Chair of Soil Science

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Four Pillars - CSS

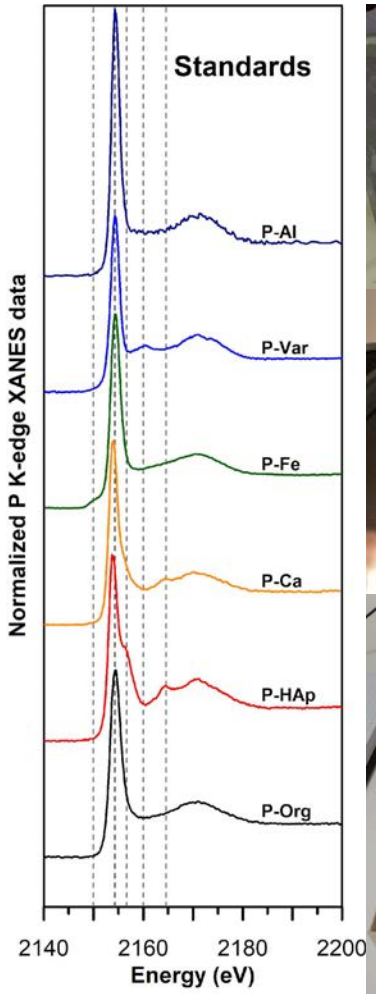
- **Environmental biogeochemistry**
  - Understand the biogeochemical cycling Nutrients & Contaminants soil-plant-human
  - Use state-of-the-art techniques and modeling mechanisms driving the fate and behavior
  - Design better technologies and improve soils management
- **Soil health and climate change**
  - Soil biodiversity + conservation + management = causes/solutions of climate change
  - Management practices that will improve C sequestration in the soil, fight climate change, and improve soil health
  - Design the way sustainable agricultural systems should look, putting all the different challenges into perspective
- **Fertilizer technology**
  - Nutrients in the soil-plant system and having specific fertilizer solutions for main soil-plant systems.
  - Embedding technology in the fertilizer granules that will improve nutrient use efficiency and plant productivity
- **Soil Security**
  - Support how soils are the foundation of our green transition, particularly in Africa
  - AU-EU R&D Partnership under the leadership of Prof. Daniel Nahon
  - Right policies to ensure soils are safe and secured Union vision for the green transition in Africa, and to make UM6P the first African Lighthouse

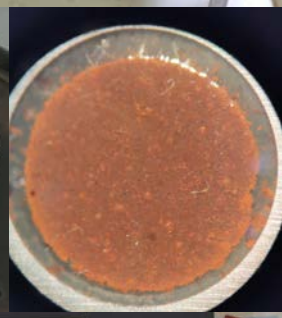
AS93 Project

Phosphorus fate, behavior, and bioavailability in long-term phosphate fertilizer and soil management trials in the Brazilian Cerrado

Research Approach

- **General goal:** To evaluate the long-term changes in soil phosphorus chemistry and the fate of added P fertilizer under conventional and more sustainable agricultural management practices
- **Two experiments**: NT vs CT (tillage system), TSP vs PR (source), F vs B (localization) – Brazilian Cerrado (EMBRAPA)
  - 17 yrs P supply and 8 yrs cropped without P – **Legacy P**
  - 20 yrs cropped soil with 3 rates of P (0, 50, 100 kg ha^{-1} yr^{-1}) – **P Balance**
- Material & Methods
  - Wet chemistry ✓
    - Phosphorus fractionation to assess labile, mod-labile, and non-labile forms
  - Synchrotron-based spectroscopy (XANES and XRF) ✓
    - P K-edge XANES spectroscopy to assess the molecular composition of phosphorus
    - To assess whether the amount of organic P has increased after long-term fertilization
    - To quantify which forms of P are depleted by the continuous cultivation
  - Microbiological and enzymes analysis ✓
    - To assess the microbiological and enzymes activity changes
  - ^{31}P-NMR chemistry WORK IN PROGRESS
    - To assess the organic P changes after long-term fertilization (to be carried out)





Bioavailability of legacy phosphorus in a long-term cultivated Brazilian Cerrado Oxisol under different tillage systems and fertilization management

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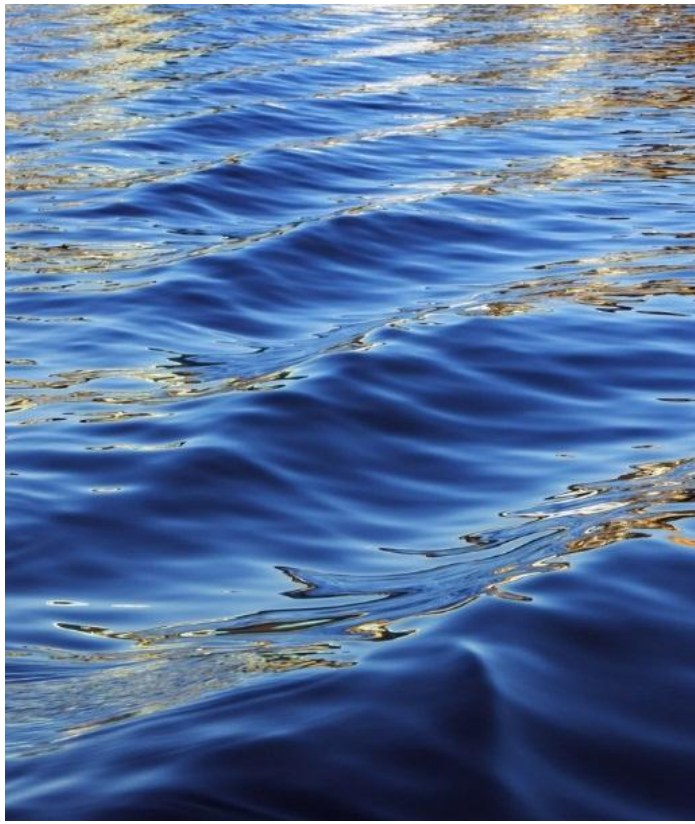
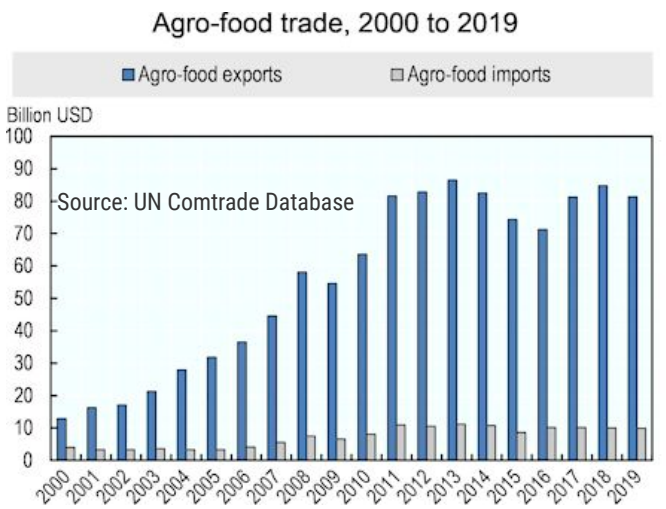
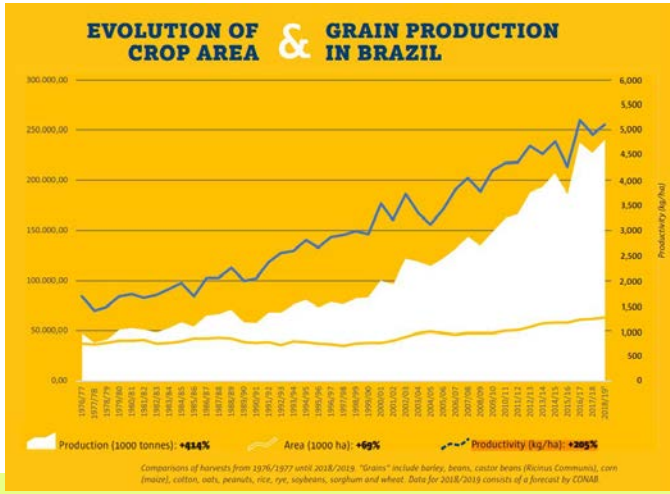


tainable Phosphorus Summit
November 2022, Raleigh - NC

Overview





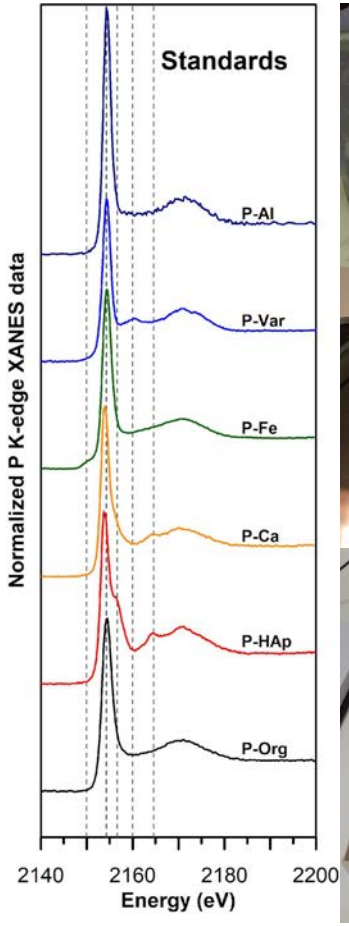
- Brazilian agriculture:
  - Brazil is the world's fourth-largest food producer
  - Cerrado (Brazilian Savanna) represents 60% of Brazilian agricultural production
  - Cerrado has highly weathered soils and Fe- and Al-(hydr)oxides clays ⚠ P fixation!
- Soil fertilization and legacy P
  - Phosphate rock contains calcium-phosphorus species (e.g., hydroxyapatite - P-HAp) that are a source of P to crops after their solubilization and diffusion in the soil
  - However, P can be fixed on Fe and Al clay surfaces and become unavailable to plants
  - This process decreases P fertilization efficiency
  - The continuous fertilization result in the buildup of P in the soil (known as legacy P), which might be available to future crops
- Synchrotron-based
  - P K-edge µXANES – To assess the P species and understand the mechanisms controlling the fate of P from the fertilizers in tropical soils

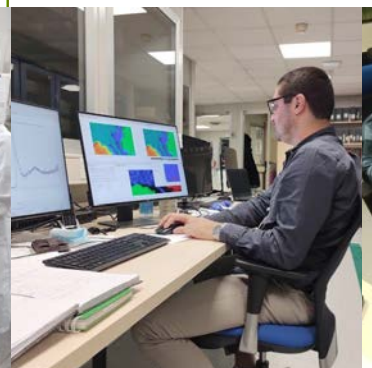
Objectives

- General
  - To evaluate the long-term changes in soil phosphorus chemistry and the fate of added P fertilizer under conventional and more sustainable agricultural management practices in tropical croplands
- Specific objectives
  - To assess the bioavailability of legacy P in a long-term experiment testing soil management systems, P sources, and methods of application
  - To assess P speciation in a Brazilian Cerrado Oxisol, under a long-term field experiment using a synchrotron-based technique (XANES)

Material & Methods

- 25 yrs field experiment, Planaltina-DF, Brazil:
  - NT vs CT; TSP vs PR; F vs B; cropped with maize
  - Oxisol 63% kaolinite 20% gibbsite 11% hematite in the clay fraction
  - Sampling 2011: after 17 yrs P supply (35 kg ha^{-1} yr^{-1} of P)
  - Sampling 2019: after 8 yrs cultivated without P
- Wet chemistry
  - Phosphorus fractionation (Gatiboni & Condron, 2021) to assess labile (M3), mod-labile (HCl 1 M and NaOH 0.5M), and non-labile forms (occluded)
- Synchrotron-based spectroscopy (XANES and XRF)
  - P K-edge XANES spectroscopy to assess the molecular composition of phosphorus
  - To assess whether the amount of organic P has increased after long-term fertilization
  - To quantify which forms of P are depleted by the continuous cultivation

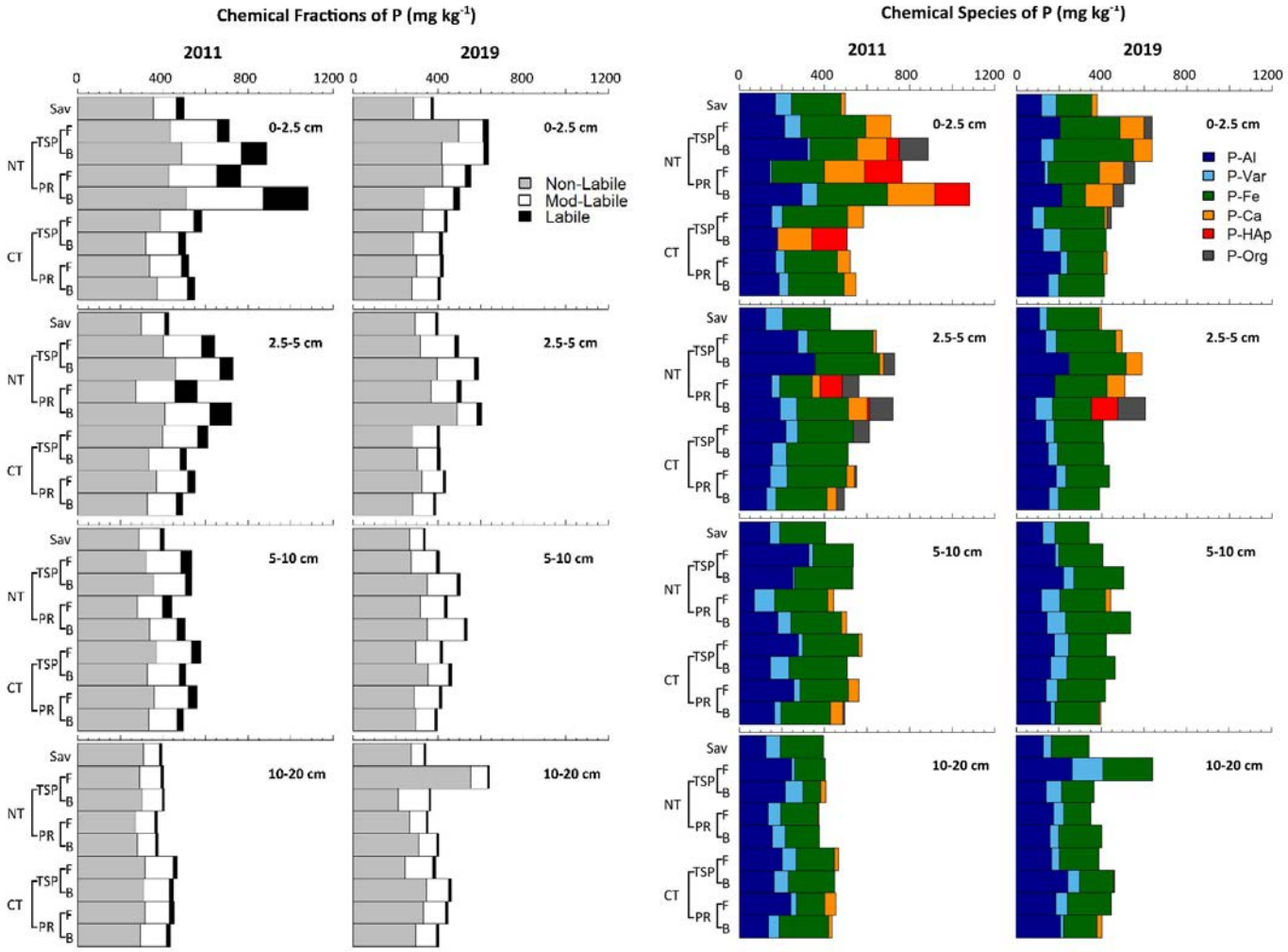


EMBRAPA - Brazil		USP - Brazil	ESRF - France	
				

Results

- After 8 years without fertilization, the total P content in the topsoil decreased under NT and CT (-197 and -123 mg kg^{-1})
- NT increased the labile P in 2011 (125 vs 34 mg kg^{-1}, NT vs CT) and in 2019 (27 vs 14 mg kg^{-1})
- In the NT, the mod-labile and labile P fractions decreased (-96 and -80 mg kg^{-1}), and in the CT non-labile fraction decreased (-59 mg kg^{-1})
- P-Fe and P-Al are the main species across all treatments and increased over time (77% in 2011 and 88% in 2019)
- P-Ca and organic-P species were depleted under CT but were still found in NT after 8 years without fertilization

Tillage System	P Source	P Local.	Maize yield: Mean with P	18°	19°	20°	21°	Mean without P
			Kg ha^{-1}					
CT	TSP	B	11743	9235	5995	6185	4682	6524
		F	11725	10419	7924	7006	5971	7830
	PR	B	11722	10302	7321	6178	5394	7299
		F	11477	10167	8249	7899	6145	8115
NT	TSP	B	12698	11429	7989	7477	6201	8274
		F	12406	10858	8622	8053	6817	8587
	PR	B	12208	11962	11436	11117	8408	10731
		F	11820	11761	11571	10139	7825	10324



Conclusions

- Fertilizer application is **mandatory** or reduction of -50 to 85% of labile P (lower crop yield)
- No-tillage P rock kept better levels of labile P higher P buffer capacity for the crops
- Non-labile fraction decreased from 2011 to 2019 in the topsoil, meaning the legacy P can be accessed by the crops build legacy P, but crop yield decreases
- P-Ca (fertilizer) transformed in P-Fe and P-Al (less labile P)
- The NT is better than CT system soil health and higher labile P (crop yield)

Acknowledgment

Sustainable Phosphorus Management across Systems and Spatial Scales

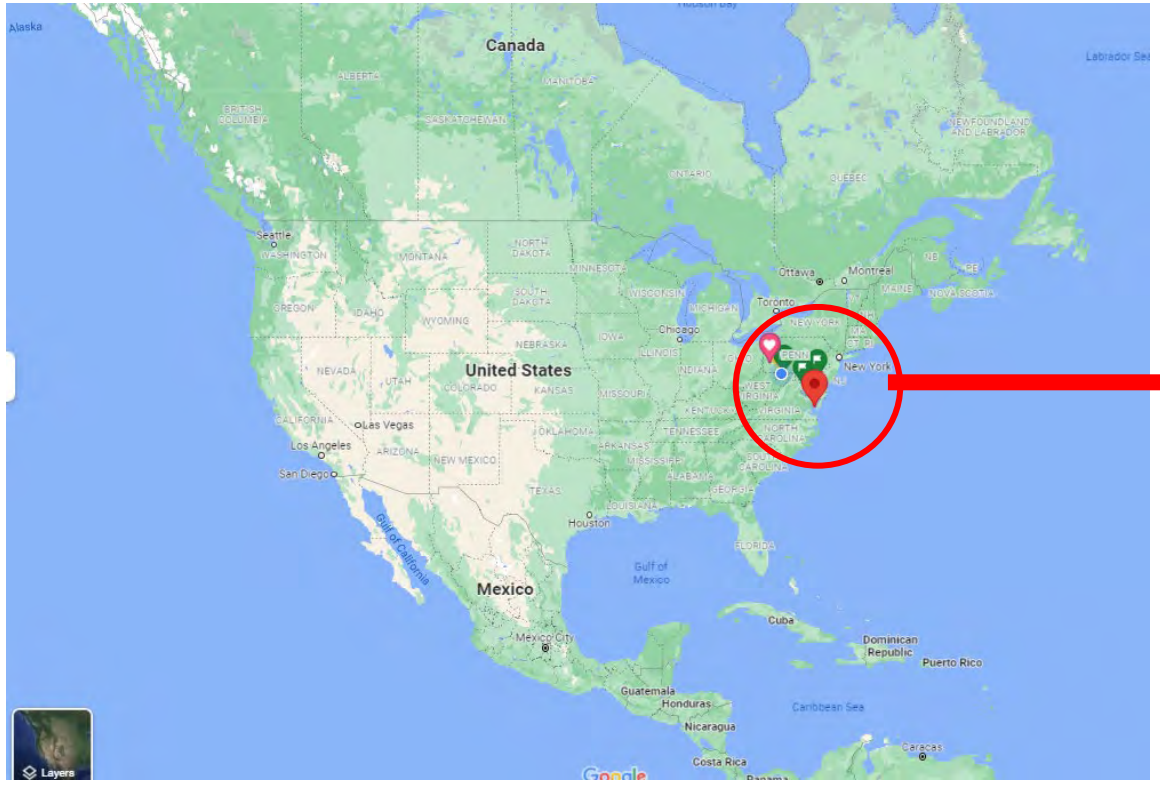
Tan Zou, Xin Zhang, Eric A. Davidson

Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, MD, USA

Research background

Chesapeake Bay watershed

- Covers 64,000 square miles
- Supports more than 18 million people, 348 species of finfish and 173 species of shellfish



