# Stock-and-Flow Assessment of Transportation Fuels

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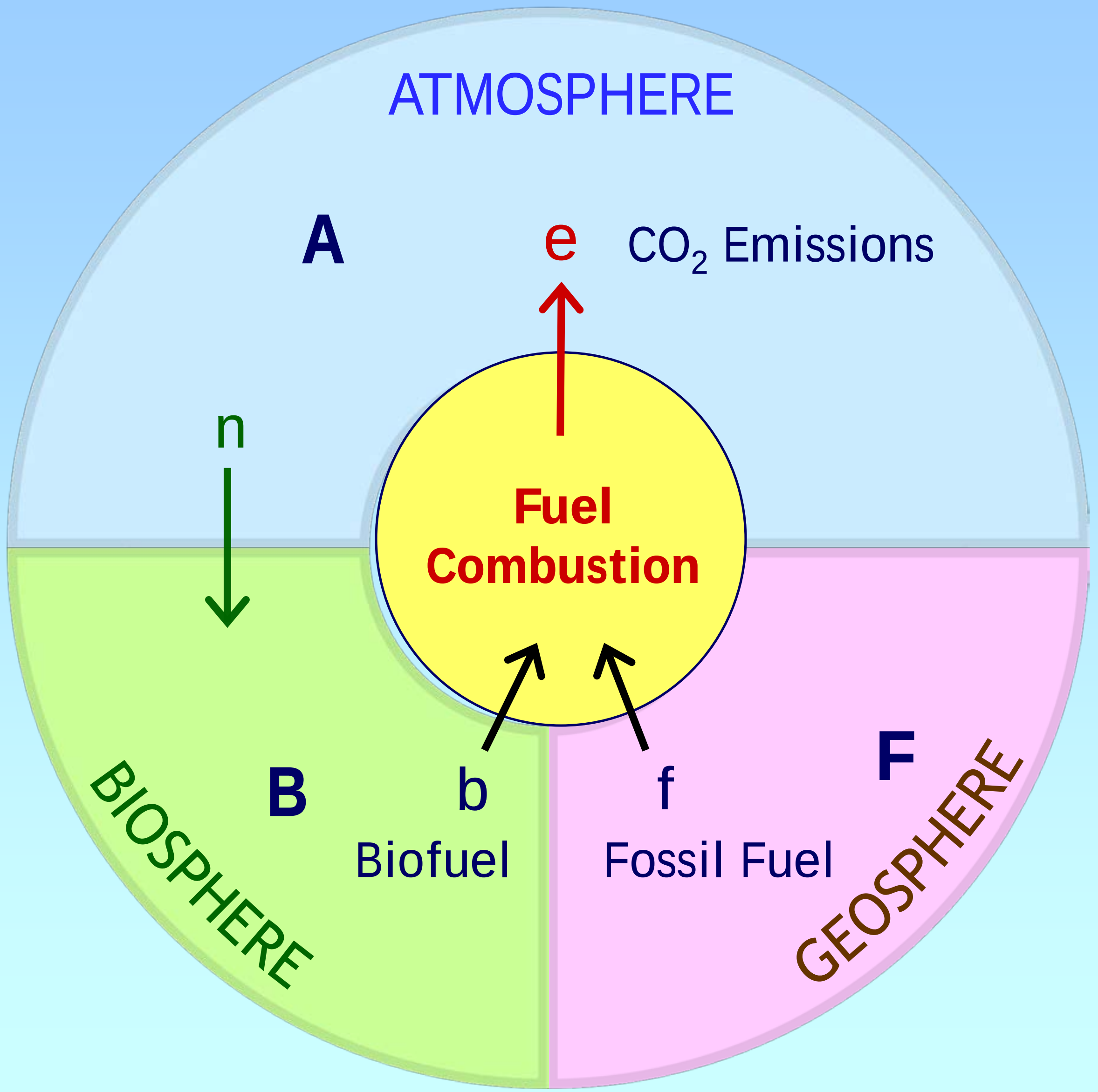
# Outline

- Why Stock-and-Flow?
- Principles
  - Carbon mass balance
  - Bounding condition for mitigation
- Applications
  - Facility level analysis: single-year time step
  - Biofuel expansion retrospective: 2005 – 2013
- Implications
  - Very different results from those of LCA
  - Meeting the scientific needs arising from policy
  - Research needs
- Conclusions

# Why a stock-and-flow (fully dynamic) method

- Mainly, because this is how the world really works
- Application of LCA to biofuels and carbon is scientifically irreducible
  - No longer “attributional,” but rather has become a form of scenario analysis
  - Consequential LCA is really just *ad hoc* (not mathematically coherent)
- The biosphere is **NOT** in a steady flow equilibrium with the atmosphere
  - Has not been since agricultural societies began clearing land; land-use change that releases terrestrial carbon stocks continues, with biofuels adding to the pressure
  - Even if in equilibrium, transition to a different equilibrium state is a dynamic process
- We have a system dynamics problem
  - Enforce conservation of mass and quantify all key flows (uptake as well as emissions)
  - Initial conditions matter (governed by differential equation, not just arithmetic)
  - Does not tell the whole story, but can constrain (put empirical bound on) the results

