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

Presented by: Alissa Kendall

Based on Work by: Mark A. Delucchi

Institute of Transportation Studies

University of California, Davis

www.its.ucdavis.edu/people/faculty/delucchi -- http://cee.engr.ucdavis.edu/Faculty/Kendall/

UC DAVIS
UNIVERSITY OF CALIFORNIA

Outline

- Overview of LCA of CO_2-equivalent GHGs from biofuels
  - Biofuels Life Cycle
  - 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

UCDAVIS
UNIVERSITY OF CALIFORNIA

Take-Home Message

- Several important factors in Life Cycle Assessments (LCAs) of Greenhouse Gases (GHGs) from biofuels are treated poorly or not at all in most analyses.
  - Direct and indirect changes in land use
  - The nitrogen cycle
  - CO_2-equivalency factors
  - The economic effects of policies
  - Omitted kinds of climate impacts
- Future analyses must better address these factors to more clearly understand the impact of biofuel policies on climate

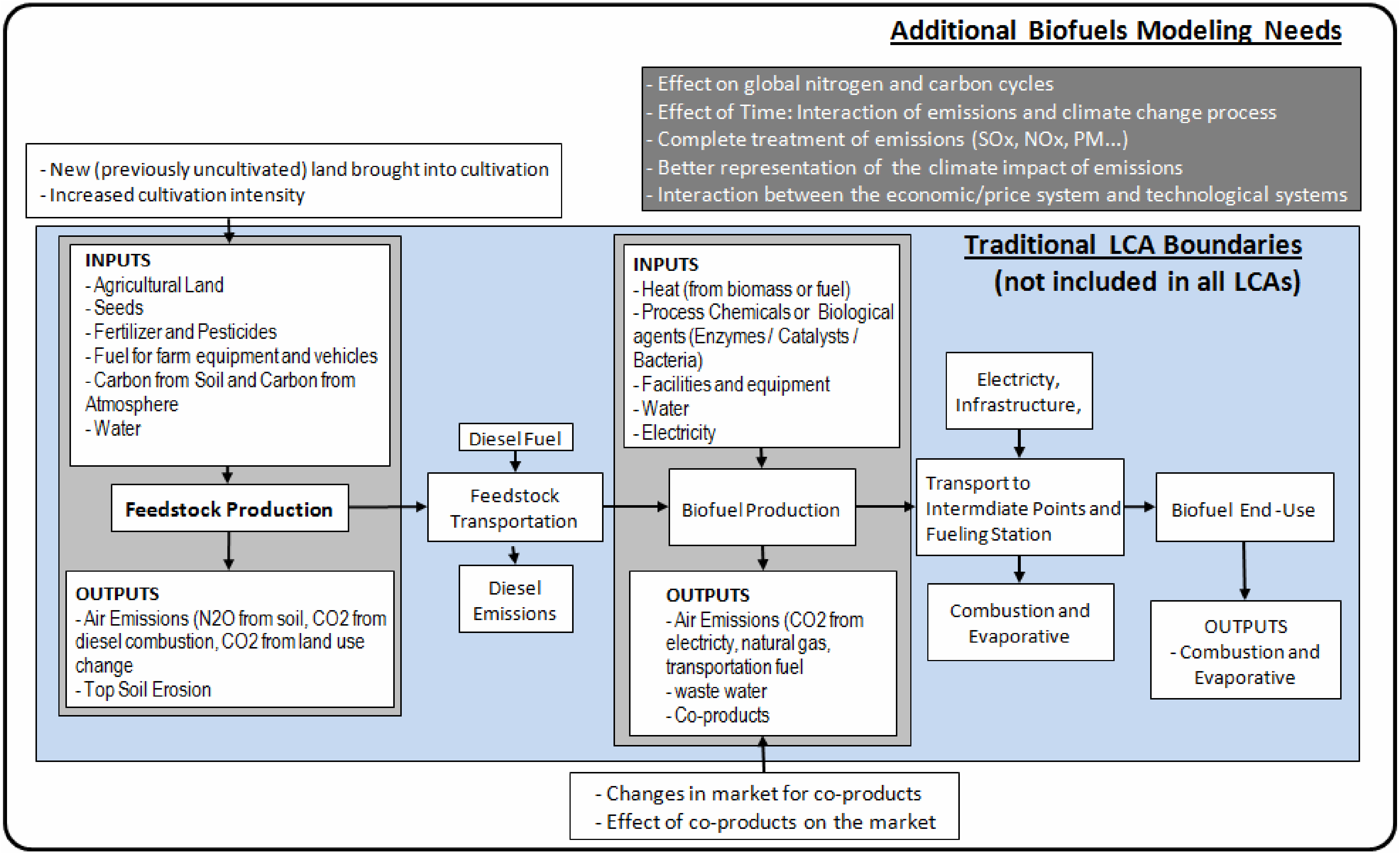
UC DAVIS
UNIVERSITY OF CALIFORNIA

Purpose of GHG LCAs for Biofuels

- Purpose: To determine the difference in climate change impacts between a “baseline” world and the world given some proposed action -- generally a policy action.
