Lifecycle Analysis of CO_2-Equivalent Greenhouse-Gas Emissions from Biofuels

CRC Workshop on Lifecycle Analysis of Biofuels

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Outline

- Overview of LCA of CO_2-equivalent GHGs from biofuels
  - Ethanol from corn, grass or wood; biodiesel from soy
- Comparison of results from some LCAs
  - UCD Lifecycle Emissions Model (LEM) vs. others
- Important issues in biofuel LCAs
  - Land-use changes
  - Changes to the nitrogen cycle
  - CO_2-equivalency factors
  - Economic (price) effects
- Findings and conclusions

Take-home message:

- Changes in land use, the nitrogen cycle, CO_2-equivalency factors, the economic effects of policies, omitted kinds of climate impacts, and other factors are important in LCAs of GHGs from biofuels, but are treated poorly or (more often) not at all in most analyses. In order for us to have a clearer understanding of the impact of biofuel policies on climate, future analyses ought to better address these factors.

What is the purpose (and shortcoming) of most LCAs of GHGs?

- Ideally, the purpose of LCA of GHGs from biofuels is to determine the difference in some measure of climate change between a "baseline" world and the world given some proposed action (generally a policy action). In principle, this requires a careful specification of the action and then an analysis of how the world changes as a result of the action. To do this, one needs an integrated engineering-economic-environment model.

- In practice, however, most LCAs do not specify or analyze a policy, or consider any economic effects, but just assume (implicitly) that one simple and narrowly defined set of activities replaces another, and then use a simple engineering I-O model to estimate impacts.

- This discrepancy between what should be done and what is done sometimes can make the results of LCAs difficult to interpret.

Approximate overall results of biofuel GHG LCAs

(Fuelcycle CO_2-equivalent GHG emissions)

Source	**Ethanol from corn**	**Ethanol from cellulose (grass)**	**Biodiesel from soy**
GREET (see various papers by Wang and GM et al.) GHGenius (see website), Kim and Dale, De Oliveira, LBST (GM et al. 2002a), CONCAWE et al., Spatari et al. (2005), Farrell et al. (2006) and others	- 50% to 0%	-100% to -40%	- 80% to -40%
LEM estimates	-30% to + 20%	-75% to -40%	-20% to + 50%

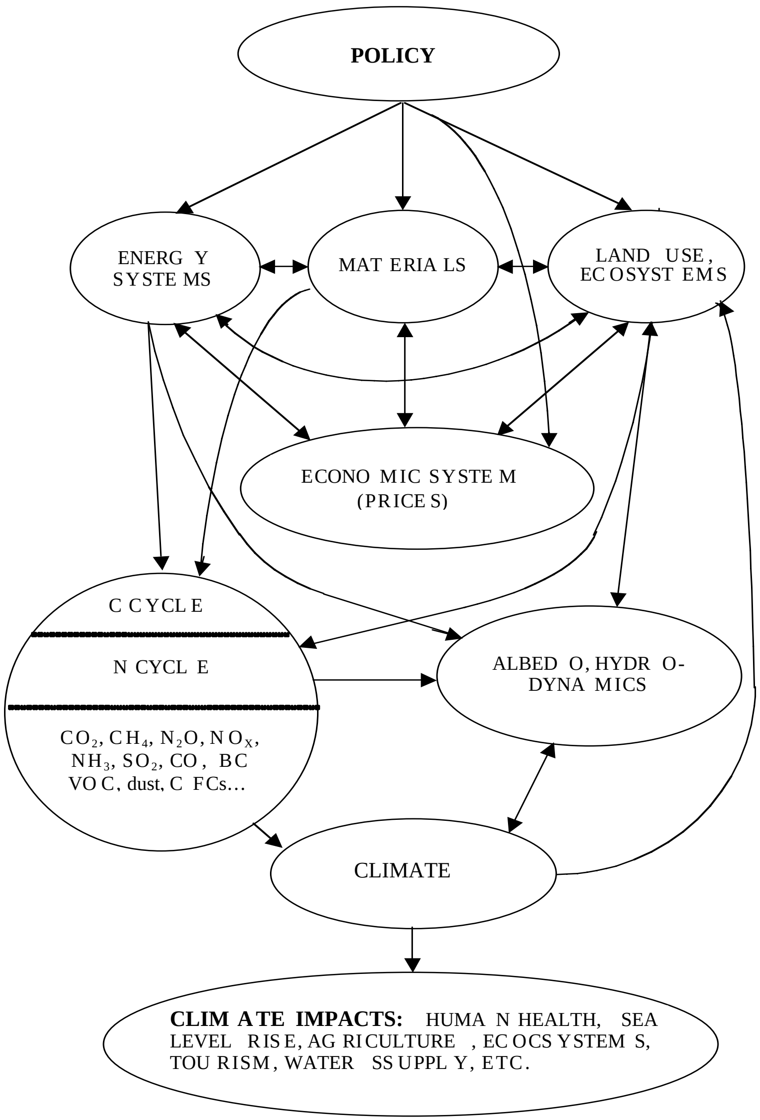
History of biofuel GHG LCA

- Existing models need improvement
  - Many are the progeny of simple energy-chain analyses with C emission factors added. Nobody started with an integrated economic/environmental/engineering systems model!
  - No theory or conceptual framework justifies the current, simplified engineering-process-analysis approach.
  - The first version of the LEM made several conceptual and methodological advances, most of which were adopted by other researchers (often independently) years later.

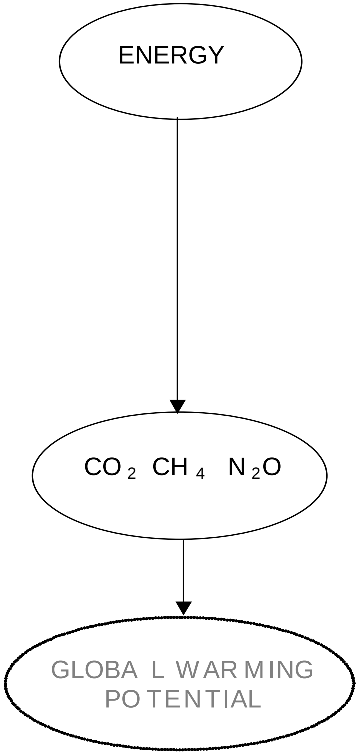
- No way of validating overall results
  - However, this is a feature of any integrated global economic environment model.

Ideal versus conventional model

REALITY (IDEAL)



CONVENTIONAL LCA



CONVENTIONAL LCA VS. REALITY

No policy analysis: conventional LCA assumes that one set of activities replaces another.

Energy systems are well represented (~90%), but materials life cycle, infrastructure, and land-use usually are not.

Conventional LCAs do not model price changes and their effects.

Some CH_4, N_2O omitted. CO, NO_X, SO_X, PM, O_3, etc., omitted. C cycle and N cycle are incomplete. Albedo, water cycle not modeled.

GWPs are simplistic and do not capture several important aspects of climate change.

Conventional LCA does not model impacts of climate change.

Contribution of key factors to total lifecycle emissions (% of fuel+vehicle lifecycle CO_2-equivalent emissions

Factor	Ethanol/corn	Ethanol/grass	Biodiesel/soy	Source
NO_2	++	+	+++	LEM.
NH_3	++	+	+++	LEM
N_2O emissions	++	+	+++	LEM.
CH_4 from plants	~ 0 ?	~ 0 ?	~ 0 ?	Literature.
ag., soil dust	?	?	?	
LUC: CO_2	++	- +	+++	LEM.
LUC: albedo, water cycle	similar to LUC CO_2?	similar to LUC CO_2?	similar to LUC CO_2?	Literature.
Co-products	- -	- -	- - -	LEM.
Price changes	+ ?	+ ?	+ ?	My judgment.

LUC = land-use change.