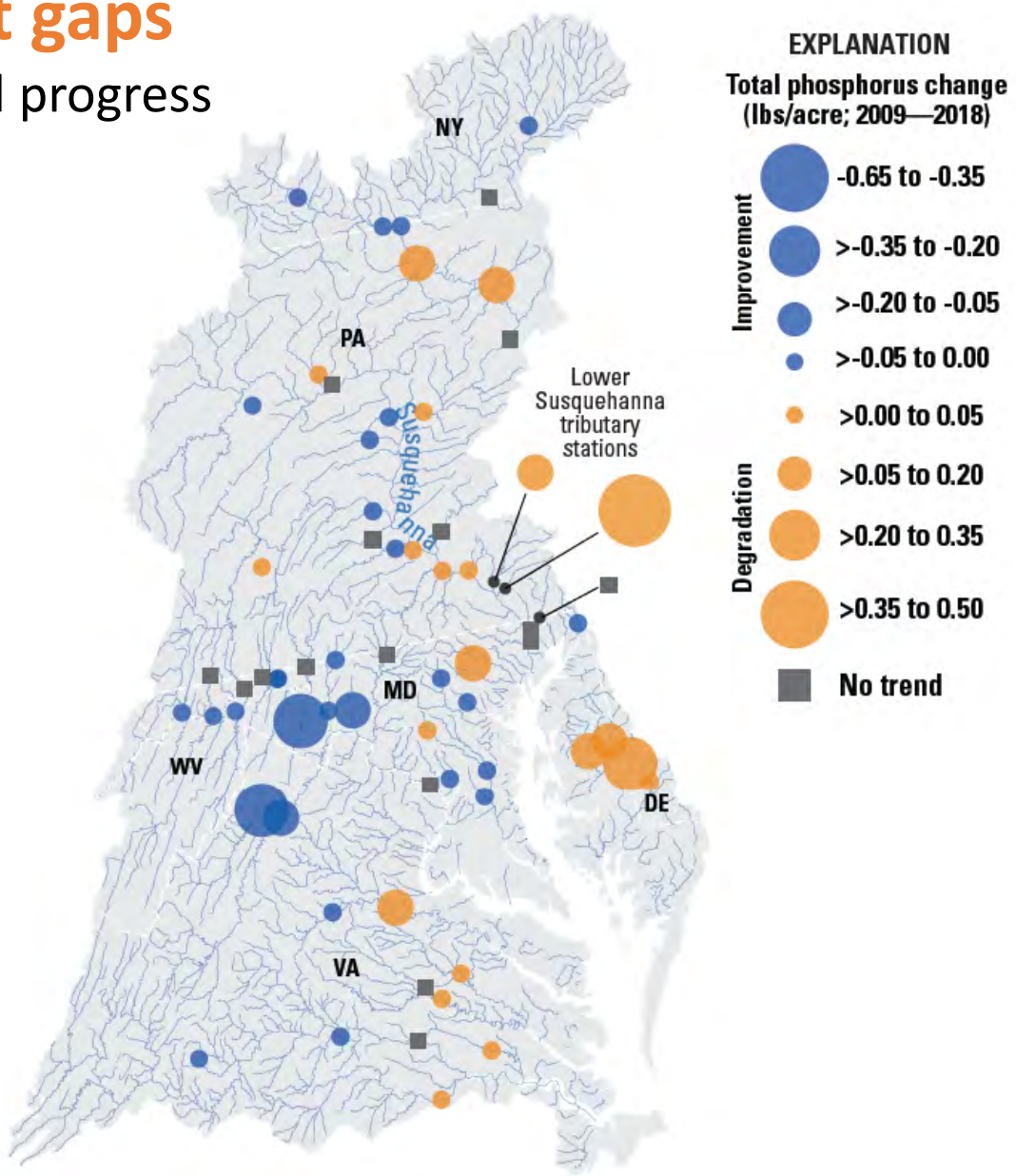
Motivations

1. Two phosphorus management gaps

1. Phosphorus (P) management – limited progress

Total phosphorus trends (lbs/acre; 2009—2018) at nontidal monitoring stations

- Reductions in total P at 44% of stations.
- Increases in total P at 32% of stations.
- No trend in total P at 24% of stations.



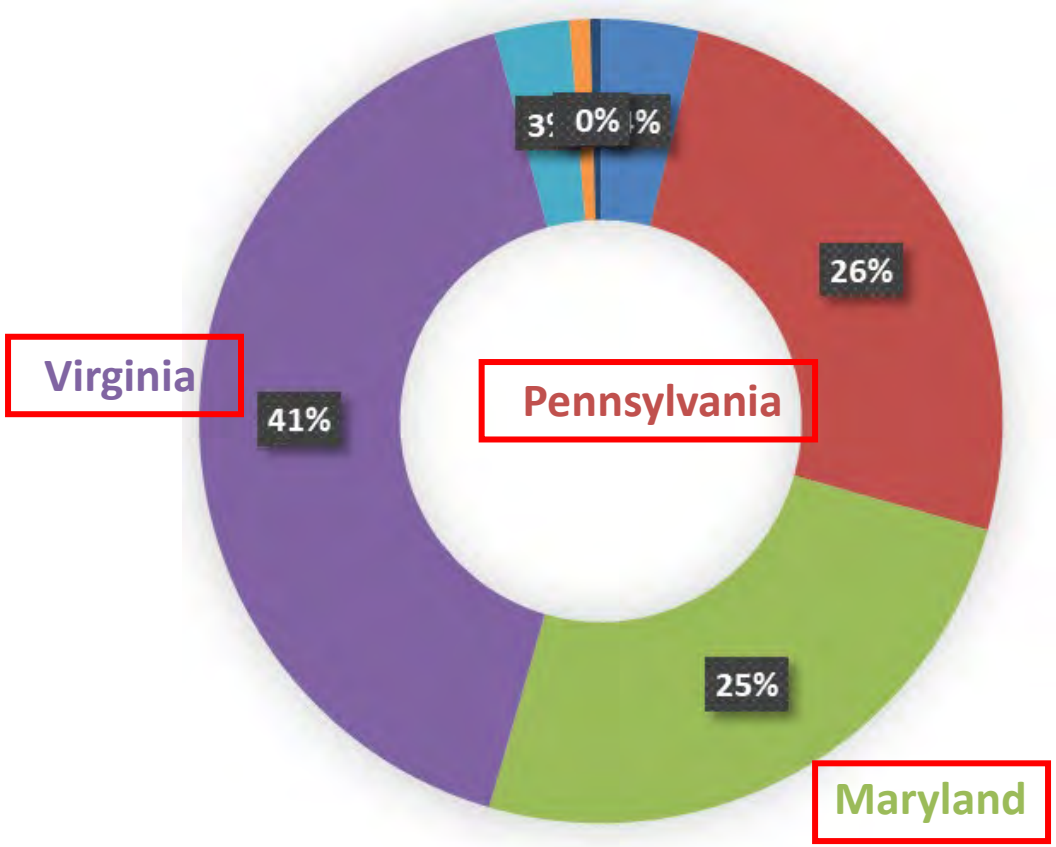
USGS 2021 Nutrient Trends and Drivers in the Chesapeake Bay Watershed

Motivations

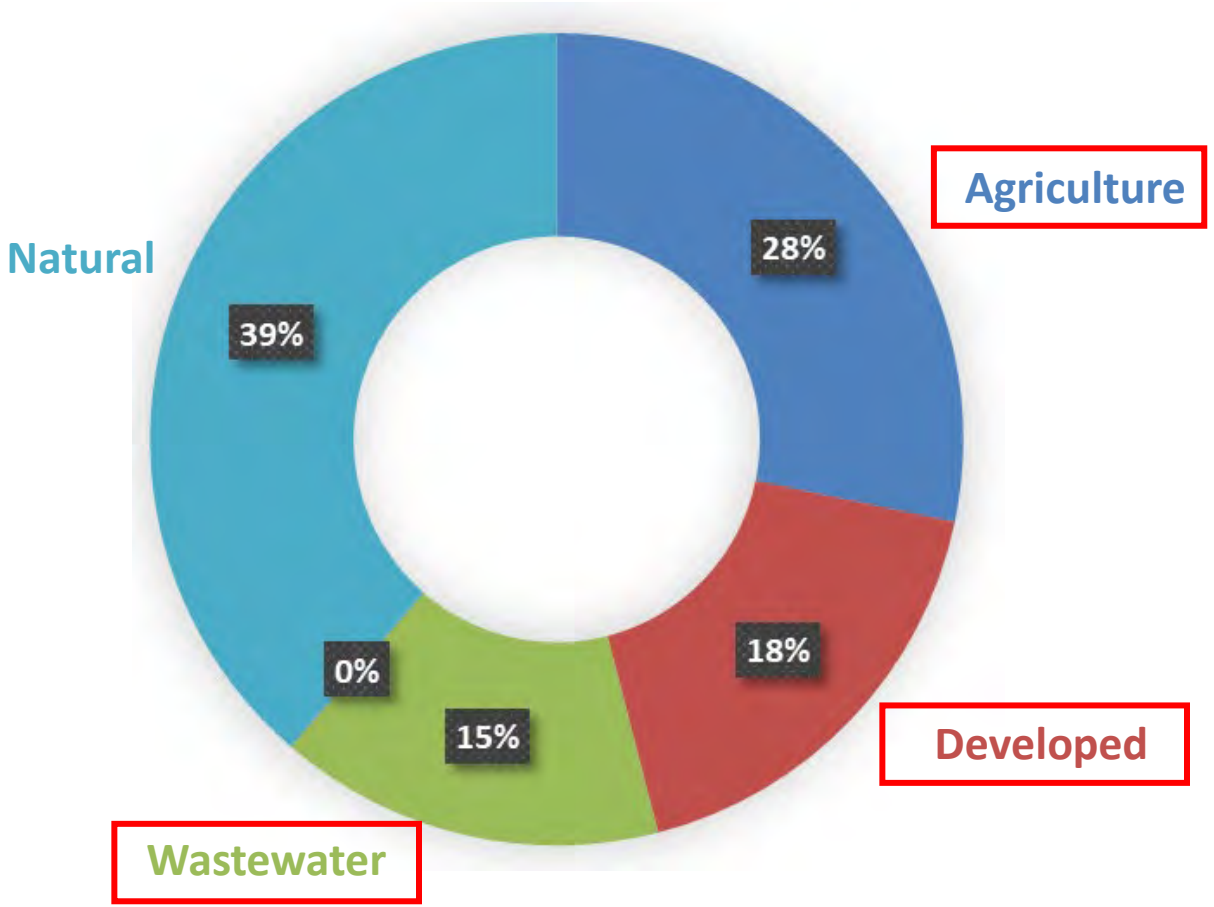
1. Two phosphorus management gaps

1. Phosphorus (P) management – limited progress
2. Management performances varying by region and source

2020 P loads by region



2020 P loads by source



2025 Watershed Implementation Plans (WIPs) - Chesapeake Progress

Motivations

1. Two phosphorus management gaps

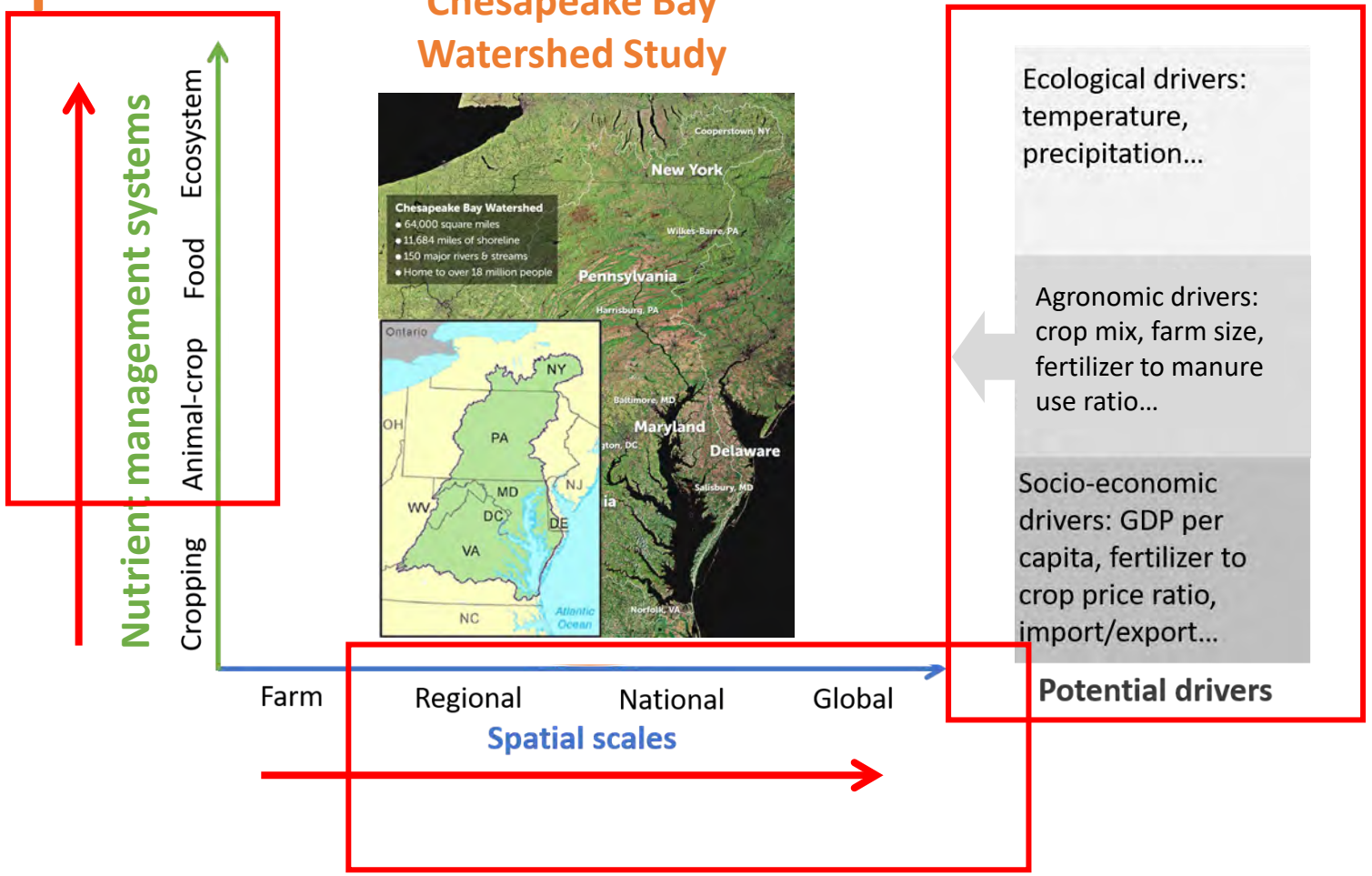
1. Phosphorus (P) management – limited progress
2. Management performances varying by region and source

2. Three knowledge gaps

1. Lack of assessment of nutrient use beyond the farm

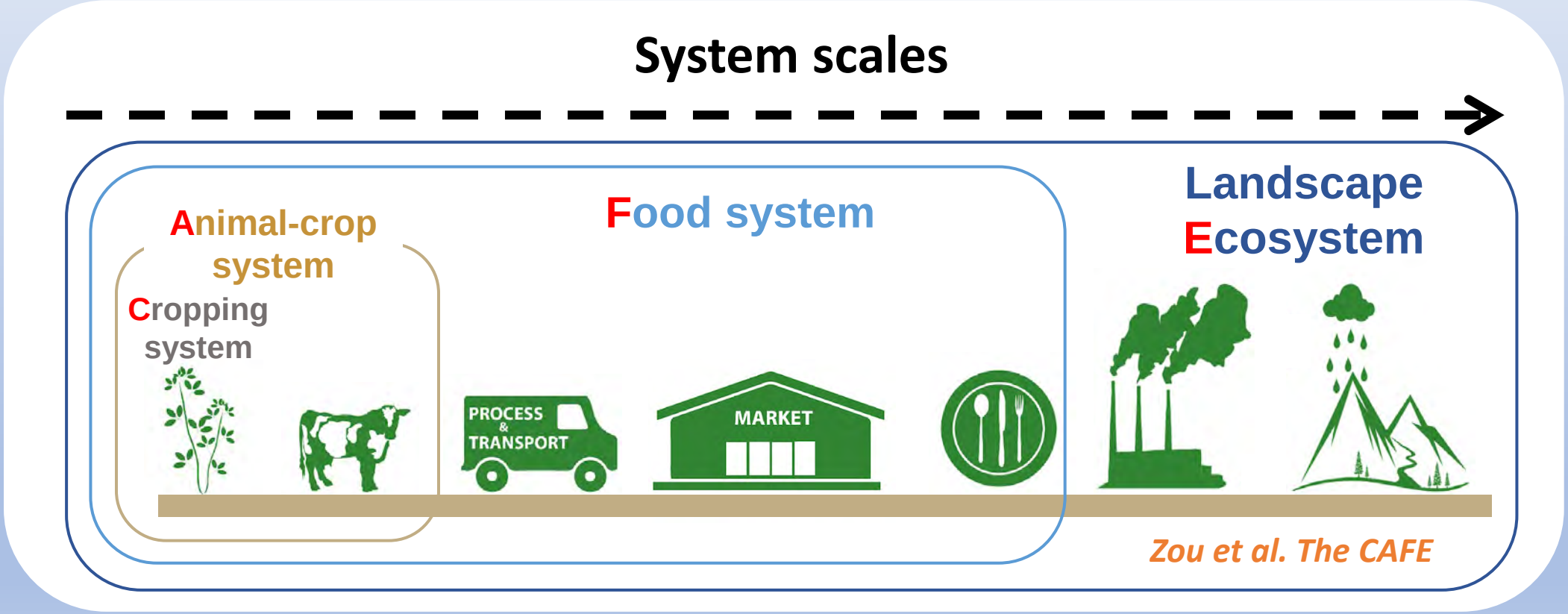
2. Lack of effective approaches to evaluate nutrient management and identify management gaps across systems and across spatial scales

