly and transport of vehicles, trains, etc.

- **operation and maintenance**: energy use and emissions associated with motor-vehicle service stations and parts shops, transit stations, and so on;

- **secondary fuel cycle** for transport modes: building, servicing, and providing administrative support for transport and distribution modes such as large crude-carrying tankers or unit coal trains.

Lifecycle of infrastructure:

- **energy use and materials production**: the manufacture and transport of raw and finished materials used in the construction of highways, railways, etc., as well as energy use and emissions associated with the construction of the transportation infrastructure.

Sources of emissions in LEM lifecycles

The LEM characterizes greenhouse gases and criteria pollutants from a variety of emission sources:

- Combustion of fuels that provide process energy (for example, the burning of bunker fuel in the boiler of a super-tanker, or the combustion of refinery gas in a petroleum refinery);
- Evaporation or leakage of energy feedstocks and finished fuels (for example, from the evaporation of hydrocarbons from gasoline storage terminals);
- Venting, leaking, or flaring of gas mixtures that contain greenhouse gases (for example, the venting of coal bed gas from coal mines);
- Fugitive dust emissions (for example, emissions of re-entrained road dust from vehicles driving on paved roads);
- Chemical transformations that are not associated with burning process fuels (for example, the curing of cement, which produces CO_2, or the denitrification of nitrogenous fertilizers, which produces N_2O);
- Changes in the carbon content of soils or biomass, or emissions of non-CO_2 greenhouse from soils, due to changes in land use.

Pollutant tracked in the LEM

The LEM estimates emissions of the following pollutants:

- carbon dioxide (CO_2)
- methane (CH_4)
- nitrous oxide (N_2O)
- carbon monoxide (CO)
- nitrogen oxides (NO_x)
- nonmethane organic compounds (NMOCs), weighted by their ozone-forming potential
- sulfur dioxide (SO_2)
- total particulate matter (PM)
- particulate matter less than 10 microns diameter (PM_{10}), from combustion
- particulate matter less than 10 microns diameter (PM_{10}), from dust
- hydrogen (H_2)
- chlorofluorocarbons (CFC-12)
- hydrofluorocarbons (HFC-134a)
- the CO_2-equivalent of all of the pollutants above

Ozone (O_3) is not included in this list because it is not emitted directly from any source in a fuel cycle, but rather is formed as a result of a complex series of chemical reactions involving CO, NO_x, and NMOCs.

The LEM estimates emissions of each pollutant individually, and also converts all of the pollutant into CO_2-equivalent greenhouse-gas emissions. To calculate total CO_2-equivalent emissions, the model uses CO_2-equivalency factors (CEFs) that convert mass emissions of all of the non-CO_2 gases into the mass amount of CO_2 with an equivalent effect on global climate. These CEFs are conceptually related, broadly, to the "Global Warming Potentials" (GWPs) used by the Intergovernmental Panel on Climate Change

(IPCC). The CEFs are discussed in Appendix D of the LEM documentation (available on Delucchi's faculty web page, www.its.ucdavis.edu/people/faculty/delucchi/).

Biofuel conversion processes in the LEM

All biofuel pathways have the same basic steps: cultivation and harvest of biomass, transport of biomass to the biomass-to-fuel conversion facility, conversion of the biomass to a finished biofuel, distribution of the finished biofuel to stations, dispensing of the biofuel, and use of the fuel in vehicles. These steps are illustrated in Figure 1, which shows the corn-to-ethanol pathway, and Figure 2, which shows the the soybean-to-biodiesel pathway.

The biomass-to-fuel conversion step is different for each biofuel pathway:

Corn to ethanol (dry mill process) (www.ethanolresearch.com/about/). To produce ethanol from corn, the starch portion of the grain is exposed and mixed with water to form a mash. The mash is heated and enzymes are added to convert the starch into glucose. Next, yeast is added to ferment the glucose to ethanol, water, and carbon dioxide. This fermentation product, called "beer," is boiled in a distillation column to separate the water, resulting in ethanol.

A variety of highly valued feed co-products, including gluten meal, gluten feed and dried distillers grains, are produced from the remaining protein, minerals, vitamins and fiber and are sold as high-value feed for livestock.

Soybeans to biodiesel (Appendix A of the LEM documentation).The production of biodiesel from raw vegetable material requires several steps. First, raw oil must be extracted from the rapeseed or soybean feedstock. Once obtained, the raw oil is filtered, collected in a tank, and then periodically pumped into an agitating transesterfication reactor. In the reactor, the oil is heated to 60-70 °C, and gradually brought into contact with a mixture of chemicals. After transesterfication, the product is transferred to the finishing reactor, where various chemicals and processes are used to neutralize or remove fats, soaps, and solids. The result is a liquid fuel similar to diesel fuel derived from crude oil.

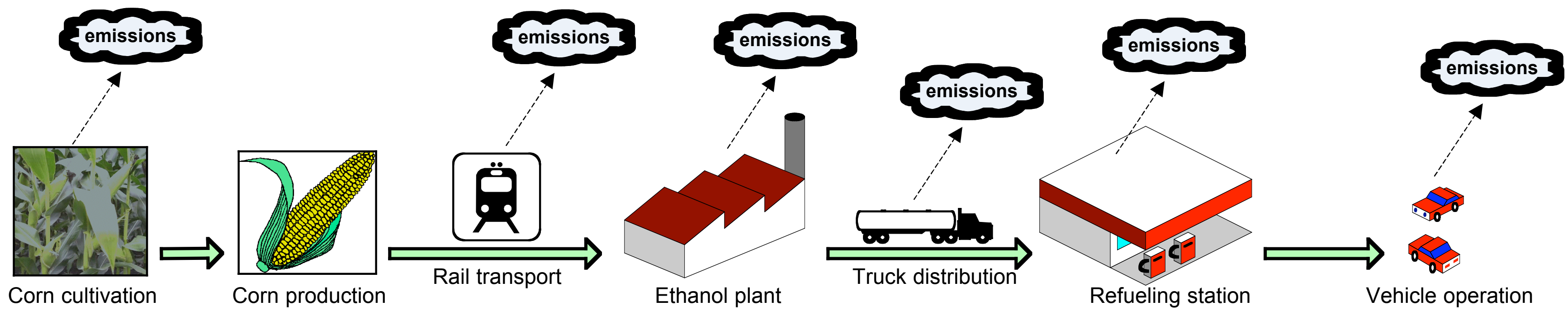

FIGURE 1. DIAGRAM OF CORN-TO-ETHANOL PATHWAY

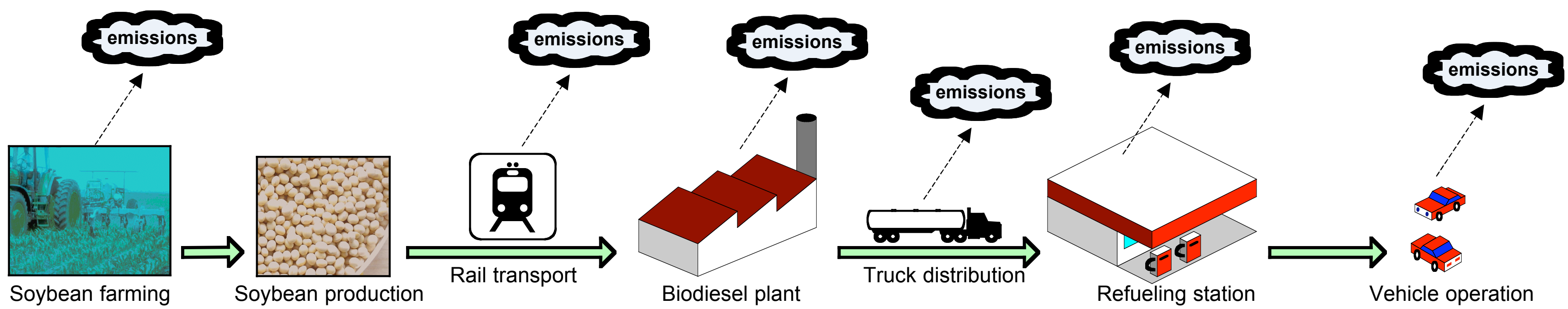

FIGURE 2. DIAGRAM OF SOY TO BIODIESEL PATHWAY

Switchgrass or wood to ethanol. (www.harvestcleanenergy.org/enews/enews_0505/enews_0505_Cellulosic_Ethanol.htm). To produce ethanol from cellulosic biomass, such as switch grass or wood, the fermentable sugars must be extracted from the feedstock (just as is done with ethanol from corn). This is more difficult with cellulosic feedstocks than with grain feedstocks because the sugars in cellulose and hemicellulose are locked in complex carbohydrates called polysaccharides.

The fermentable sugars are extracted with either acid hydrolysis or enzymatic hydrolysis. With acid hydrolysis, acid breaks down the complex carbohydrates into simple sugars. With enzymatic hydrolysis, the feedstock first is pre-treated to make it more accessible to hydrolysis. After pretreatment, enzymes are added to convert the cellulosic biomass to fermentable sugars. In either case, in the final step the sugars are fermented to produce ethanol and carbon dioxide.

A key difference between grain-to-ethanol processes and cellulose-to-ethanol processes is that the former use fossil fuels to produce heat during the conversion process, whereas the latter use the unfermentable parts of the original biomass feedstock (such as lignin) for process heat.

Wood or grass to methanol, synthetic natural gas, or hydrogen (www.ieiglobal.org/ESDVol1No5/biomasstransport.pdf). The production of liquid methanol or gaseous fuels (hydrogen or synthetic natural gas) from biomass involves several steps. The feedstock is first gasified (by heating it to above 700 ^oC in the presence of little or no oxygen) into a synthesis gas (syngas) consisting of CO, H_2, CO_2, $H_2O(g)$, and in some cases CH_4 and small amounts of other hydrocarbons. There are a number of different gasification technologies, with slightly different operating conditions, energy requirements, and costs; see the reference cited at the start of this paragraph for a good discussion.

The syngas exiting the gasifier is cooled and then quenched with a water spray to remove particulates and other contaminants. Additional cleanup of sulfur compounds (especially important with coal) is needed to prevent poisoning of downstream catalysts. The syngas then undergoes a series of chemical reactions that lead to the desired end-product (methanol, hydrogen, or synthetic natural gas). (The equipment downstream of the gasifier for conversion to methanol is the same as that used to make methanol or hydrogen from natural gas feedstock.)

In these processes, the biomass feedstock supplies the energy for process heat. Some external electricity may be purchased.

Three levels of lifecycle emission estimates for biofuels in the LEM

In this section we present LEM estimates of CO_2-equivalent GHG emissions from biofuels at three different levels of aggregation: at the level of the farm (e.g., land-use and cultivation emissions per hectare); for the whole upstream fuel lifecycle (also known as "well-to-tank"), and for the entire fuel and vehicle-use lifecycle (in grams/mile; sometimes called "well-to-wheel," but in this case also including the vehicle lifecycle).

<u>Emissions from land use and cultivation</u>. The LEM produces a comprehensive accounting of GHG emissions related to the cultivation of biomass feedstocks. Table 1 shows the contribution of each land-use and cultivation emission category to total CO_2-equivalent emissions per bushel (corn, soybeans) or dry ton (grass, wood).

TABLE 1. BREAKDOWN OF CO_2-EQUIVALENT EMISSIONS FROM CULTIVATION AND LAND-USE (U. S. YEAR 2010) (G/BU [CORN, SOY] OR G/DRY-TON [WOOD, GRASS])

Cultivation or land-use emission category	Corn	Grass crop	Wood SRIC	Soy
N_2O related to input of synthetic fertilizer N (on-site and off-site)	4,262	47,506	9,209	330
N_2O related to input animal manure N (on-site and off-site)	137	0	0	0
N_2O related to input of biologically fixed atmospheric N (on-site and off-site)	0	0	0	11,311
N_2O related to crop residue N (on-site and off-site)	1,250	5,668	1,216	4,452
Emissions related to incremental use of synthetic N fertilizer induced by incremental use of manure-N fertilizer	55	0	0	0
Credit for emissions foregone from displaced alternative uses of animal manure	108	0	0	0
Credit for synthetic N displaced by leftover N made available to co-rotated crops	0	0	0	(2,143)
Emissions from use of synthetic N that substitutes in generic ag. for leftover N "stolen" away by recipient crop E in question	515	0	0	0
N_2O from cultivation, independent of N input (on-site only)	58	1,840	1,704	201
NO_X related to all N inputs (except deposition and leftover) (includes NH3 emissions) (on-site and off-site)	(3,090)	(31,719)	(6,628)	(12,838)
CH_4 soil emissions related to all N inputs (except deposition and leftover) (on-site and off-site) and CH4 emissions independent of fertilizer use	65	2,965	1,030	236
CO_2 sequestered in soil due to all N inputs (except deposition and leftover) (on-site only). Includes discounted re-emission of CO_2 at end of life.	(4)	(360)	(14)	(333)
CO_2 sequestered in soil and biomass due to fertilization of off-site ecosystems by all N (except deposition and leftover) leached from field of application. Includes discounted re-emission of CO_2 at end of life.	(1,589)	(11,646)	(1,974)	(2,853)
CO_2 sequestered in soil, due to cultivation (on-site only). Includes discounting of C lifetimes.	4,595	33,241	116,878	19,447
CO_2 sequestered in biomass, due to cultivation (on-site only). Includes discounting of C lifetimes.	258	14,456	(179,827)	2,922
Non- CO_2 GHGs from burning of agricultural residues	106	443	670	121
TOTAL	6,725	62,393	(57,737)	20,855

Source: LEM calculations (see LEM model documentation for details).

We emphasize that Table 1 shows emissions related directly to cultivation and land use *only*; it does not include *any* emissions from the use of energy on the farm or to make fertilizers, for example.

The largest sources of cultivation and land-use emissions are: changes in soil C and biomass C due to cultivation; changes in soil and biomass C due to fertilization of off-site ecosystems by all N input; N_2O emissions from fertilizer use, crop-residues, and biological fixation; and NO_X emissions from all N inputs. Other sources of N_2O, emissions of CH_4, emissions from burning of agricultural residues (assuming that only very small amounts of residue are burned), and various credits are relatively minor.

