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The role of economics and integrated modeling for sustainability science

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Today

- What is sustainability science, and what is the role of economics?
 - Short answer: Economics is at the heart of this
- Integrated land-hydrological modeling of agricultural watersheds for sustainability assessment
 - Interdisciplinary research: Western Lake Erie & Great Lakes Region
 - NSF Coupled Human-Natural Systems and Innovations at the Nexus of Food, Energy, Water Systems
- Perceptions of interdisciplinary research
 - A few preliminary results from Fenichel et al. survey



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SUSTAINABILITY INSTITUTE

Sustainability Science

- *Defined* by the practical problems it addresses, specifically the **problems of sustainable development**
- *Focused* on scientific understanding of (strongly) **interacting human and environmental systems**
- *Conducted* with **integrated research from multiple disciplines** (natural, social, medical, engineering sciences), and by **engaging the world** of action

-- from William C. Clark, Harvard U



Weak sustainability (WS): non-declining social welfare over time

- **Benefit-Cost Analysis:** traditional approach based on PPI
- **Sustainability Assessment:** accounts explicitly for inter-generational equity (& discount rate is an ethical issue)
 - Hartwick (1977) rule: net investment in economy = 0 → maximum constant per capita consumption over time
 - Dasgupta (2001, 2009) and coauthors (Arrow, Dasgupta, Mäler 2003; Dasgupta and Mäler 2000): non-declining social welfare is equivalent to non-declining aggregate wealth
 - Approximated by change in comprehensive wealth = change in the value of all **productive capital stocks** evaluated at constant **shadow prices** = comprehensive investment $I(t)$

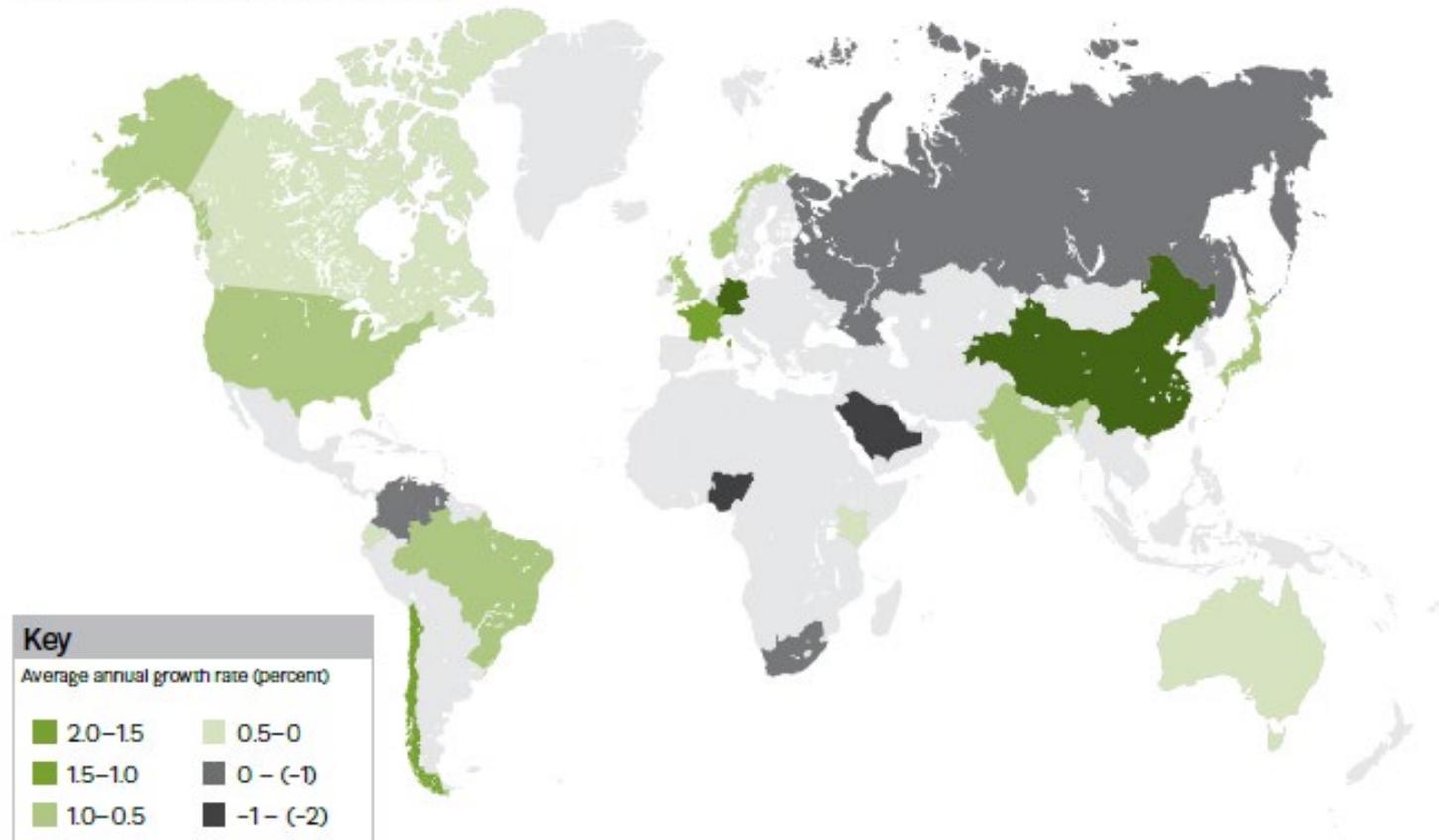
$$\frac{dV(S(t))}{dt} = I(t) = p(t) \frac{dK(t)}{dt} + q(t) \frac{dL(t)}{dt} + n(t) \frac{dN(t)}{dt}$$



Example: Inclusive Wealth Index (IWI) Average Annual Growth Rate (2012)

(International Human Dimensions Programme on Global Environmental Change and the United Nations Environment Programme)

Inclusive wealth index per capita



However, WS is based on strong assumptions...

- Unlimited substitutability of $K(t)$ for declining $N(t)$ and/or sufficient technological progress
- Population growth is either ignored or assumed to not matter (assuming rate of tech change is higher)
- Most readily understood at the global level → breaks down at regional and national levels given openness of economies – how does one assess the impact of globalization on **regional sustainability**?
- Consumer surplus can be approximated by linear index of change in capital stocks in which stocks are aggregated using accounting (shadow) prices that reflect full social marginal value...

...BUT we know that **nonconvexities are not uncommon in ecological systems** and that these lead to thresholds or nonlinear change → implies **limits to substitution** & underscores importance of accounting for **uncertainty**

Strong sustainability (SS): Physical and ecological limits

- Human well-being is subject to physical & ecological limits
- Sustainability = critical levels or flows of natural capital (NC) stocks are maintained over time:
 - Minimum levels of ecosystem services (e.g., biodiversity, climate regulation, nutrient cycling)
 - Maximum sustainable yields of renewable resources (e.g., fishing, deforestation)
 - Maximum rates of pollution (e.g., GHG emissions, nutrient run-off)

Example: “Planetary boundaries” identify “safe operating space” for humanity with respect to the Earth’s critical biophysical systems and processes

In practice: A very mixed bag

- **Sustainability indicators:** A kind of “dashboard” approach with no connection to welfare, WS or SS
- **Strong sustainability (SS) measures** are dominant, but methods are eclectic, e.g. footprint analysis; indicators of resource scarcity, environmental quality, ecosystem health, etc
- **Weak sustainability (WS) measures** as we conceive of it are seldom, but often some indicator of economic prosperity or some aspects of IW

→ *These assessments have done little to clarify welfare implications of current or alternative policies or assess sustainability as non-declining welfare over time*



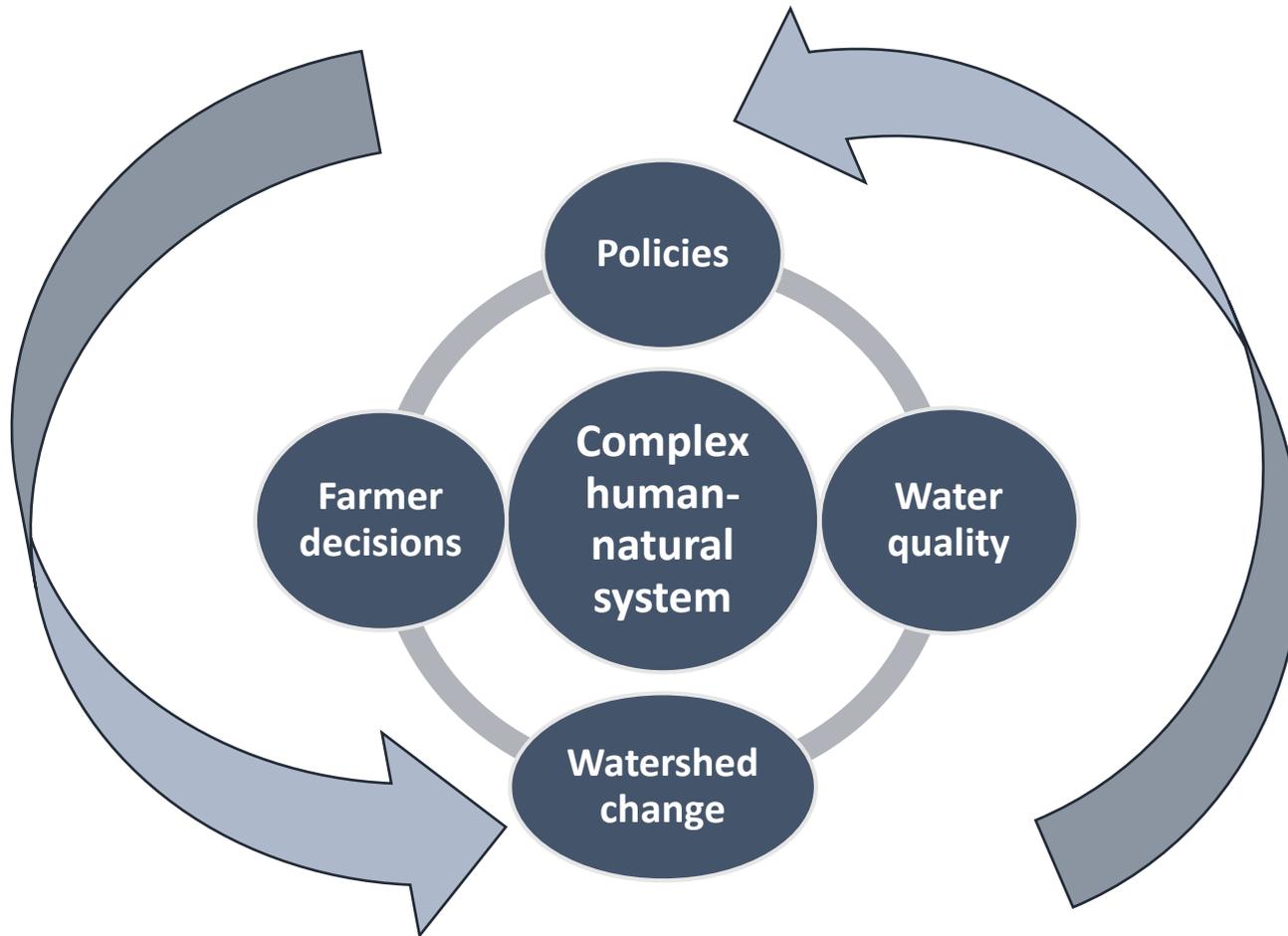
WS+ Models: Integrated models of natural and human systems for policy analysis