3. Lack of understanding of socioeconomic drivers for nutrient use



Methods

The *CAFE* framework connecting 4 nutrient management systems



Zhang et al. 2020 Quantifying Nutrient Budgets for Sustainable Nutrient Management

Methods

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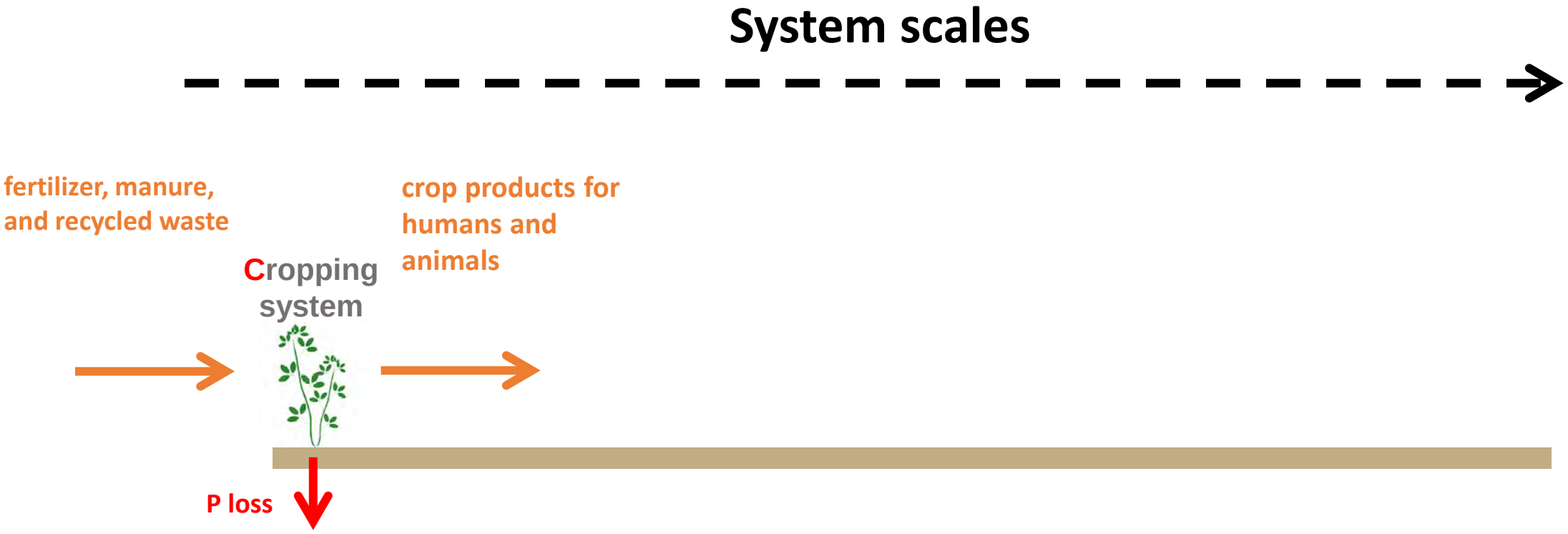

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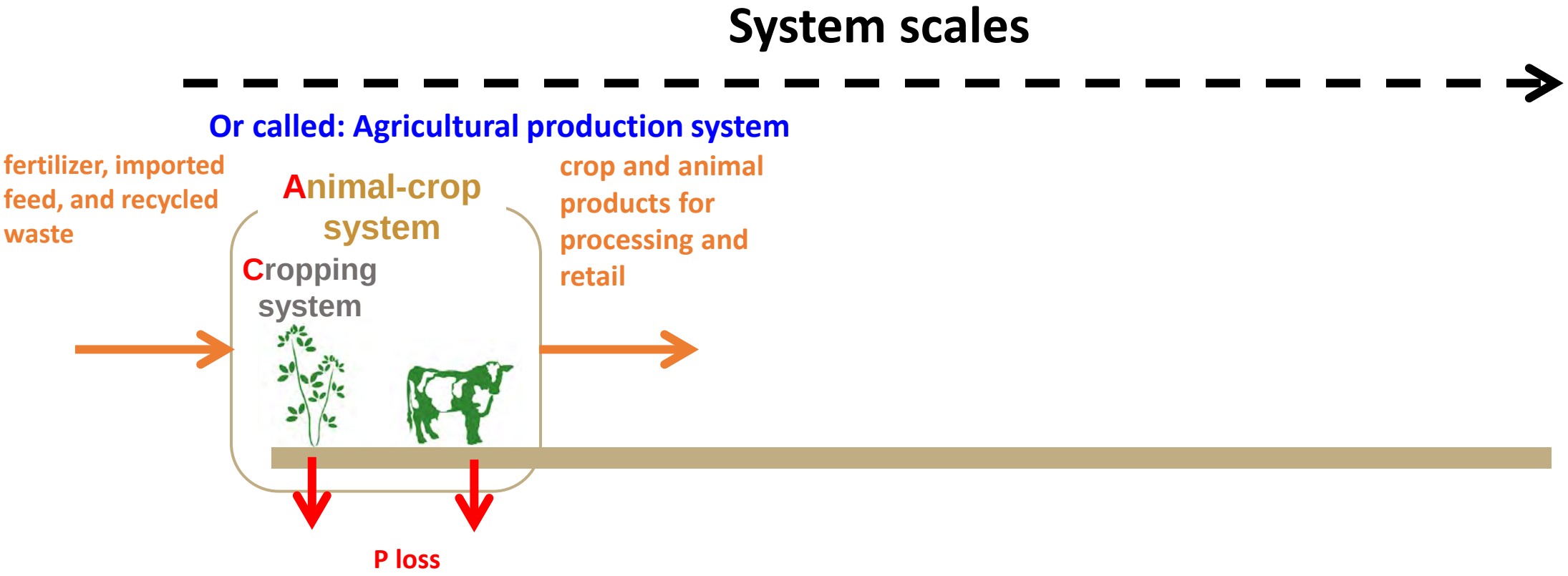

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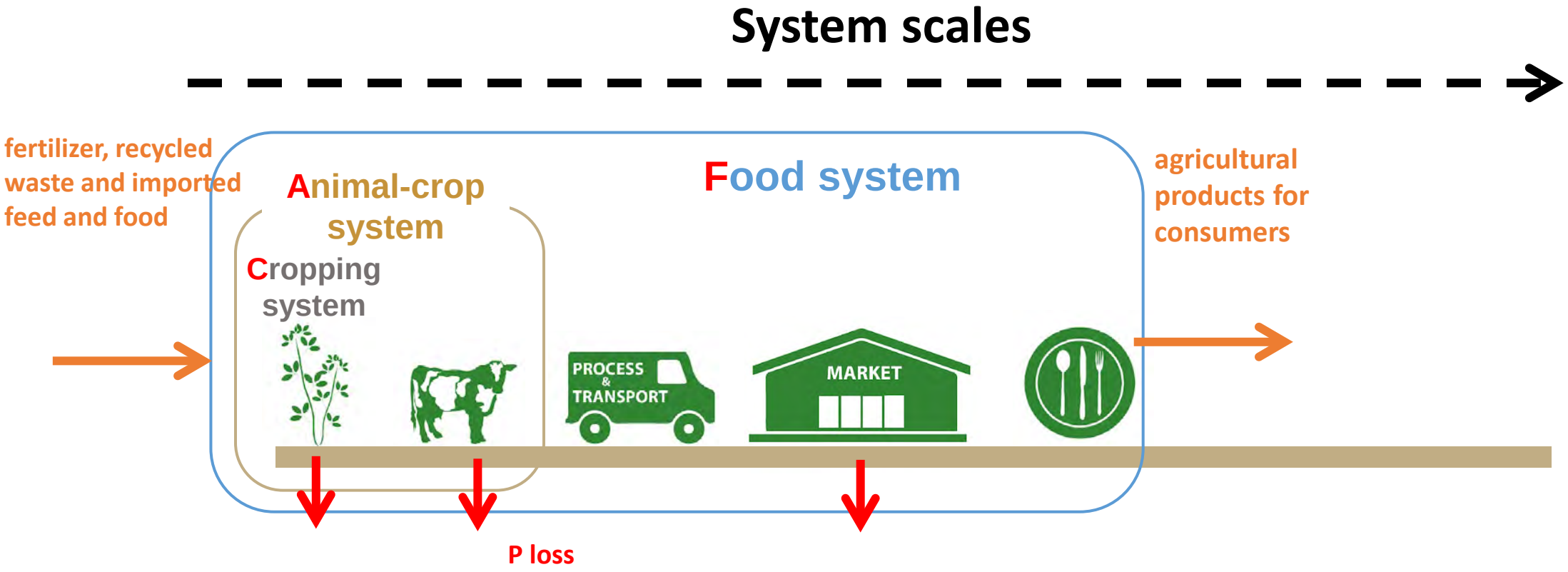

Methods

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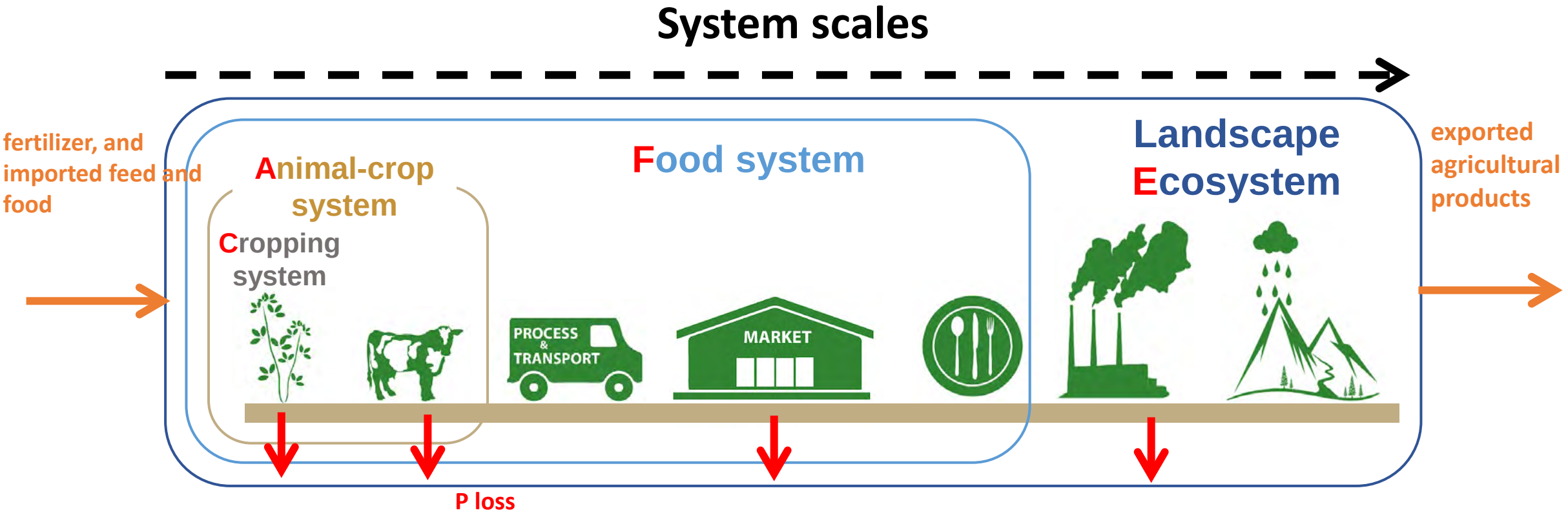
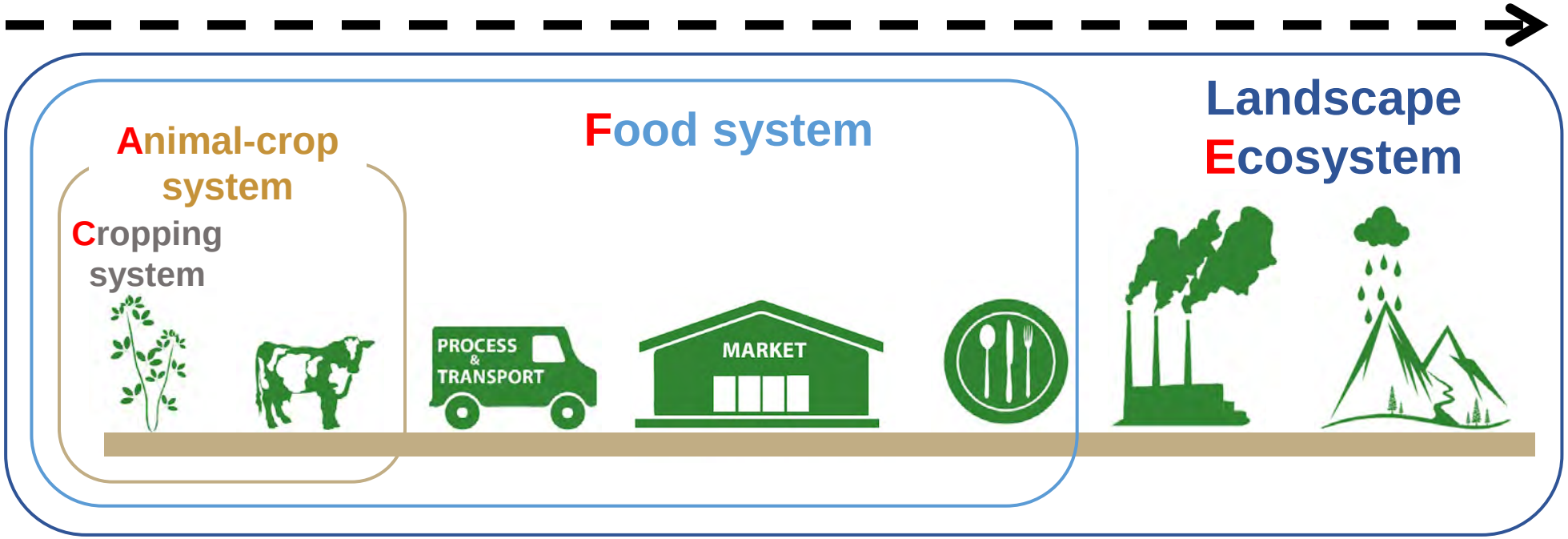


Methods

Data sources

- **Time scale:** 1985-2019
- **Data sources:** Chesapeake Assessment Scenario Tool (CAST), and literature
- **P budget database**: study nutrient use patterns and management performances by county and year

System scales



Result 1: Importance of P management beyond crop farms

P loss potential at crop farms

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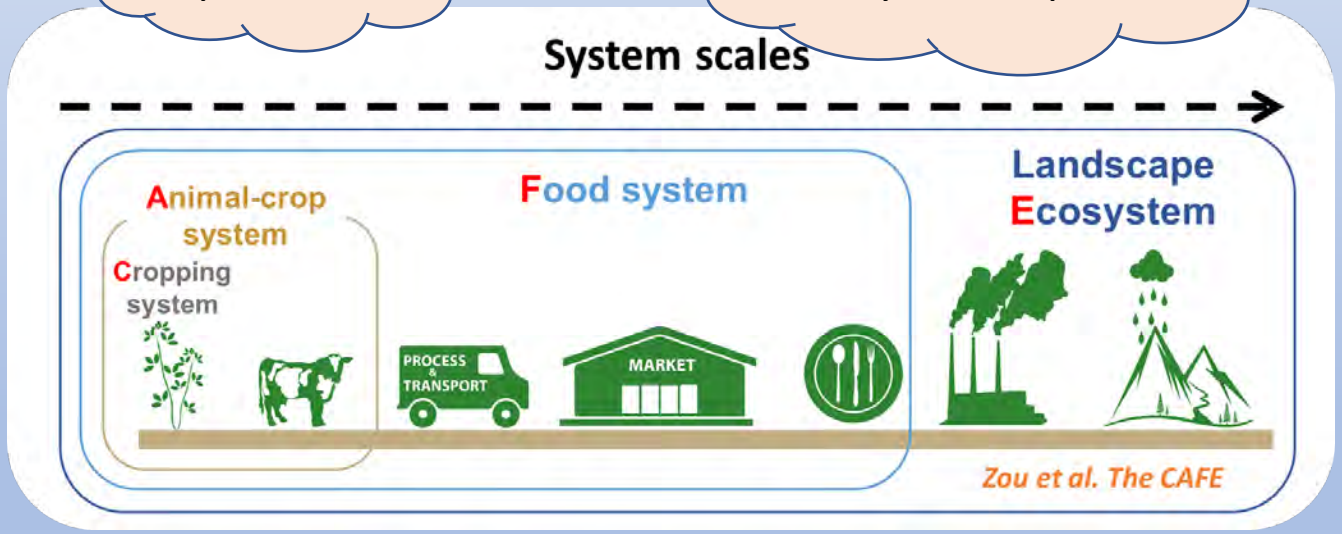
P loss potential beyond crop farms