There are two reasons why changes in the carbon content of soil and biomass are large: 1) in general, soils and plants store a great deal of carbon, and 2) cultivated lands generally have much less carbon than do undisturbed native lands. (The important exception to this is the carbon content of biomass in wood plantations, which as indicated above is estimated to be larger than the carbon content of the biomass on the displaced land uses.) I have assumed that ultimately the alternative to any energy-crop system is the undisturbed, native vegetation. This, of course, is one of the key sets of assumptions of the analysis. Other assumptions are possible, and could result in more or less of an impact on soil and biomass carbon than I have estimated here. For example, it is possible to assume that the alternative to an energy crop system are the maximum carbon-storing land uses. In the case, CO_2 emissions attributable to cultivation would be higher than estimated here.

CO_2-equivalent emissions related to NO_X and NH_3 are large because there are substantial emissions of these compounds in biofuel lifecycles, and because the CEF for NO_X, while very uncertain, may not be trivial. This highlights the importance of doing a complete N accounting as part of a biofuel LCA, and of developing a comprehensive CEF for NO_X.

CO_2-equivalent N_2O emissions are large because of the large CEF for N_2O and the careful, comprehensive accounting in the LEM of all sources of N_2O. In this respect, the very large N_2O emissions from N inputs to soy farming merit further discussion. Further analysis (reported in the LEM documentation) indicates that our model estimates are consistent with the range of measurements reported in the literature. Still, the large impact of this source N_2O on lifecycle CO_2-equivalent emissions from soy farming, and the uncertainty in actual measurements of emissions suggests that we need more research in this area.

As we will see in the next section, emissions related to cultivation and land use are a substantial percentage – typically around ±30% -- of total "upstream" emissions from biofuel lifecycles. Thus, our analysis of emissions related to cultivation and land use clearly illustrates that these may be significant sources of emissions in biofuel lifecycles, and hence that it is important to perform a comprehensive accounting of N flows and the impacts of cultivation in biofuel lifecycles.

Emissions from the entire upstream lifecycle of biofuels. Table 2 shows the contribution of emissions from different stages to total CO_2-equivalent emissions from the entire lifecycle of biofuels excluding end use (and excluding the vehicle lifecycle). The gasoline lifecycle is shown for comparison.

TABLE 2. BREAKDOWN OF "UPSTREAM" FUELCYCLE CO_2-EQUIVALENT EMISSIONS, BY STAGE (U. S. YEAR 2010)

Fuel ------>	**RFG**	**Methanol**	**Ethanol**	**Ethanol**	**SCG**	**Biodiesel**	**CH2**
Feedstock ------>	*oil*	*wood*	*corn*	*grass*	*wood*	*soy*	*wood*
Fuel dispensing	2%	3%	1%	1%	22%	0%	64%
Fuel distribution and storage	5%	11%	2%	5%	5%	1%	2%
Fuel production	61%	57%	50%	39%	33%	29%	11%
Feedstock transmission	10%	14%	3%	8%	14%	2%	10%
Feedstock recovery	20%	32%	14%	21%	32%	26%	23%
Land-use changes, cultivation	0%	-32%	33%	25%	-33%	81%	-23%
Fertilizer manufacture	0%	16%	18%	23%	16%	24%	11%
Gas leaks and flares	2%	0%	0%	0%	10%	0%	3%
CO_2, H_2S removed from NG	0%	0%	0%	0%	0%	0%	0%
Emissions displaced	0%	0%	-22%	-23%	0%	-64%	0%
Total (g-CO_2-eq/10^6 BTU)	*20,778*	*18,960*	*89,668*	*34,494*	*14,309*	*132,242*	*25,174*

Notes: RFG = reformulated gasoline; SCG = synthetic compressed gas; CH2 = compressed hydrogen.

The largest sources of emissions in the upstream lifecycle of biofuels are land-use changes and cultivation, fuel production, feedstock recovery, fertilizer manufacture, and "displaced" emissions, which sometimes are referred to unwisely as "coproduct credits." Emissions related to feedstock transmission, fuel distribution, and liquid-fuel dispending are relatively small, but emissions related to dispensing gaseous fuels can be substantial, an account of the energy required to compress gaseous fuels.

The large contribution of land-use and cultivation emissions is notable because they are treated cursorily or not at all in most other biofuel LCAs. (Note that for the wood-based fuelcycles, land-use changes and cultivation result in "negative" emissions, or net C sequestration. As indicated in Table 1, this is because the C content of the biomass in wood plantations is estimated to greatly exceed C content of the biomass on the displaced land uses.)

Table 3 shows much of the same information as Table 2, but also includes end-use fuelcycle emissions and vehicle-lifecycle emissions, and shows results for biofuel light-duty vehicles (LDVs), biofuel heavy-duty vehicles (HDVs) and fuel-cell LDVs .

In contrast to many other studies, this analysis finds that corn ethanol does not not have significantly lower GHG emissions than does gasoline, and that cellulosic ethanol has only about 50% lower emissions (Table 3 Part A). The main reasons for this difference are that we estimate relatively high emissions from feedstock and fertilizer production, from land use and cultivation, and from emissions of non-CO_2 GHGs from vehicles.

Table 3 Part C presents results for biofuel HDVs. This table includes biodiesel from soybeans, a biofuel not included in Table 3 Part A. Perhaps surprisingly, the LEM estimates that soy biodiesel has *higher* lifecycle GHG emissions than does conventional diesel. This is because of the large (and usually overlooked) N_2O emissions from soyfields, and the large (and again usually overlooked) emissions of carbon due to changes in land use (Table 2).

TABLE 3. TOTAL FUELCYCLE CO_2-EQUIVALENT EMISSIONS, BY STAGE (U. S. YEAR 2010)

Part a. Biofuel LDVs

General fuel --> *Fuel specification -->*	**Ethanol** *E90 (corn)*	**Ethanol** *E90 (grass)*	**Methanol** *M85 (wood)*	**Natural gas** *CNG (wood)*
Vehicle operation: fuel	343.8	343.8	331.7	269.5
Fuel dispensing	2.5	2.0	2.4	14.6
Fuel storage and distribution	8.3	8.4	8.8	3.4
Fuel production	198.1	65.0	55.0	22.4
Feedstock transport	14.3	12.8	12.3	9.6
Feedstock and fertilizer production	122.6	66.5	37.7	32.6
Land use changes and cultivation	124.7	36.8	(22.3)	(22.2)
CH_4 and CO_2 gas leaks and flares	0.2	0.2	0.4	7.0
C in end-use fuel from CO_2 in air	(282.9)	(282.9)	(232.9)	(251.8)
Emissions displaced by coproducts	(81.1)	(33.3)	0.0	0.0
Sub total (fuelcycle)	***450.6***	***219.3***	***193.1***	***85.2***
% changes (fuelcycle)	***-2.4%***	***-52.5%***	***-58.2%***	***-81.6%***
Vehicle assembly and transport	19.2	19.2	19.2	20.4
Materials in vehicles	55.9	55.9	56.0	59.2
Road dust, tire wear, brake wear PM	0.2	0.2	0.2	0.2
Lube oil production and use	4.5	4.5	4.5	2.3
Refrigerant (HFC-134a)	9.2	9.2	9.2	9.2
Grand total	***539.8***	***308.5***	***282.3***	***176.5***
% changes (grand total)	***-2.0%***	***-44.0%***	***-48.7%***	***-67.9%***

Note: percentage changes are relative to conventional gasoline LDVs.

Part b. Fuel-cell LDVs

General fuel -->	Gas	MeOH	MeOH	EtOH	H_2	H_2	H_2	H_2
Fuel spec (feedstock) -->	*RFG (crude)*	*M100 (NG)*	*M100 (wood)*	*E100 (grass)*	*CH2 (water)*	*CH2 (NG)*	*CH2 (wood)*	*CH2 (coal)*
Vehicle operation: fuel	203.8	180.9	180.9	195.5	0.2	2.8	3.3	3.3
Fuel dispensing	1.2	2.0	1.5	1.2	33.0	33.0	33.0	33.0
Fuel storage and distribution	2.8	7.1	5.9	5.3	1.4	0.0	1.0	1.2
Fuel production	36.4	48.6	30.7	39.0	7.7	145.3	5.5	61.8
Feedstock transport	6.3	3.2	7.5	7.8	0.0	7.7	5.2	2.4
Feedstock & fertilizer production	11.9	9.9	25.3	43.9	0.0	6.2	17.7	3.5
Land use changes and cultivation	0.0	0.0	(17.3)	25.3	0.0	0.0	(12.1)	0.1
CH_4 and CO_2 gas leaks and flares	1.1	8.5	0.0	0.0	1.7	13.6	1.6	10.2
C in end-use fuel from CO_2 in air	0.0	0.0	(180.4)	(194.8)	0.0	0.0	(3.0)	0.0
Emissions displaced by coproducts	0.0	0.0	0.0	(22.9)	0.0	0.0	0.0	0.0
Sub total (fuelcycle)	***263.4***	***260.4***	***54.2***	***100.2***	***44.0***	***208.6***	***52.2***	***115.6***
% changes (fuelcycle)	***-43.0%***	***-43.6%***	***-88.3%***	***-78.3%***	***-90.5%***	***-54.8%***	***-88.7%***	***-75.0%***
Vehicle assembly and transport	18.2	18.3	18.3	18.2	18.0	18.0	18.0	18.0
Materials in vehicles	60.6	61.1	61.1	60.9	62.9	62.9	62.9	62.9
Road dust, tire wear, brake wear PM	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Lube oil production and use	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refrigerant (HFC-134a)	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2
Grand total	***351.6***	***349.2***	***143.0***	***188.8***	***134.4***	***298.9***	***142.5***	***205.9***
% changes (grand total)	***-36.2%***	***-36.6%***	***-74.0%***	***-65.7%***	***-75.6%***	***-45.7%***	***-74.1%***	***-62.6%***

Note: percentage changes are relative to conventional gasoline LDVs.

Part c. Biofuel HDVs

General fuel -->	**Diesel**	**Biodiesel**	**Ethanol**	**Ethanol**	**Methanol**
Fuel specification -->	*LSD*	*SD100 (soy)*	*E100 (corn)*	*E100 grass*	*M100 (wood)*
Vehicle operation: fuel	3,523.3	3,651.4	3,447.1	3,447.1	3,280.6
Vehicle operation: refrigerant	0.0	0.0	0.0	0.0	0.0
Fuel dispensing	14.3	18.0	23.4	17.8	23.1
Fuel storage and distribution	33.5	61.2	79.2	80.2	90.5
Fuel production	267.0	1,821.5	1,968.7	587.5	474.3
Feedstock transport	104.0	116.2	133.6	117.3	115.5
Feedstock and fertilizer production	197.3	3,108.0	1,243.9	662.1	391.6
Land use changes and cultivation	0.0	5,004.7	1,294.6	382.0	(266.7)
CH_4 and CO_2 gas leaks and flares	17.6	0.0	0.0	0.0	0.0
C in end-use fuel from CO_2 in air	0.0	(3,477.3)	(2,937.8)	(2,937.8)	(2,788.3)
Emissions displaced by coproducts	0.0	(3,942.9)	(841.7)	(346.0)	0.0
Sub total (fuelcycle)	***4,157.0***	***6,361.0***	***4,411.0***	***2,010.2***	***1,320.7***
% changes (fuelcycle)	***-0.0%***	***53.0%***	***6.1%***	***-51.7%***	***-68.2%***
Vehicle assembly and transport	65.2	65.9	65.5	65.5	65.7
Materials in vehicles	131.1	132.4	131.6	131.6	132.0
Road dust, tire wear, brake wear PM	1.4	1.4	1.4	1.4	1.4
Lube oil production and use	39.2	48.9	39.2	39.2	39.2
Refrigerant (HFC-134a)	8.7	8.7	8.7	8.7	8.7
Grand total	***4,402.5***	***6,618.3***	***4,657.4***	***2,256.6***	***1,567.7***
% changes (grand total)	***-0.1%***	***50.2%***	***5.7%***	***-48.8%***	***-64.4%***

Note: percentage changes are relative to conventional diesel HDVs.

Table 3 Part B presents results for biofuel and fossil fuel-cell LDVs. Methanol from wood, hydrogen from wood, and hydrogen from wood offer the largest reductions in lifecycle GHG emissions compared with conventional gasoline ICEVs: about 90% on a fuelcycle basis, and 75% on a fuel+vehicle lifecycle basis.

Other results: energy use and pollutant emissions

In this section we present LEM estimates of energy use and individual pollutant emission in selected biofuel lifecycles.

Table 4 shows BTUs of process energy consumed per BTU of net fuel output to end users, for selected biofuel lifecycles. Although for some fuelcycles there is a decent correlation between energy use and greenhouse-gas emissions, for biofuels there is not because on the one hand a substantial part of lifecycle biofuel emissions is essentially unrelated to energy use (e.g., emissions from land-use changes and cultivation), but on the other much of the input energy is from the biomass itself which sequesters approximately as much CO_2 as it emits.

TABLE 4. ENERGY INTENSITY OF BIOFUEL LIFECYCLES (BTU-IN /BTU-END USE) (U. S. YEAR 2010)

Fuel -->	**Methanol**	**SCG**	**Ethanol**	**Ethanol**	**Biodiesel**	**CH2**
Feedstock ---->	*wood*	*wood*	*wood/grass*	*corn*	*soy*	*wood*
Fuel dispensing	0.0037	0.0221	0.0028	0.0028	0.0021	0.0855
Fuel distribution, storage	0.0176	0.0411	0.0150	0.0135	0.0100	0.0399
Fuel production	1.8395	1.3945	2.1231	0.5108	0.4057	1.7085
Feedstock transmission	0.0190	0.0147	0.0194	0.0285	0.0185	0.0182
Feedstock recovery	0.0331	0.0255	0.0402	0.0849	0.2032	0.0317
Ag. chemical manufacture	0.0170	0.0131	0.0789	0.1891	0.4138	0.0163

The Table 5 series shows emissions of individual pollutants (without the CO_2-equivalency weights) by stage of the *upstream* lifecycle of biofuels. The largest sources of CO_2 and CH_4 emissions are fuel production, land-use changes and cultivation, fertilizer manufacture and feedstock recovery. The largest source of N_2O emissions, of course, is land-use changes and cultivation. The largest sources of CO emissions are feedstock recovery (due to tractors), fuel production, and land-use changes and cultivation. The largest sources of NO_2 and NMOC emissions are land-use changes and cultivation, fuel production, and feedstock recovery. The largest sources of SO_2 and PM-black carbon emissions are feedstock recovery and fuel production.