Issues in GHG LCA of biofuels, and their treatment in the LEM and in other studies: land-use change

- Land-use changes and cultivation: carbon emissions
  - **LEM**: Present-value, time-discounted (with declining discount rate), life-cycle analysis of climate damages due to changes in carbon sequestration in soils and biomass, by crop type and displaced ecosystem. Accounts for price-induced intensification and consumption suppression and for reversion of land at end of program.
  - **Other studies**: Some recent detailed analyses with economic models, but improper conceptual framework (improper exclusion of reversion, improper treatment of time).

- Land-use changes: albedo, hydrodynamics
  - **LEM**: Presently not included. Plan to add albedo in a year or two; no plans to add hydrodynamics.
  - **Other studies:** Not in any LCAs (lots of work outside of LCA, of course).

Issues in GHG LCA of biofuels, and their treatment in the LEM and in other studies: nitrogen cycle

- Nitrogen cycle
  - **LEM**: Complete N input-output balance calculation, accounting for residue, fertilizer, N fixation, manure, deposition, gaseous losses, crop output, runoff, N transfer between co-rotated crops, and more, with explicit changes over time (e.g., reduced run-off losses) (under development; to be completed by December 2009).
  - **Other studies**: The treatment of the N cycle is much less comprehensive.

- Climate impacts of NO_X and NH_3 emissions
  - **LEM**: Full accounting for multiple fates of N (particulate matter, N_2, NO_X, N_2O, NH_3 etc.), with global N-deposition, N transfer, and N transformation (under development; to be completed by December 2009).
  - **Other studies**: Not included in other biofuel LCAs.

Issues in GHG LCA of biofuels, and their treatment in the LEM and in other studies: non-CO_2 GHGs

- CO_2 equivalency of non-CO_2 GHGs
  - **LEM**: Estimation of present value of damages from climate change over 1000 years, accounting for direct and indirect radiative forcing, climate sensitivity, lag to reach equilibrium temperature, overlapping forcing bands, and more.
  - **Other studies**: Integrated radiative forcing over 100 years.
- Climate impacts of CO, aerosols (black carbon, organic carbon, and dust), SO_X, and other gases
  - **LEM**: Included.
  - **Other studies**: Not included.
- CH_4 from plants, agricultural dust
  - **LEM**: Not included.
  - **Other studies**: Not included.

Issues in GHG LCA of biofuels, and their treatment in the LEM and in other studies: materials

- Material inputs
  - **LEM**: Detailed LCA of major materials for vehicles, with conceptually correct, detailed treatment of manufacturing recycling and post-consumer recycling (under development).
  - **Other LCA models**: Now in some biofuel LCA models (e.g., materials added to GREET recently).

- "Indirect" energy embodied in machinery
  - **LEM**: Simple representation of energy inputs to manufacture, maintenance, repair of farm equipment; more detailed analysis underway.
  - **Other studies**: Several simple but not definitive analyses in the literature. (Unpublished analysis for GREET?).

Issues in GHG LCA of biofuels, and their treatment in the LEM and in other studies: economics

- Economic/price effects (policy → prices → output/use → emissions)
  - **LEM**: presently the LEM has a few quasi-elasticities; a systematic, integrated treatment is planned for 2011.
  - **Other studies**: Not included.
  - Potentially big deficiency in all models.

- Treatment of "coproducts"
  - **LEM**: Explicit estimation of emission changes in co-product markets (only coherent method, nothing else makes any sense!); with crude accounting for impacts of co-products on prices and final consumption.
  - **Other studies**: There are good partial treatments of this in other studies (some better than in LEM), but without economics.

Issues in GHG LCA of biofuels, and their treatment in the LEM and in other studies: other issues

- Trends in energy use, farming, emissions, etc.
  - **LEM**: Projections of all important energy-use parameters, farming variables, emission factors, and so on, based on historical data, regulations, and professional judgment.
  - **Other studies**: Traditional area of focus in LCA, so this is handled well in most other models.

- Representation of petroleum lifecycles for comparison
  - **LEM**: Specific energy-use and emission factors for oil production, oil refining, and transport, for every major oil-producing region, with changes over time. Includes explicit regional treatment of heavy oil, NG venting and flaring emissions, and so on. (Future refinements planned).
  - **Other studies**: In most models, not as much spatial and temporal detail as in the LEM.

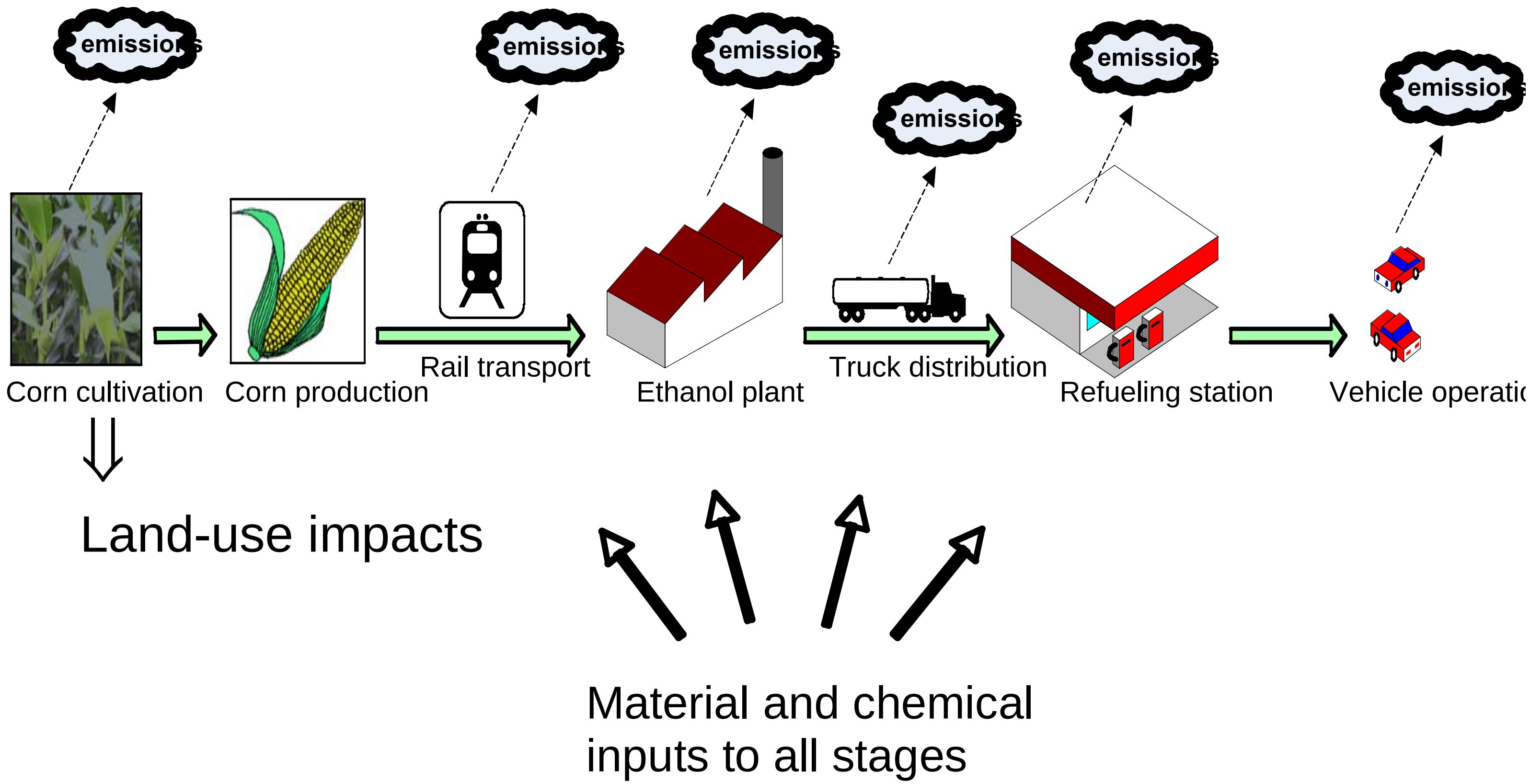
Vehicle fuels and feedstocks in the LEM

(Biofuel pathways in blue)

