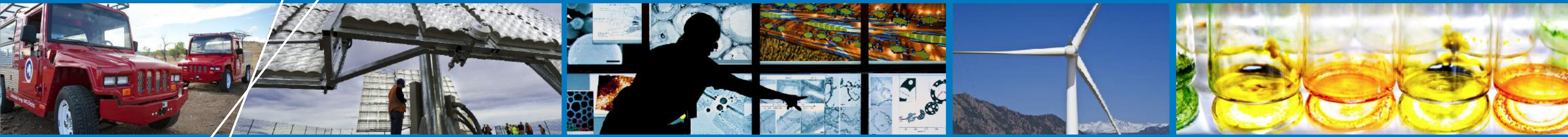
Biofuel Sustainability Analysis



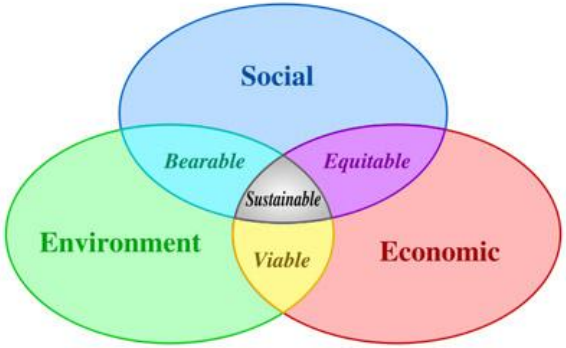
CEBES

Daniel Inman, PhD

July 26, 2012

Sustainability is a relative concept

- A search for *sustainability* on Google yields circa 40,000,000 results…
  - "…is the capacity to endure…" *Wikipedia*
  - "…conditions under which humans and nature can exist in productive harmony…" *US EPA*
  - "…meet present needs without compromising the ability of future generations to meet their needs…"

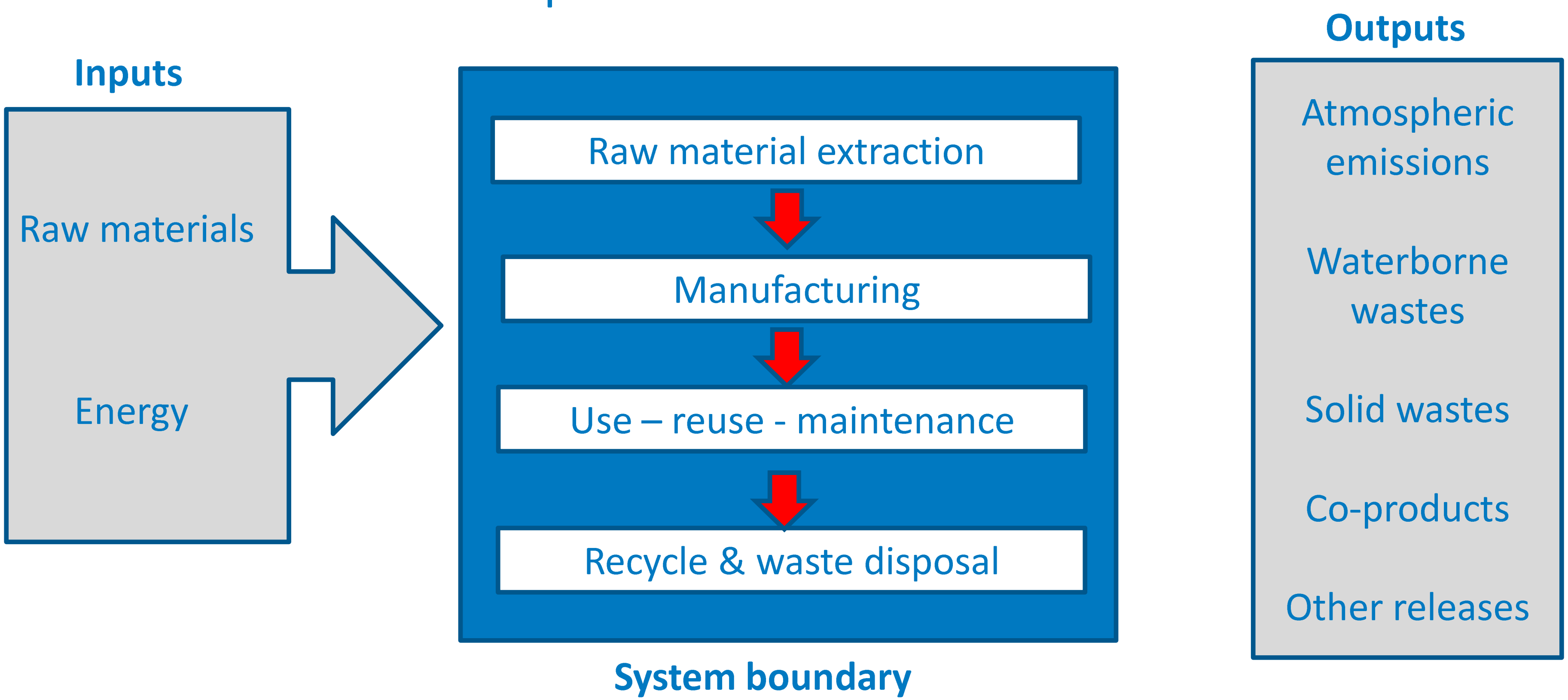


Quantification requires computer modeling

- Overall sustainability is difficult to measure [estimate, forecast] and typically requires complex computer models with numerous simplifying assumptions.
- Most "sustainability" studies are actually focused on only one aspect of one of the "pillars" of sustainability, usually one or more components (measures) of the environment or the economy.
  - E.g., GHG, EROI, consumptive water use, human health impacts

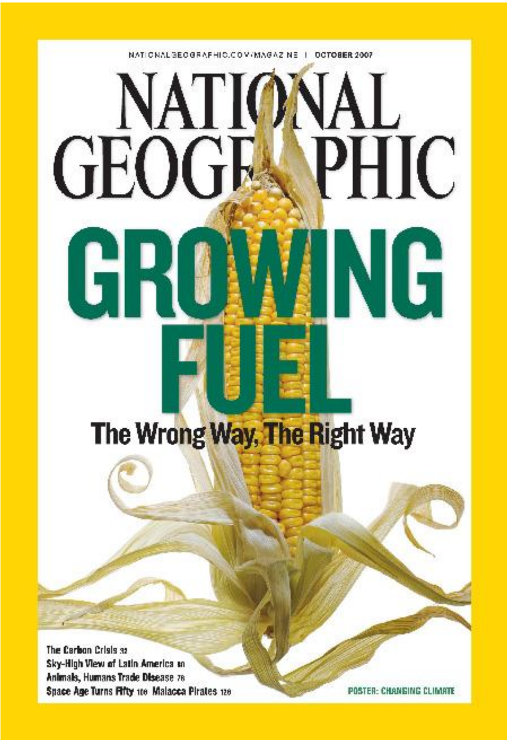
Lifecycle assessment (LCA) and sustainability

- LCA is a framework to assess the cradle-to-grave impacts of any industrial system.
- All energy inputs and environmental emissions are summed over the life of the product.



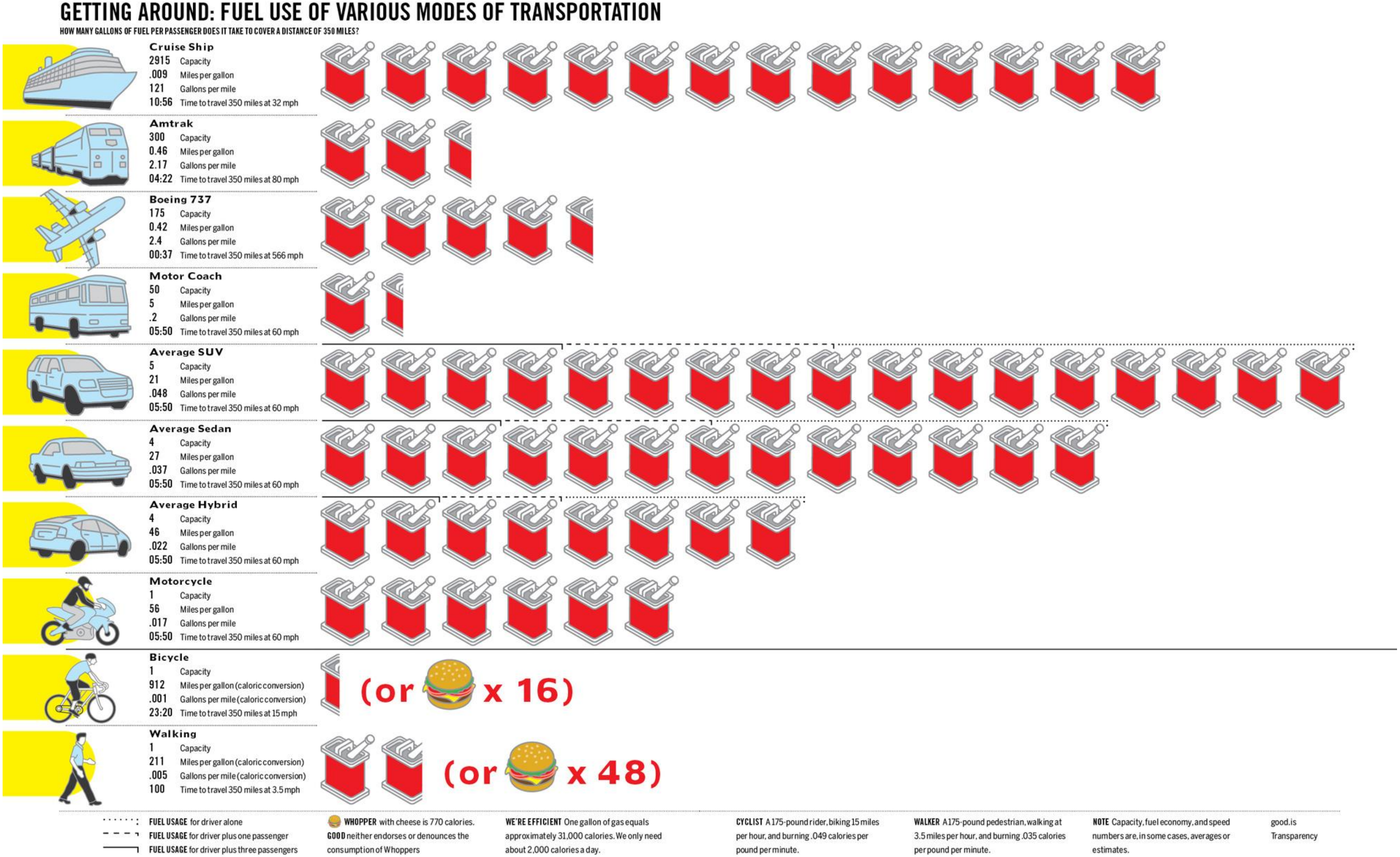
* Modified from EPA 2006

The biofuel sustainability message has been muddled



Contradictory results have caused confusion and loss of public support.