TABLE 5. INDIVIDUAL POLLUTANT EMISSIONS, BY STAGE (NO CEFS) (U. S. YEAR 2010) (G-POLLUTANT/10^6-BTU-FUEL)

Part A. CO_2

Fuel ------>	**RFG**	**Methanol**	**Ethanol**	**Ethanol**	**SCG**	**Biodiesel**	**CH2**
Feedstock ------>	*oil*	*wood*	*corn*	*grass*	*wood*	*soy*	*wood*
Fuel dispensing	395	543	560	413	3,267	414	17,169
Fuel distribution and storage	967	2,045	1,734	1,777	575	1,279	441
Fuel production	12,491	9,688	44,294	12,252	4,233	38,242	1,921
Feedstock transmission	1,278	2,452	3,295	2,502	1,890	2,342	2,348
Feedstock recovery	4,217	4,556	10,400	5,530	3,511	26,300	4,362
Land-use changes, cultivation	0	(6,939)	14,496	4,943	(5,348)	95,954	(6,644)
Fertilizer manufacture	0	2,656	13,049	6,461	2,047	31,433	2,543
Gas leaks and flares	249	0	0	0	(711)	0	12
CO_2, H_2S removed from NG	0	0	0	0	0	0	0
Emissions displaced	0	0	(12,852)	(8,371)	0	(84,278)	0
Total	*19,597*	*15,001*	*74,976*	*25,507*	*9,465*	*111,684*	*22,152*

Part B. CH_4

Fuel ------> *Feedstock ------>*	RFG *oil*	Methanol *wood*	Ethanol *corn*	Ethanol *grass*	SCG *wood*	Biodiesel *soy*	CH2 *wood*
Fuel dispensing	0.7	1.1	1.1	0.9	6.7	0.8	33.0
Fuel distribution and storage	2.0	5.2	4.3	4.5	13.8	3.2	5.0
Fuel production	47.0	33.8	146.4	54.5	18.2	146.9	6.4
Feedstock transmission	70.1	6.1	7.8	6.3	4.7	5.8	5.9
Feedstock recovery	24.7	12.1	33.6	14.7	9.3	80.4	11.6
Land-use changes, cultivation	0.0	6.9	29.3	23.3	5.3	41.5	6.6
Fertilizer manufacture	0.0	4.8	52.3	23.0	3.7	95.5	4.6
Gas leaks and flares	76.7	0.0	0.0	0.0	63.7	0.0	1.1
CO_2, H_2S removed from NG	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Emissions displaced	0.0	0.0	(38.6)	(17.3)	0.0	0.0	0.0
Total	*221.2*	*70.1*	*236.3*	*109.8*	*125.7*	*374.1*	*74.2*

Part C. N_2O

Fuel ------> *Feedstock ------>*	RFG *oil*	Methanol *wood*	Ethanol *corn*	Ethanol *grass*	SCG *wood*	Biodiesel *soy*	CH2 *wood*
Fuel dispensing	0.0	0.0	0.0	0.0	0.1	0.0	0.5
Fuel distribution and storage	0.1	0.1	0.1	0.1	0.3	0.1	0.1
Fuel production	0.3	1.3	1.1	1.8	0.9	1.6	1.0
Feedstock transmission	0.0	0.3	0.2	0.3	0.2	0.2	0.2
Feedstock recovery	0.1	0.2	0.5	0.3	0.2	1.6	0.2
Land-use changes, cultivation	0.0	5.1	113.2	30.8	3.9	269.6	4.9
Fertilizer manufacture	0.0	0.8	8.3	4.5	0.6	1.6	0.7
Gas leaks and flares	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CO_2, H_2S removed from NG	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Emissions displaced	0.0	0.0	(39.1)	(0.4)	0.0	0.0	0.0
Total	*0.6*	*7.8*	*84.3*	*37.5*	*6.2*	*274.7*	*7.7*

Part D. CO

Fuel ------>	**RFG**	**Methanol**	**Ethanol**	**Ethanol**	**SCG**	**Biodiesel**	**CH2**
Feedstock ------>	*oil*	*wood*	*corn*	*grass*	*wood*	*soy*	*wood*
Fuel dispensing	0.2	0.3	0.2	0.2	1.9	0.2	7.3
Fuel distribution and storage	4.5	11.2	10.4	10.8	28.1	7.7	1.3
Fuel production	13.0	61.5	33.3	70.8	37.5	43.6	56.4
Feedstock transmission	4.6	22.4	16.9	22.8	17.3	19.9	21.4
Feedstock recovery	35.4	59.3	216.2	76.4	45.7	757.8	56.8
Land-use changes, cultivation	0.0	26.9	187.1	25.8	20.7	153.8	25.7
Fertilizer manufacture	0.0	2.0	15.4	5.5	1.5	34.6	1.9
Gas leaks and flares	1.5	0.0	0.0	0.0	340.7	0.0	7.4
CO_2, H_2S removed from NG	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Emissions displaced	0.0	0.0	(137.7)	(5.0)	0.0	0.0	0.0
Total	*59.2*	*183.5*	*341.7*	*207.4*	*493.5*	*1,017.6*	*178.3*

Part E. NO_2

Fuel ------>	**RFG**	**Methanol**	**Ethanol**	**Ethanol**	**SCG**	**Biodiesel**	**CH2**
Feedstock ------>	*oil*	*wood*	*corn*	*grass*	*wood*	*soy*	*wood*
Fuel dispensing	0.7	1.1	1.0	0.8	6.7	0.8	31.7
Fuel distribution and storage	5.0	13.2	8.4	10.4	21.0	6.2	5.9
Fuel production	25.4	67.6	100.6	70.7	32.6	109.3	27.3
Feedstock transmission	11.0	11.6	28.6	11.8	8.9	12.5	11.1
Feedstock recovery	37.1	34.1	68.0	41.1	26.3	188.4	32.7
Land-use changes, cultivation	0.0	45.6	950.8	289.8	35.1	3,789.2	43.6
Fertilizer manufacture	0.0	4.9	32.8	11.4	3.7	80.5	4.7
Gas leaks and flares	1.1	0.0	0.0	0.0	0.0	0.0	0.0
CO_2, H_2S removed from NG	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Emissions displaced	0.0	0.0	(343.1)	(17.2)	0.0	0.0	0.0
Total	*80.3*	*178.2*	*847.1*	*418.8*	*134.4*	*4,186.8*	*157.0*

Part F. NMOCs

Fuel ------> *Feedstock ------>*	**RFG** *oil*	**Methanol** *wood*	**Ethanol** *corn*	**Ethanol** *grass*	**SCG** *wood*	**Biodiesel** *soy*	**CH2** *wood*
Fuel dispensing	8.2	2.5	3.4	3.4	0.4	0.0	0.8
Fuel distribution and storage	23.2	7.8	10.1	10.2	0.5	0.6	0.1
Fuel production	2.6	6.4	203.5	6.7	3.0	40.6	44.9
Feedstock transmission	1.7	1.2	1.6	1.3	1.0	1.2	1.2
Feedstock recovery	1.4	6.1	15.4	7.6	4.7	51.8	5.9
Land-use changes, cultivation	0.0	2.4	13.6	2.5	1.8	15.2	2.3
Fertilizer manufacture	0.0	0.3	2.2	0.8	0.2	6.2	0.3
Gas leaks and flares	4.9	0.0	0.0	0.0	0.0	0.0	0.0
CO_2, H_2S removed from NG	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Emissions displaced	0.0	0.0	(10.4)	(1.1)	0.0	0.0	0.0
Total	*42.1*	*26.7*	*239.6*	*31.3*	*11.8*	*115.6*	*55.5*

Part G. SO_2

Fuel ------> *Feedstock ------>*	**RFG** *oil*	**Methanol** *wood*	**Ethanol** *corn*	**Ethanol** *grass*	**SCG** *wood*	**Biodiesel** *soy*	**CH2** *wood*
Fuel dispensing	0.8	1.2	1.2	0.9	7.1	0.9	38.1
Fuel distribution and storage	2.4	2.8	2.3	2.4	1.3	1.7	0.6
Fuel production	13.1	19.5	51.8	20.7	10.3	38.6	5.1
Feedstock transmission	6.0	2.6	6.1	2.7	2.0	2.6	2.5
Feedstock recovery	5.1	5.2	12.1	6.4	4.0	28.5	5.0
Land-use changes, cultivation	0.0	0.7	3.8	0.9	0.5	1.3	0.7
Fertilizer manufacture	0.0	0.5	6.7	1.4	0.4	30.6	0.5
Gas leaks and flares	25.6	0.0	0.0	0.0	0.0	0.0	0.0
CO_2, H_2S removed from NG	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Emissions displaced	0.0	0.0	(8.5)	(18.2)	0.0	0.0	0.0
Total	*52.9*	*32.5*	*75.5*	*17.1*	*25.7*	*104.2*	*52.5*

Part H. PM (black carbon)

Fuel ------> *Feedstock ------>*	**RFG** *oil*	**Methanol** *wood*	**Ethanol** *corn*	**Ethanol** *grass*	**SCG** *wood*	**Biodiesel** *soy*	**CH2** *wood*
Fuel dispensing	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Fuel distribution and storage	0.0	0.1	0.1	0.1	0.2	0.1	0.0
Fuel production	0.2	1.7	0.9	1.9	0.8	0.6	0.7
Feedstock transmission	0.0	0.2	0.2	0.2	0.2	0.2	0.2
Feedstock recovery	0.1	1.3	2.0	1.6	1.0	6.2	1.3
Land-use changes, cultivation	0.0	0.1	1.1	0.2	0.1	1.2	0.1
Fertilizer manufacture	0.0	0.1	0.4	0.1	0.1	0.9	0.1
Gas leaks and flares	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CO_2, H_2S removed from NG	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Emissions displaced	0.0	0.0	-1.2	-0.1	0.0	0.0	0.0
Total	*0.5*	*3.6*	*3.5*	*4.1*	*2.3*	*9.2*	*2.5*

Note: see notes to Table 2.

LEM results for different target years, different CEFs, and different countries.

The LEM can perform lifecycle analyses for up to 30 different countries, and for any target year between 1970 and 2050. The Tables 1-5 show results for the U. S. for the year 2050. In this section, we briefly examine how the results change for different target years and countries.

Results for different target years. Table 6 shows lifecycle emissions summary results for biofuels for LDVs and HDVs, for different years from 1970 to 2050.

TABLE 6. LIFECYCLE EMISSIONS FOR BIOFUEL VEHICLES, U. S., 1980, 2010, AND 2040

	Year 1980		*Year 2010*		*Year 2040*	
LDVs (versus 26 mpg LDGV)	*fuelcycle*	*fuel+veh*	*fuelcycle*	*fuel+veh*	*fuelcycle*	*fuel+veh*
Baseline: Gasoline (CG) (g/mi)	482.7	596.4	461.8	550.7	439.1	504.1
Ethanol (E90 (corn))	-11%	-9%	-2%	-2%	-11%	-9%
Ethanol (E90 (grass))	-23%	-18%	-53%	-44%	-81%	-71%
Methanol (M85 (wood))	-52%	-42%	-58%	-49%	-65%	-57%
Natural gas (CSNG (wood))	-71%	-57%	-82%	-68%	-92%	-79%
HDVs (versus 3 mpg HDDV)	*fuelcycle*	*fuel+veh*	*fuelcycle*	*fuel+veh*	*fuelcycle*	*fuel+veh*
Baseline: Diesel (LSD) (g/mi)	5,694.8	5,985.9	4,158.2	4,405.1	3,671.4	3,869.8
Biodiesel (SD100 (soy))	61%	59%	53%	50%	17%	16%
Ethanol (E100 (corn))	-30%	-28%	6%	6%	-8%	-7%
Ethanol (E100 (grass))	-41%	-39%	-52%	-49%	-92%	-87%
Methanol (M100 (wood))	-76%	-72%	-68%	-64%	-84%	-80%
Natural gas (CSNG (wood))	-80%	-76%	-74%	-70%	-89%	-84%

Notes: LDGV = light-duty gasoline vehicle; HDDV = heavy-duty diesel vehicle; mpg = miles per gallon; CG = conventional gasoline, E90 = 90% ethano/10% gasoline; M85 = 85% methanol/15% gasoline; CSNG = compressed synthetic natural gas; LSD = low-sulfur diesel; SD100 = 100% soydiesel; fuel+veh = lifecycle of fuels and lifecycle of vehicles. For baseline LDGV and baseline HDDV, total lifecycle CO_2-equivalent emissions are shown; for alternatives, percentage changes relative to basline are shown.

Two general results are noteworthy. First, the emissions from the baseline gasoline and diesel vehicles decline over time, even though the baseline vehicle fuel economy is held constant. This is because in the LEM emissions of non-CO_2 criteria pollutants are projected to decline over time, and because some (but not all) upstream and vehicle lifecycle processes are assumed to become more energy efficient overtime.

Second, in all cases except one the percentage change for alternatives compared with the baseline also declines, which implies that lifecycle CO_2-equivalent emissions from alternatives decline faster than do emissions from the baselines. There are several reasons for this. First, the fuel economy of the alternatives *relative* to the fixed fuel economy of the baseline is projected to increase. Second, almost all important processes in alternative-fuel lifecycles are projected to become more efficient, whereas petroleum refining is not, because any technical efficiency gains in refining are assumed to be nullified by the declining quality of crude oil input on the one hand and increasingly stringent product requirements on the other. Third, major sources of emissions unique to biofuel lifecycles, such as those related to the N cycle, are projected to decline over time.