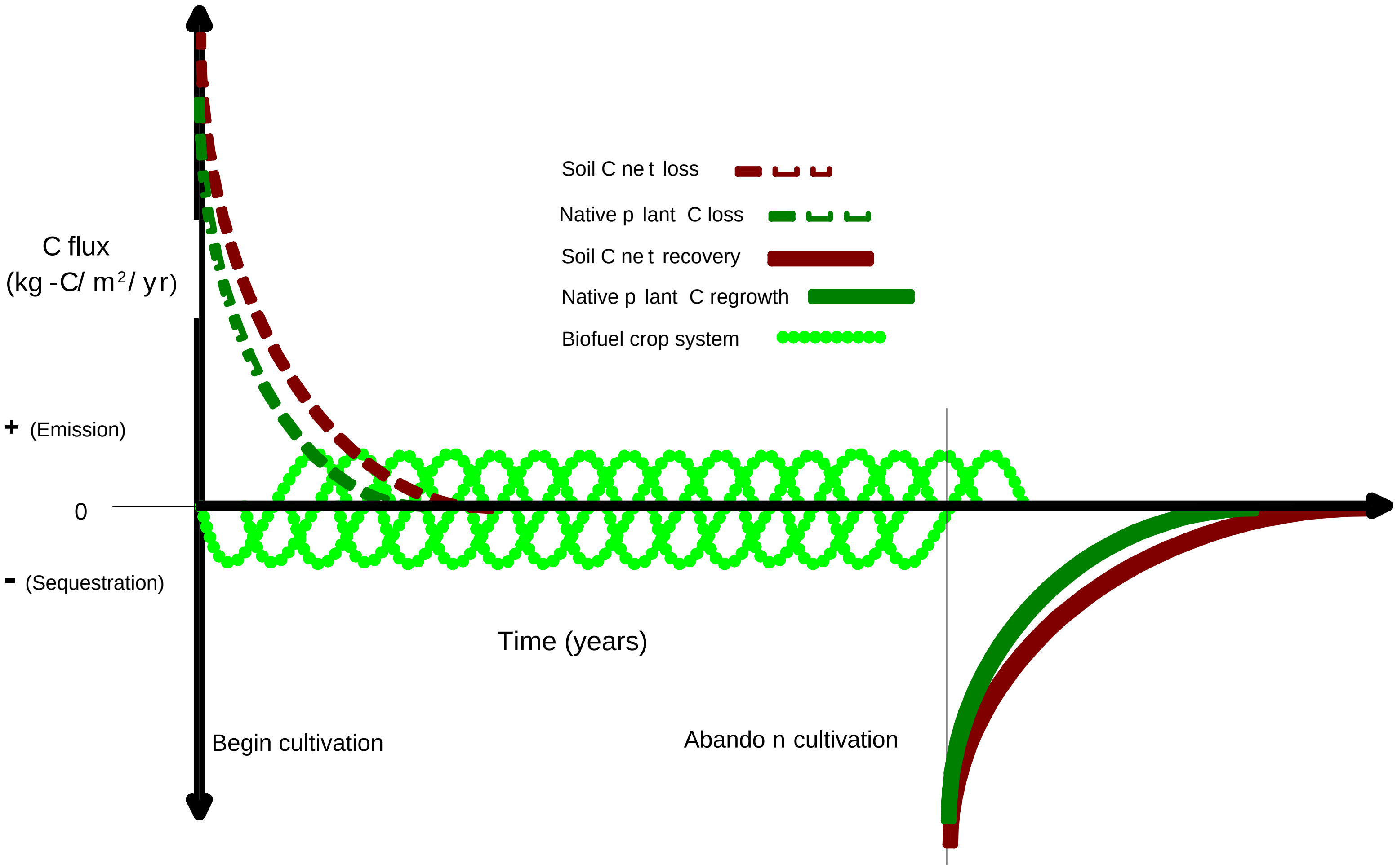
Fuel --> **Feedstock**	*Gasoline*	*Diesel*	*Methanol*	*Ethanol*	*CNG, LNG*	*LPG*	*CH2, LH2*	*Electric*
Petroleum	ICEV, FCV	ICEV				ICEV		BPEV
Coal	ICEV	ICEV	ICEV, FCV				FCV	BPEV
Natural gas		ICEV	ICEV, FCV		ICEV	ICEV	ICEV, FCV	BPEV
Wood, grass			ICEV, FCV	ICEV, FCV	ICEV		FCV	BPEV
Soybeans		ICEV						
Corn				ICEV				
Solar							ICEV, FCV	BPEV
Nuclear							ICEV, FCV	BPEV

ICEV = internal combustion engine vehicle; BPEV = battery electric vehicle; FCV - fuel cell electric vehicle

