Global Analysis of Biofuel Policies, Feedstock and Impacts

Date: May 21st 2013

Technology Area Review: Analysis

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Organization: Oak Ridge National Laboratory

Goal Statement

- Contribute to DOE's goal to:
  - "deepen the understanding of the environmental, economic, social, and energy security benefits of biofuels, biopower, and bioproducts" - MYPP 2012

- Provide analytical support to BETO to:
  - "quantify and communicate the long-term benefits of biomass RD&D... The quantified costs and benefits are used to evaluate the most viable biomass utilization technologies and routes. Results are also used in cross-cutting benefits analysis." – MYPP 2012
  - Facilitate the life-cycle assessment of biofuels through estimates of national and global indirect effects

Quad Chart Overview

Timeline

- Project start date: FY09
- Project end date: FY15
- Percent complete: 50%

Budget

- FY11 DOE funding: $370k
- FY12 DOE funding: $300k
- FY13 DOE funding: $250k
- Years funded: 6
- Avg. annual funding: $300k

Barriers being addressed

- At-B: Limitations of analytical tools and capabilities for system-level analysis
- St-G. Representation of Land Use and Innovative Landscape Design
- Ct-C. Inconsistent and Unpredictable Policy Landscape and Priorities

Partners

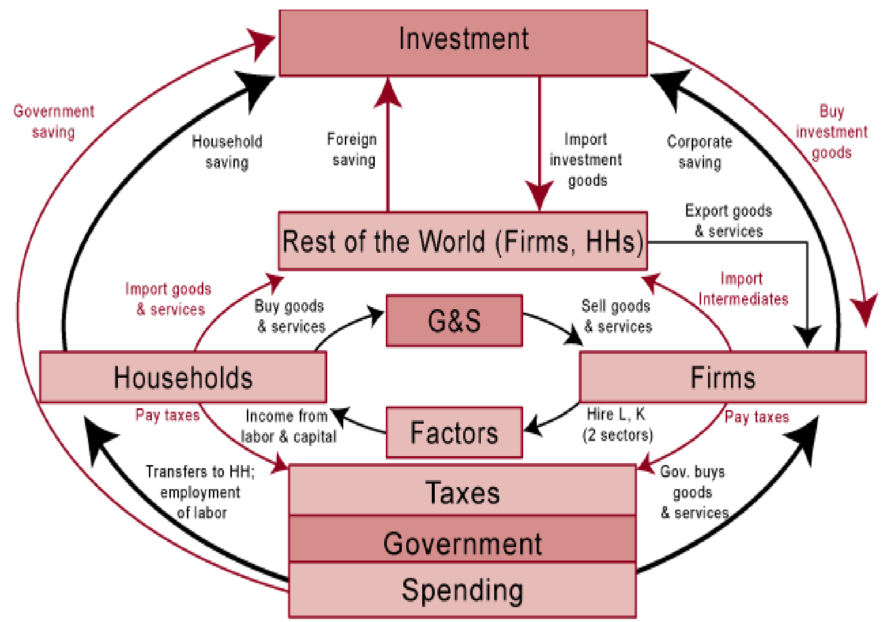
- National Renewable Energy Laboratory (NREL)
- International Food & Policy Research Institute

Project Overview

- The EISA includes cross-cutting economic, environmental and social targets for the RFS2
  - Indirect effects (land use change) became important
- Develops tools to evaluate these cross-cutting targets, including:
  - Economic contributions of biofuels
  - Impacts on land use and GHG emissions, and food markets
  - Global feedstock availability and competition
- Publishes studies that:
  - To help understand the benefits of biofuels under different scenarios for meeting the RFS2 targets
  - Evaluate the impacts of changes in policies, technological developments, and other market changes
  - Account for the crucial influence of global market interactions
- Interact with researchers/industry on project findings

Approach

- Computable General Equilibrium (CGE) modeling framework:
  - a comprehensive framework for analyzing the activities & interactions of economic agents in an economy
    - Economic agents: individuals, households, institutions
    - Activities: production, consumption, trade, investment, government policies, etc.
- GTAP-DEPS[1] CGE Model:
  - Based on the widely used global CGE database known as GTAP[2]
  - Major improvements to properly capture the role of biofuels in the economy
- Other approaches
  - Review/evaluation of existing studies
  - Other tools have been applied to evaluate the role of biofuels in the corn market and the potential of eucalyptus as a feedstock



Cycle of Economic Transactions in a CGE Model

1. GTAP-DEPS:GTAP for Dynamic Energy Policy Simulations (see Oladosu, 2012).
2. GTAP stands for Global Trade Analysis Program: "While there is one GTAP data base, there are many GTAP-based models (hundreds or more)." – Hertel (2009)

Approach cont'd

- CGE-based evaluation of biofuel policy captures:
  - Important interactions among biofuels, agriculture, energy and other markets

Simplified description of the expected impacts of a biofuel mandate in the USA relative to a baseline

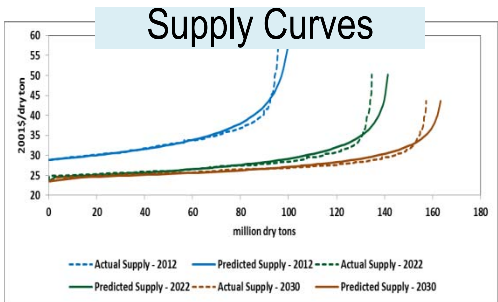
	Regional Characteristics			
	Net Oil Importer/ Net Agric. Exporter	Net Oil Importer/ Net Agric. Importer	Net Oil Exporter/ Net Agric.Exporter	Net Oil Exporter/ Net Agric. Importer
Main Sources of Economic Effects				
Oil Price Decrease	+	+	-	-
Corn Price Increase	+	-	+	-
Oil Displacement	+	*NA*	*NA*	*NA*
Biofuel Cost Increase	-	*NA*	*NA*	*NA*
Overall Effects				
Economic Performance	+	+/-	+/-	-
Agricultural Land Use Change	+	+/-	+/-	-
Example Region	USA	Japan	Brazil	Saudi Arabia

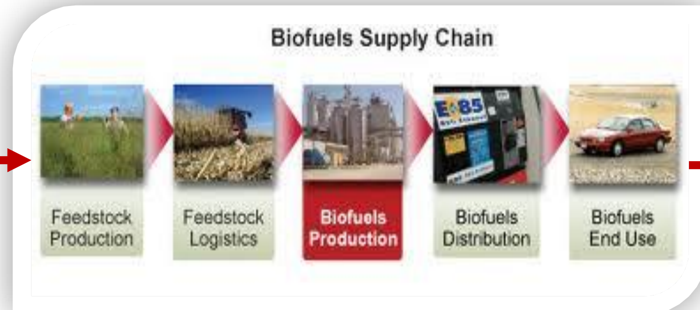
NA = Not Applicable (only USA is assumed to enact biofuel policy)

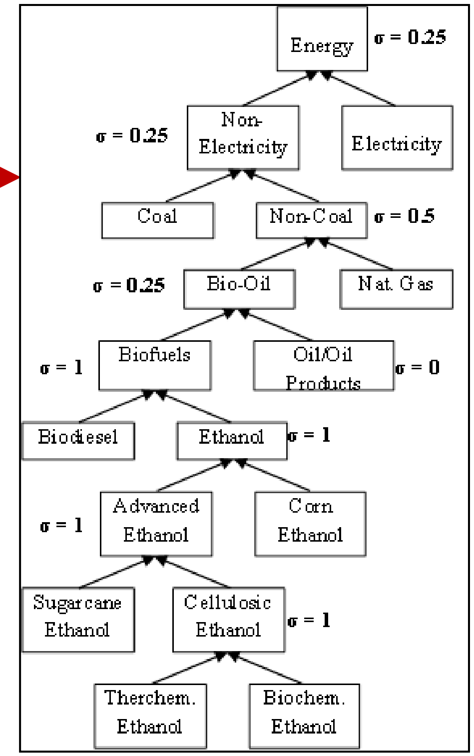
Summary of accomplishments

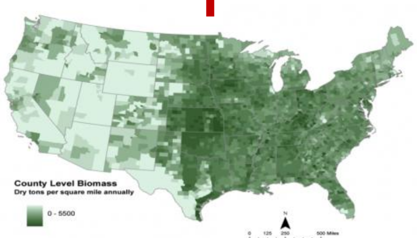
- Completed major enhancements to the GTAP-DEPS model:
  - Incorporated explicit dynamics: 2001-2030
  - Incorporated cellulosic ethanol production with endogenous feedstock allocation
  - Incorporated billion-ton (BT2) cellulosic feedstock data
  - Incorporated empirical estimates of oil, coal & natural gas supply curves
  - Improved land sub-models, including three sources of crop yield change
    - Yield changes motivated by changes in input prices (input substitution)
    - Yield changes motivated by output price changes e.g. crop managements changes
    - Yield changes unexplained by price changes e.g. weather
- Reports and studies with the GTAP-DEPS model
  - Peer-reviewed publications
  - Others under review or in preparation
  - Internal reports to BETO
- Continued interactions with researchers/industry:
  - Participation and presentations at conferences and webinars
  - Comparison of LUC results with NREL and Brazil counterparts

Accomplishments: improved modeling of biofuel policy in GTAP-DEPS







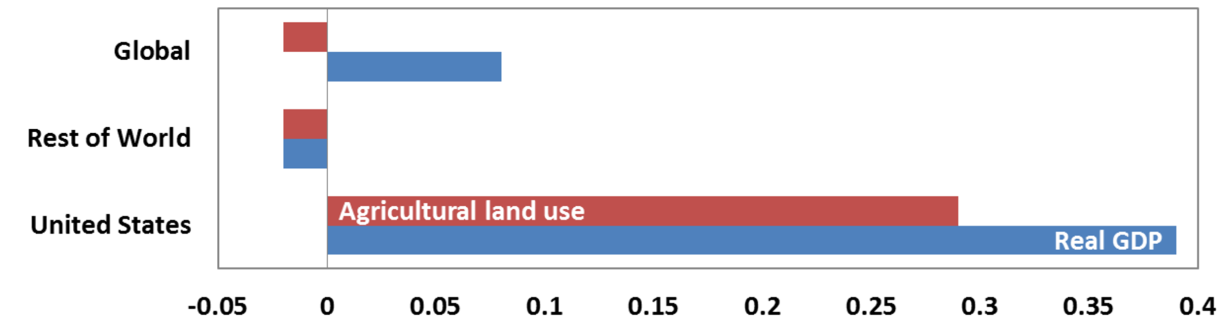


- Techno-economic analysis studies provide initial cost profile of biofuel technologies (NREL and others)
- Cellulosic feedstock data from billion-ton study (DOE, 2012).
- Energy sub-model of GTAP-DEPS captures implementation of the RFS2 policy

Accomplishments: comprehensive economic analysis of the RFS2

- Questions addressed:
  - What are the economic benefits of conventional biofuels?
  - What are the indirect land use change impacts?

