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

Mark A. Delucchi
Institute of Transportation Studies
University of California, Davis
www.its.ucdavis.edu/people/faculty/delucchi

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
  - 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.

Approximate overall results of biofuel GHG LCAs

Source	**Ethanol from corn**	**Ethanol from cellulose (grass)**	**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), 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%

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 and NH_3	-10% to -15%	-10%	-70%	LEM.
N_2O emissions	20%	10% to 15%	70% to 80%	LEM.
CH_4 from plants	small?	small?	small?	Literature.
ag., soil dust	?	?	?	
LUC: CO_2	0% to 30%	-20% to 20%	50% to 100%	LEM.
LUC: albedo, water cycle	similar to LUC CO_2?	similar to LUC CO_2?	similar to LUC CO_2?	Literature.
Co-products	-10% to -20%	-10% to -20%	-60% to -90%	LEM.
Price changes	at least 10%?	at least 10%?	at least 10%?	My judgment.

LUC = land-use change.

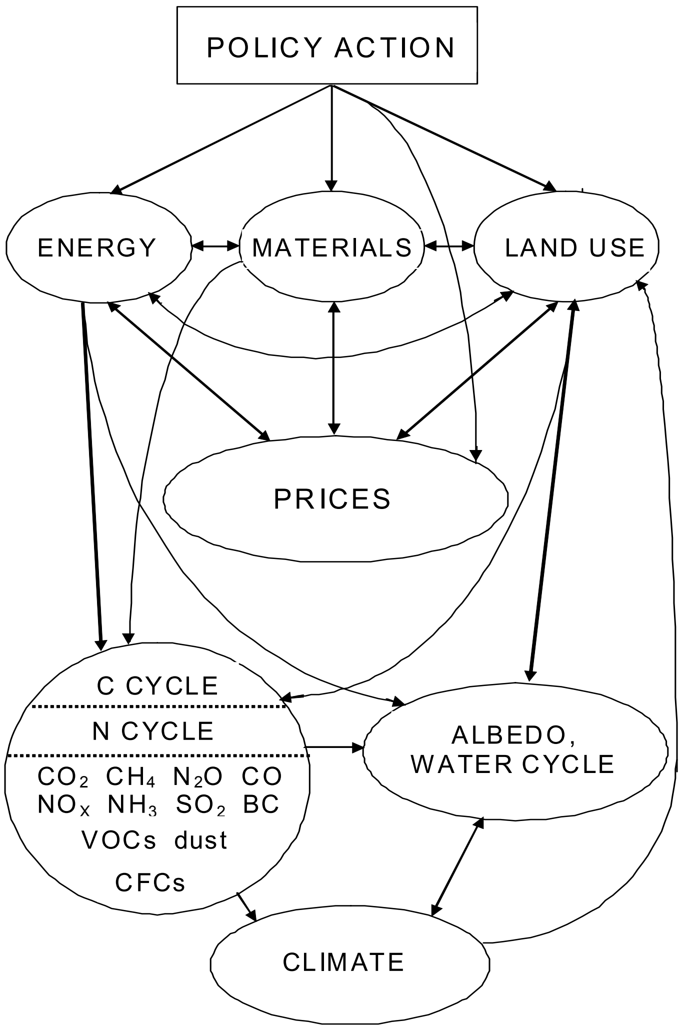
History of biofuel GHG LCA

- 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.

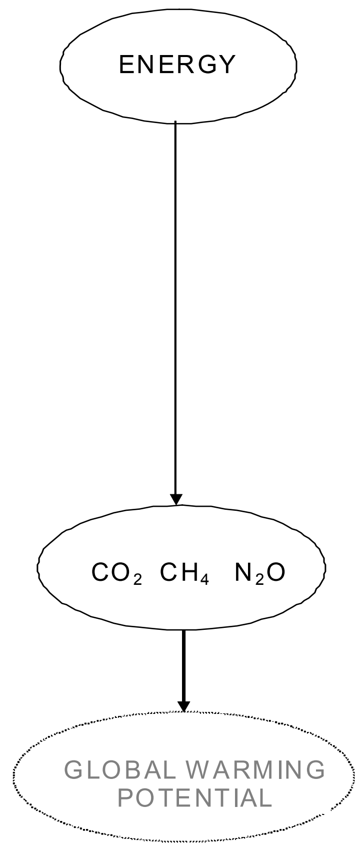
- No way of validating overall results
  - However, this is a feature of any integrated global economic environment model.

Ideal versus conventional model

REALITY (IDEAL)



CONVENTIONAL LCA



CONVENTIONAL LCA VS. REALITY

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

Energy systems are well represented (~90%), but materials lifecycle, 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.

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

- Land-use changes and cultivation
  - **LEM**: Present-value, time-discounted (with declining discount rate), life-cycle analysis of changes in carbon sequestration in soils and carbon by crop type and displaced ecosystem (including intensification and consumption suppression), accounting for reversion of land at end of program.
  - **Other studies**: Some recent detailed analyses, but incomplete conceptual framework.

- 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).
  - **Other studies**: In other biofuel LCA the treatment of the N cycle is 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.
  - **Other studies**: Not included in other biofuel LCAs.

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

- Climate impacts of CO, PM (BC, OC, and dust), SO_X other gases
  - **LEM**: Comprehensive, detailed, long-term (~1000-year) accounting of direct and indirect, time-discounted, climate-related damages.
  - **Other studies**: Not included in other biofuel LCAs.
- CH_4 from plants, albedo changes, hydrodynamics, agricultural dust
  - **LEM**: Not included.
  - **Other studies**: Not included.
- 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 studies**: Now in some (but not all) biofuel LCAs (e.g., materials added to GREET recently).