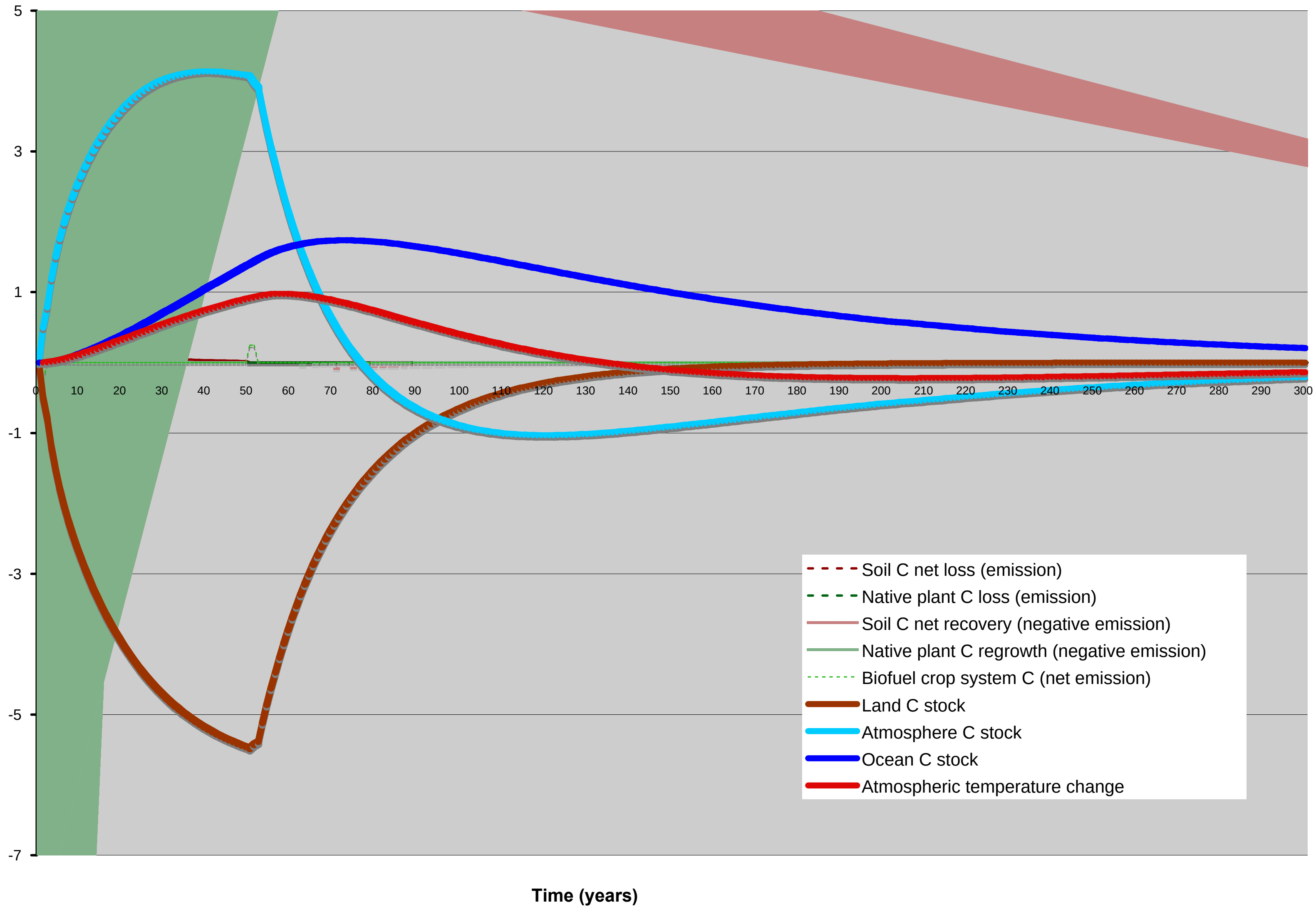
Corn-to-ethanol fuel pathway



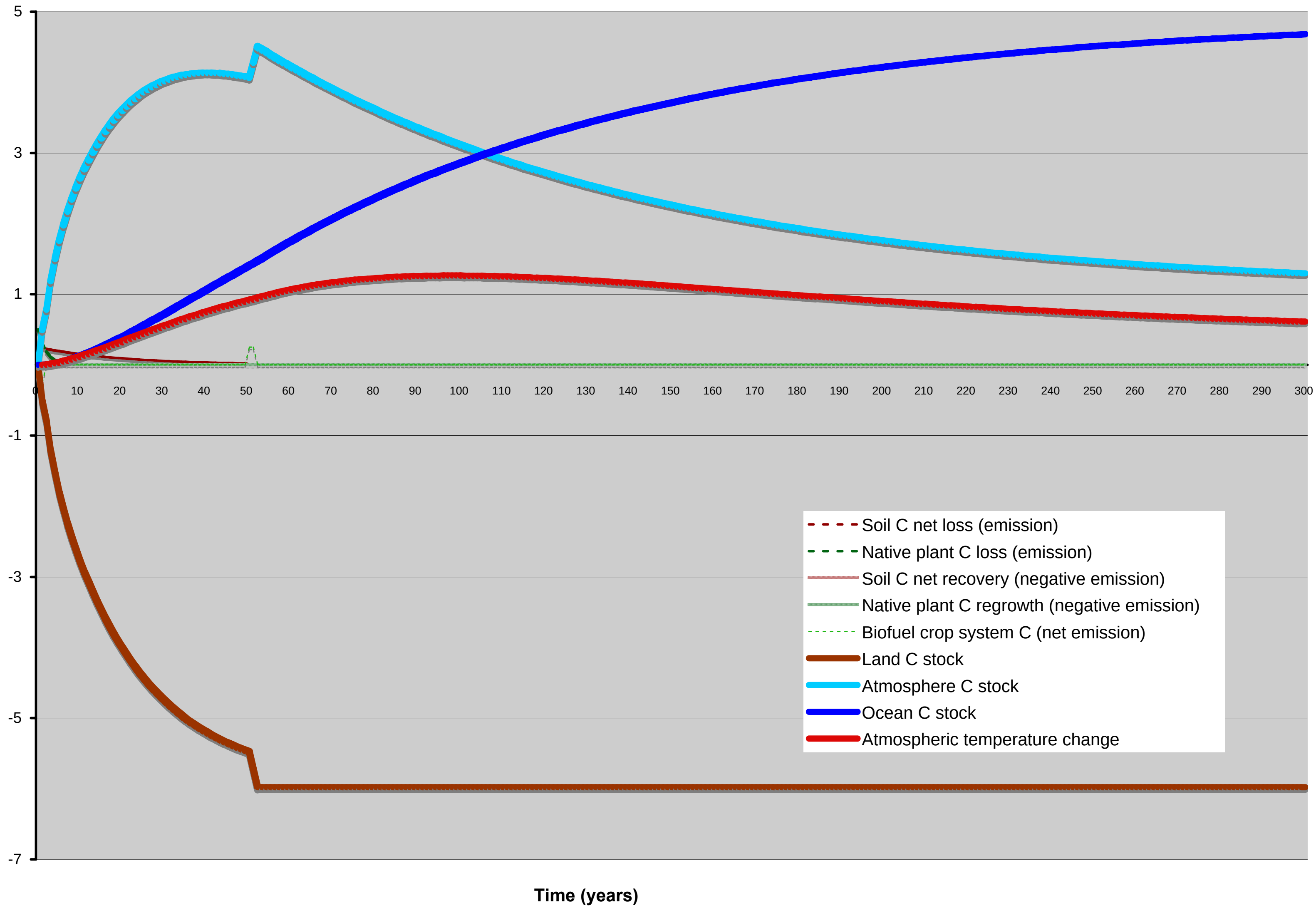
Emissions over time from plants and soil due to land-use change



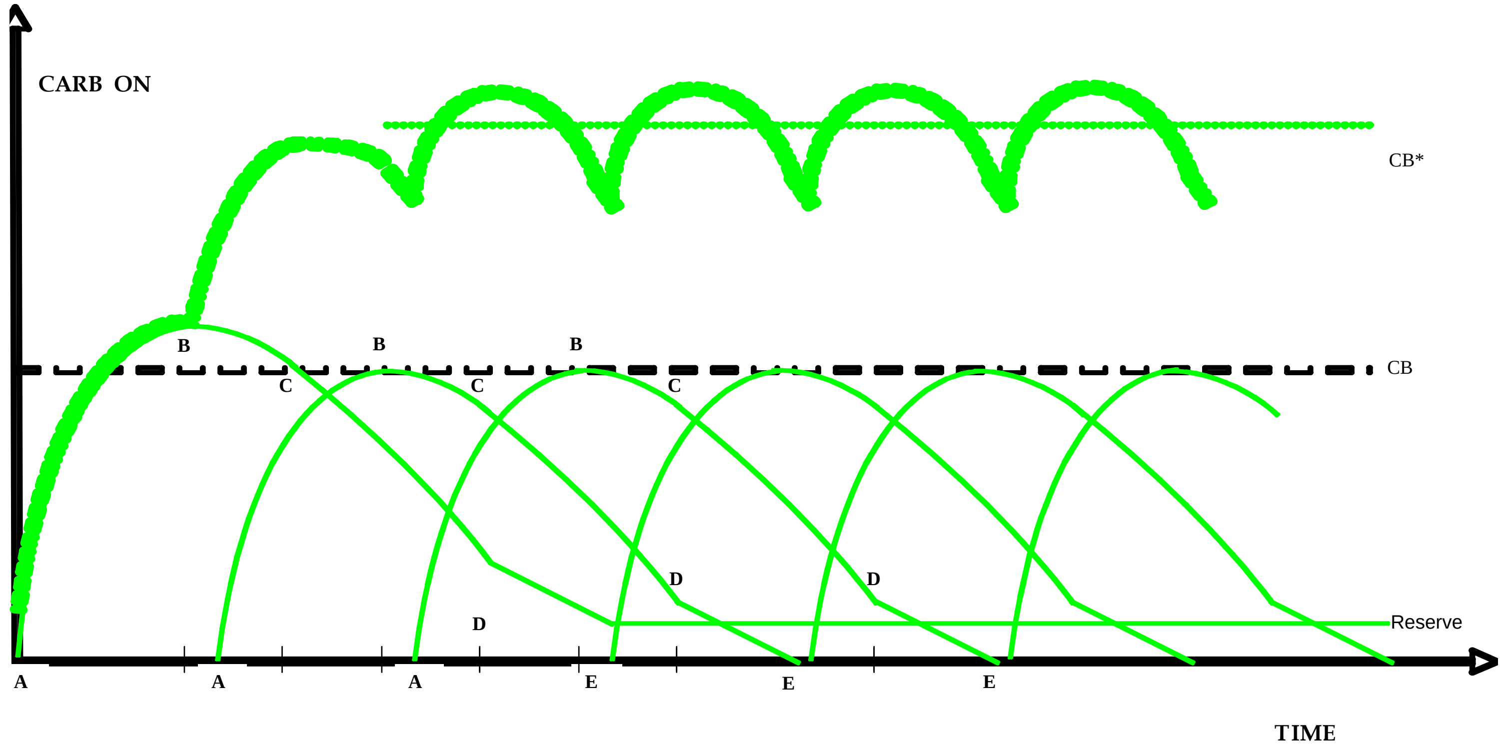
Changes in land, atmosphere, and ocean C stocks due to C emissions from land-use change (with reversion of land use at end of cultivation)



Changes in land, atmosphere, and ocean C stocks due to C emissions from land-use change (no reversion of land use at end of cultivation)



The history of C in plant and fuel product in a biomass energy system



A = beginning of planting; B = harvest (maximum plant biomass); C = beginning of oxidation of fuel and other products; D = end of oxidation of fuel and other products; E = end of oxidation of non-marketed products; Reserve = reserve stocks of fuel.