Estimates of the Potential Economic and Land Use Impacts of USA Conventional Biofuels in 2022 (% change)

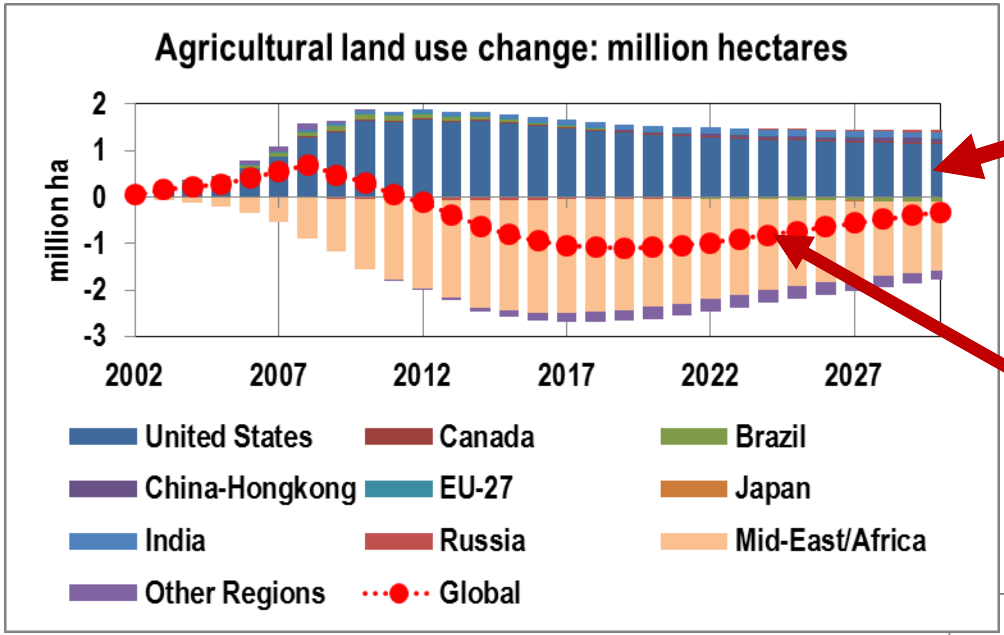


	United States	Rest of World	Global
Agricultural land use	0.29	-0.02	-0.02
Real GDP	0.39	-0.02	0.08

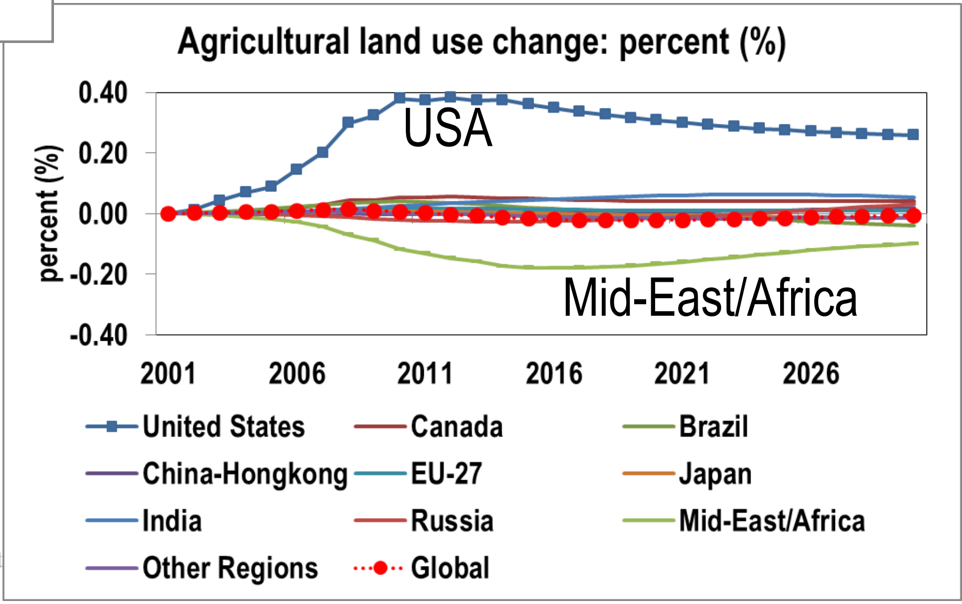
Change in Regional Gross Domestic Product and Agricultural Land Use (%)

- Positive economic effects on the USA economy
- Largely neutral economic effect in rest of world
- Land use to support biofuels is concentrated in the USA

Accomplishments: new insights into the LUC effects of conventional biofuels

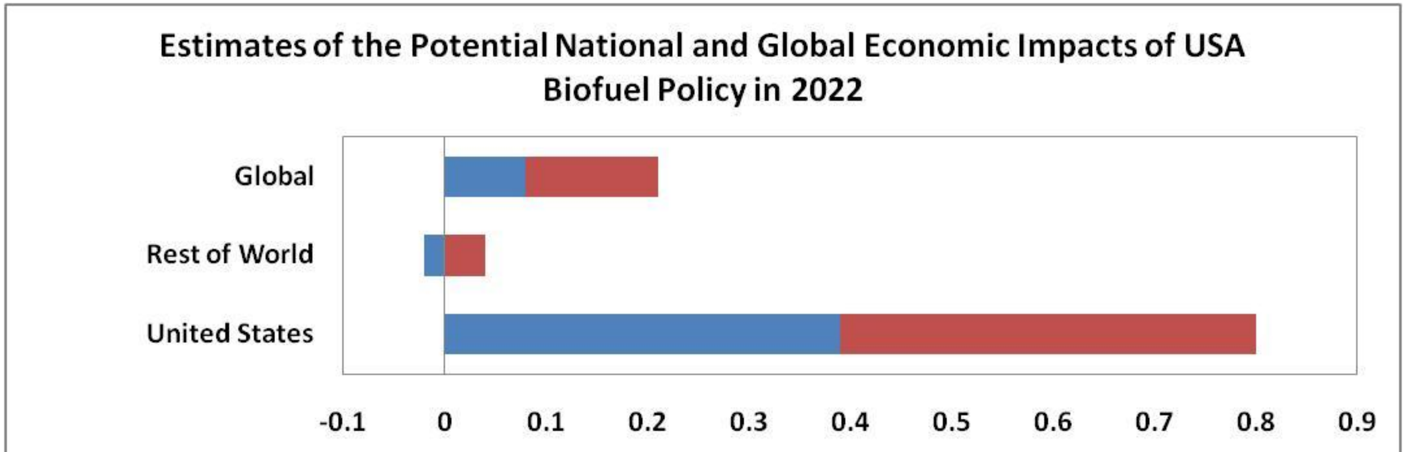


- Increases in agricultural land use mainly in the USA
- Net global LUC becomes negative over time



- Negative LUC in a few regions
  - Effects of oil displacement on oil-export dependent economies
  - Offsets positive LUC in the USA

Accomplishments: potential economic benefits of advanced biofuels



	United States	Rest of World	Global
Conventional Biofuels	0.39	-0.02	0.08
Advanced Biofuels	0.41	0.04	0.13

Change in Size of Regional Gross Domestic Product (%)

- Incremental impacts of advanced biofuels
  - Difference between the economic effects of conventional biofuels up to 2014 (RFS2 to 2014) and of the full RFS2 (RFS2 to 2022)
  - Slightly larger than from conventional biofuels in the USA
  - Positive, but small, in the rest of world

Relevance

- Meeting the cross-cutting targets of the RFS2 means:
  - "deepening the understanding of the environmental, economic, social, and energy security benefits of biofuels, biopower, and bioproducts" - MYPP 2012
- Biofuel policy is motivated by global market developments
  - Implies a need to evaluate the benefits of biofuels in the global context
- Project results provide information to demonstrate that these targets are being met, accounting for their global dimensions
- Results support evaluation of the lifecycle energy and greenhouse gas emissions impacts of biofuel by estimating the indirect effects

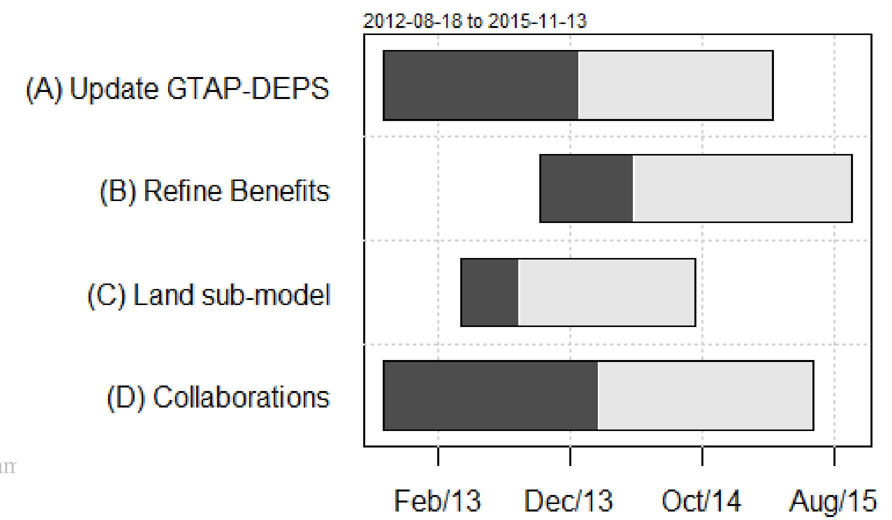
Critical Success Factors

- Analytical tool developed under this project:
  - Accounts for potential interactions and trade-offs among different goals of the RFS2
  - Enables evaluation of biofuel policy under different scenarios
  - Capable of accounting for technological developments, market barriers, and policy changes in order to weigh benefits of biofuels against costs and risks
  - Accounts for the crucial global dimensions of the impacts of biofuels
- Project results demonstrate the benefits of biofuels:
  - Recent peer-reviewed economic analysis of the RFS2 has received wide recognition:
    - Study highlighted at two industry meetings
    - Study summarized in recent issue of "Ethanol Producer Magazine"
    - Presentations made to research/industry representatives to discuss findings
  - Positive impacts on the United States economy
  - Minimal impacts on overall global economy and land use change

Future Work

- (A) Updates to the GTAP-DEPS model
  - Incorporate technologies for advanced biofuel production
    - BETO has recently identified 8 priority pathways
  - Account for the by-products of advanced biofuels
  - Improve consumer fuel choice representation
- (B) Refine estimates of the benefits of advanced biofuels
  - Evaluate the impact of infrastructure costs on advanced biofuels use and benefits
  - Evaluate the impact of blend wall constraints and the role of different programs/policies
  - Evaluate biofuels against other options for meeting fuel requirements in the USA
- (C) Revised land allocation model
  - For detailed land use impact evaluation and calculation of GHG effects
- (D) Continued interactions with the biofuel community

Timeline for tasks



Summary

- **Approach**: Computable general equilibrium (CGE) modeling - framework that captures the national/global dimensions of biofuel policy and its interactions with the rest of the economy
- **Technical accomplishments**: Produced the dynamic GTAP-DEPS model incorporating extensive data and specifications needed to adequately model biofuel policies, benefits and indirect effects
- **Relevance:** Project meets the need to deepen "understanding of the environmental, economic, social, and energy security benefits of biofuels, biopower, and bioproducts" - MYPP 2012
- **Critical Success factors and challenges:**
  - Analytical tool developed can account for technological developments, market barriers, and policy changes in order to weigh benefits of biofuels against costs and risks
  - Published peer reviewed economic analysis demonstrates the positive economic impacts of the RFS2 on the United States economy, and minimal economic and land use impacts on the rest of the world
- **Future Work**: Continued enhancement of the modeling framework and evaluation of policy, technology and market scenarios to support advanced biofuels

Additional Slides

Acknowledgements

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- **Collaborators**: Keith Kline, Paul Leiby, Rocio Uria-Martinez, Maggie Davis, Mark Downing, Laurence Eaton

References

- Hertel TW (2009) “Strength and limitations of the GTAP modeling framework”. http://www.arb.ca.gov/board/books/2009/042309/hertel.pdf

- Oladosu G., K Kline, P Leiby, R Uria-Martinez, M Davis, M Downing and L Eaton (2012) “Global Economic Effects of US Biofuel Policy and the Potential Contribution from the Advanced Biofuel Targets”, Future Science – Biofuels Journal 3(6)

- Oladosu G. (2012) “Estimates of the Global Indirect Energy-Use Emission Impacts of USA Biofuel Policy.” Applied Energy Journal 99: 85–96

Responses to Selected Reviewer Questions from 2011 Peer Review

Comment: The existing GTAP model is customized and applied to determine the indirect land-use impacts of biofuels. Simulations were conducted to determine the effects of corn use on indirect land-use. Incorporation of new feedstock data and model dynamics works are well underway. The project also contributed to the analysis and recommendations of CARB working groups on modeling uncertainty, land availability, and determining the effects of food-fuel interactions. Sig. Strength: Looked at LUC, but also GDP and other variables - this is a good example of looking at LUC in the larger context. Observation: After identifying that corn did not act the way expected (yield increases vs. export decrease), need to (and the plan is to) go back to make the model predict that, with an understanding that corn yield increases may not accurately reflect switchgrass (for example) increases. This is a key finding that could significantly change the way the model reacts, and must be fully and carefully understood. So far, model was assessed and somewhat modified to suit current needs. The modified model was used to analyze empirical data. Much of the more important work on modeling new feedstocks for ethanol remains.

Response: Thank you for these useful and supportive suggestions. We plan to complete current updates to the model as well as incorporate findings from the empirical data analysis in our simulations. The corn yield behavior seen over the last few years made a big contribution to meeting the corn demand for ethanol production and exports with minimal land use change. Although, the pattern of behavior is unlikely to be the same for switchgrass and other feedstocks, yields improvements are likely to make significant contributions to meeting future cellulosic ethanol feedstock requirements. The Billion-Ton Study being prepared at ORNL currently includes different yield scenarios that we will be considering in simulations of cellulosic biofuels with the GTAP-ORNL (i.e. GTAP-DEPS) model. As resources permit, we also plan to incorporate empirically-based assessments of yield changes in these crops from other studies.

Comment: The main contribution of this project is to customize GTAP model and data to determine indirect land-use effects of biofuels production and use. Although the project generates useful insights its impact relative to other GTAP analyses may not be high. When dynamic GTAP models are extensively used to predict the impacts of biofuels production and use by other institutions, it is not clear why additional efforts must be devoted through this project to do somewhat similar work. It would useful to explore synergistic opportunities.

Response: Thanks for your comments. The project involved a lot of mutually beneficial interactions with Purdue University in the initial phase, and builds on that effort. However, the Purdue GTAP-BIO CGE simulations for future years were not dynamic. Similarly, most versions of the GTAP-based models are not dynamic. GTAP-ORNL (i.e. GTAP-DEPS) is introducing dynamics and incorporating cellulosic data from the DOE Billion-Ton study, key improvements which no other GTAP model is currently considering. We will continue to collaborate with DOE national laboratories and other organizations as we continue our efforts to further develop the model.

