Economic Modeling of Phosphorus Management from Local to Global Scales

Justin S. Baker, PhD*

Ziqian Gong*, Chanheung Cho*, Zachary Brown*, Chris Wade', Petr Havlik^

*NC State University
'RTI International
^International Institute for Applied Systems Analysis

Science and Technologies for Phosphorus Sustainability

The STEPS 25-IN-25 Vision

Facilitate a **25% reduction** in human dependence on mined phosphates and a **25% reduction** in losses of point and non-point sources of phosphorus to soils and water resources within **25 years**, leading to enhanced resilience of food systems and reduced environmental damage.

The STEPS Mission Statement

Develop and implement convergence research on phosphorus sustainability across disciplines, scales, sectors, and communities that:
generates new knowledge across the natural, engineered, and social systems that impact the phosphorus cycle;
innovates new phosphorus sustainability solutions; and
trains a diverse group of scholars who are equipped to address complex societal challenges.

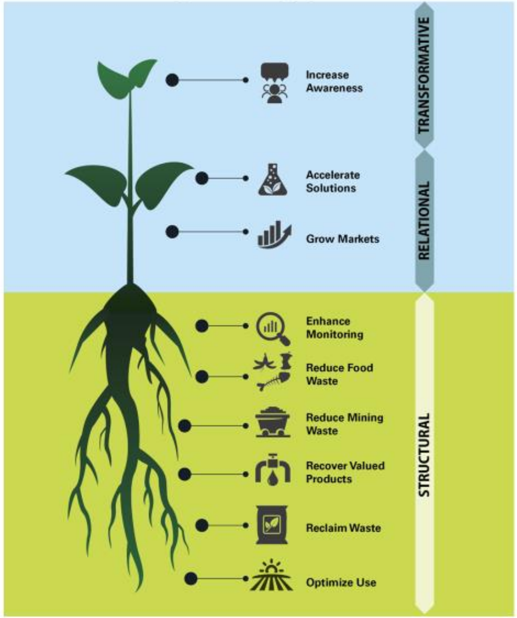
STEPS
Science and Technologies for Phosphorus Sustainability

Roadmapping Engages Stakeholders

Kicked off in-person collaboration on roadmap at P Week

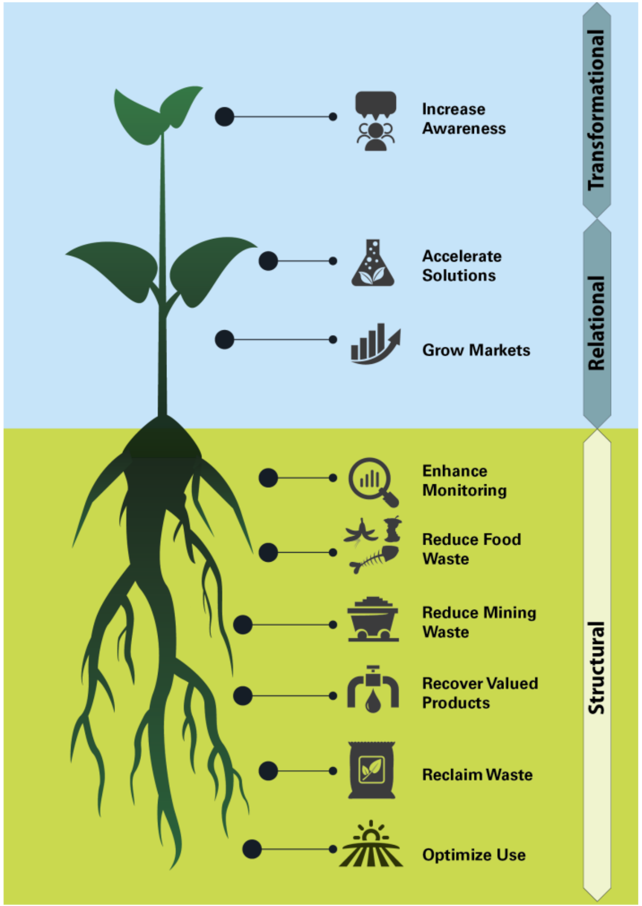
- A process led by RTI International by Cary Strickland, Jessie Man, and Taylor Moot within a research project led by Justin Baker and contributed from dozens of individuals in Working Groups
- This roadmap will serve as a guide for the activities required to improve sustainable management of phosphorus in the United States

Nine Impact Opportunities



Objectives

- Improved modeling of **P consumption** in US agricultural system
- Improving regional P boundaries for **enhanced food security**
- Analysis of P interventions and STEPS ***Impact Opportunities***
- Capturing **Global-to-Local** scale dependencies
- Analyzing tradeoffs across **P, N, and C** policy objectives

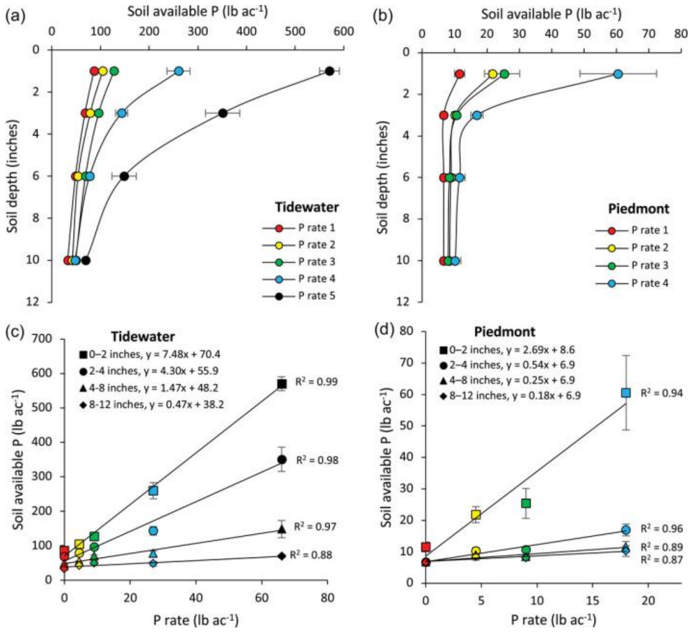


Economic modeling of P management interventions

- Advancing economic modeling of P management options at local, regional, and global scales
- Economic models help us quantify tradeoffs of different P interventions and policy strategies
- Economic models offer insight on how market drivers, policy incentives, and behavioral factors influence land management choices
    - Site- or farm-scale models to analyze specific interventions
        - capture dependencies between physical P flows and farm management
    - Global-scale models to evaluate the influence of broad market drivers on land and P management at regional/global scales

Optimal legacy P management at farm scale

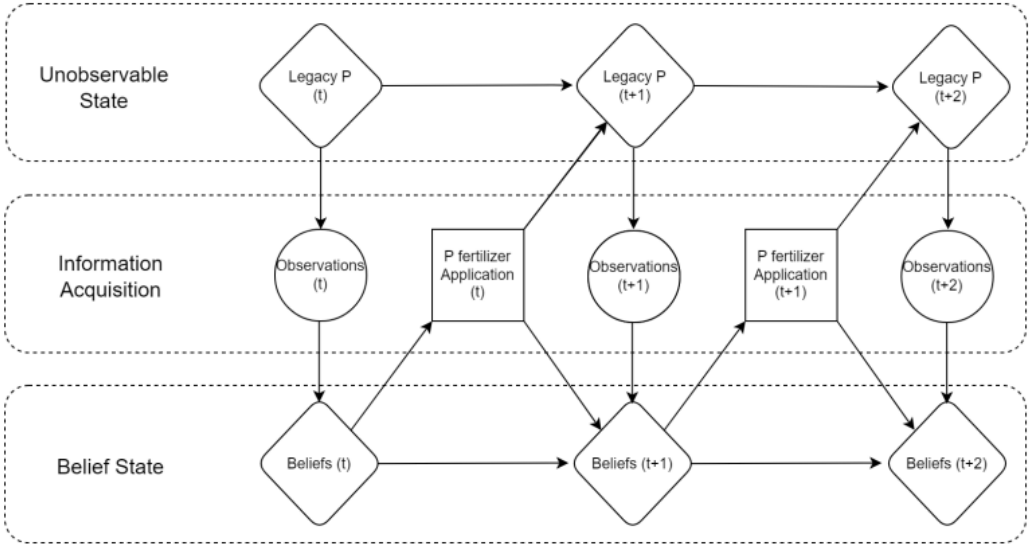
- Farm-scale economic model calibrated to Tidewater (NC) field data
- Model accounts for uncertainty in legacy P stocks, input and output prices
- Incorporates behavioral components (e.g., risk aversion)
- Captures legacy P dynamics
- Highlights how new information can affect management decisions



Tiecher, Gatiboni, et al. (2023)

Optimal legacy P management at farm scale

- We model farm management of legacy P as a ***Partially Observable Markov Decision*** process
- Farmers learn about their systems, update beliefs and (maybe) change practices
- Farmers can invest in soil sampling

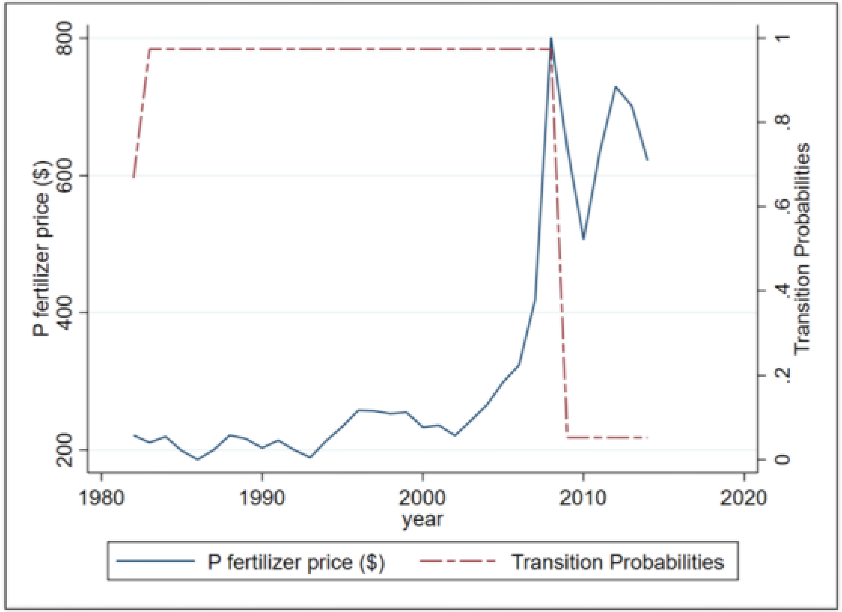


Optimal legacy P management at farm scale

- Uncertainty in input and output prices
  - We introduce a “regime switching” model to reflect moderate and high price states.