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

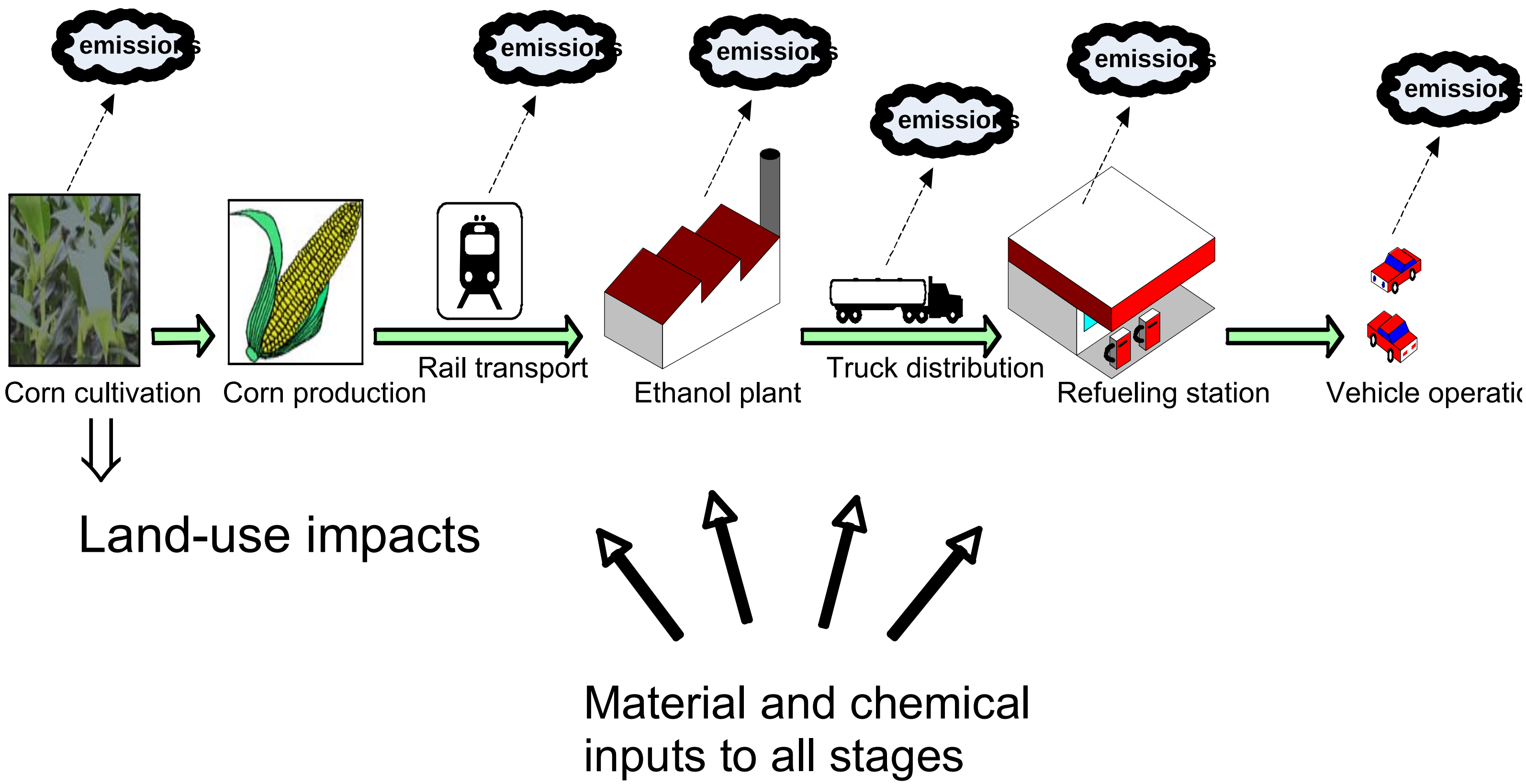
- “Indirect” energy embodied in machinery
  - **LEM**: Simple representation of energy inputs to manufacture, maintenance, repair of farm equipment; more detailed analysis underway.
  - **Other studies**: Several simple but not definitive analyses in the literature. (Unpublished analysis for GREET?).
- 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).
- Trends in energy use, farming, emissions, and so on
  - **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 in most other models.

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

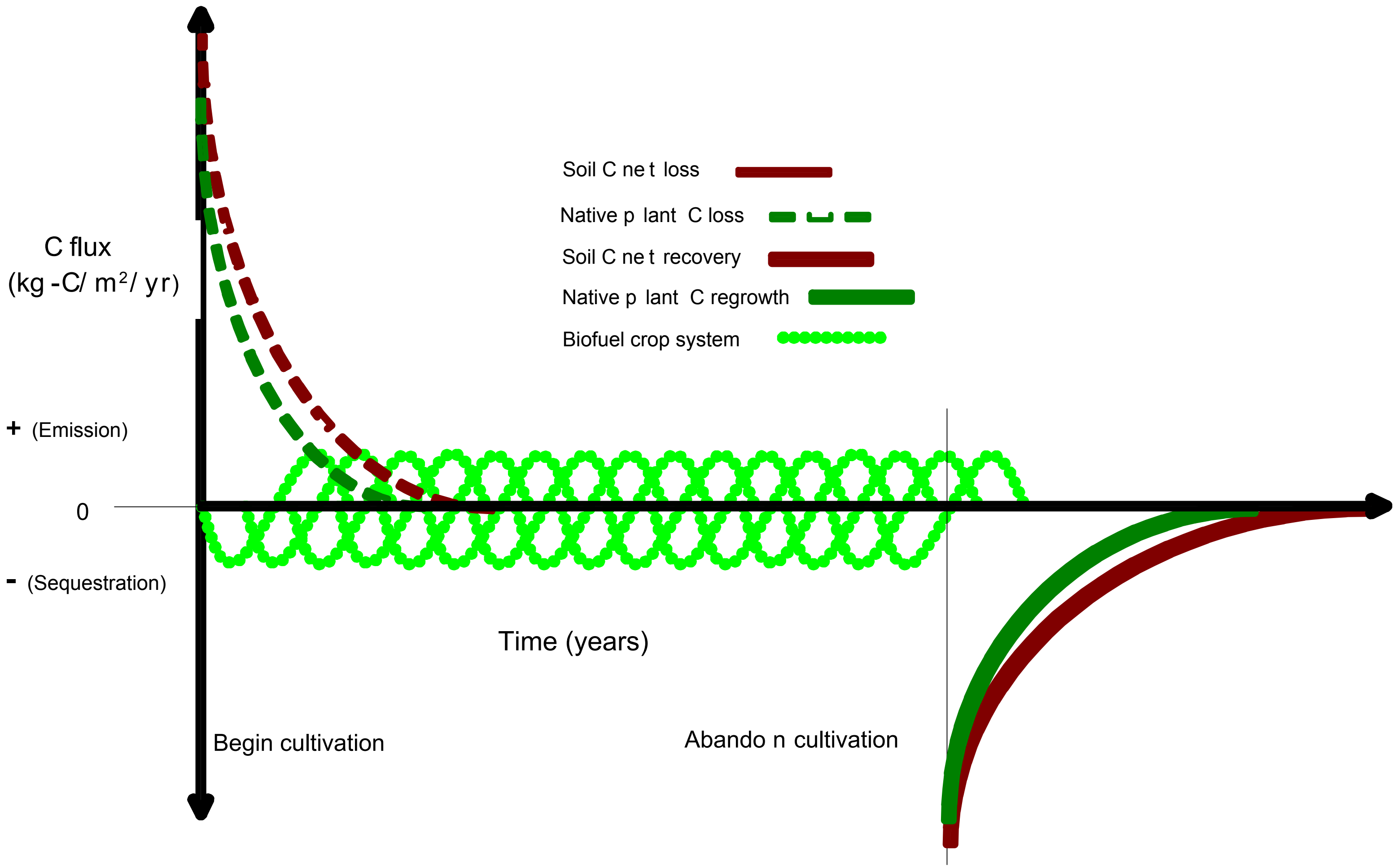
- Representation of petroleum lifecycles for comparison
  - **LEM**: Specific energy-use and emission factors for oil production, oil refining, and transport, for every major oil-producing region, with changes over time. Includes explicit regional treatment of heavy oil, NG venting and flaring emissions,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