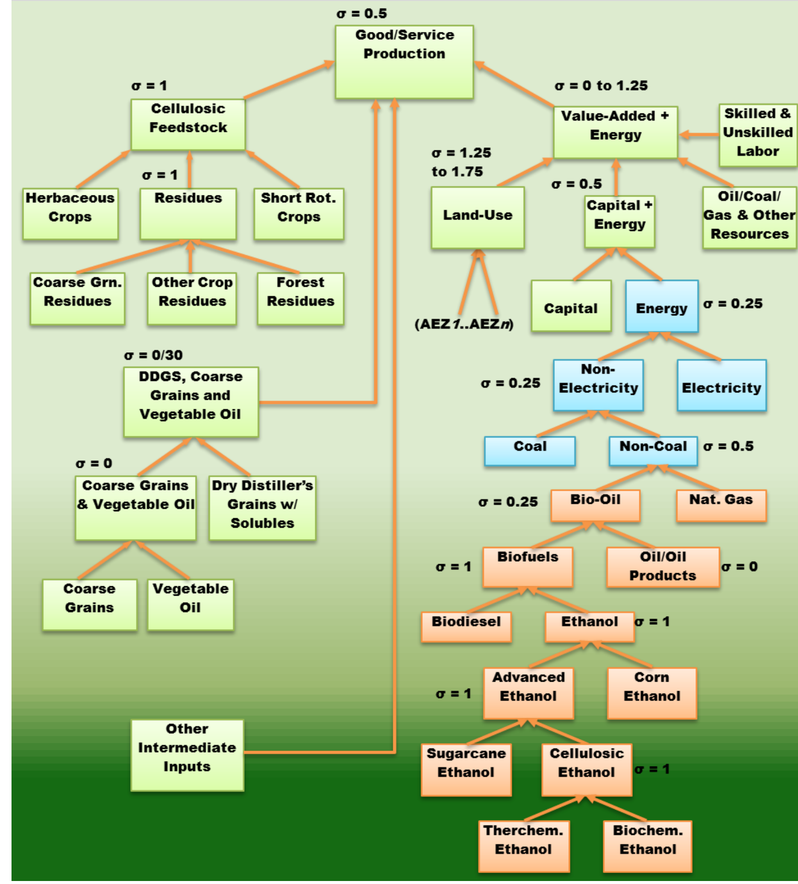
Selected Publications/Presentations

- Oladosu G., K Kline, P Leiby, R Uria-Martinez, M Davis, M Downing and L Eaton (2012) "Global Economic Effects of US Biofuel Policy and the Potential Contribution from the Advanced Biofuel Targets", Future Science – Biofuels Journal 3(6)
- Oladosu, G., and S. Msangi. (2013) "Biofuel-Food Market Interactions: A Review of Modeling Approaches and Findings." Agriculture 3.1: 53-71. http://www.mdpi.com/2077-0472/3/1/53/pdf
- Oladosu G. (2012) "Estimates of the Global Indirect Energy-Use Emission Impacts of USA Biofuel Policy." Applied Energy Journal 99: 85–96
- Oladosu G., K. Kline, R. Uria-Martinez, and L. Eaton (2011) "Sources of Corn for Ethanol Production in the United States: A Decomposition Analysis of the Empirical Data", Biofuels, Bioproducts & Biorefining (BioFPR) Journal 5:640-653(2011) DOI:10.1002/bbb.305 http://onlinelibrary.wiley.com/doi/10.1002/bbb.305/abstract
- Oladosu GA and Kline KL 2010 "The Role Of Modeling Assumptions And Policy Instruments in Evaluating The Global Implications Of U.S. Biofuel Policies." Proceedings of the 33rd International Association of Energy Economics International Conference "The Future of Energy: Global Challenges, Diverse Solutions" Rio de Janeiro, Brazil, June 6-9, 2010
- Oladosu G, K. Kline, P. Leiby, Rocio Uria-Martinez, Maggie Davis, Mark Downing and Laurence Eaton. (2012) "Evaluating the Potential Economic Effects of the US RFS2 Advanced Biofuel Targets", 244th American Chemical Society National Meeting, Philadelphia.
- Oladosu G (2011) "Estimates of the Indirect Energy and Emission Effects from Biofuels", Presented at the 30th USAEE/IAEE North American Conference: Changing Roles of Industry, Government and Research, Washington D.C., USA, October, 2011
- Oladosu GA and Kline KL "Empirical Analysis of the Sources of Corn Used for Ethanol Production in the United States: 2001-2009", Presentation at the National Corn Growers Association (NCGA) AgEnergy Symposium, Nov. 4 2010, Washington, D.C.
- Carolyn Sarls and G Oladosu (2010) "A Comparison of Empirical and Theoretically Estimated Eucalyptus Yield in Brazil", Poster Presentation, Oak Ridge National Laboratory
- G. Oladosu (2010) "Global Indirect Land Use Implications of U.S. Biofuel Policies: A Review of the Evidence", University of Tennessee Department of Agricultural Economics Fall Seminar Series, Sept. 2010
- Oladosu, GA, and Kline KL "Land Use Impacts of Corn Ethanol: Reconciling Models, Empirical Data and Policy" at the National Corn Growers Association Conference on Land Use and Carbon Impacts of Corn-Based Ethanol, St. Louis, Missouri August 26 2009

Summary of the GTAP-DEPS Model

- GTAP-DEPS* is a version of the GTAP modeling framework
- Model dimensions:
  - 33 Sectors; 18 Regions; 2001-2030
- Major enhancements
  - Dynamic simulation: 2001-2030
  - Cellulosic ethanol production
  - Endogenous allocation of feedstock
  - BT2 feedstock supply curve data
  - Supply curves for oil, gas and coal
  - Land supply/demand sub-models
- Results on many economic variables:
  - Production, consumption, investment, labor use, energy use, prices, etc

Production structure in GTAP-DEPS

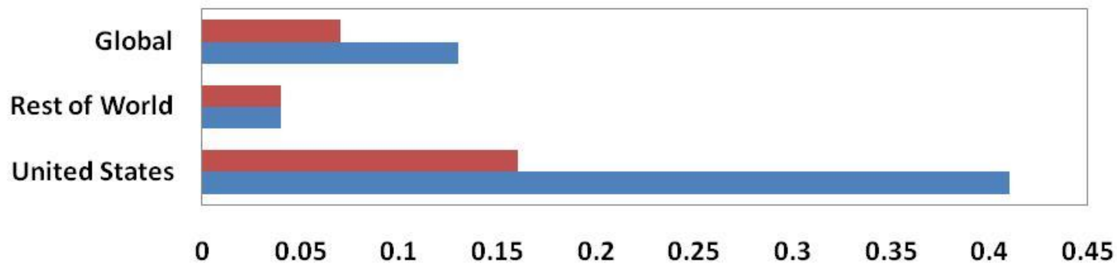


•***GTAP-DEPS**:GTAP for Dynamic Energy Policy Simulations ((see Oladosu, 2012; Oladosu et al, 2012). The standard GTAP (Global Trade Analysis Program) model is described in Hertel et al., 1997)

Prospects for meeting Advanced Biofuel Targets: Higher imports

Incremental Economic Benefits from Advanced Biofuels without and with Higher Imports

Estimates of the Potential National and Global Incremental Economic Impacts of USA Advanced Biofuels in 2022

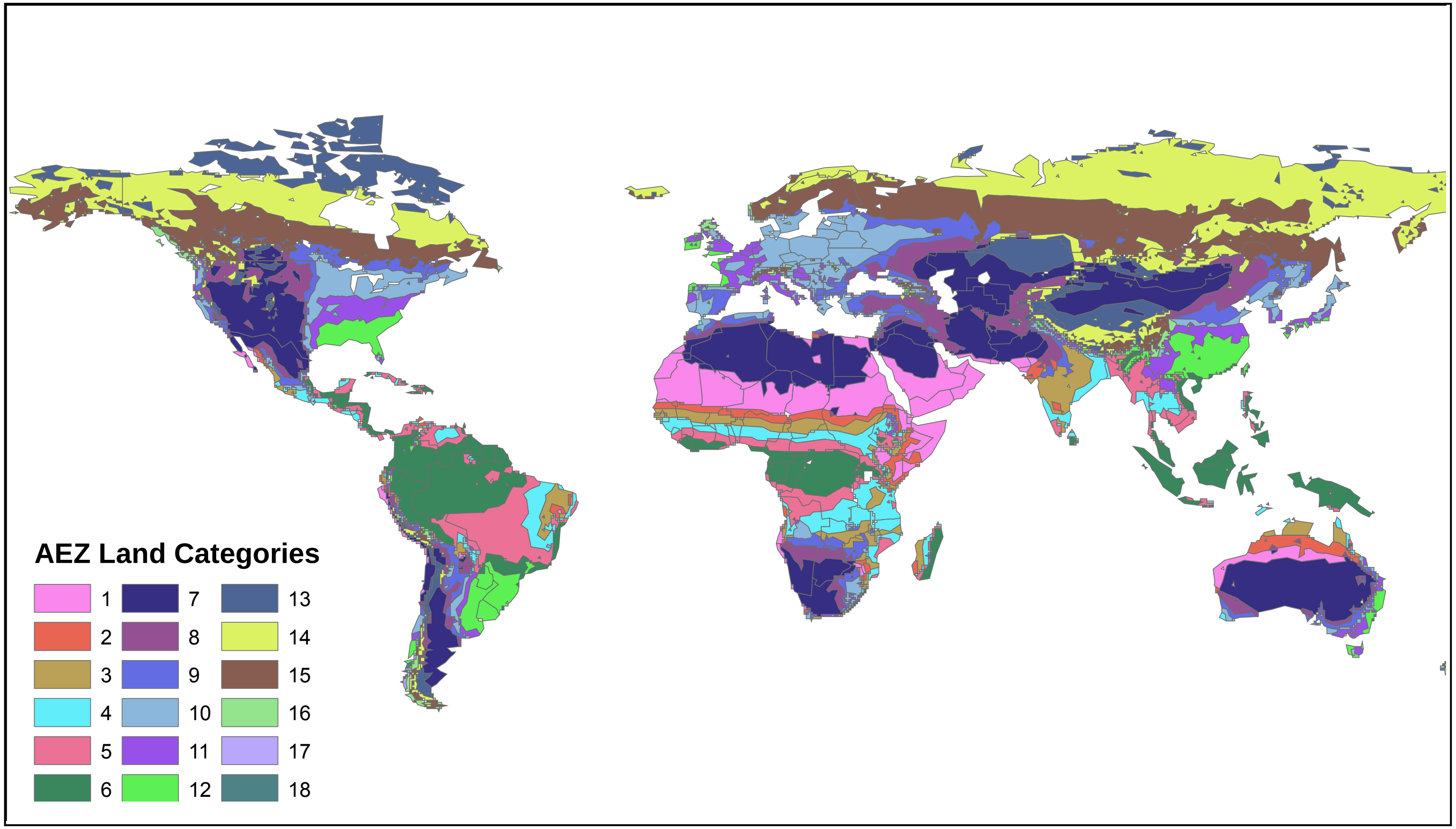


	United States	Rest of World	Global
RFS2 Advanced Biofuels (with Higher Imports)	0.16	0.04	0.07
RFS2 Advanced Biofuels	0.41	0.04	0.13

Change in Size of Regional Gross Domestic Product (%)

- Increase in advanced biofuel imports from 4 to 11bgal
  - Takes advantage of lower sugarcane ethanol supply costs
  - US loses benefits of domestic production of advanced biofuel from residues
  - Reduces incremental benefits of advanced biofuels to the USA by >50%

Agricultural Ecological Zones in the GTAP-DEPS Model



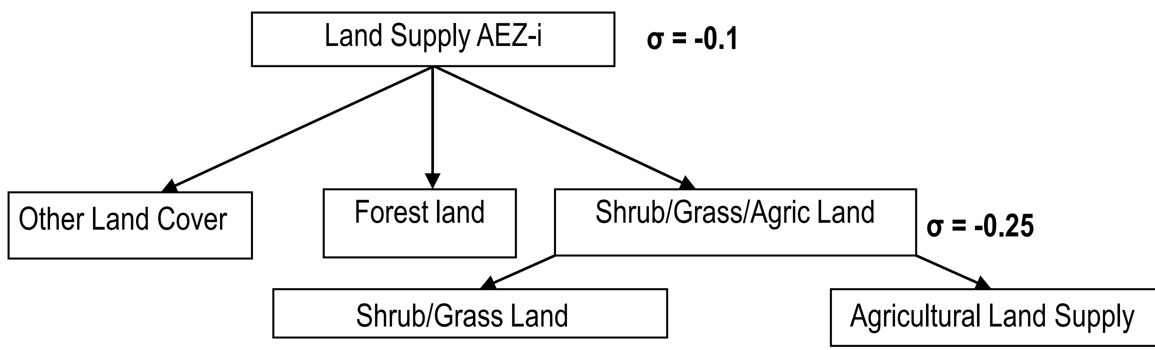
- Agro-ecological zones is a classification of the global land base into 18 categories to support land use modeling with the GTAP database.
- The 18 AEZs represent a combination of climate regions and length of growing periods.