# Biofuel's carbon balance: key stocks and flows




Stocks (tons of carbon)

- A  Carbon in atmosphere
- B  Carbon in biosphere
- F  Fossil carbon in geosphere

Flows (tons of carbon per year)

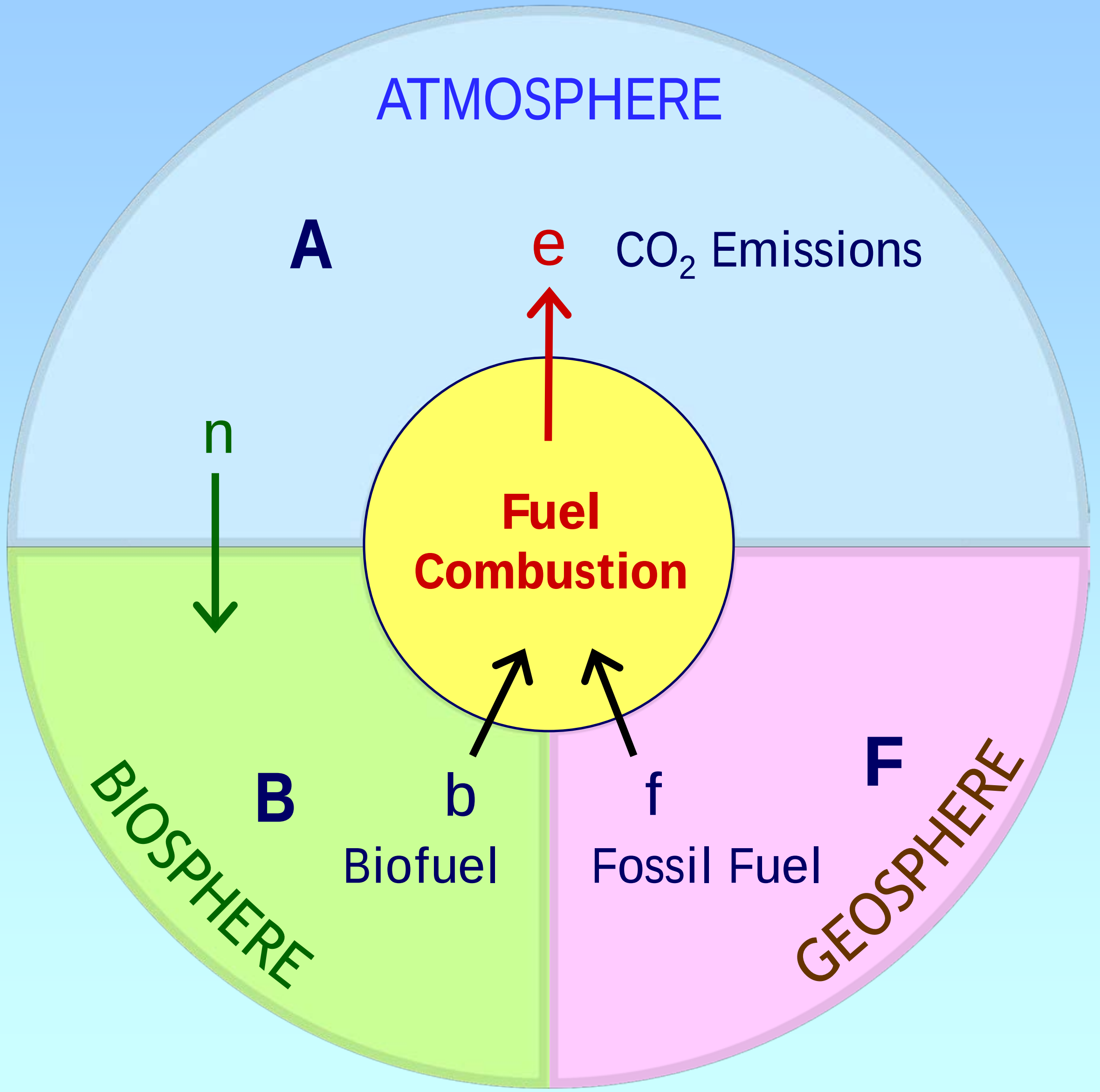
- e  $CO_2$ emitted by energy use
- n  Net $CO_2$ uptake by plants*
- b  Biogenic carbon
- f  Fossil carbon

Change of carbon in atmosphere

$A' = e - n$    $(x' = dx/dt)$

*n = Net Ecosystem Production (NEP)

# Condition for carbon mitigation when using biofuel




At present, the amount of carbon in the atmosphere is rising, i.e.,
$A' > 0$ (positive 1st derivative)

Mitigating $CO_2$ emissions means slowing the rate of rise, i.e.,
$A'' < 0$ (negative 2nd derivative)

And so we need $A'' = e' - n' < 0$ by either reducing emissions ($e' < 0$) or increasing net uptake ($n' > 0$).