LCA are often compared blindly in the press and the literature



* From Good Magazine, 2009

Sustainability changes [improves] as technology matures

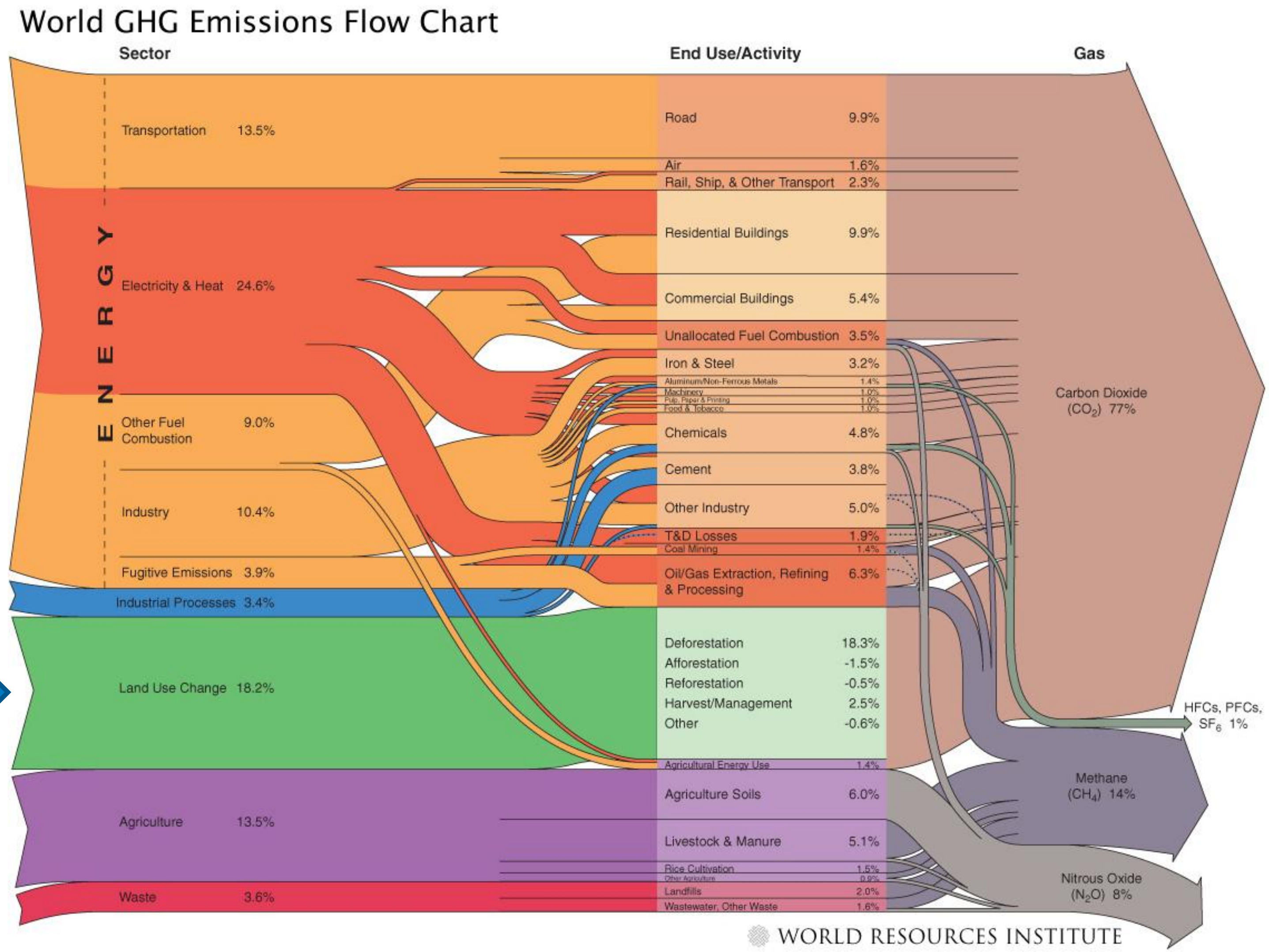
Greenhouse gasses and net energy of corn-based ethanol [1]

	Patzek 2004	Pimentel et al 2005	De Olivera et al 2005	Shapouri et al 2004	Farrell et al 2006	Gasoline
GHG g CO_2 MJ^{-1}	122	117	99	61	77	94
Net Energy MJ L^{-1}	-5	-6.1	1.6	8.9	4.6	-0.24

[1] Data from Farrell et al 2006; GHG based on IPCC 100a; Net energy = fuel energy (MJ L^{-1}) - energy input (MJ)

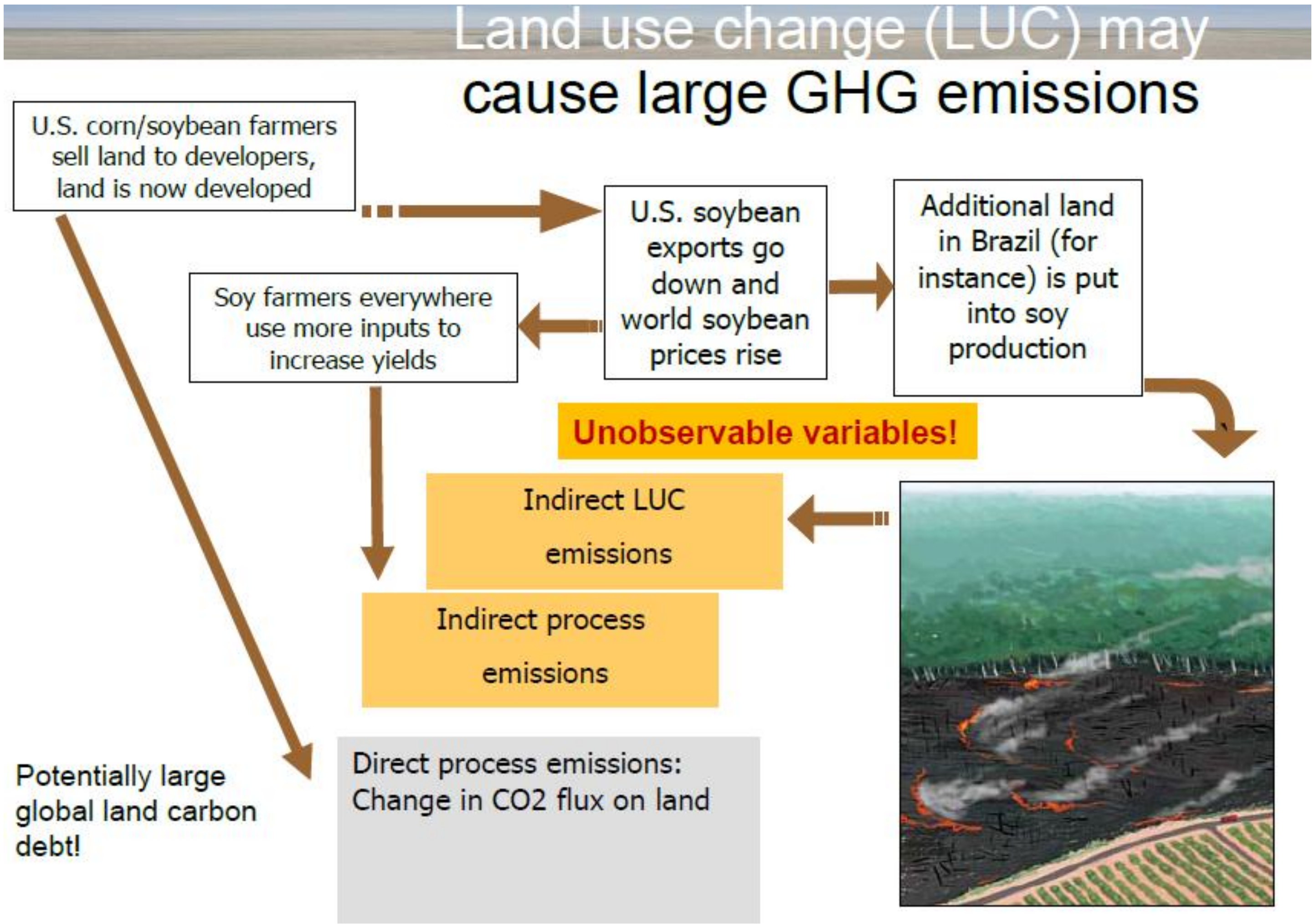
- A survey of the literature, by NREL, indicates that there are > 60 ethanol studies published that use LCA to some extent.
- Large discrepancies exist between studies.

Is an elephant is in the room?

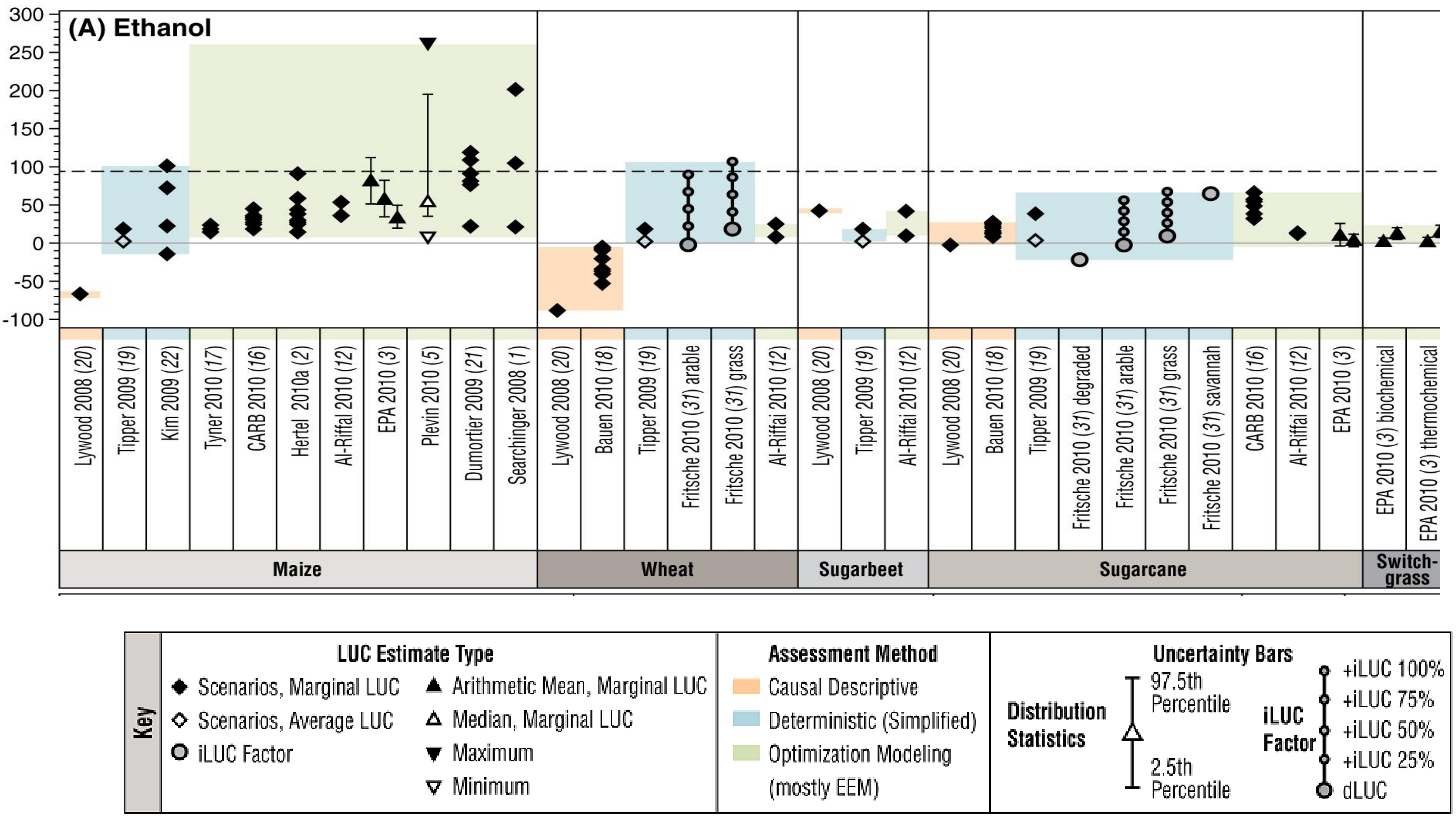


Significant changes to the global agricultural system will affect LUC

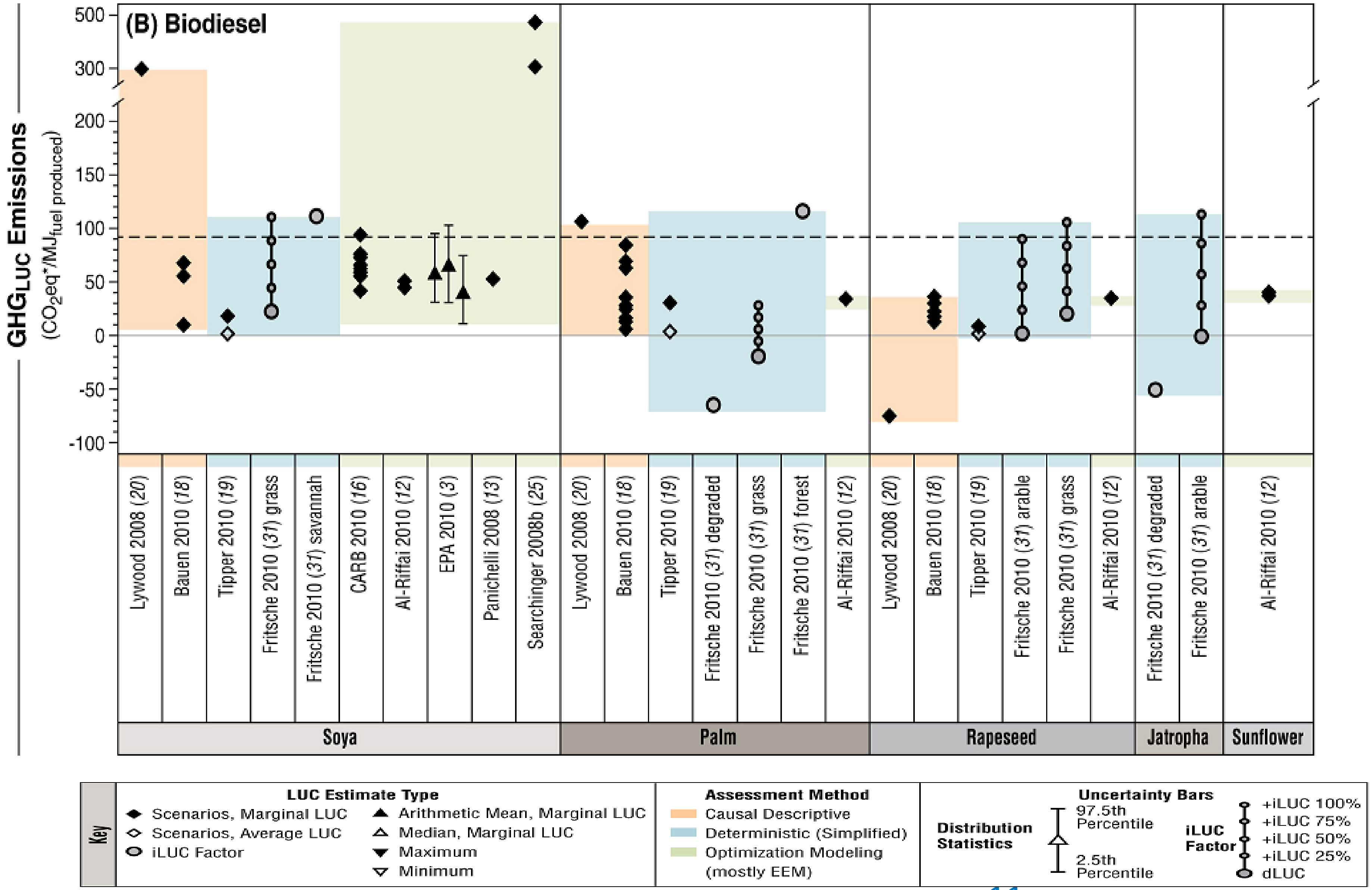
CO_2 emissions from biofuel-induced LUC



Modeled results are highly variable



Variance in magnitude and sign across studies, pathways, and feedstocks



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LUC is not unique to biofuels