Land supply sub-model in GTAP-DEPS

- Expansion/contraction of agricultural land in response to changes in agricultural land rents
  - Changes in other land cover categories: forest, shrubland and other uses
- Nesting structure captures transition possibilities among land types
  - Matrix of own- and cross-price supply elasticities ( ) for each land cover type
    represents a price-based markov chain process in each AEZ ( ) where
    = initial share of land use *j*

- Changes in agricultural land use requirements in one region potentially lead to responses around the globe

Structure of land supply by AEZ in GTAP-DEPS



United States – AEZ10

	Forest	Otherland	Shrub/grass	Agric
Forest	0.056	-0.003	-0.010	-0.043
Otherland	-0.044	0.097	-0.010	-0.043
Shrub/grass	-0.044	-0.003	0.211	-0.164
Agric	-0.044	-0.003	-0.039	0.086

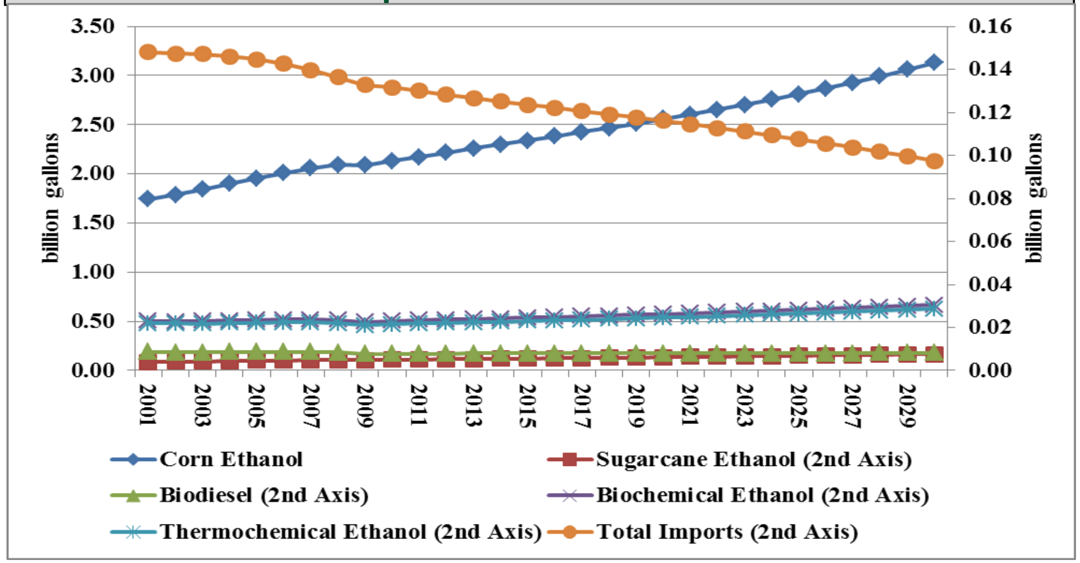
Brazil – AEZ5

	Forest	Otherland	Shrub/grass	Agric
Forest	0.060	0.000	-0.020	-0.039
Otherland	-0.040	0.100	-0.020	-0.039
Shrub/grass	-0.040	0.000	0.179	-0.138
Agric	-0.040	0.000	-0.071	0.112

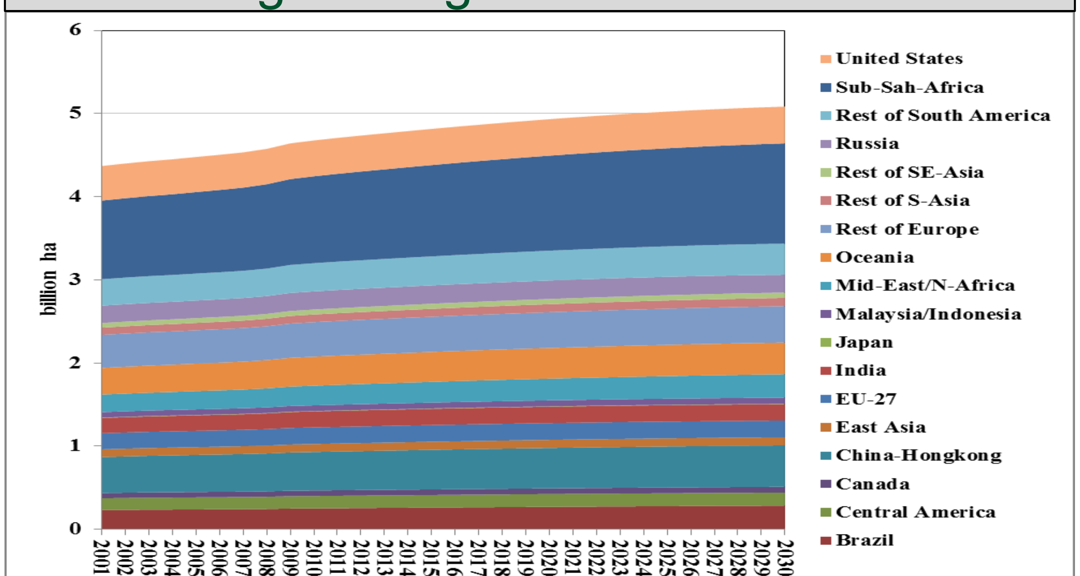
- Potentially 18x18 of these matrices depending on the number of AEZs in each region

Baseline simulation: biofuels/land use

Production/imports of biofuels in the USA



Regional agricultural land use



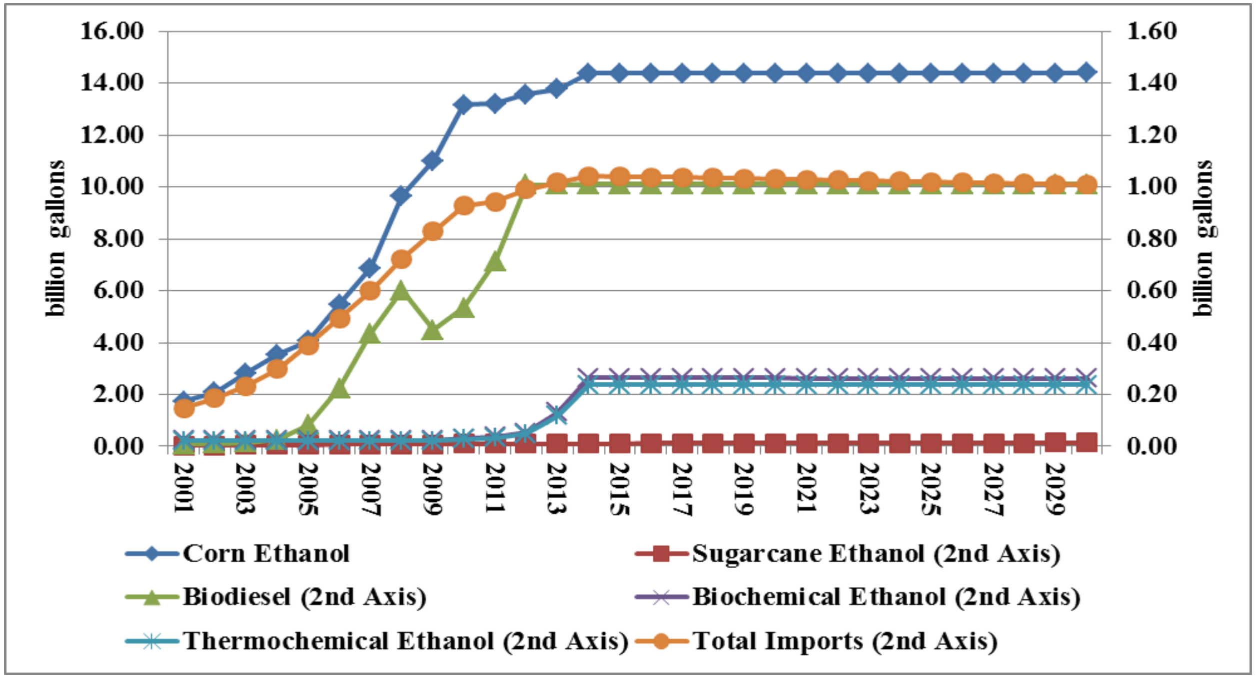
- Baseline simulations: To evaluate model variables **without recent biofuel policy changes**

Oak Ridge National Laboratory

Policy simulation: Changes in USA biofuel under RFS2 to 2014

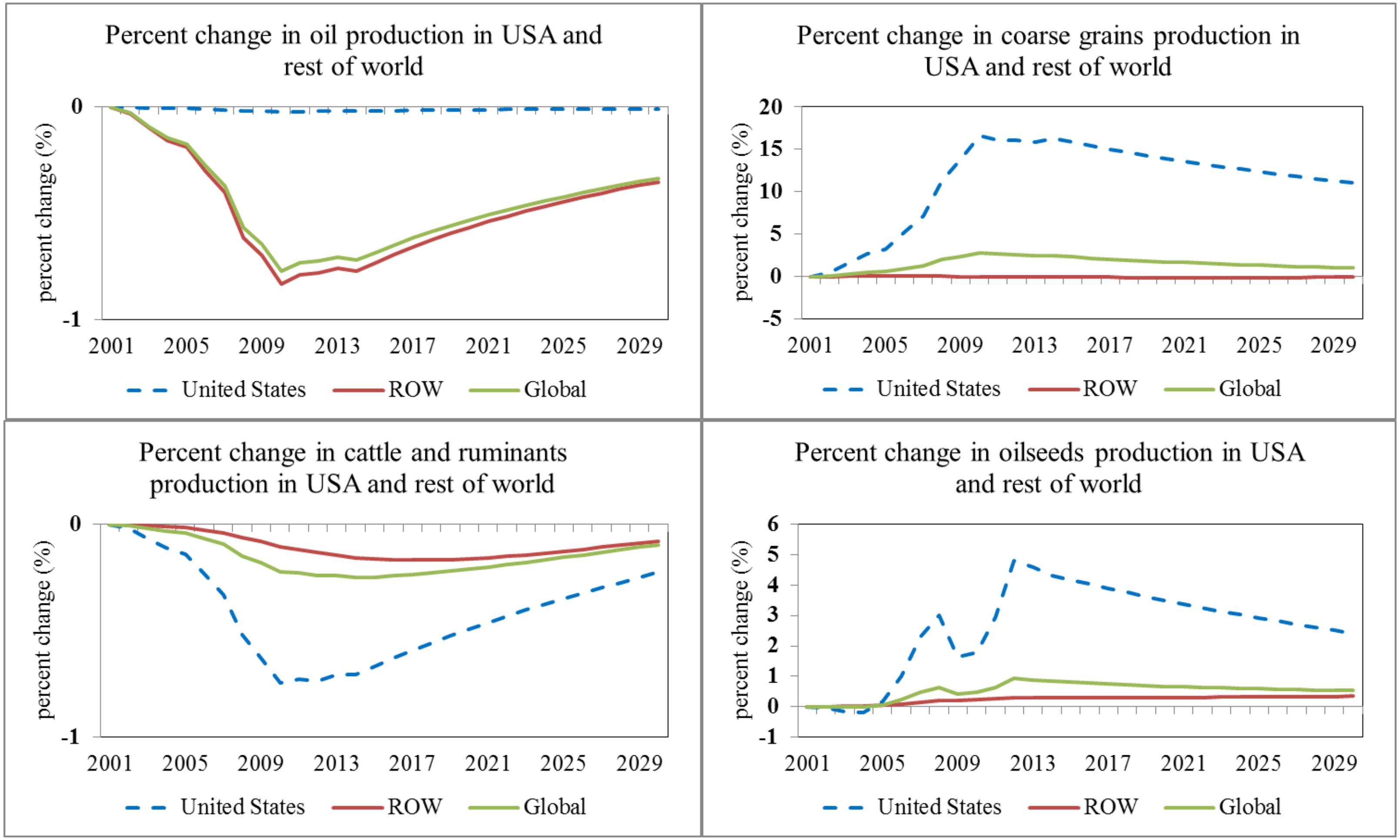
- Simulation of policy targets: RFS2 targets up to 2014