- More realistic representation of the **biophysical and human processes** that determine the evolution of natural capital and other stocks
- **Assess policies:** Have a welfare-theoretic foundation that can be used to evaluate WS or max net social benefits
- Dynamic IM models: provide a means to develop and evaluate **future scenarios** by generating projections of future consumption and changes in stocks

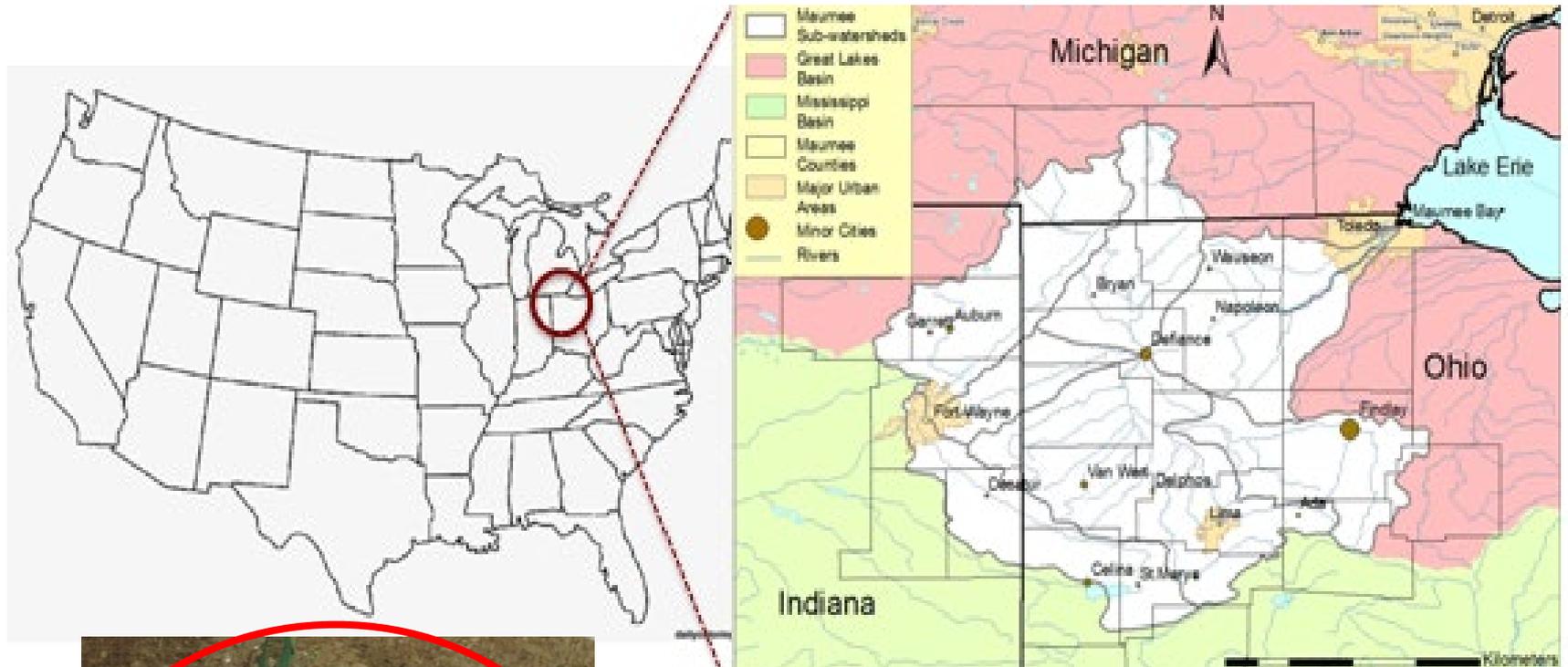
Irwin, Elena G, Sathya Gopalakrishnan, Alan Randall. 2016. Welfare, wealth and sustainability. *Annual Review of Resource Economics* 8: DOI: 10.1146/annurev-resource-100815-095351.



Integrated modeling of agricultural land use-hydrological systems



Western Lake Erie basin & Maumee watershed



Main research focus: Policy scenarios to assess cost effectiveness

- Nutrient management policy scenarios
 - Fertilizer tax
 - Incentives (payments, cost share) for BMP adoption, including
 - 4 R's (Right source, Right rate, Right time, Right place)
 - Cover crops
 - Filter strips
 - Controlled drainage
 - Grid sampling
 - Spatial targeting (of tax or monetary incentives)



Key elements of modeling approach

- Farmer decision making model
 - Choice experiments using surveys of corn and soybean operators
 - Focus on agricultural land management decisions as a function of costs, farm & farmer characteristics, land & geographic attributes
- Spatial predictions of land management (a map!)
 - Spatial data on land characteristics (field level); Ag Census data on farm & farmer characteristics (county level)
 - Use data & estimated parameters to predict probability of BMP adoption
- Hydrological model (SWAT)
 - Calculate predicted land use/management shares within hydrological response unit (HRU) (similar land use, slope, soils ~24,000 HRUs)
 - Calibrate hydrological and nutrient flows for the Maumee Watershed
 - Generate predictions of TP and DRP loadings



Some findings to-date

- **Heterogeneity in farmer identity and perceptions matters**
 - Farmers tend to fall into one of several classes: innovators (22-45%), future adopters (45-55%), laggards (10%)
 - Perceived efficacy (confidence in ability to implement practices; belief in effectiveness) and conservation identity are positive and significant across all or most; other factors vary with BMP
 - 60-70% of farmers are willing to use BMPs (subsurface placement, cover crops). For those who are willing, but not acting, biggest barrier is perceived efficacy.
- **BMP cost-share payments are effective in spurring adoption**
 - Farmers require the least compensation for grid sampling and require the most compensation for implementing strict nutrient limits. Using winter cover crops falls somewhere in between.
 - \$50/acre payment for subsurface placement (cover crops) results in ~58% (~40%) predicted adoption rate (**Liu et al. 2019**)



Some Key Findings To-Date

- However, **cost share policies are less cost effective at reducing nutrient run-off than a tax**
 - Uniform policies that target a single practice (BMP or P application) have limited effectiveness in reducing loadings to Lake Erie (**Liu et al. 2019**)
- **Political economy matters**
 - Controlling for cost to household, residents have a preference for reducing nutrient pollution via implementing regulations and PES programs over fertilizer taxes. No significant differences between support for PES and regulations.
 - Substantial time lags due to legacy P in soils → it will take years for reductions in P to generate the desired water quality improvement

Some Nagging Challenges

- **Spatial mismatch** between the land unit (parcel) and hydrologic response unit (HRU)
 - About 155,000 cropland parcels; at best we can disaggregate HRUs into about 2,400 units (252 subwatersheds)
 - Challenges in translating predicted land management and crop changes at parcel scale to impacts on P loadings at HRU scale
- **Linking farmer variables to spatial land prediction model**
 - Lack individual data for population of farmers
 - The best we can do is draw randomly from distributions of characteristics from ag census or surveyed farmers (county level) or use means of surveyed farmers (township level) → translate into distributions of crop and BMP choices at subwatershed level
- **Extreme policy scenarios** needed to achieve full reductions
 - Need to better understand whether this is accurate (e.g., due to legacy effects) or model misspecification

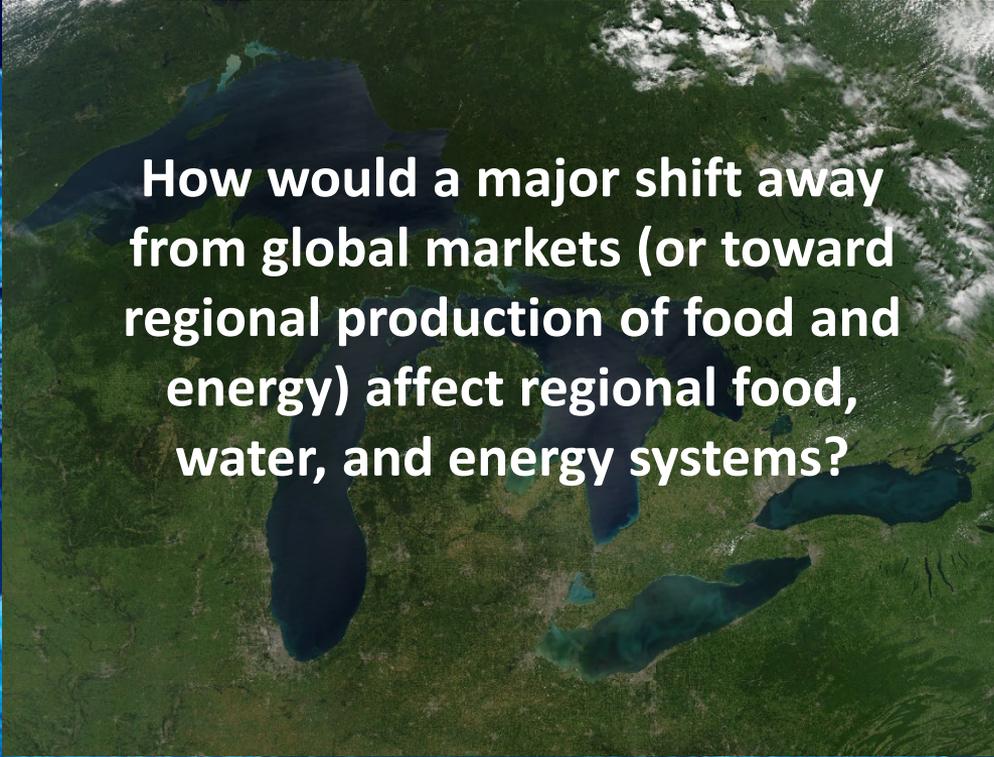


Bigger Challenges

- Not accounting for **endogenous prices or feedbacks**
- No **dynamics** or **uncertainty**
 - Model can generate changes over time, but farmer decision making is static; parameters estimated from single snapshot
 - Dynamic model would have to account for forward-looking behavior and possible learning over time
 - Expectations: Farmer cares about future prices, soil P; does not care about future P loadings; however, social planner cares about all
 - Given many sources of uncertainty, role of expectations is key
- Can't use model to assess **sustainability**
 - We can consider costs and benefits and identify potential solutions that maximize net social benefits, but unable to assess changes in water quality, agricultural profits or other outcomes over time



INFEWS: Impacts of Deglobalization on the Sustainability of Regional Food, Energy, Water Systems



How would a major shift away from global markets (or toward regional production of food and energy) affect regional food, water, and energy systems?