The exception mentioned above is corn ethanol, which has relatively low emissions in 1980, then higher emissions in 2010, and then relatively low emissions again in 2040. Table 7 shows the breakdown of emissions from corn ethanol by target year and stage of the lifecycle.

TABLE 7. CORN ETHANOL LIFECYCLE EMISSION BY STAGE AND TARGET YEAR (G/MI)

	1970	**1980**	**1995**	**2000**	**2010**	**2025**	**2040**
Vehicle operation: fuel	341	338	355	354	344	335	334
Fuel dispensing	0	1	2	3	3	3	2
Fuel storage and distribution	12	10	9	9	8	7	7
Fuel production	131	153	188	197	198	190	181
Feedstock transport	21	18	16	16	14	13	11
Feedstock and fertilizer production	148	142	137	137	123	105	96
Land use changes and cultivation	166	154	139	134	125	113	100
CH_4 and CO_2 gas leaks and flares	2	2	1	0	0	(0)	(1)
C in end-use fuel from CO_2 in air	(282)	(282)	(282)	(283)	(283)	(283)	(283)
Emissions displaced by coproducts	(118)	(108)	(96)	(92)	(81)	(67)	(57)
Sub total (fuelcycle)	421	428	***469***	475	***451***	***415***	***392***
% changes (fuelcycle)	-17%	-11%	***-3%***	-1%	***-2%***	***-7%***	***-11%***
Vehicle assembly and transport	23	21	21	21	19	17	14
Materials in vehicles	68	63	59	59	56	50	43
Road dust, tirewear, brakewear PM	0	0	0	0	0	0	0
Lube oil production and use	9	7	5	5	5	4	4
Refrigerant (HFC-134a)	30	22	14	12	9	6	4
Grand total	552	542	***569***	573	***540***	***492***	***457***
% changes (grand total)	-14%	-9%	***-2%***	0%	***-2%***	***-6%***	***-9%***

In the case of corn ethanol, total fuelcycle emissions actually increase from 1970 to about 2000, and then begin to decrease. The increase is due mainly to an increase in

CO_2-equivalent emissions from the fuel-production stage and a decrease in the "credit" from emissions displaced by co-products. CO_2-equivalent fuel-production (and vehicle tailpipe) emissions increase because of reductions in emissions of NO_2 and SO_2, which have *negative* (i.e., "cooling") CEFs. The co-product emissions-displacement credit decreases because the co-products are assumed to displace soy products, and the lifecycle emissions from the soy products decrease over time.

Results for different countries. Table 8 shows fuel lifecycle emissions summary results for biofuels for LDVs and HDVs, for six different countries, including the U. S., for the year 2010. The table shows CO_2-equivalent fuelcycle emissions for the gasoline and diesel vehicles (in grams/mile) and the percentage difference from the baseline for the alternatives.

TABLE 8. FUELCYCLE EMISSIONS FOR BIOFUEL VEHICLES IN DIFFERENT COUNTRIES (YEAR 2010)

LDVs (versus 26 mpg LDGV)	U. S.	China	India	S. Africa	Chile	Japan
Baseline: Gasoline (CG) (g/mi)	461.8	454.3	373.0	594.8	471.1	457.5
Ethanol (E90 (corn))	-2%	17%	10%	0%	-6%	1%
Ethanol (E90 (grass))	-53%	-36%	-47%	-53%	-56%	-45%
Methanol (M85 (wood))	-58%	-50%	-53%	-59%	-65%	-61%
Natural gas (CSNG (wood))	-82%	-73%	-74%	-79%	-90%	-85%
HDVs (versus 3 mpg HDDV)	**U. S.**	**China**	**India**	**S. Africa**	**Chile**	**Japan**
Baseline: Diesel (crude oil) (g/mi)	4,158.2	1,713.1	1,767.1	2,600.6	2,695.9	4,920.0
Biodiesel (SD100 (soy))	53%	183%	183%	78%	38%	54%
Ethanol (E100 (corn))	6%	16%	12%	2%	4%	-8%
Ethanol (E100 (grass))	-52%	-44%	-55%	-61%	-56%	-53%
Methanol (M100 (wood))	-68%	-69%	-71%	-78%	-78%	-77%
Natural gas (CSNG (wood))	-74%	-75%	-76%	-82%	-84%	-84%

Table 8 shows that lifecycle emissions from biofuels, both in absolute terms and relative to emissions from gasoline, can vary from one country to another. Differences are particularly pronounced for corn ethanol and soy diesel in China or India versus the U.

S. (By contrast, there is relatively little difference in percentage changes when wood is the feedstock.) As indicated in Table 9, the differences between China, India and the U. S. in the case of soy diesel are due almost entirely to differences in emissions related to land use and cultivation, which in turn are due to differences in land types used for crops and in the amount and efficiency of fertilizer use. Some of the difference also is due to the higher emissions from fertilizer manufacture, which result from the greater N intensity. This highlights, once again, the importance of assumptions regarding the types of land uses displaced by biofuel plantations.

TABLE 9. SOY DIESEL UPSTREAM EMISSION BY STAGE AND COUNTRY (G/10^6 BTU)

	U. S.	China	India	S. Africa	Chile	Japan
Fuel dispensing	386	380	561	461	187	231
Fuel distribution and storage	1,309	1,279	1,426	1,400	1,125	1,306
Fuel production	38,933	39,332	45,694	41,071	32,266	36,105
Feedstock transmission	2,484	2,419	2,516	2,602	2,325	2,710
Feedstock recovery	34,365	34,002	35,247	35,662	32,792	34,112
Land-use changes, cultivation	106,975	213,625	206,766	131,679	100,577	123,944
Fertilizer manufacture	32,068	39,127	42,366	36,324	32,235	32,921
Gas leaks and flares	0	0	0	0	0	0
CO_2, H_2S removed from NG	0	0	0	0	0	0
Emissions displaced	(84,278)	(84,278)	(84,278)	(84,278)	(84,278)	(84,278)
Total	*132,242*	*245,885*	*250,298*	*164,920*	*117,229*	*147,049*

Differences between using LEM CEFs and IPCC GWPs

CO_2-equivalency factors (CEFs), which convert gases other than CO_2 to the amount of CO_2 with some equivalent effect on climate or the global economy, are an integral part of the calculation of CO_2-equivalent lifecycle emissions. Appendix D of the LEM documentation details the development of the CEFs used in the LEM (hereinafter referred to as "LEM CEFs").

The LEM CEFs differ in a number of important respects from the widely used CEFs – called "Global Warming Potentials," or GWPs – adopted by the Intergovernmental

Panel on Climate Change (IPCC). The most important difference is that the IPCC has not formally estimated CEFs (qua GWPs) for CO, NMOCs, NO_X, SO_X, PM and H_2 (apart from accounting for the effect of CO and C in NMOCs oxidizing to CO_2), whereas we have. Table 10 shows the LEM CEFs and the IPCC 100-year GWPs.

TABLE 10. LEM CEFS USED IN THIS ANALYSIS AND IPCC 100-YEAR GWPS

Pollutant	LEM CEFs (yr. 2010)	IPCC 100-yr. GWPs
NMOC-C	3.664	3.664
NMOC-0_3/CH_4, SOA	4.8	not estimated
CH_4	18.8	23
CO	2.9	1.6
N_2O	251	296
NO_2	-15.5	not estimated
SO_2	-52.4	not estimated
PM (black carbon)	1,410	not estimated
PM (organic matter)	-161.8	not estimated
PM (dust)	-2.9	not estimated
H_2	5.6	not estimated
SF_6	126,617	22,200
CFC-12	12,369	8,600
HFC-134a	1,275	1,300
CF_4	32,782	5,700
C_2F_6	69,933	11,900
HF	2000	not estimated

In addition, the IPCC GHG accounting methods ignore temporary carbon sequestration or emission due to changes in land use, whereas we do not. This of course matters greatly in the estimation of lifecycle emissions from biofuels.

How important are the differences between the LEM CEFs and the IPCC GWPs? In this section, we compare results from the LEM using LEM CEFs with results using IPCC GWPs, for a selected number of biofuel lifecycles.

Table 11 presents this comparison for the U. S, for the year 2010. The table shows the percentage change in the g/mi emissions going from the IPCC g/mi results to the LEM CEF g/mi results, and two different measures of the percentage change in emissions relative to gasoline. As one would expect, there are significant differences in using IPCC GWPs rather than LEM CEFs in those cases where there are significant differences in emissions of the pollutants for which LEM CEFs differ significantly from IPCC GWPs – mainly PM, SO_2, and NO_2 – or else significant emissions associated with changes in land use (which are counted in the LEM CEF case but not in the IPCC GWP case).

TABLE 11. FUELCYCLE EMISSIONS WITH LEM CEFS AND WITH IPCC 100-YEAR GWPS (U. S., YEAR 2010)

	LEM CEFs		IPCC GWPs		IPCC GWPs vs. LEM CEFs		
	g/mi	*% ch.*	*g/mi*	*% ch.*	*Δ g/mi*	*Δ rel.*	*Δ abs.*
Baseline LDGV	462	n.a.	492	n.a.	-6.1%	n.a.	n.a.
Baseline HDDV	4,158	n.a.	4,100	n.a.	1.4%	n.a.	n.a.
ICEV, diesel (low-sulfur)	350	-24%	357	-27%	-2%	-11%	3%
ICEV, natural gas (CNG)	345	-25%	370	-25%	-7%	2%	-1%
ICEV, LPG (P95/BU5)	347	-25%	370	-25%	-6%	0%	-0%
ICEV, ethanol (corn)	451	-2%	479	-3%	-6%	-7%	0%
ICEV, ethanol (grass)	219	-53%	225	-54%	-2%	-3%	2%
ICEV, methanol (wood)	193	-58%	234	-52%	-17%	11%	-6%
ICEV, soy diesel (vs. HDDV)	6,361	53%	4,603	12%	38%	332%	41%

Notes: %/ch. is percentage change in g/mi emissions relative to gasoline or diesel baseline; Δ g/mi is the percentage difference between the IPCC and the LEM-based g/mi estimates; Δ rel. is the percentage change in the IPCC-based % ch. relative to the LEM-based %ch.; Δ abs is the difference between IPCC % ch. and LEM % ch.

For a few biofuel lifecycles there can be significant differences between using the LEM CEFs and the IPCC GWPs. In general, there are two reasons for these differences. First, biofuel lifecycles can emit substantial amounts of NO_2, and this has a significant CEF in the LEM but is not counted as an IPCC GWP. The importance of differences in the CO_2-

equivalent effect of NO_2 is shown in Table 12, which provides a breakdown of lifecycle CO_2-equivalent emissions by pollutant.

TABLE 12. BREAKDOWN OF LIFECYCLE CO_2-EQUIVALENT EMISSIONS BY POLLUTANT, BIOFUEL PATHWAYS (U. S., YEAR 2010)

General fuel -->	**RFG**	**Ethanol**	**Ethanol**	**Methanol**	**Natural gas**	**Biodiesel**
Fuel specification -->	crude oil	*E90 (corn)*	*E90 (grass)*	*M85 (wood)*	*CNG (wood)*	SD100 (soy)
Net CO_2 from vehicles	60%	8%	8%	15%	0%	0%
Lifecycle CO_2	93%	82%	44%	44%	22%	124%
CH_4	4%	5%	3%	3%	5%	8%
N_2O	3%	19%	10%	4%	4%	76%
CO	3%	3%	3%	3%	4%	5%
NMOC	1%	1%	1%	1%	0%	1%
NO_2	-4%	-13%	-8%	-5%	-4%	-74%
SO_2	-4%	-5%	-3%	-3%	-3%	-6%
PM (BC+OM)	2%	4%	4%	4%	3%	17%
PM (dust)	-0%	-0%	-0%	-0%	-0%	-0%
H_2	0%	0%	0%	0%	0%	0%
SF_6	0%	0%	-0%	0%	0%	1%
HFC-134a	2%	2%	2%	2%	2%	0%

Notes: Net CO_2 from vehicles is equal to tailpipe CO_2 less any "credit" for C fixed by biomass used to make biofuel. All pathways for LDVs except biodiesel, which is for HDVs.

The second reason for any differences in Table 11 is that the IPCC GWP method effectively ignores carbon emissions related to land use, whereas our method does not (this is discussed more fully in the next paragraph). I note, however, that in general the two differences – the counting of the climate impacts of NO_X and land use changes in the LEM CEF case but not the IPCC GWP case – work in opposite directions, because the CEF for NO_X actually is negative. This means that in the LEM, the effect of NO_X can tend to offset the effect of land-use changes. As a result, in some biofuel pathways there actually little difference between the LEM CEF case and the IPCC GWP case (Table 11). I note, though, that the CEF for NO_X is uncertain, and might even be positive, in which case the NO_X effect and the land-use effect would work in the same direction, and there would be significant differences between the LEM CEF case and the IPCC GWP case for all biofuel pathways.

<u>Treatment of land-use changes.</u> Our methods for estimating GHG emissions related to land-use changes are similar to those recommended by the IPCC except for this key difference: we use a time-varying discount rate with a very long time horizon, whereas the IPCC apparently assumes a zero discount rate and a 100-year time horizon (IPCC, 1997, 2000, 2003). Our methods and the IPCC methods both assume that any initial change in land use – say, the clearing of forest to plant crops – eventually is reversed when the program that gave rise to the initial change (planting crops, in our example) is abandoned. Following abandonment, the carbon content of the soils and biomass begins a gradual return to the original values (in our example, those of a forest). If the discount rate is zero and the carbon content after reversion is the same as the original carbon content – and if the complete reversion occurs within the time horizon – 100 years in the IPCC recommendations – then the *net* carbon emission due to the program is zero. However, if the discount rate is not zero, then the present value of the future carbon gain following reversion is less than the value of the carbon loss at the start of the program, resulting in a non-zero net emission due to the program. As a result, whether one uses the LEM CEFs (which incorporate a non-zero discount rate, and hence count emissions related to land-use changes) or the IPCC GWPs (which ignore emissions related to changes in land use) can have a big impact on absolute and relative emissions in biofuel lifecycles.