US Biofuels Production/Imports under the RFS2 to 2014



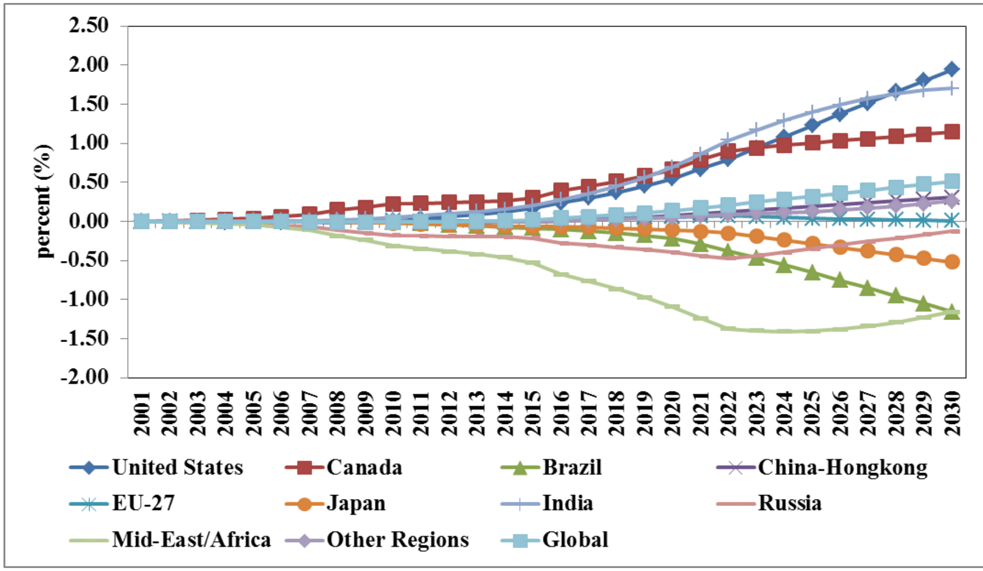
- Differences between policy and baseline results are the effects of policy

Results: agricultural/energy production changes under RFS2 to 2014



- Global oil production decreases – almost all in the rest of world
- Decreases in livestock production/demand and land moves to crops

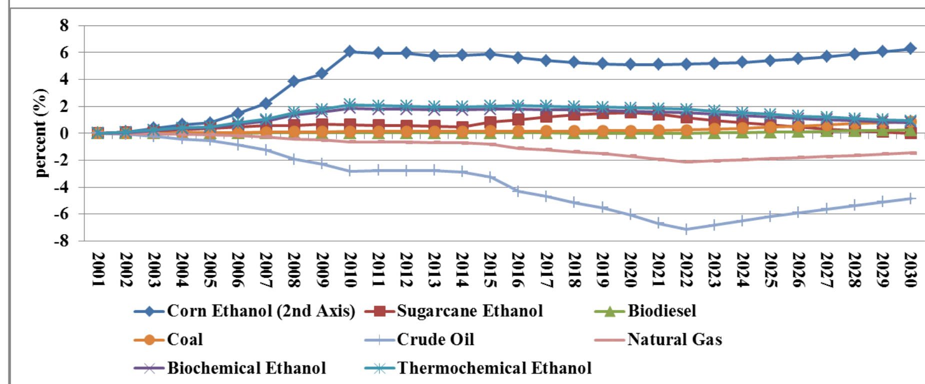
iLUC impacts: new insights into the determinants of iLUC

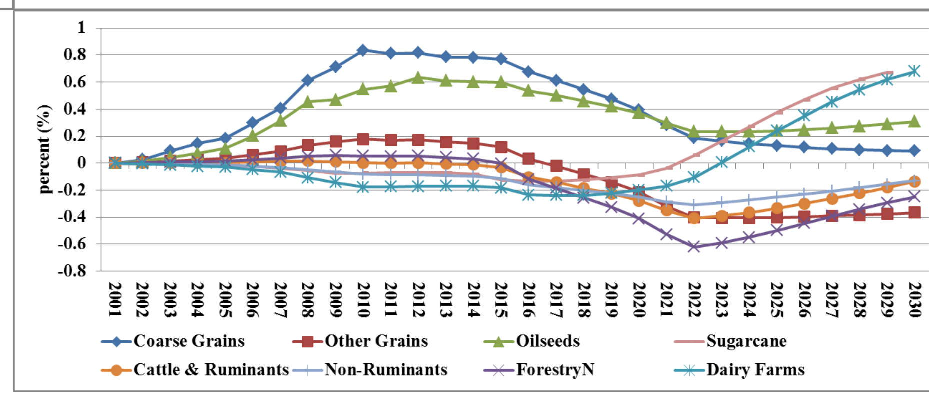


•Changes in regional gross domestic product

- Income effects are important to regional indirect impacts of USA biofuel policy

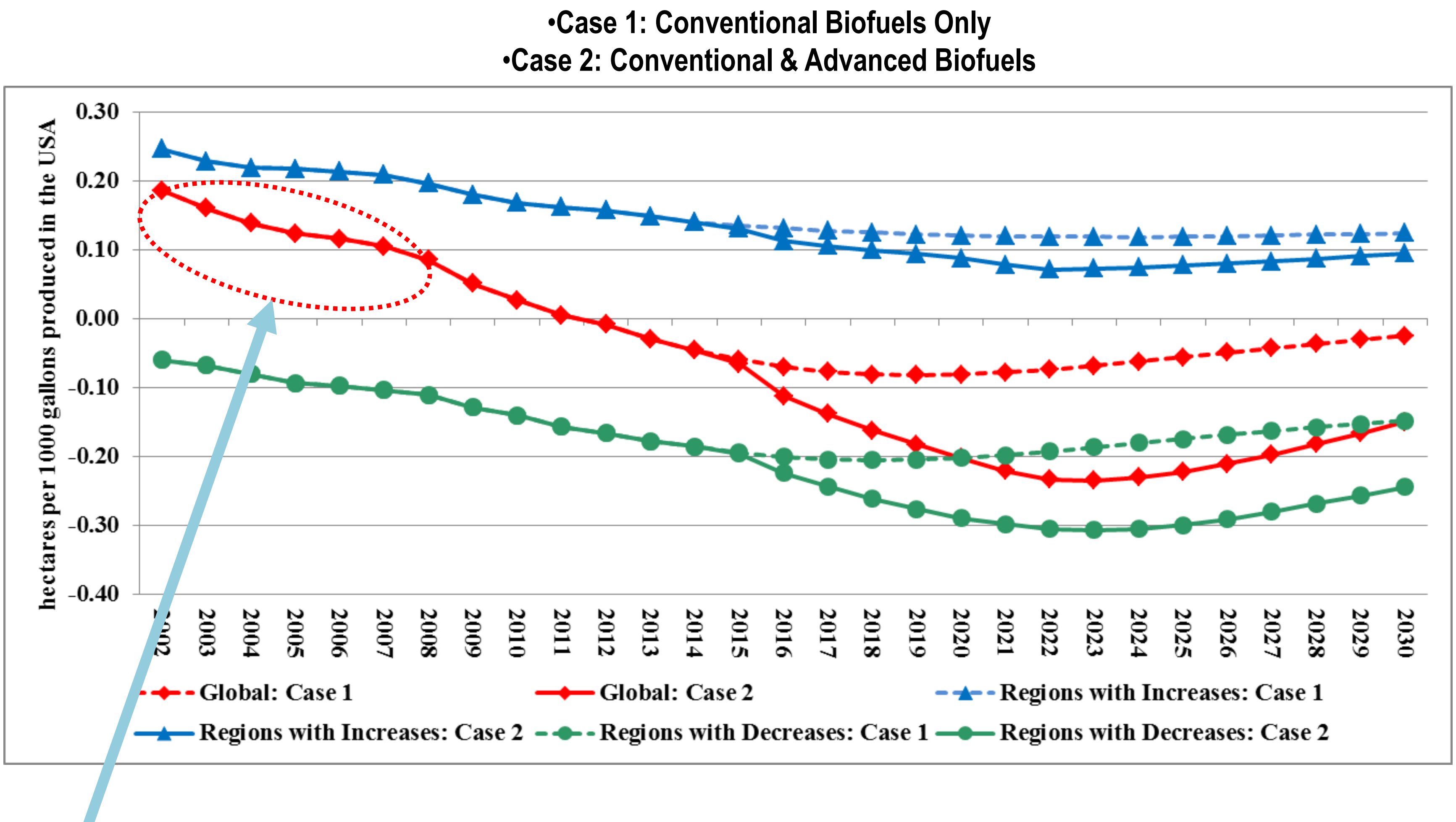
•Changes in energy and agricultural prices





- Reflects the pattern of biofuel mandates and the global response

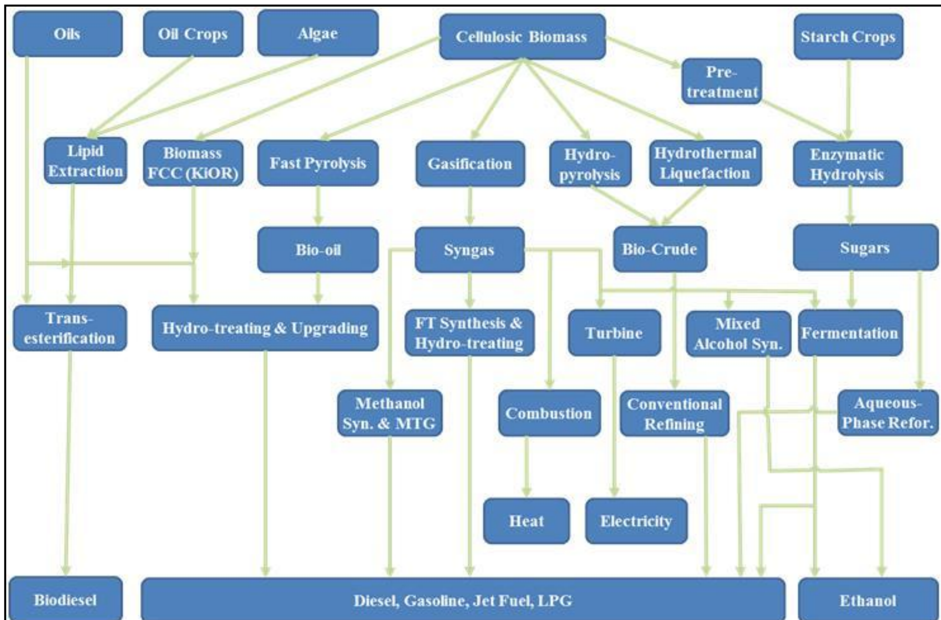
Accomplishments: comparison of iLUC from conventional/advanced biofuels



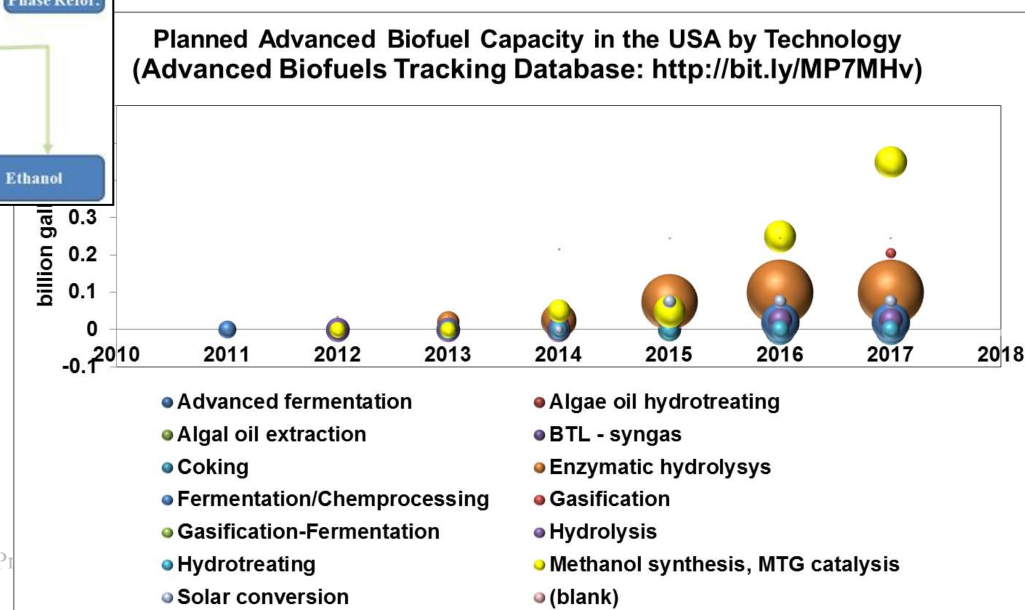
- Range is similar to previous estimates using static versions of the GTAP model
- Dynamics allow endogenous pattern to emerge as the global economy reacts
- **Note**: Oil market assumed to remain tight under these simulations

Ongoing Activities: Technology-based Biofuel Production in GTAP-DEPS

- Many technologies under development – available techno-economic data being incorporated