P fertilizer Price and State Transition Probability (1960-2014)

(Super-phosphate 44-46% Phosphate, $ per material short ton)

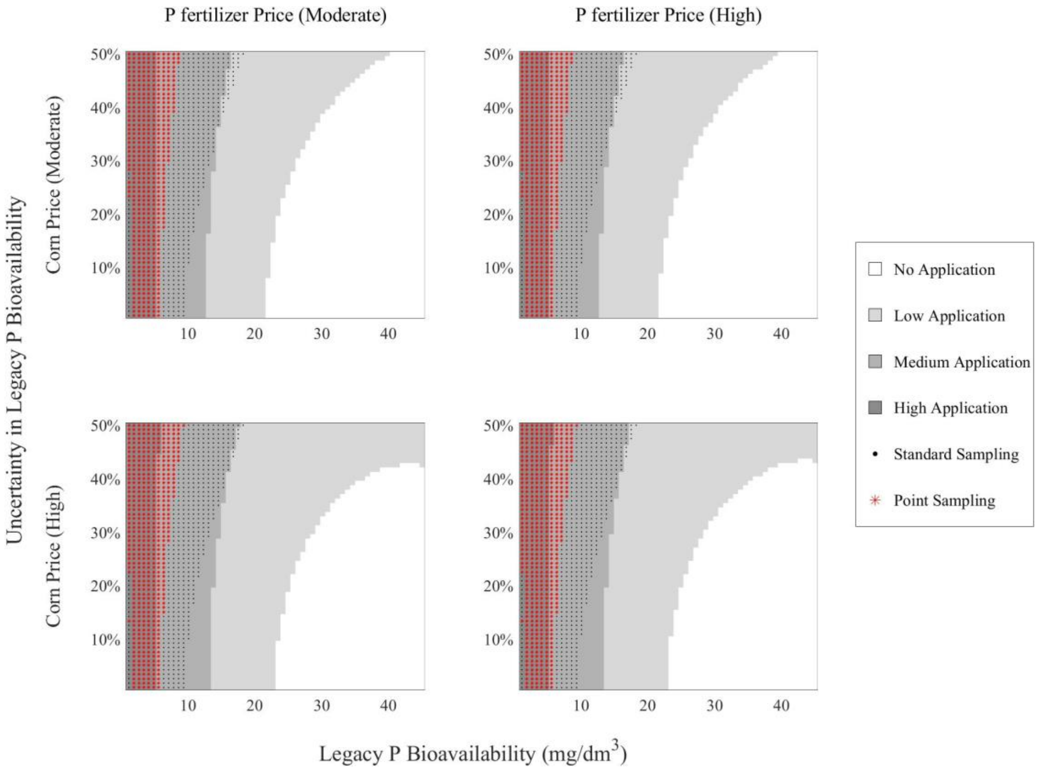


Optimal legacy P management under limited information

How should farmers use info on bioavailable soil P?

Consider two soil sampling techniques:

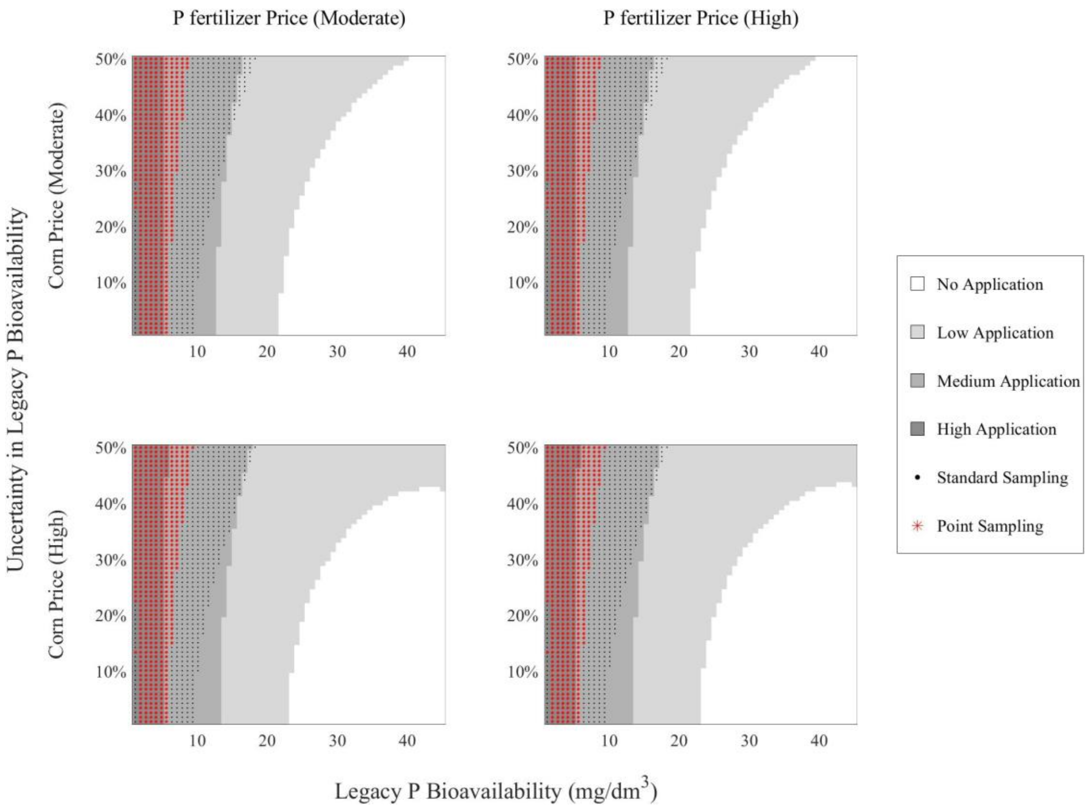
- **Standard sampling:**
  - Samples are collected per acre.
- **Point sampling** (low observation error, High Sampling Cost):
  - 4 samples per acre, collected at a specific grid point.



Optimal legacy P management under limited information

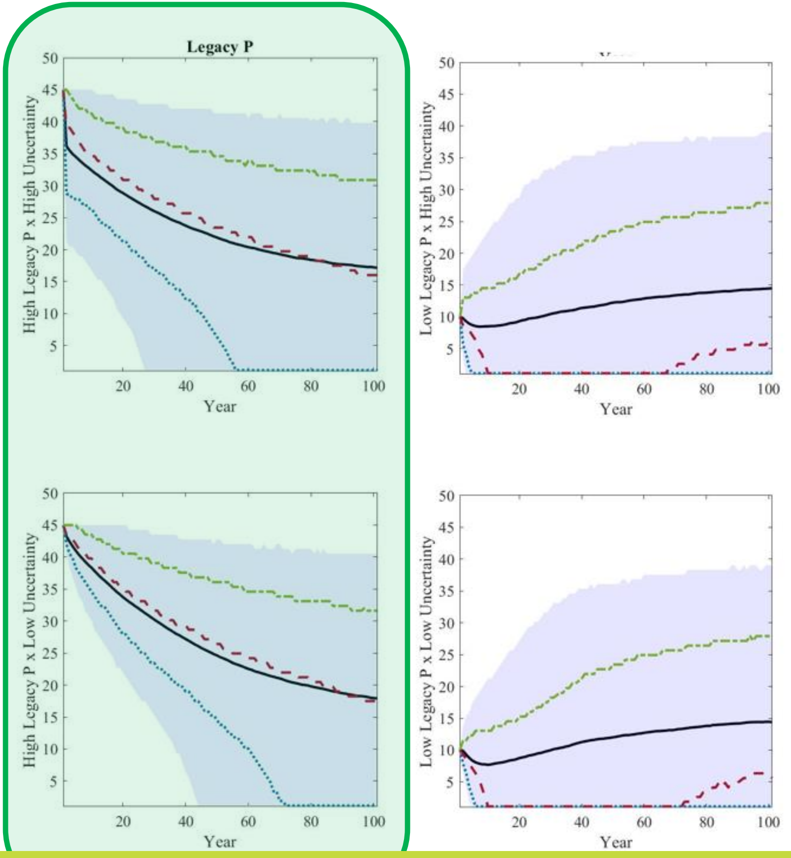
How should farmers use info on bioavailable soil P?