- Economic/price effects (policy → prices → output/use → emissions)
  - **LEM**: A few quasi-elasticities, but no systematic, integrated treatment.
  - **Other studies**: Not included.
  - Potentially big deficiency in all models.

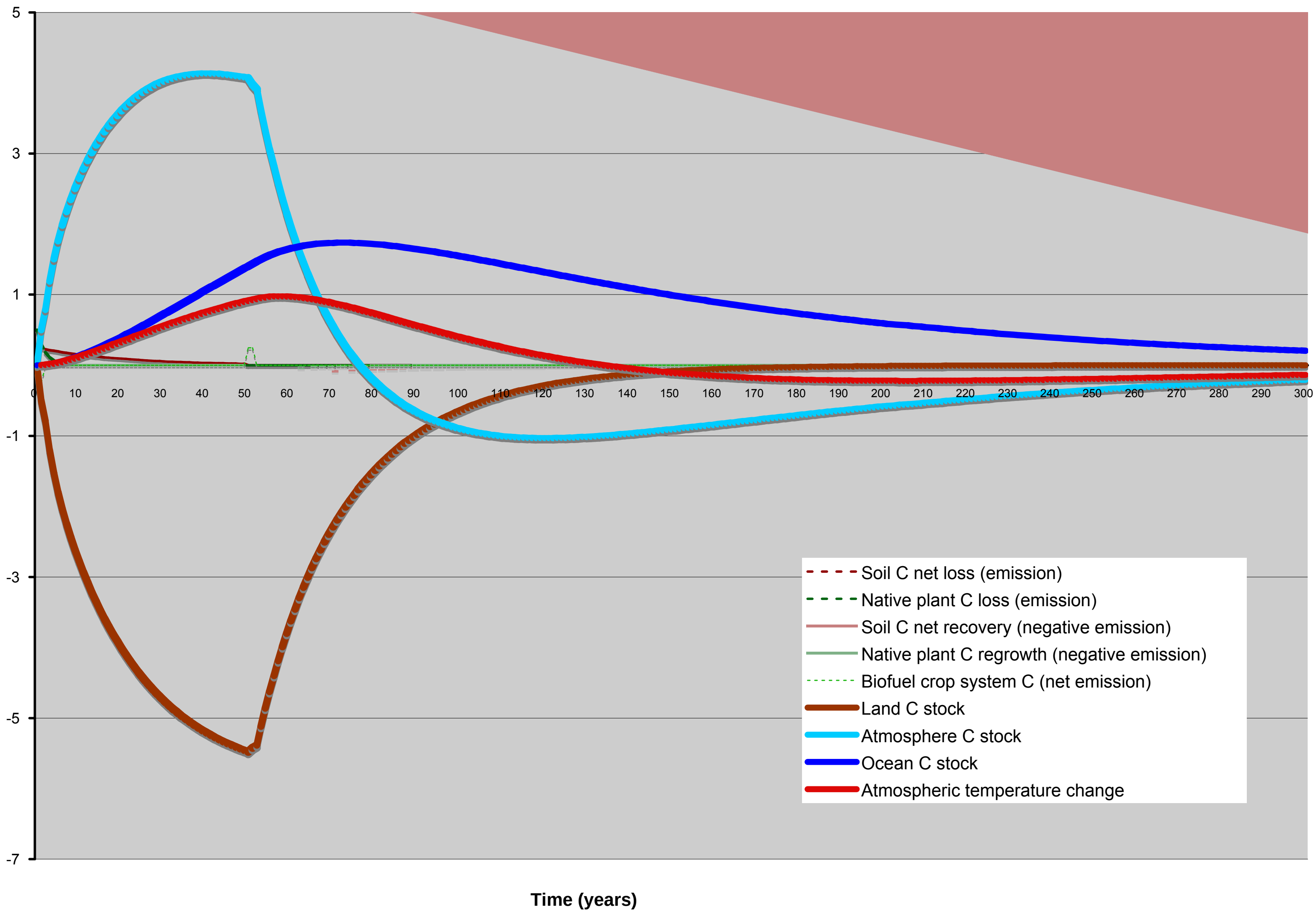
Corn-to-ethanol fuel pathway