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Explore

INFEWS: Ohio State University Project Team



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(economics, land use modeling)



Yongyang Cai

(**DYNAMIC** economic modeling)



Robyn Wilson

(behavior & decision making)



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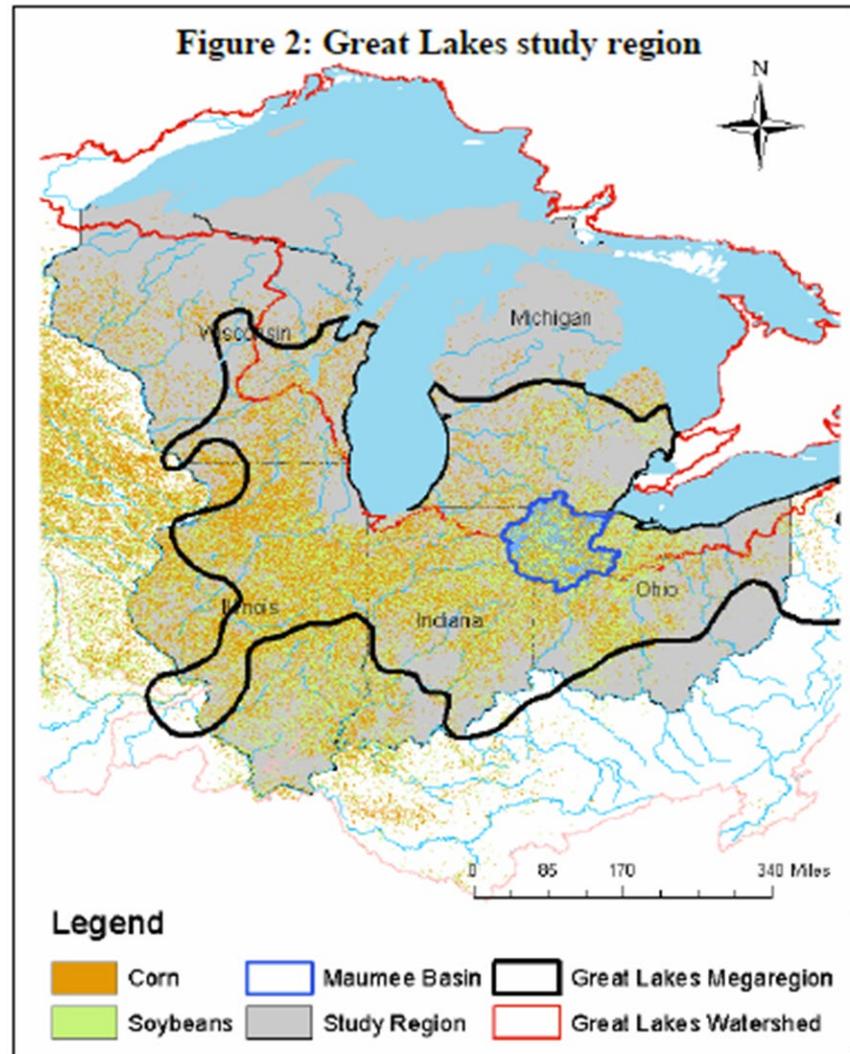
(supply chain modeling)



OUR STUDY REGION



- Almost 40% land in crops
- Great Lakes have 5% of global fresh water
- Agriculture accounts for 10% of the region's exports



Rough Intersection of Great Lakes states, Eastern Corn Belt, Great Lakes megaregion

Approach

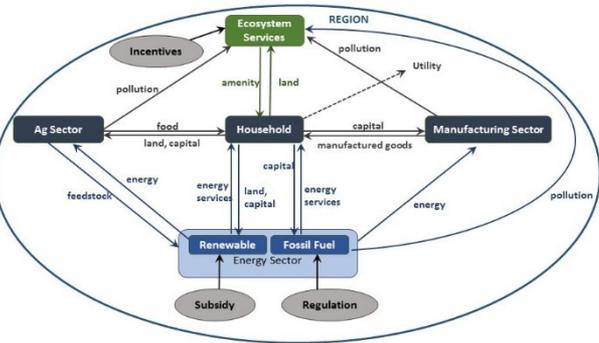
1. Develop future scenarios to capture 'deglobalization'
2. Develop Dynamic Regional Economic Model for Food/Energy/Water System (DR FEWS)
3. Incorporate information about farmer/landowner responses and landscape diversity
4. Simulate FEW system responses to future shocks for baseline and alternative scenarios
5. Develop and apply theory and methods to assess regional sustainability



1. Scenarios

- 1. National Economy with Carbon Tax (Prices)
- 2. National Economy under Baseline (Prices)
- 3. National Economy with Fossil Fuel Supports (Prices)

2. Regional Economy



3. Farmer Decisions

Prices and Outcomes

I'm out! I'm selling my land

I'm staying put!

Eh.. I'll grow something else instead

5. Sustainability Assessment

- 1. National, Regional & Local Outcomes
- 2. National, Regional & Local Outcomes
- 3. National, Regional & Local Outcomes

4. Land-Water-Environment



Land use changes, nutrient loadings from heterogeneous decisions

1. Scenarios

Specify policy or market shocks that might lead to decreased engagement with global markets

Broadly these could include:

- Changes that originate from the rest of the world
- Regional or local shocks
- Trends that change consumer preferences
- Policies and regulations
- Technological innovation



Examples:

- Tariffs and trade wars
- Restrictions on immigration
- Growth in demand for regionally produced food & energy

Scenarios Development

Project Team Discussions

Research Advisory Council – RAC

- 26 people heavily involved in FEW issues for Great Lakes Region

Participatory Modeling Assessment Teams – PMATs

- Meet 2-3 times per year in addition to the RAC

Farmer Focus Groups



Stakeholder Engagement
(at various levels)

Businesses As Usual

STRONGER ENVIRO. PROTECTIONS

Increased regulation on producers (water, air quality)
Increased subsidies for renewable energy
Decreased subsidies for fossil fuel energy

HIGH TRADE

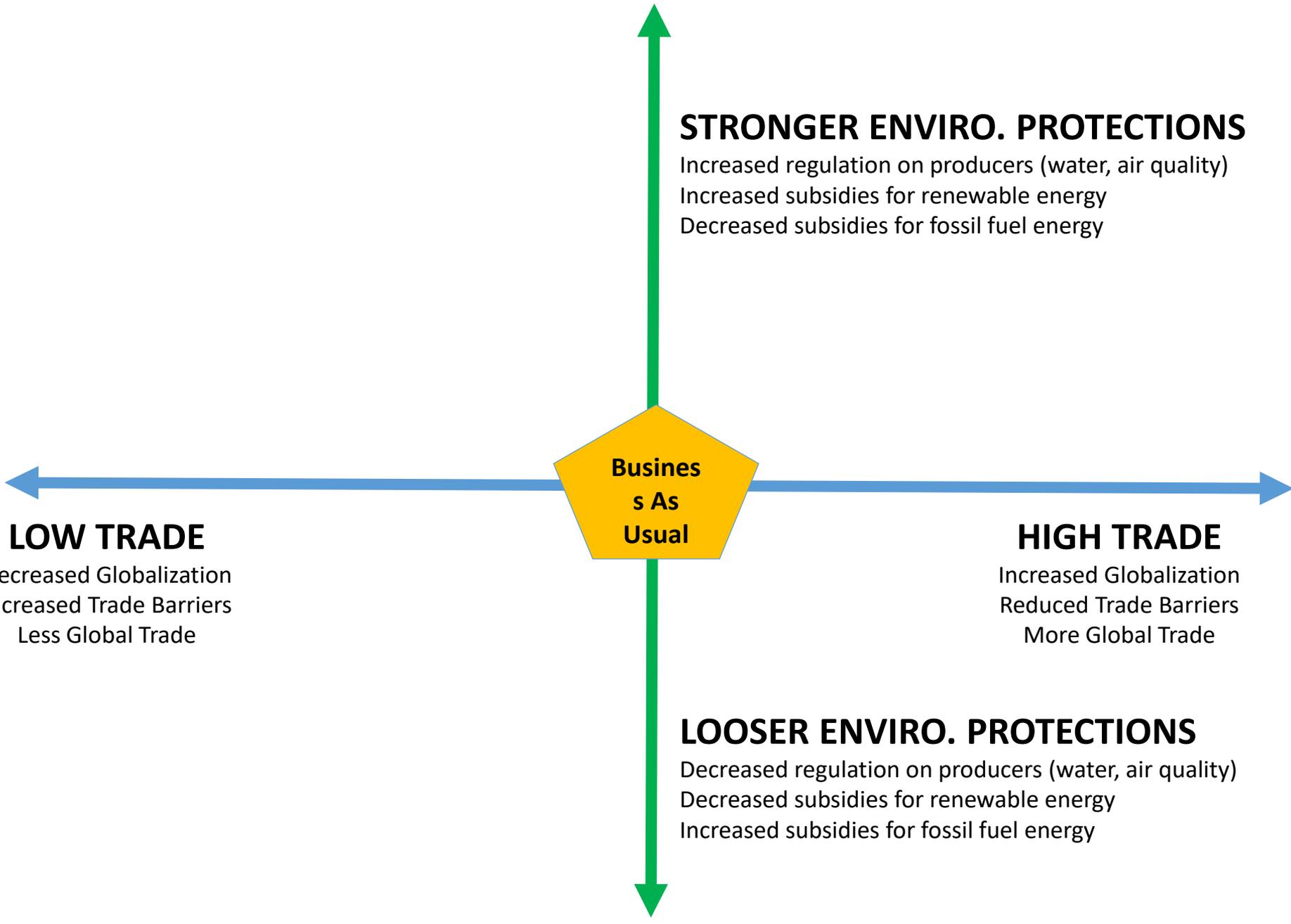
Increased Globalization
Reduced Trade Barriers
More Global Trade

LOOSER ENVIRO. PROTECTIONS

Decreased regulation on producers (water, air quality)
Decreased subsidies for renewable energy
Increased subsidies for fossil fuel energy

LOW TRADE

Decreased Globalization
Increased Trade Barriers
Less Global Trade



Scenario Framework

Five Scenarios:

1. Business As Usual (BAU)

Environmental Protections and Trade

2. (High, High)

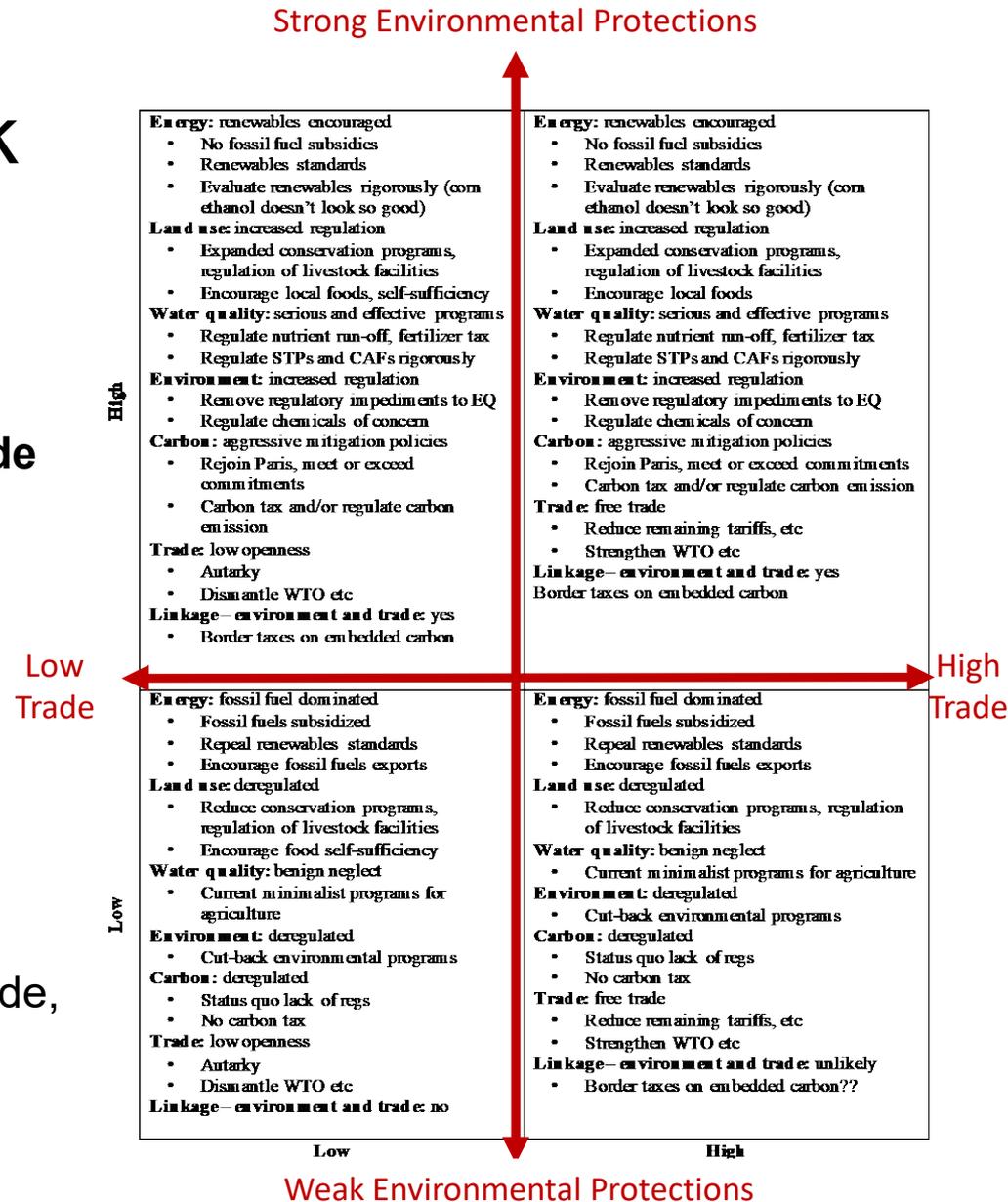
3. (High, Low)