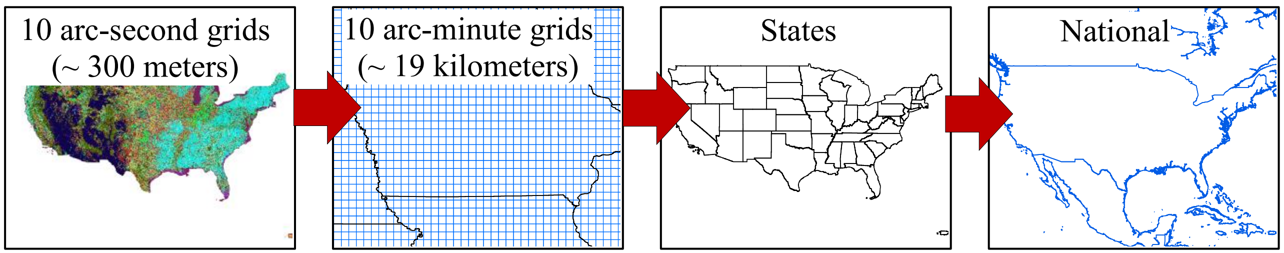
- National Advanced Biofuels Consortium (NABC) focusing research on viable pathways



- Industry R&D complementing publicly funded research (see King, 2012; Lewis, 2012; Harmon 2012)

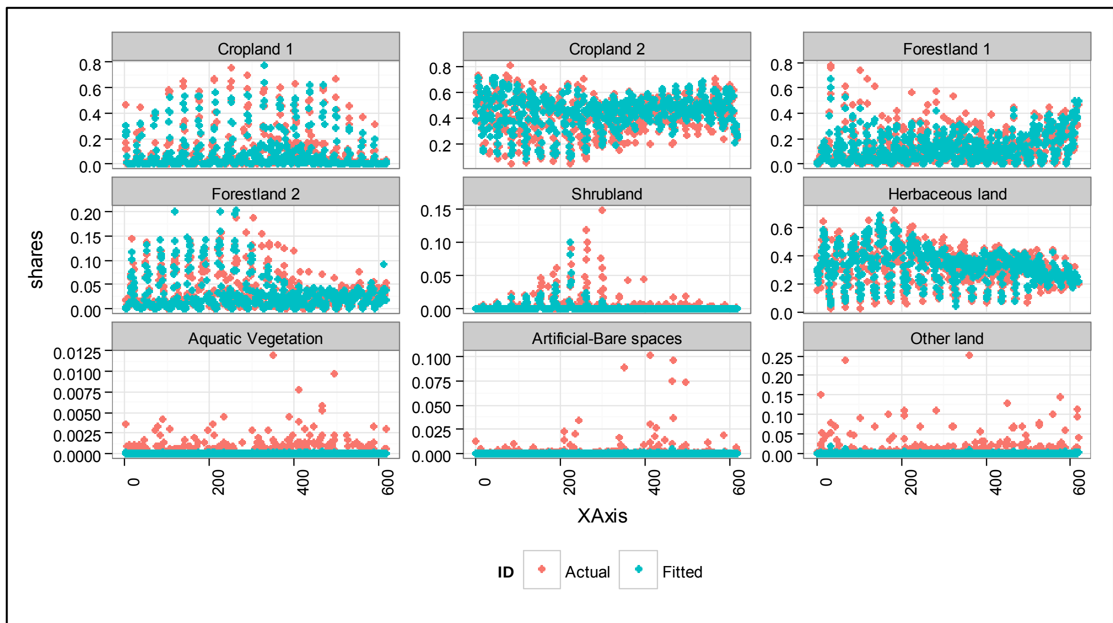
Ongoing Activities: Land allocation sub-model

- Currently being implemented for the United States
  - Model will reflect the structure of land-supply sub-model in GTAP-DEPS but provide greater detail and account for the potential influence of relevant non-price factors.



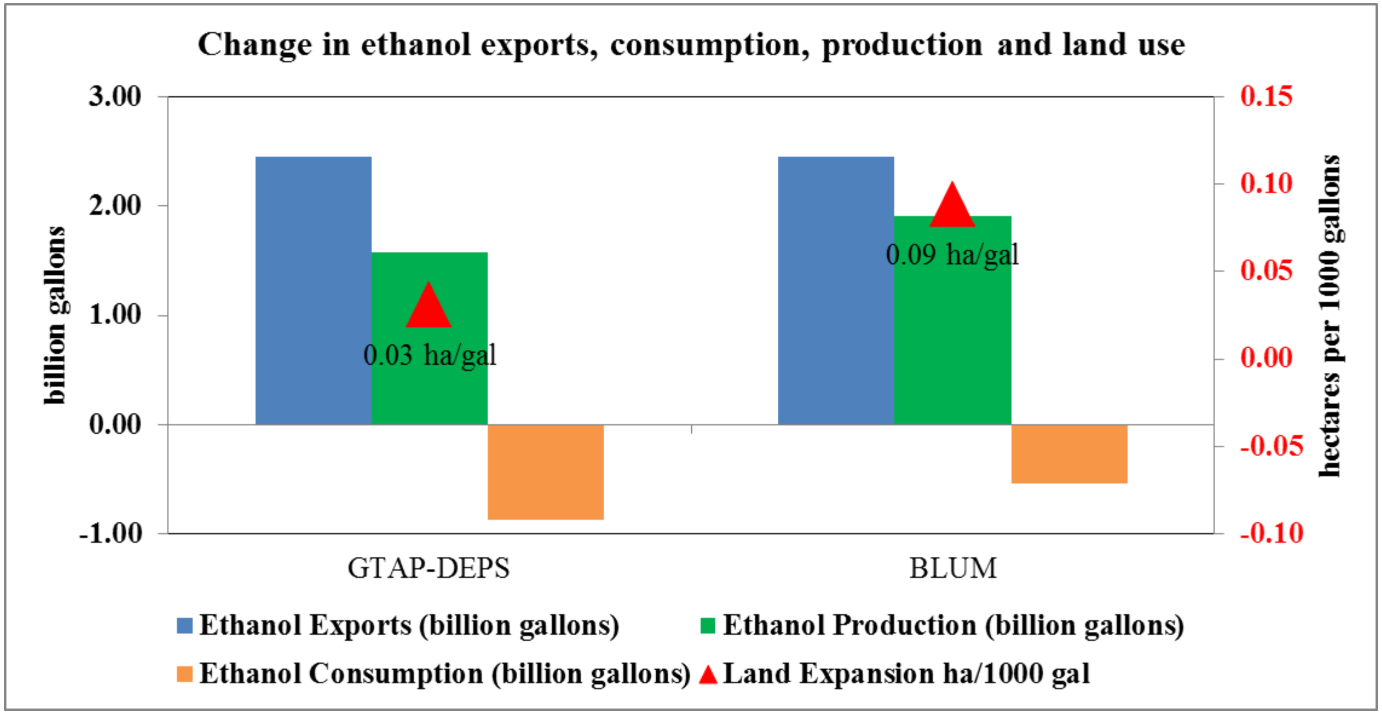
Hierarchical relationship in the proposed land allocation model

- Comparison of actual and fitted land shares data in the prototype model based data for Iowa



Comparison of LUC Impacts with BLUM

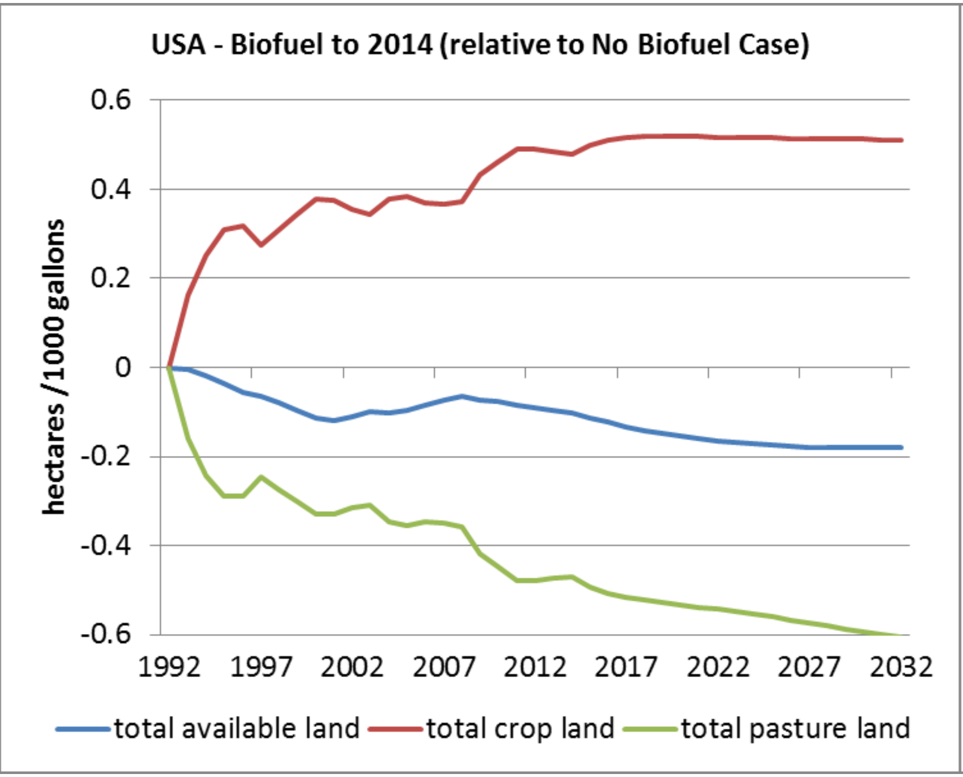
- Imports by the United States in GTAP-DEPS implied under RFS2
- Exports of the same amount in Brazilian Land Use Model (BLUM)

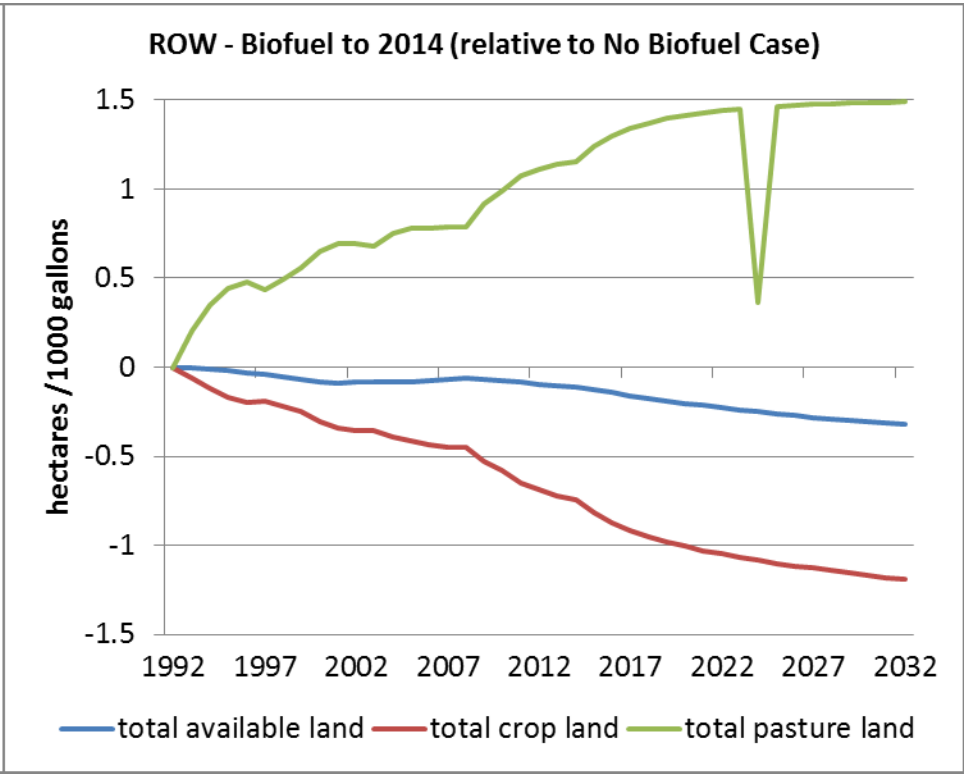


- Larger reduction in ethanol consumption and smaller increase in production in GTAP-DEPS relative to BLUM
- Smaller increase in per gallon land expansion in GTAP-DEPS
- Results reflect differences in scope and specifications of the two models

LUC Impacts per 1000 gallons (BioLUC)

- RFS Case : RFS2 to 2014 in the US (~17 billion gallons) and ROW (~23 billion gallons) of ethanol