- This requires a:
  - Careful specification of the proposed action
  - An analysis of how the world changes as a result of the action
  - An integrated engineering-economic-environment model
- In practice most LCAs do not specify or analyze a policy, but a product or system

UCDAVIS
UNIVERSITY OF CALIFORNIA

Generic Biofuels Pathway and LCA System Boundaries



Approximate Range of Results for Biofuel GHG LCAs

GHG reductions compared to gasoline (well-to-wheels)

Source	Corn-derived Ethanol	Cellulosic Ethanol	Soy-derived Biodiesel
Total Range	-50% to 20%	-100% to 40%	-80% to 50%
Various Studies*	-50% to 0%	-100% to 40%	-80% to 40%
LEM Estimates	-30% to 20%	-75% to -40%	-20% to 50%

* GREET (See various papers by Wang and GM et. al), GHGenius, Kim and Dale, De Oliviera, LBST (GM et al. 2002), CONCAWE et al., Spatari et al. (2005), Farrell et al. (2006)

The wide range of results reflects:

(1)Modeling-derived differences

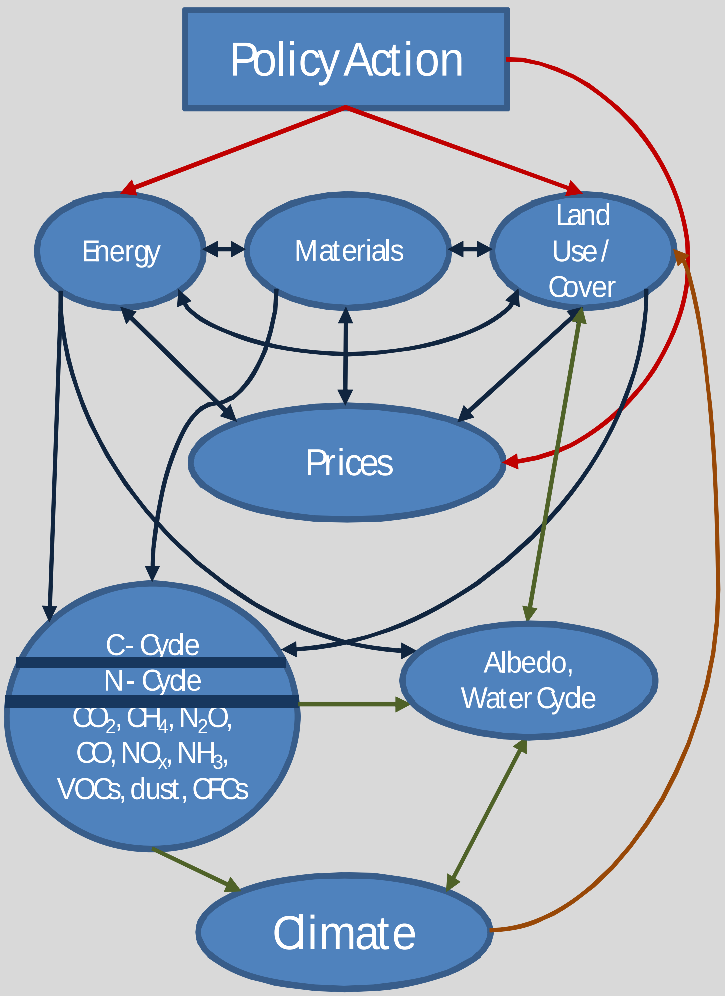
- Differences in system boundaries, co-product treatment, climate modeling assumptions, time-horizon, treatment of land use change, etc.