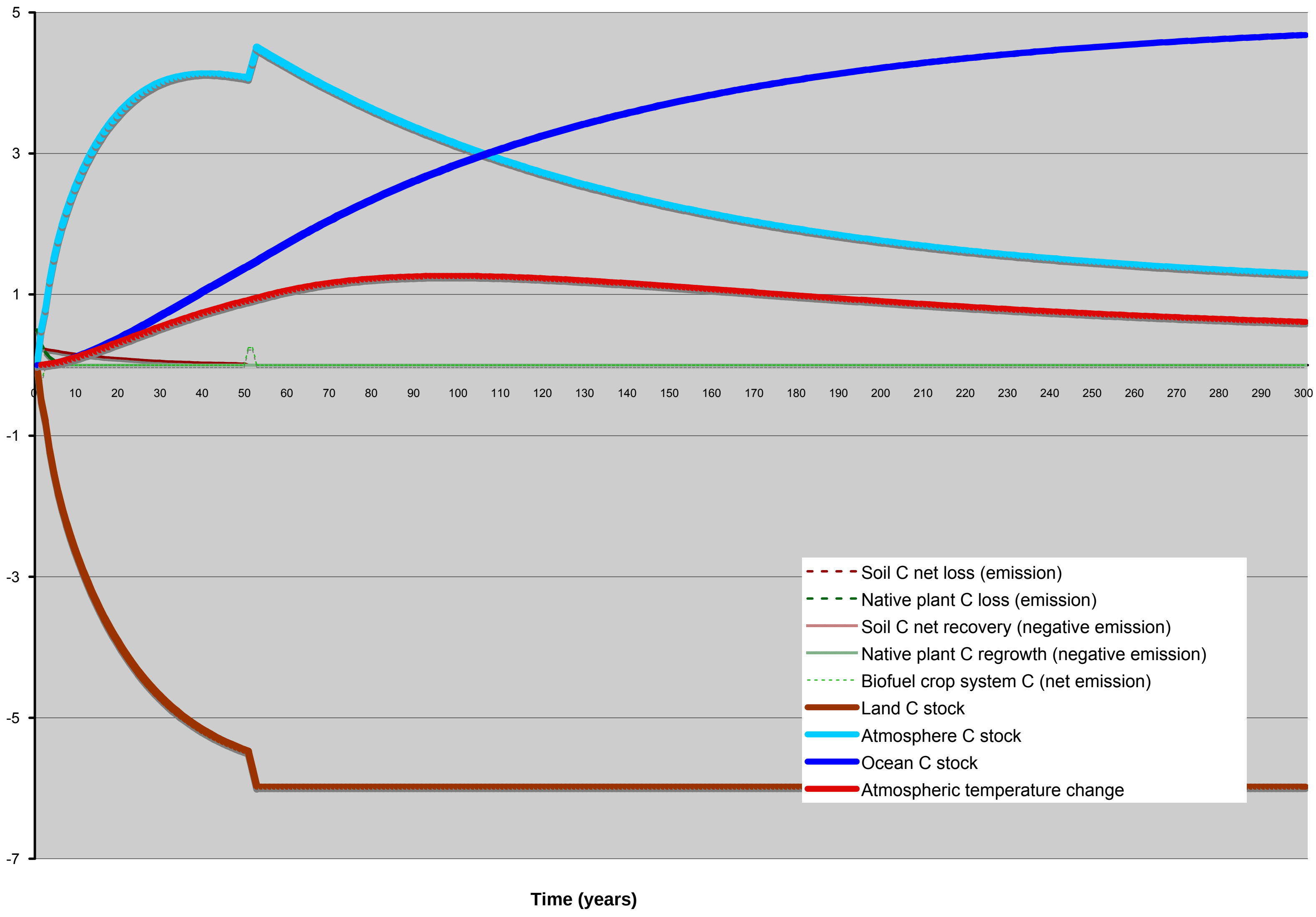
Emissions from plants and soil due to land-use change



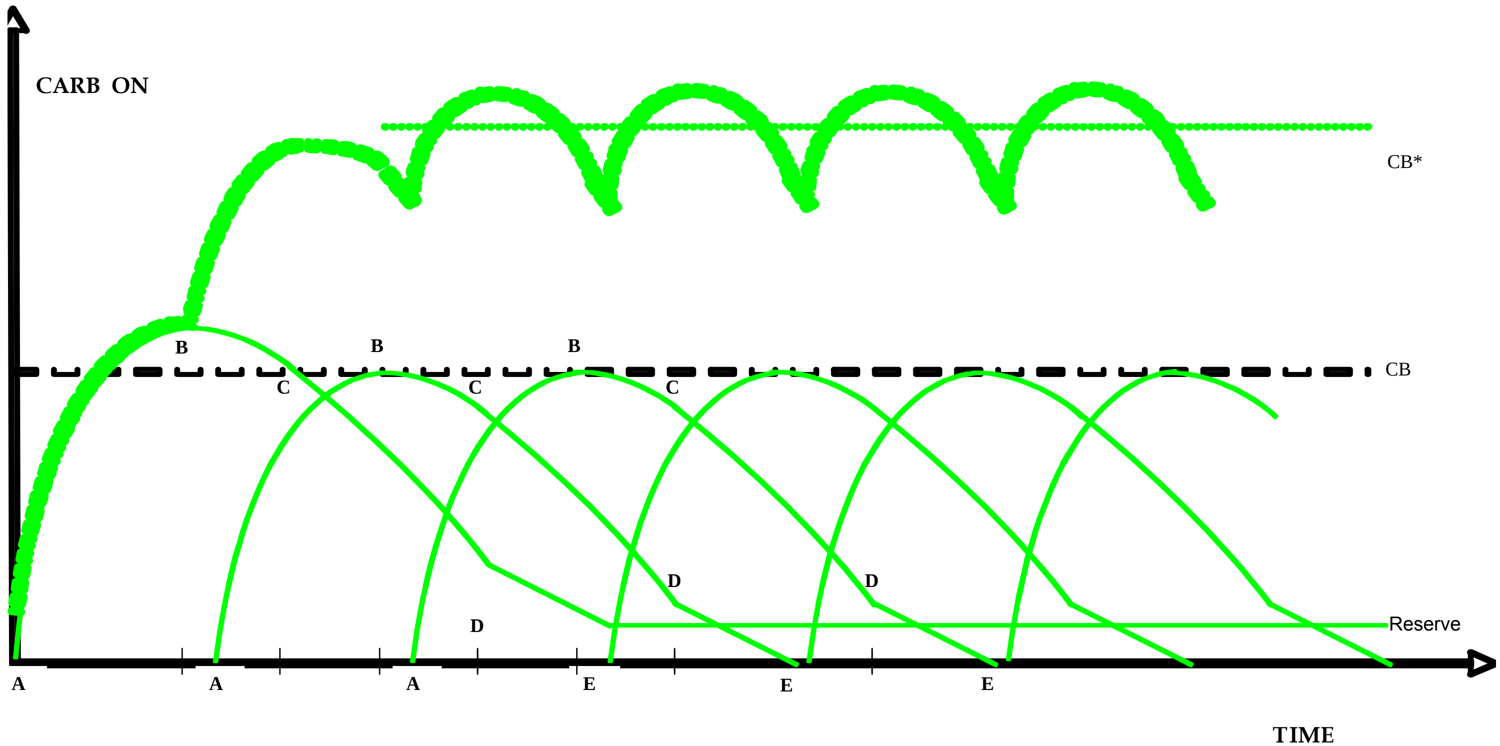
Changes in land, atmosphere, and ocean C stocks due to C emissions from land-use change (with reversion of land use at end of cultivation)