If $e' = 0$, as when b replaces f, then need $n' > 0$

# Condition on NEP offers crucial insights

- Condition for mitigation is: $n' > 0$, i.e., $d(NEP)/dt > 0$
  - Merely replacing fossil carbon with biogenic carbon as an energy carrier is not a sufficient condition for reducing the net flow into atmosphere.
  - The necessary condition is an increase in the net rate of carbon uptake.
- Therefore, biomass energy is not inherently carbon neutral (as assumed by construction in product-based LCA)
  - This restriction is due to system dynamics and conservation of mass.
  - The act of substitution is a change in the use of carbon and does not necessarily create "new" carbon: there is no such thing as "free" carbon.
- Sustainable biomass ***production*** does not imply atmospheric ***protection***
- Point of potential $CO_2$ mitigation is not downstream; substituting one carbon-based fuel for another does not change flow into atmosphere

# Localizing the necessary condition for mitigation

- Global condition is $n' > 0$
  - Physically, a gain in the net rate of carbon uptake is not the same as an emissions reduction ($e' < 0$) even though the effect on the atmosphere may be the same.
    - But it can be achieved by a reduced loss of carbon from an uptake process (e.g., removing crop residues that would otherwise decay on cropland).
- Carbon uptake can be localized by spatially partitioning global NEP:

$$n = \sum_k n_k \quad \text{where } k \in \{\text{discrete parcels of global land area}\}$$

$$\text{and so} \quad n' > 0 \quad \text{implies that} \quad \exists\, k \text{ such that } n_k' > 0$$

- For a location of increased carbon uptake to be attributed to biofuel, it must be a location where biofuel feedstock is grown.

# Re-analysis of a corn ethanol case study

Facility produced 56 Mgal of ethanol in its first year of operation.

GREET analysis found an ethanol carbon intensity of 55 $gCO_2e/MJ$, 40% lower than petroleum gasoline.

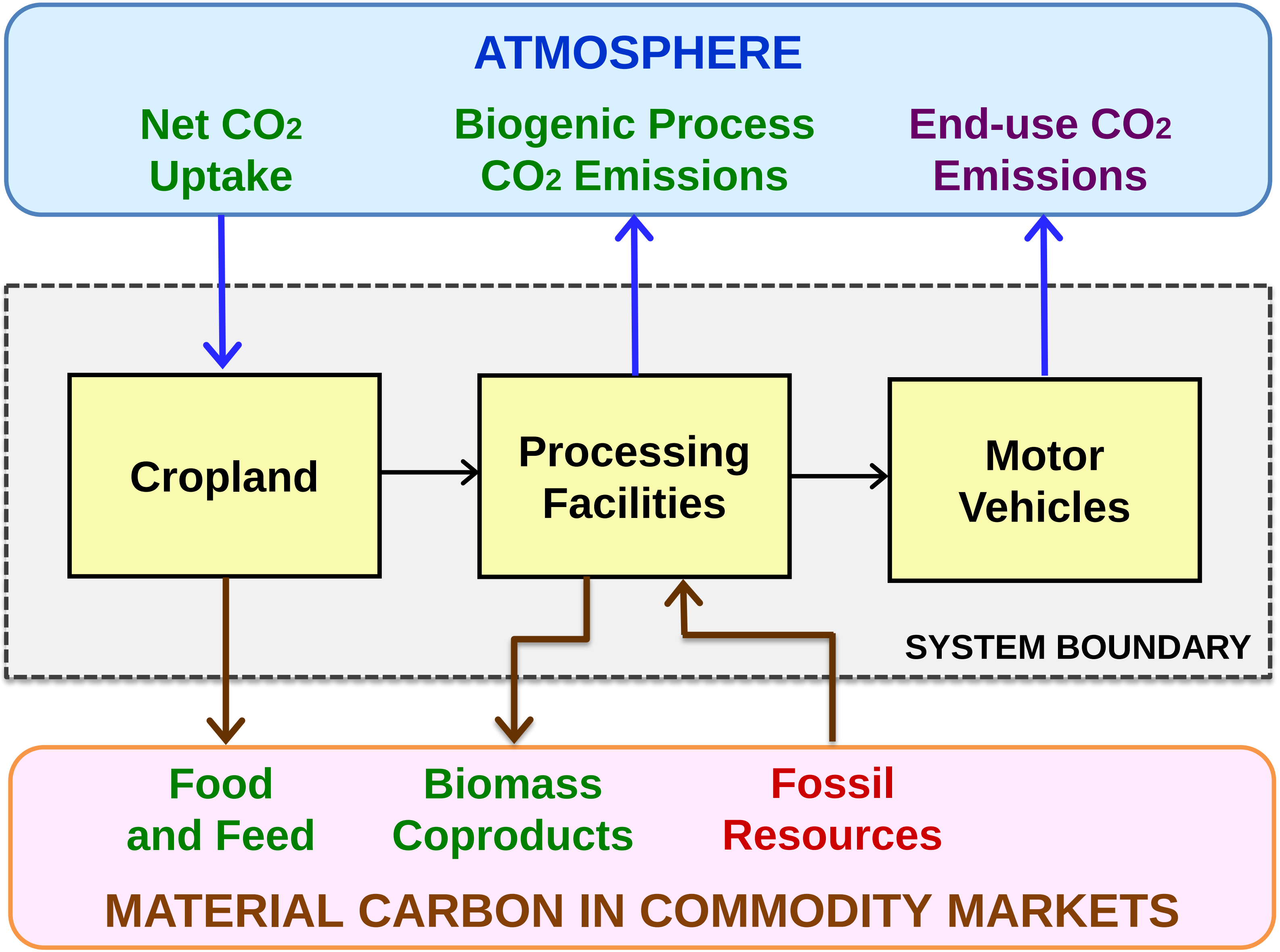
*Original study:* Mueller, S., *et al.* 2008. ***The Global Warming and Land Use Impact of Corn Ethanol Produced at the Illinois River Energy Center.*** Report for Illinois Corn Marketing Board and Illinois River Energy. Chicago: Energy Resources Center, University of Illinois at Chicago.