(2) Real differences in production pathways and geography (climate, soil conditions, etc.)

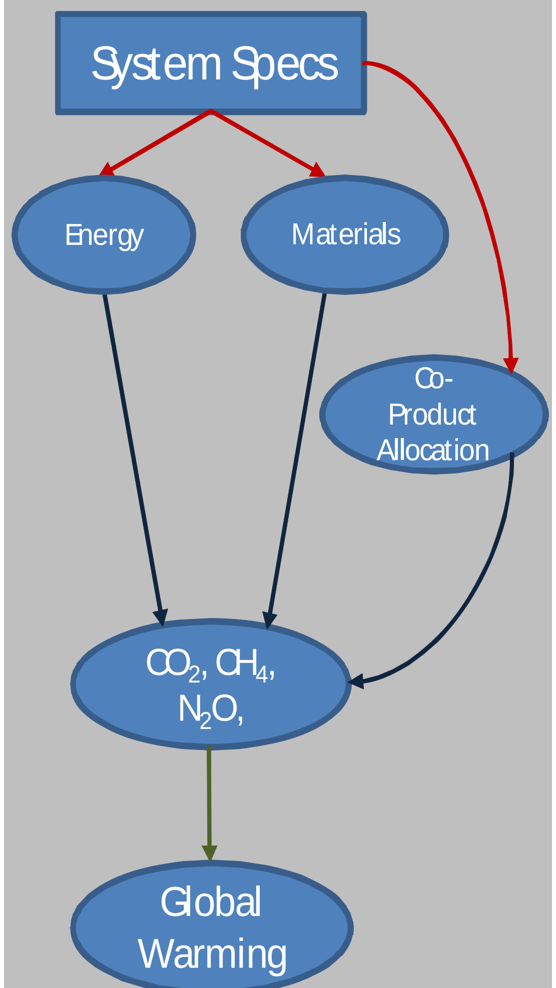
UCDAVIS
UNIVERSITY OF CALIFORNIA

Ideal Model versus Conventional LCA Model

Ideal Model



Conventional GHG LCA



Conventional LCA vs. Ideal Model

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

Energy systems and direct material inputs are well represented, infrastructure and land use usually are not

Conventional LCAs do not model the effects of price changes

Some CH4 and N2O emissions omitted. CO, NOx, SOx, PM, etc. omitted from climate change effect calculations. Incomplete N and C-Cycles. Albedo, water cycle not considered

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

Treatment of life cycle carbon calculation parameters in the LEM and in other studies

1. **Land-use changes and cultivation**
2. **Climate effects other than CO_2, N_2O, and CH_4**
   - **CO, PM (BC, OC, and dust), SO_X, other gases, albedo, hydrodynamics**
   - **Differences in Carbon Equivalency Factors (CEFs) and IPCC GWPs**
3. **Nitrogen cycle**
   - **Climate impacts of NO_X and NH_3 emissions**
4. Material inputs and “Indirect” energy considerations
5. Co-product treatment
6. Temporal trends in farming, technology, resource availability, etc.
7. Treatment of petroleum products for comparison
8. Economic/Price Effects over time

UC DAVIS
UNIVERSITY OF CALIFORNIA

Contribution of Key Factors to Total Lifecycle Emissions for LEM Results

Factor	Ethanol (Corn)	Ethanol (Grass)	Biodiesel (Soy)	Source
NO_2 and NH_3 emissions	-10% to -15%	-10%	-70%	LEM
N_2O emissions	20%	10% to 15%	70% to 80%	LEM
LUC: CO_2	0% to 30%	-20% to 20%	50% to 100%	LEM
Co-products	-10% to -20%	-10% to -20%	-60% to -90%	LEM

Units: % of fuel + vehicle lifecycle CO2-equivalent emissions)

Possible key factors not quantified in any LCAs of Biofuels:

(1) Net CH_4 from plants – Expected to be small

(2) Soil and other agric. dust - Effect unknown

(3)Price changes – Perhaps effects as high as 10%

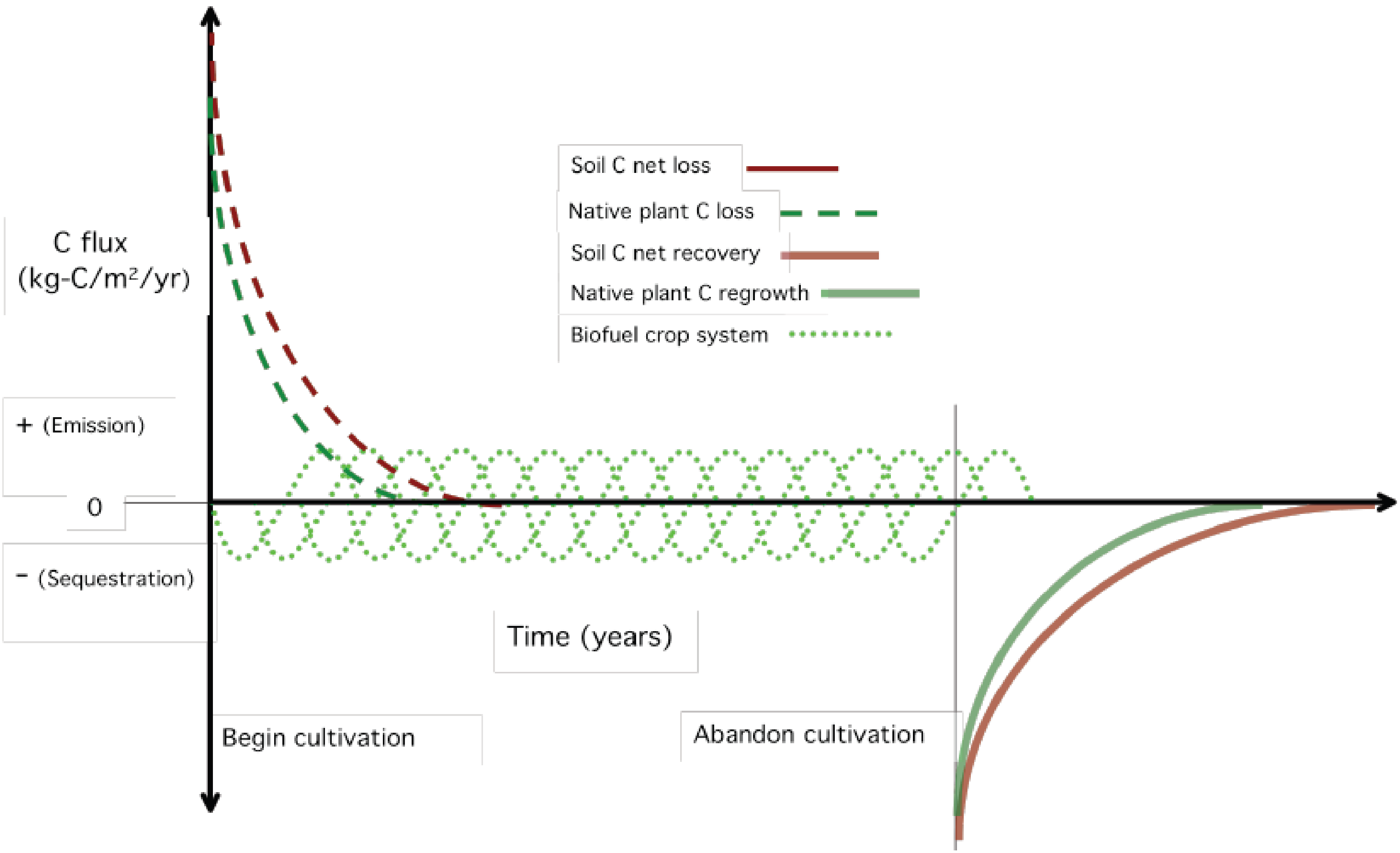
UCDAVIS
UNIVERSITY OF CALIFORNIA

Issues in GHG LCA of Biofuels: Land Use Change (LUC)