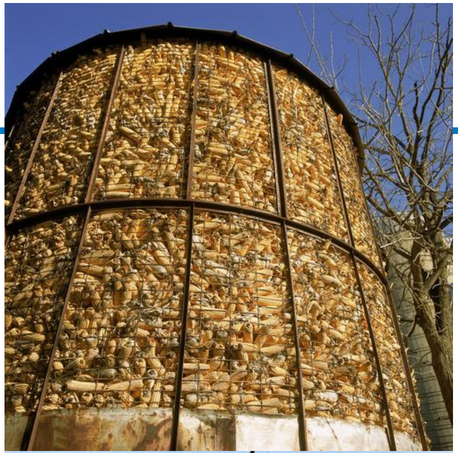
- Very few studies consider the LUC impacts of petroleum extraction.
- There are studies that suggest that resource extraction is the first-order cause of LUC, biofuels are a 2nd-order impact.

Limited Fuel Coverage of GHG_{LUC}

- Current generation biofuels - Studied extensively

- Cellulosic biofuels – Limited Study

- Petroleum fuels – No study could be found
  - Limited assessment of direct land disturbance caused by conventional oil (1-4 g CO_2eq MJ^{-1}) and oil sands (19.6 g CO_2eq MJ^{-1}) was found.
    - (Yeh et al. 2010 and Unnasch et al. 2009)



LUC is not the “only” sustainability issue

- LUC is arguably the most controversial topic of conversation in biofuel sustainability, but…
- Local human health impacts of biofuels
  - Criteria air emissions are linked to quantifiable (i.e., monetized) human health impacts.
  - These impacts exhibit a high degree of spatio-temporal dependence. In other words, national/regional/state averages are not informative.

Air quality impacts from biofuels

Goal: Compare air pollutant-related health impacts (and monetization thereof) from scenarios of large scale deployment of ethanol using next generation feedstocks to a BAU case of mostly gasoline on a life cycle basis

Objectives:

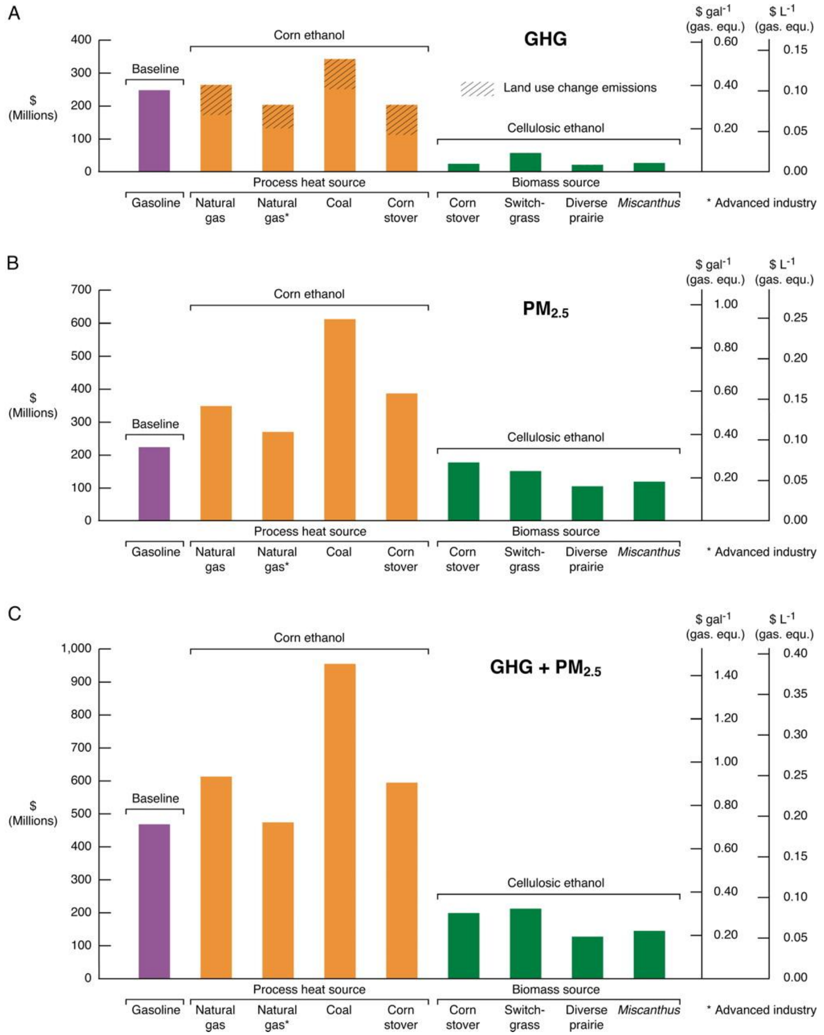
1. Develop credible air pollutant emissions inventory for all life cycle processes
2. Spatially and temporally disaggregate our life cycle assessment model
3. Utilize state of the science air quality modeling methods to estimate air pollutant concentrations and resultant health impacts

Motivation

Very few studies have investigated air quality and human health impacts of various ethanol pathways

1. Jacobson (2007): health impacts from *use* of corn E85 compared to gasoline (not full life cycle)
2. Huo et al (2008): *mass emissions* from life cycle of many fuel/LDV systems, urban vs rural
3. Jones (2010): *mass emissions* from seven pre-commercial cellulosic ethanol plants based on permitted emission levels
4. EPA (2010): health impacts from RFS2 vs. Baseline (RFS1) considering all life cycle processes
    1. So detailed and specific to regulatory purpose that not useful for DOE programmatic purposes
5. Hill (2009)

Motivation: Hill et al 2009



Costs of GHG (A) and PM2.5 (B) emissions.

Hill J et al. PNAS 2009;106:2077-2082

Opportunities to Build from Hill 2009

1. Approached by UMN to form partnership
    1. We access their AQ modeling capability
    2. They access our LCA model
2. Much better AQ models available
    1. Kilometer spatial resolution for full US
    2. Full year hourly simulation
    3. Can predict ozone
3. Align AQ modeling to NREL’s LCA model
    1. Additional feedstocks
    2. Process-level model

Multi-Institutional Project Team

NREL

Role

- Develop air pollutant emissions inventory for all processes in NREL LCA model
  - PM and precursors
  - Ozone and precursors
- Assign temporal signal and spatial location to all emissions

Team

- Garvin Heath – co-PI
- Yimin Zhang – lead
- Other staff and interns

University of Minnesota

Role

- Refine advanced airshed model (CAMx) to state-of-the-science temporal and spatial resolution
- Develop air pollutant concentration output
- Assess population inhalation exposure and health effects
- Monetize health impacts

Team

- Jason Hill – co-PI
- Julian Marshall – co-PI
- Post-doc and grad students

Tentative Schedule (proposed)

1. FY11
   1. Initiate gap-filling of air pollutant emission factors
      - Focus on feedstock production and pre-processing
      - Conversion requires additional effort
   2. As an inventory for a life cycle stage is completed, assign temporal signal
   3. As an inventory for a life cycle stage is completed, assign a spatial location (using GIS)
      - Coordinate with UMN for similar processes
      - Develop our own for dissimilar processes
2. FY12
   1. Submit emissions inventory for at least feedstock production stage for journal publication
      - Possibly broader or more than 1 publication
   2. Develop spatially and temporally disaggregated emissions inventory ready for use in AQ model
   3. Wait for UMN results – air pollutant concentrations (maps), health impacts estimates (national) and monetized impacts
   4. Initiate publication of results
   5. Share results (e.g., inventory) with DOE stakeholders (GREET)
3. FY13
   1. Submit manuscript for journal publication
   2. Develop inventories into US LCI files so other researchers can use them

Comparative LCA of multiple pathways

Life cycle assessment (LCA) of ethanol in 2022 published in *Environmental Science and Technology*, June 2010.

Inform management stakeholders of study results

- Describe the implications
- Compare to EPA and GREET analyses

Request feedback on our plans

- Additional studies for FY10-FY11
- ES&T communications strategy
- Role of NREL LCA analysis with regard to NBTRP feedback

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Life Cycle Environmental Impacts of Selected U.S. Ethanol Production and Use Pathways in 2022

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Projected life cycle greenhouse gas (GHG) emissions and net energy value (NEV) of high-ethanol blend fuel (E85) used to propel a passenger car in the United States are evaluated using attributional life cycle assessment. Input data represent national-average conditions projected to 2022 for ethanol produced from corn grain, corn stover, wheat straw, switchgrass, and forest residues. Three conversion technologies are assessed: advanced dry mill (corn grain), biochemical (switchgrass, corn stover, wheat straw), and thermochemical (forest residues). A reference case is compared against results from Monte Carlo uncertainty analysis. For this case, one kilometer traveled on E85 from the feedstock-to-ethanol pathways evaluated has 43%−57% lower GHG emissions than a car operated on conventional U.S. gasoline (base year 2005). Differences in NEV cluster by conversion technology rather than by feedstock. The reference case estimates of GHG and NEV skew to the tails of the estimated frequency distributions. Though not as optimistic as the reference case, the projected median GHG and NEV for all feedstock-to-E85 pathways evaluated offer significant improvement over conventional U.S. gasoline. Sensitivity analysis suggests that inputs to the feedstock production phase are the most influential parameters for GHG and NEV. Results from this study can be used to help focus research and development efforts.

Introduction

Forty-one billion liters of ethanol were produced in the United States in 2009, mostly from corn grain (*Zea mays* L.) (*1*). As part of a strategy to address national security, greenhouse gas (GHG) emissions, and rural economic development, the Energy Independence and Security Act of 2007 (EISA) (*2*) amended the 2005 renewable fuel standard (RFS) to mandate that approximately 136 billion liters per year (bLy) be produced by 2022. Under the 2007 RFS, a maximum of 56.6 bLy of ethanol derived from conventional sources (e.g., corn grain) may qualify as a renewable fuel (*2*); the remainder must be met by biofuel derived from second-generation feedstocks, such as agricultural residues, forest residues, and perennial grasses.

Life cycle net energy value (NEV) and GHG emissions have been used as metrics to compare different feedstock-to-ethanol production systems and gasoline. With a few exceptions (*3, 4*), most studies conclude that corn ethanol has NEV and GHG advantages compared to gasoline (*5*−*9*). After harmonizing the methods of six previous life cycle assessments (LCA), Farrell and colleagues (*10*) found that current corn ethanol production yields an NEV of approximately 5 MJ L^{-1} and a GHG intensity of −18% (uncertainty range: −36% to +29%) compared with that of conventional gasoline. Similarly, ethanol derived from both switchgrass and corn stover has been shown to have higher NEV and lower GHG emissions when compared to gasoline (*11, 12*). An LCA consistently comparing multiple feedstocks in the same production year would contribute to current research.

This study uses attributional LCA to compare projected GHG emissions and NEV of ethanol-based transportation fuel derived from five feedstocks grown and used in the conterminous United States in 2022 to that of conventional gasoline in 2005. Advanced designs for all life cycle stages of a first-generation feedstock (corn grain) and four next-generation feedstocks (corn stover, wheat straw, switchgrass, and forest residues) are considered. Life cycle GHG and NEV of gasoline are considered for the base year of 2005, similar to the mandates in EISA. Because EISA and other environmental mandates demand performance often far beyond current practice, this analysis aims to inform industrial and governmental research and development decisions by (1) determining the key input parameters that impact life cycle GHG emissions and NEV, and (2) quantifying the distribution of two environmental performance metrics. To do so, sensitivity and uncertainty analysis methods are applied.