- Higher soil P stocks, lower uncertainty ➔ more soil P mining
- Higher output prices ➔ more synthetic P
  - Interactions between input/output prices



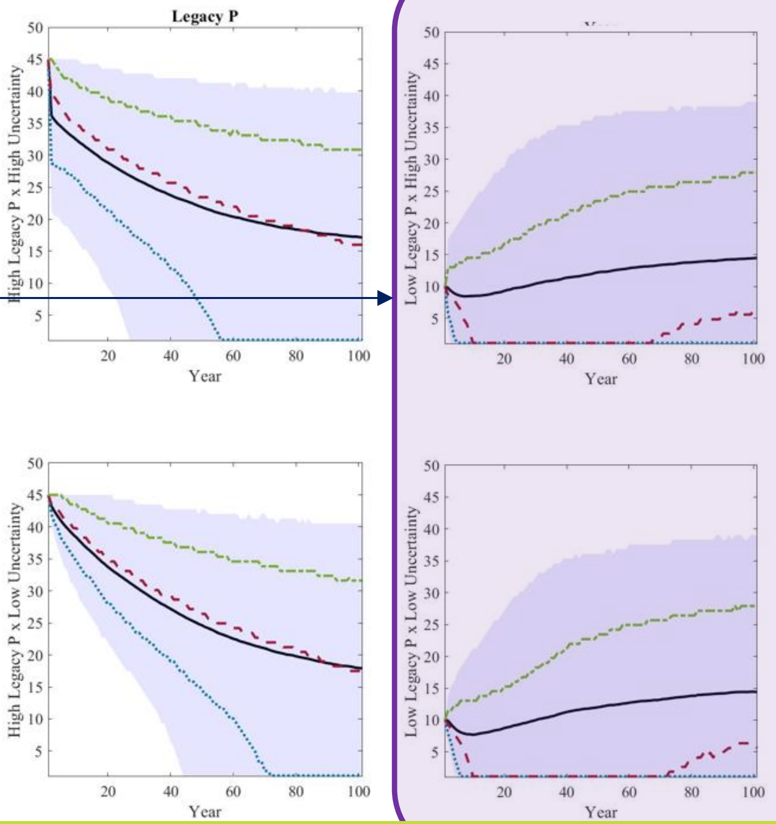
Optimal management of legacy P over time

Higher stocks, higher uncertainty ➔ depletion of legacy P stocks



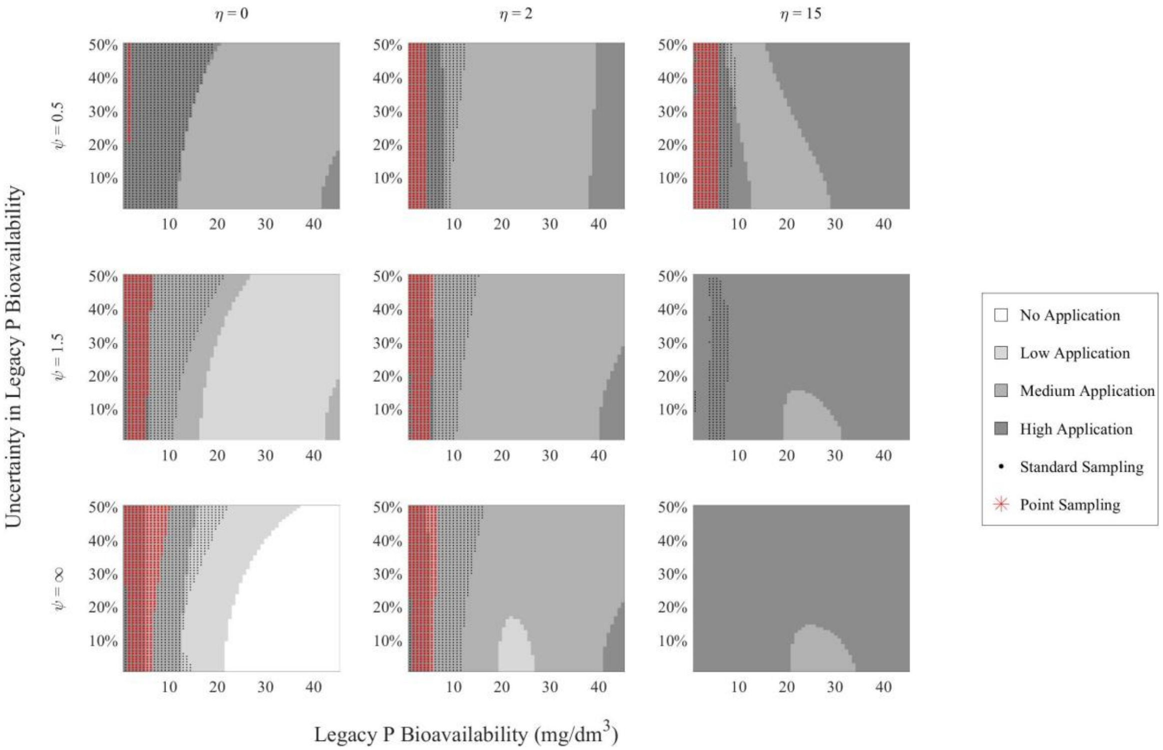
Optimal management of legacy P over time

Lower initial stocks ➔ accumulation of legacy P stocks



What about behavior?

Higher risk aversion ➔ more sampling, but also more P application



- Incorporating **risk aversion** and **time preferences**

Greater elasticity of intertemporal substitution ➔ more sampling, less application

Modeling legacy P management at farm scale

- What have we learned from this exercise:
  - Legacy P stock dynamics are affected by crop management choices
  - Investments in information can affect management decisions, increase legacy P mining
  - Behavioral factors such as risk aversion and intertemporal consumption preferences have a large impact on P management decisions
- Next steps:
  - Expanding the model to include an Ohio case study
  - Adding environmental damages of P runoff
  - Assessing policy options to improve outcomes
- BUT…
  - This is only one intervention at a farm scale

Sectoral Economic Modeling

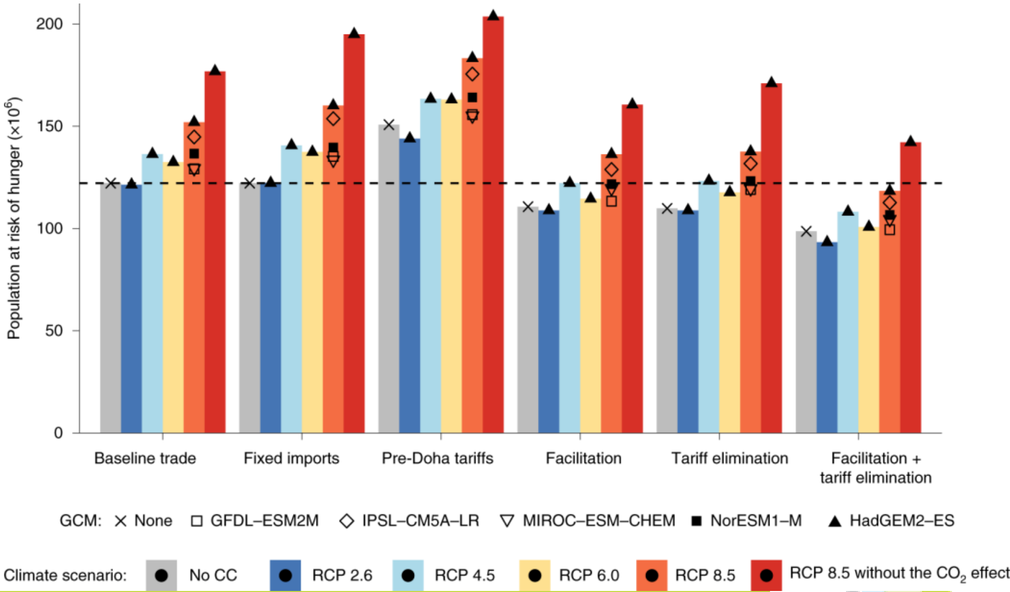
Article | Published: 20 July 2020

Global hunger and climate change adaptation through international trade

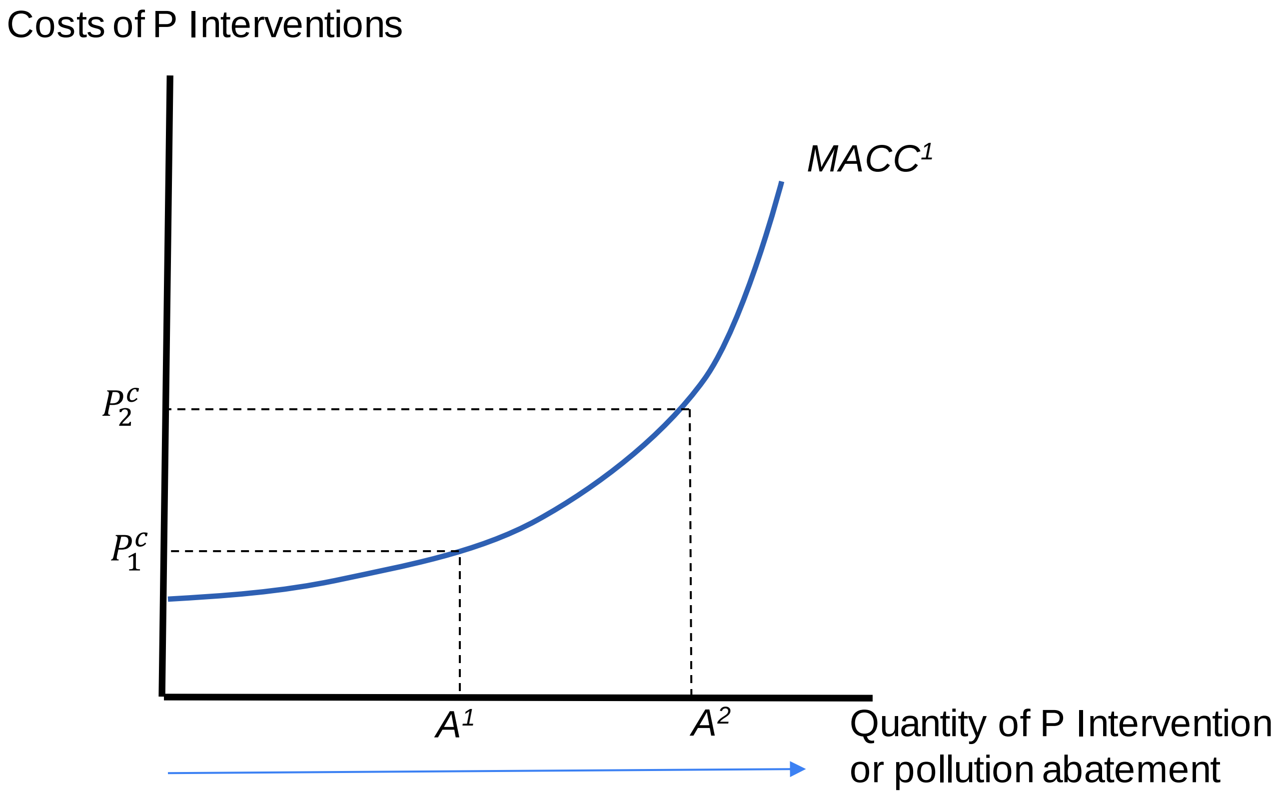
Charlotte Janssens, Petr Havlík, Tamás Krisztin, Justin Baker, Stefan Frank, Tomoko Hasegawa, David Leclère, Sara Ohrel, Shaun Ragnauth, Erwin Schmid, Hugo Valin, Nicole Van Lipzig & Miet Maertens