4. (Low, High)

5. (Low, Low)

Dimensions for study region:

- Energy, Land Use, Water Quality, Environment, Carbon (Climate), Trade, Linkages between trade and environmental policies



Example: High Environmental Protections, Low Trade Openness

Priorities:

- Climate-Benign Energy
- Land Conservation
- Water Quality
- Environmental Protection
- Climate Mitigation
- Trade and Immigration: Protectionism and Nationalism

Trade and Environment Linkage

- Rest of the world taxes U.S. exports for embedded carbon

Energy: renewables encouraged

- No fossil fuel subsidies
- Renewables standards
- Evaluate renewables rigorously (corn ethanol doesn't look so good)

Land use: increased regulation

- Expanded conservation programs, regulation of livestock facilities
- Encourage local foods, self-sufficiency

Water quality: serious and effective programs

- Regulate nutrient run-off, fertilizer tax
- Regulate STPs and CAFs rigorously

Environment: increased regulation

- Remove regulatory impediments to EQ
- Regulate chemicals of concern

Carbon: aggressive mitigation policies

- Rejoin Paris, meet or exceed commitments
- Carbon tax and/or regulate carbon emission

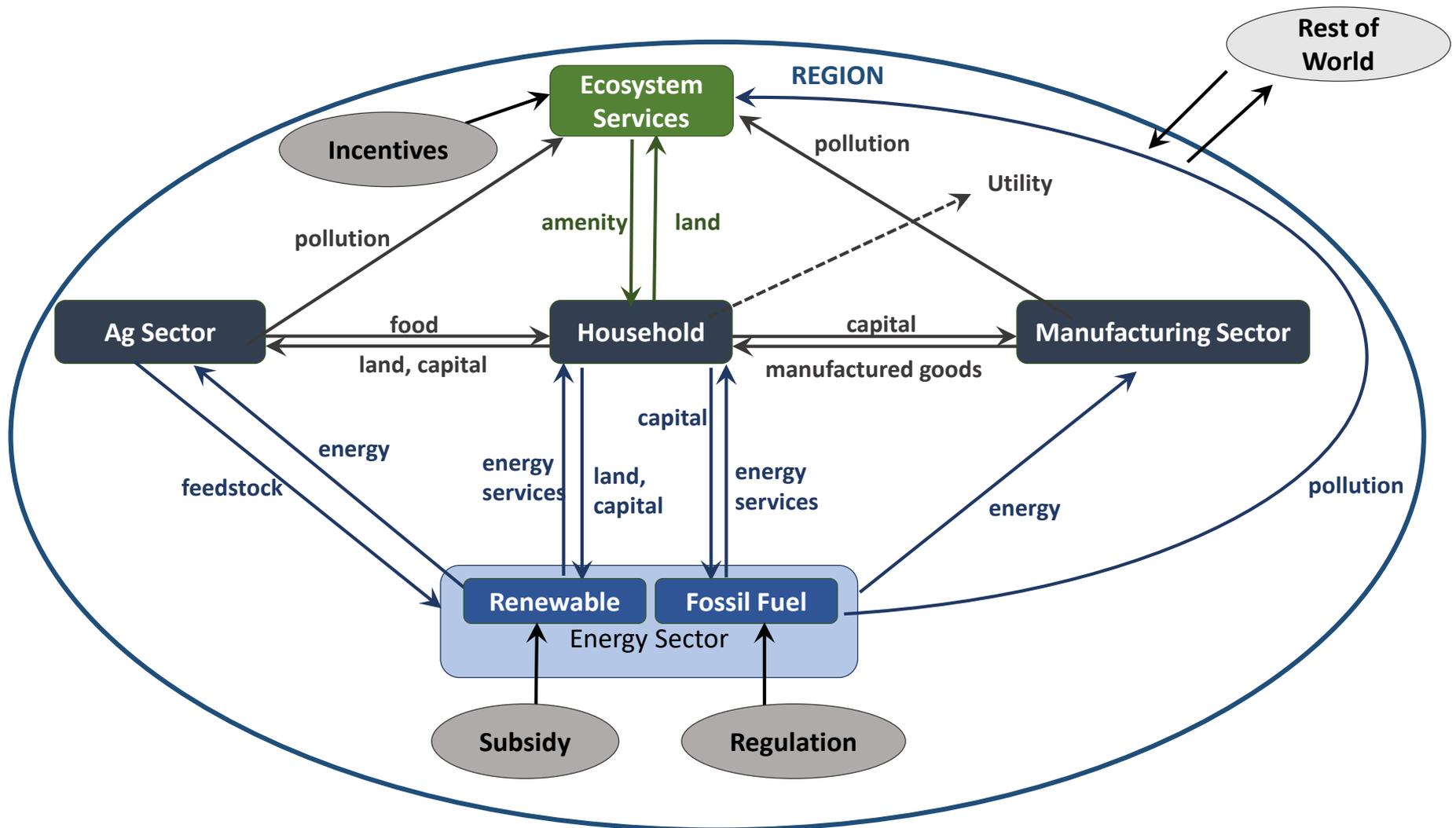
Trade: low openness

- Autarky
- Dismantle WTO etc

Linkage – environment and trade: yes

- Border taxes on embedded carbon

2. Dynamic Regional Economy Model (DRFEWS 1.0: semi-closed economy, deterministic)



DRFEWS (Dynamic Regional Food Energy Water Systems) Model

- Social Planner model
 - Representative household: Max sum of PDV of $U(y_t)$ over time; discount factor and intertemporal elasticity of substitution given $y_t = (y_t^{\text{food}}, y_t^{\text{energy}}, y_t^{\text{manu}}, y_t^{\text{eco}})$
 - Food = (corn, soy, wheat, livestock, specialty)
 - Land allocation: corn, soy, wheat, specialty, ecosystem services
 - Energy resources = (coal, oil, natural gas, biofuel, other renewable)
 - Energy services = (electricity, transportation, heat)
 - Energy used as input into (manu, energy)
 - Stocks: capital, coal, oil, natural gas
 - Imports: oil, specialty, livestock
 - Exports: corn, soy, natural gas
- Dynamic General Equilibrium (DGE) model
 - Households own land, share of all firms; receive share of profits in each period
 - Firms maximize profits; sectors: farming, food, manufacturing, fossil fuel extraction, transportation, electricity



Model specification

Time-series data on regional production, consumption, prices of intermediate and final goods from study region, including:

- **Agricultural:** commodity production yields, returns, and costs, including energy costs (ERS and NASS); input use, including fertilizer and chemicals (ERS) and other capital inputs (University of Minnesota InSTePP); agricultural land use (NASS); farm income and wealth (ERS)
- **Energy:** electricity production, consumption, energy production, consumption, inputs to production, extraction costs (EIA), wind turbine production (USGS)
- **Manufacturing:** GDP data (BEA), electricity consumption (EIA)
- Estimate key parameters of production and transition equations (least square & least absolute deviation methods)
- Model simulation: GAMS and MatLab



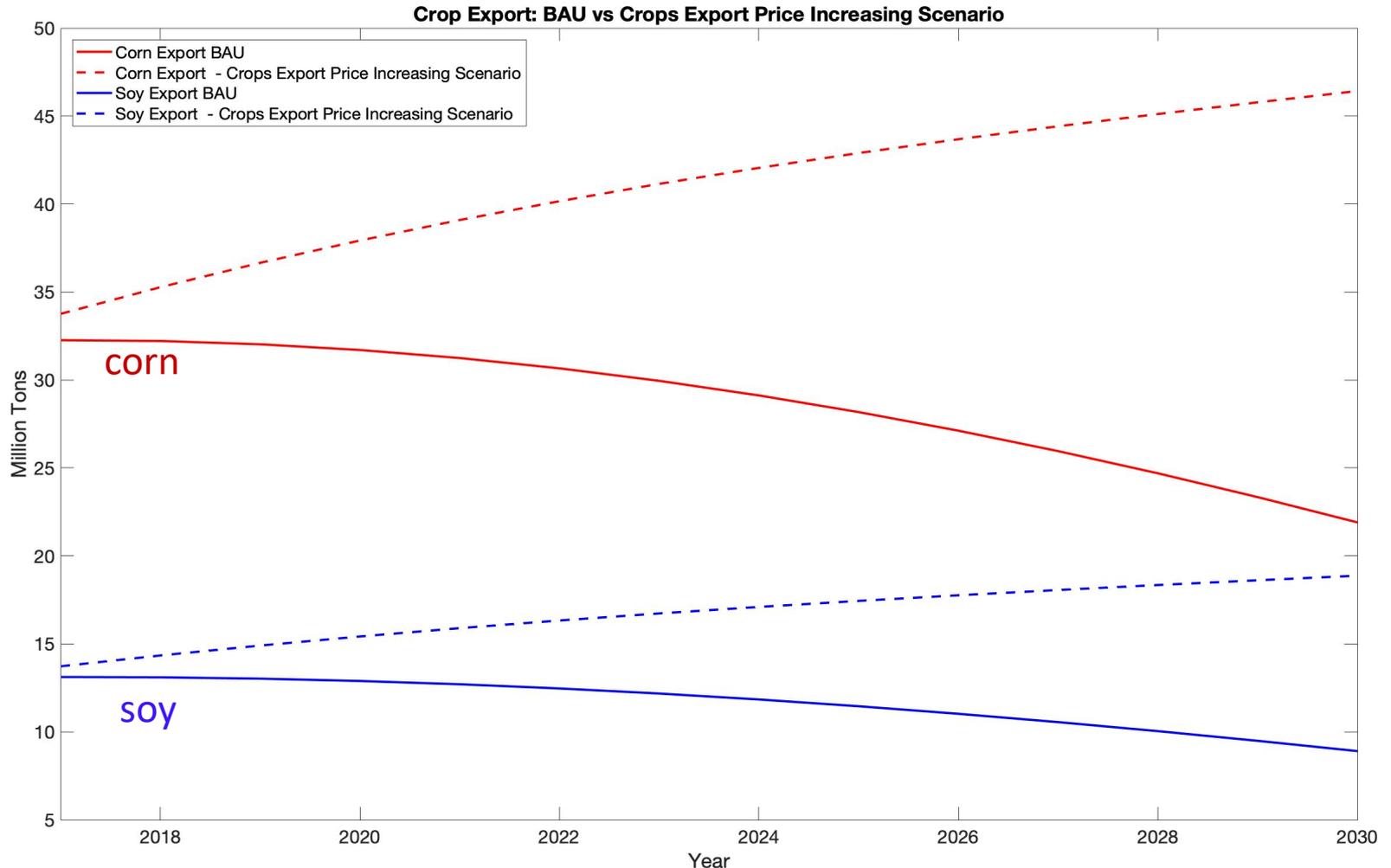
Example of simple scenarios

- Baseline (BAU) scenario: Trends in economy today extend into the future
 - Production processes becomes more productive at the rate we observed in recent decades, substitution and other key relationships are stable over time
- Alternative scenarios
 - Increase in export prices of corn and soy (3%)
 - Decrease in oil imports (5%)
- In this current version
 - No prices for ecosystem services
 - No representation of carbon emissions or water pollution
 - Limited openness of region (import and export sectors determined based on historical trends, ROW prices are exogenous)
 - Projections from current to 2030