= carbon history of one cycle

= CB, the average carbon content of biomass at mature biocrop, at harvest

= carbon history of whole system (all individual cycles summed);

= CB*, the average annual carbon in the plant biomass+bioproducts energy system

Sensitivity of lifecycle CO_2-equivalent emissions to wetland share of displaced land use

	Wetlands displaced (% of land cultivated)				
Corn ethanol lifecycle	*0%*	*1%*	*2%*	*3%*	*5%*
Land use, cultivation (g/mi)	121	154	187	220	287
Co-product displacement (g/mi)	-99	-110	-122	-134	-158
Sub total (fuelcycle) (g/mi)	443	464	485	507	549
% change vs. LDgasoline vehicle (fuelcycle)	2.6%	7.5%	12.4%	17.4%	27.2%
Soy biodiesel lifecycle					
Land use, cultivation (g/mi)	9,726	11,141	12,556	13,970	16,800
Co-product displacement (g/mi)	-3,943	-3,943	-3,943	-3,943	-3,943
Sub total (fuelcycle) (g/mi)	11,177	12,592	14,006	15,421	18,251
% change vs. HDiesel vehicle (fuelcycle)	132%	162%	191%	220%	279%
Switchgrass-ethanol lifecycle					
Land use, cultivation (g/mi)	26	55	84	112	169
Co-product displacement (g/mi)	-27	-27	-27	-27	-27
Sub total (fuelcycle) (g/mi)	248	277	306	334	391
% change vs. LDgasoline vehicle (fuelcycle)	-42.4%	-35.8%	-29.2%	-22.6%	-9.3%

Note: shaded column shows the base case. Fuel cycle does not include vehicle/material lifecycle.

Sensitivity of lifecycle GHG emissions to the length of the biofuels program

CORN-ETHANOL	**20 yrs**	**35 yrs**	**50 yrs**	**75 yrs**	**100 yrs**	**150 yrs**
Land use changes and cultivation (g/mi)	263.0	202.0	176.8	155.6	143.4	127.4
Emiss. displaced by coproducts (g/mi)	(118.0)	(99.5)	(91.9)	(85.5)	(81.8)	(76.9)
% Æ vs. gasoline (fuel cycle)	29.1%	19.1%	14.9%	11.5%	9.4%	6.8%
SOY-BIODIESEL						
Land use changes and cultivation (g/mi)	14,510.6	11,075.0	9,631.0	8,392.3	7,657.2	6,684.8
% Æ vs. diesel (fuel cycle)	296.1%	202.4%	163.0%	129.2%	109.2%	82.7%
CELLULOSIC-ETHANOL						
Land use changes and cultivation (g/mi)	147.6	114.0	100.3	89.0	82.5	74.3
% Æ vs. gasoline (fuel cycle)	-28.2%	-36.2%	-39.4%	-42.1%	-43.6%	-45.6%

Note: length of time is from beginning of planting of first crop to abandonment the specific biofuel program (i.e, to beginning of reversion to original land uses). Fuel cycle does not include vehicle/material lifecycle

Sensitivity of lifecycle CO_2-equivalent emissions to ratio of system C to plant C

	Corn-to-ethanol	Grass-to-ethanol	Soy–to-biodiesel
Change CB*:CB from 1.0 to 1.5	-5%	-5%	-10% or more

Values are absolute percentage changes (percentage points) in fuel lifecycle GHG emissions.

Sensitivity of lifecycle CO_2-equivalent emissions to the time path of the discount rate

	Year base value of 1.8% is reached				
Corn ethanol (g/mi)	**2030**	**2065**	**2100**	**2130**	**2150**
Land use, cultivation	127	154	156	141	132
Coproduct displacement	-76	-85	-85	-81	-78
Sub total (lifecycle)	467	481	471	450	438
% change w.r.t. gasoline	2.7%	8.4%	11.4%	11.3%	10.8%

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Note: shaded column shows the base case.

Other factors are looking to be important

- C in ag. sector has short turnover time -- this reduces the C sink capacity of the biosphere and increases atmospheric CO_2.

- Changes in albedo and evapotranspiration due to land-use change and agricultural practices (such as irrigation) can have significant local, regional, and even global climate impacts.
  - Deforestation in northern latitudes might even cause net cooling, with higher albedo (due to more snow, due to clearing) outweighing the release of C from deforestation.

Calculation of CO_2-equivalency factors

$$CEF_{i,F,TH} =$$

$$\frac{MW_{CO2}\cdot\sum_0^{TH}\Delta D_{i,\Delta N}\left(\Delta T_{i,\Delta N}\left[\Delta X_{i,\Delta N..0}\left(L_{i,\bar{N}..0}(C_{i,\bar{N}..0}),t\right)\,F_{i,\bar{N}..0}\left(C_{i,\bar{N}..0}\right)\,\lambda'_i\right]\right)DF_{\bar{N}}\left(r_{\bar{N}}(t)\right)}{MW_i\cdot\sum_0^{TH}\Delta D_{CO2,\Delta N}\left(\Delta T_{CO2,\Delta N}\left[\Delta X_{CO2,\Delta N..0}\left(L_{CO2,\bar{N}..0}(C_{CO2,\bar{N}..0}),t\right)\,F_{CO2,\bar{N}..0}\left(C_{CO2,\bar{N}..0}\right)\,\lambda'_{CO2}\right]\right)DF_{\bar{N}}\left(r_{\bar{N}}(t)\right)}$$

$CEF_{i,F,TH}$ = the CO_2-equivalency factor for the direct radiative forcing effect *F* of gas or aerosol *i* over a period of *TH*.

$^2D_{i,^2N}$ ($^2T_{i,^2N}$ […]) = the change in damages due to changes in temperature ^{2}T over the time interval ^{2}N (nominal units are dollar damages).

$^2T_{i,^2N}$ […] = the change in temperature over the time interval ^{2}N (degree-years).

$\Delta X_{i,\Delta N..0}\left(L_{i,\bar{N}..}\right)$ = the amount of gas or aerosol *i* remaining over intervals from 0 to ^{2}N (gram-years or ppmv-years).

$L_{i,\bar{N}..0}(C_{i,\bar{N}..0})$ = e-folding lifetime of gas or aerosol *i* at times *t=0* to *t* = $\bar{N}$ (years).

$F_{i,\bar{N}..0}\left(C_{i,\bar{N}..0}\right)$ = the radiative forcing per unit of gas or aerosol *i* in the atmosphere at times *t* = 0 to *t* = $\bar{N}$ (W-yrs per g-yr or W-yrs per m^2 per ppmv-year).

$C_{i,\bar{N}..0}$ = the concentration of gas or aerosol *i* in the atmosphere at times *t* = 0 to *t* = $\bar{N}$ (ppmv).

λ'_i = relative climate sensitivity of gas or aerosol *i* (unitless).

$DF_{\bar{N}}\left(r_{\bar{N}}(t)\right)$ = the discount factor at time *t* = $\bar{N}$ as a function of the discount rate.

$r_{\bar{N}}(t)$ = the discount factor at time *t* = $\bar{N}$.

MW_i = molecular mass of gas or aerosol *i* (g / mol).

t = time (years).

TH = the total period of time over which the CEF is calculated (years).

subscript ^{2}N is the interval from time *t = N-1* to time *t = N*.

subscript $\bar{N}$ is the midpoint of interval ^{2}N, equal to (N+[N-1])/2.