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. LD gasoline 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. HD diesel 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. LD gasoline 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)
% Δ vs. gasoline (fuelcycle)	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
% Δ vs. diesel (fuelcycle)	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
% Δ vs. gasoline (fuelcycle)	-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 (fuelcycle)	467	481	471	450	438
% change w.r.t. gasoline	2.7%	8.4%	11.4%	11.3%	10.8%

.

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 albedo effect outweighing C release effect.

Calculation of CO_2-equivalency factors

$$CEF_{i,F,TH} = \frac{MW_{CO2} \cdot \sum_{0}^{TH} \Delta D_{i,\Delta N}\left(\Delta T_{i,\Delta N}\left[\Delta T_{i,\Delta N-1},\ \Delta X_{i,\Delta N}\left(L_{i,\bar{N}}(C_{i,\bar{N}}),t\right) F_{i,\bar{N}}\left(C_{i,\bar{N}}\right) \lambda'_i,\ LAG\right]\right) DF_{\bar{N}}\left(r_{\bar{N}}(t)\right)}{MW_i \cdot \sum_{0}^{TH} \Delta D_{CO2,\Delta N}\left(\Delta T_{CO2,\Delta N}\left[\Delta T_{CO2,\Delta N-1},\ \Delta X_{CO2,\Delta N}\left(L_{CO2,\bar{N}}(C_{CO2,\bar{N}}),t\right) F_{CO2,\bar{N}}\left(C_{CO2,\bar{N}}\right) \lambda'_{CO2},\ LAG\right]\right) DF_{\bar{N}}\left(r_{\bar{N}}(t)\right)}$$

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

$\Delta D_{i,\Delta N}(\Delta T_{i,\Delta N}[\ldots])$ = change in damages due to changes in Δ T over the time interval Δ N, due to emission of gas *i*.

$\Delta T_{i,\Delta N}[\ldots]$ = change in temperature over the time interval Δ N, due to emission of gas *i*.

$\Delta X_{i,\Delta N}\left(L_{i,\bar{N}}\ldots\right)$ = amount of gas *i* remaining over interval Δ N (gram-years or ppmv-years).

$L_{i,\bar{N}}(C_{i,\bar{N}})$ = e-folding lifetime of gas *i* at time $t = \bar{N}$, a function of concentration *C*.

$F_{i,\bar{N}}\left(C_{i,\bar{N}}\right)$ = radiative forcing of gas *i* in the atmosphere at time $t = \bar{N}$ (W-yr per m^2 per ppmv-yr).

$C_{i,\bar{N}}$ = the concentration of gas *i* in the atmosphere at time $t = \bar{N}$ (ppmv).

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

LAG = the lag between changes in radiative forcing and changes in temperature.

$DF_{\bar{N}}\left(r_{\bar{N}}(t)\right)$ = 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 *i* (g/mol) (1.0 in the case of aerosols and ozone, because *F(C)* already is in W/g).

t = time (years).

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

subscript ΔN is the interval from time $t = N\text{-}1$ to time $t = N$.

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

Pollutants and climate effects in the LEM

Pollutant --> effects related to global climate	CEF (U.S. 2050)	CEF (U.S. 1990)	IPCC 100yr GWP
CO_2 → +R	1	1	1
CH_4 → +R, -OH, +O_3 (t), +CH_4, +H_2O (s), +CO_2, +CO, +SO_4	17	19	23
N_2O → +R	230	260	296
O_3 → +R, -soil C, -plant C; see CO, H_2, CH_4, NMOCs, NO_2	4	4	n.e.
PM (black carbon) → +R, clouds, more	1,300	1,400	n.e.
PM (organic matter) → -R, clouds, more	-150	-163	n.e.
PM (sulfate [SO_4]) → -R, clouds, more	-78	-85	n.e.
PM (nitrate [NO_3]) → -R, clouds, more	-97	-106	n.e.
PM (organic aerosol) → -R, clouds, more	-65	-70	n.e.
PM (generic dust) → -R, clouds, more	-3	-3	n.e.
CO → -OH, +O_3 (t), +CH_4, +CO_2, +SO_4	3	3	1.57 [a]
H_2 → -OH, +O_3 (t), +CH_4	5	5	n.e.
NMOCs → -OH, ±O_3 (t), +CH_4, +CO_2, +SO_4	6 + C	3 + C	n.e.
NO_2 → -CO_2, +N_2O, ±OH, +O_3 (t), -CH_4, +PM, +SO_4	-12	-16	n.e.
NH_3 → -CO_2, +N_2O, + NO_3, +SO_4	n.e.	n.e.	n.e.
SO_2 → +PM	- 48	- 53	n.e.
H_2O → +R (s), +OH, -CH_4, clouds, more	n.e.	n.e.	n.e.
CFC-12 → +R, -O_3 (s)	12,500	11,400	8,600
HFC-134a → +R	1,300	1,200	1,300
SF_6 → +R	130,000	120,000	22,200

The climate impact of NO_X

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 O_3, 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, which oxidizes CH_4 and thereby affects the lifetime of CH_4.

iii) In the atmospheric chemistry mentioned in *i)*, NO_X affects the production of sulfate aerosol.

iv) As nitrate, NO_X deposits onto soils and oceans and then denitrifies or nitrifies into N_2O and NO (which starts the NO_X cycle again), and also affects soil emissions of CH_4.

v) As nitrate, 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.