*New study:* DeCicco, J.M., & R. Krishnan. 2015. ***Annual Basis Carbon (ABC) Analysis of Biofuel Production at the Facility Level***. Ann Arbor: University of Michigan Energy Institute.

# Material carbon flows a vehicle-fuel system

*If, as claimed, biogenic $CO_2$ emissions are neutralized during biofuel production and use, then a gain in NEP must be verified on the cropland from which feedstocks are sourced.*

*Regarding flows of fixed carbon to/from external markets: expanding the system boundary results in an inability to verify outcomes.*



# Carbon uptake on cropland

| Net Ecosystem Production (NEP) in metric tons per year on a carbon mass basis ($t_C$/yr) | | | |
|---|---|---|---|
| **Item** | **Year 0** | **Year 1** | $\Delta$NEP |
| C in corn harvest | (88,888) | (188,075) | |
| C in soy harvest | (29,727) | - | |
| C in total harvest | (118,615) | (188,075) | |
| $\Delta$SOC | | (600) | |
| **Total for cropland serving the IRE facility** | **(118,615)** | **(188,675)** | **(70,060)** |

Sign convention is that emissions from the system into the atmosphere are positive, and so carbon flow from the atmosphere into the vehicle-fuel system is negative.

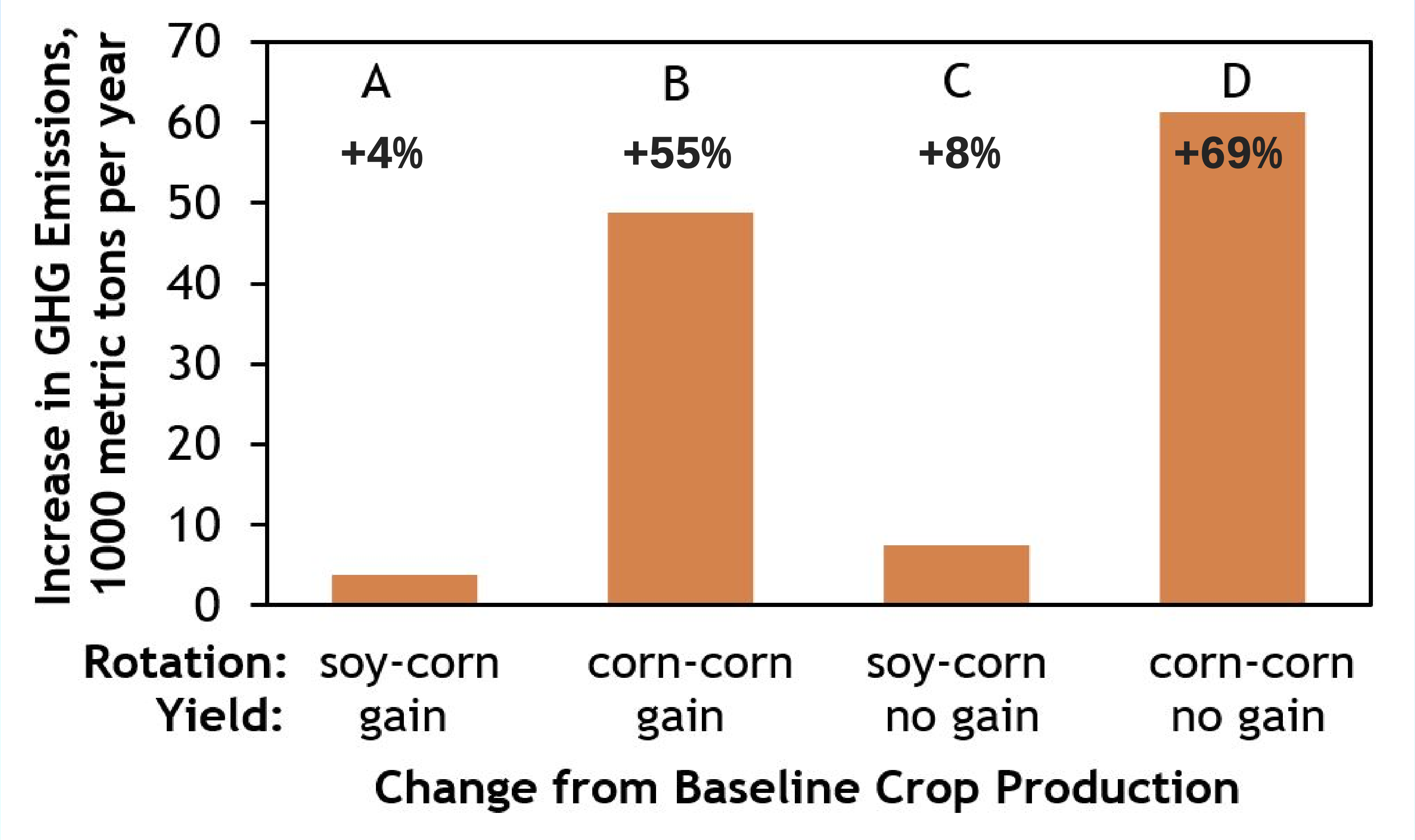
From DeCicco & Krishnan (2015), based on data from Mueller et al (2008) GREET analysis of the Illinois River Energy Facility.