II. REVIEW OF LIFECYCLE ANALYSES OF BIOFUELS

Overview

Recently, several good reviews of major biofuel lifecycle analyses have been published. (Fleming et al., 2006; Farrel et al., 2006; Hammerschlag, 2006; Larson, 2005; Wang, 2005a, 2005b; International Energy Agency, 2004). In addition, several other recent reports provide more general summaries of a large number of biofuels studies worldwide (e.g., Quirin et al., 2004).

These recent summaries and comparisons of biofuel lifecycle analyses have identified many of the major areas of uncertainty, disagreement, and incompleteness in the existing literature. However, all of these areas, and others, have been discussed qualitatively in Delucchi's (2004) white paper on conceptual, methodological, and data issues in lifecycle analysis, much of which is included as Part III of this report. Moreover, our own analyses as part of the development of the LEM have begun to address some of the issues raised in the recent literature reviews.

Because on the one hand there already are comprehensive, up-to-date reviews of the major biofuels lifecycle analyses, and on the other hand we have a good conceptual framework and have begun to address some of the major problems in existing studies, we decided that rather than create yet another typical review and comparison of biofuels studies, we would begin where the current reviews leave off and our own work has started: with a focus on the major areas of uncertainty, disagreement, and incompleteness in the existing literature. These areas include:

- treatment of lifecycle analyses within a dynamic economic-equilibrium framework;
- major issues concerning energy use and emission factors; and
- incorporation of the lifecycle of infrastructure and materials.
- representation of changes in land use;
- treatment of market impacts of co-products;

- development of CO_2 equivalency factors for all compounds;
- detailed representation of the nitrogen cycle and its impacts;

In this part, we present a summary of the findings of the recent published reviews of major biofuel LCAs, including results from the LEM. Then, in the next part, we examine the areas of uncertainty, disagreement, and incompleteness listed above, within the context of a comprehensive conceptual framework for biofuel LCAs.

Summary of reviews of major biofuel LCAs

As mentioned above, a number of excellent reviews of major biofuel LCAs have been published recently, including Farrel et al. (2006), Hammerschlag (2006), Fleming et al. (2006), Larson (2005), Wang (2005a, 2005b), the International Energy Agency (2004), and Quirin et al. (2004). These studies are *not* themselves original biofuel LCAs, but rather are reviews of a number of such original LCAs. The original biofuel LCAs considered by four review papers are shown in Table 13.

TABLE 13. ORIGINAL BIOFUEL LCAS INCLUDED IN RECENT REVIEW PAPERS

Review article	Original biofuel LCAs reviewed (post-2000 only)	Biofuel pathways in original
Farrel et al. (2006)	Patzek (2004)	ethanol from corn
	Pimentel and Patzek (2005)	ethanol from corn, switchgrass, and wood; biodiesel from soy and sunflower
	Shapouri and McAloon (2004)	ethanol from corn
	Graboski (2002)	ethanol from corn
	Wang (2001)	ethanol from corn and cellulosic; biodiesel from soybeans
	De Oliveira et al. (2005)	ethanol from corn, sugarcane
Hammerschlag (2006)	Graboski (2002)	ethanol from corn
	Shapouri et al. (2002)	ethanol from corn
	Pimentel and Patzek (2005)	ethanol from corn, switchgrass, and wood; biodiesel from soy and sunflower
	Kim and Dale (2005a)	ethanol from corn
	Lynd and Wang (2004)	ethanol from corn, cellulose
	Sheehan et al. (2004)	ethanol from corn stover
Fleming et al. (2006)	Ahlvik and Brandberg (2001)	hydrogen, ethanol, and FTL from lignocellulose
	General Motors et al. (2001)	ethanol from lignocellulose
	General Motors et al. (2002)	hydrogen, ethanol, and FTL from lignocellulose; ethanol from corn and/or sugar beet
	European Council for Automotive R&D (CONCAWE et al., 2004)	hydrogen, ethanol, or FTL from lignocellulose; ethanol from corn and/or sugar beet
	GREET model (Fleming et al. runs of GREET model)	ethanol from lignocellulose; ethanol from corn
	GHGenius model (Fleming et al. runs of GHGenius model)	hydrogen and ethanol from lignocellulose; ethanol from corn and/or sugar beet

Wang (2005a)	Delucchi et al. (2003)	ethanol from corn, switchgrass, and wood; biodiesel from soy; methanol from wood; CNG from wood
	Delucchi (2001)	ethanol from corn, switchgrass, and wood
	Graboski (2002)	ethanol from corn
	Kim and Dale (2005a)	ethanol from corn
	Kim and Dale (2002)	ethanol from corn
	Natural Resources Canada (2005)	ethanol from corn, wheat, switchgrass, and wood
	Patzek et al. (2005)	ethanol from corn
	Pimentel (2003)	ethanol from corn
	Pimentel and Patzek (2005)	ethanol from corn, switchgrass, and wood; biodiesel from soy and sunflower
	Shapouri and McAloon (2004)	ethanol from corn
	Shapouri et al. (2002)	ethanol from corn
	Wang et al. (2003)	ethanol from corn

Note: FTL = Fischer-Tropsch liquids.

Although Table 13 does not include Larson's (2005) review, I note that it also is an excellent and comprehensive review.

Table 14 summarizes the lifecycle GHG emissions results presented in the review papers mentioned above, and compares the results with those from the LEM.

TABLE 14. APPROXIMATE TYPICAL OVERALL RESULTS OF LIFECYCLE GHG-EMISSION ANALYSES OF BIOFUELS

Source	**Ethanol from corn**	**Ethanol from cellulose**	**biodiesel from soy**
GREET (see various papers by Wang and GM et al.) GHGenius (see web site), Kim and Dale, De Oliveira, LBST (GM et al. 2002a), CONCAWE et al., Spatari et al. (2005), and others	- 50% to -10%	-100% to -40%	- 80% to -40%
LEM estimates	-30% to + 20%	-80% to -40%	0% to +100%

The LEM typically estimates higher lifecycle GHG emissions from biofuel pathways than do other studies. (Studies by Pimentel and Patzek [see P&P, Table 15] also estimate high non-renewable energy use and hence implicitly high CO_2 emissions, but Farrel et al. [2006] and Hammerschlag [2006] have identified several shortcomings with those studies.) The main reasons have to do with treatment of the nitrogen cycle, land-use changes, CO_2 equivalency factors, co-products, and market impacts.

In the following sections we first delineate the structure and assumptions of major, original biofuel LCAs (including the LEM), and then analyze biofuel LCAs within a general conceptual framework.

Structure, general methods, and assumptions of original LCAs of biofuels

Table 15 shows the structure, general methods, and key assumptions of several original biofuel LCAs.

TABLE 15. STRUCTURE, GENERAL METHODS, AND KEY ASSUMPTIONS OF ORIGINAL BIOFUEL LCAS.

Study set #1.

	LEM	GREET	GM –LBST Europe	Kim & Dale (KD)	GHGenius
Region	Can represent up to 30 countries. Most detail for U. S.	United States.	Europe.	United States	North America
Time frame	Any year from 1970 to 2050 (built in projections of energy and material use and emissions).	Near term or long term.	Year 2010.	Apparently near term.	Any year from 1970 to 2050 (built in projections of energy and material use and emissions).
Biomass pathways	Ethanol from corn, switchgrass, and wood; biodiesel from soybeans; methanol, SNG and hydrogen from wood.	Ethanol from corn and cellulosic biomass; biodiesel from soybeans.	Ethanol from sugar beet, crop residue, wood; hydrogen, methanol, and SNG from wood; biodiesel from rape seed.	Ethanol from corn grain and corn stover; biodiesel from soybeans.	Ethanol from corn, wood, grass, and wheat; methanol and SNG from wood; biodiesel from soybeans; hydrogen from wood, corn, and wheat.
Fuel lifecycle model	Detailed, original internal model.	Detailed, original internal model.	LBST E^2 I-O model and data base.	No model per se; own calculations based on literature review and analysis.	Detailed internal model (built on 2001 version of LEM).
Fuel production	Input-output representation based on review and analysis of literature.	Review and analysis of literature.	Detailed process descriptions based on review and analysis of literature.	Literature review.	Input-output representation based on review and analysis of literature (similar to LEM).

Study set #1 continued.

	LEM	GREET	GM –LBST Europe	Kim & Dale (KD)	GHGenius
Treatment of coproducts	DDGS (corn to ethanol) displaces corn grain and soybeanns; excess electricity (wood to ethanol) displaces grid power; soybyproducts displace glycerin.	DDGS (corn to ethanol) displaces corn and soy; excess electricity (wood to ethanol) displaces grid power.	Sugar beet pulp displaces US soybeans; rape seed byproducts displace glycerin.	System of linear equations for corn ethanol co-product displacement; soy byproducts displace solvents; excess electricity (stover to ethanol) displaces grid power.	DDGS (corn to ethanol) displaces corn and soy; excess electricity (wood to ethanol) displaces grid power; soybyproducts displace glycerin. (Expanded and refined version of LEM treatment.)
Crop production	Detailed analysis of primary USDA and other data on energy and fertilizer inputs.	Detailed review and analysis of USDA and other data sources on energy adn fertililizer inputs.	Review of literature on energy use; review and analysis of N requirements.	Review and analysis of USDA and other sources of data (such as GREET).	Review and analysis of literature and government data.
Fertilizer and pesticide production	Complete lifecycle of fertilizer based on primary survey data (U. S. national average). Pesticide use based on literature review.	Detailed review and analysis of literature.	Review of literature.	Own calculations based on literature data.	Based on the LEM.
Land use changes	Comprehensive accounting of changes in land use associated impacts on soil and plant carbon.	USDA analysis of land-use changes combined with 1998 LEM estimates of C sequestration rates.	Discussed but not included (GM et al., 2002b, p. 292).	Not included. (DAYCENT model used to simulate soil-carbon changes on site due to tillage practices.)	Based on 2003 version of LEM, but with different assumptions regarding displaced land uses.
Nitrogen cycle	Complete accounting of N flows, fates, and impacts.	Not included. (Review and analysis of some literature pertinent to N_2O emissions.)	Partial treatment of N requirements, N sources, and associated N_2O emissions.	Not included per se, but DAYCENT model used to simulate N_2O and soil carbon.	Partial accounting of N-related emissions, based on improved version of 2003 LEM.

Study set #1 continued.

	LEM	GREET	GM –LBST Europe	Kim & Dale (KD)	GHGenius
GHGs and CO_2-equivalency factors	LEM CEFs (Table 10). (But IPCC GWPs can be specified.)	IPCC GWPs for CO_2, CH_4, and N_2O; other pollutants represented as non-GHGs.	IPCC GWPs for CO_2, CH_4, and N_2O.	IPCC GWPs for CO_2, CH_4, and N_2O.	ca. 2000 version of LEM CEFs, or 100-year IPCC GWPs.
Vehicle energy-use modeling, including drive cycle	Assumed fuel economy for baseline vehicles, simple model of energy use of alternatives relative to baseline. U. S. combined city/highway driving.	Assumed fuel economy values for baseline vehicles, % change in fuel use for alternatives relative to baseline.	GM simulator, European Drive Cycle (urban and extra-urban driving).	Assumed fuel economy values.	Based on the LEM.
Vehicle and materials lifecycle	Comprehensive, detailed internal model based on detailed literature review and analysis	Not included.	Not included.	Not included.	Based on LEM treatment.
Infrastructure	Crude representation.	Not included.	Not included.	Not included.	Not included.
Price effects	A few simple quasi-elasticities.	Not included.	Not included.	Not included.	Not included?
Documentation	Delucchi (2003).	Wang (1999, 2001, 2005a, 2005b); Wang et al. (1999, 2003).	GM et al. (2002a, 2002b, 2002c).	Kim and Dale (2002, 2004, 2005a, 2005b).	$(S\&T)^2$ Consulting (2005a).

Study set #2.

	Graboski	USDA	Pimentel & Patzek (PP)	STELLA	U. Toronto
Region	United States.	United States.	United States	United States and Brazil.	Ontario, Canada
Time frame	2000 and 2012	About year 2000.	Roughly 2000.	About year 2000.	Near term (2010) and mid term (2020).
Biomass pathways	Ethanol from corn.	Ethanol from corn.	Ethanol from corn, switchgrass, and wood; biodiesel from soy	Ethanol from corn (U. S.); ethanol from sugarcane (Brazil).	Ethanol from switchgrass and corn stover.
Fuel lifecycle model	Own detailed analysis of lifecycle stages.	Some stages based on GREET model.	No model per se; own calculations based on literature review and analysis.	STELLA systems modeling *framework* used with data assumptions based on literature reviews.	Developed own life-cycle modules based on literature review and analysis.
Fuel production	Detailed review and analysis of literature.	Assumptions based on an industry survey.	Literature review.	Literature review.	Literature review.
Treatment of coproducts	Original, detailed analysis of products displaced by co-products of dry mills and wet mills.	Assumes soymeal is replacement product.	Co-products assumed either to have no market value, or else small value as soy protein substitute.	Not included. (See Farrel et al. [2006] supporting online material p. 10.)	Excess electricity sold to regoinal power grid.
Crop production	Detailed analysis of primary USDA and other data on energy and fertilizer inputs.	Detailed analysis of primary USDA and other data on energy and fertilizer inputs.	Analysis and review of USDA and other data.	Literature review (e.g., Shapouri et al. 2002).	Literature review.
Fertilizer and pesticide production	Original analysis of stages of fertilizer lifecycle; review of data on pesticide production.	Fertilizer estimates from industry expert; pesticide data from GREET.	Literature review of energy for fertilizer, pesticide, and seed production.	Literature review (e.g., Shapouri et al. 2002).	Literature review.

Study set #2 continued.