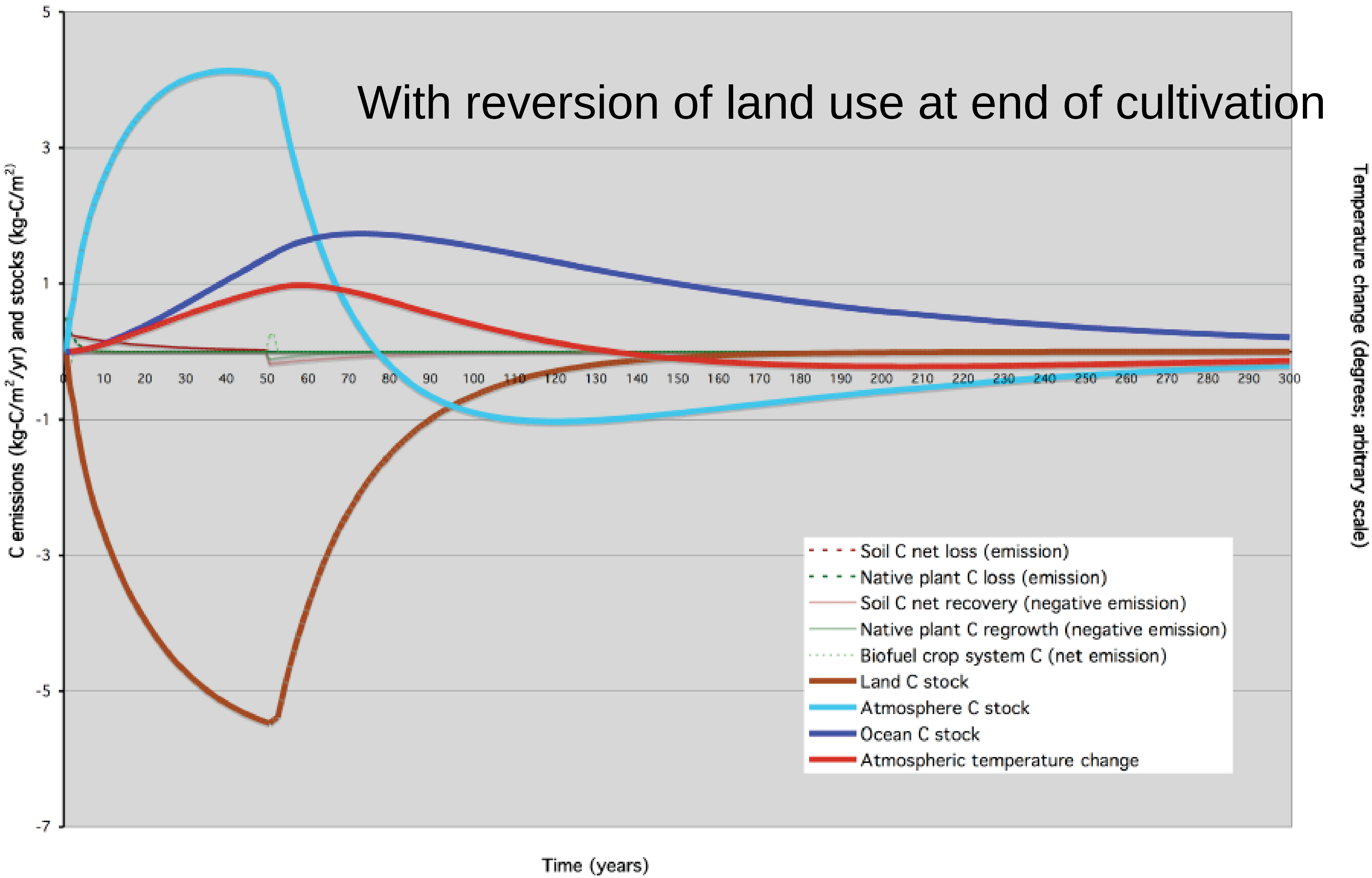
- 1. LUC and cultivation
  - **LEM**: life-cycle analysis of changes in carbon sequestration in soils and carbon by crop type and displaced ecosystem (including intensification and consumption suppression), accounting for reversion of land at end of program.
    - Present-value, time-discounted (with declining discount rate)
  - **Other studies**: Some recent detailed analyses, but
    - The conceptual frameworks do not include reversion
    - They don't address the timing of emissions