Result 1: Importance of P management beyond crop farms

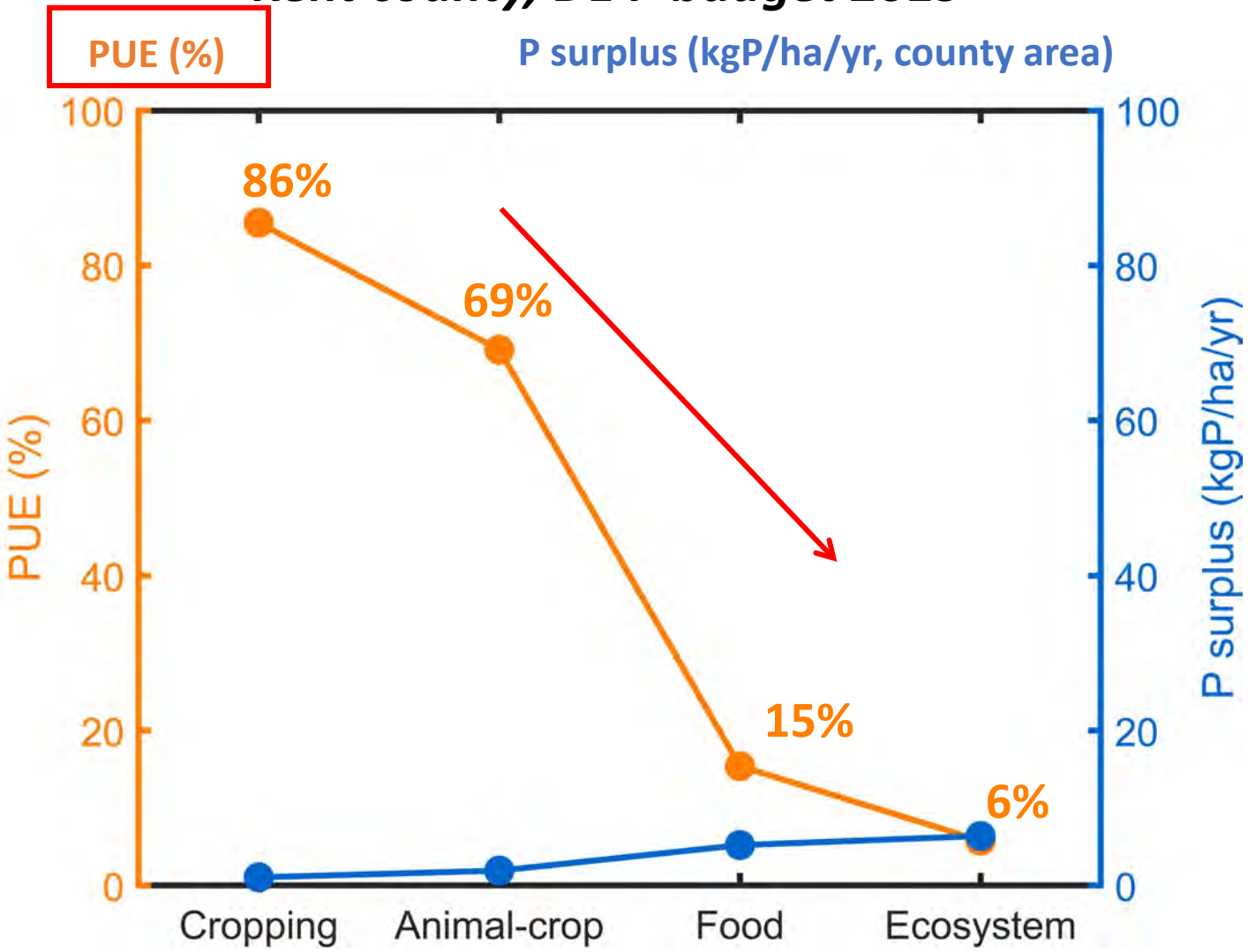
PUE beyond crop farms was decreasing

Phosphorus use efficiency (PUE)
= productive outputs/inputs

Strategies to improve PUE

1. Improving subsystems' PUEs
2. Improving the interconnection between subsystems

Kent county, DE P budget 2019

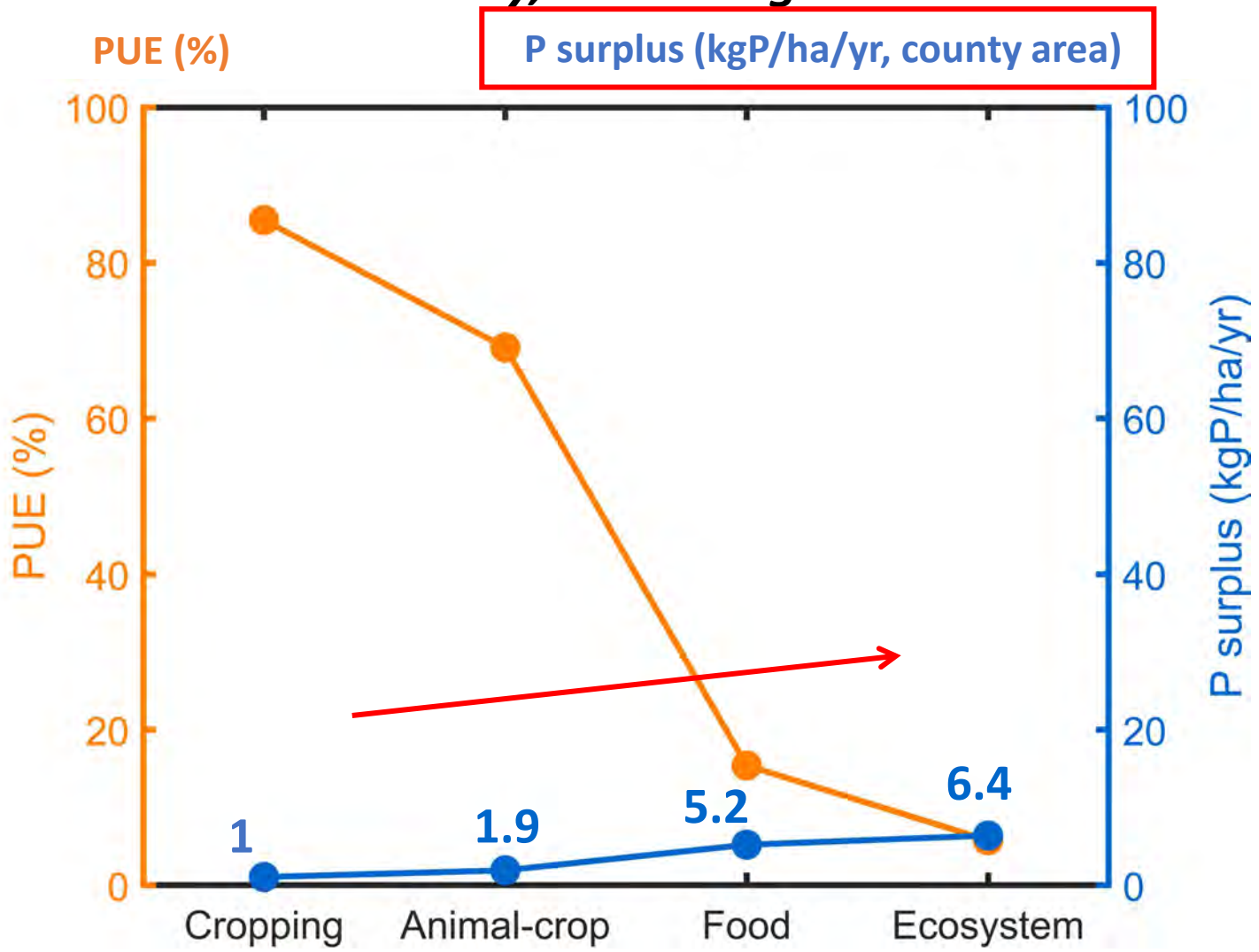


Result 1: Importance of P management beyond crop farms

P surplus beyond crop farms was increasing

Phosphorus surplus (P surplus)
= inputs - productive outputs

Kent county, DE P budget 2019



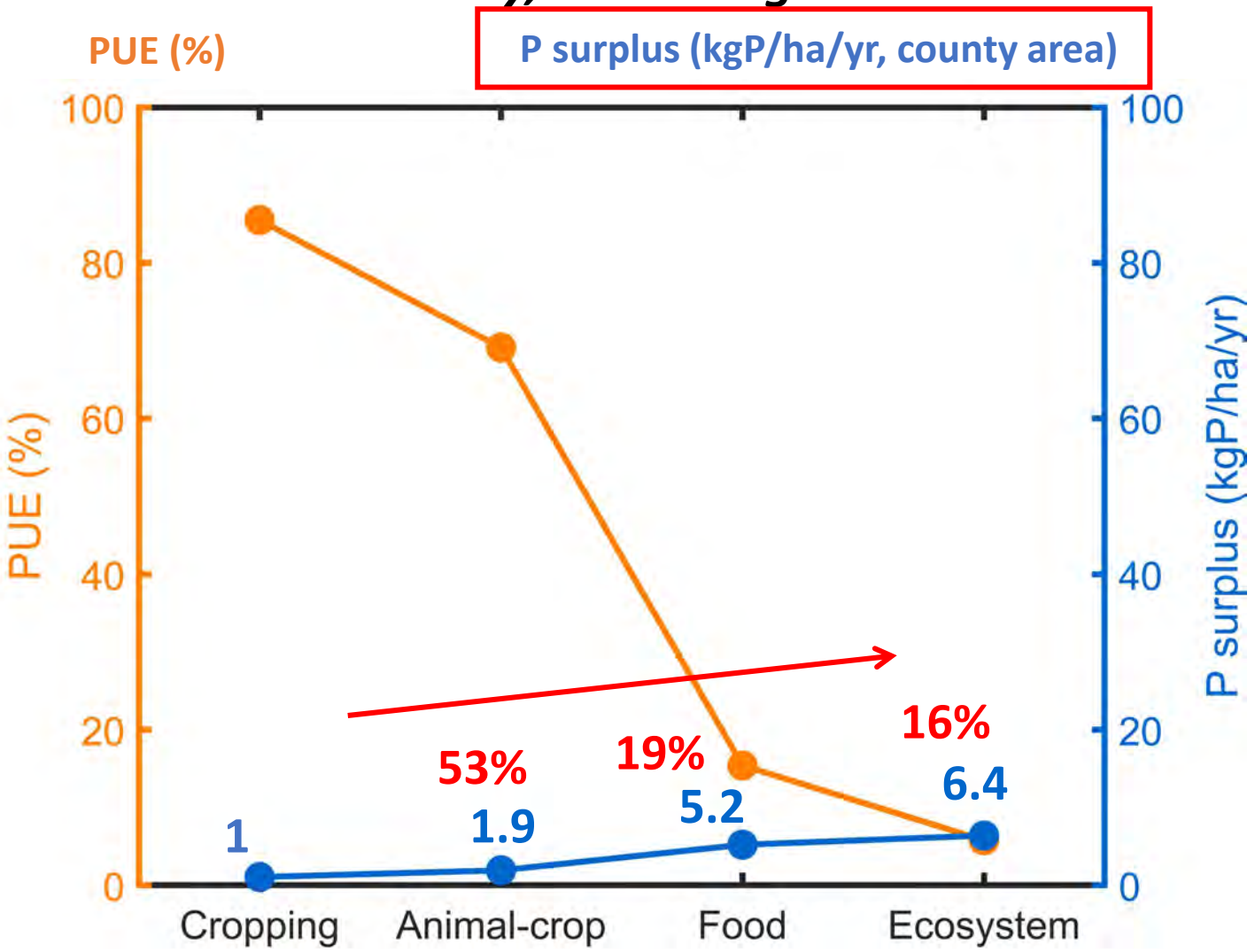
Result 1: Importance of P management beyond crop farms

P surplus beyond crop farms was larger than P surplus at crop farms

Cropping system P surplus = 16% ecosystem P surplus

In the watershed, 96% counties has P surplus beyond crop farms larger than P surplus at crop farms.

Kent county, DE P budget 2019



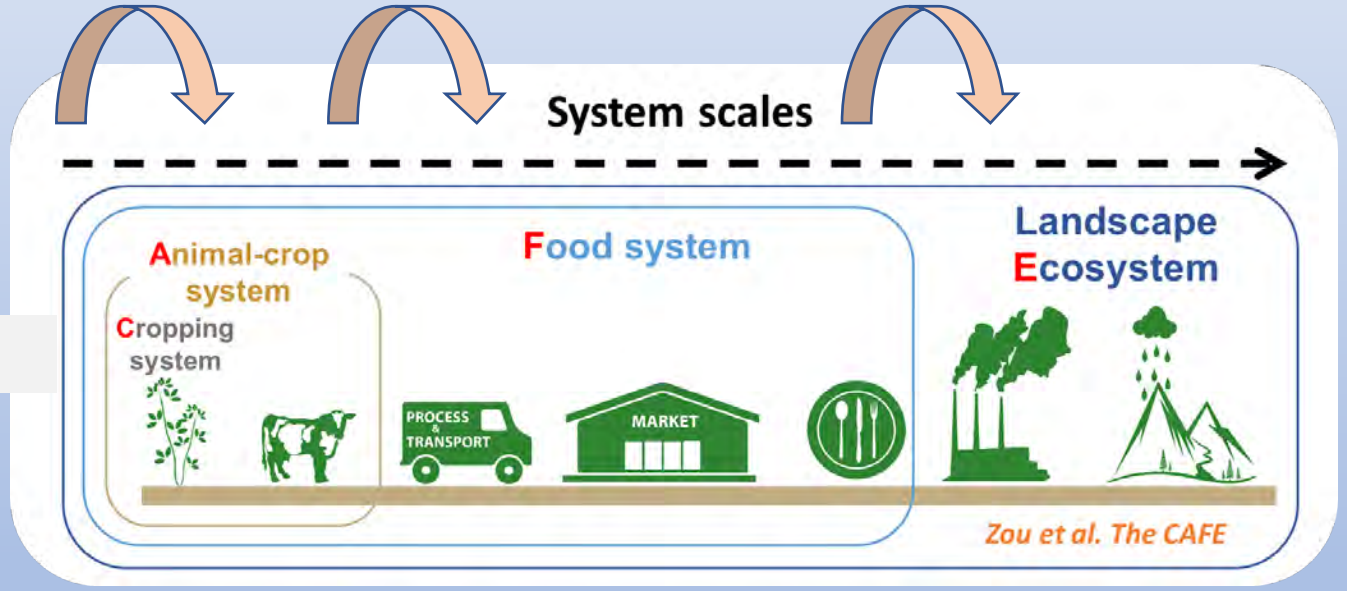
Result 2: Identifying management priorities by comparing surplus changes

C-A surplus increase

A-F surplus increase

F-E surplus increase

C-C surplus increase

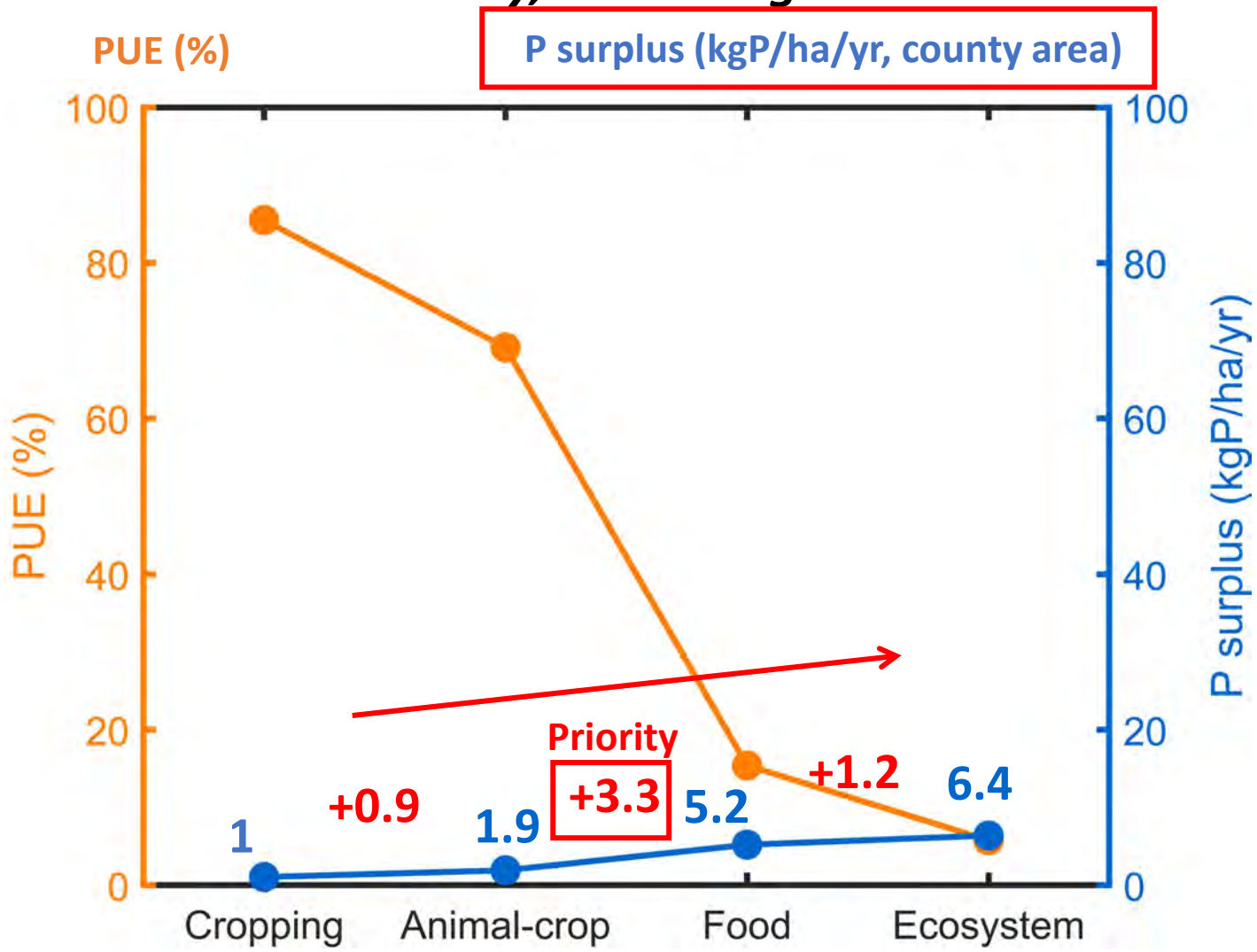


Result 2: Identifying management priorities by comparing surplus changes

Using between-system surplus change to identify management priorities

Between-system surplus change =higher system surplus – lower system surplus

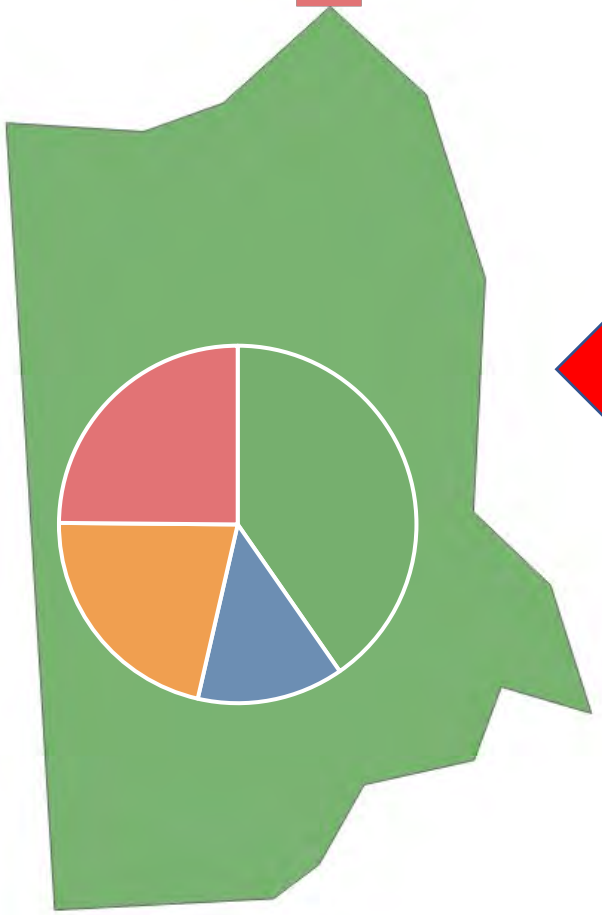
Kent county, DE P budget 2019



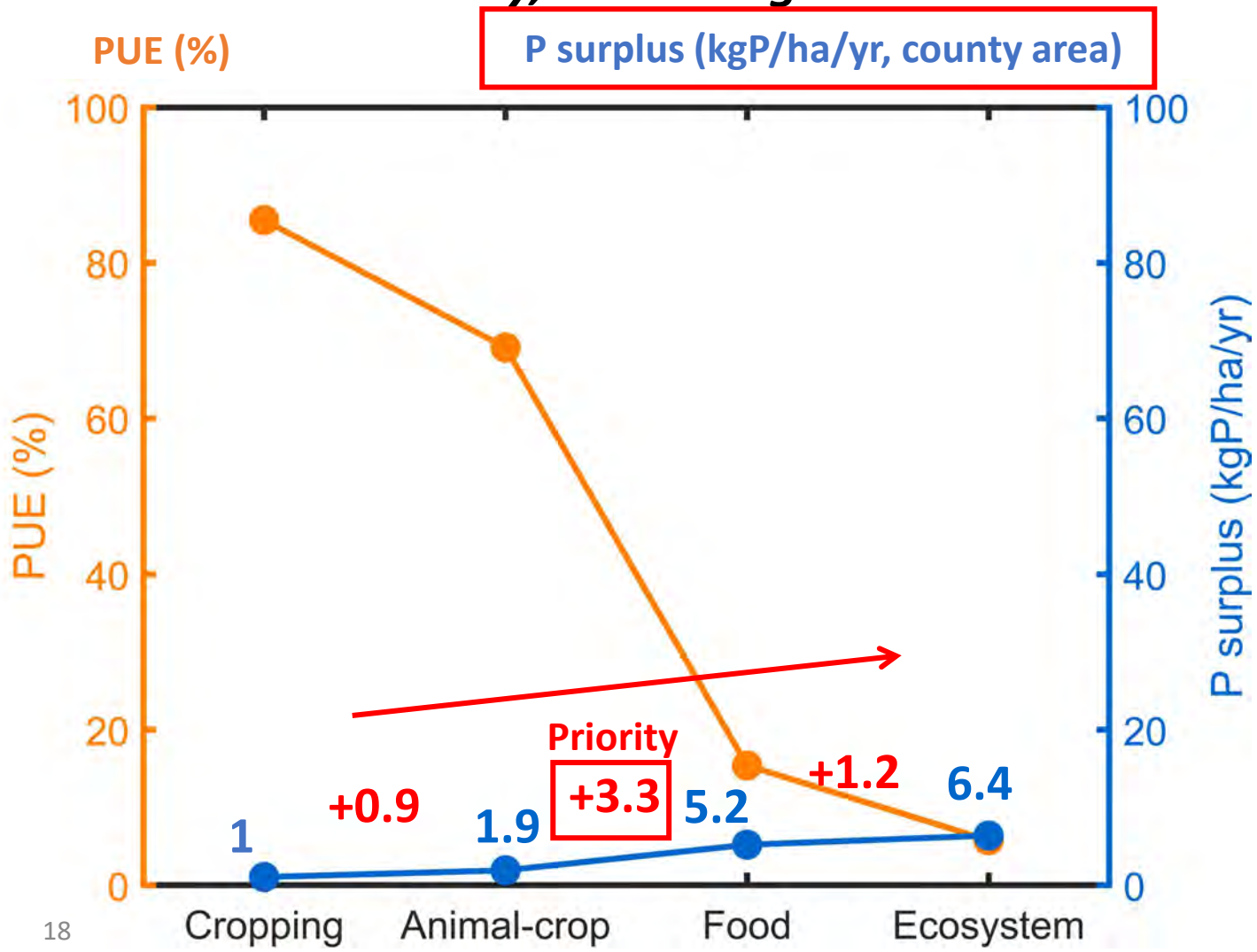
Result 2: Identifying management priorities by comparing surplus changes