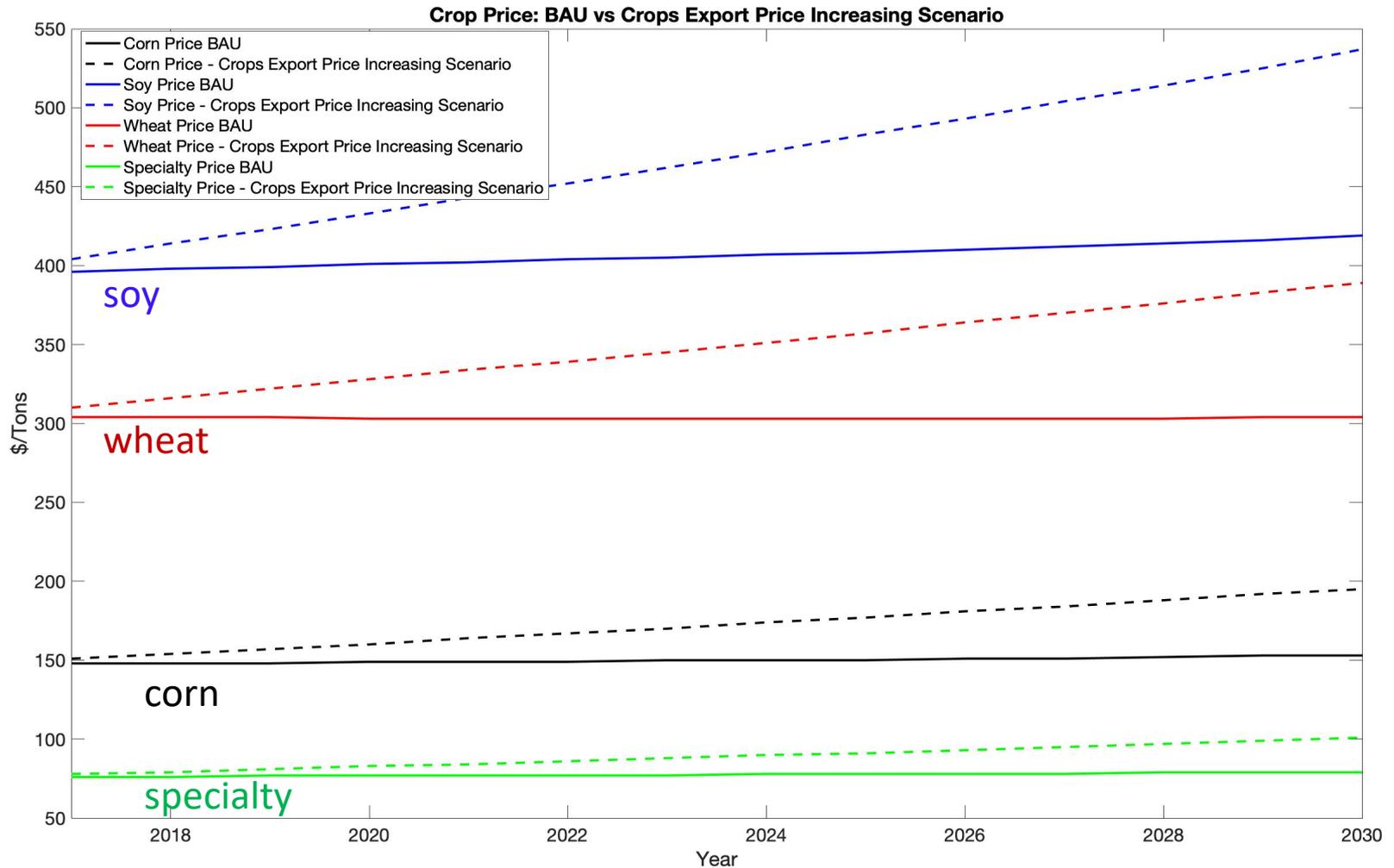
PRELIMINARY RESULTS – DO NOT CITE

Crop Exports: BAU (solid) vs. Increase in Corn and Soy Export Prices (dotted)



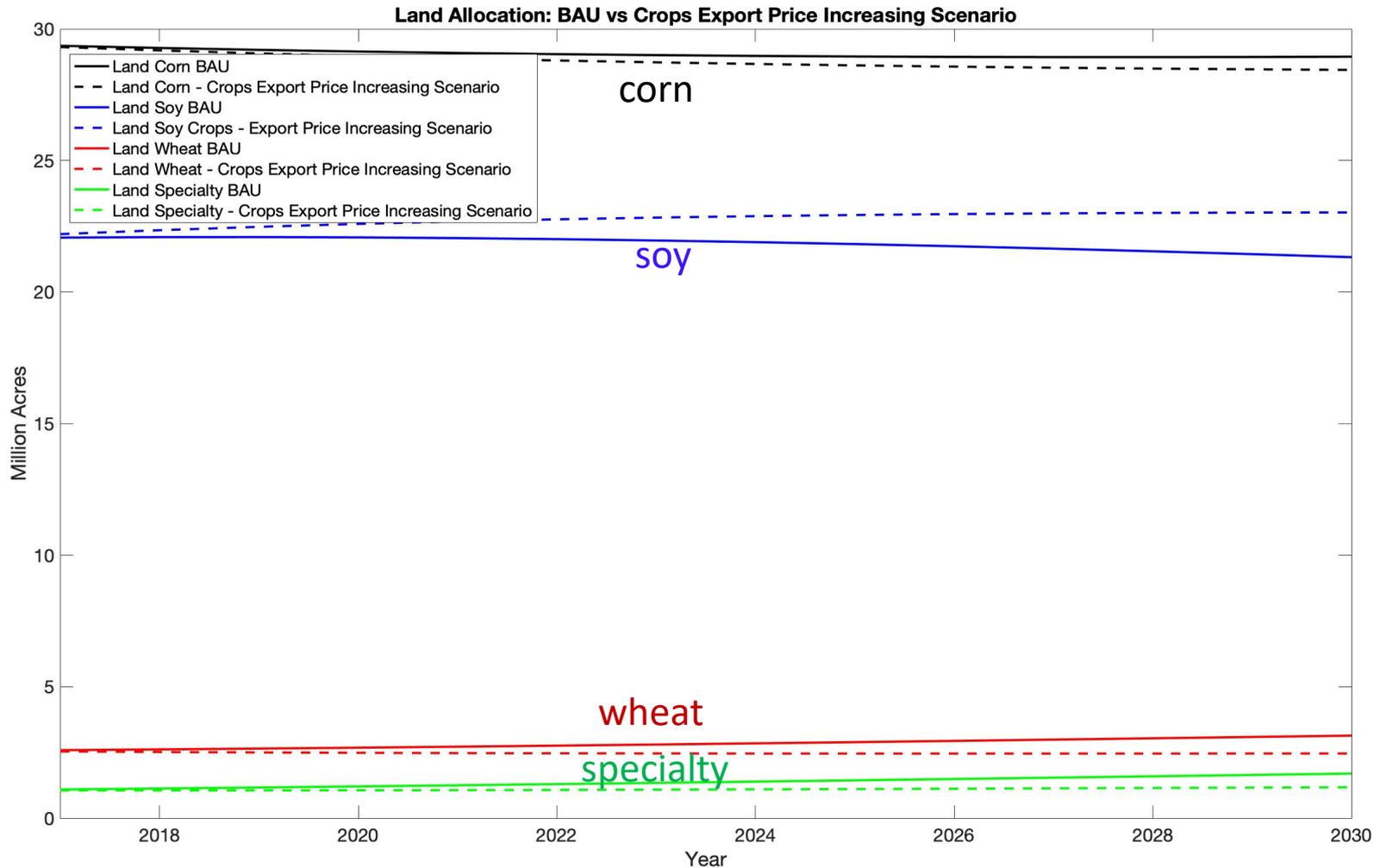
PRELIMINARY RESULTS – DO NOT CITE

Regional Prices: BAU (solid) vs. Increase in Corn and Soy Export Prices (dotted)



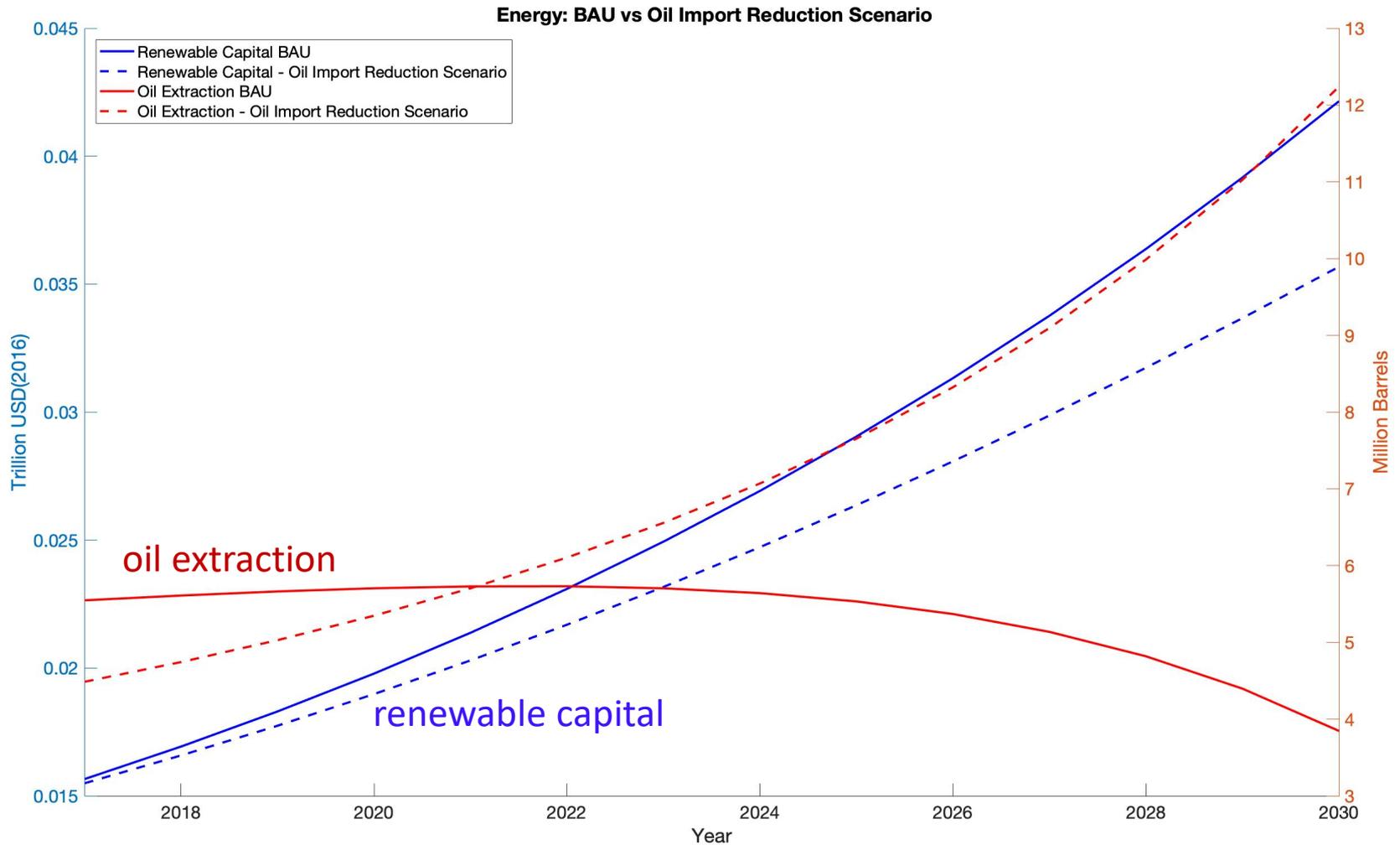
PRELIMINARY RESULTS – DO NOT CITE

Land Allocation: BAU (solid) vs. Increase in Corn and Soy Export Prices (dotted)