Methods

SimaPro v.7.1 life cycle assessment modeling software (*13*) is used to develop and link unit processes. Most processes are custom created using primary, publicly available data. In the absence of such data, we use the Ecoinvent v.2.0 (*14*) and, to a lesser extent, the U.S. Life Cycle Inventory (U.S. LCI) (*15*) processes. For some processes that are developed from Ecoinvent and the U.S. LCI, we modify the former to be reflective of U.S. conditions and the latter to account for embodied emissions and energy flows. This study follows International Organization for Standardization standards for LCA, including stakeholder and external reviews (*16, 17*); all processes underwent external review by experts from industry, academia, and government.

Modeling Approach and Assumptions. The modeling boundary for this study is from field to wheels including embodied energy and material flows. The functional unit is 1 km traveled by a light-duty passenger car operated on E85 in the year 2022. The ethanol is assumed to be produced in the conterminous United States (*18*). For our reference case, E85 is assumed to be 78 v% ethanol and 22 v% conventional unleaded gasoline, which includes gasoline denaturant (2 v% of ethanol). (This composition is based on an average of regional and seasonal blends (*19*)). The reference case evaluated in this study is based on extrapolation of national average data and anticipated industry learning and improvement. Therefore, the reference case is not necessarily indicative of any region of the country. Sensitivity and uncertainty analyses explore the impact of variability (considered on a national average basis) of a large set of input parameters on projected GHG and NEV results.

Avoided impacts are accounted for using product displacement (boundary expansion) (*16, 17*). For products that

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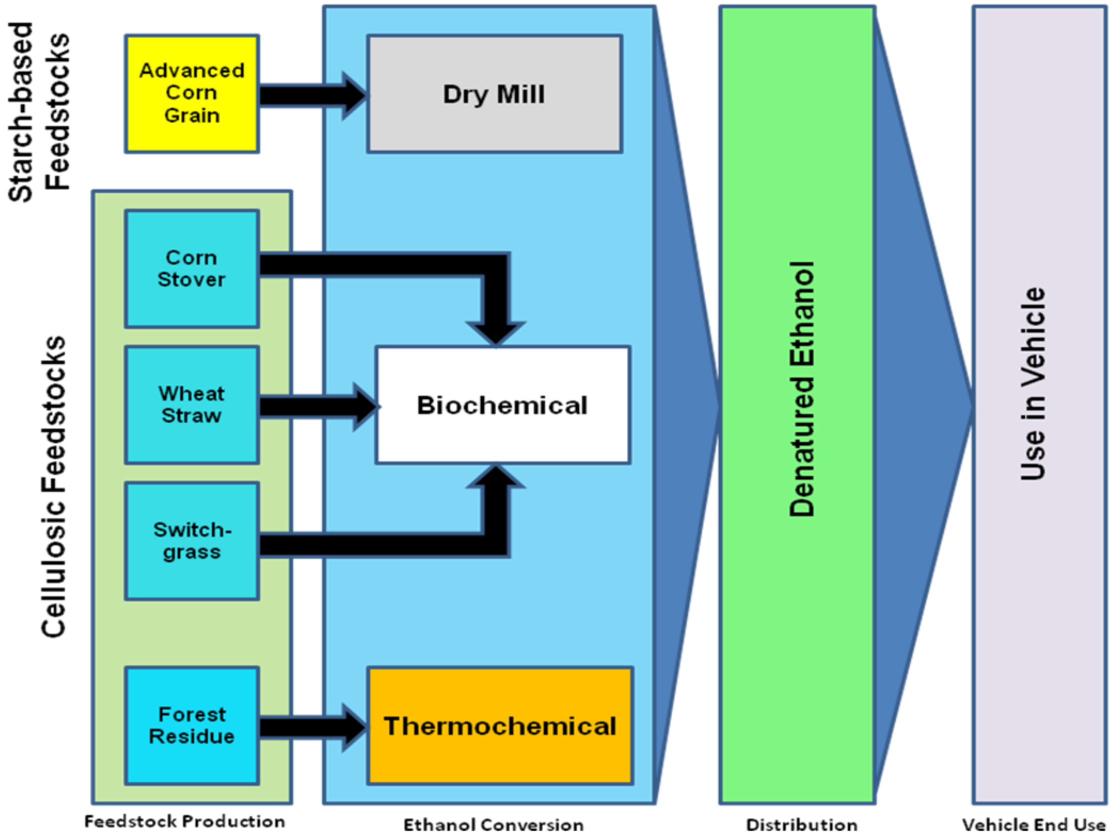
Multiple feedstocks and conversion technologies were assessed for the year 2022



Model NOT designed for policy assessment but for guiding sustainability metrics development and technology development

- Consistently compare 5 feedstock-conversion pathway options
- Consider advanced system (2022) designs for all life cycle stages
- National-average conditions
- Evaluates the incremental kilometer driven, not at-scale policy impacts

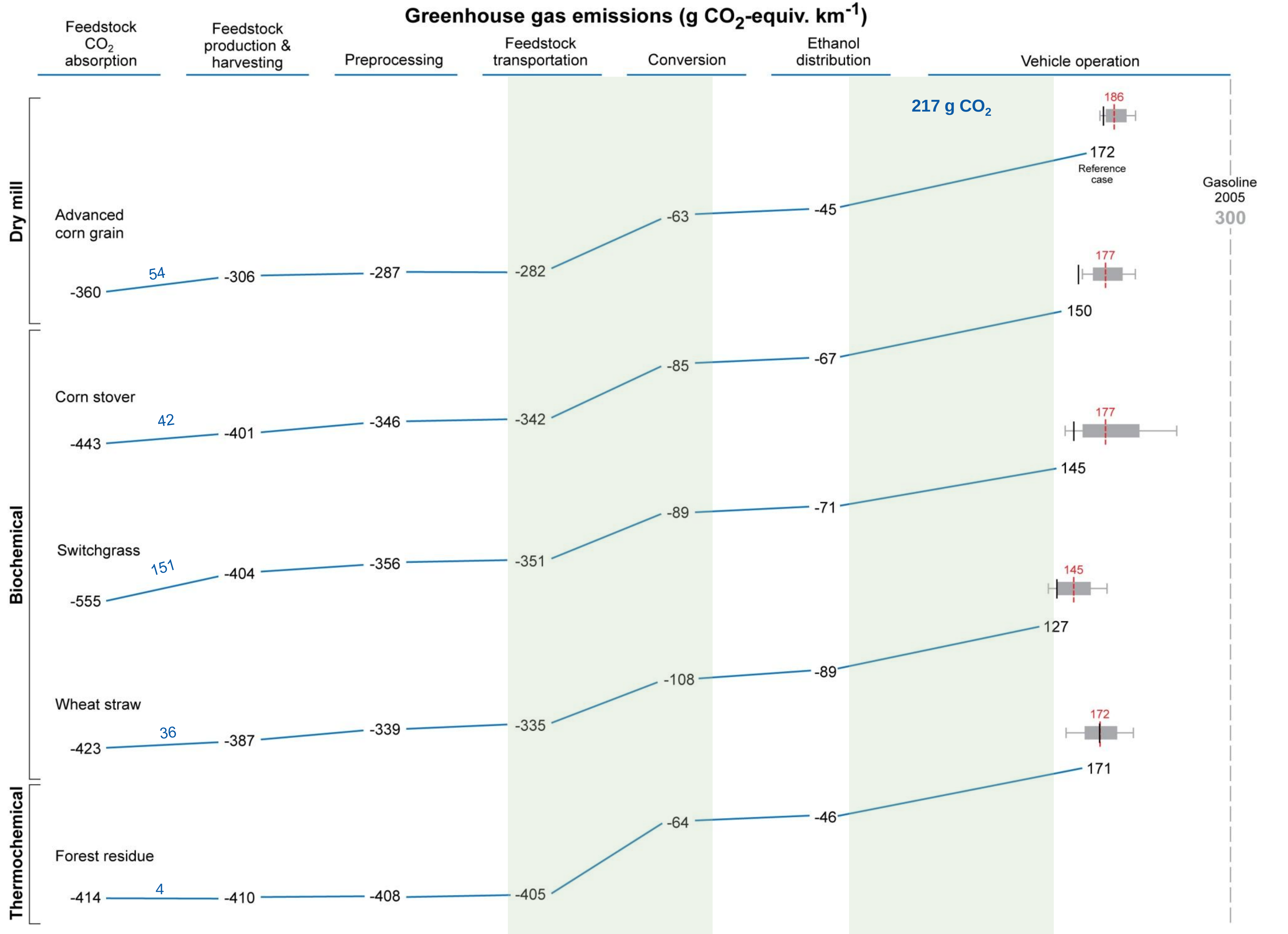
Not Just Another Ethanol LCA

How is this different from past ethanol LCAs?

- Comparison of multiple feedstocks/technologies in the same timeframe (2022)
- Linking multiple DOE models
  - NREL cellulosic and corn ethanol design reports
  - INL feedstock design report
  - ANL GREET vehicle emissions
- Rigorous sensitivity and uncertainty methods to create a probabilistic assessment
- Transparent and documented LCA model (published in Supplemental Information)
- Extensive stakeholder input and review

What are shortcomings of this LCA?

- No indirect effects (land use change) and soil carbon sequestration
- Results limited to Greenhouse Gases and Net Energy Value. Water results not published
- Future work addresses these shortcomings


Greenhouse gas emissions (g CO_2-equiv. km^{-1})
Feedstock CO_2 absorption
Feedstock production & harvesting
Preprocessing
Feedstock transportation
Conversion
Ethanol distribution
Vehicle operation
Dry mill
Biochemical
Thermochemical
Advanced corn grain
Corn stover
Switchgrass
Wheat straw
Forest residue
217 g CO_2
Reference case
Gasoline 2005
300
-360
54
-306
-287
-282
-63
-45
172
186
177
-443
42
-401
-346
-342
-85
-67
150
177
-555
151
-404
-356
-351
-89
-71
145
145
-423
36
-387
-339
-335
-108
-89
127
172
-414
4
-410
-408
-405
-64
-46
171

Input data uncertainty drives the distribution

Few input parameters drive sustainability

- Mostly in feedstock production stage

Substantial uncertainty in estimation of even direct life cycle impacts

- Switchgrass generally highest → pre-commercial systems, gaps in data
- GHG results for all evaluated feedstocks have substantial overlap in range of results
- NEV clustered by conversion technology

Reference case results from a set of optimized parameters and often lies outside the middle 50% of the distribution

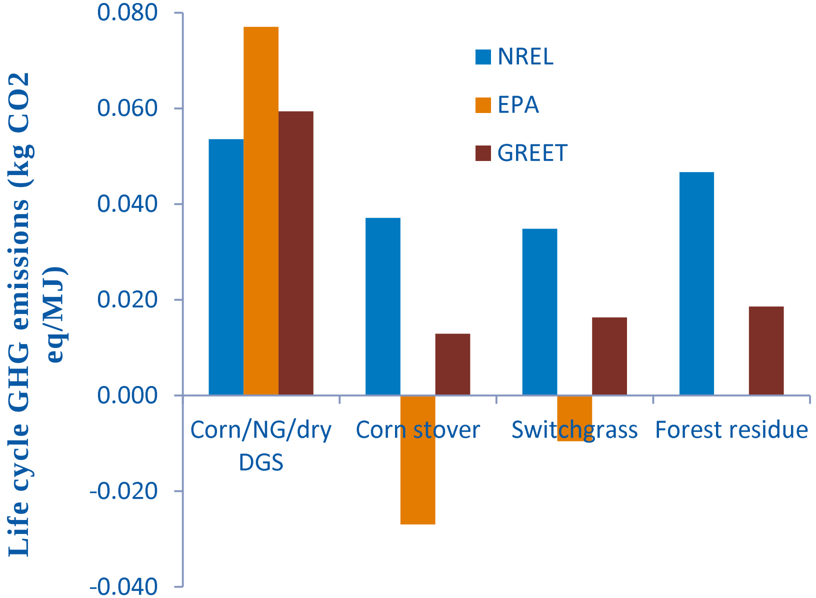
- Often <25 percentile and sometimes <10 percentile
- Driven by skewness in input distributions of key input parameters
- Results may have important impact on conclusions drawn from LCAs of biofuels