System with the largest surplus increase

- Cropping system
- Cropping to Animal-crop
- Animal-crop to Food
- Food to Ecosystem



Kent county, DE P budget 2019



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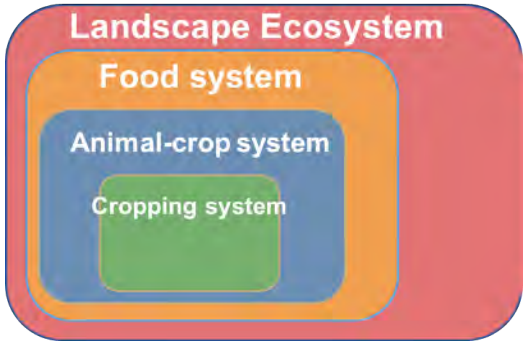
Result 2: Identifying management priorities by comparing surplus changes



System with the largest surplus increase

- Cropping system
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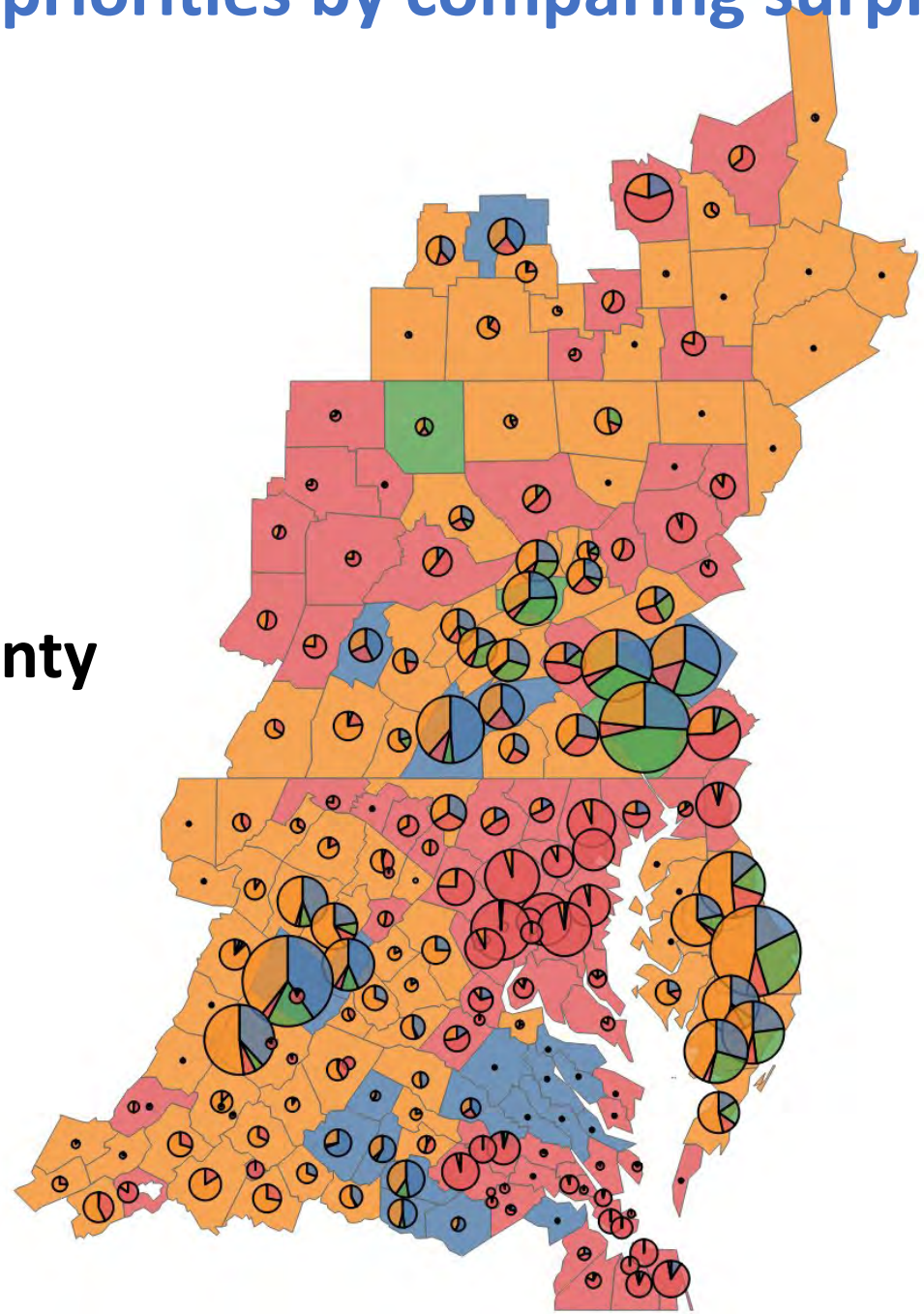
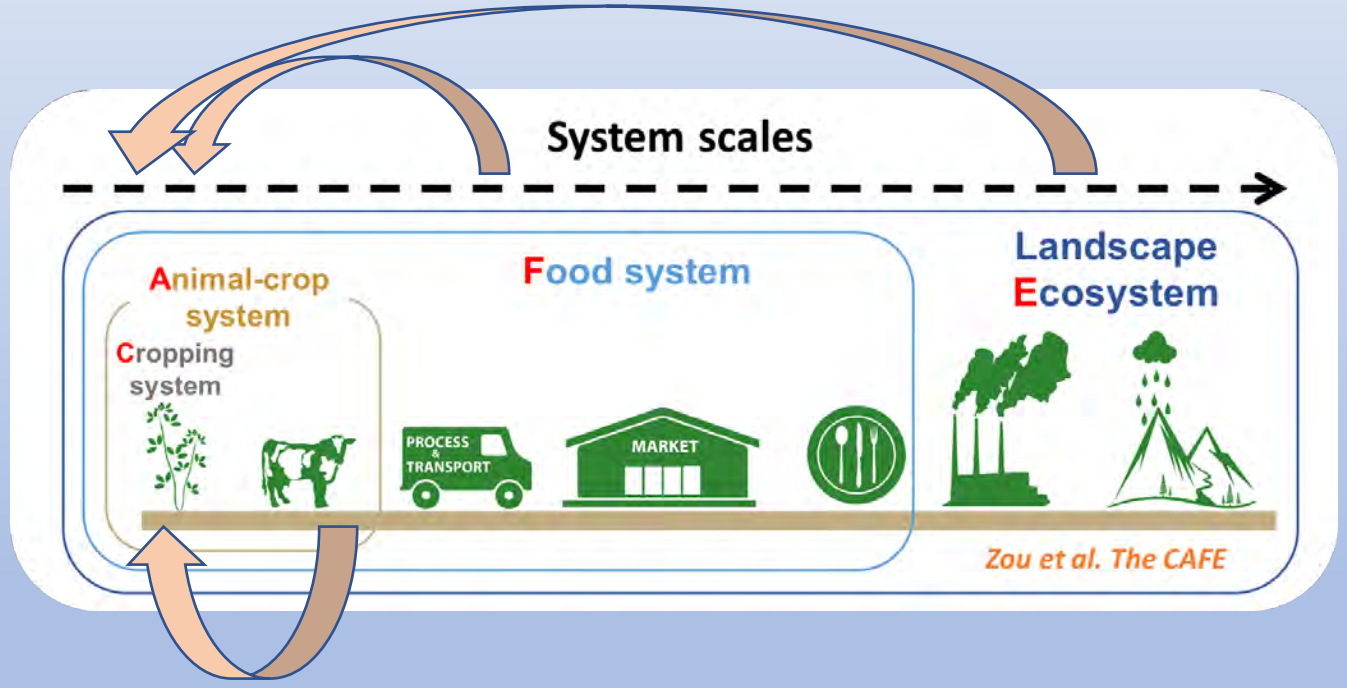


2019 P management priories by county

- 4 (2%) at Cropping system
- 22 (11%) at Animal-crop system
- 81 (41%) at Food system
- 90 (46%) at Ecosystem

Result 3: Large potential to meet P demand by recycling waste

P in food and human waste

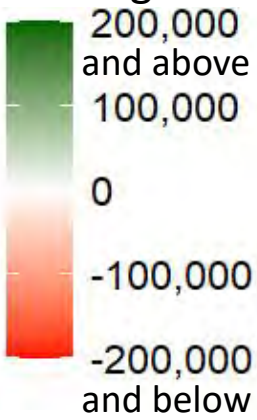


P in manure

Result 3: Large potential to meet P demand by recycling waste

P difference between unrecycled waste and inorganic fertilizer input in 2019

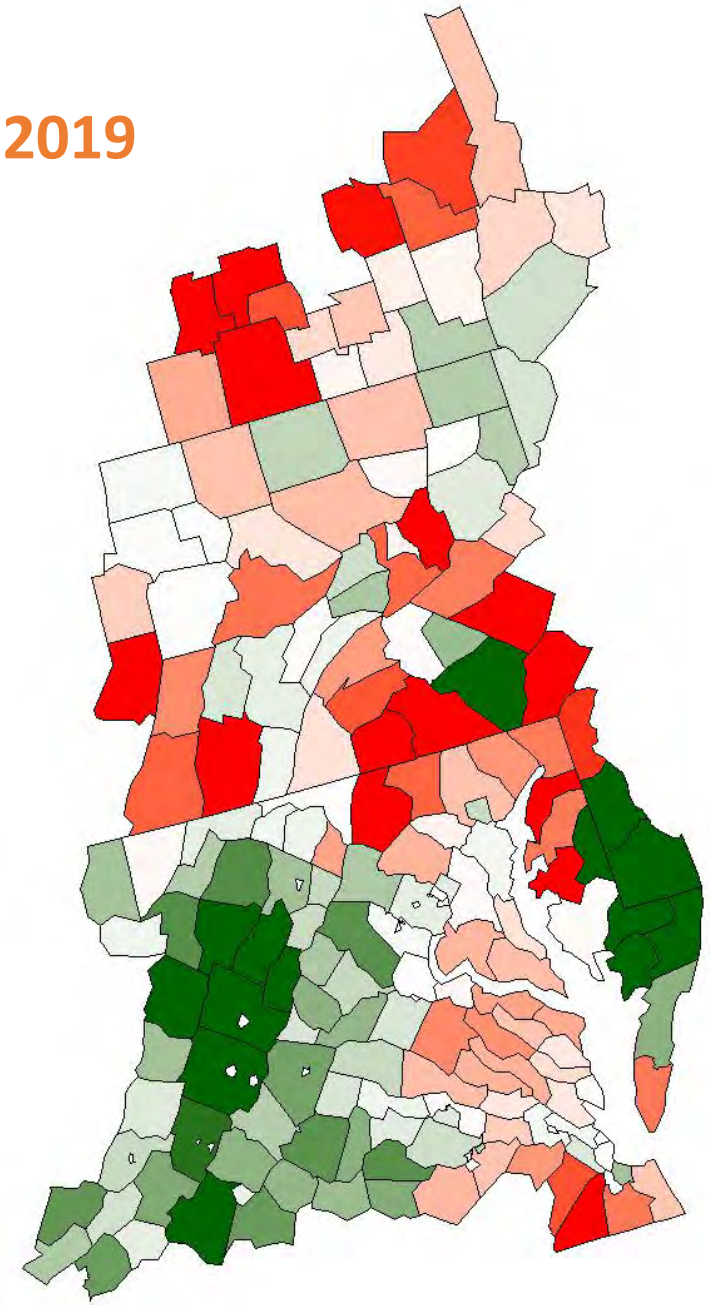
Unit: kgP



Green counties :
unrecycled waste
> cropland inorganic fertilizer input

Red counties:
unrecycled waste
< cropland inorganic fertilizer input

- **Waste recycle potential = unrecycled food and human waste - cropland inorganic fertilizer input**
- **Recycle potentials vary among counties.**



Result 3: Large potential to meet P demand by recycling waste

P difference between unrecycled waste and inorganic fertilizer input in 2019

Unit: kgP

200,000 and above

100,000

0

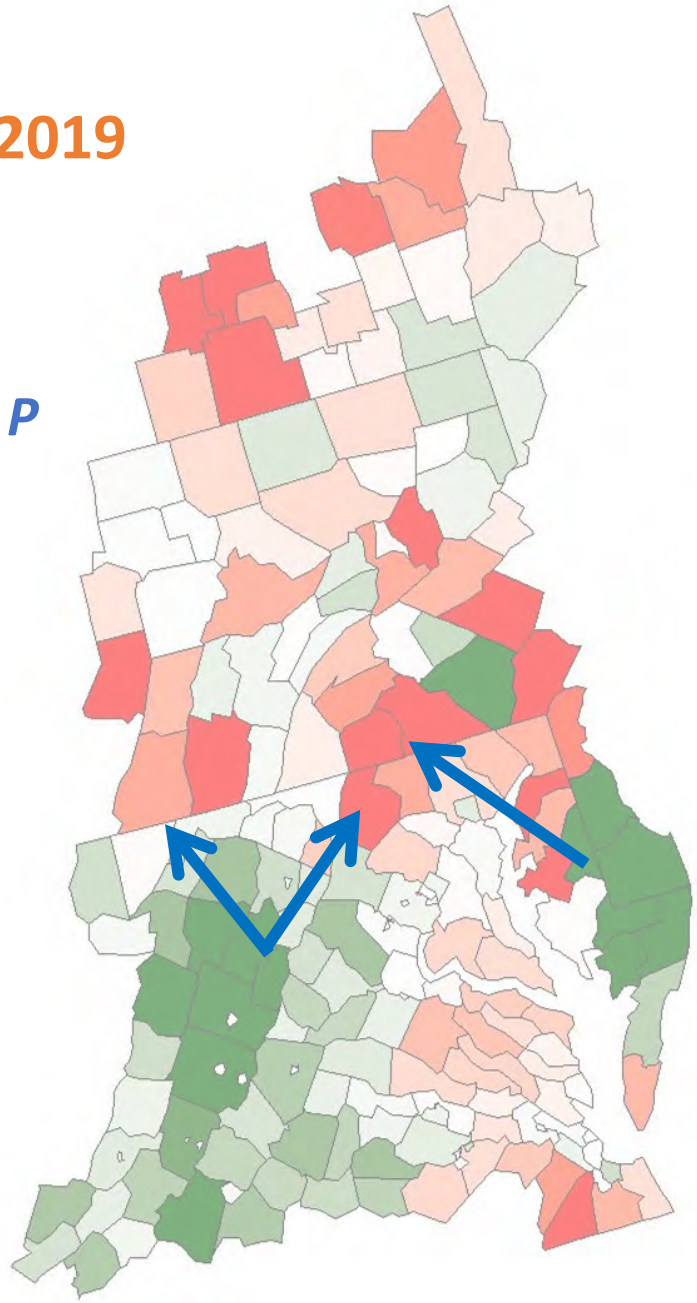
-100,000

-200,000 and below

Green counties :
unrecycled waste
> cropland inorganic fertilizer input

Transport P

Red counties:
unrecycled waste
< cropland inorganic fertilizer input



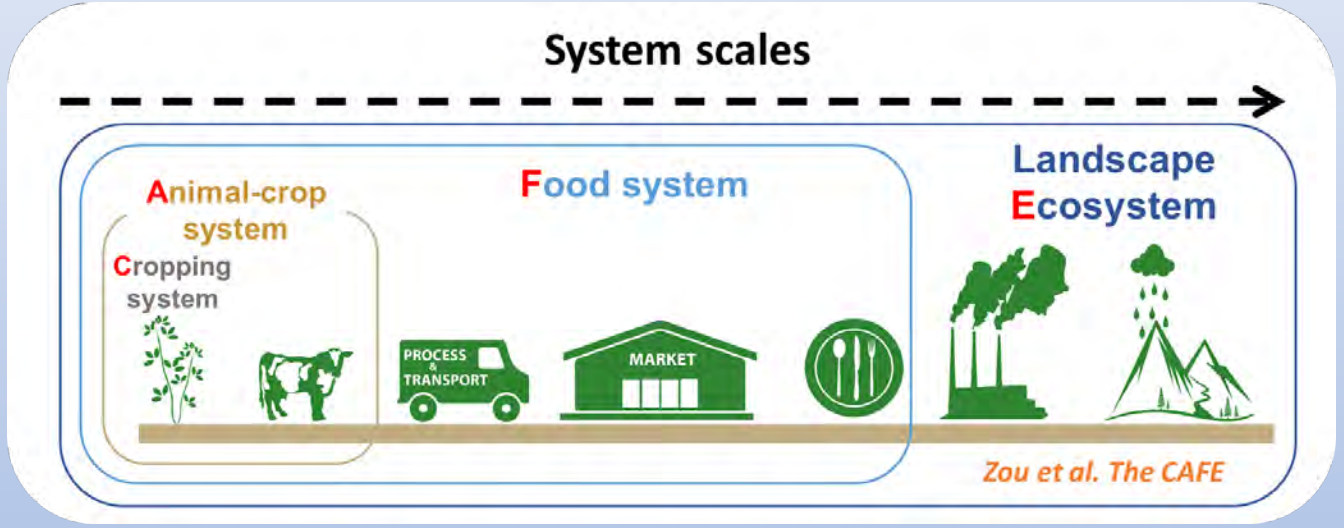
- **Waste recycle potential = unrecycled food and human waste - cropland inorganic fertilizer input**
- **Recycle potentials vary among counties.**
- **Transporting P from green counties to red counties to improve P recycling.**