# Summary of facility-level vehicle-fuel system GHG flows

| Carbon mass equivalent flow rates ($kt_c$/yr) | Year 0 | | Year 1 | |
|---|---|---|---|---|
| Pathway: | Fossil | Biomass | Fossil | Biomass |
| Carbon balance on cropland | | (119) | | (189) |
| Process emissions | | | | |
| GHG emissions of farm operations | | 11 | | 21 |
| Biogenic $CO_2$ emissions at biorefinery | | | | 44 |
| Other GHGs from refinery operations | 22 | | | 25 |
| Farm and biorefinery inputs (offsite) | | 6 | | 26 |
| Subtotal process emissions | 22 | 17 | 0 | 115 |
| Vehicle end-use $CO_2$ emissions | 89 | 0 | 0 | 87 |
| Subtotals by pathway | 111 | (101) | 0 | 14 |
| Total net GHG exchange to atmosphere | 10 | | 14 | |
| Material carbon exported from system | 119 | | 65 | |
| Changes from Year 0 to Year 1: | | | | |
| **Net GHG emissions** | **4** | | | |
| Material carbon exported | 53 | | | |

# Facility-level sensitivity analysis

## Effect on direct GHG emissions of different initial conditions



# National scale retrospective analysis

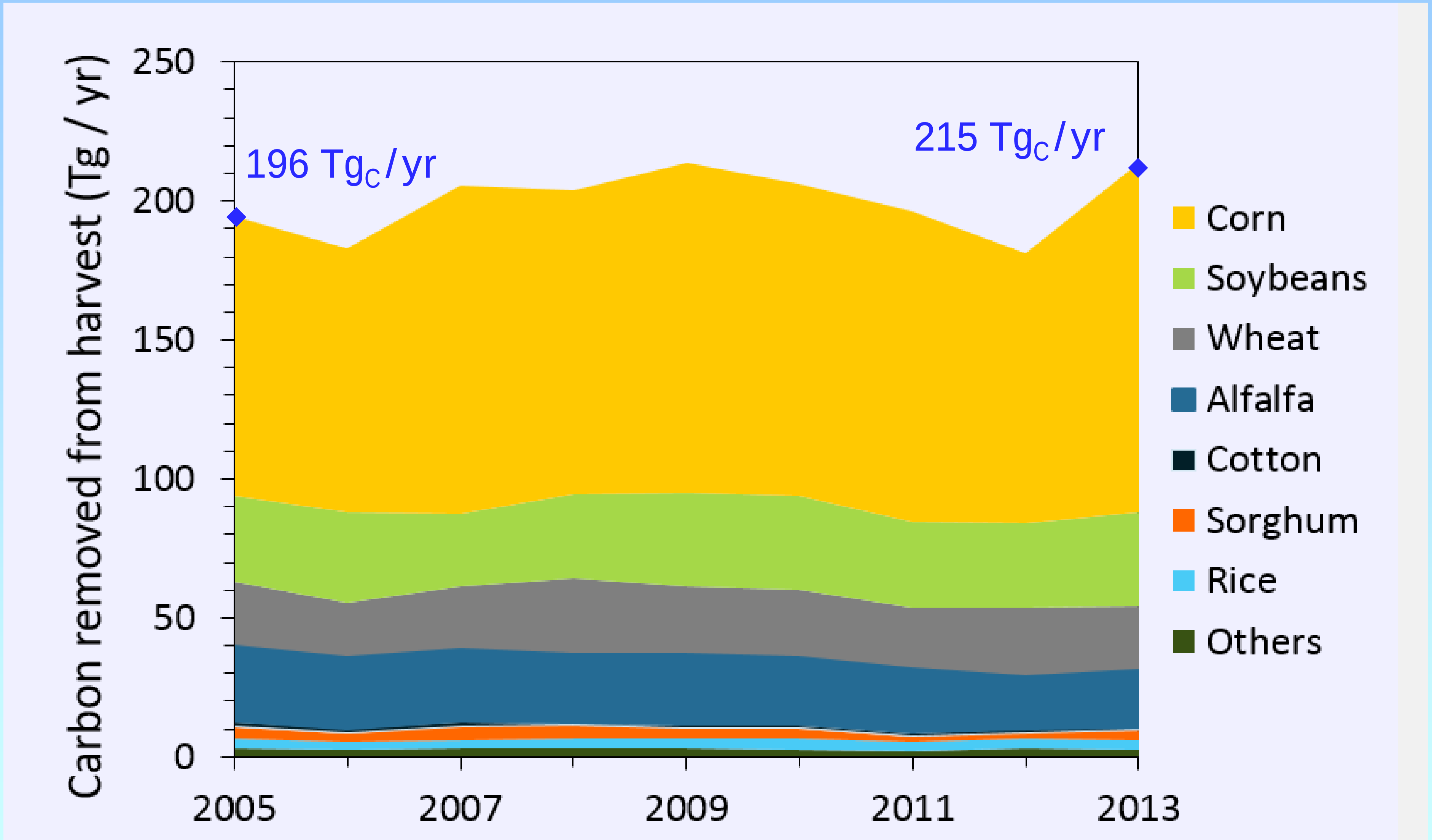
Applied Annual Basis Carbon (ABC) accounting to the U.S. biofuel expansion over 2005-2013.