The climate impact of NO_X

i) NO_X participates in a series of atmospheric chemical reactions involving CO, NMOCs, H_2O, OH^-, O_2, and other species that affect the production of tropospheric ozone. The production of ozone, 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) In the atmospheric chemistry mentioned in *i)*, NO_X affects the production of sulfate aerosol.

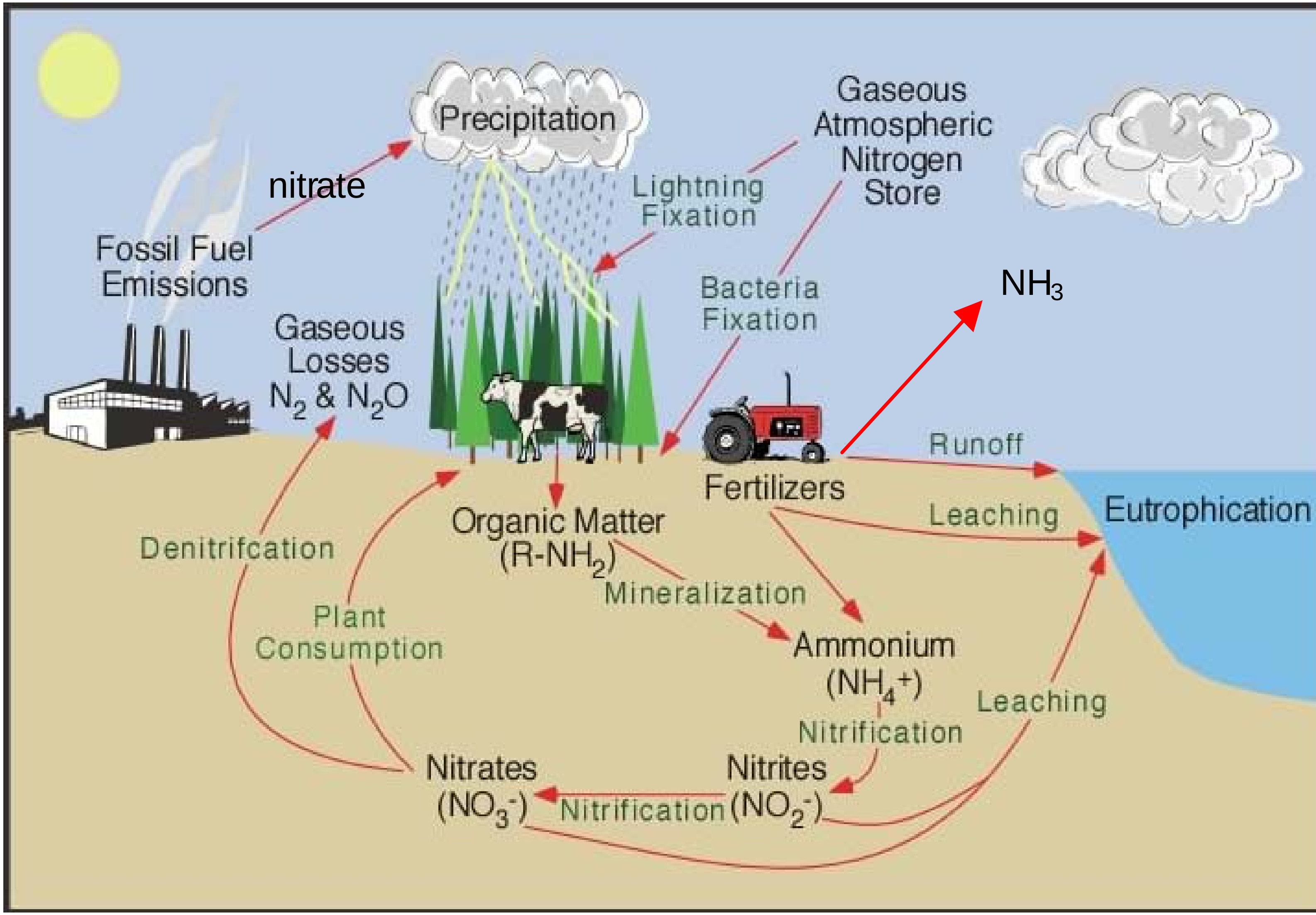
iv) NO_X converts to nitrate which deposits onto soils and oceans and then denitrifies or nitrifies into N_2O (a strong, long-lived direct climate-change gas) and NO (which oxidizes back to the indirect GHG NO_2 that was the source of the deposited N in the first place). Nitrate deposition also affects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

v) Nitrate from NO_X fertilizes terrestrial and marine ecosystems and thereby stimulates plant growth and carbon sequestration in nitrogen-limited ecosystems.

vi) NO_X forms particulate nitrates, which as aerosols have a net *negative* radiative forcing (and thereby a beneficial effect on climate) but also adversely affect human health.

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

Schematic of the nitrogen cycle



INCORPORATING PRICE EFFECTS INTO LIFECYCLE ANALYSIS

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Incorporating price effects into LCA -- what is the issue?

- In the real world, any policy or assumed market action that affects the production or consumption of a fuel may affect the price of the fuel (say, gasoline), the price of the inputs to the production of the fuel (crude oil), and the price of coproducts (e.g., diesel fuel). These price effects will ripple throughout all linked sectors of the world economy and affect equilibrium levels of production and consumption, which finally will affect GHG emissions.
- Conventional LCA does not represent these price effects, and hence mis-estimates what actually happens to climate in the real world (with real economies).
- How can we incorporate these economic effects into LCA? (The best way to do this isn't obvious.)

But first -- can we make a case that this really isn't an important issue? Can we argue that prices won't change?

- *Argument:* Politics, regulation, culture, or technology actually constrain inputs and outputs such that price changes do not occur or else have no effect. *Response:* This is possible in particular cases, but as a general rule it does not appear to apply to most of the important major commodities in the world (e.g., energy commodities such as oil and coal or raw materials such as inputs to steel production).