Result 4: Potential drivers for P use

Agronomic drivers

Ecological drivers

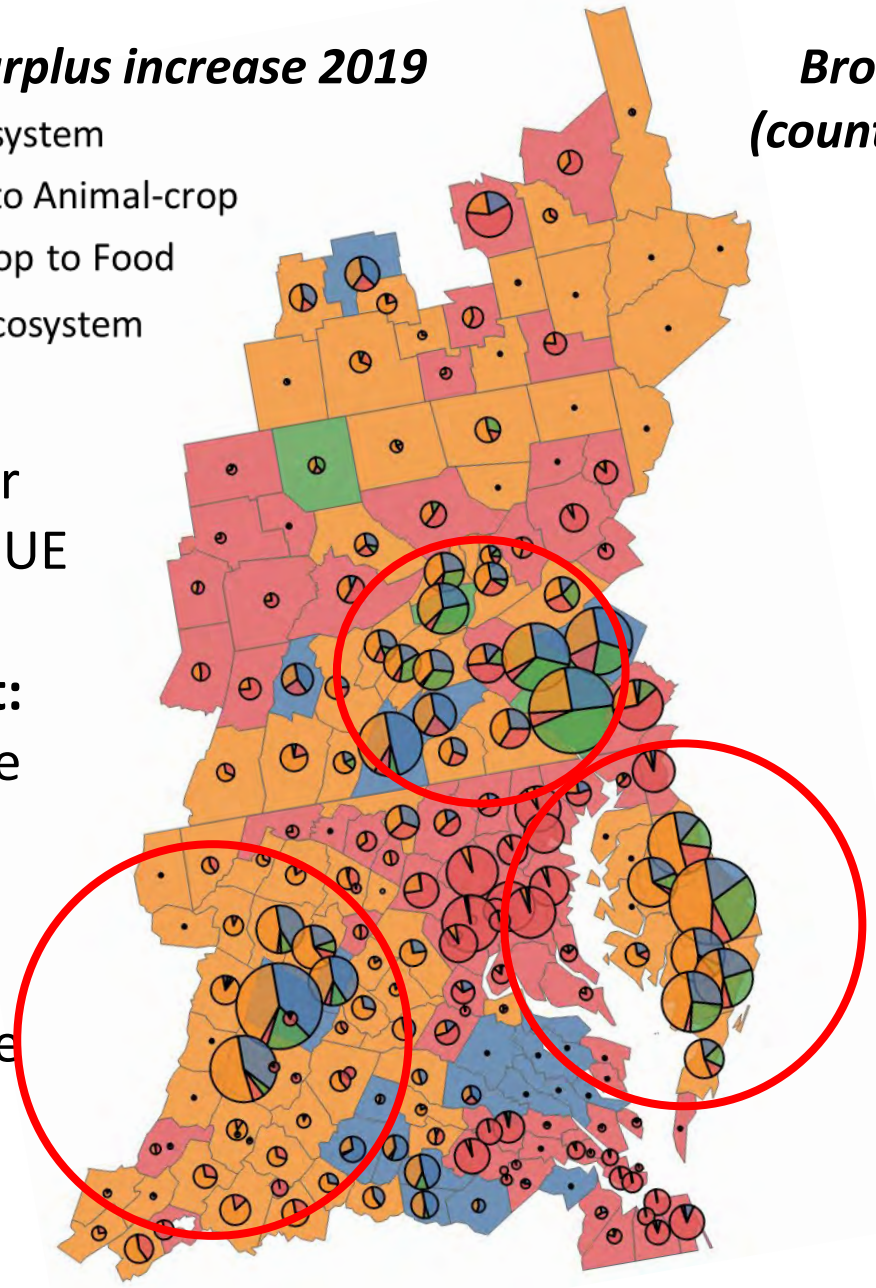
Socio-economic drivers



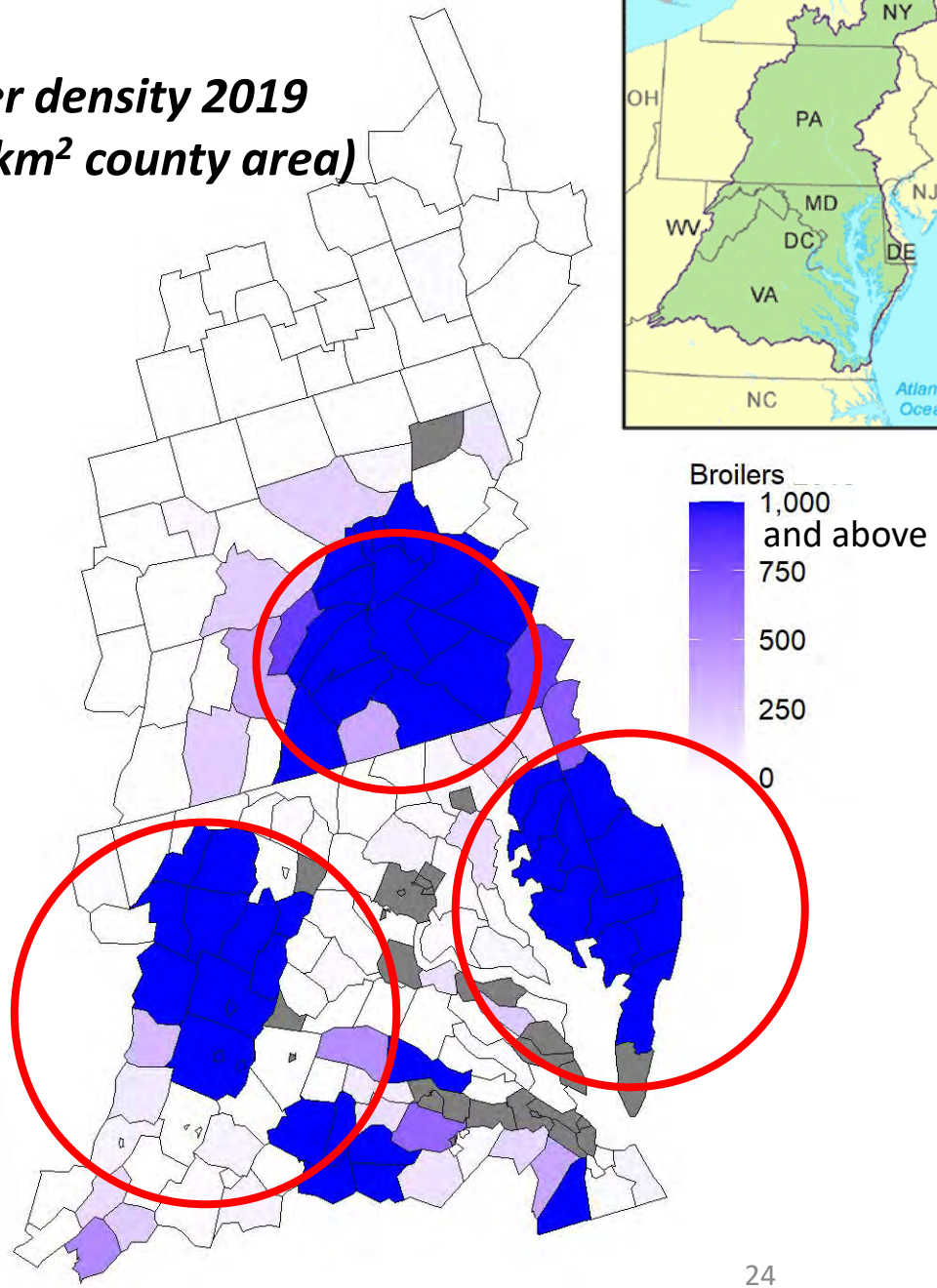
Result 4: Potential drivers for nutrient use

Largest P surplus increase 2019

- Cropping system
- Cropping to Animal-crop
- Animal-crop to Food
- Food to Ecosystem



Broiler density 2019 (count/km² county area)



Prepotential drivers:

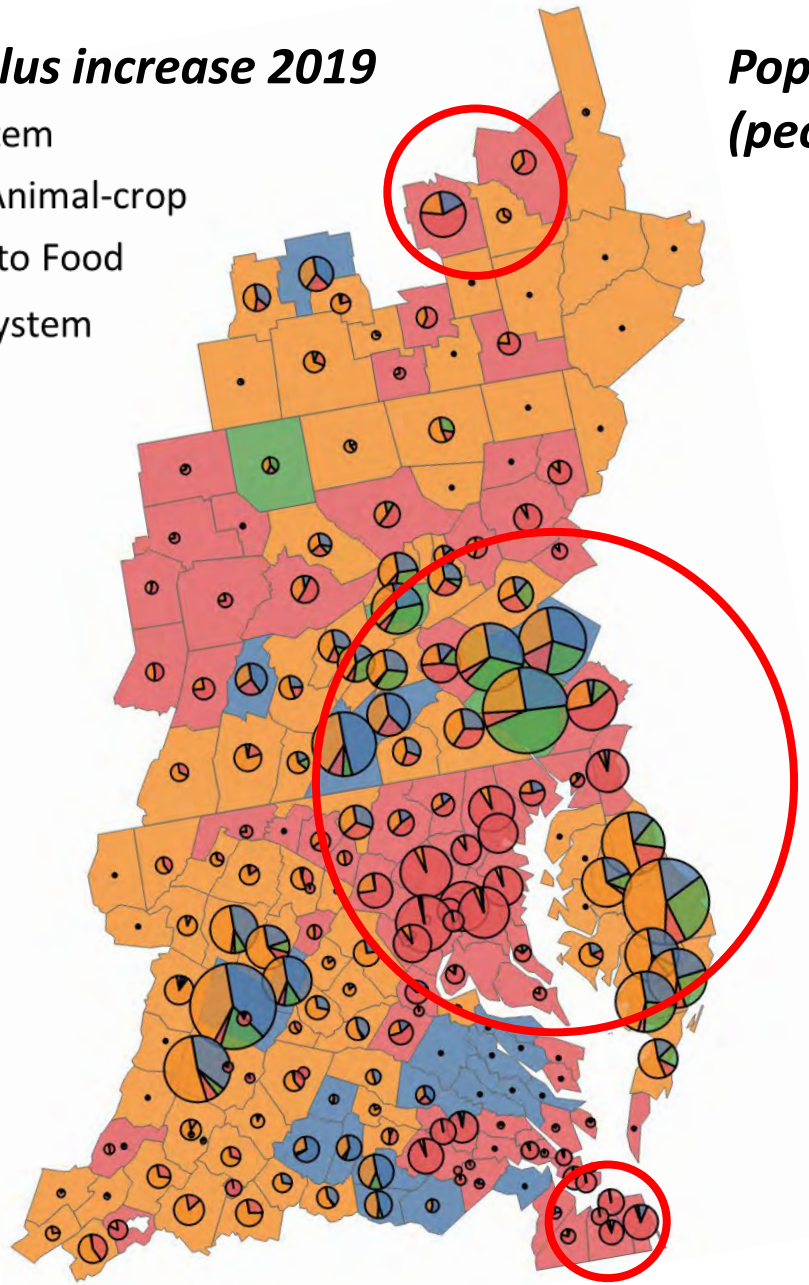
Animal production (broiler density) → Food system PUE

Pearson's correlation test:

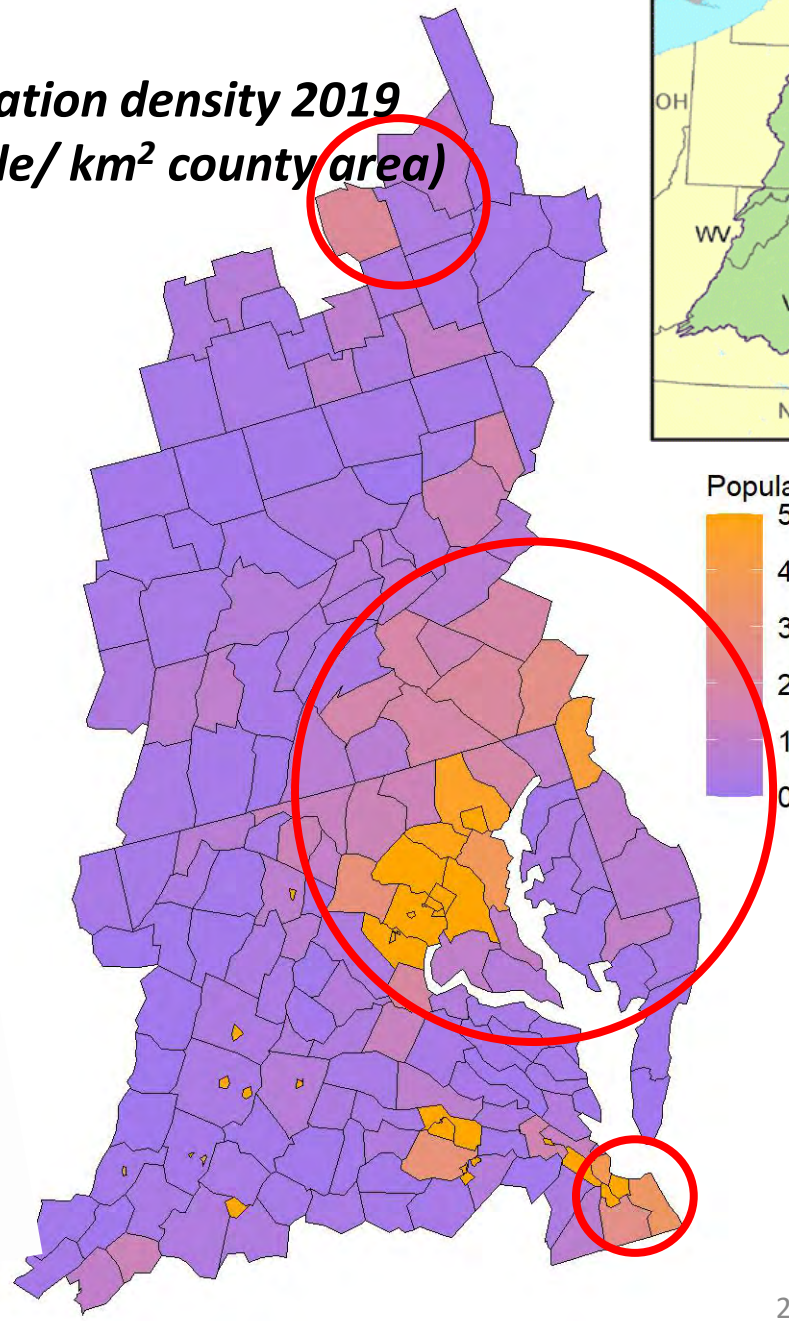
- significant and negative correlation across counties
- 60% counties show significant and negative correlation

Result 4: Potential drivers for nutrient use

Largest P surplus increase 2019



Population density 2019 (people/ km² county area)

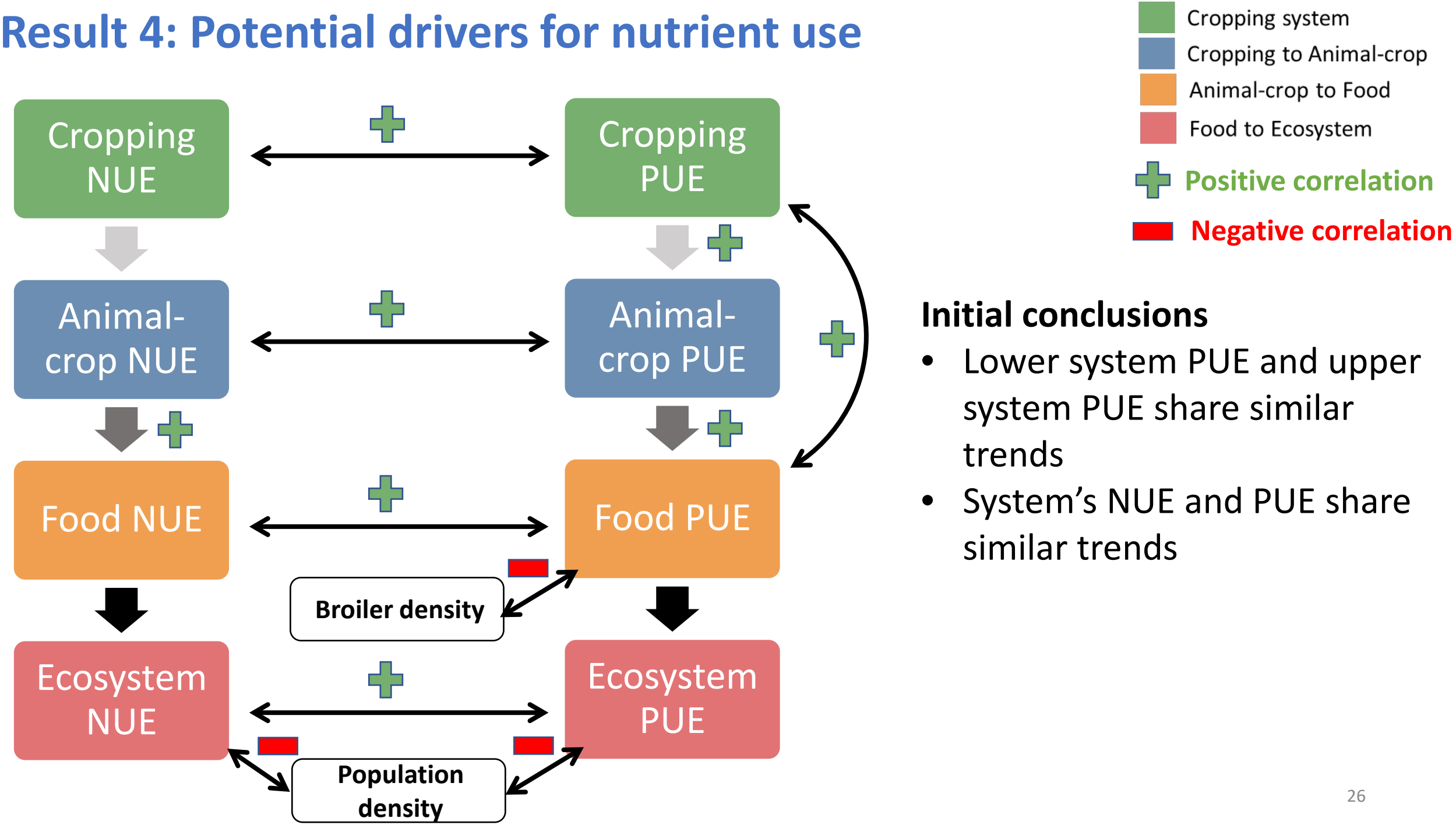


Prepotential drivers:
Population density → ecosystem PUE

Pearson's correlation test:

- significant and negative correlation across counties
- 52% counties show significant and negative correlation

Result 4: Potential drivers for nutrient use



Initial conclusions

- Lower system PUE and upper system PUE share similar trends
- System's NUE and PUE share similar trends

Take home messages

1. It is important to improve P management beyond crop farms.
2. P management gaps and priorities vary by region.
3. Considering P management across systems and spatial scales can serve to improve overall efficiencies
    1. Recycling food and human wastes to replace some inorganic fertilizer inputs to improve cropping system PUE
    2. Finding healthy and sustainable diets to improve all systems' PUE
4. Various socioeconomic factors affect P surplus, loss, and use efficiency.