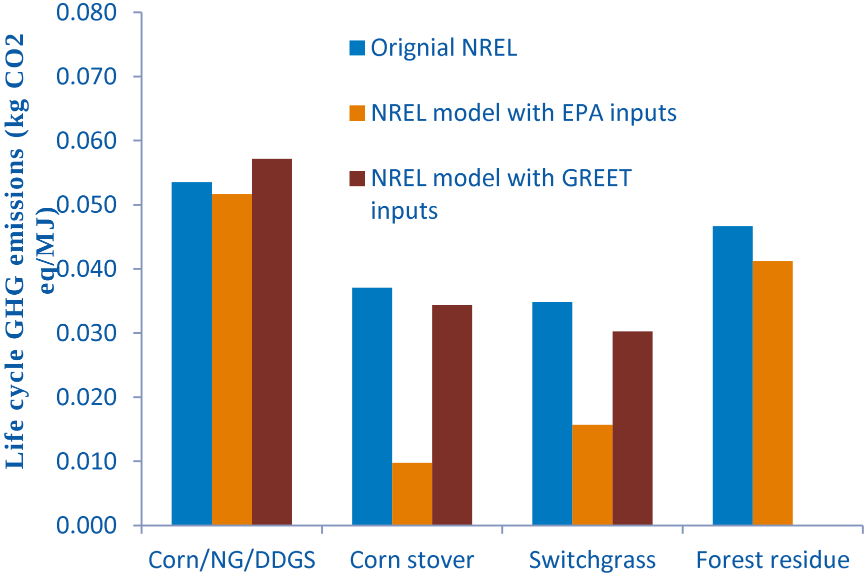
Many important processes in feedstock production and conversion need to be well controlled to ensure sustainability

- Most skewed input parameters are result of lack of data rather than variability of data

Nevertheless, all feedstock-to-ethanol pathways better than gasoline for GHG and NEV (full range) (excluding land use change)

Comparison with GREET and EPA





	NREL	EPA	GREET
Methodology/ System boundaries	Attributional	Consequential (i.e., includes indirect effects)	Attributional
INL preprocessing	Included. Drying, size reduction, and storage	Not included	Not included
Chemical/ enzymes in conversion	Included	Not included	Not included

- With inputs into NREL model
  - GREET results are almost the same
  - EPA still lower. EPA inputs lead to less GHG
- Results documented in technical memo (Y. Zhang)
  - After management approval, will be distributed to national lab stakeholders and EPA
  - Keep in NBC for reference

Current NREL Model Already Being Used

- Biofuels pathways analysis
  - Results feed into biofuels and biopower analysis
- Sustainability metrics
  - Work requested by DOE's Sustainability Program (A. Goss Eng)
  - Assists in evaluation of Office of the Biomass Program tasks
    - Biofuel conversion analyzed
    - Preprocessing importance highlighted
- Update of GREET inputs
  - Several cellulosic ethanol conversion issues identified
    - Ethanol yield
    - Electricity co-product
    - Factors coming from 2002 and 2007 cellulosic ethanol design reports
  - ANL interest in update increased after manuscript published

What is the NREL LCA Role in Future Policy?

NREL Biofuels Technical Review Panel:

- *Become involved in RFS III. NREL is in a good position to advise Congress and DOE about real and practical targets as well as the R&D efforts needed to reach these goals.*
- *There is a clear need to get NREL's analysis in front of policy makers in a timely manner so that [a] better decision can be reached [DOE Staff]*
- *Could NREL reconcile its LCA models with those of EPA, or publish peer-reviewed reports that industry can point to when dealing with EPA?*

Feedback points to extending outside NREL-DOE OBP world
(Ideas are for brainstorming purposes only)

- Aggressively pursue relationship with EPA
  - Short-term assignment with EPA
- Maintain strong contact with multiple offices of DOE
- Proactively communicate ES&T results with state and federal policymakers

NATIONAL RENEWABLE ENERGY LABORATORY

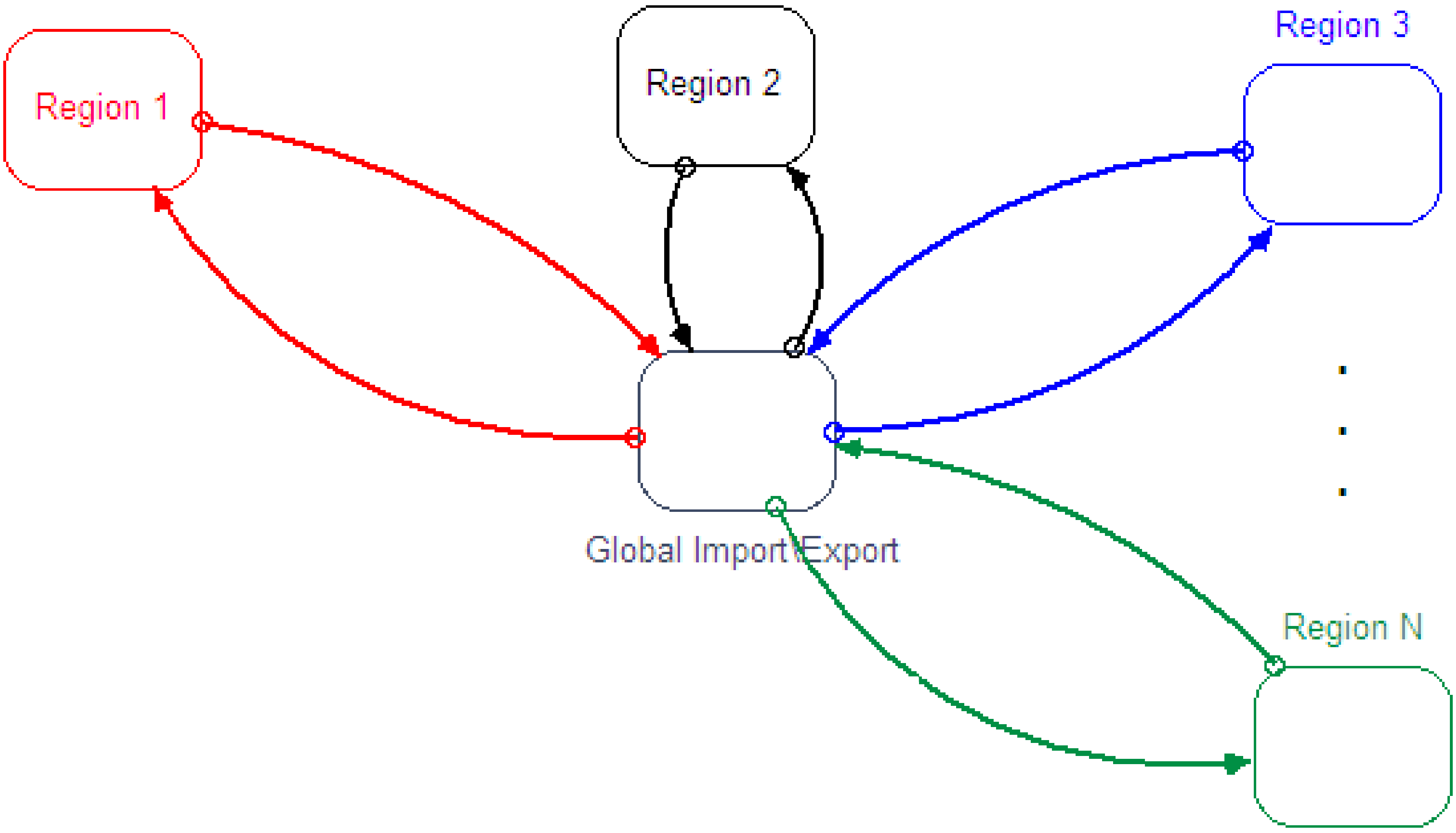
Innovation for Our Energy Future

LUC model back up slides

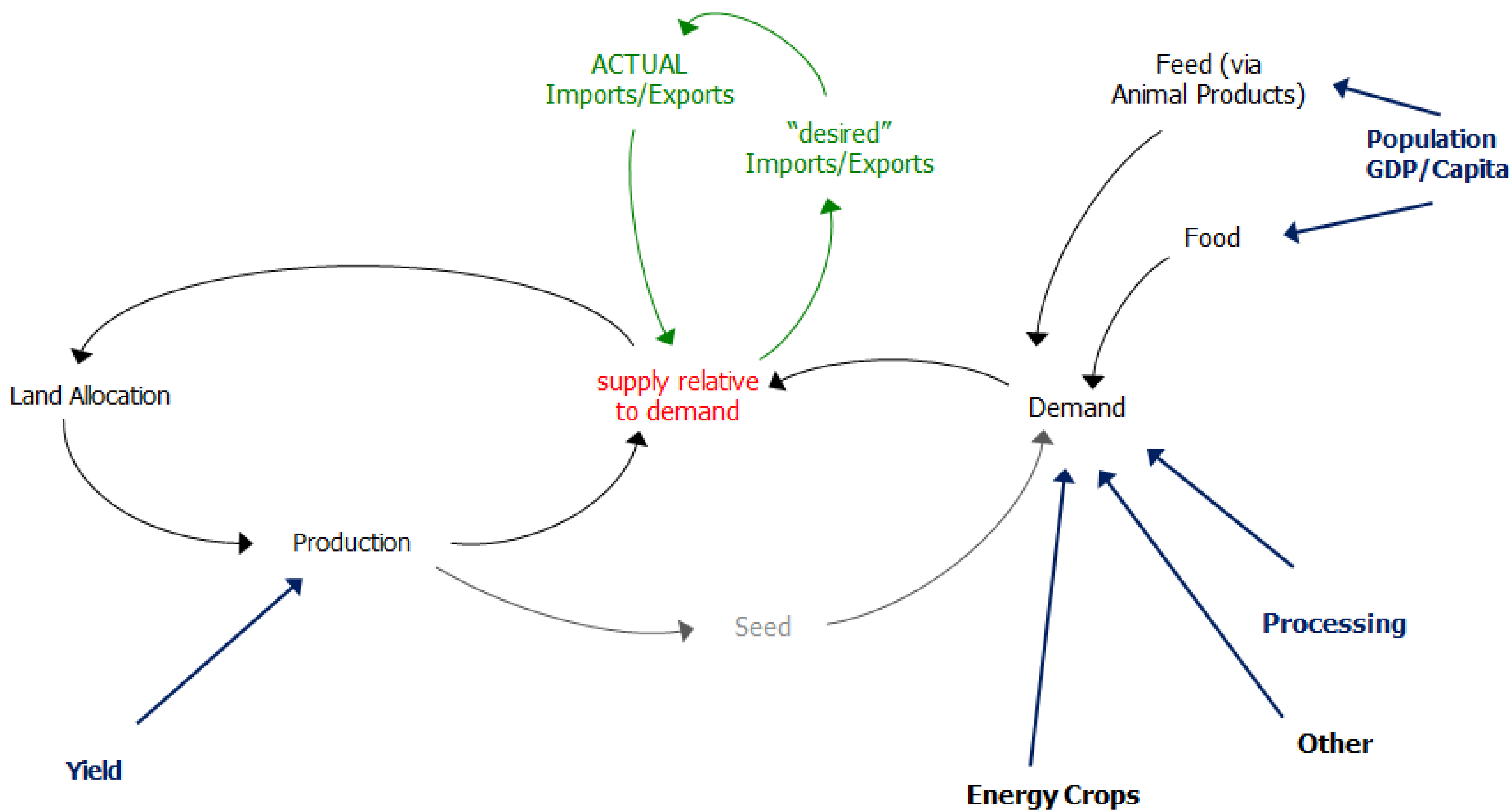
Modeling Strategy & Approach

- **"System Dynamics Framework"**
  - Stocks/flows
  - Feedback within and across stages in supply chain
- **Modular, "Regional" model architecture**
  - "Region" can reflect world, nation, geographical region, level of development, etc.
  - Enables rapid extension of model from 1 → 2 → n regions
  - Current structure includes US + 18 regions
- **Reliance on GDP/capita scenarios and FAO data to drive dynamics around population, yield, food demand.**
- **Calibrate model against FAO datasets for land use and disposition.**
- **Avoidance of explicit market mechanism**