UCDAVIS
UNIVERSITY OF CALIFORNIA

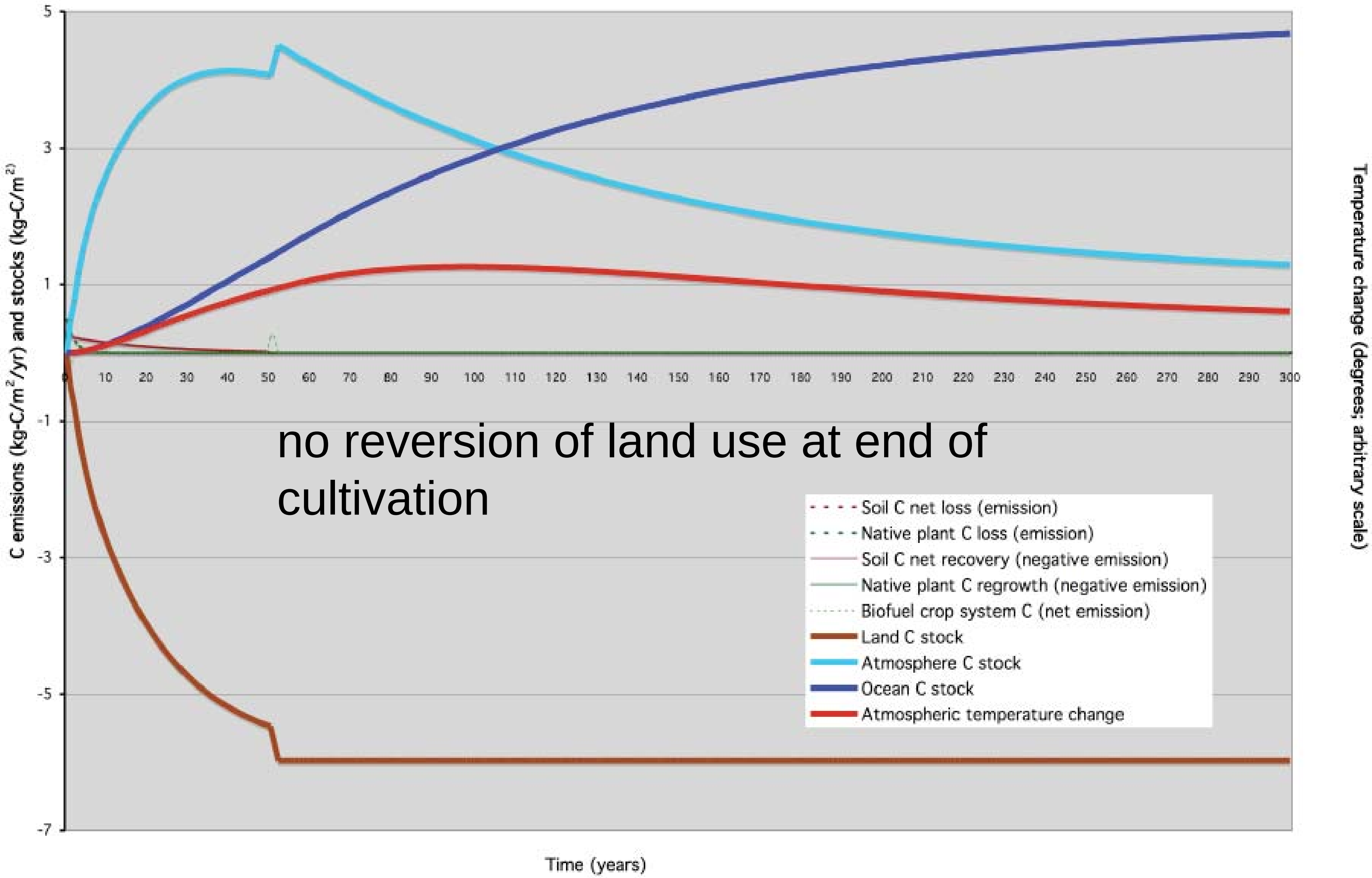
Emissions Over Time from Plants and Soil due to Land-Use Change



Changes in land, atmosphere, and ocean C stocks due to C emissions from land-use change



Changes in land, atmosphere, and ocean C stocks due to C emissions from land-use change