Nature Climate Change **10**, 829–835 (2020) | Cite this article

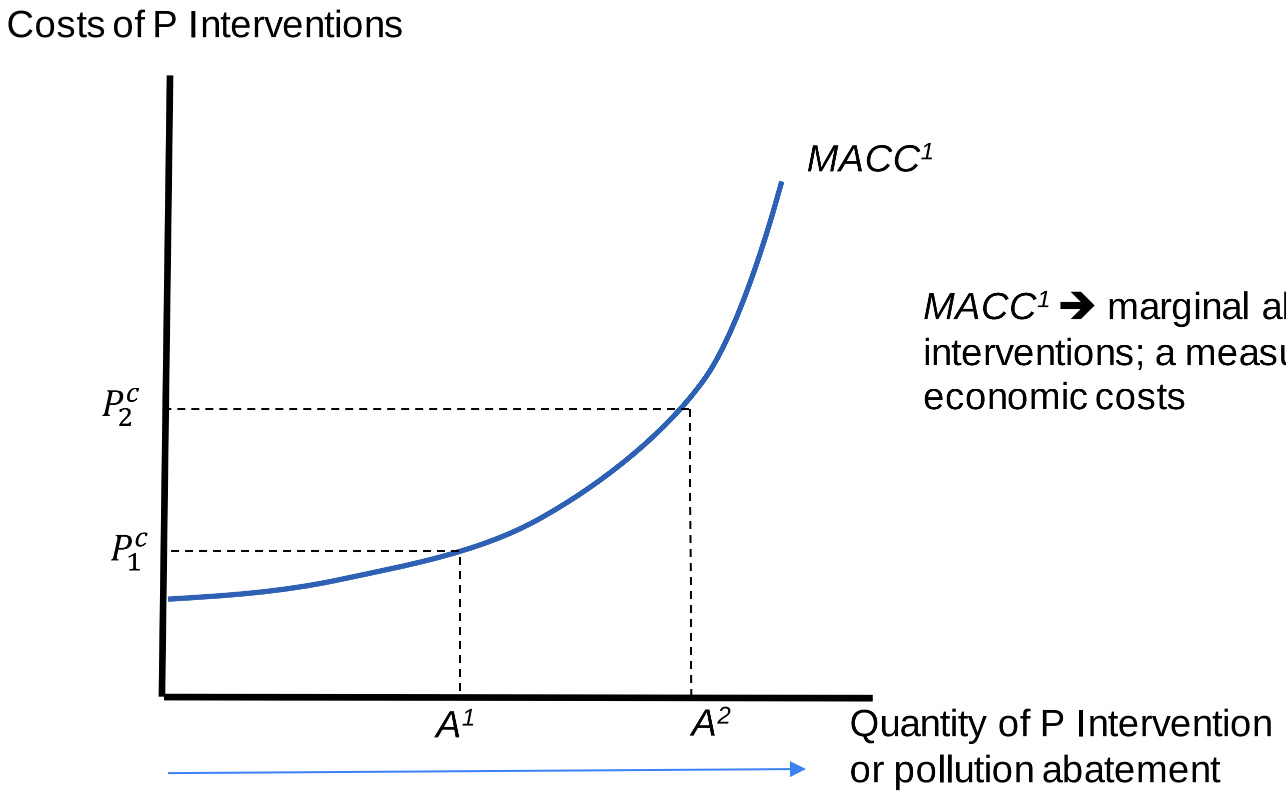
- Capturing ***market dynamics across regions***
  - E.g., trade flows
- Incorporates ***spatial heterogeneity*** in crop production practices
- Accounts for ***market opportunity costs*** of P interventions
- Supply and market outcomes tied to environmental and development factors
  - E.g., ***food security***



The role of economic modeling – a quick primer

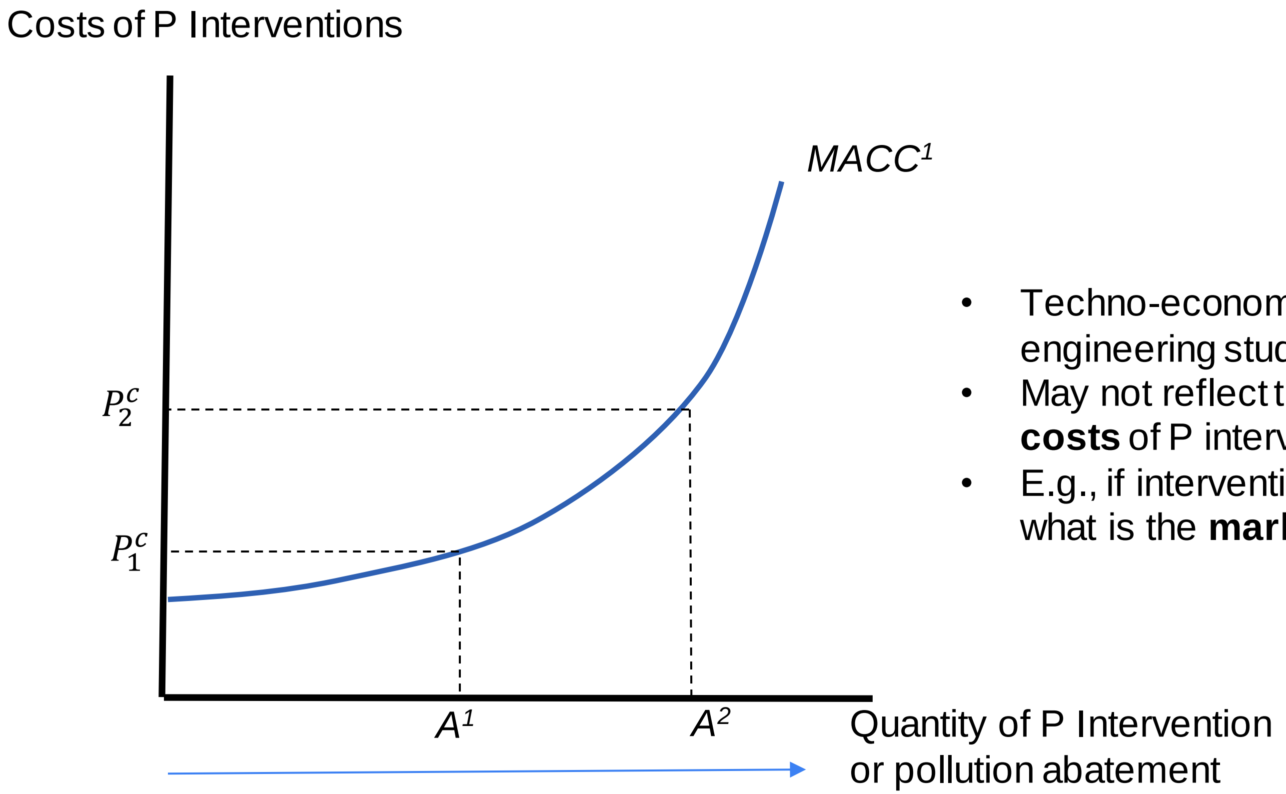


The role of economic modeling – a quick primer



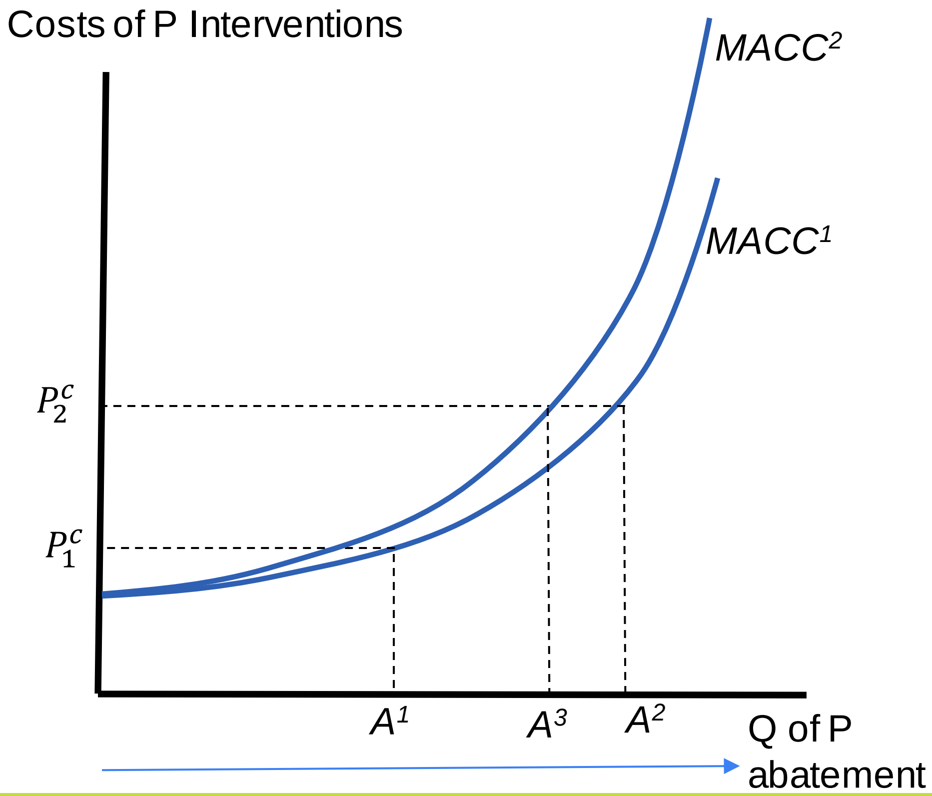
MACC[1] ➔ marginal abatement costs of P interventions; a measure of techno-economic costs