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

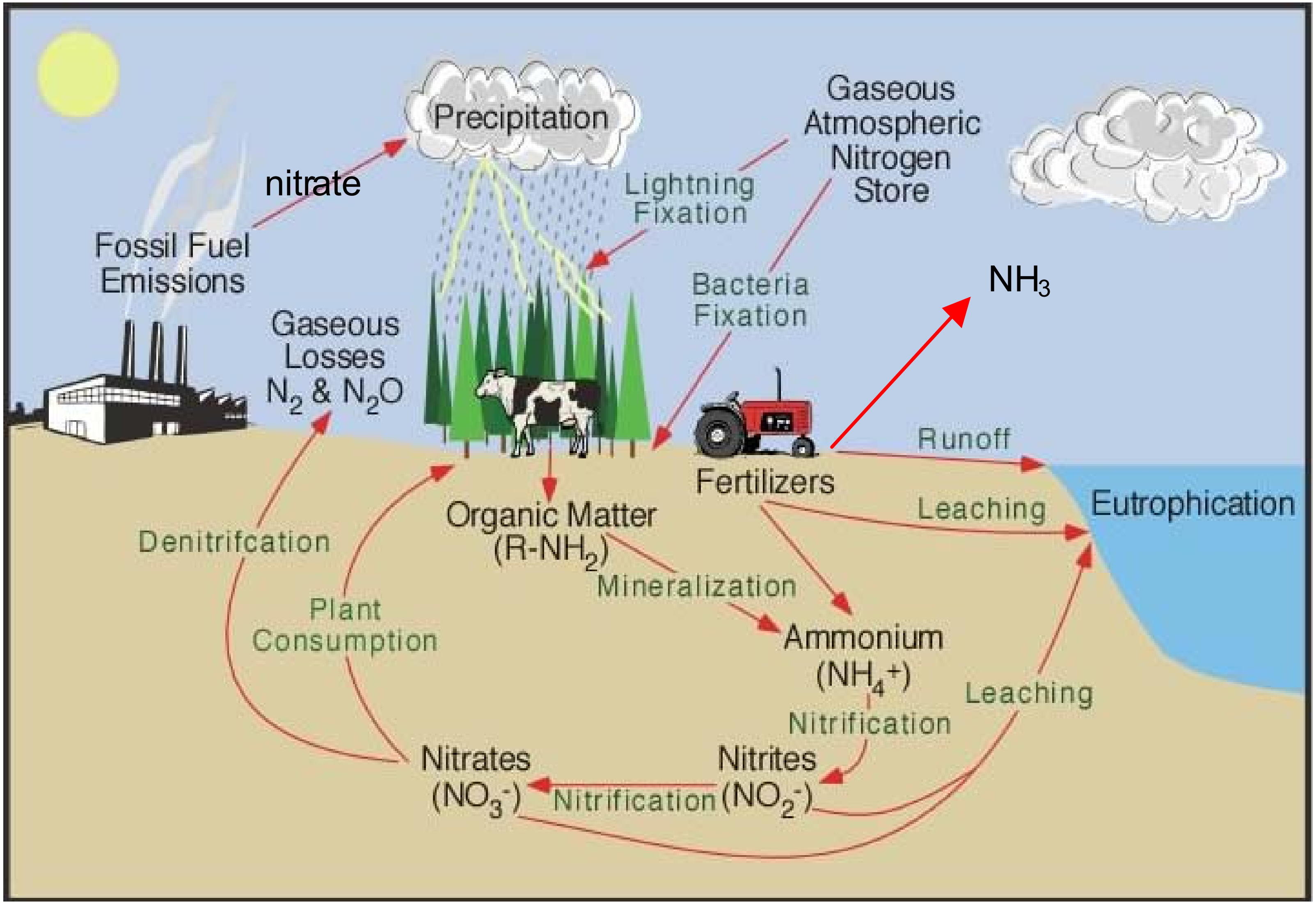
The NO_X CO_2-equivalency factor

--PRELIMINARY, DO NOT CITE--

Component of CEF	**NO_X**	**NH_3**	**Comments**
Effect of NO_X on tropospheric O_3	35	0.0	Major effect of O_3 is on plant and soil C. Assume NH_3 has no effect.
Effect of NO_X on lifetime of ambient CH_4	-12	0.0	NO_X effect on CH_4 varies regionally. NH_3 assumed to have no effect.
Effect of N deposition on CH_4 emissions	0.06	0.16	NH_3 and NO_X assumed to have same effect, except for MW adjustment.
Effect of N deposition, leaching on N_2O emissions	2.2	not est.	N_2O emission factors based on total N inputs, not inputs less leaching losses.
Effect of N deposition on C sequestration	-7	not est.	Based on allocation of total N inputs to soil, and biomass, in N-limited systems only.
Effect of particulate nitrate	-50	not est.	Based on estimated 12% conversion of NO_X to particulate nitrate.
Effect of acidification on plant C	0.0	0.0	Not estimated; assumed to be zero.
Effect of NO_X on sulfate aerosol	-1.1		