Sensitivity of lifecycle CO_2-equivalent emissions to soil carbon emissions from land-use change

Scenario	*corn/ ethanol*	*soy/ biodiesel*	*grass/ ethanol*	*wood/ methanol*
with land-use changes (g/mi)	3,467	8,297	2,024	1,202
without land-use changes (g/mi)	2,565	3,079	1,282	673
difference (g/mi)	902	5,218	742	529
% change with vs. without	26%	63%	37%	44%

UC DAVIS
UNIVERSITY OF CALIFORNIA

Sensitivity of LC CO_2-e Emissions to Wetlands Displacement

Increasing Proportion of Wetlands

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%

Declining CO_2-e Performance

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

Other factors are looking to be important in LUC Effects on Climate Change

- 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.

UCDAVIS
UNIVERSITY OF CALIFORNIA

Pollutants and Climate Effects in the LEM: Alternatives to IPCC GWP

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, +O3 (t), +CH4, +H2O (s), +CO2, +CO, +SO4	17	19	23
N_2O → +R	230	260	296
O_3 → +R, -soil C, -plant C; see CO, H_2, CH4, NMOCs, NO_2	4	4	n.e.
PM (black carbon) → +R, clouds, more	1,300		n.e.
PM (organic matter) → -R, clouds, more	-150		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, +O3 (t), +CH4, +CO2, +SO4	3	3	1.57
H_2 → -OH, +O3 (t), +CH4	5	5	n.e.
NMOCs → -OH, ±O3 (t), +CH4, +CO2, +SO4	6 + C	3 + C	n.e.
NO_2 → -CO2, +N2O, ±OH, +O3 (t), -CH4, +PM, +SO_4	-12	-16	n.e.
NH_3 → -CO2, +N2O, + NO_3, +SO4	n.e.	n.e.	n.e.
SO_2 → +PM	-48	-53	n.e.
H_2O → +R (s), +OH, -CH4, clouds, more	n.e.	n.e.	n.e.
CFC-12 → +R, -O3 (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

Not Estimated

No Sensitivity to time of emission

Effect of LEM CEFs on Fuelcycle Emissions

Preliminary: DO NOT CITE

	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, soydiesel (vs. HDDV)	6,361	53%	4,603	12%	38%	332%	41%