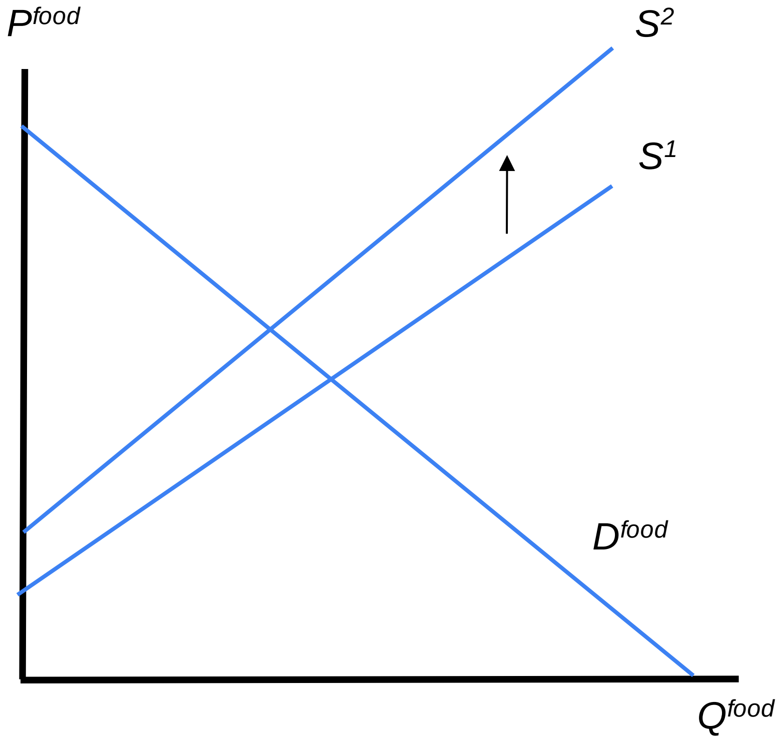
The role of economic modeling – a quick primer



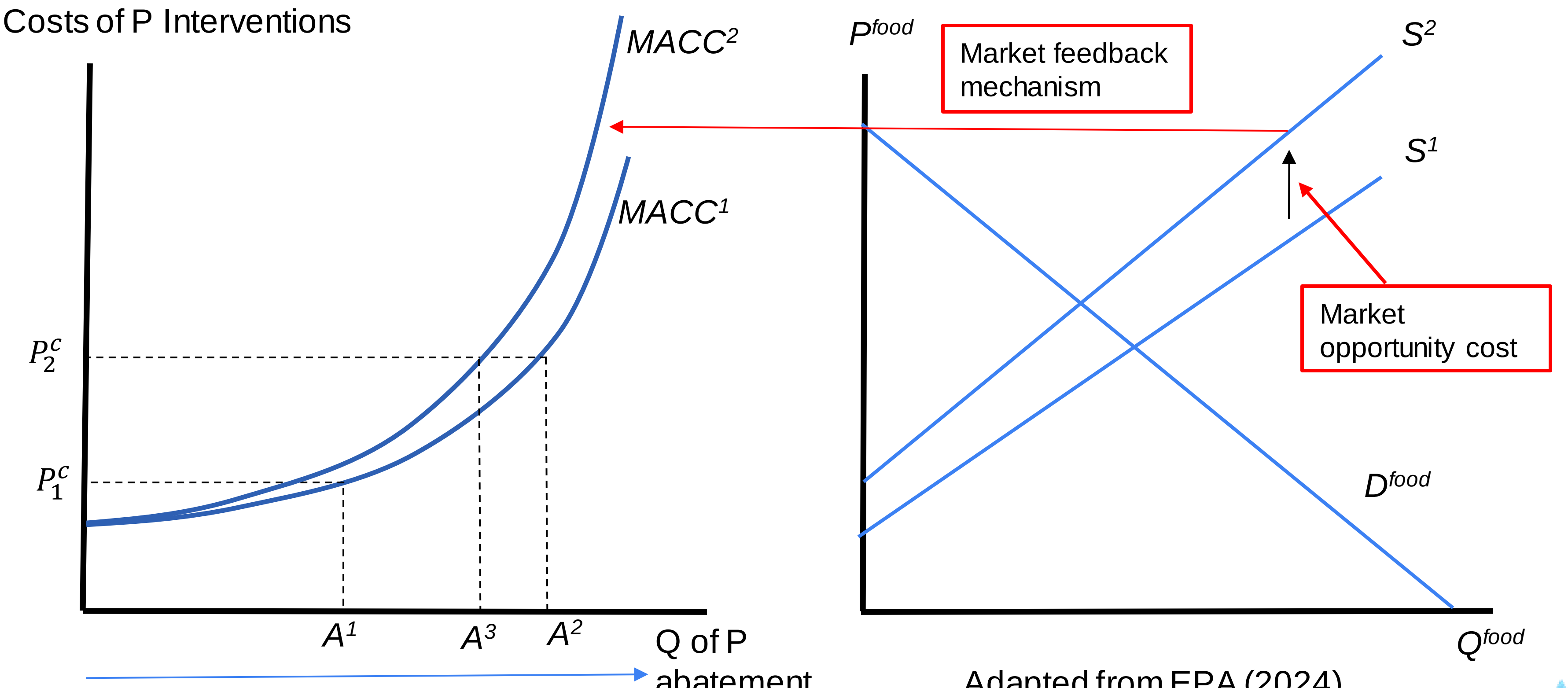
- Techno-economic costs are derived from engineering studies
- May not reflect the **economic opportunity costs** of P interventions
- E.g., if interventions reduce total productivity, what is the **market tradeoff**?

The role of economic modeling – a quick primer





The role of economic modeling – a quick primer



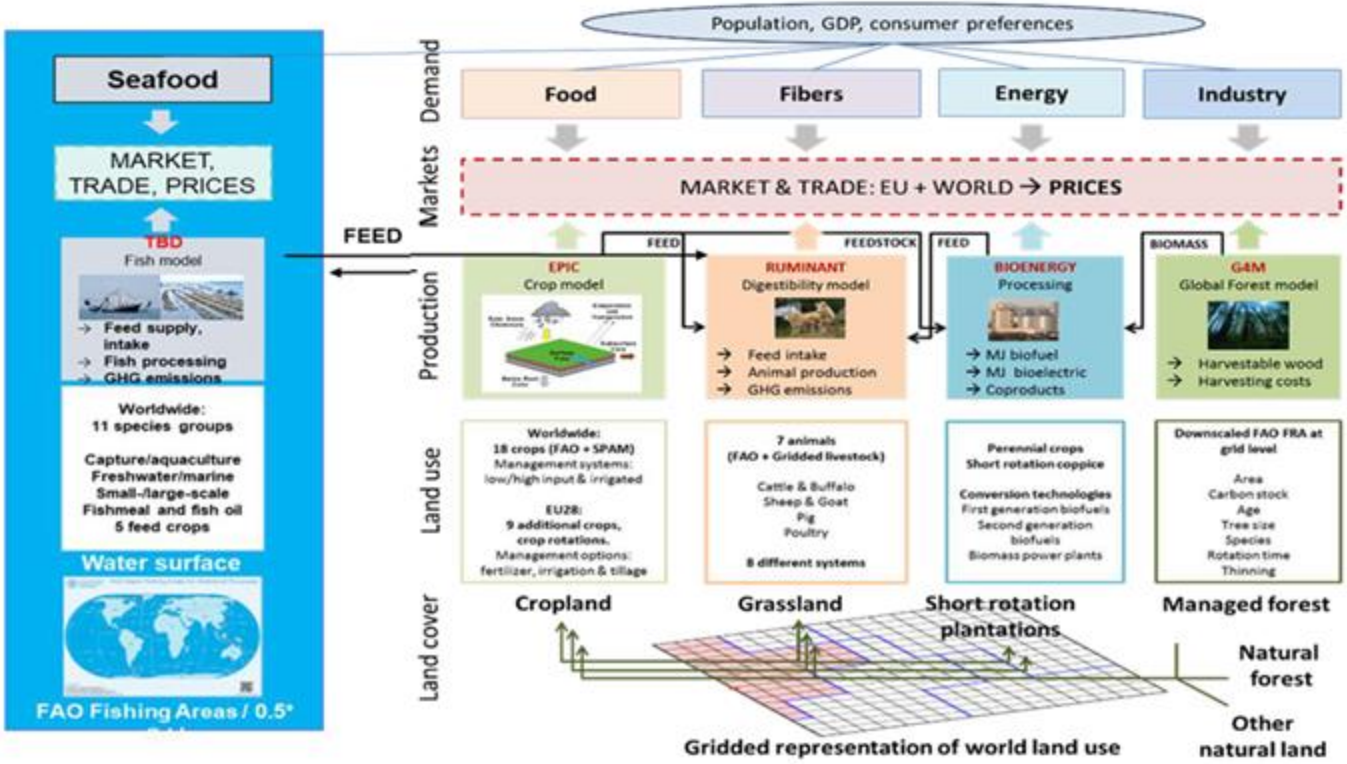
Adapted from EPA (2024)