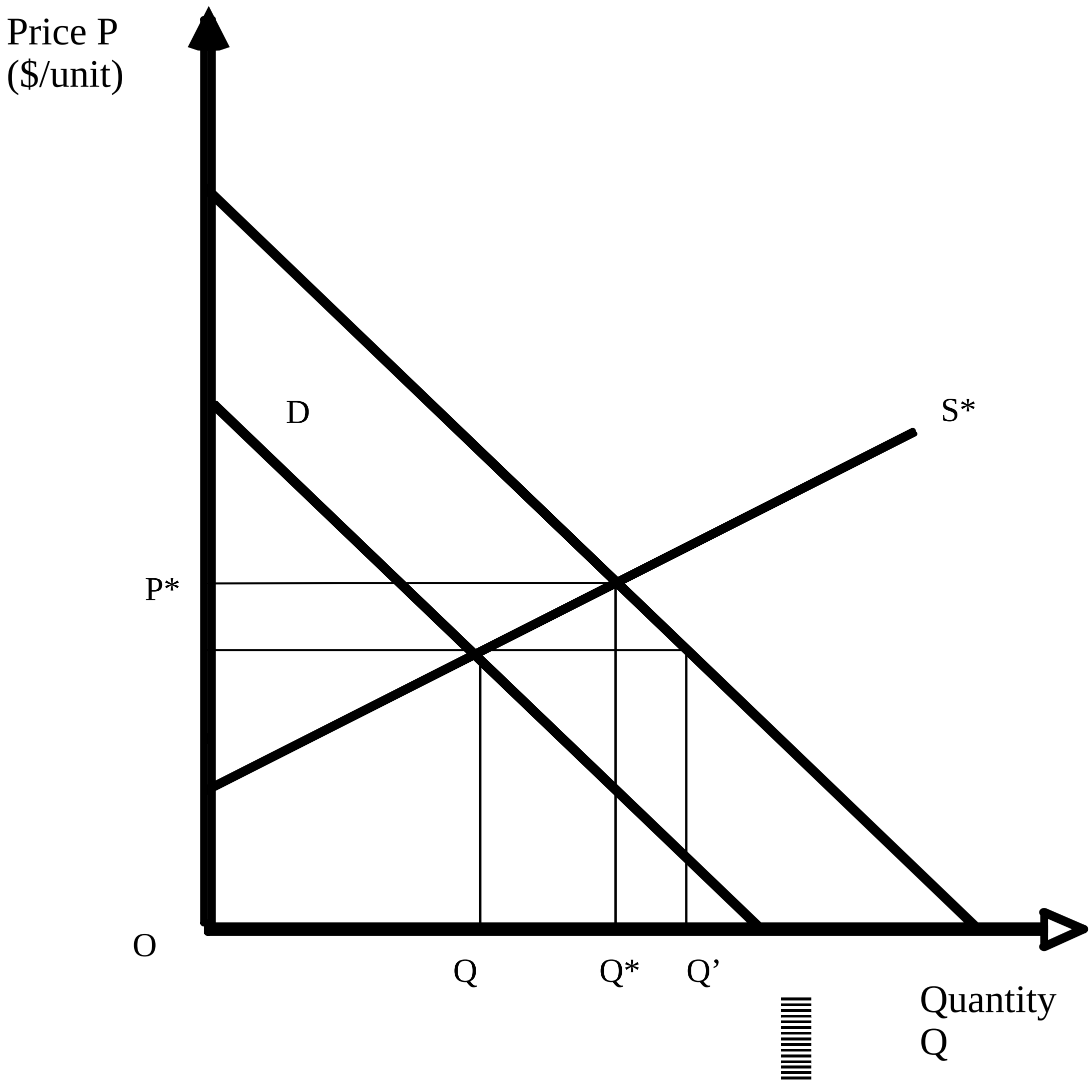
- *Argument:* Prices do not change in response to "small" changes in supply or demand; and in most instances in our problem the change in supply or demand will not be large enough to affect prices. *Response:* In the absence of constraints (already discussed above), such thresholds in theory do not exist, because in theory, supply and demand functions are continuous. (Put another way, supply curves aren't step functions.)

- *Argument:* Apart from the foregoing, the relevant elasticities are otherwise zero (e.g., supply curves are completely "flat"), with the result that prices don't change. *Response:* Empirically, I believe that this is almost never the case; e.g., long-run rising marginal costs generally are rising because of increasing economic scarcity of factors of production.

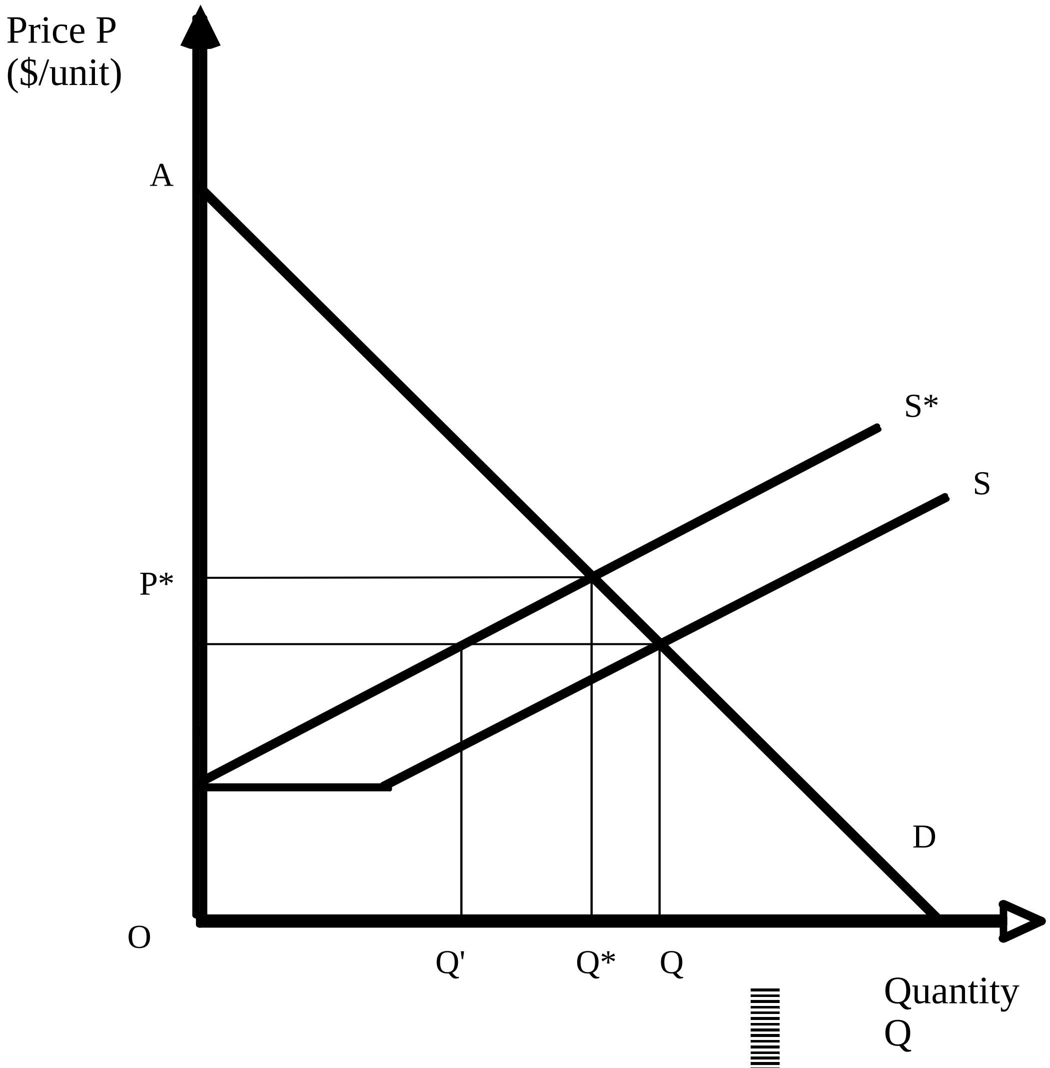
Comparing conventional LCA with economically realistic LCA

Issue	Conventional LCA	Economically realistic LCA
The aim of the analysis	Evaluate impacts of replacing one limited set of activities with another (e.g., replace petroleum production and use processes with biofuel production and use processes).	Evaluate worldwide impacts of a realistic policy or market-action scenario compared with a no-policy or no-action scenario.
Scope and method of analysis	Fixed I-O representation (energy-in/product and emissions-out) of the set of linked processes and activities that define the lifecycle.	Input/output representation of processes and activities in the lifecycle but with dynamic price linkages between all the climate-relevant sectors of the economy.