Model Overview: Modular, Regional Approach



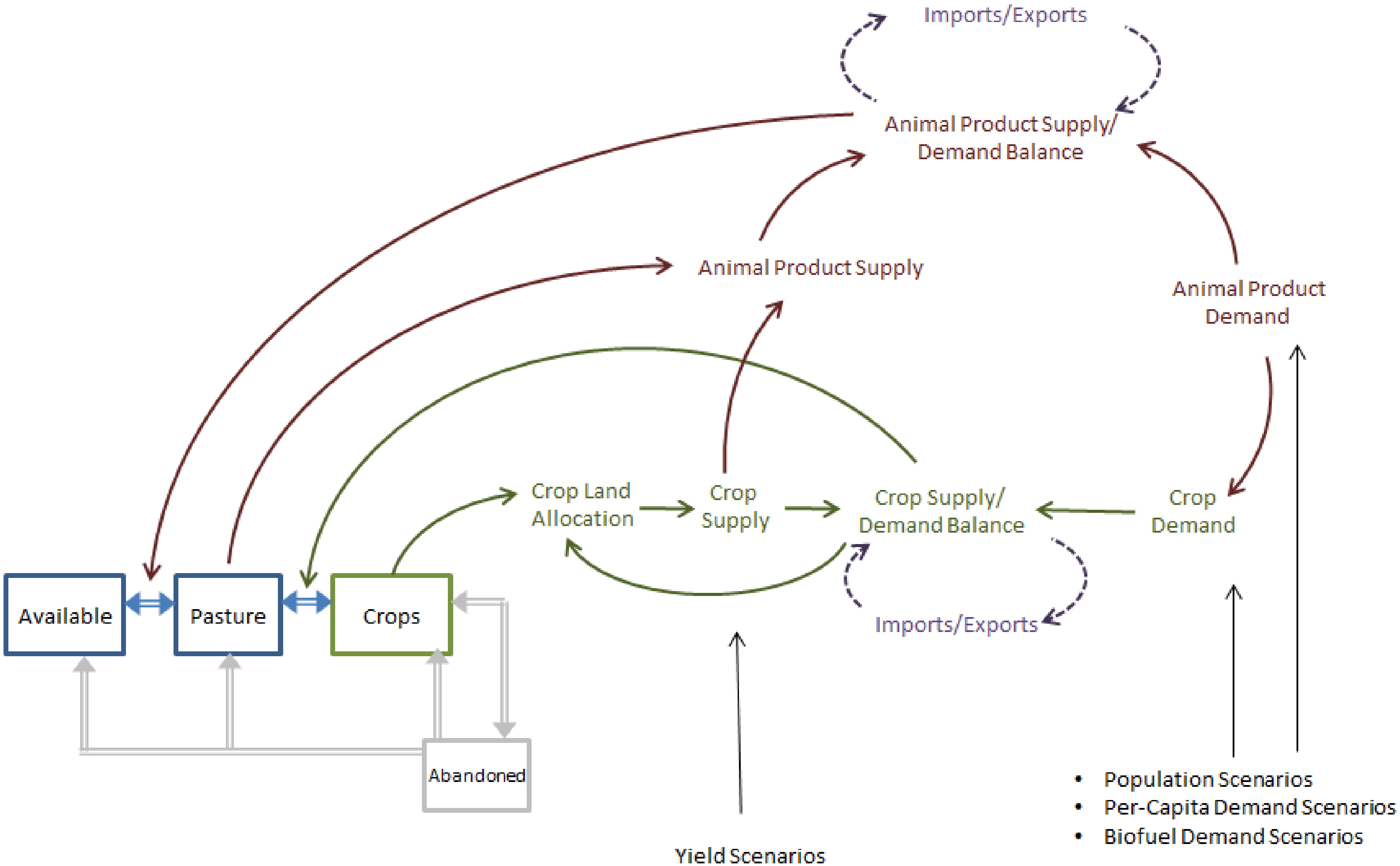
Simplified view of Model Feedbacks



Detail Complexity

- **4 x 2 Land Bases**
  - "Available" | Pasture | Cropland | Abandoned
  - Grassland | Forest
- **12 Cropland uses**
  - Fallow
  - Forage
  - Fiber | Vegetable Fruit Nut | Other
  - Maize | Wheat | Rice | Grains NEC | Oilcrops | Sugar
  - Energy Crops
- **Four Animal Product Categories**
  - Cattle/Sheep/Goat | Dairy | Swine | Chicken
- **Induced demand from animal product to commodity crops, pasture, forage**

Influence diagram for one region



Import/Export Structure

- ***Basic Challenge:*** **Provide simple mechanism for handling product movements across regional boundaries**

- ***Approach:*** **View x-region product movements as equilibrium-seeking, but with a constraint**
  - Supply/demand imbalance in one region drives "desire" for import/export
  - Total GLOBAL Imports must match total GLOBAL Export
  - *Key insight:* Global pressure (as reflected by difference in global desired import/export vs total ACTUAL import/export) translates into land use pressure.

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Land-use drivers

- Foundation of model development
- Many land-use drivers
- Land-use drivers considered inconsistently in literature

- **Land-use drivers (to be ranked)**
  - GDP
  - Population
  - Fertility/Mortality rates
  - Crop productivity
  - Land degradation
  - Demand for food types, including meat
  - International land-use/carbon agreements
  - Domestic biofuel and land-use policies

Data Processing Strategy

- **Most of the raw data comes from the FAO data sets.**
- **The FAO data was processed (organized, normalized) to provide calibration data sets.**
- **Regressions against GDP and other variables where used to develop forecasts of demands and yields.**
- **Literature searches yielded information on land and crop inputs to livestock production, forage characteristics, and other incidental input parameters.**

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Meat consumption drives demand for grains, forages, and pasture

- Determining the amount of grains, forage, and pasture it takes to produce a quantity of meat/dairy involved an extensive search of the literature.

- The direct consumption of "feed" per unit finished meat is readily available, but is no adequate for our purposes.

- We decided to use a life-cycle approach, which views the production of finished meat as an output of a production system …

Our base-case meat product I/O table is based on intensive systems

	Base case system input per kg of product								
Animal Class	Forage	Pasture	Maize	Wheat	Rice	NEC	Oil Crop	Sugar	Total kg
Cow Goat Sheep	6.1	4.9	2.6	0.1	0.0	0.0	1.1	0.0	14.8
Dairy	4.5	0.0	1.2	0.0	0.0	2.0	0.0	0.0	7.7
Pig	0.0	0.0	1.2	1.4	0.0	0.3	0.7	0.0	3.6
Poultry	0.0	0.0	1.4	0.3	0.0	0.0	0.6	0.0	2.4

FAO Data Issues

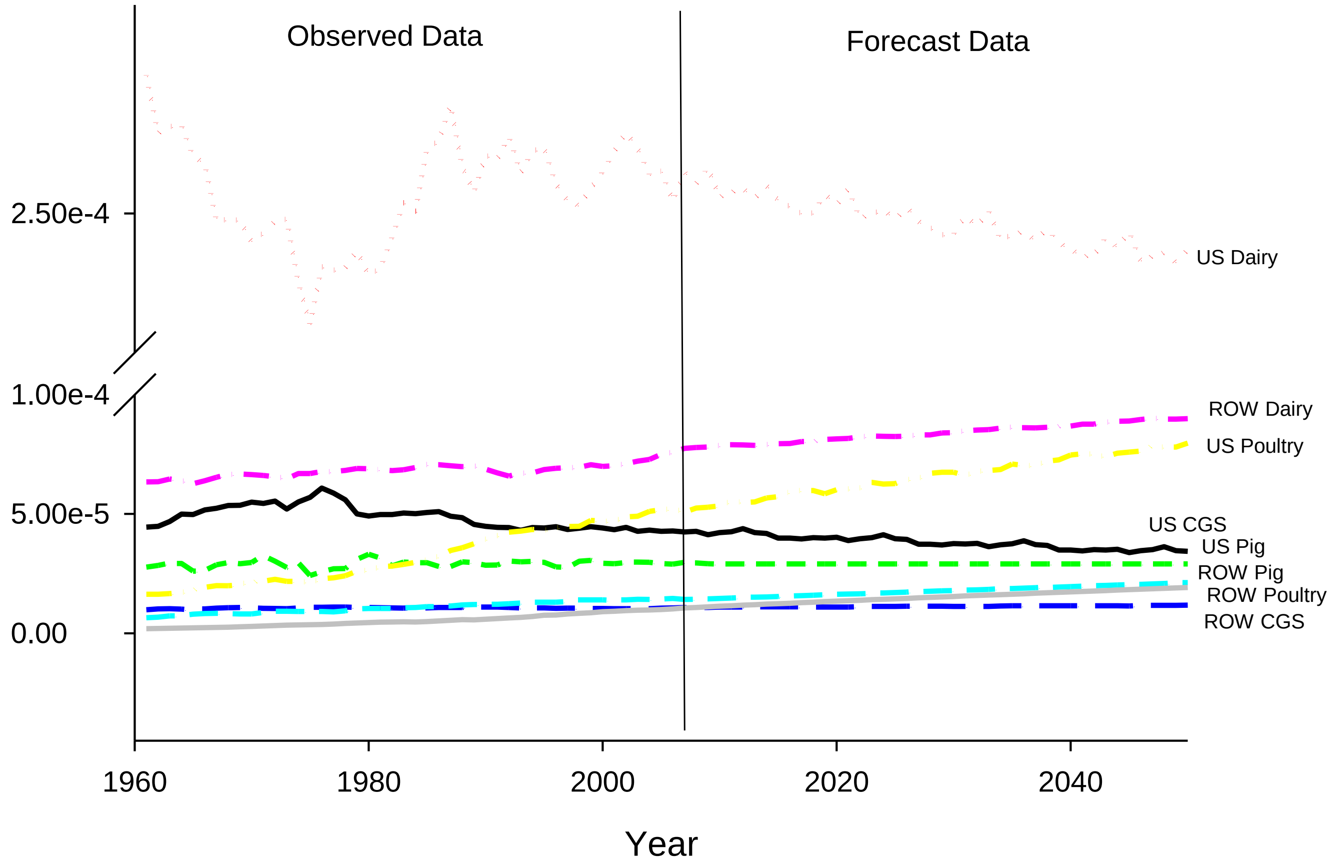
- The FAO data sets possess gaps, inconsistencies, noise, and category misalignments that make it difficult to use the data "as is" to construct a self-consistent input data set that is of sufficient quality for simulation.

- We have devoted extensive project resources to processing the FAO data so it is suitable for this global land use change model.

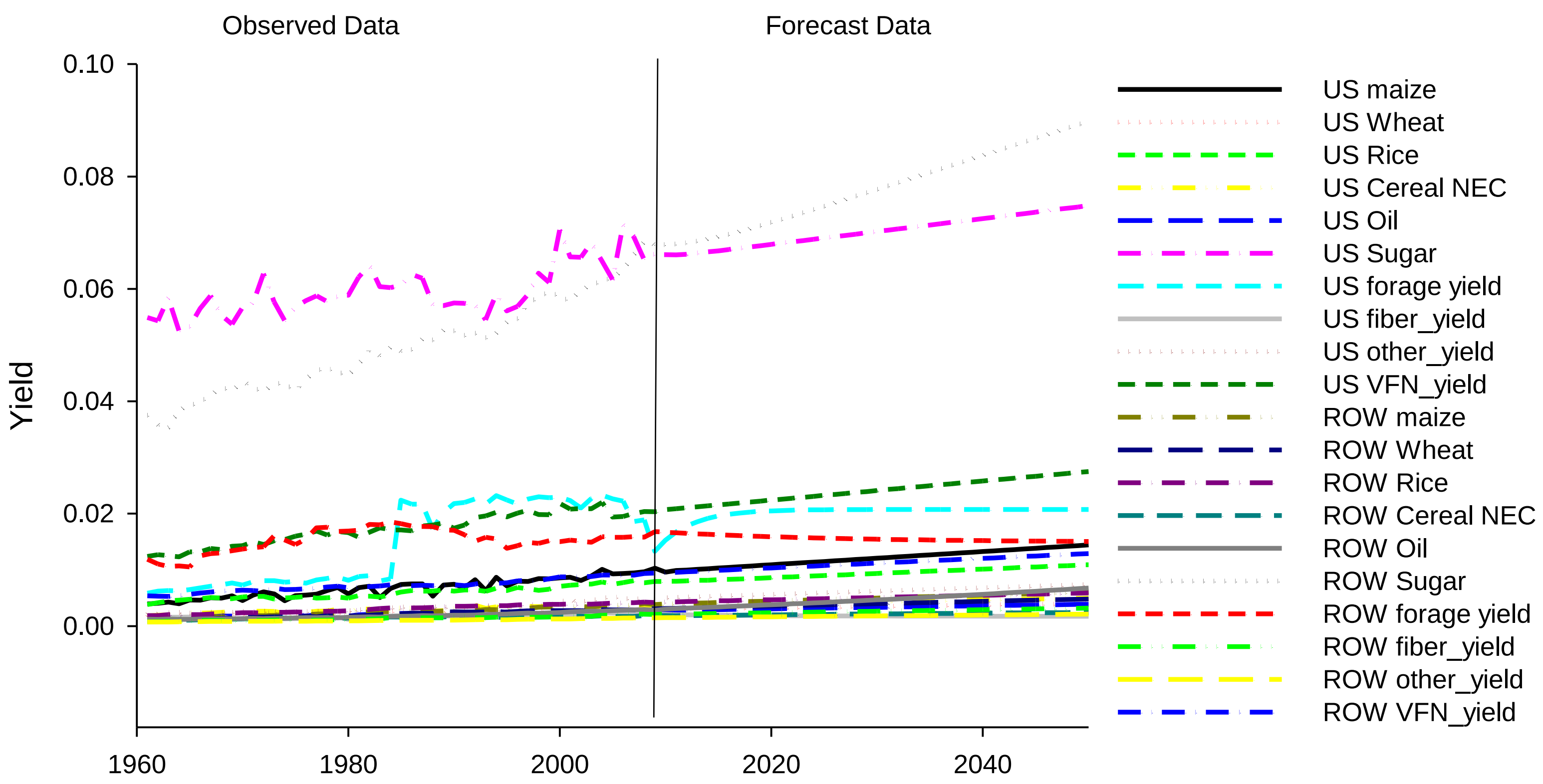
- Several "correction factors" have been added to the model to deal with input data quality issues.

- We are working with ORNL, UMN, and others to obtain a deeper understanding of the problems with the FAO data.