	Graboski	USDA	Pimentel & Patzek (PP)	STELLA	U. Toronto
Land use changes	Not included.	Not included.	Not included.	Not included. (However, they do assume that tillage practices result in soil C sequestration.)	Discussed but assumed no impact.
Nitrogen cycle	Not included.	Not included.	Not included.	Not included.	Not included.
GHGs and CO_2-equivalency factors	Not included. (Graboski analyzes lifecycle fossil energy use only.)	Not included. (USDA analyzes lifecycle energy use only.)	Not included. (P&P analyze energy use only.)	Not included. (Analysis of CO_2 emissions only.)	IPCC GWPs for CO_2, CH_4, and N_2O.
Vehicle energy-use modeling, including drive cycle	Not included. (Graboski analyzes lifecycle fossil energy use only.)	Not included. (USDA analyzes lifecycle energy use only.)	Not included. (P&P analyze energy use only.)	2001 Ford Taurus	26 mpg Chevy Impala combined city/highway driving; 3% efficiency advantage on ethanol.
Vehicle and materials lifecycle	Analysis of energy embodied in farm equipment and ethanol plants.	Not included. (USDA analyzes lifecycle energy use only.)	Includes an estimate of embodied in farm equipment.	Not included.	Not included.
Infrastructure	Not included.	Not included.	Not included.	Not included.	Not included.
Price effects	Not included.	Not included.	Not included.	Not included.	Not included.
Documentation	Graboski (2002)	Shapouri et al. (1995, 2002); Shapouri and McAloon (2004).	Pimentel (2003); Pimentel and Patzek (2005); Patzek (2004); Patzek et al. (2005)	De Oliveira et al. (2005).	Spatari et al. (2005)

In the next part we examine the important aspects of biofuel LCAs within the context of a comprehensive conceptual framework for doing LCAs of biofuel pathways.

III. A COMPREHENSIVE CONCEPTUAL FRAMEWORK FOR DOING LCAS OF BIOFUELS.

Conceptual framework for biofuel LCA: current practice

Brief historical background. Current LCAs of transportation and climate change can be traced back to "net energy" analyses done in the late 1970s and early 1980s in response to the energy crises of the 1970s, which had motivated a search for alternatives to petroleum. These were relatively straightforward, generic, partial "engineering" analyses of the amount of energy required to produce and distribute energy feedstocks and finished fuels. Their objective was to compare alternatives to conventional gasoline and diesel fuel according to total fuelcycle use of energy, fossil fuels, or petroleum.

In the late 1980s, analysts, policy makers, and the public began to worry that burning coal, oil, and gas would affect global climate. Interest in alternative transportation fuels, which had subsided on account of low oil prices in the mid 1980s, was renewed. Motivated now by global (and local) environmental concerns, engineers again analyzed alternative transportation fuelcycles. Unsurprisingly, they adopted the methods of their "net-energy" engineering predecessors, except that they took the additional step of estimating net CO_2 emissions, based on the carbon content of fuels. By the early 1990s analysts had added other GHGs (methane and nitrous oxide) weighted by their "Global Warming Potential" (GWP) to come up with fuelcycle CO_2-equivalent emissions for alternative transportation fuels. Today, most LCAs of transportation and global climate are not appreciably different in *general* method from the analyses done in the early 1990s. And although different analysts have made different assumptions and used slightly different specific estimation methods, and as a result have come up with different answers, few have questioned the validity of the general method that has been handed down to them.

The problem with the pedigree. LCAs of transportation and climate in principle are *much* broader than the net-energy analyses from which they were derived, and hence have all of the shortcomings of net-energy analyses *plus* many more. If the original net-energy analyses of the 1970s and 80s could be criticized for failing to include economic variables, on the grounds that any alternative-energy policy would affect prices and hence uses of all major sources of energy, then the lifecycle GHG analyses they spawned can be criticized on the same grounds, but even more severely, because in the case of lifecycle GHG analyses we care about any economic effect anywhere in the world, whereas in the case of net-energy analysis we cared about economic effects only in the country of interest. Beyond this, lifecycle GHG analysis encompasses additional areas of data (such as emission factors) and additional systems (such as the global climate) which introduce considerable additional uncertainty.

The upshot is that LCAs of transportation and climate are *not* built on a carefully derived, broad, theoretically solid foundation, but rather are an ad-hoc extension of a method -- net-energy analysis -- that was itself too incomplete and theoretically ungrounded to be valid on its own terms and which could not reasonably be extended to the considerably broader and more complex problem of global climate change. And although recent LCAs of transportation and climate have been been made to be consistent with LCA "guidelines" established by the International Organization for Standardization (ISO; see the ISO web site, www.iso.ch/iso/en/iso9000-14000/iso14000/iso14000index.html), the ISO guidelines have only recently properly addressed *some* of the issues discussed here, and have not yet developed a proper policy/economic conceptual framework. (See the Main Report of the LEM documentation for further discussion.)

Comparison of current practice with an ideal model

Indeed, when we begin to examine the development and application of lifecycle models for transportation we find right away that often it is not even clear what precise questions the models are supposed to answer. This turns out to be a serious flaw, because if we don't know what question a model is meant to answer, we cannot comprehend the answers (outputs) the model provides. In the case of LCAs of transportation and global climate, we are forced often to infer a question from the nature of the outputs and the methods used. What we find, generally, is an unrealistic and irrelevant research question and a limited modeling method.

The strengths of weaknesses of current LCAs applied in transportation can be seen best by comparing current practice with an ideal model. An ideal model, of course, would replicate reality. In this major section, I first outline an ideal LCA model of reality, and then compare actual conventional LCA with this ideal.

Figure 3 shows a conceptual flow chart of an ideal model, one which replicates reality. The ideal, shown on the left side of Figure 3, comprises several components, in boxes, with arrows showing relationships between components. Across from each component, on the right side, is a yellow box that discusses whether and how the component is treated in conventional LCA. I begin by discussing the ideal model.

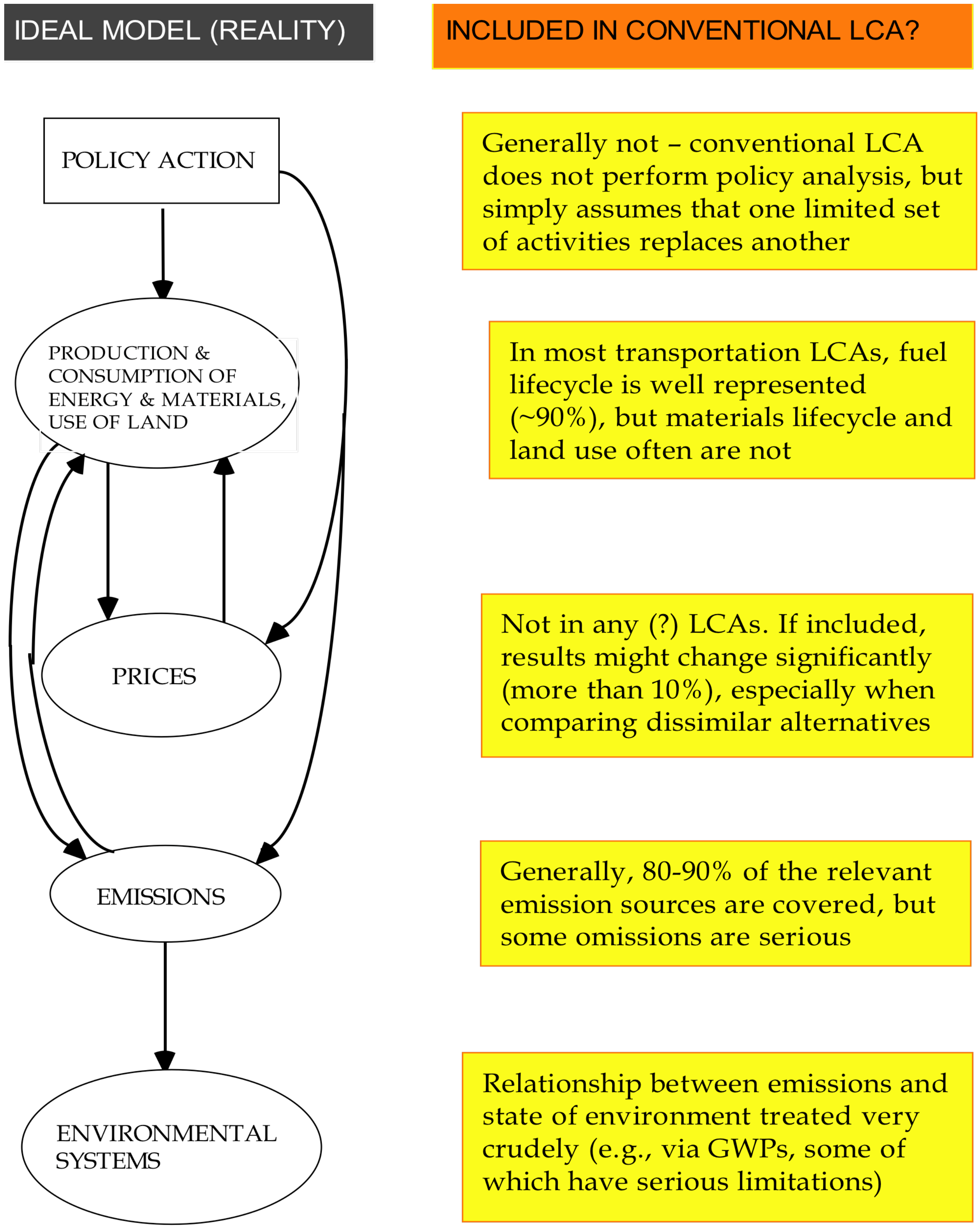

Figure 3. Ideal versus conventional LCA

An ideal model of LCA of transportation and climate change

In principle, LCAs of transportation and climate change are meant to help us understand the impact on global climate of some proposed transportation action. Let us call the proposed action to be evaluated a "policy," and refer generally to the impacts of the policy on "environmental systems." Hence, in Figure 3, the model starts with the specification of a policy, and ends with the impacts on environmental systems. In between are a series of steps that constitute the conceptual components of our model of reality.

In reviewing these components, it is easiest to work backwards from the output of interest, the impact on environmental systems. The state of an environmental system – the ultimate output of interest -- is determined by the magnitude and quantity of emissions and by other environmental variables. Hence, in Figure 3, an "emissions" component is shown affecting the "environmental systems" output component. Emissions, in turn, are related to the production and consumption of energy and materials and the use of land (PCEM); hence, Figure 3 shows an arrow from the PCEM box to the emissions box. But emissions also may be affected directly by policy measures; this is indicated by the arrow directly from the policy box to the emissions box.

Thus far the main aspects of our model of reality is that changes in PCEM result in changes in emissions which result in changes in environmental systems. This much generally appears in conventional LCA. But the next and critical question is: what affects changes in PCEM? Here the ideal model has an important component that as we shall see is missing from conventional LCAs of transportation. Changes in PCEM can be related directly to policy, which is what most conventional LCAs assume – but usually only *implicitly* – and which is shown by the arrow from the policy box to the PCEM box. But changes in PCEM also are related to changes in prices of major goods and services throughout the global economy. Prices, in turn, are affected directly by policies, but also by – and here is the nub – indirectly by changes in PCEM. There is thus a circular feedback between changes in PCEM, changes in prices, and further changes in PCEM.

Our conclusion, then, is that economic systems, whose states are determined partly by prices, are an inextricable part of the real world. As a result, prices are a necessary part of an ideal model of the impact of policy on climate change. Unfortunately, conventional LCAs of transportation and climate change do not consider prices or other aspects of economic systems. This omission introduces an error of unknown but potentially large magnitude, and thereby *may* render the results of conventional LCAs virtually meaningless.

Comparing conventional LCAs of transportation and climate change with the ideal model: policy

Conventional LCAs of transportation and climate change typically do not analyze a specific policy. Indeed, conventional LCAs typically do not even posit a specific question for analysis. The implicit questions of conventional LCA must be inferred from the conclusory statements and the methods of analysis. In transportation, the *conclusory statements* of lifecycle analysis typically are of the sort: "the use of fuel F in light-duty vehicles has X% more [or less] emissions of CO_2-equivalent GHG emissions per mile than does the use of gasoline in light-duty vehicles". The *method of analysis* usually is a limited input-output representation of energy use and emissions for a relatively small number of activities linked together to make a lifecycle, with no parameters for policies or the function of markets. Recalling that CO_2-equivalent emissions (which typically are part of the conclusory statements, as mentioned above) are equal to emissions of CO_2 plus equivalency-weighted emissions of non-CO2 gases, where the equivalency weighting usually is done with respect to temperature change over a 100-year time period, we then can *infer* that the question being addressed by most LCAs of GHG emissions in transportation is something like:

> "What would happen to climate forcing over the next 100 years if we simply replaced the set of activities that we have defined to be the 'gasoline lifecycle' with the set of activities that we have defined to be the 'fuel *F* lifecycle,' with no other changes occurring in the world"?

The problem here is that this question is irrelevant, *because no action that anyone can take in the real world will have the net effect of just replacing the narrowly defined set of 'gasoline activities with the narrowly defined set of 'fuel-F activities'*. Any action that involves fuel *F* – *any* action – will have complex effects on production and consumption activities throughout the world, via global political and economic linkages. These effects *will* occur, and a priori cannot be dismissed as insignificant. To omit them, therefore, is to introduce into the analysis an error of unknown sign and magnitude.

To recap, in the real world one evaluates specific policies, but conventional LCAs do not evaluate specific policies, they evaluate implicit, unrealistic questions. As a consequence, it is difficult if not impossible to relate the results of conventional LCAs to any actual policy actions we might be considering.

Now, one cannot conceive of any *potential* use of the results of an LCA apart from the evaluation of policy. And the details of the specification of the policy are important, because different policies will have different effects on climate. For example, considering the case of ethanol from corn, a policy to increase (or eliminate) the ethanol subsidy will have a different impact on climate than will a policy to mandate ethanol vehicles, mainly because different policies affect people, prices, and choices differently. One thus cannot make heads or tails of an analysis that not only is unrelated to any particular policy, but, what's worse, does not even have any important policy relevant variables, such as price, supply, or other market parameters. In order to analyze the impacts of a particular policy, or indeed of any conceivable policy, one must, include all of the variables affected directly by policy. Many of these are economic variables, which are conspicuously absent from conventional transportation LCAs.