Economic Modeling to Evaluate **STEPS** to P Sustainability

- How do global change forces affect US P consumption and the opportunity costs of interventions?
- How can we better account for “scale dependencies” when modeling P intervention scenarios?
- What are important tradeoffs of P interventions in the U.S. given its importance to global agricultural markets

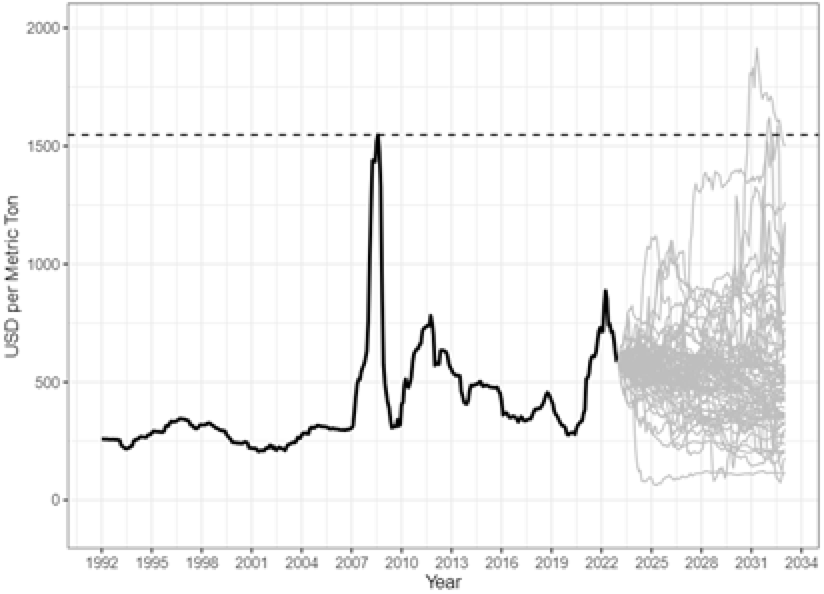
Modeling Approach

Global-Local-Global Scale Modeling of P Intervention Scenarios using a detailed global model of the land use and food systems (GLOBIOM)



Fertilizer Prices, Agricultural Production, and Food Security

Importance of P affordability to the global food supply

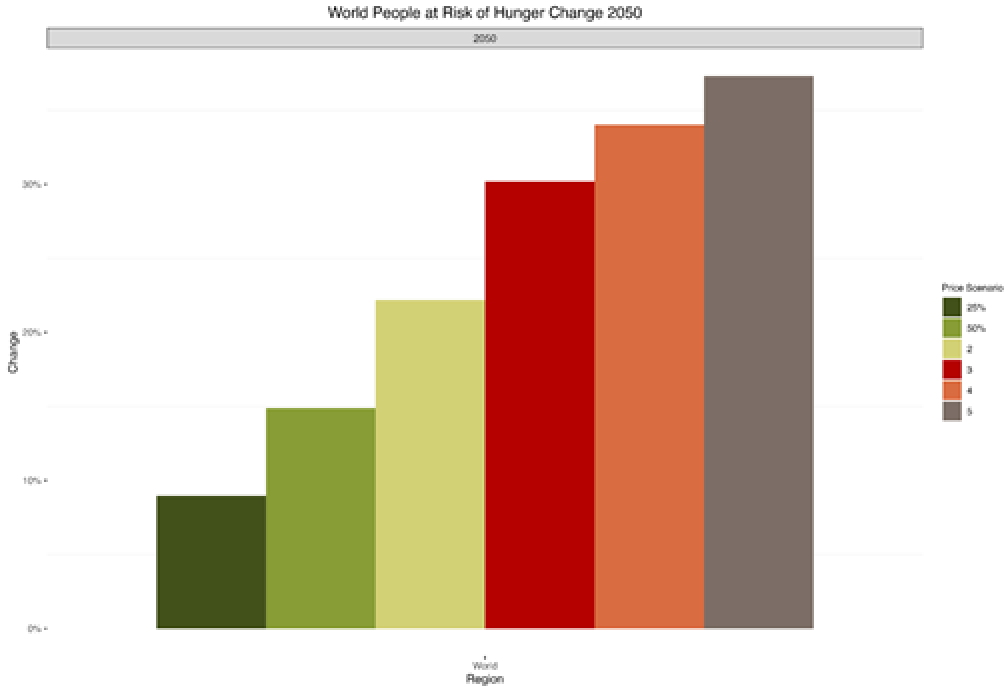


Ho and Baker, 2024.

- P rock and fertilizer prices have been high and volatile since 2020
  - Where are prices headed in the future?
  - What will this mean for global food production and the distribution of fertilizer use?
- Price scenarios: 25%, 50%, 100%, 200%, 300% and 400% increase in **P** and **N** fertilizers in GLOBIOM

Importance of P affordability to the global food supply

- Fertilizer price impacts on food security at regional and global scales
- Population at risk of hunger grows with sustained higher fertilizer prices



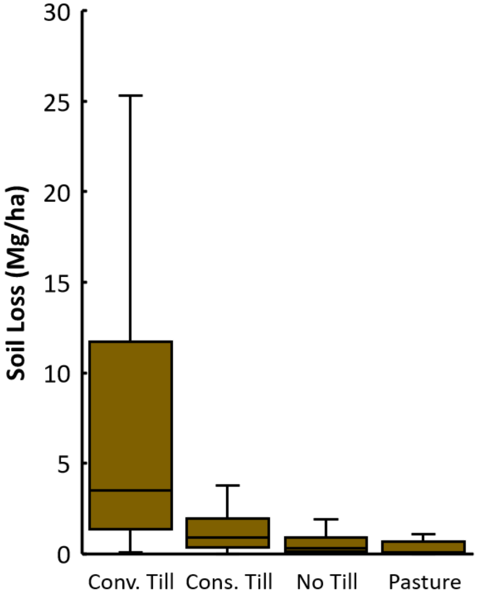
Gong et al., 2024.

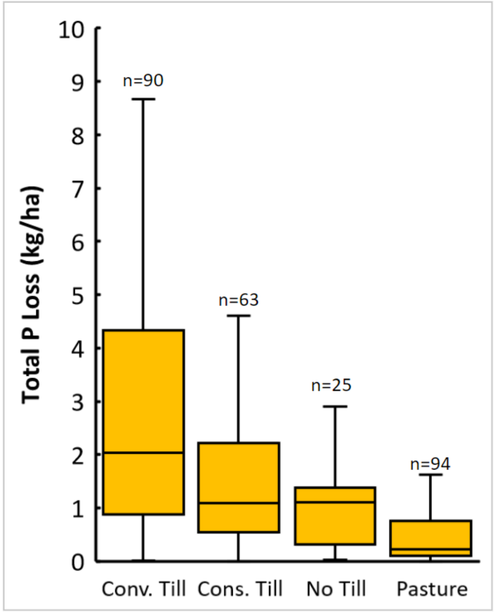
Analyzing tradeoffs across **P, N, and C** policy objectives

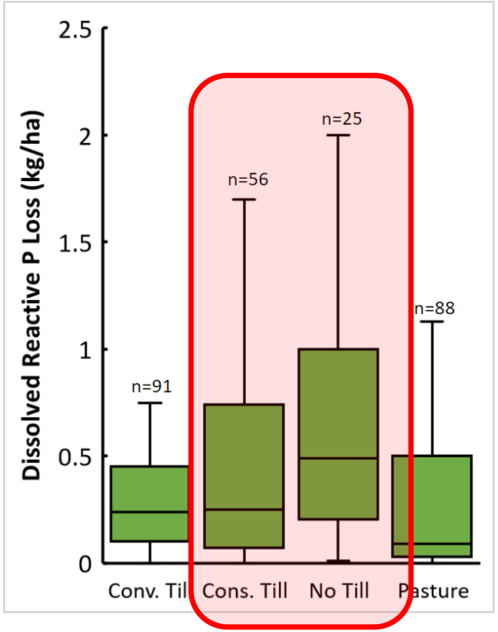
Analyzing tradeoffs across **P, N, and C** policy objectives

- Climate and energy policies drive changes in land use / production strategies
- Productions shifts ➔ intensive and extensive margin adjustments in fertilizer use
- Potential synergies (and tradeoffs) between climate mitigation in agriculture/forestry and P management
  - Reduced fertilizes ➔ improved water quality?
  - Reduced runoff ➔ lower indirect CH_4 emissions from eutrophication?
  - Will climate policy induce regional water quality leakage in regions with limited C sequestration capacity?
- Other considerations;
  - What is optimal from a C perspective might be suboptimal from a P or N perspective…

Carbon-Water Tradeoffs of Climate-smart Practices?