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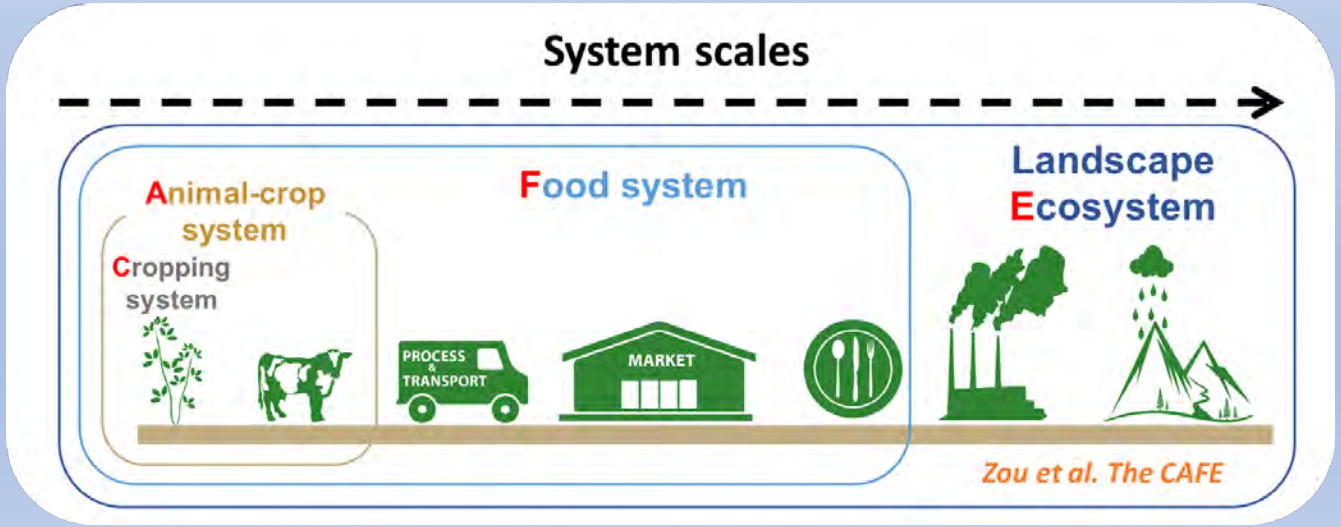
We would like to thank those who have contributed to our work:
Graham K. MacDonald (McGill University)
Robert Sabo (US Environmental Protection Agency)
Dong Liang (Chesapeake Biological Laboratory , Center for Environmental Science, University of Maryland)
Bill Dennison (Science Applications, University of Maryland Center for Environmental Science)
Olivia Devereux



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Quantifying and Mapping P-Flows in the Economy of Ontario, Canada

Edgar Martín Hernández, Jorge A. Garcia, Tian Zhao, Samantha Gangapersad, Roy Brouwer, Céline Vaneeckhaute, and Sidney Omelon

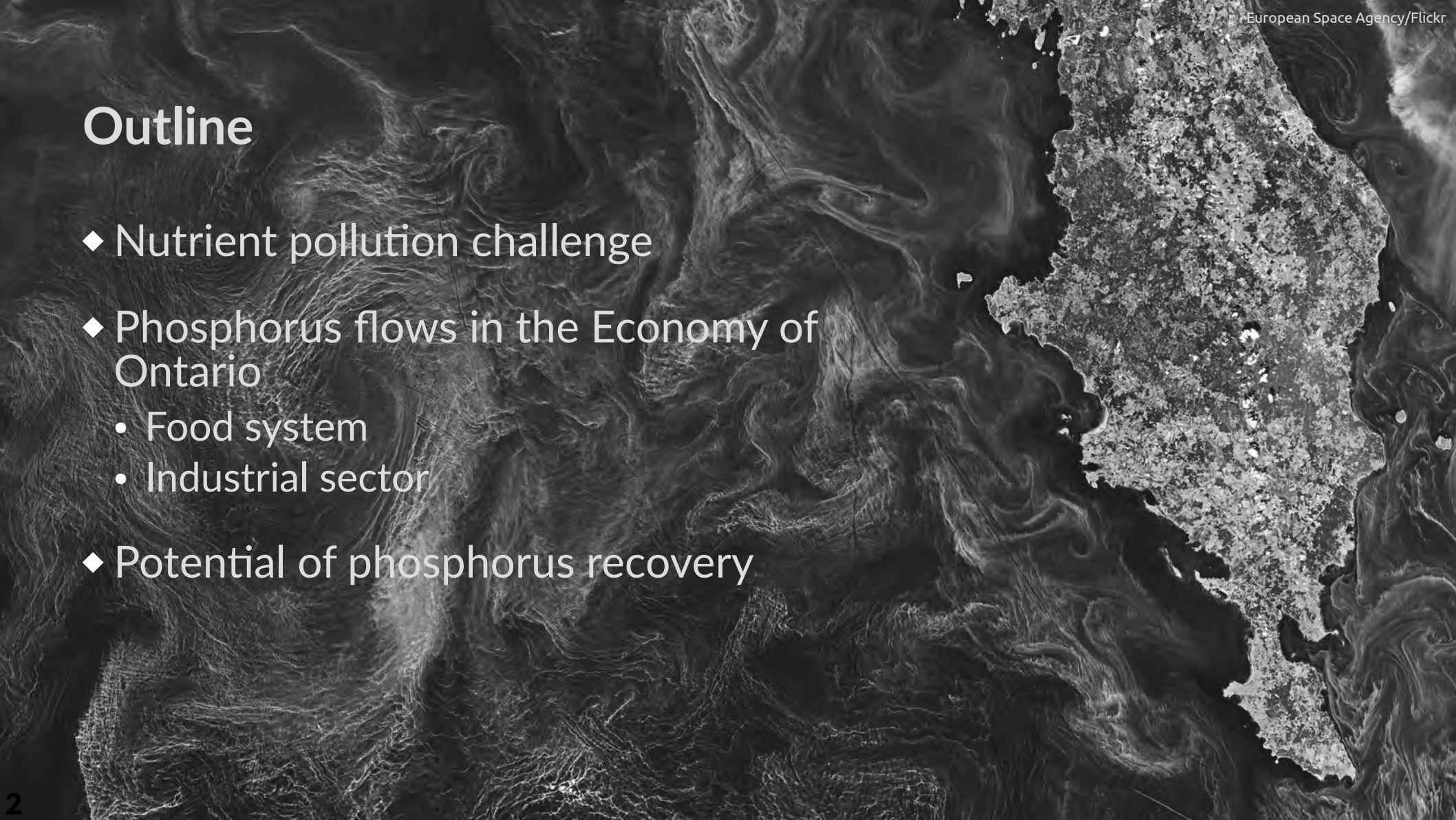
November 2022

UNIVERSITÉ LAVAL

BioEngine

McGill UNIVERSITY

UNIVERSITY OF WATERLOO



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Outline

- Nutrient pollution challenge
- Phosphorus flows in the Economy of Ontario
  - Food system
  - Industrial sector
- Potential of phosphorus recovery

European Space Agency/Flickr

Nutrient pollution challenge

Nutrient pollution is one of the major worldwide water quality problems

SUSTAINABLE DEVELOPMENT GOALS

Nutrient pollution is a major environmental threat

- Eutrophication
- Algal blooms

Algal blooms are a global and recurring environmental problem

Lake Erie,
United States & Canada

NASA, 2017, https://earthobservatory.nasa.gov/images/91038/lake-erie-abloom

NASA, 2019, https://earthobservatory.nasa.gov/images/145453/eerie-blooms-in-lake-erie

Geopolitical concerns: Phosphorus is one of the most sensitive elements to depletion

It is essential for food production

Phosphorus is a non-renewable material:

No synthetic substitute is known yet

P

Phosphorus

Reserves controlled by a few number of countries (mainly Morocco)

Phosphorus reserves are expected to be depleted in the next 50 to 100 years

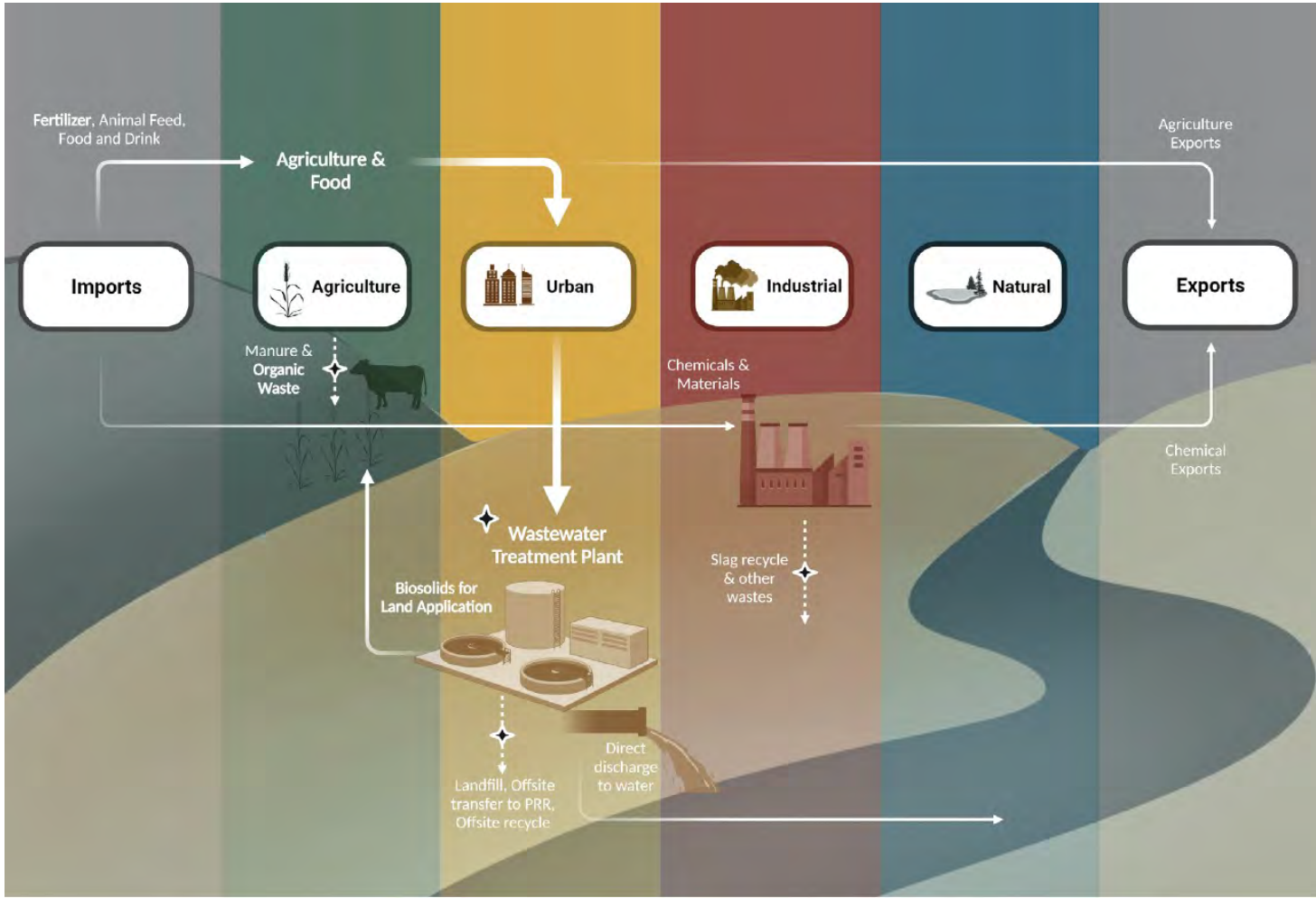
European Space Agency/Flickr

Phosphorus flows in the Economy of Ontario

Objectives

Map P flows in the province of Ontario

Highlight recovery options



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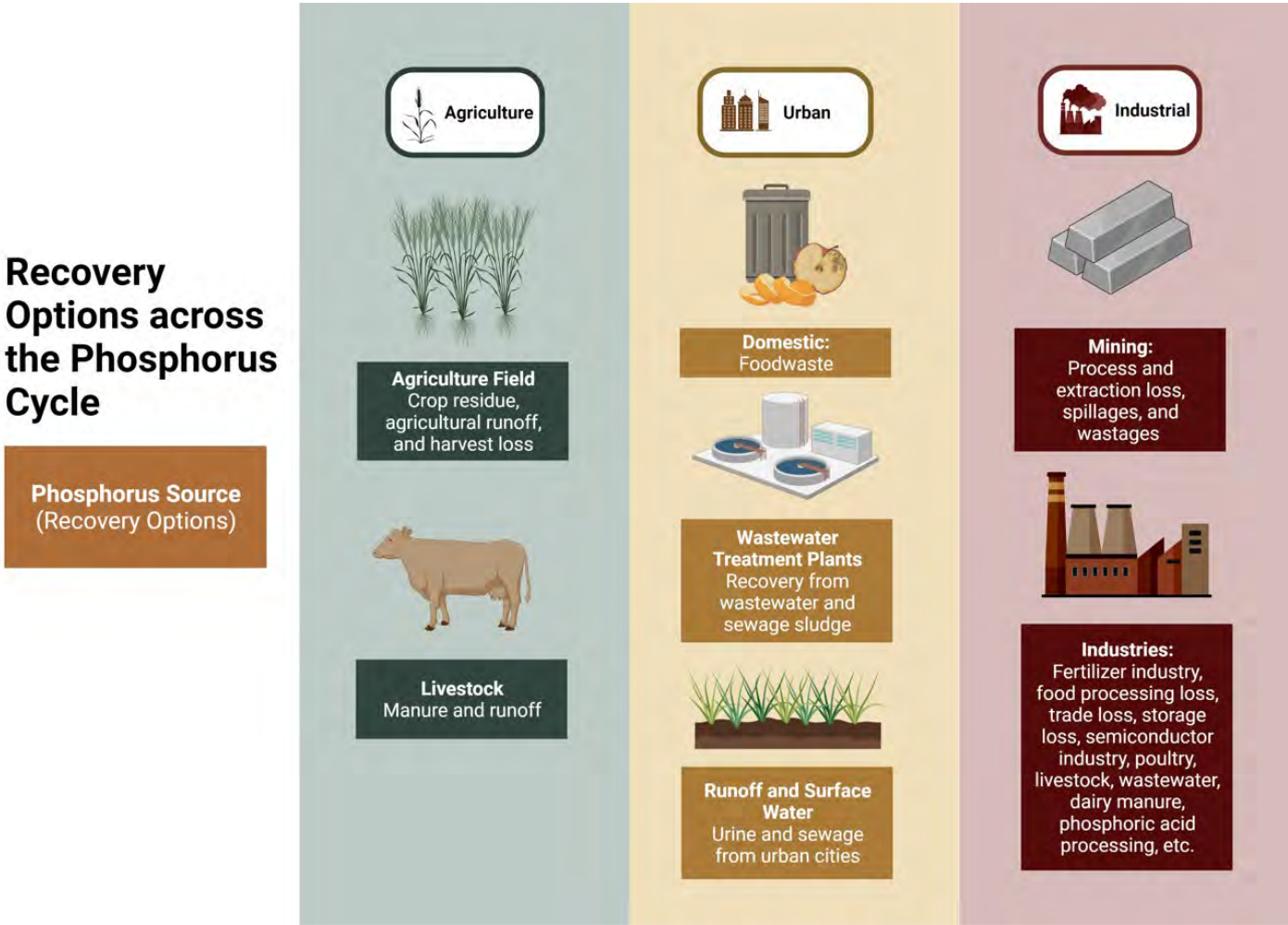
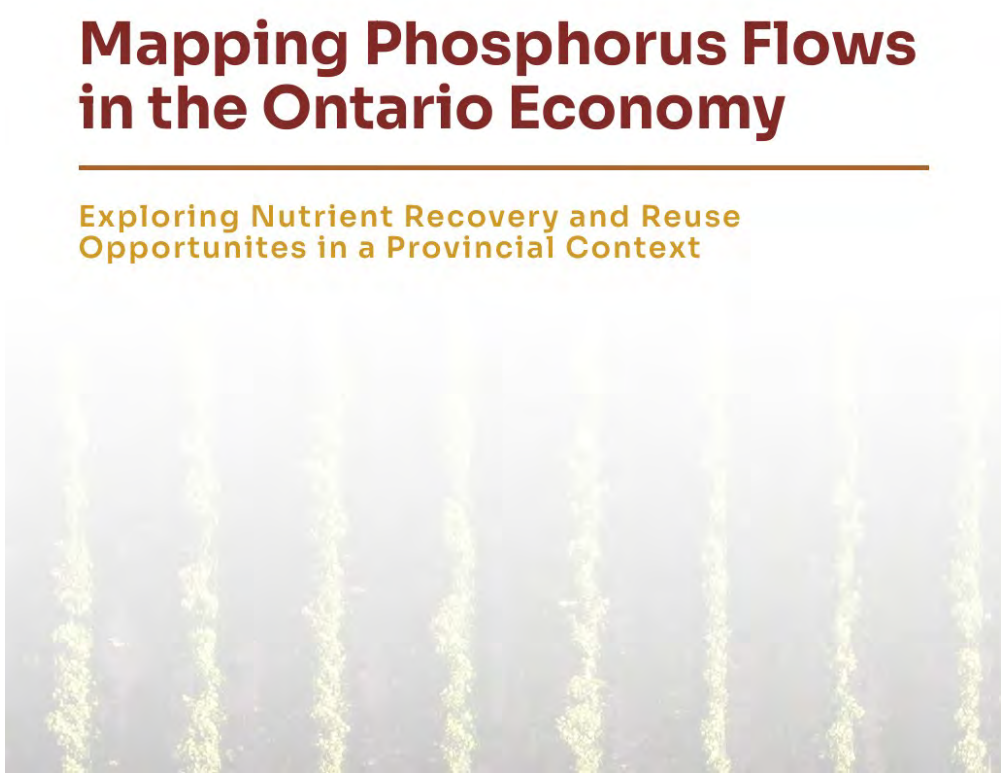