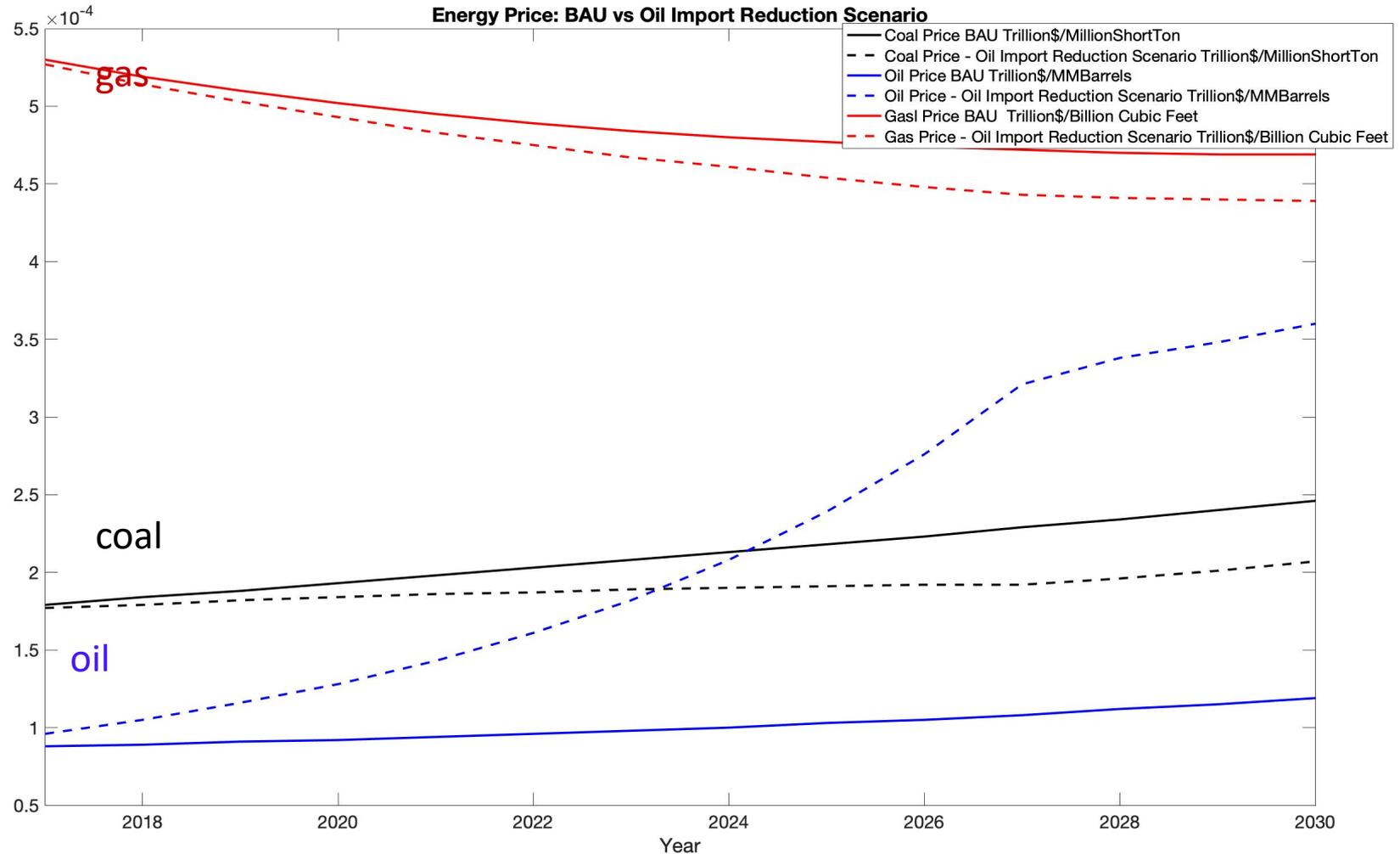


PRELIMINARY RESULTS – DO NOT CITE

Regional Oil Extraction and Renewables: BAU (solid) vs. Reduced Oil Imports (dotted)

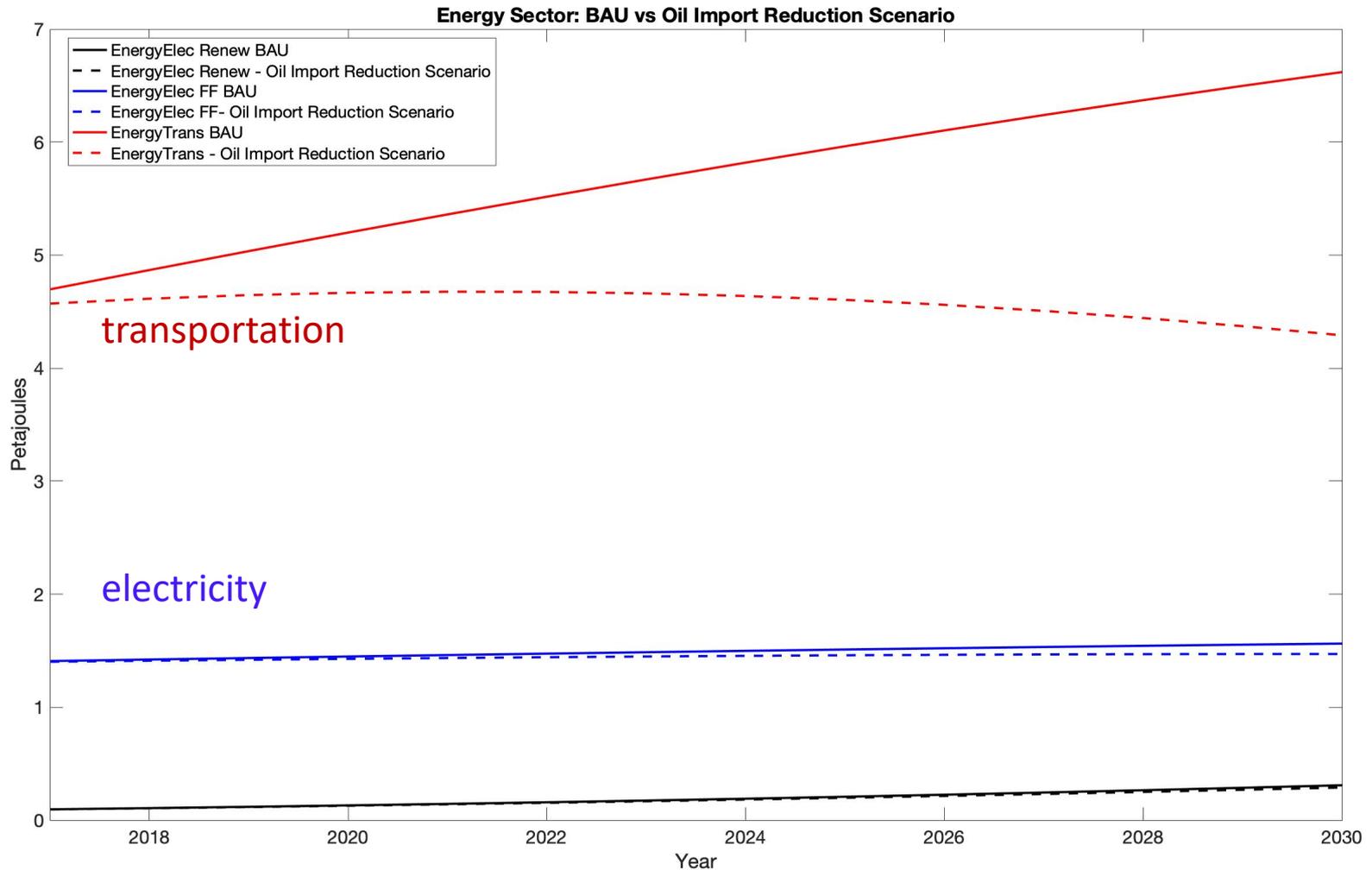


Energy Prices: BAU (solid) vs. Reduced Oil Imports (dotted)

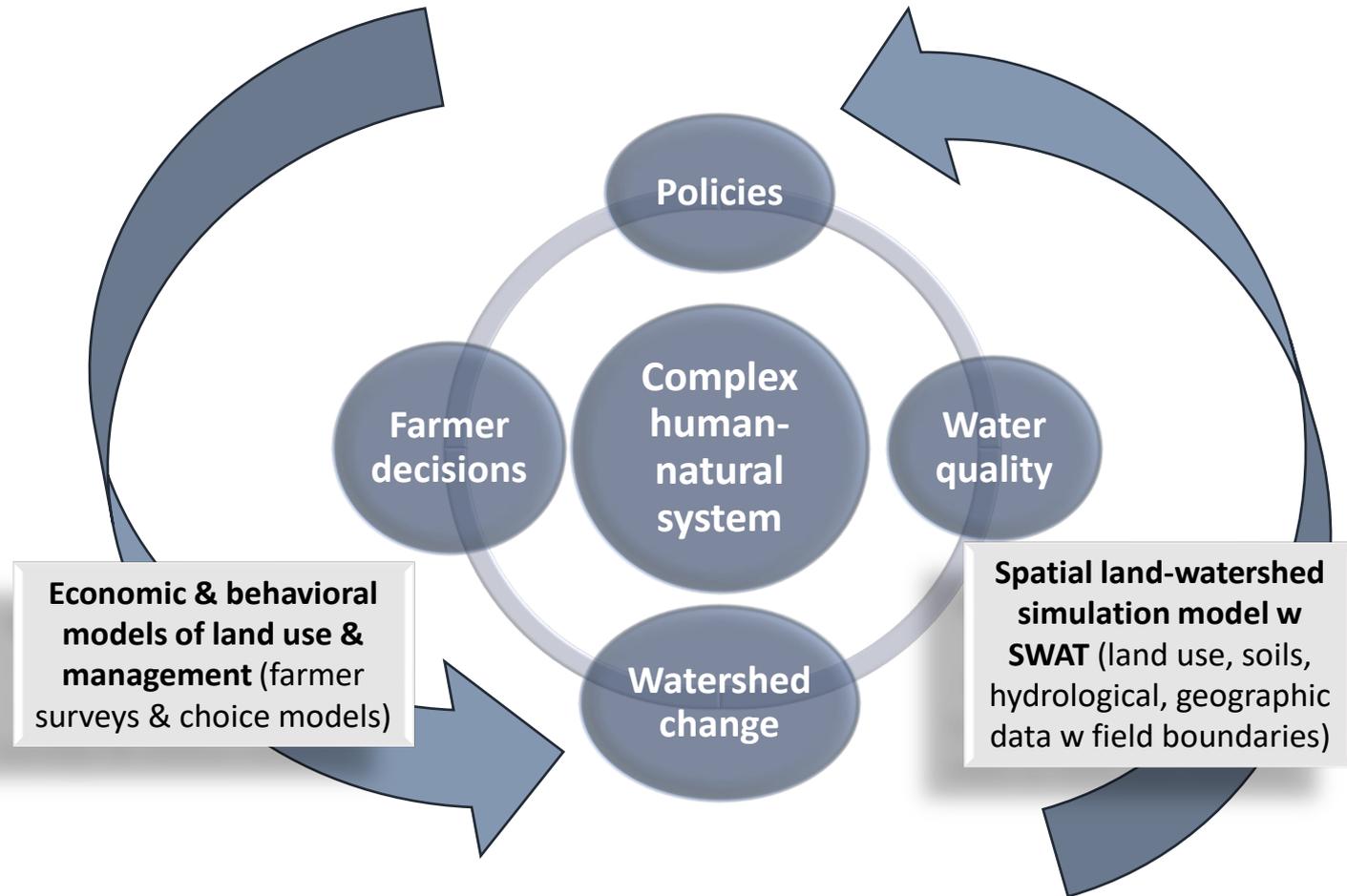


PRELIMINARY RESULTS – DO NOT CITE

Energy Sector: BAU (solid) vs. Reduced Oil Imports (dotted)