A related deficiency of conventional LCA is the failure to specify clearly the counterfactual, or alternative world, with which a specific policy (say, a specific policy regarding ethanol) is being compared. It is conceptually impossible to evaluate a fuel such as ethanol "by itself;" rather we must estimate the difference between doing one thing rather than another. These differences between alternative worlds are a function of the initial conditions in each world, the initial perturbations (or changes), and dynamic economic, political, social, and physical forces. Yet no transportation fuelcycle study, old or new, has any sort of serviceably modeled counterfactual, or alternative world -- most likely because such a model requires something like general economic equilibrium analysis, at the least, and fuelcycle analysts are not familiar with general equilibrium models.

Comparing conventional LCAs of transportation and climate change with the ideal model: production and consumption of energy and materials, and use of land (PCEM).

Although virtually all LCAs of transportation and climate have focused intensively on the energy and to a much lesser extent the materials part of PCEM, and data and methods of analysis in this area have improved over the past 15 years, there remain serious omissions and oversimplifications, which by themselves undermine any claims of definitive knowledge of the effects of transportation policies on climate.

<u>Energy-use data</u>. There are many sources of primary, basic data on the energy intensity of various feedstock production and transport processes (e.g., oil recovery, coal mining, natural gas transport, and petroleum shipments) yet no analysis makes use of all of them, and many analyses make use of few or none of them. On the basis of results from my Lifecycle Emissions Model (LEM), and the work of others, I surmise that the difference between using primary data in an appropriately detailed input/output flow model, and using literature-review estimates in a more aggregated approach, can amount to a percent or two of simple, first-order, fuelcycle GHG emissions.

More uncertain, and more important, are estimates of the energy intensity of fuel production (e.g., petroleum refining, ethanol production) and the energy efficiency of motor vehicles. Most analysts acknowledge the latter, and even check the sensitivity of their results to assumptions regarding the relative efficiency of motor vehicles. Many analysts, too, are aware of the importance of assumptions regarding the energy intensity of, say, corn-to-ethanol production. But even though there are plenty of analyses and models of, for example, refinery input and output and refinery energy usage, under different economic scenarios, no recent transportation LCA, as far as I know, uses such models, or even the results of the such models run specifically for fuelcycle policy evaluation. This weakness may again have a nontrivial impact on the results. For example, my analysis suggests that uncertainty as regards refinery energy production is at least three absolute percentage points in the fuelcycle analysis.

Generally, the LEM uses national-average input-output data for energy use and emissions. These data typically are estimated on the basis of a detailed review of primary survey data or of the relevant technical literature. The data are specified for a base year, and then projected into the future, generally assuming that the use of energy materials becomes more efficient and that emission factors decrease. Thus, to some extent, the LEM avoids the problem of relying on out-dated data sources.

Most estimates of energy use and emission factors in the LEM are broadly similar to those in other comprehensive LCA models, such as GREET. In any event, whatever differences remain among LCA modelers concerning the appropriate assumptions for major energy-using processes, such as ethanol production from corn, are not completely resolvable without further analysis of policy and economic factors. This is because decisions such as which fuels to use and how much technological efficiency and emission control to invest in depend on anticipated prices of fuel and capital, government policies, world economic conditions, and other factors. Without an explicit analysis or at least discussion of these factors, it can be difficult to make a case for one set of assumptions over another.

<u>Materials and infrastructure.</u> More seriously, many recent studies have ignored energy and materials associated with building and maintaining fuel production and distribution infrastructure, transportation equipment, farm equipment, and so on, even though some analyses indicate that such energy and materials usage might be a non-trivial fraction of total fuelcycle energy and material usage. For example, my own recent analysis suggests that the simple, first-order GHG emissions associated with building and servicing pipelines, ships, trucks, and tractors -- but not fuel-production facilities -- might be about 3% of the total, simple, first-order GHG emissions in the corn/ethanol fuelcycle. Whether or not these are included can make a difference of two to three absolute percentage points in the comparison of ethanol with gasoline. In addition, a few studies indicate that emissions associated with the fuel-production facilities might be of the same order of magnitude, although there is much uncertainty. Thus, all told, emissions associated with construction and maintenance of facilities might be on the order of 5% of fuelcycle GHG emissions, and shift the standing of ethanol, for example, relative to gasoline, by as much as five percentage points (although this appears to be a maximum, and 3% might be more likely).

The LEM contains a detailed, original, comprehensive representation of the lifecycle of materials used in light- and heavy-duty vehicles, but relatively simple representations of the lifecycle of materials, infrastructure, and repair for things like tractors and ethanol production facilities. Pimentel and Patzek (2005) estimate the energy embodied in farm machinery, but the estimates are not well documented. Graboski (2002) provides a much lower estimate of embodied energy, but based partly on farm expenditure data. LEM estimates appear to be between these two, but closer to Pimentel and Patzek's. This is an area for further research.

<u>Land use changes.</u> Finally, but of potentially great quantitative significance, conventional transportation LC models ignore (or treat too simply) changes in land use related to the establishment of biomass grown to make biofuels. The replacement of native vegetation with biofuel feedstocks and the subsequent cultivation of the biomass can 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 no-policy alternative. An ideal representation of land-use changes would involve an integrated model of land-use characteristics, land productivity, and commodity prices, constraints on use of land, and other factors. To my knowledge no transportation LCA embodies such a model. The LEM's relatively simple but conceptually comprehensive treatment of the impact of land-use changes suggests that *a proper treatment of land-use changes could change CO_2-equivalent emissions from transportation lifecycles by ten or more percentage points in some cases* (see for example Tables 1 and 2 here). It thus becomes of paramount importance to conduct biofuel LCAs within the context of a global economic model of land use and production and consumption of crops, wood products, and substitutes.

Now, some analysts have suggested that in some cases the production of a biofuel feedstock, such as corn, will not bring new land into production and hence will not cause any change in land uses because the incremental production of the biocrop will be "supplied" by increases in crop yield (Graboski, 2002, p. 72; $(S\&T)^2$ Consulting, 2005a, p. 286) As demonstrated next, this argument depends logically on an implausible assumption.

In order for there to be no expansion of total land in corn production as a result of incremental corn production, the argument *must* be that the increase in demand for corn spurs increases in per-acre corn yields *that would not otherwise occur*. If, to the contrary, the increases in corn yield would have occurred anyway, it is easy to see that incremental corn production must require "new" land relative to the no-incremental production baseline. If corn yield is independent of corn output, then in the no-incremental-production baseline, the amount of land devoted to corn production will *decrease* by exactly the rate of increase in yield. With respect to this baseline, any incremental corn production must be on new or additional land; it cannot be on any of the old land because that land already is yielding at the assumed (increased) rate. Now, it may well be that the new land brought into production for the incremental corn will about balance the amount of old land taken out of production due to the increase in yield, but it would be an unambiguous error to assume that because the total amount of land in production remained roughly the same, the incremental corn production did not require incremental land. The correct comparison is with the no-incremental-corn baseline in which the amount of land in production *decreases,* and with respect to which a constant amount of land in production represents an *increase* in total land in production.

The logical kernel of this demonstration can be put as follows: if corn yield does *not* depend on corn output, then any incremental corn production must always occur on new land because all other land already is yielding at the assumed, output-independent rate.

Comparing conventional LCAs of transportation and climate change with the ideal model: prices

All energy and environmental policies affect prices. Changes in prices affect consumption, and hence output. Changes in consumption and output change emissions. Price effects are ubiquitous.

Research done by the U. S. Department of Energy (DOE) and Oak Ridge National Laboratory indicate which kinds of price effects are likely to be important. First and foremost, perhaps, are those that involve the price of oil. The substitution of a non-petroleum fuel for gasoline probably will reduce the price of crude oil. A reduction in the world price of oil will stimulate increased consumption of petroleum products, for *all* end uses, *worldwide*. Analyses by DOE have shown that the additional worldwide oil consumption induced by the lower prices is quite large compared to the initial substitution in the U. S. transportation sector.

Whatever the exact magnitude of these price effects, they are potentially important enough that they ought to be taken seriously in an evaluation of the impact of transportation policies on climate. There is no way to escape this conclusion. We cannot dismiss the effects because they occur outside of the U. S., or outside of the transportation sector, because in an analysis of global warming, we care about all emissions, everywhere. We cannot dismiss price effects on the grounds that a policy will not really affect price, because in principle even the smallest change has a nonzero-probability of leading to a nonzero affect on price. (In any event, if the price effects really are so small, then the policy must be so unimportant or ineffective as to have no affect on climate worth worrying about anyway.) And we certainly cannot argue that all such price effects are likely to be substantially "similar" for all policies, and hence of no importance in a *comparison* of alternatives, because this clearly is not the case: policies related to LPG, which can be made from crude oil, may have an effect different from policies related to natural gas, which is a substitute for oil, and different again from policies related to new fuels derived from biomass, which has little to do with oil.

The economic modelers will be quick to remind us that the web is even more complex. For example, a large price subsidy, such as is enjoyed by corn ethanol, ultimately causes a deadweight loss of social welfare, on account of output being suppressed below optimal levels due to the inefficient use of [tax] resources. This loss of output probably is associated ultimately with lower greenhouse gas (GHG) emissions. Thus, in this case, a subsidy policy may have countervailing effects: on the one hand, there will be an increase in GHG emissions caused by increased use of petroleum due to the lower price of oil due to the substitution of ethanol, but on the other, there will be a decrease in GHG emissions due to the reduction in output caused by the economic deadweight loss from the subsidy. By contrast, an R & D policy that succeeds in bringing to market a new, low-cost fuel, will, on account of the more efficient use of energy resources, unambiguously improve social welfare. (This is another argument in favor of stimulating the development of low-cost biofuels from cellulosic materials.)

It is easy to go on. For example, economists have pointed out that price effects might eliminate and even reverse the environmental benefits of EVs as estimated in simple fuelcycle analyses: if EVs are mandated, but are really quite costly, the resultant increase in the cost of vehicles will cause car buyers to delay purchase of new, clean, efficient vehicles -- to the possible detriment of the local and global environment.

As a final example, changes in prices are an important determinant of equilibrium uses of different types of land. The extent to which a new biofuel program displaces native vegetation, existing agricultural production, unproductive set-aside land, or something else, matters a great deal in analyses of lifecycle CO_2-equivalent emissions, because of the different carbon-storage characteristics of these ecosystems. In the real world, this displacement ultimately is determined strongly by prices of land and commodities derived from land.

<u>Prices in the context of "joint production."</u> Nearly as important are price effects in cases of joint production. It is well known that corn-ethanol plants, for example, produce goods other than ethanol. A policy promoting ethanol therefore is likely to result in more output of these other goods, as well as more production of ethanol. What is the impact on climate of the production of the other goods? The only way to answer this question is to model the market for the other goods to see, in the final equilibrium, what changes in consumption and production occur in the world with the ethanol policy. If the production of the other goods is large compared with the production of ethanol, then we reasonably may expect that the effect on climate of the production of the other goods is not trivial compared to the "first order" effect of using or making ethanol.

Note that what is required is a general-equilibrium model of the markets affected by co-products, *not* an analysis that assumes that, say, the co-products of ethanol production simply displace alternative products (such as soy meal). Fundamentally, this is because we reasonably may expect that the introduction of low-cost co-products to world markets will shift supply curves downward and induce additional consumption as well as simply displace alternative sources. To the extent that co-products induce additional consumption rather than displace alternatives, an analysis that assumes 100% displacement will overestimate the emissions "credit" impact of co-products.

No transportation LCA done to date has used a full global equilibrium model to determine the impact of coproducts on world markets. Although the best recent biofuel LCAs do at least adopt the correct "displacement" or "system expansion" approach to estimating the consequences of joint production (Graboski, 2002; Kim and Dale, 2002), they do not consider the impact of co-products on prices, and hence overestimate the "displacement credit." (The LEM uses simple quasi-elasticities to account for the impact of price changes on co-product markets.)

The same issue of joint production arises in petroleum refineries. But even though these sorts of effects are well known and widely studied, no engineering fuelcycle analyst has done, or incorporated, an appropriate economic analysis of these effects, in any fuelcycle. Many analyses have used so-called "apportioning" schemes, which bear no real formal relation to the general equilibrium analysis of alternative policies.

<u>Minor effects of prices.</u> Finally, there are a practically infinite number of what are likely to be relatively minor effects of price changes. For example, different fuelcycles use different amounts of steel, and hence have different effects on the price and thereby the use of steel in other sectors. The same can be said of any material, or of any process fuel, such as coal used to generate electricity used anywhere in a fuelcycle. It might be reasonable to presume that in these cases the associated differences in emissions of GHGs are a second-order effect on a second-order process (e.g., that the price effect of using steel use is no more than 10% of the "first-order" or direct effect of using steel, which itself probably is less than 10% of fuelcycle emissions), and hence relatively small. On the other hand, we might be surprised, and sometimes many individually quite small effects add up (rather than cancel each other). For these reasons, it would be wise for fuelcycle analysts to investigate a few classes of these apparently minor price effects. (It is possible that some input-output [I/O]energy analysts have done this already, although most if not at all I/O studies used in LCA assume that prices are fixed.)

Comparing conventional LCAs of transportation and climate change with the ideal model: emissions and the climate environmental systems

The ultimate objective of LCAs of GHG emissions in transportation is to determine the effect of a particular policy on global climate. This requires a number of steps beyond the macro-economic modeling of commodity production and consumption discussed above: identification of gases that are emitted from fuelcycles and can affect climate directly or indirectly; identification of sources of emissions of the identified direct and indirect GHGs; estimation of emission factors for the identified sources; modeling the effect of "indirect" GHGs on "direct" GHGs; and representation of the effect of direct GHGs on climate. None of these steps are as well characterized as one might like, and as a result one might reasonably have little confidence in the soundness of the overall representation of the climatic effect of a particular policy.

i). Identification of emitted GHGs. The more researchers study climate, the more they learn about the gases that affect climate. As a result, the list of identified GHGs has grown considerably since early fuelcycle analyses, and can be expected to continue to grow.