CEF = CO_2 equivalency factor

Schematic of the nitrogen cycle



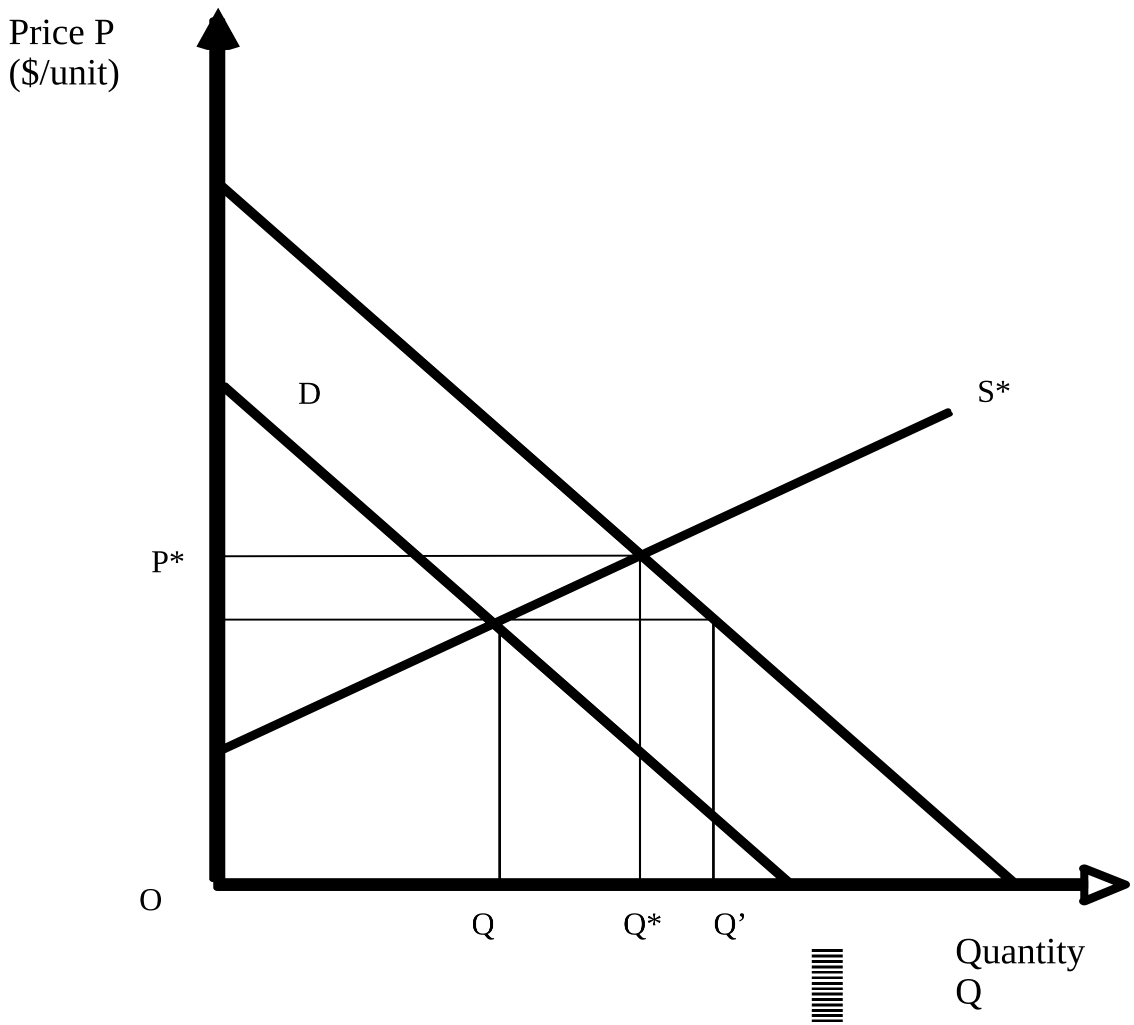
Incorporating price effects into LCA -- what is the issue?

- 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.

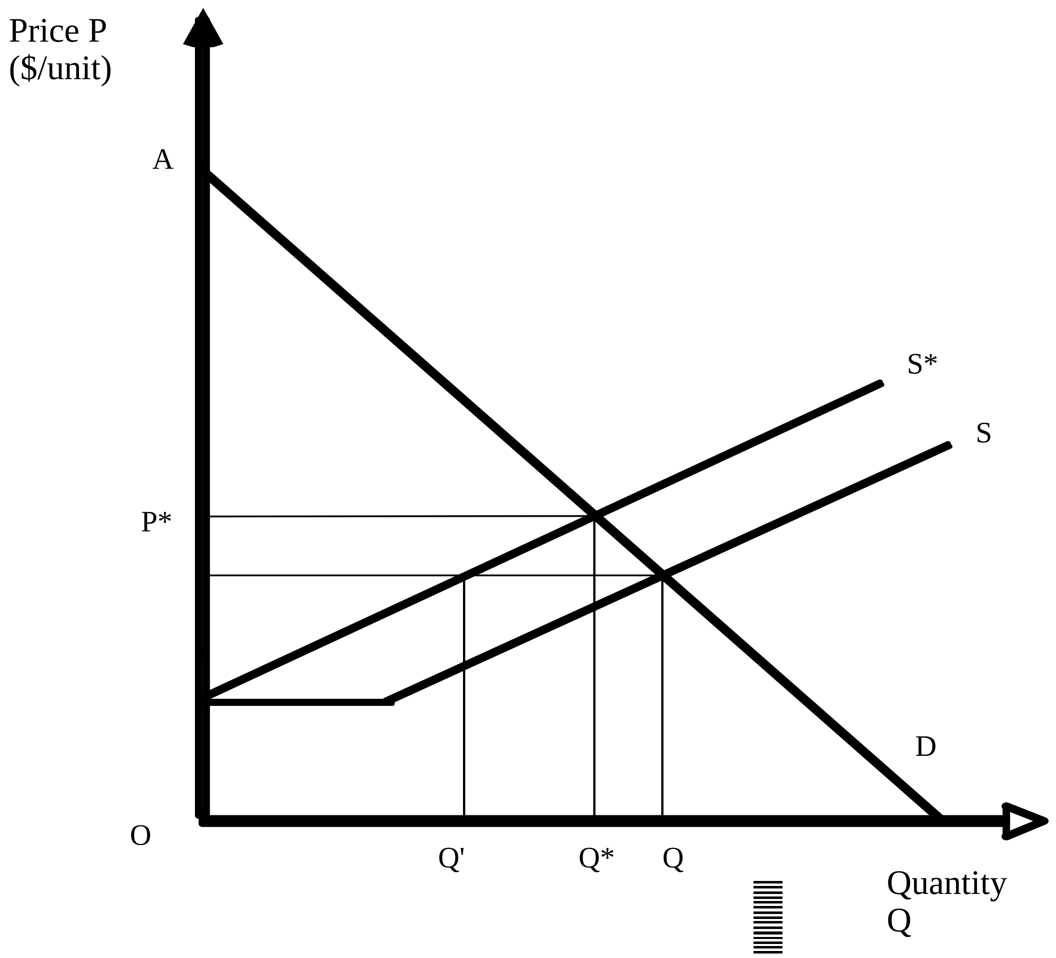
- Conventional LCA does not represent these price effects, and hence mis-estimates what actually happens to climate in the real world (with real economies).