3. Land use-watershed modeling



Farmer survey

- Modified choice experiment to model farmers' crop, energy & conservation choices
- Survey launched earlier this year, stratified by farm size
- 4,605 surveys sent to farmers and non-operator landowners in Great Lakes study region
- 893 surveys completed to-date
 - Second mailing to farm operators this summer (still collecting data)
- Responses ~equal between operators and NOLOs
 - 482 operators, 411 non-operators

Respondent Characteristics

	All	Operator	NOLO
Age (years)**	62	60	63
Education***	Some college	Some college	Some college
Gender (% male)***	88%	96%	77%

*** p<0.01, ** p<0.05, * p<0.1

Farm Characteristics

	Mean	Median	Min	Max
Total acres	1,100	705	10	10,300
Years experience	38	40	5	80
Future farming years	13	10	0	55
Conservation acres (y/n)	32%			
Conservation acres	34	0	0	600

Non-operator landowners rented land characteristics

	Mean	Median	Min	Max
Total acres owned	487	337	38	3,500
Largest parcel rented (acres)	254	80	10	2,000
Ag experience	88%			
% income from land	0-25% (median)			
Production primary use	91%			



Variable changes

	Revenue	Rental rate	Conservation payments	Wind lease rate	Duration
baseline →	\$215	\$250	\$120	\$6,000	-
	\$0	\$125	\$60	\$3,000	5 years
	\$100	\$185	\$90	\$4,500	5 years
	\$325	\$315	\$180	\$7,500	10 years
	\$430	\$375	\$240	\$7,500	10 years



Increase in acres allocated to production

- No significant impact of age, education, duration of change, farmer identity, location (state)

	Operators	Landowners
Production revenue (\$100)	157.3 ^{***}	56.2 ^{***}
Conservation payments (\$100)		-90.1 ^{***}
Wind lease payments (\$100)		-2.4 ^{**}
Initial production choice (100 acres)	-19.0 ^{***}	-8.4 ^{***}

*** p<0.01, ** p<0.05, * p<0.1

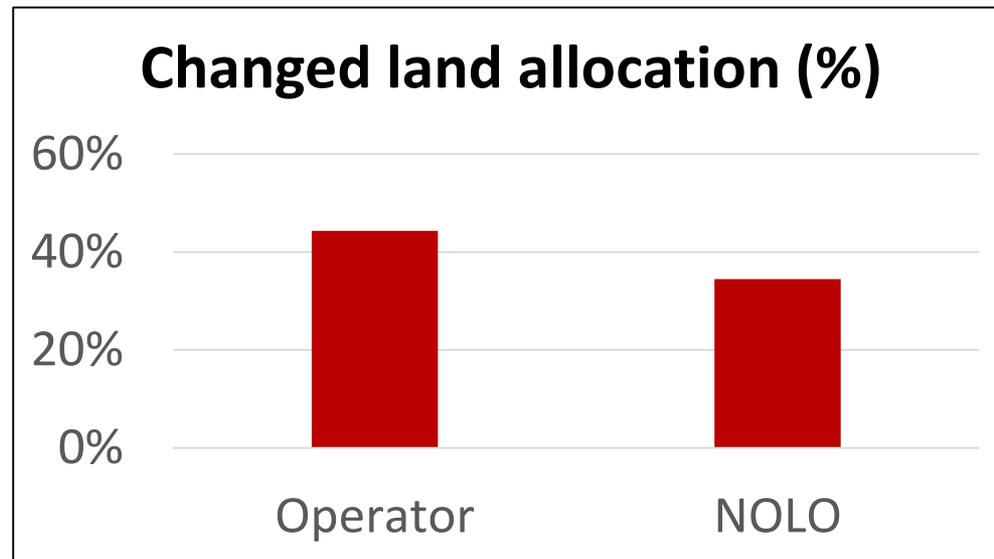
Increase in acres allocated to conservation

- No significant impact of age, education, farm size, location (state)

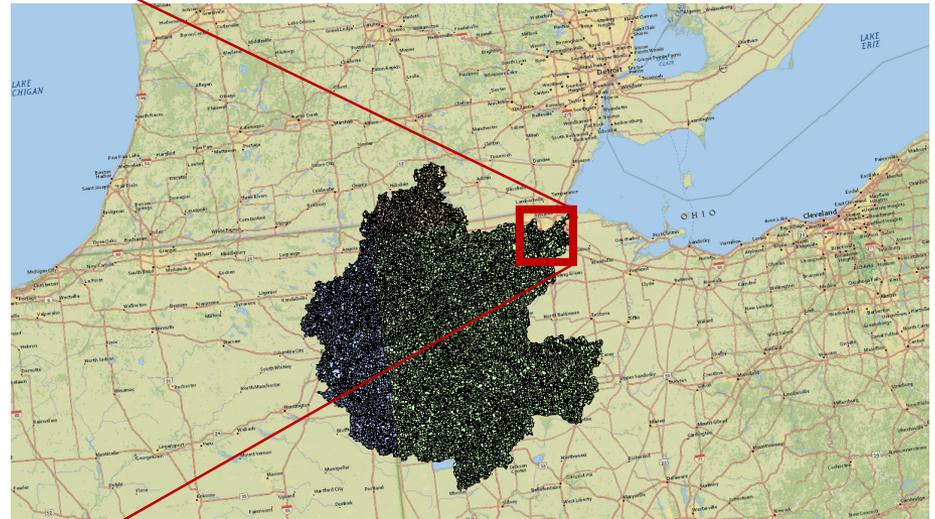
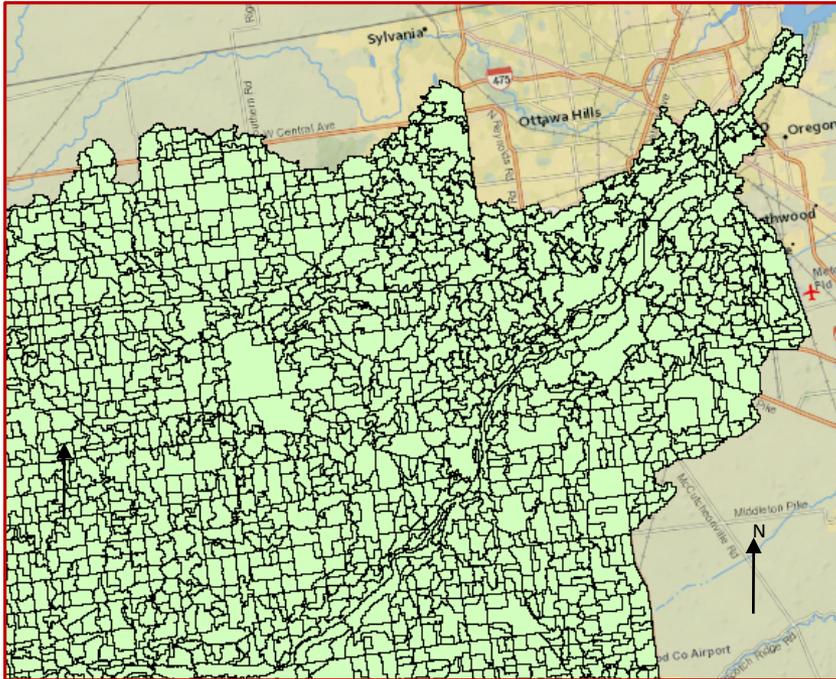
	Operators	Landowners
Production revenue (\$100)	-184.3 ^{***}	-82.3 ^{***}
Conservation payments (\$100)		113.6 ^{***}
Wind lease payments (\$100)	5.4 ^{***}	4.2
Duration of change	-29.4 ^{**}	
Conservationist identity	79.8 ^{**}	
Initial production choice (100 acres)		7.7 ^{**}

*** p<0.01, ** p<0.05, * p<0.1

Proportion of all participants who changed land allocation (meaning that more than half did not!)