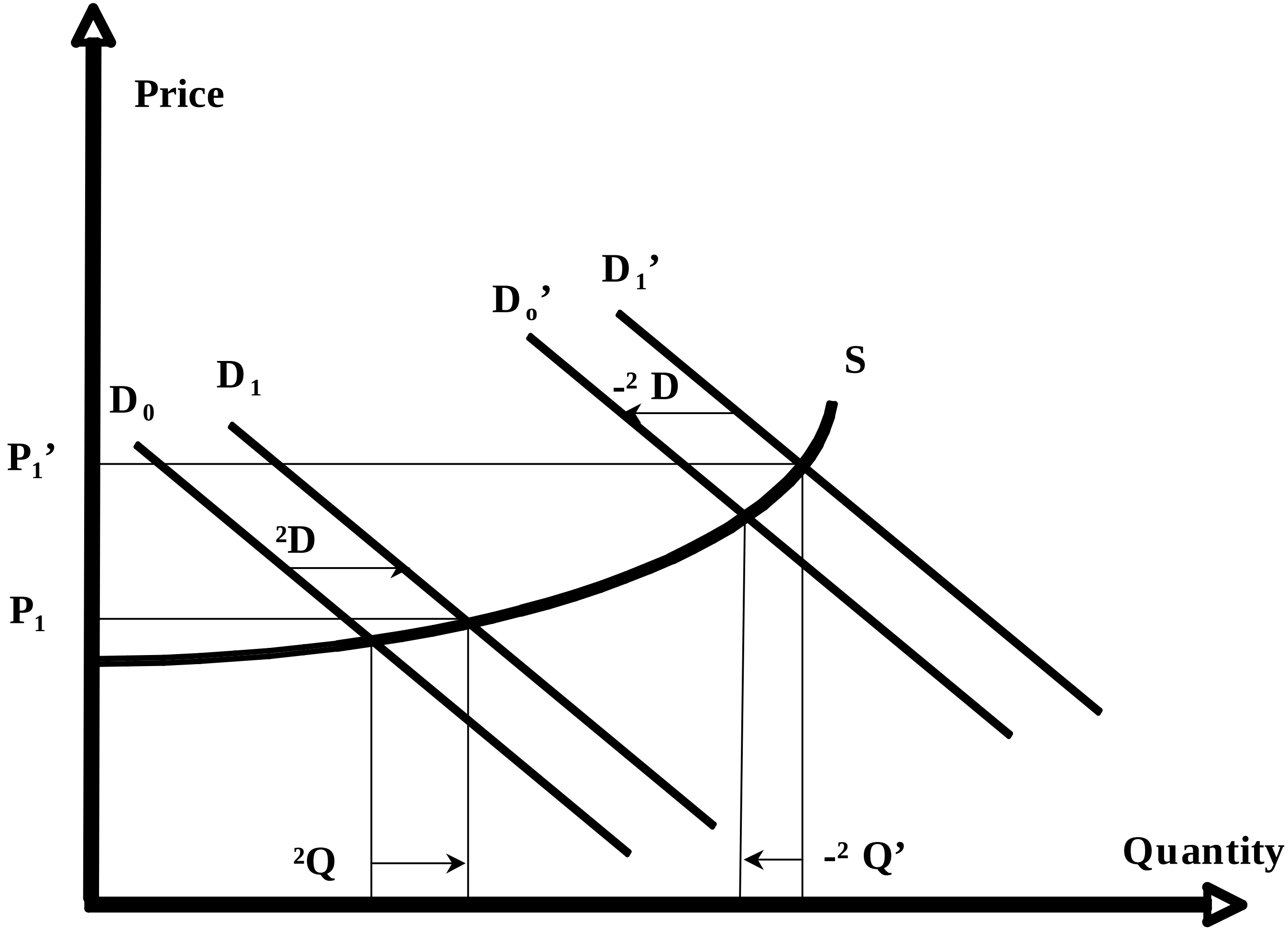
How changes in demand affect prices and quantities



How changes in supply can affect prices (co-product case)



Another example: land supply curves



D_0 = demand curve just prior to start of biofuels program; D_1 = demand curve just after start of biofuels program; D_1' = demand curve just prior to end of biofuels program; D_0' = demand curve just after end of biofuels program; S = supply curve; ² D = expansion of demand due to start of biofuels progam; -²D = contraction of demand due to end of biofuels prog am; ² Q = increase in quantity of land cultivated due to expansion of demand for bio fuels; -² Q' = decrease in quantity of land cultivated due to contraction of demand for biofuels; P_1 = price just after start of biofuels program; P_1' = price just prior to end of biofuels program.

At least four modeling ways to address this issue

- Modify CGE model. Start with a general equilibrium model, ideally one with good representation of the sectors of the economy relevant to the analysis we are conducting.
  - Add the technology, process, and I-O linkage details necessary to adequately characterize the "lifecycles" of interest.
  - Add emission factors and other climate-relevant factors (e.g., albedo) as outputs of production and consumption activities, wherever the occur.
  - Add a climate model or simplified representation of climate effects to determine the climate impacts of changes in emissions and other climate-relevant factors.

- Modify LCA model. Start with an existing "conventional" LCA model.
  - Add supply and demand functions for the important processes or activities in the lifecycle (where importance ultimately is defined with respect to climate impacts).
  - Estimate how shifts in supply or demand functions due to new fuel policies or market outcomes affect prices of important climate-relevant commodities.
  - Estimate how price changes affect production and consumption of important climate relevant commodities.
  - Estimate how changes in production and consumption (due to price changes) affect emissions.

Four ways, continued

- “Link” existing economic, LCA, climate models. Not as straightforward as it might sound, because the linkages between processes, prices, and emissions should be fairly extensive. (It probably would be relatively straightforward, though, to run an economic model first to capture a few of the big effects.)

- Build a new economic-equilibrium/LCA model from scratch. Probably harder than the other three ways, but then, you’ll get exactly what you want.

Some details on the LCA-first method

- The essence of the proposed expansion is to add to an LCA model an independent calculation that produces an estimate of the change in lifecycle emissions worldwide due to changes consumption a commodity (due to changes in prices due to shifts in demand), per unit of the commodity used in an AFL.
- The first task is figuring out where to attach these price-related emission factors. (Ideally, to any activity or process in the lifecycle that directly or indirectly significantly impacts climate.)

More details

Each price-related emission factor could have up to 8 components:

- the direct effect on the commodity of interest in price-affected commodity uses;
- the effect on products derived from the commodity of interest (call these "derivative" products);
- the effect on commodities from which the commodity of interest is derived (call these "generative" commodities);
- same as the previous, except that the effect is on other products derived from the commodities from which the commodity of interest is derived (call these "parallel" products)
- the effect on *substitutes* for the commodity of interest;
- the effect on *substitutes* for products derived from the commodity of interest;
- the effect on *substitutes* for the commodities from which the commodity of interest is derived;
- same as the previous, except that the effect is *substitutes* for the other products derived from the commodities from which the commodity of interest is derived.

A price-related emission factor could be calculated thusly:

a) define the incremental "unit" of the commodity input of interest (e.g., a BTU of natural gas);

b) estimate the supply and demand curves for the commodity of interest in the largest pertinent market area (e.g., North America), in terms of the incremental unit defined in a) (e.g., a slope expressed in $/BTU/BTU);

c) estimate a functional relationship between shifts in the demand curve and changes in price for the commodity in the same market;

d) use the relationship from c) and the estimates from b) to estimate the change in the price of the commodity;

e) estimate the price elasticity of demand, the baseline price, and the baseline consumption of the commodity for each of the direct price-affected commodity uses (PACUs) for the commodity within the pertinent market;

f) with the change in price from d) and the quantities from e), estimate the change in quantity consumed (*along* the PACU demand curve) for the commodity in each PACU;

g) identify the appropriate lifecycle emission factors for the use of the commodity in each PACU;

h) multiply the change in quantity consumed for the commodity from f) by the lifecycle emission factor from g) to obtain the change in emissions, for each PACU;

i) sum the emissions changes from h) over all PACUs.

Some major issues in economic analysis

- Which activities/processes/sectors do we construct supply or demand functions for?

- In how much detail do we represent the price effect of an initial change in an activity (e.g., natural gas use by ethanol plants) on other sectors of the economy? Can we just identify all major uses of (for example) natural gas and the major substitutes for natural gas in each use, or do we need to also account for further linkages?

- Assuming that the model can represent the effect of policies that affect prices directly, by taxes or subsidies, do we represent the effects on government revenue and expenditures and on household net income and consumption?

Important things to research

- Incorporate price-dynamic economic effects of transportation policies on use of (and hence emissions from) vehicles and fuels (*major project underway*).
- Develop more detailed treatment of byproducts and coproducts.
- Improve estimates of changes in land use due to production of biofuel crops.
- Complete representation of nitrogen cycle (*major project underway*).
- Finish revisions of estimates of CO_2-equivalency factors (preliminary analyses completed; *major project underway*).
- Finish analyses of energy embodied in seeds, tractors, and equipment in biofuel LCAs.
- Add agricultural dust emissions.
- CH_4 from plants, changes in albedo and evapotranspiration due to changes in land use?
- Add new vehicle/energy pathways (e.g., ethanol from corn stover and sugar cane, biodiesel from waste oil)