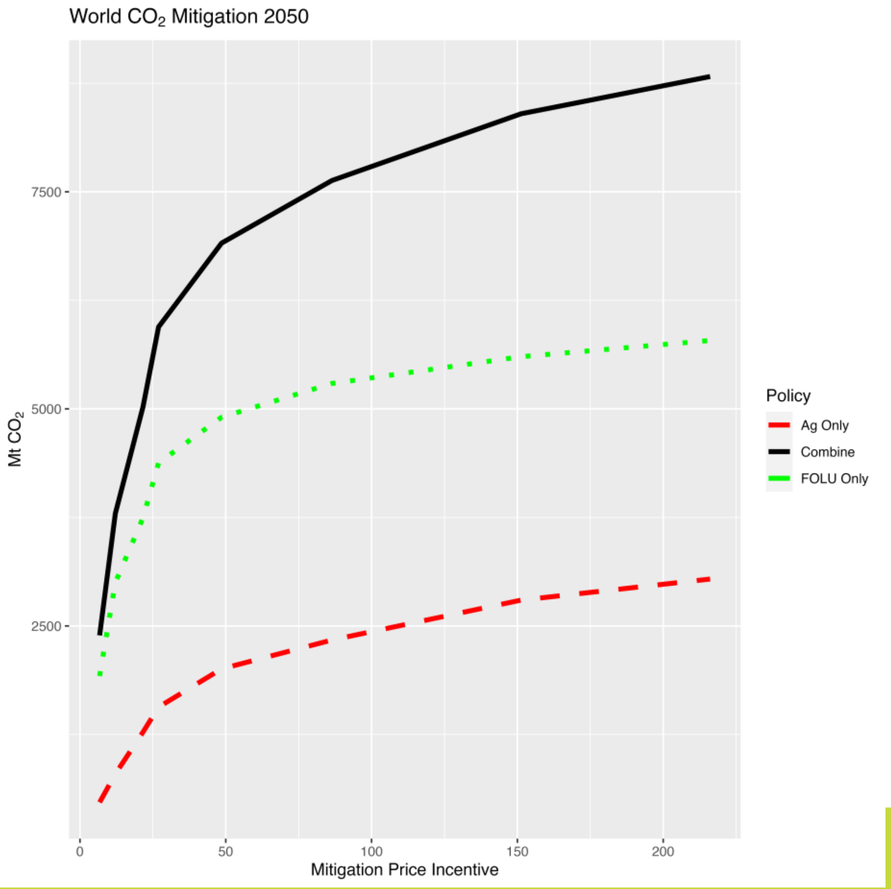




MANAGE Database v.5 (Harmel et al., 2016, https://doi.org/10.1111/1752-1688.12438)

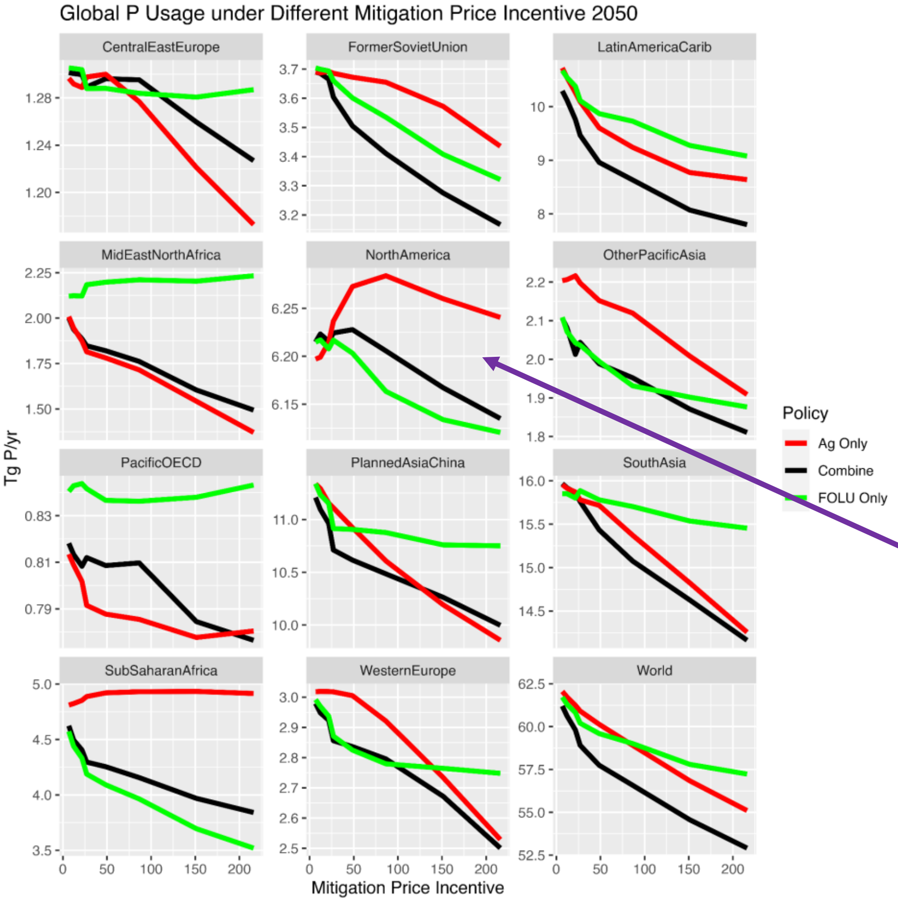
n=number of watersheds (sites) included in the dataset, adapted from Nelson (2024)

Tradeoffs across P, N, and C Policies



- Modeled MACC Curves using the GLOBIOM model and many different combinations of price incentives
  - Ag sector only
  - Forestry / land use only
  - Combined

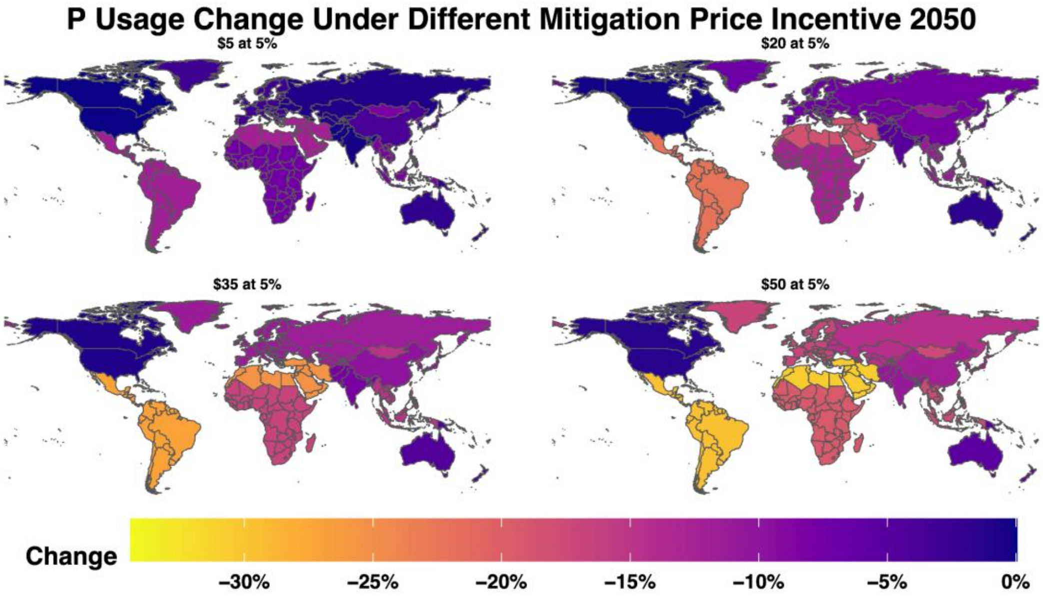
Tradeoffs across P, N, and C Policies



- How do global climate policy incentives affect the distribution of P consumption?
    - Depends on intensive and extensive margin adjustments in land use

Intensification in the U.S.