Maumee Watershed Field-Scale Land Use-SWAT Model

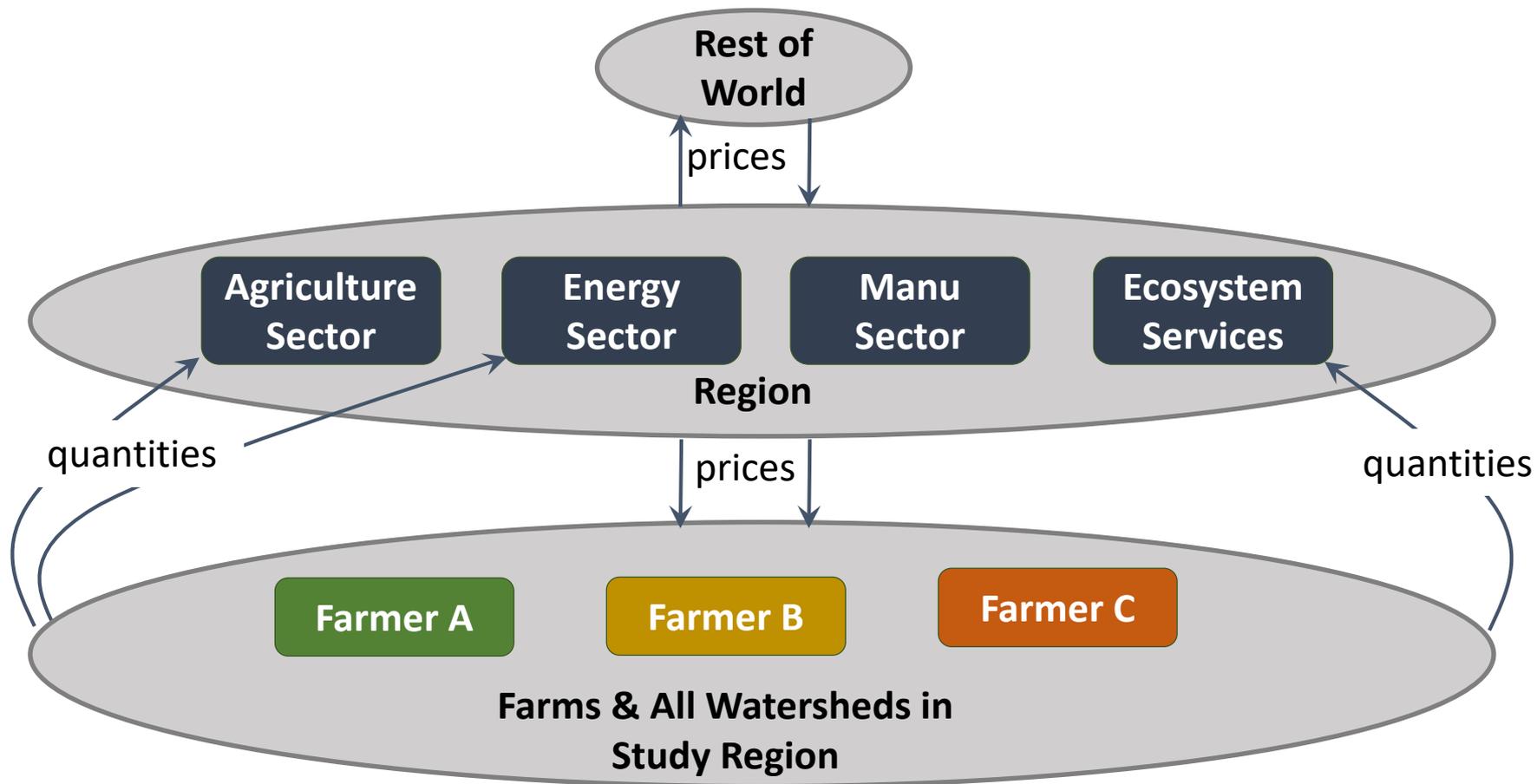


For current land uses: SWAT has been calibrated for Flow, Total Phosphorus, Mineral Phosphorus, etc. (Moriassi et al., 2007)

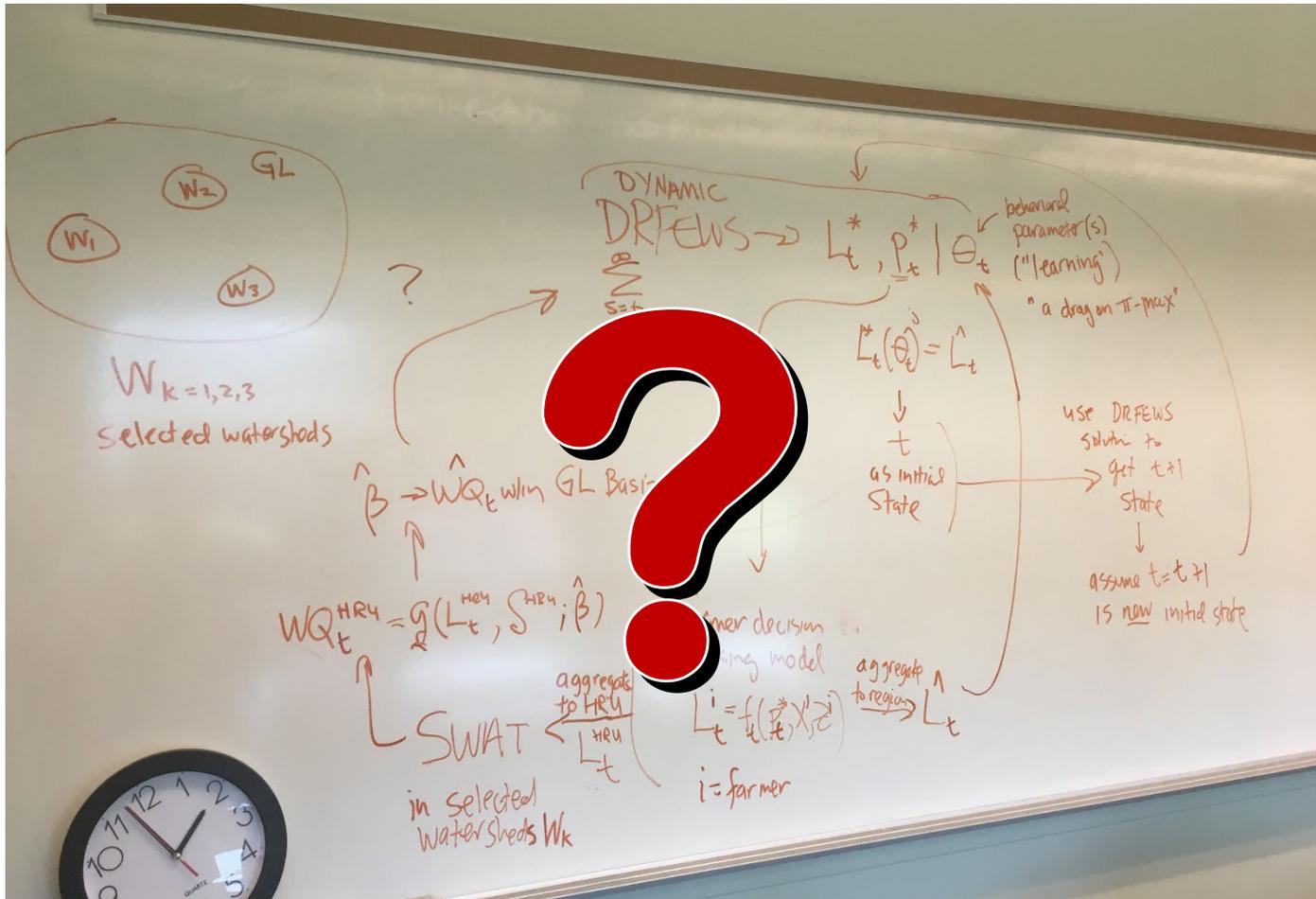
Use estimated parameters to project field-level crop and energy outcomes for Maumee watershed (*still to do*)

Over 18,000 Ag HRUs

4. Simulate FEW system responses using integrated regional economic-land use-watershed models



...still thinking about how to aggregate field-level outcomes to region & integrate with DRFEWS model



5. Regional sustainability assessment

- **Supply chain modeling**

- Develop region-specific value chain model with inter-regional export/import flows

- Evaluate multiple sustainability criteria

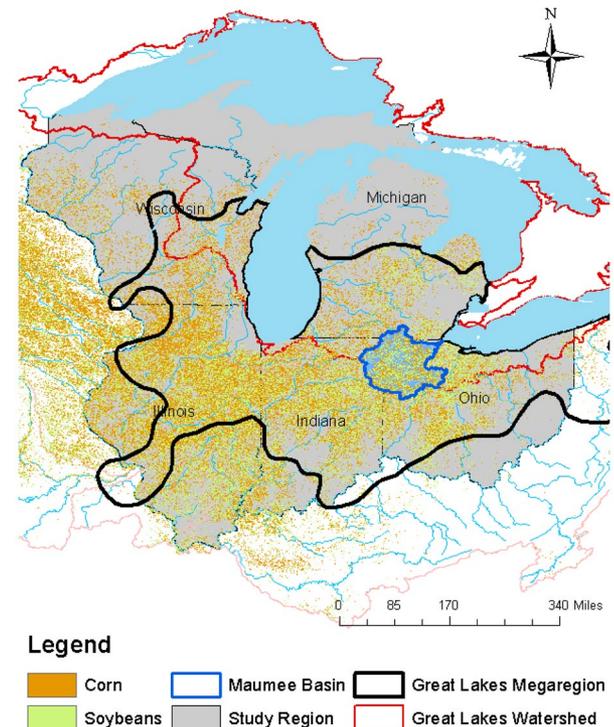
- **Strong sustainability**

- Regional limits on physically quantified ecosystem services

- **Weak sustainability**

- Accounting prices for ecosystem services and pollution to construct IW measures

- **BUT:** How does one account for openness of regional economy in assessing sustainability?



What does sustainability mean for a region?

- **Scale matters:** Size (e.g. geographic area), diversity of natural, built, and human capital, complexity of organization, openness to trade, finance, migration
- At smaller scales, regions will experience scarcity of natural resources that are plentiful at the global level
 - underscores the **critical role of trade** for regions to be sustainable
 - also underscores the need for a region to retain sources of wealth so that it can **fund imports to meet WS**
- **Regions contribute to sustainability at national and global scales** – e.g., even less competitive regions may contribute to a nation's sustainability (e.g., regions with globally scarce resources)
 - there may be a role for **SS constraints at a regional scale** if they contain natural stocks that are critical at global scale



A theory of regional sustainability?

- A loose theorem of regional sustainability:
 - A valid **WS criterion** for a sub-national region is that (i) expected welfare/wealth in the nation is non-decreasing and (ii) expected regional welfare/capita and planned natural plus built and human capital are non-decreasing.
 - A valid **WS-plus criterion** would incorporate the WS criterion as above and impose SS restrictions on any natural resources that are critical at the global level.



And what about the first law of thermodynamics...?!

- Energy cannot be created or destroyed it can only change forms... which implies that mass cannot be created or destroyed... which somehow implies something about production functions...?

First Law of Thermodynamics:

$$\Delta E_{\text{universe}} = \Delta E_{\text{system}} + \Delta E_{\text{surrounding}} = 0$$



$$\frac{Q_t^{\text{corn}}}{Q_0^{\text{corn}}} = A_t^{\text{corn}} \cdot \left(\omega^c + (1 - \omega^c) \frac{F_t^{\text{corn}}}{F_0^{\text{corn}}} \right)^{\alpha_c} \left(\frac{L_t^{\text{corn}}}{L_0^{\text{corn}}} \right)^{\beta_c} \left(\frac{\ell_t^{\text{corn}}}{\ell_0^{\text{corn}}} \right)^{1 - \alpha_c - \beta_c}$$

$$\frac{Q_t^{\text{soy}}}{Q_0^{\text{soy}}} = A_t^{\text{soy}} \cdot \left(\omega^s + (1 - \omega^s) \frac{F_t^{\text{soy}}}{F_0^{\text{soy}}} \right)^{\alpha_s} \left(\frac{L_t^{\text{soy}}}{L_0^{\text{soy}}} \right)^{\beta_s} \left(\frac{\ell_t^{\text{soy}}}{\ell_0^{\text{soy}}} \right)^{1 - \alpha_s - \beta_s}$$



Fenichel et al. survey: How do we (and others) view interdisciplinary research?

- Researchers: Eli Fenichel (Yale University), Elena Irwin (Ohio State University), Bill Jaeger (Oregon State University), Simon Levin (Princeton University)
- Purpose: Better understand collaboration between economists and researchers from the natural sciences and engineering who study bio-physical systems
- Online survey:
 - Distributed over Summer 2019
 - Sample: Authors in environmental & ecological journals over last five years (natural & social sciences)
 - Email sent: 19,813, Good email: 17,479
 - Completed (as of this week): 1,572 (9%)
 - Results are forthcoming

Choice Experiment: Trade-Offs Across Different Journal Types

On each of the following pages, we will present two multi-year projects: **Project A** and **Project B**. For each project, we will present the **number of manuscripts published** and **where these manuscripts have been published**. Imagine that you were a co-author on both of these projects: both projects took an equal amount of time to complete, and you contributed equally to both. Imagine looking back on the publication records from both projects, and indicate **which of the two projects you would be most happy with**.

EXAMPLE

Type of Journal	Project A	Project B
General Interest		
Multidisciplinary Science	0	3
General Interest Economics	0	2
Top Disciplinary Natural Science	2	2
Top Environmental Economics	6	4
Specialized (but not top) journals in your field	4	4

Choices: Prefer Project A , Prefer Project B, Equally happy, Don't know