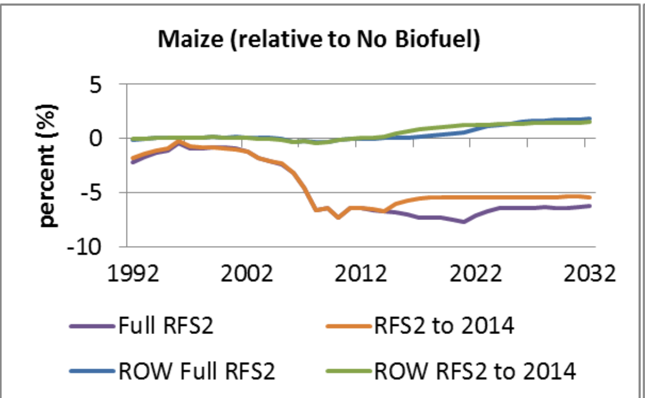


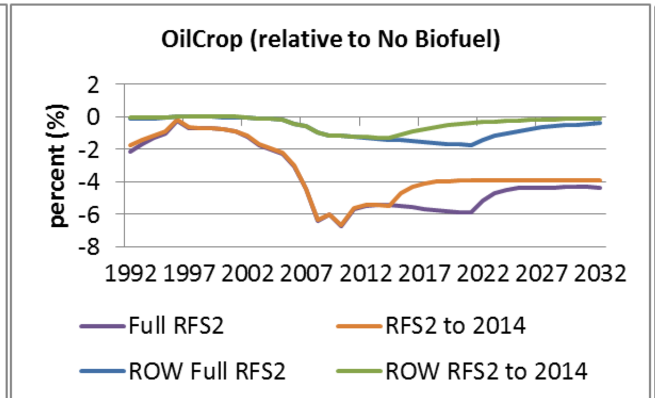


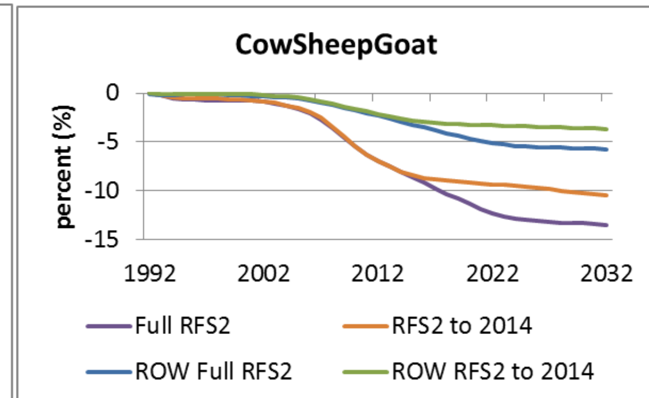
- Global LUC hectares per gallon is total of US and ROW - global production used as denominator (40billion gallons)

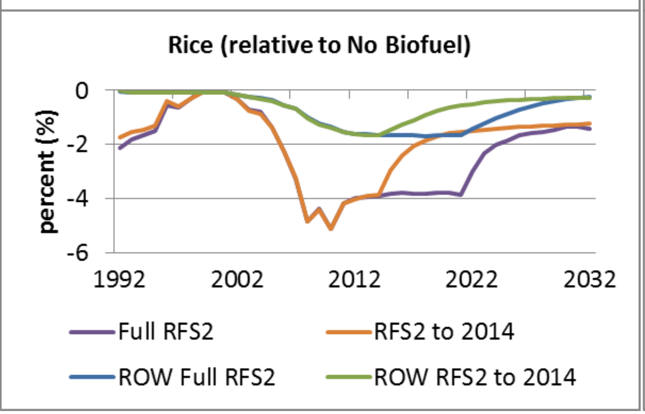
Agricultural production changes under Full RFS2 and RFS2 to 2014 (BioLUC)

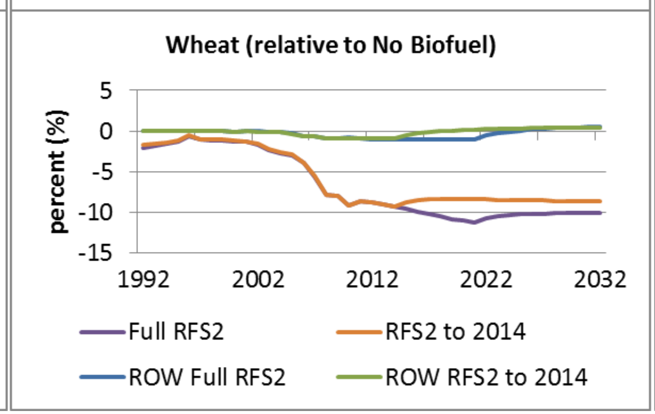
- US RFS2: Full RFS2 (17 billion gallons) ; RFS2 to 2014 (23 billion gallons)
- ROW RFS: Full RFS (23 billion gallons) ; RFS2 to 2014 (37 billion gallons)

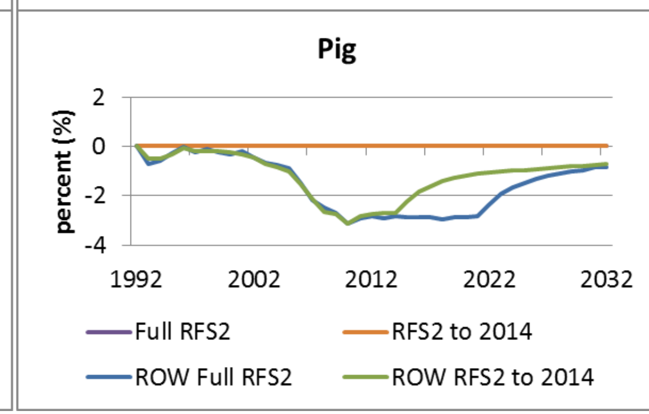








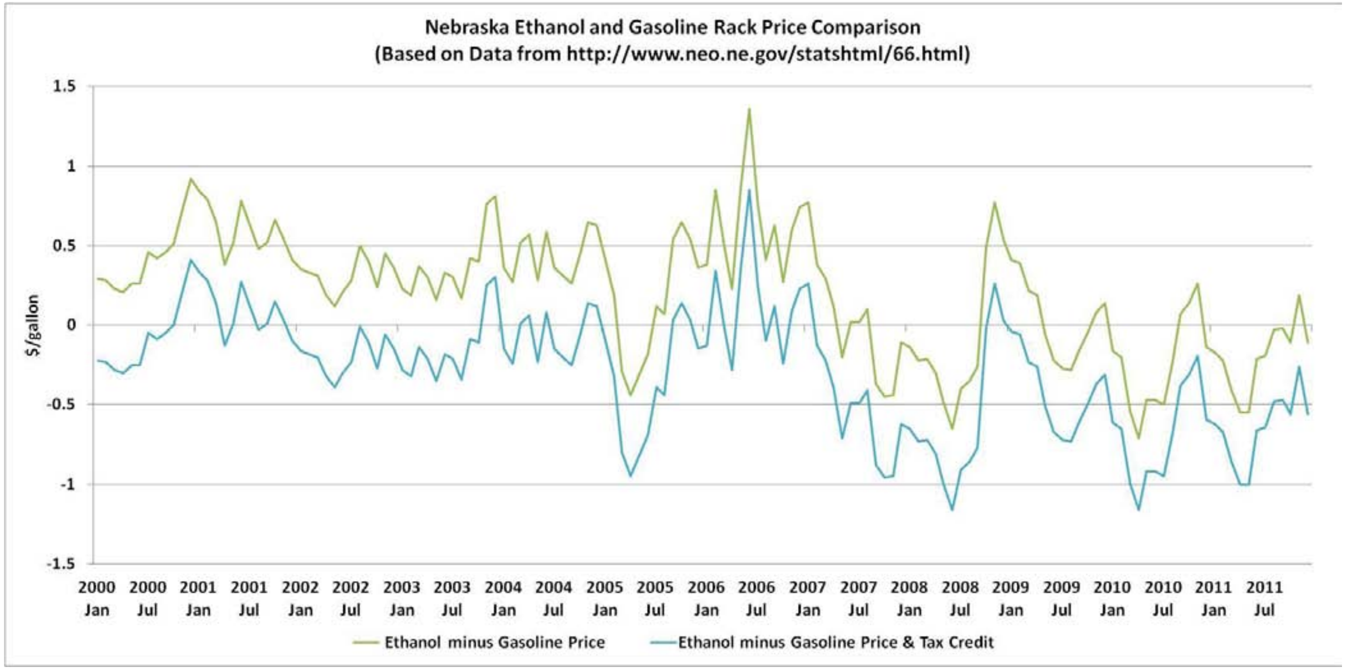




- Crop/livestock production decreases in the US and ROW generally
- Effects will be captured by the gap between desired and actual consumption

Gasoline vs. Ethanol Prices

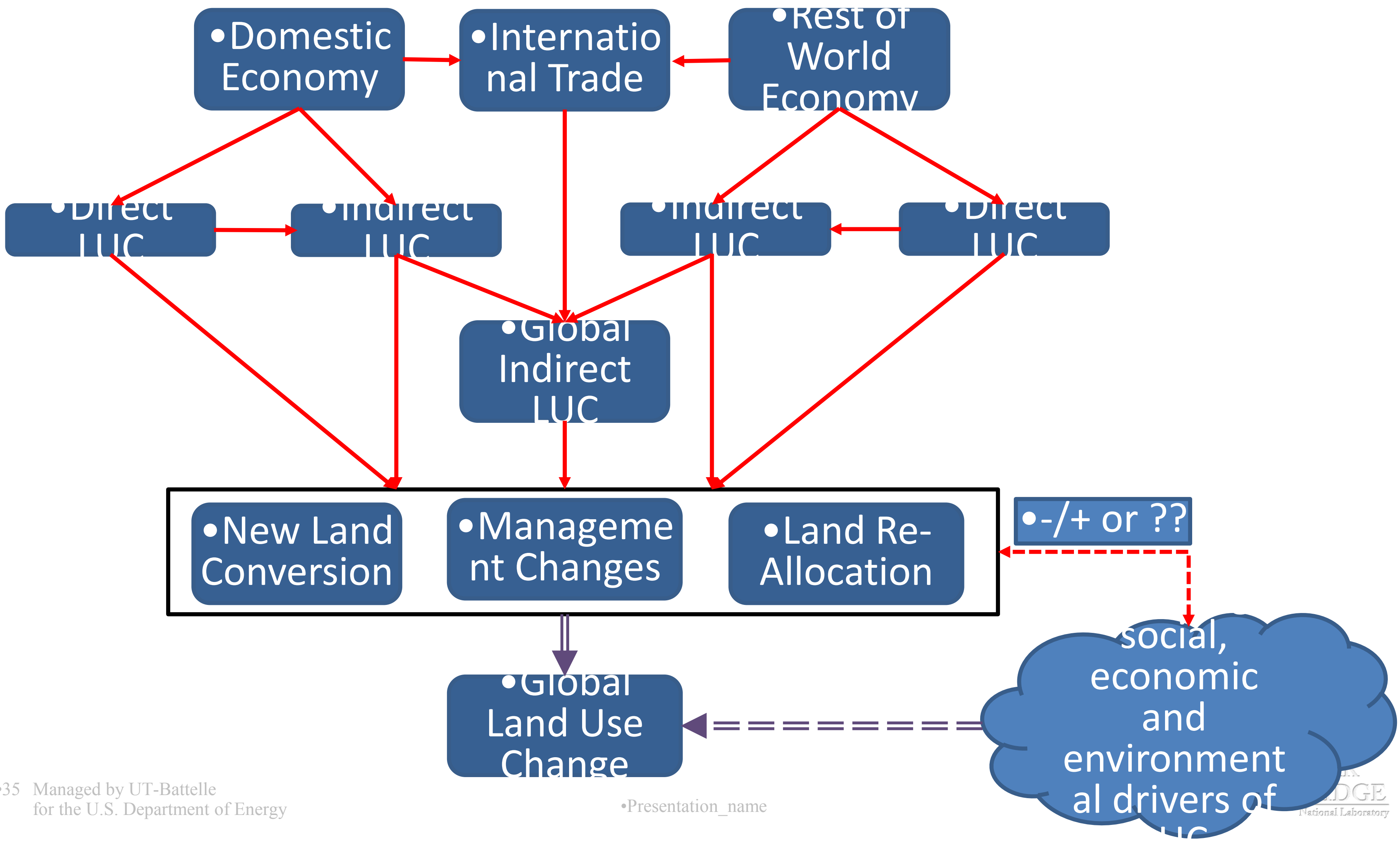
- Were recent increases in biofuel production and use in the USA driven by price competitiveness with gasoline?



- Price margins (not accounting for the fact that 1 gallon of ethanol equals 0.7 gallons of gasoline) do not suggest so.
- Mandates guaranteed the market necessary to overcome systemic risks to industry development.

Potential sources of LUC from Biofuels

- **Distinction between direct and indirect land use change is important**
  - Need to understand what are captured by models, through which channels and how.