The authors of the early studies of net fuelcycle CO_2 emissions were well aware that other gases, emitted at various stages in fuelcycles, affect climate. Shortly after the early fuelcycle CO_2 fuelcycle studies were done, other fuelcycle analysts began to include other GHGs, first methane (CH_4), then nitrous oxide (N_2O). These three are referred to as "direct" GHGs, because they affect climate directly, as themselves, rather than indirectly via an effect on *other* gases. Ozone (O_3) also affects climate directly, but is not emitted as such from fuelcycles; rather, its concentration is influenced by other gases that *are* emitted from fuelcycles: nitrogen oxides (NO_X), carbon monoxide (CO), nonmethane organic compounds (NMOCs), hydrogen (H_2), and others. By 1990 NO_x, CO, and NMOCs had been identified as "indirect" GHGs because of their effects on ozone. In 1993, I included them in my first LCA model (the forerunner of the LEM), weighting them by the IPCC's "global warming potential" (GWP) factors.

More recently, aerosols have been identified as direct and indirect GHGs, and work is proceeding to identify which kinds or components of aerosols affect climate most. The most recent research indicates that sulfate aerosols tend to cause global cooling, but that the black-carbon (BC) component of aerosols has a very strong global warming effect. [The latest version of my Lifecycle Emissions Model (LEM) includes BC and sulfate from particulate matter (PM). See Table 10 here.] The list of GHGs undoubtedly will continue to grow as researchers identify more GHGs, direct and indirect.

ii) Identification of sources of GHGs. Not surprisingly, the more we look for sources of GHGs, the more we find. Sometimes the newly identified or quantified sources are surprisingly significant. For example, in the case of the soy/biodiesel lifecycle, emissions of N_2O from nitrogen fixation by soybeans may be enormous – on a par with CO_2 emissions from fuel combustion. In fact, including these emissions in an LCA of biodiesel may result in biodiesel emitting considerably *more* CO_2–equivalent fuelcycle emissions than petroleum diesel, rather than considerably less as is estimated in conventional LCAs. Although this source has been identified and even quantified in IPCC emission-inventory guidelines for years, it has not been included in any biodiesel LCAs performed to date (other than my own).

iii) Estimation of emission factors. In many cases, data on GHG emissions are lacking or of poor quality. For example, even if one identifies N_2O emissions from nitrogen fixation by soybeans, one still is faced with considerable uncertainty regarding the appropriate emission factor for this source.

Because CH_4 emissions typically are multiplied by a CEF of on the order of 10 to 30, and N_2O emissions by a factor of 250 to 350, a doubling or having of assumed emissions of these gases can have a large impact on the calculated CO_2-equivalent total. Unfortunately, in many cases there are so few real emissions data that we are happy if we have reason to believe that we 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 fuelcycle emissions. (Only a year or so ago, this range might have been about 2% to 15% -- so we do make progress!) Moreover, virtually all analysts assume that all vehicles emit the same amount of N_2O, even though in many cases this assumption probably will prove to be appreciably in error.

Another often poorly characterized source of emissions is changes 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 lifecycle CO_2-equivalent emissions by several percentage points.

Finally, there has been less research into emission factors for newly identified (but potentially important) GHGs, such as black carbon (BC). First-cut comprehensive emission-factor databases and emissions inventories for BC have been published only recently. In many cases, the uncertainty in BC emission-factors is 50% or more. Given the possibly quite large CO_2-equivalency factor for BC (on a mass basis, it may be well over 1000 – Table 10), this degree of uncertainty in emission-factor estimates translates directly into a large uncertainty in the effect of BC emissions on climate.

<u>iv) The effects of indirect GHGs on direct GHGs</u>. The difficulties with emission factors may be serious, but at least they are familiar to most fuelcycle modelers. By contrast, this fourth step -- modeling the environmental flows and fates of the emissions – is unfamiliar to most fuelcycle modelers. The problem is not that nothing is known about these flows and fates, for indeed quite bit is known; rather, the problem is that nobody seems to have the complete, integrated picture of all of the interactions that ultimately affect climate.

The complexity and possible importance of these environmental interactions are nicely illustrated by the nitrogen cycle, one of the more complex of the pollutant/environment/climate pathways. Virtually all fuelcycles produce very large amounts of NO_X. Some biomass fuelcycles -- particularly the corn/ethanol cycle -- also produce large amounts of inorganic nitrate. These nitrogen compounds undergo a number of transformations, in a variety of media, and have several different kinds of effects on climate. These effects are discussed and quantified in Appendix D of the LEM documentation. In summary:

i) NO_X participates in a series of atmospheric chemical reactions that involve CO, NMOCs, H_2O, OH^-, O_2, and other species, and which affect the production of tropospheric ozone, which in turn has two kinds of effects:

i-a) a direct radiative-forcing effect;

i-b) an indirect effect on carbon sequestration in plants and soil.

ii) In the atmospheric chemistry mentioned in i), NO_X affects the production of the hydroxyl radical, OH, which oxidizes methane and thereby affects the lifetime of methane.

iii) As nitrate, NO_X deposits onto soils and oceans and then denitrifies or nitrifies into N_2O (a strong, long-lived direct climate-change gas) and NO (which oxidizes back to the indirect GHG NO_2 that was the source of the deposited N in the first place), and also affects soil emissions of CH_4.

iv) As nitrate, it fertilizes terrestrial and marine ecosystems and thereby stimulates plant growth and carbon sequestration in nitrogen-limited ecosystems.

v) NO_X forms particulate nitrates, which as aerosols probably have a net negative radiative forcing (see the section on aerosols).

vi) As deposited nitrate, NO_X can increase acidity and harm plants and thereby reduce CO_2 sequestration.

As shown in Table 10, we estimate that the CEF for NO_X may be negative. Tables 12 shows that the in biofuel lifecycles, the climate impact of NO_X emissions can be significant. These LEM results indicate that the climatic effect of changes to the nitrogen cycle may be on the order of 5% of fuelcycle CO_2-equivalent emissions of CO_2, CH_4, and N_2O for fossil-fuel lifecycles, and 10% or more for biofuel lifecycles. This 5% to 10% excludes the impact of N_2O from the use of fertilizer, which itself is roughly another 3-4% in the some fuelcycles.

Given the large nitrogen flows in some biomass fuelcycles, and the possibility that the nitrogen cycle will have a total effect equivalent to more than 10% of fuelcycle emissions, it is evident that a complete analysis of the climate impacts of energy policies ought to include a total nitrogen-cycle balance, with all of the relevant fates (especially nitrogen fertilization, and denitrification to N_2O), fully specified. The LEM traces most of these effects of nitrogen but in some cases only crudely and with poor data.

By comparison, the pathways for CH_4, CO, NMOCs, and N_2O are at least a bit simpler (the N_2O cycle appears to be quite simple). However, the aerosol (PM) pathways are quite complex and, as we shall see momentarily, potentially quite important in LCAs of CO_2-equivalent GHG emissions.

<u>v) The effect of direct GHGs on climate</u>. Once we have estimated the final, net changes in emissions of climate-relevant gases, we either can run global climate models to estimate the effect of the emissions on climate (this is most accurate but also the least convenient and the most costly), or else we can convert non- CO_2 emissions to an "equivalent" amount of CO_2, in essence using the results of simplified climate models. Most fuelcycle analysts have used the IPCC's global-warming potentials (GWPs), which tell us the grams of a gas that produce the same integrated radiative forcing, over a specified period of time, as one gram of CO_2, given a single pulse of emissions of each gas. Typically, analysts use the GWPs for a 100-year time horizon.

But as some economists, and indeed some of the original developers of GWPs themselves pointed out, the IPCC GWPs should not be used in any analysis that purports to be, or contribute to, anything like a cost-benefit evaluation. The 100-year GWPs give radiative forcing 99 years from now the same weight as radiative forcing tomorrow, but give no weight at all to radiative forcing 101 years from now. Neither ordinary people, let alone cost-benefit analysts, evaluate the future in this way; rather, people and analysts weigh the future against the present by discounting the future at some typically nonzero rate. Intuitively and analytically useful CEFs should incorporate a discount rate. (Again, some of the original analysts in this area also developed GWP expressions with a discount rate.)

Furthermore, because we do not care about the radiative forcing or even the mean global temperature per se, but rather about the actual physical, economic, social, and biological impacts of climate change, CEFs ideally should be estimated on the basis of equivalent *impacts*, rather than equivalent temperature change. The most natural numeraire for impacts, of course, is their dollar value[1].

Thus, if one does not run a model of climate and climate-impacts to estimate the effects of changes in emissions of "greenhouse" gases, for each policy scenario to evaluated, one should use CEFs that equilibrate on the present dollar value of the impacts of climate change. Ideally, these present-value CEFs would be derived from runs of climate-change models for generic but explicitly delineated policy scenarios.

Researchers have begun to develop such CEFs, and the simple ones developed so far (including some developed for the LEM; see Table 10) can differ from the IPCC 100-year GWPs by more than 10%. I would not be surprised if sophisticated present-value

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[1] In addition to these problems of incorporating an arbitrary time cutoff and defining equivalence with respect to radiative forcing rather than with respect to impacts, the IPCC GWPs have the problem of estimating equivalence for a one-time unit emission of a gas given constant concentrations of all gases, as opposed to considering a more realistic pattern of emissions changes over time.

CEFs, developed with advanced climate and economic models, differed from the IPCC GWPs by 20% – a potentially important difference.

More importantly, as discussed above, estimating and applying CEFs for gases for which the IPCC has not developed GWPs can have a significant effect on lifecycle CO_2-equivalent emissions.

Towards a more comprehensive model

This overview has identified major deficiencies in the development and application of conventional LCAs of transportation and climate. In this concluding section, I delineate a more comprehensive and accurate model.

If we wish the results of lifecycle analysis of transportation to be interpretable and relevant, then lifecycle models must be designed to address clear and realistic questions. In the case of lifecycle analysis comparing the energy and environmental impacts of different transportation fuels and vehicles, the questions must be of the sort: "what would happen to [some measure of energy use or emissions] if somebody did X instead of Y," where – *and here is the key* – X and Y are *specific and realistic alternative courses of actions.* These alternative courses of actions ("actions," for short) may be related to public policies, or to private-sector market decisions, or to both. Then, the lifecycle model must be able to properly trace out all of the differences – political, economic, technological -- between the world with X and the world with Y. Identifying and representing all of the differences between two worlds is far more complex than simply representing the replacement of one narrowly defined set of engineering activities with another.

As noted above, current lifecycle models do not put the questions they address clearly, and are not capable of tracing out all of the effects of clearly put questions. A major part of the problem is that there always will be *economic* differences between world X and world Y that do affect energy and emissions but that present lifecycle models do not account for.

To begin to develop a more realistic lifecycle evaluation framework, we must understand how public or private actions regarding transportation fuels might affect prices and ultimately emissions. In general, actions may affect prices directly, for example by changing tax rates, or indirectly, by affecting the supply of or demand for commodities[2] used in transportation. In an integrated and complex global economy, changes in the prices of important commodities ultimately will affect production and consumption of all commodities in all sectors throughout the world. In the final equilibrium of prices and quantities, there will be a new global pattern of production and consumption. Associated with this new pattern of production and consumption will be a new pattern of emissions of criteria pollutants and greenhouse gases. The difference between the global emissions pattern associated with the transportation action being evaluated and the global emissions pattern without the action may be said to be the "emissions impact" of the action being evaluated.

Hence, I propose that rather than ask what would happen if we replaced one very narrowly set of defined activities with another, and then use a technology lifecycle model to answer the question, we instead ask what would happen in the world were to take one realistic course of action rather than another, and then use an integrated economic and engineering model to answer the question. This juxtaposition reveals three key differences between what we current conventional approach and the expanded approach that I believe is likely to be more accurate (Table 16):

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[2] Actions may affect demand or cost functions directly, for example by mandating production or consumption, or indirectly, for example by affecting incomes and hence household consumption decisions.

Table 16. Comparison of the conventional lifecycle approach in transportation with an expanded approach

Issue	conventional approach	Expanded approach
The aim of the analysis	Evaluate impacts of replacing one limited set of "engineering" activities with another	Evaluate worldwide impacts of one realistic action compared with another
Scope of the analysis	Narrowly defined chain of material production and use activities	All major production and consumption activities globally
Method of analysis	Simplified input/output representation of technology	Input/output representation of technology with dynamic price linkages between all sectors of the economy

Ideally, then one would construct a model of the world economy, with sectoral and geographic detail where we think it is most important for evaluating energy policies (e.g., world oil production and demand; vehicle production in the U. S.; agricultural markets for crops and biomass). Within the sectors we would have detailed input/output data and emission factors for the processes now modeled in fuelcycle analyses.

One could do this either by expanding an economic/policy-evaluation model into an integrated economic/fuelcycle/climate model, suitable for the all-in-one evaluation of the impact of energy policies on climate, or by adding to an engineering fuelcycle model demand and supply functions or simple price, quantity, and elasticity parameters. Either way -- whether starting from "economic" or from "engineering-fuelcycle" models -- it is a formidable project.

The policy-manipulable inputs to such an integrated economic/engineering model might be things like projections of the cost of fuels or vehicles, taxes or subsidies on fuels and vehicles, mandates regarding the supply of certain types of vehicles or fuels, demand side restrictions or inducements, environmental constraints, demographic and macroeconomic variables, and representations of consumer preferences. The major outputs of interest might be emissions, energy use, vehicle travel, GNP, and the like. In principle, all emissions could be monetized, and a total change in social welfare estimated. If one chose not to monetize all of the outputs, then one simply would report all of the different outputs, and leave commensurability and overall evaluation for someone else. In this case, one would make compound statements of this sort: "policy-option 1 results in lower greenhouse-gas emissions than does policy-option 2, but also lower vehicle miles of travel and lower GNP".

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