Evaluated only the direct GHG exchanges between vehicle-fuel system and the atmosphere.

Focused on key material carbon flows: how did the increase in biogenic carbon uptake compare to the increase in biofuel-related biogenic $CO_2$ emissions?

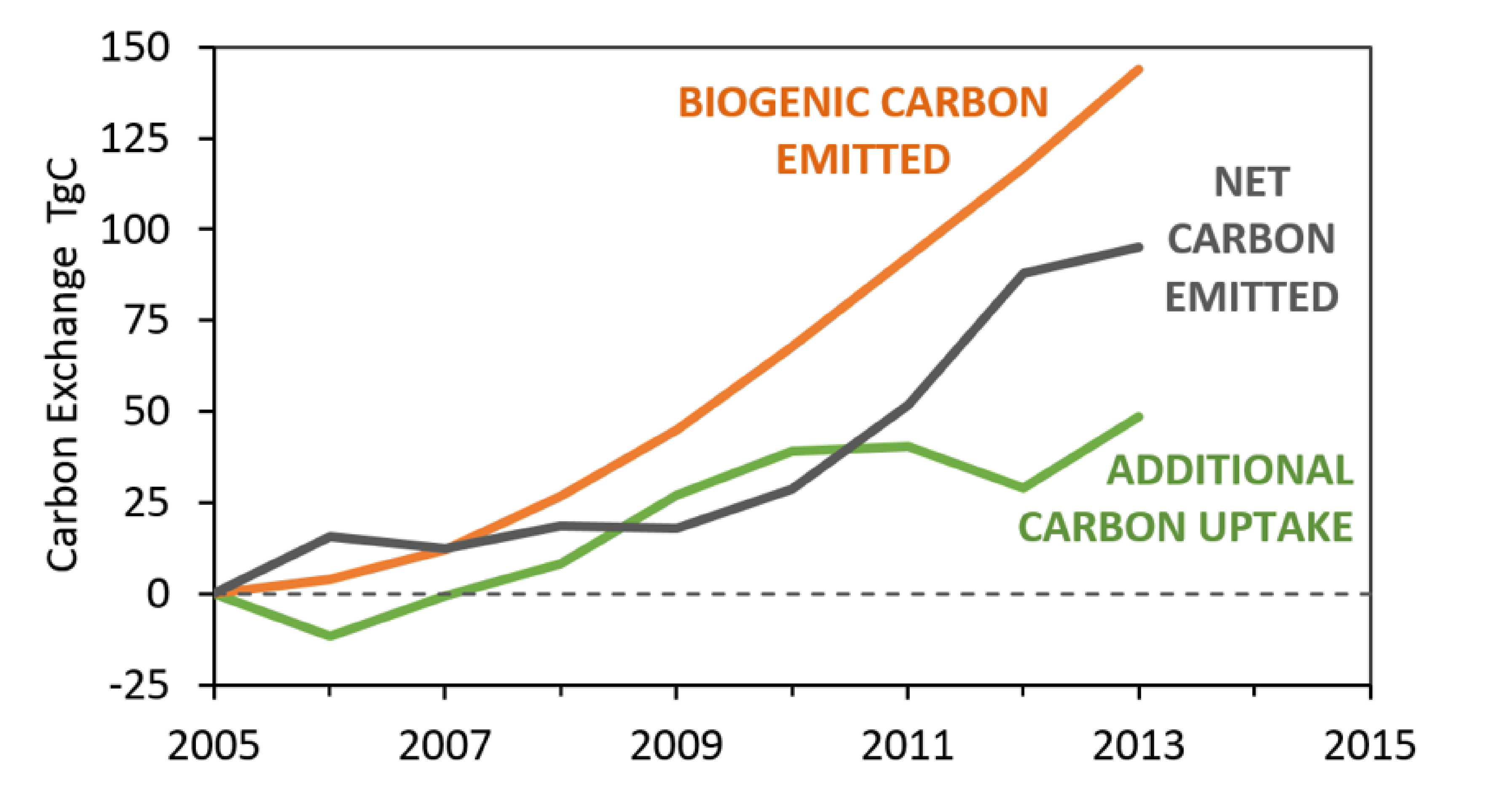
DeCicco, J.M., *et al.* 2016. Carbon balance effects of U.S. biofuel production and use. ***Climatic Change*** 138(3): 667-80. http://dx.doi.org/10.1007/s10584-016-1764-4