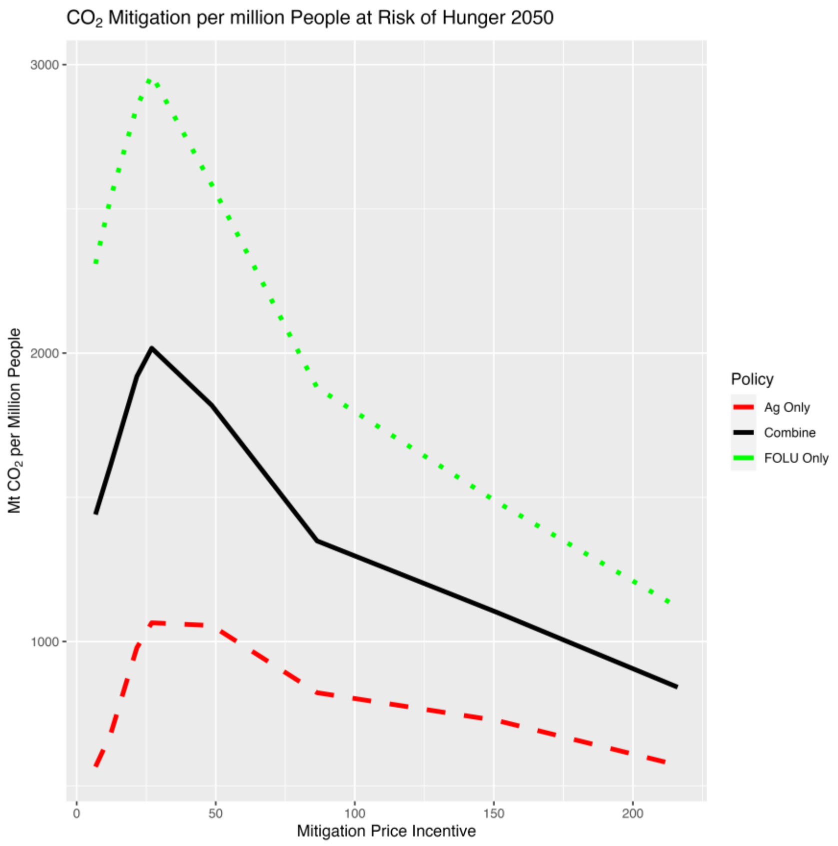
Tradeoffs across P, N, and C Policies



- Distribution of P consumption changes in response to climate policy signal

Tradeoffs across P, N, and C Policies

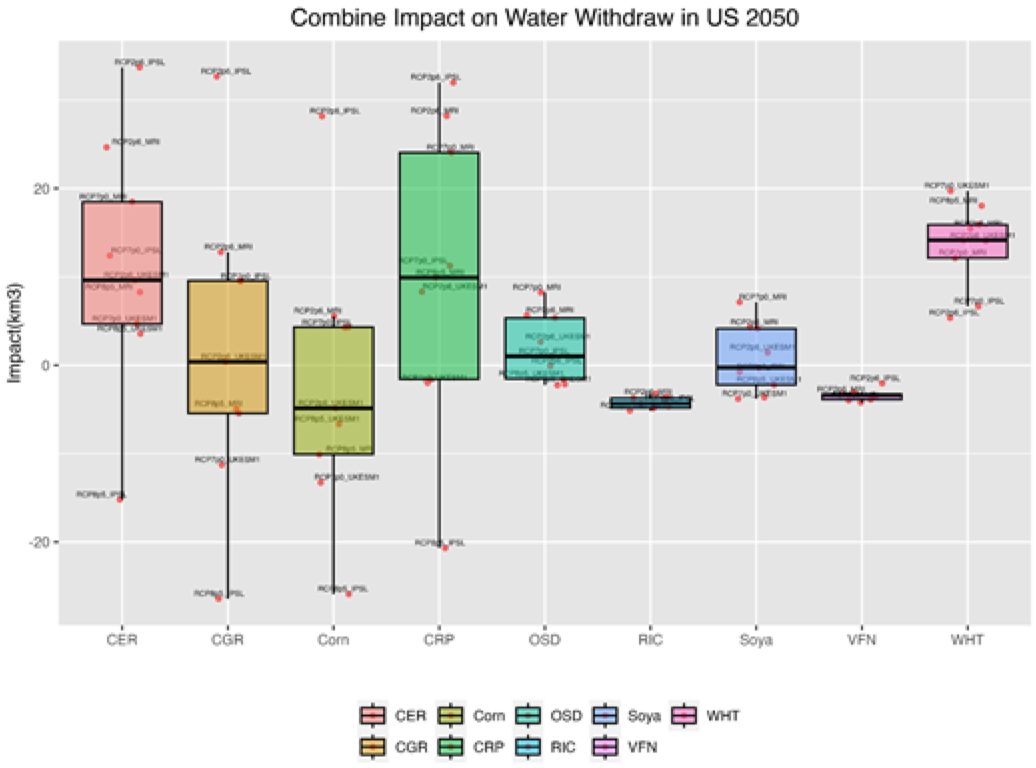
- Mitigation can exacerbate hunger risk
  - Plot shows ration of mitigation per
  - Mitigation slows down at higher CO2 prices, hunger risk increases non-linearly
- $30/tCO2e appears to be a critical threshold



Global-to-Local Scale Dependencies: Climate Change and Trade

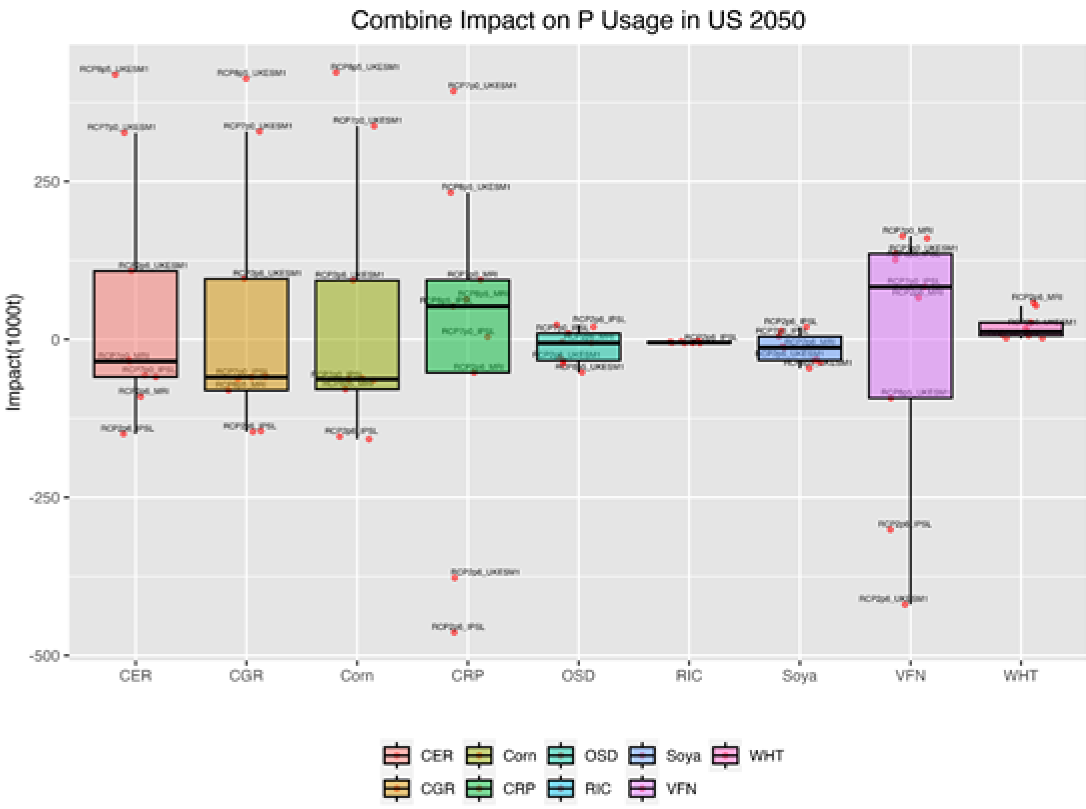
Global-to-Local Scale Dependencies: Climate Change and Trade

- Decomposing climate change and trade-induced impacts on US crop mix and input use decisions
  - In general, US ***water use for irrigation increases under climate change***

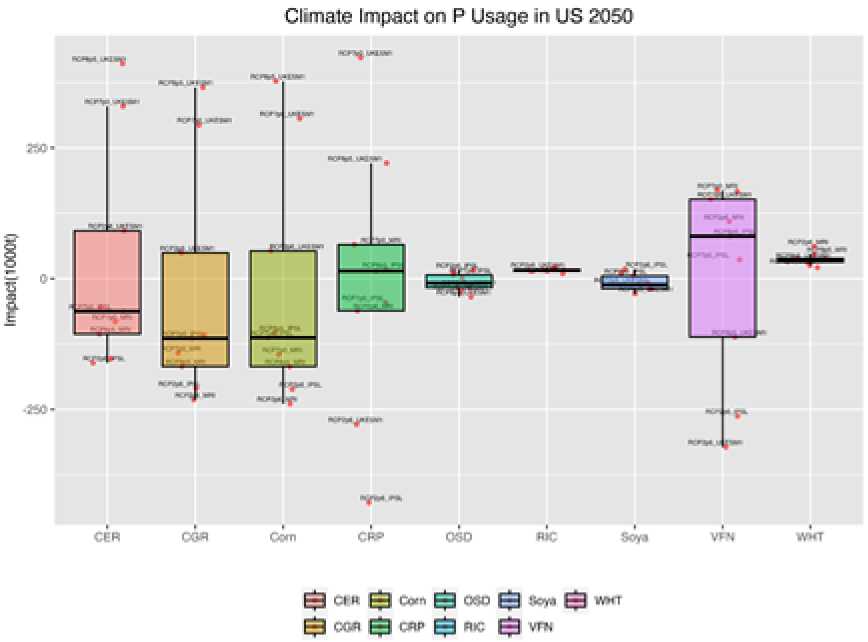


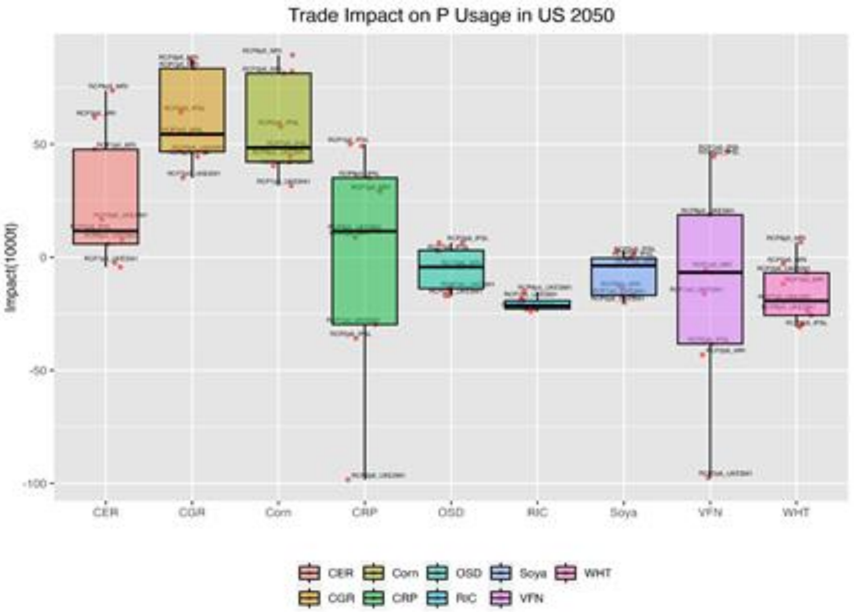
Global-to-Local Scale Dependencies

- Decomposing climate change and trade-induced impacts on US crop mix and input use decisions
  - But ***P consumption decreases on average***
    - Driven by changes in regional crop mix patterns.
    - Holds for most crop groups



Isolating Climate and Trade-Induced Impact





Trade adjustments ➔ upward pressure on input use intensity as US comparative advantage increases

Why is this important?

- Local/regional P consumption patterns are affected by global market adjustments
- Estimates of local impacts of policy and/or environmental change forces could be biased if they do not consider global market connections
- Economic effectiveness of P interventions tied to global market conditions and trade flows.

Thank you!

Justin Baker: justinbaker@ncsu.edu
Ziqian Gong: zgong5@ncsu.edu