Potential sources of LUC from Biofuels

- Potential sources of the LUC impacts of biofuels
  - Substitution of other crops/livestock and other commodities
    - Displacement of land under other crops/livestock
    - Displacement of other commodities in consumption
  - Changes in crop/livestock management
    - Changes in rotation and other management practices
  - By-products of biofuels displace other animal feeds
  - Changes in trade of agricultural and other commodities
    - Re-alignment of the production and supply of commodities
    - Expansion/contraction of land-using activities
  - Movement of land between agriculture and other land uses
- Markets are crucial to indirect LUC impacts of biofuels
  - Changes in agricultural and other commodity prices:
    - Farmers and other producers re-optimize production processes
    - Consumers re-optimize food and other commodity consumption
  - Income changes accompany changes in production/consumption
  - Leads to LUC impacts identified above
  - Other potential impacts are also possible

Summary and Future Research Needs (USDA, 2011)

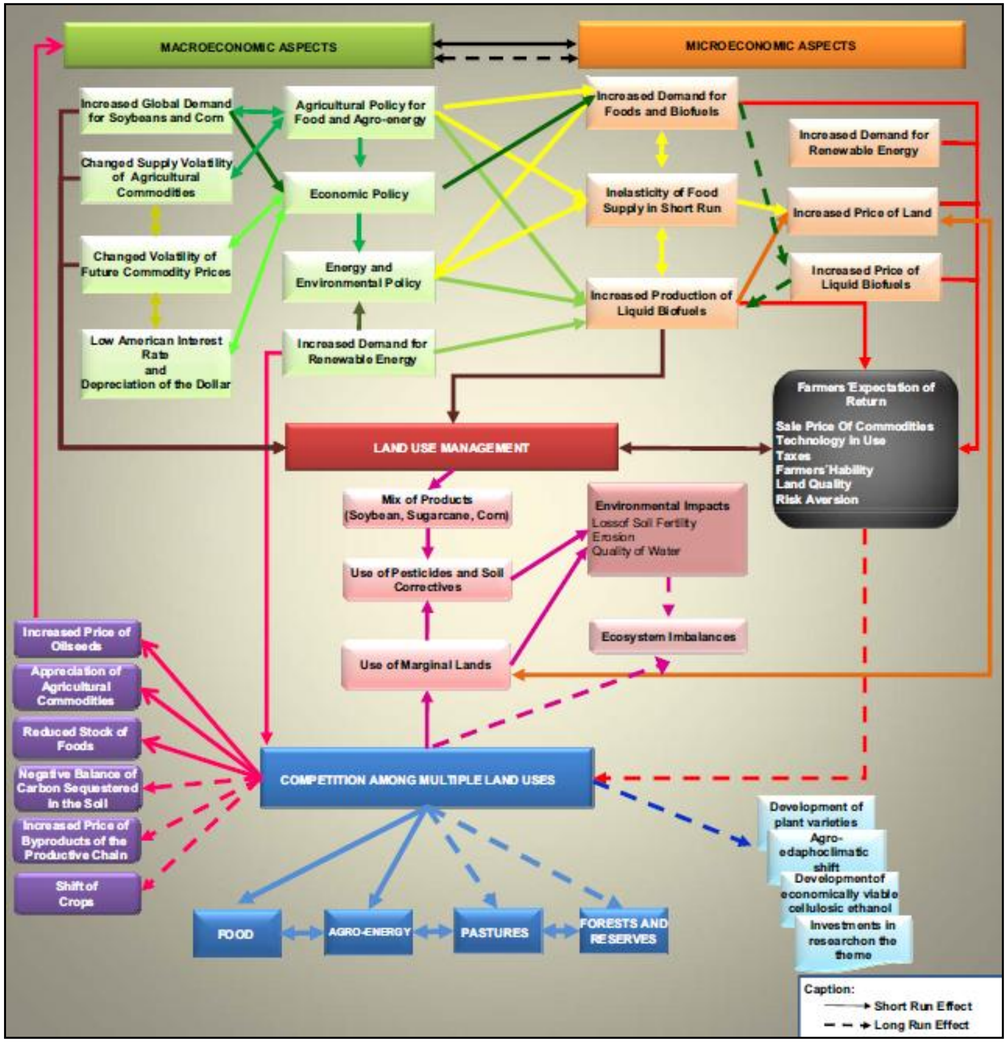
- Differences in model estimates due to differences in assumptions about:
  - Crop yields and the projected elasticity of response to demand-driven price increases;
  - The baseline that is used from which to measure change;
  - The anticipated productivity of newly converted land and the amount of land required to meet increased production demands by region;
  - The structure and flexibility of trade flows;
  - The price elasticity of demand for agricultural food and feed products;
  - The scope of the life-cycle assessment–including, for instance, whether the livestock and forest sectors are explicitly modeled as competitors for land.

Summary and Future Research Needs (USDA, 2011)

- Uncertainty in modeling indirect land-use change has involved:
  - Identifying the variables that are particularly important in contributing to the uncertainty of estimates and improving the precision with which such variables are represented with the analysis (e.g., future crop yields, the productivity of newly converted lands, and the substitutability of DDGs in livestock diets);
  - Identifying relevant relationships that require more refined analysis (such as the importance of trade relations in determining likely sources of increased agricultural production);
  - Understanding the nature of the remaining uncertainty, its effects on the distribution of potential outcomes, and the implications of incorporating different measures of that uncertainty into policy;
  - Designing policy to ensure that existing regulations evolve as the science becomes more sophisticated.

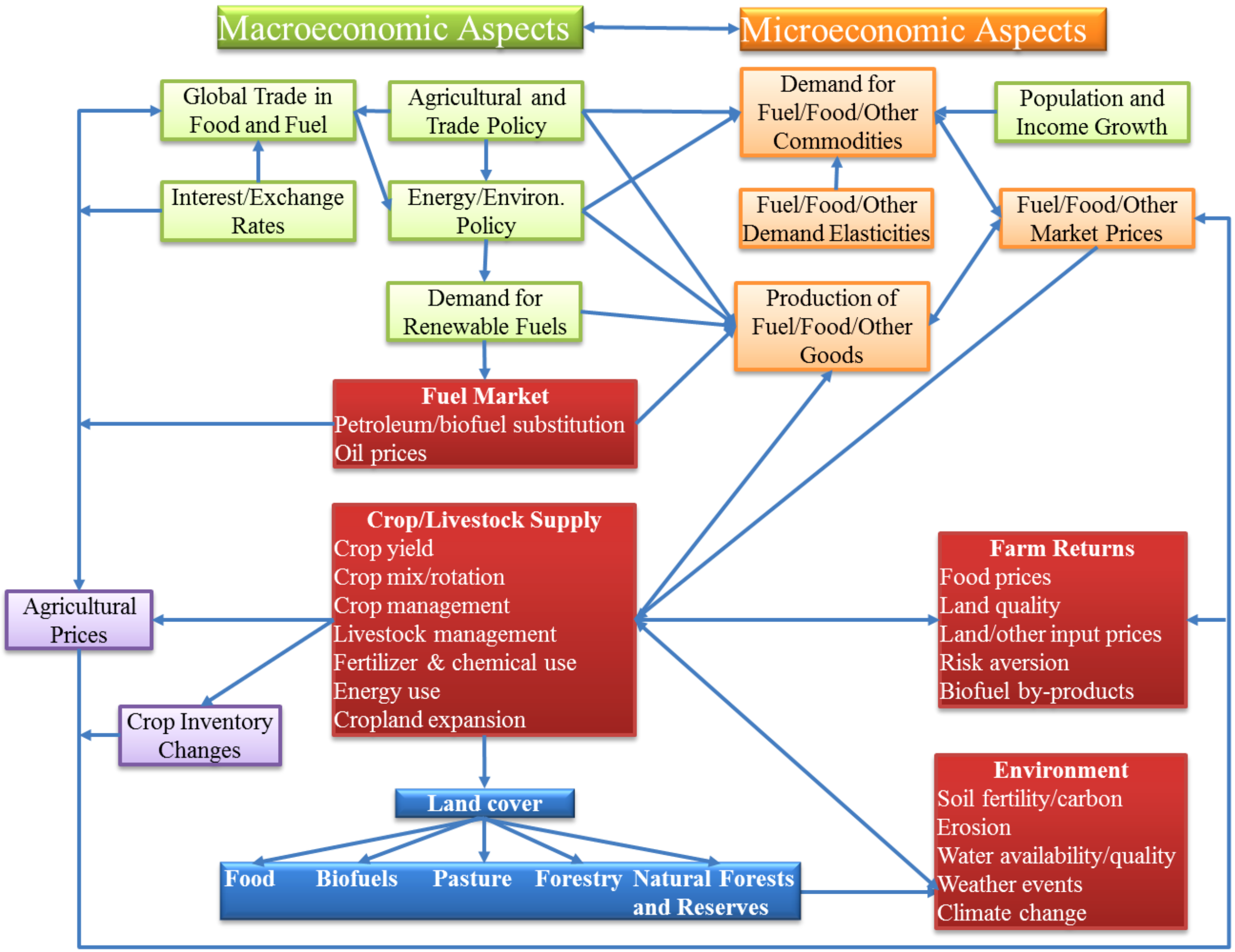
Indirect land-use change modeling

- LUC effects of biofuels depend on many factors and their complex interactions
- Models account for these complexities in different ways
- Price-based models behavioral models:
  - Partial equilibrium (PE)
  - General equilibrium (GE)
- Econometric models:
  - Vector auto-regression models
- Enumerative models:
  - System dynamics models
  - Causal-descriptive
  - Index decomposition



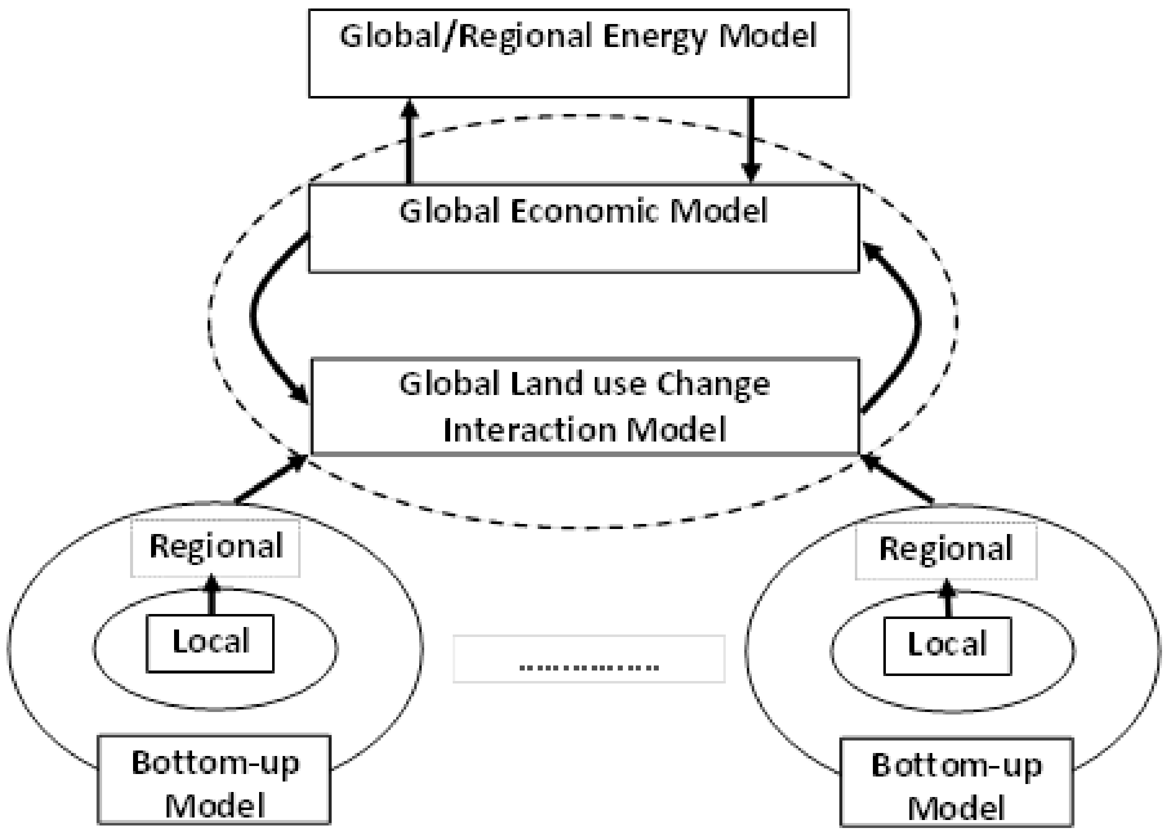
•**Source**: Rathmann et al (2010). Land use competition for production of food and liquid biofuels: An analysis of the arguments in the current debate

A framework for analyzing biofuel-food market interactions



•A framework for analyzing biofuel-food market interactions Oladosu and Msangi (2013)

Local-to-Global Modeling of the LUC Impacts of Biofuel



•Proposed linkages for local-to-global modeling of land use change impacts