# Carbon harvested from U.S. cropland, 2005-2013




Teragrams ($10^{12}$g, i.e., million metric tons) on a carbon mass basis; derived from USDA

# Cumulative biogenic carbon emissions compared to gains in carbon uptake on cropland




*Additional carbon uptake covered only 37% of biogenic emissions over the period, and so most of the biofuel carbon was not "neutralized."*

# Impact of other effects

- With less than the full offset of biogenic emissions that is commonly assumed, process emissions and displacement effects make the net biofuel emissions greater than those from petroleum fuels
  - Processing emissions for biofuels are generally greater than for petroleum fuels
- Displacement effects

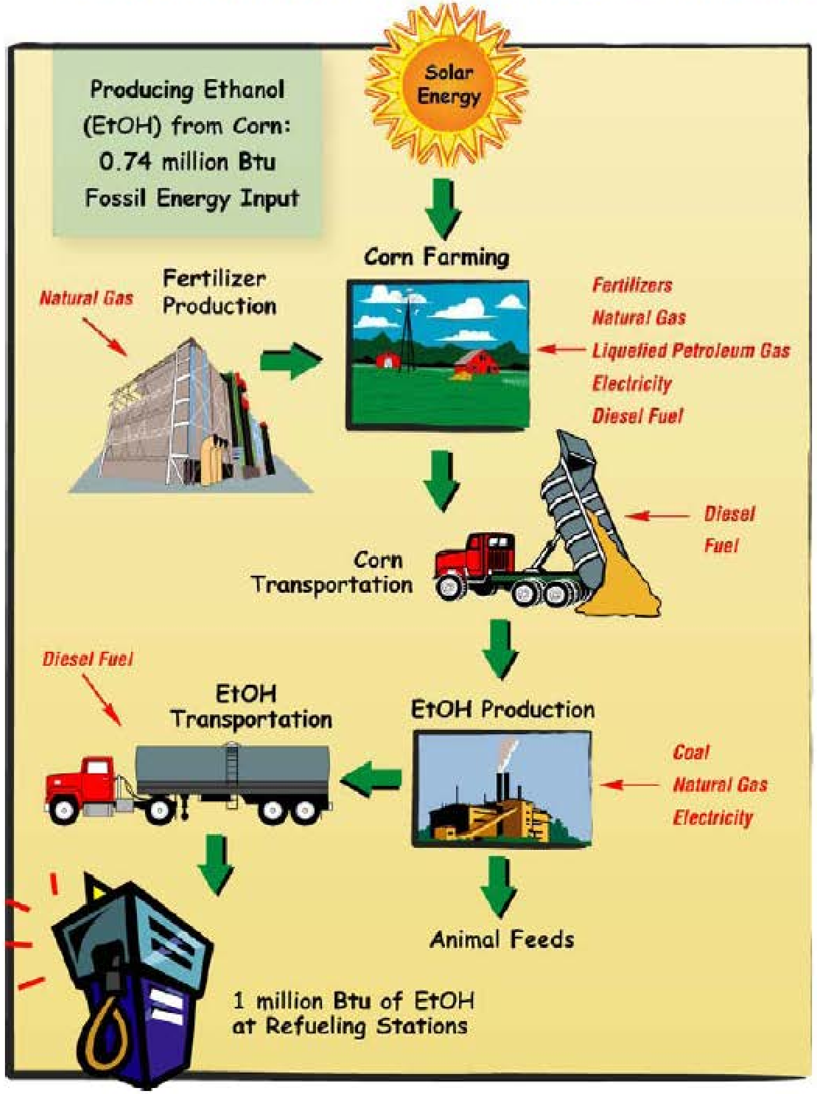
| Displacement effects | GHG emissions impact |
|---|---|
| Substitution of agricultural products | – |
| Deprivation of agricultural products (food and feed) | – |
| Intensification of agriculture (improved yields) | – |
| Expansion of agriculture (land conversion) | ++ |
| Petroleum market rebound | + |