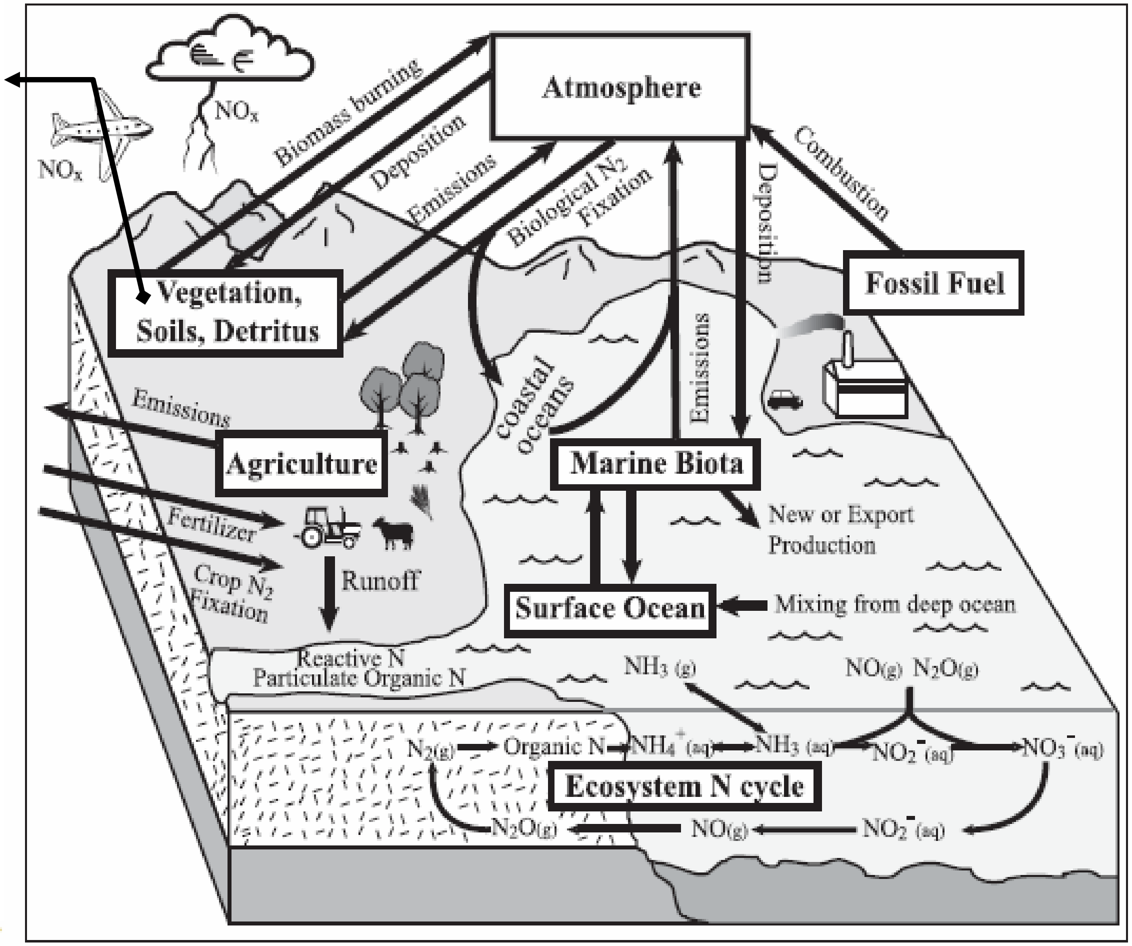
Values are for U.S. Year 2010

UCDAVIS
UNIVERSITY OF CALIFORNIA

The Nitrogen Cycle

- Nitrogen Cycling between reservoirs at local, regional and global scales

Interaction with C-cycle



Source: Holland et. al, U.S. (2005) "Nitrogen Science Plan Focuses Collaborative Efforts" *Eos*, 86(27), 253-260

UCDAVIS
UNIVERSITY OF CALIFORNIA

The Nitrogen Cycle in GHG LCA of Biofuels

- 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.

UCDAVIS
UNIVERSITY OF CALIFORNIA

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

UC DAVIS
UNIVERSITY OF CALIFORNIA

Important Future Research Directions

- **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 co-products.**
- 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.
- Can we model net 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)

UC DAVIS
UNIVERSITY OF CALIFORNIA

Questions and Comments

UCDAVIS
UNIVERSITY OF CALIFORNIA

Additional Slides

UCDAVIS
UNIVERSITY OF CALIFORNIA

Sensitivity of LC CO_2-e Emissions to Length of 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

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.)

UC DAVIS
UNIVERSITY OF CALIFORNIA

Price Effects in LCA

Mark, should this be “market” or “price” effects?

	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.

- Economic/price effects (policy → prices → output/use → emissions)
  - **LEM**: A few quasi-elasticities, but no systematic, integrated treatm
  - **Other studies**: Not included.

  Potentially significant deficiency in all models

UCDAVIS
UNIVERSITY OF CALIFORNIA

Preliminary Overall Findings

- The largest sources of emissions in the upstream lifecycle of biofuels are land-use changes and cultivation
  - (impacts on wetlands are especially important), fuel production, feedstock recovery, fertilizer manufacture, and emissions displaced by co-products.
- This analysis finds that corn ethanol does not have significantly lower GHG emissions than does gasoline, and that cellulosic ethanol from grass has only about 50% lower emissions.
  - 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, emissions of carbon due to changes in land use.

UC DAVIS
UNIVERSITY OF CALIFORNIA

Additional Issues in GHG LCA of biofuels

- "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.

- Treatment of "co-products"
  - **LEM**: Explicit estimation of emission changes in co-product markets; 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.

UCDAVIS
UNIVERSITY OF CALIFORNIA

Additional Issues in GHG LCA of biofuels

- 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.

- Net 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 models**: Now in some (but not all) biofuel LCAs (e.g., materials added to GREET recently).

UCDAVIS
UNIVERSITY OF CALIFORNIA

Additional Issues in GHG LCA of biofuels

- 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.

UCDAVIS
UNIVERSITY OF CALIFORNIA

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?