- How can we incorporate these economic effects into LCA? (The best way to do this isn't obvious.)

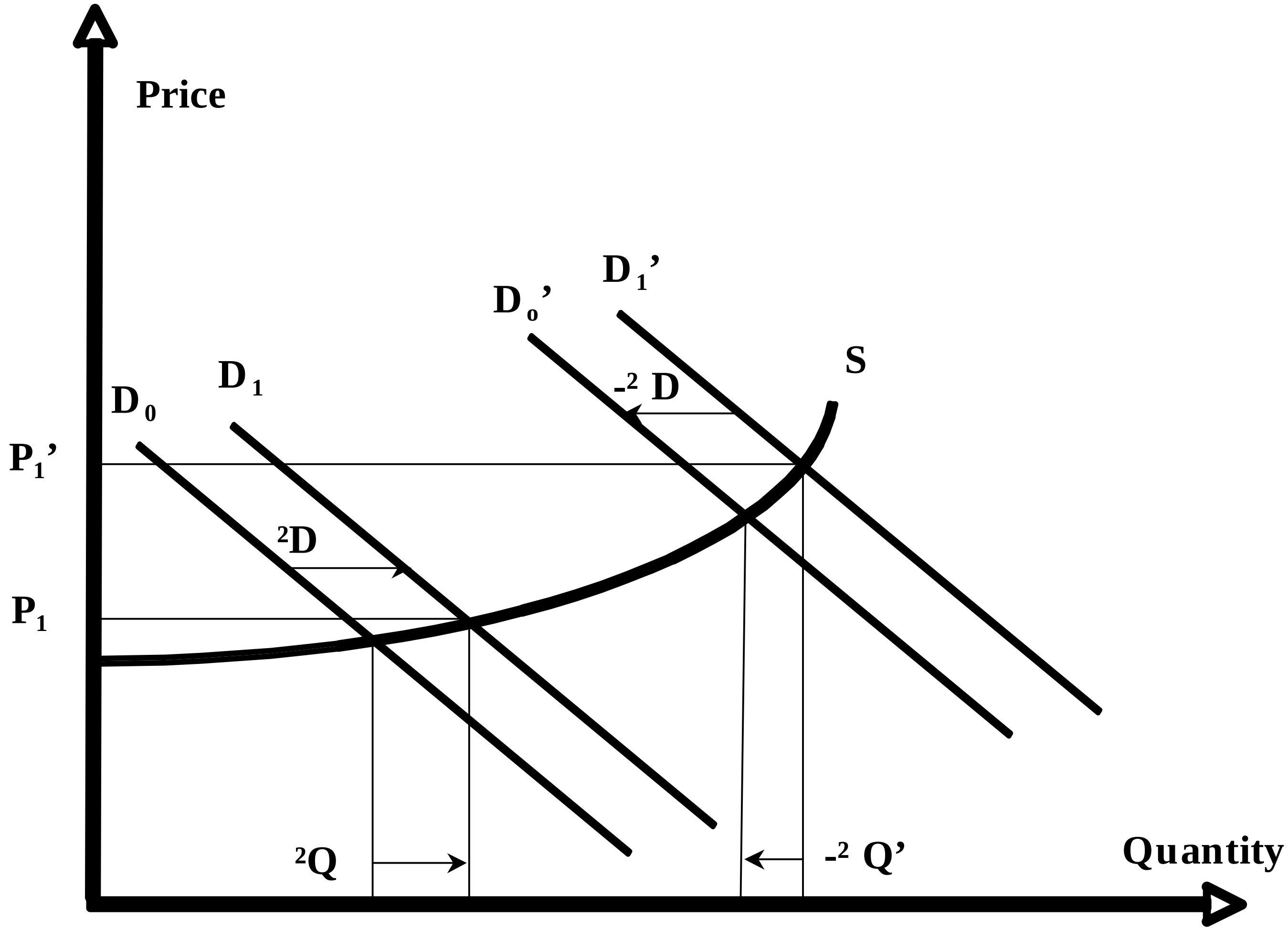
How changes in demand affect prices



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; ΔD = expansion of demand due to start of biofuels progam; $-\Delta D$ = contraction of demand due to end of biofuels progam; ΔQ = increase in quantity of land cultivated due to expansion of demand for biofuels; $-\Delta Q'$ = 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.

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.

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?

Preliminary Overall Findings

- The largest sources of emissions in the upstream lifecycle of biofuels are land-use changes and cultivation (impacts on wetlands especially important!), fuel production, feedstock recovery, fertilizer manufacture, and emissions displaced by co-products.
- 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 from grass has only about 50% lower emissions. 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.
- This analysis finds 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.
- Many often overlooked questions may be important: how long are energy crop programs? What are CO emissions from tractors? Does the high cost of seeds mean high energy use in seed production? Does the production of enzymes (for enzymatic hydrolysis) require large amounts of energy? What is the appropriate discount rate time-path? What is the time-history of the crop-fuel-use cycle? What is the alternative fate of degraded land? What about dust emissions, changes in albedo…?
- Economic/price effects in all lifecycles may be important.
- Note on other environmental impacts: Recent analyses by Jacobson at Stanford indicates that ethanol ICEs may slighly worsen air quality, partially on account of high acetaldehyde formation. Biofuel programs may have adverse impacts on water quality if soil erosion and N runoff are high.
- Note #2: these findings do not apply in full force to fuels derived from agricultural wastes.

Important things to research

- Incorporate price-dynamic economic effects of transportation policies on use of (and hence emissions from) vehicles and fuels.
- Develop more detailed treatment of byproducts and coproducts.
- Improve estimates of changes in land use due to production of biofuel crops.
- Finish revisions of estimates of CO_2-equivalency factors (preliminary analyses completed).
- 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)