Observed and forecast data for meat demand: US and ROW



Observed and forecast crop yields: US and ROW



Calibration

- *Purpose:* **Not to replicate history, but to force out weaknesses in model structure, data, assumptions**
- **Calibration provides us with a BASELINE against which we evaluate scenarios**
- **Approach:**
  - Identify calibration data sets; develop comparison graphs (land use, product disposition)
  - Populate model with best available data set
  - Compare model results against calibration metrics
  - Identify, diagnose, work to ameliorate problem areas
    - Unexplained discontinuities in input data set a plausible start time
    - Significant calibration disconnects provide mechanism to ensure MECE characterization of production, consumption categories
  - Significant calibration disconnects—may imply inconsistent input data— need for calibration factors (including rationale)
  - Algebraic initialization can help provide consistency (e.g., land allocation)
  - Behavioral parameters can be adjusted to tighten fit
  - Remaining issues put back to team for further refinement (e.g., animal product crosswalk)

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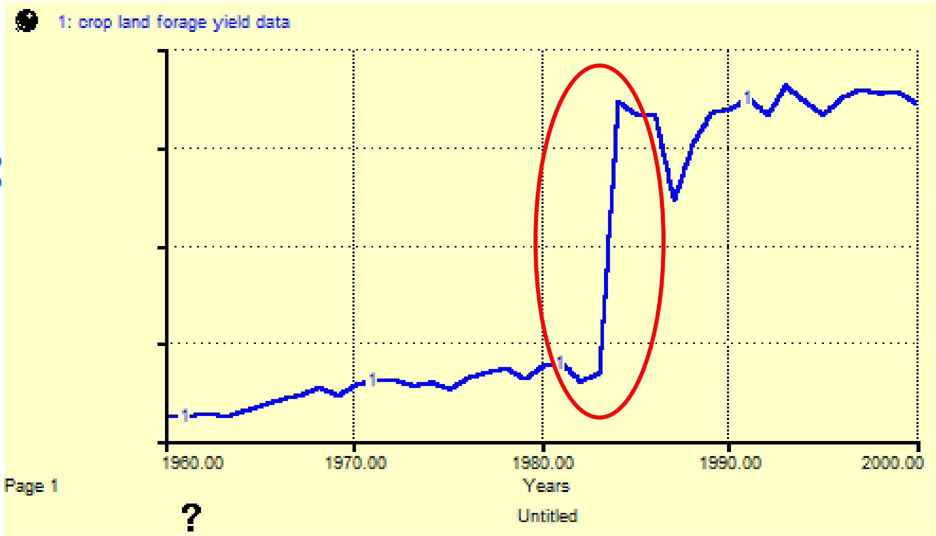
Calibration

- **Unexplained discontinuities:**
- **US Forage yield data set**
  → start time of ~1984…



- **Calibration factors provided for:**
  - Crop land forage yield
  - Pasture yield (expressed as fraction of forage yield data)
  - Animal product demands for pasture, commodity products

- **Algebraic initialization used for land bases, land allocation, product inventories**

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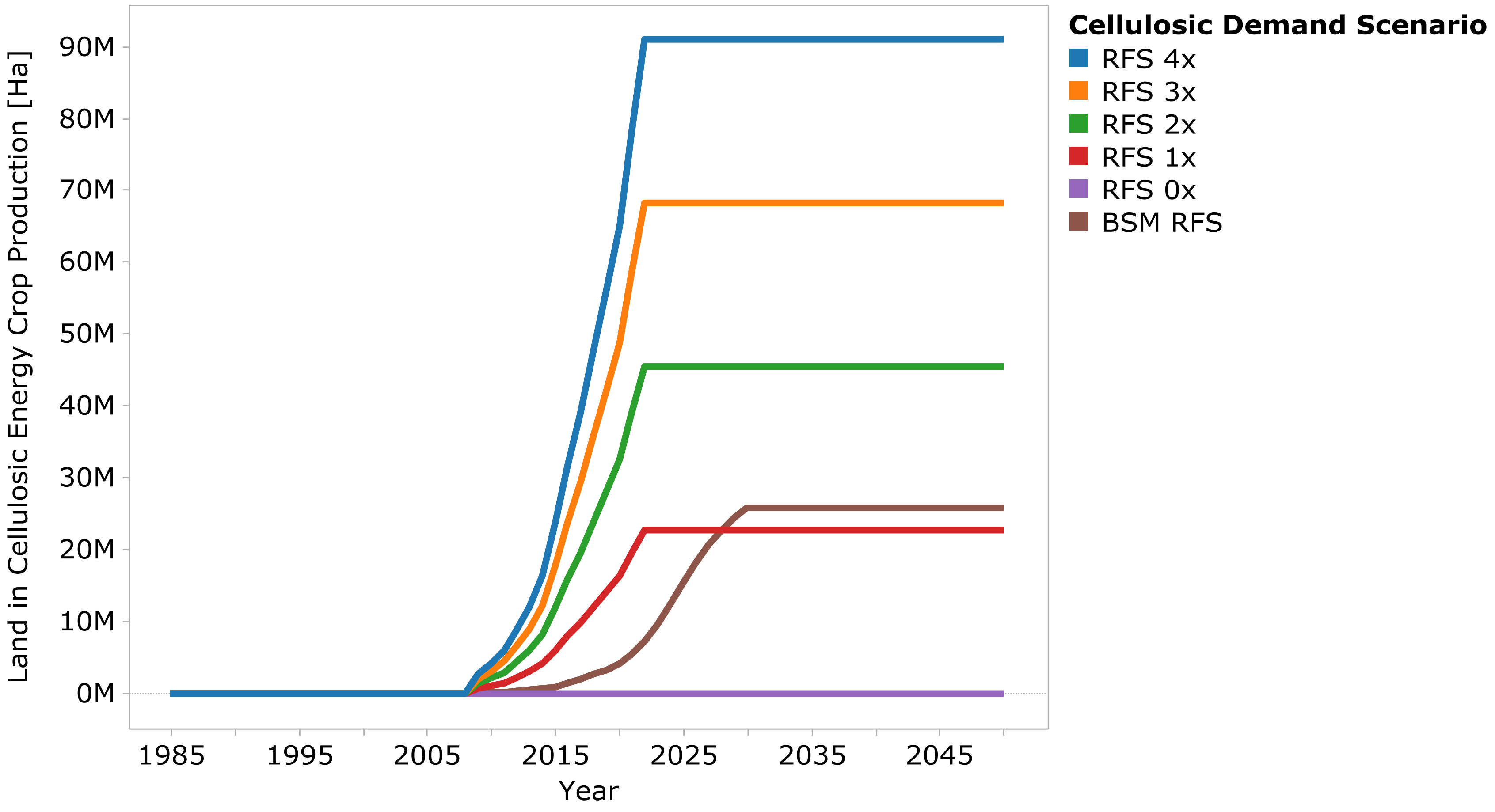
Sample Results

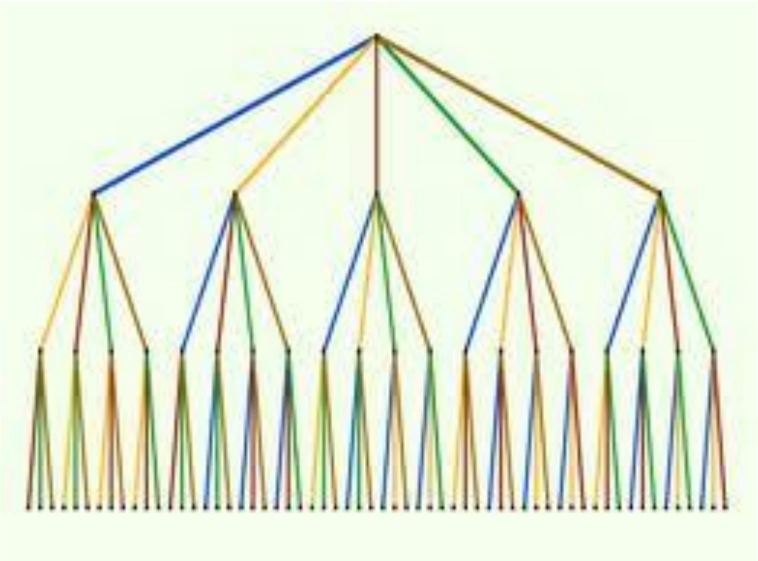
- Model calibration still "in process"
- Possible to begin to view results of different scenarios
- THESE sample results should be viewed as illustrative only
- Approach: Drive model with US scenarios based on RFS Schedule
  (see http://en.openei.org/wiki/Renewable_Fuel_Standard_Schedule#5)

Sample Results—Baseline Behavior (RFS 1x)



Development of scenarios

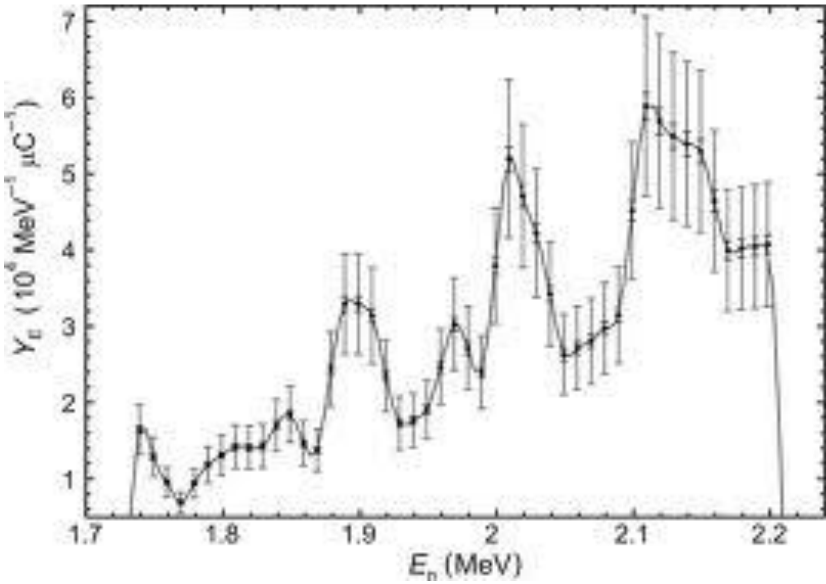
- Unique component: testing effect of many land-use drivers at once
- Scenarios include modifications of one parameter as well as modifications of many parameters
- Scenarios will include other scenarios tested in the literature



- Potential Scenarios
- Business as usual (base case)
- GDP growth
  - High and low GDP growth
  - Global and regional GDP changes
- Population growth
  - High and low population growth
  - Global and regional population changes
- Societal changes
  - Changes in average age composition of population
  - Changes in meat consumption
- Crop productivity changes
  - Productivity increases and decreases
  - Global and regional productivity changes
  - Effects on land degradation
- Land-use change policies
  - Unrestricted land-use change
  - Global and regional land conservation policies
- Domestic biofuel policies
  - Varying biofuel penetration policies
  - U.S. domestic policies vs. larger regional policies

Uncertainty and sensitivity analyses

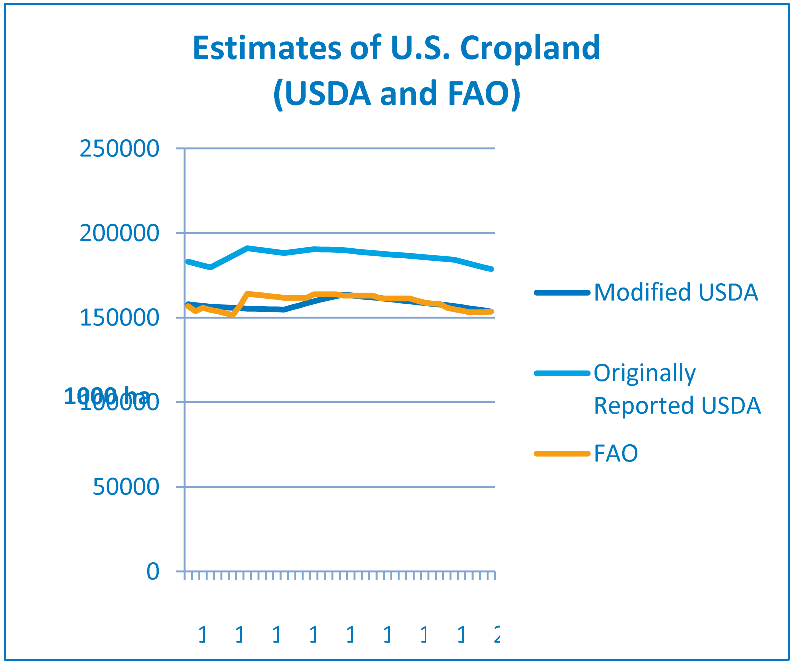
- Data can have significant uncertainties
- Quantifying uncertainty is necessary
- Model can be highly sensitive to assumptions
- Assumptions to model (for assumptions backed by literature and those not backed by literature) have been documented
- examples: % of land that is fallow or degraded, crop productivity, etc.