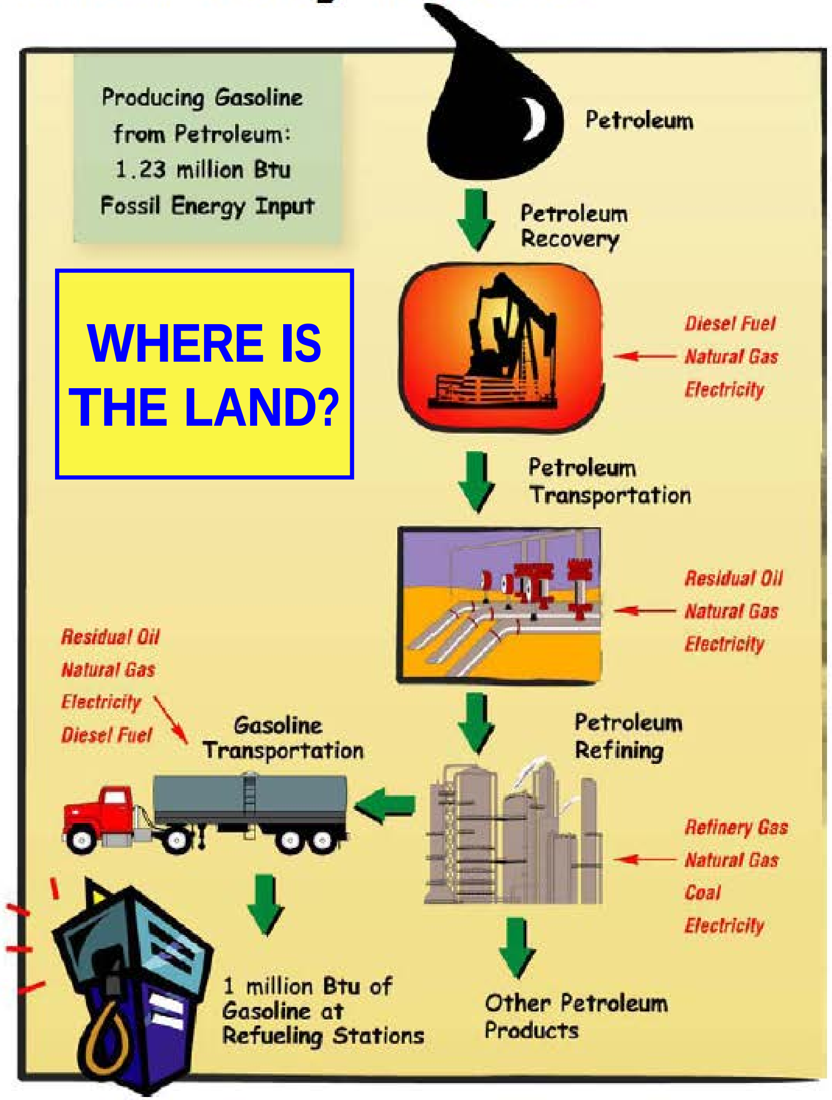
- These effects are all uncertain, but dominated by land conversion

# Why such divergence from LCA?

- Not due to difference in processing emissions
  - ABC method does not yield a carbon intensity (CI) value
  - However, using (for example) a 37% offset rather than a 100% offset would change a typical ALCA result of corn ethanol having a CI of, say, 44% less than petroleum gasoline (Wang et al 2012) to being 27% higher.
- The big reason is system dynamics
  - Explicit evaluation of carbon uptake: initial conditions matter
  - ABC result is time dependent; will differ for different time periods
  - ABC result is a bounding result: empirical constraint on net emissions impact
  - N.B. -- counterfactual analysis is yet to be done
- We cannot assume that a biofuel system is *a priori* "sustainable" with respect to the terrestrial carbon cycle.

# Comparative Results Between Ethanol and Gasoline Are More Relevant to Policy Debate




**WHERE IS THE LAND?**

Source: Wang, M.Q. 2005. Updated energy and greenhouse gas emissions results for fuel ethanol.

# Relation to carbon accounting issues

- Some key conditions for creditable carbon offsets:
  - Additionality
  - Permanence (offsets also need to be Real and Verifiable)
  - Leakage
- Additionality pertains to the initial condition
- Permanence: a clear advantage for bioenergy, which enables fossil carbon to remain "in the ground" when using carbon-based fuels
- Leakage: the ILUC and rebound problems
- But note:
  - Keeping it "in the ground" does not necessarily keep it "out of the air"
  - Without additionality, permanence doesn't matter
  - Leakage is a difficult problem regardless of the core analytic method

# Conclusions

- First principles show that dynamic analysis is essential
  - Time-varying processes cannot be reduced to a time-averaged lifecycle.
  - Further data gathering and LCA model development will never get us to a clear-cut answer to an ill-posed question.
- It is possible to constrain net $CO_2$ emission effects
  - Field data show that observed gain in carbon offset (additionality) falls well short of full offset of biogenic $CO_2$ emissions.
  - Empirically confirms that LCA has misled policymakers.
- On workshop question about ability of LCA to meet technical needs arising out of policy actions: the answer is NO.
- New (and different) research and re-analysis are needed
  - Retrospective evaluations, including counterfactual analysis
  - Development of program-scale carbon stock-and-flow models