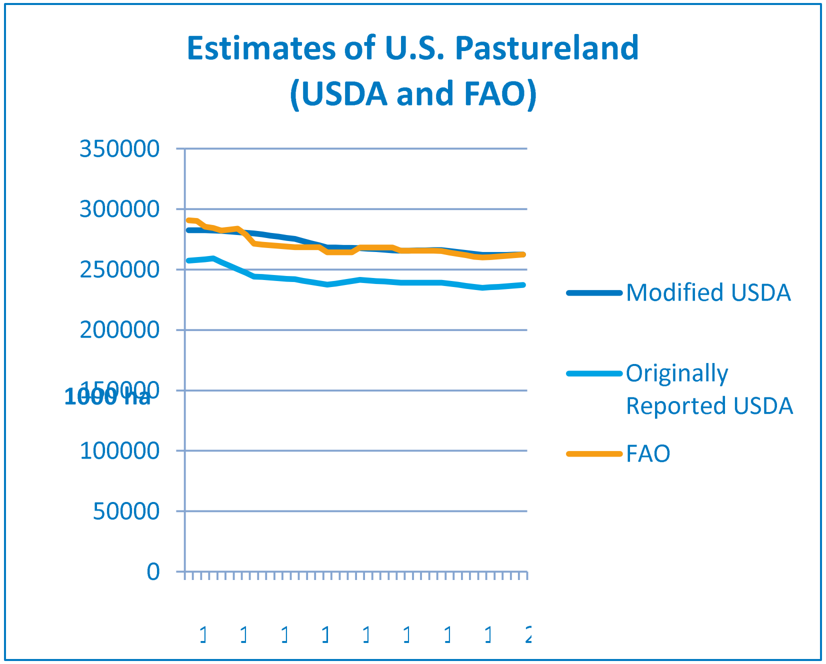


- **Quantification of uncertainty of input data**
  - Current land-uses
  - Population
  - Dietary composition
  - Pollutant emissions
- **Sensitivity analyses for model assumptions**
  - Individual model assumptions
  - Relationships between assumptions

Example Analysis: Comparison of U.S. historical land-use and crop data from USDA and FAO data

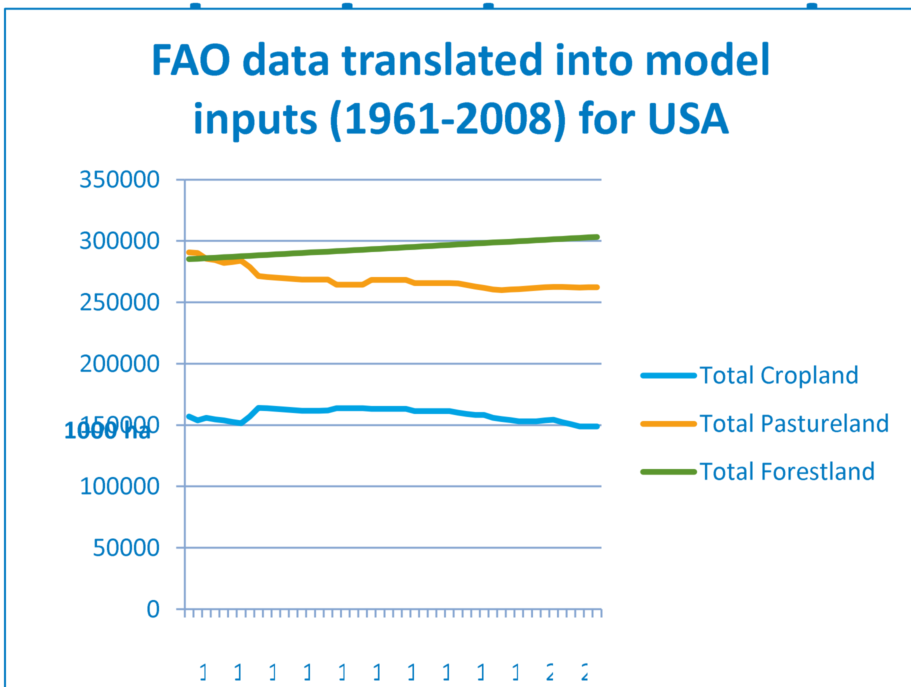
- **USDA and FAO use different land-use categories and definitions (especially related to cropland used for pasture)**
- **After correcting for definitional differences, values are similar**

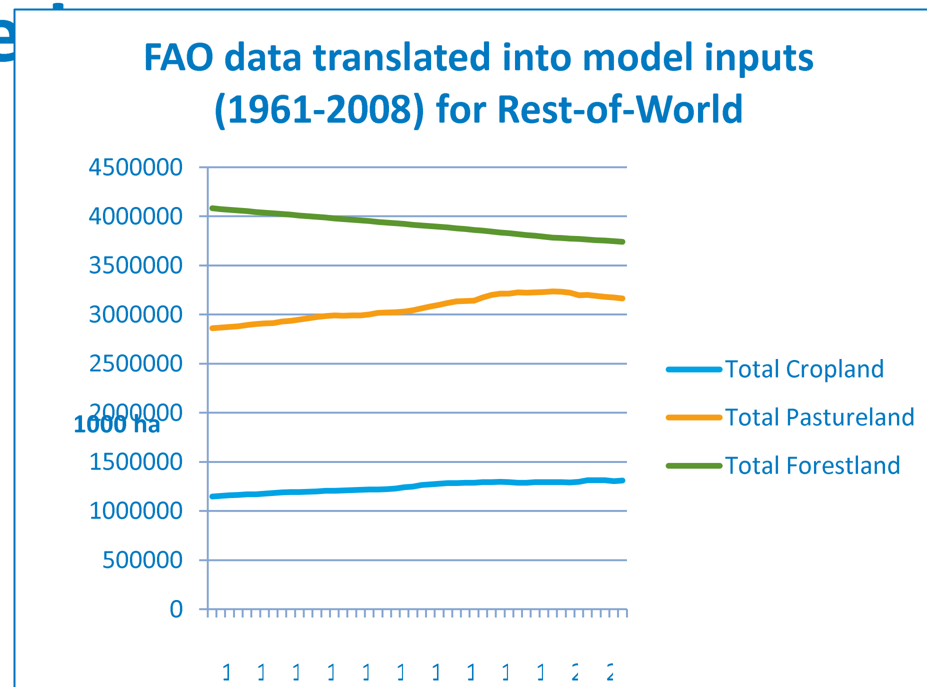




Example Analysis: Translating FAO land-use data into model inputs (USA and ROW)

- **FAO data is inconsistent in data reported for each year. Extrapolation, interpolation, and outside data sources have been used to fill in gaps. Quality/Uncertainty of FAO land-use**





Risks & Strategies

1. **Data quality**
   - We are designing scenarios to be robust with respect to input data quality.

2. **Measurable Impact of Biofuels**
   - We plan to broadly explore scenarios around biofuels and other drivers in order to rank these and demonstrate at what point they strongly perturb the system.

3. **Outreach**
   - Sheehan has agreed to assist with outreach efforts.

Future plans

- **Plans for the remainder of FY12**
  - ERL special issue submission-August 2012
  - Milestone report on expansion of the model to 19 regions
  - GTAP-8 data
  - WAO 2012 data (ERL baseline)
- **FY13**
  - Final year of “development”
  - Model release- KDF, other labs
  - More in-depth analysis

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Innovation for Our Energy Future

LUC literature review back up slides

Varied methods

- **How are GHG emissions from LUC estimated**

$$GHG_{LUC} = \sum A_{kij} \times EF_{kij}$$

- Three fundamentally approaches to estimating *A*

1) Optimization models (mostly economic equilibrium models)

2) Simple deterministic model

3) Causal descriptive model

Each model has its limitations contributing to the lack of consensus on which, if any, model is most appropriate to evaluate LUC

Varied Assumptions and Data

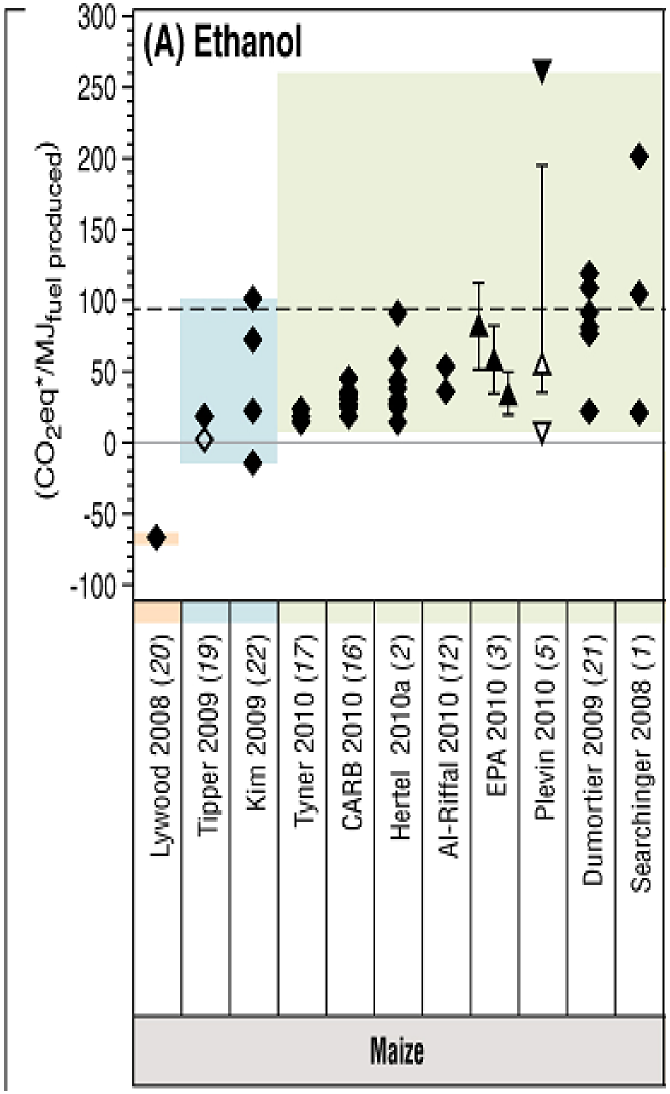
- **How are GHG emissions from LUC estimated (continued)**

$$GHG_{LUC} = \sum A_{kij} \times EF_{kij}$$

  - The assumed biofuel volume increment (Δ in model conditions)
  - The assumed reference or baseline scenarios (model comparison conditions)
  - The location where LUC is projected to occur (k)
  - Carbon stocks and emissions for different land covers (i and j)
  - The LUC emission factors (EF)

Lack of Thorough Uncertainty Analysis

- **A few limited efforts have characterized potential ranges**
  - National Research Council 2007
    - Probabilistic analysis is often infeasible for large models
- **Plevin et al. 2010: Advocates using a reduced form model**
  - Parameterized using previous LUC study data to quantify the plausible ranges of GHG_{LUC} estimates
  - Significant characterization of uncertainty, but limited by source data biases



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AQ back up slides

Key Substantive Challenges

1. **Multitude of gaps in existing life cycle inventories (e.g., EcoInvent) for air pollutant emissions**
2. **Availability and quality of data/models to fill emission inventory gaps**
3. **Availability of information to assign spatial locations to all processes**
4. **Making air quality indicators meaningful**
    1. Two facilities in the same location and emitting at same rate at same time can be compared by their mass emissions
        1. E.g., comparing two designs of same plant
    2. If emitting in different location or at different time, then resulting concentrations or human exposure isn't the same, thus health impacts aren't the same
        1. Clearly large scale scenarios of deployment are complex in temporal and spatial emission profile, so mass emissions isn't good proxy for health impacts

Relationship to MYPP?

- Overall Performance Goal:
- “By 2013, identify metrics and set targets for soil quality and air quality for agricultural residues, energy crops, and forest resources pathways.”

- R9.2.1.1.1M: Demonstrated Pathways
- 2013: Metrics identified and baselines set for air quality for existing biorefinery pathways
-

Existing Studies and Research Gaps

- **1) Jason Hill et al. (2009)**
  - Scope: life cycle comparison of atmospheric $PM_{2.5}$ concentration and the associated human heath impacts of producing and combusting an additional billion gal of ethanol (from corn, swtichgrass, mascanthus, corn stover, prairie grass), and energy equivalent volume of gasoline
  - Limitations: 1) unmatched ethanol volume compared to RFS requirements, 2) only considers PM2.5, 3) based on GREET, which does not include chemicals/enzymes consumed by conversion processes, etc.

2) Jacobson (2007)

- Scope: cancer, mortality, and hospitalization from corn E85 (compared to gasoline)
- Limitations: 1) focuses only on vehicle operation air pollutant emissions (i.e., not a LC study), 2) does not use a transparent state-of-the-art AQ model

3) Jones (2010)

- Scope: air emissions of seven of the first group of pre-commercial cellulosic ethanol plants using forest and ag. residues, switchgrass, hardwood chips, landfill MSW, bagasse, etc.
- Limitations: 1) conversion process emissions only, 2) no AQ and human impact analysis