Report



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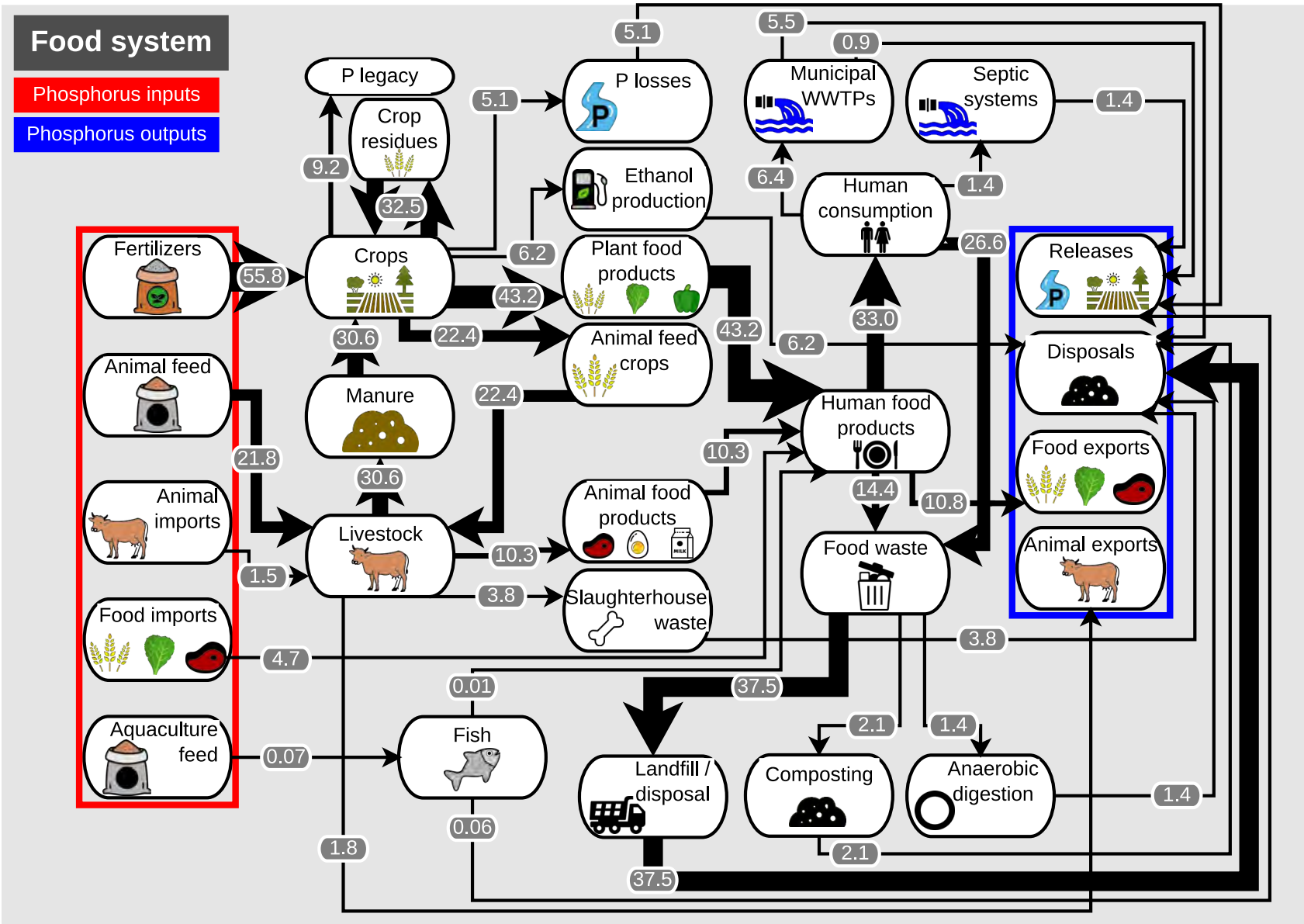
P flows

3 P flows networks:

- Food system
- Chemistry & steel industry
- Forestry industry



P flows in Ontario

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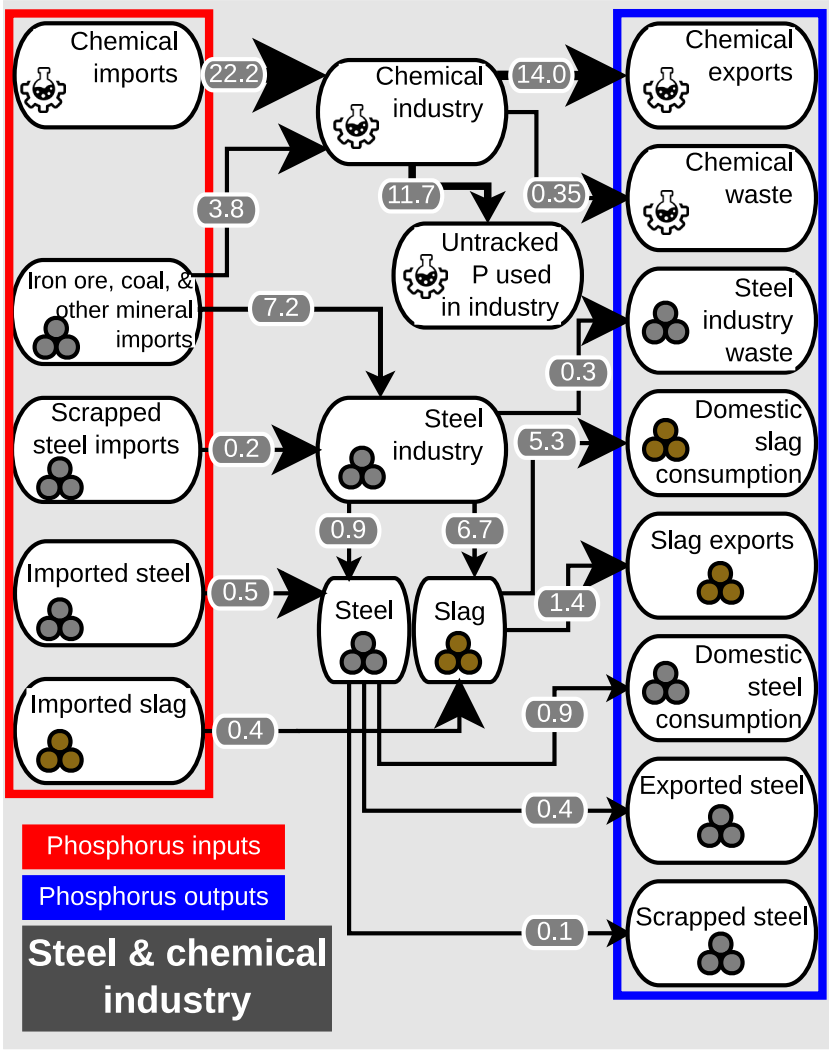
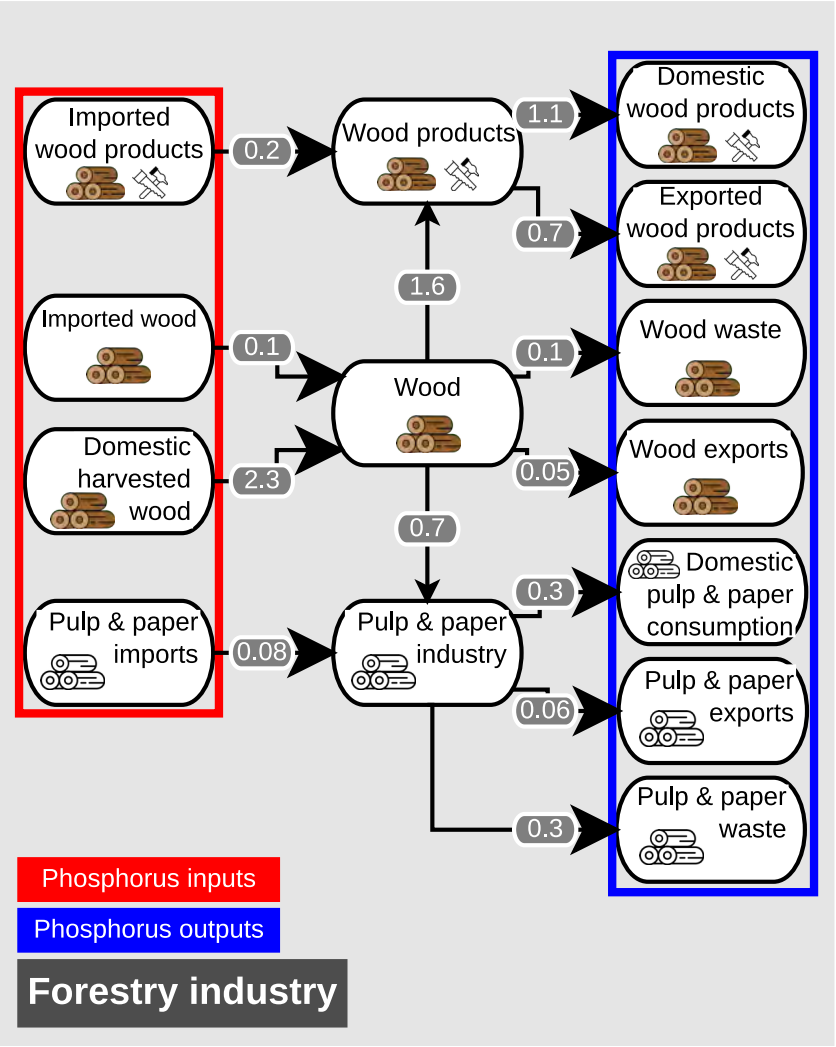
- Forestry industry





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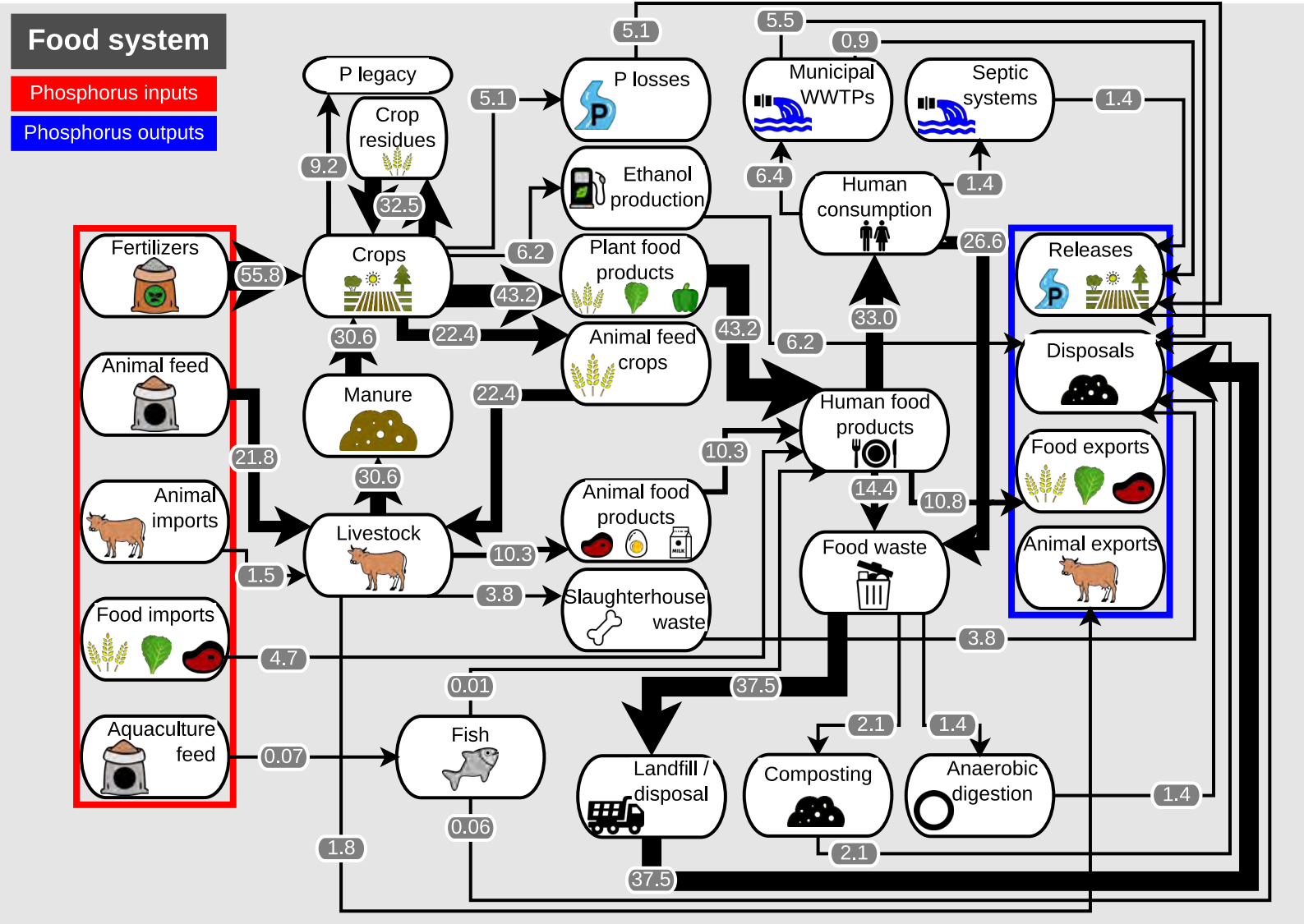
Phosphorus flows in the Economy of Ontario

- Food system

Food system flows

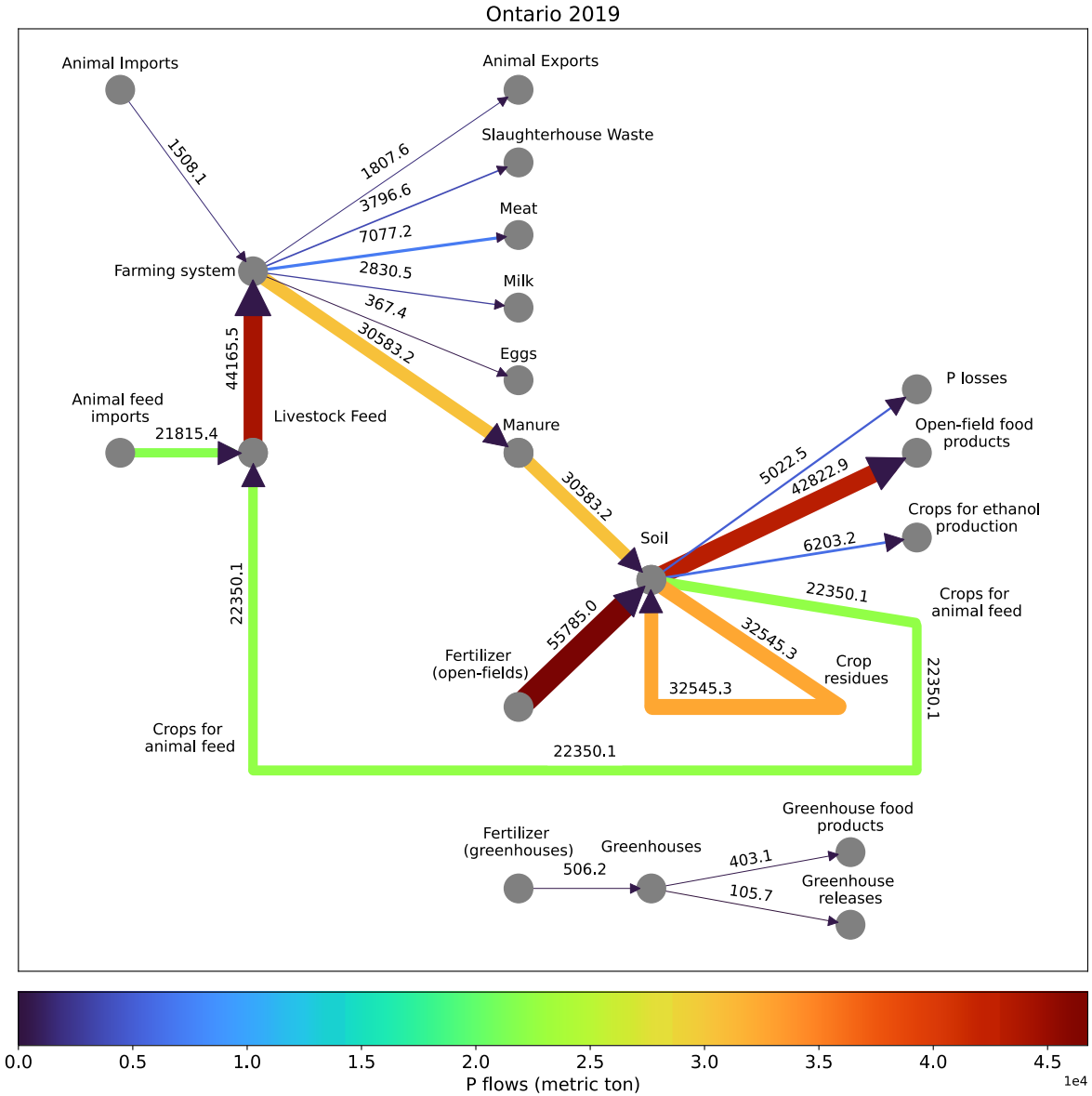


Agricultural flows

Provincial flows

Spatial distribution:

- Overall flows
- Livestock flows
- Crop flows



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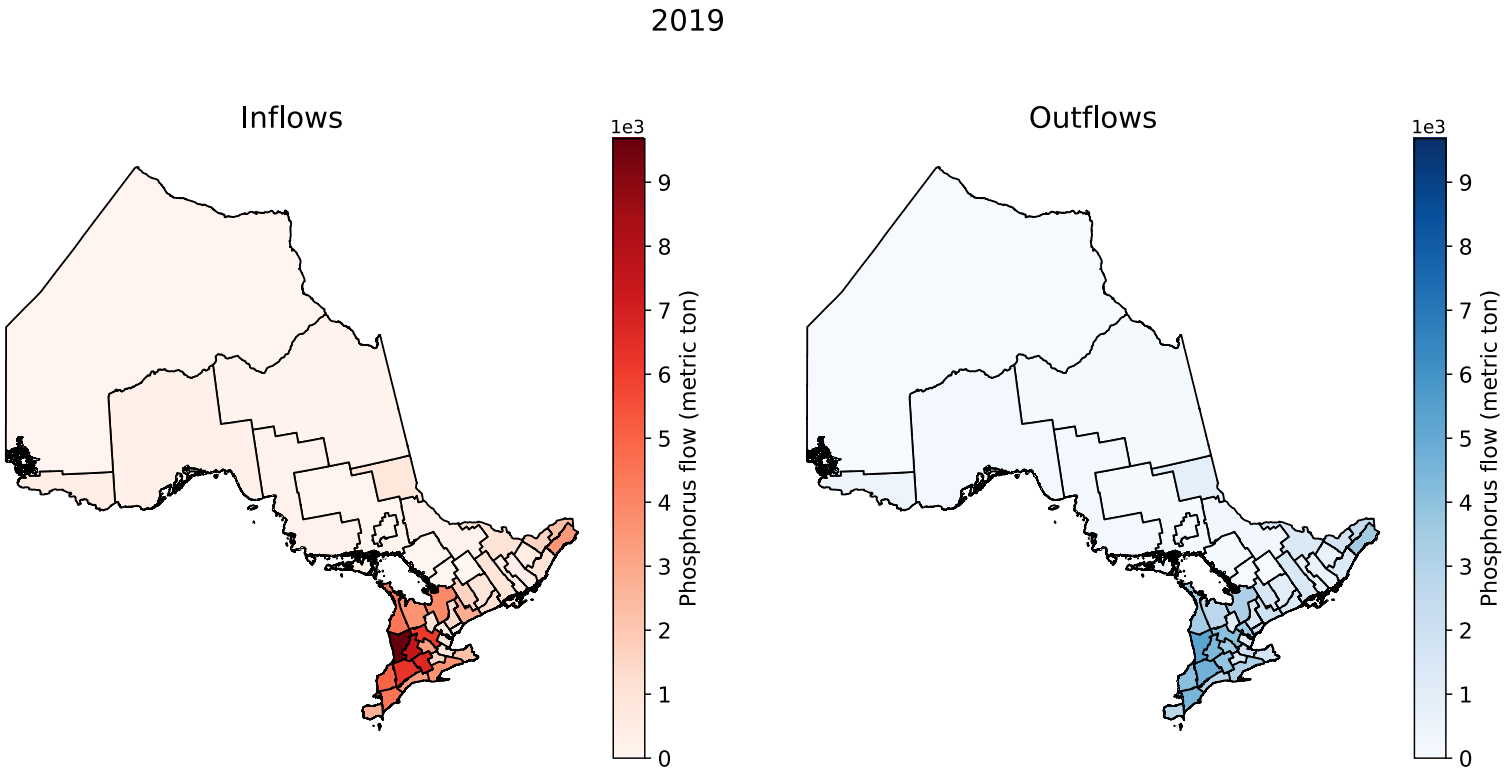

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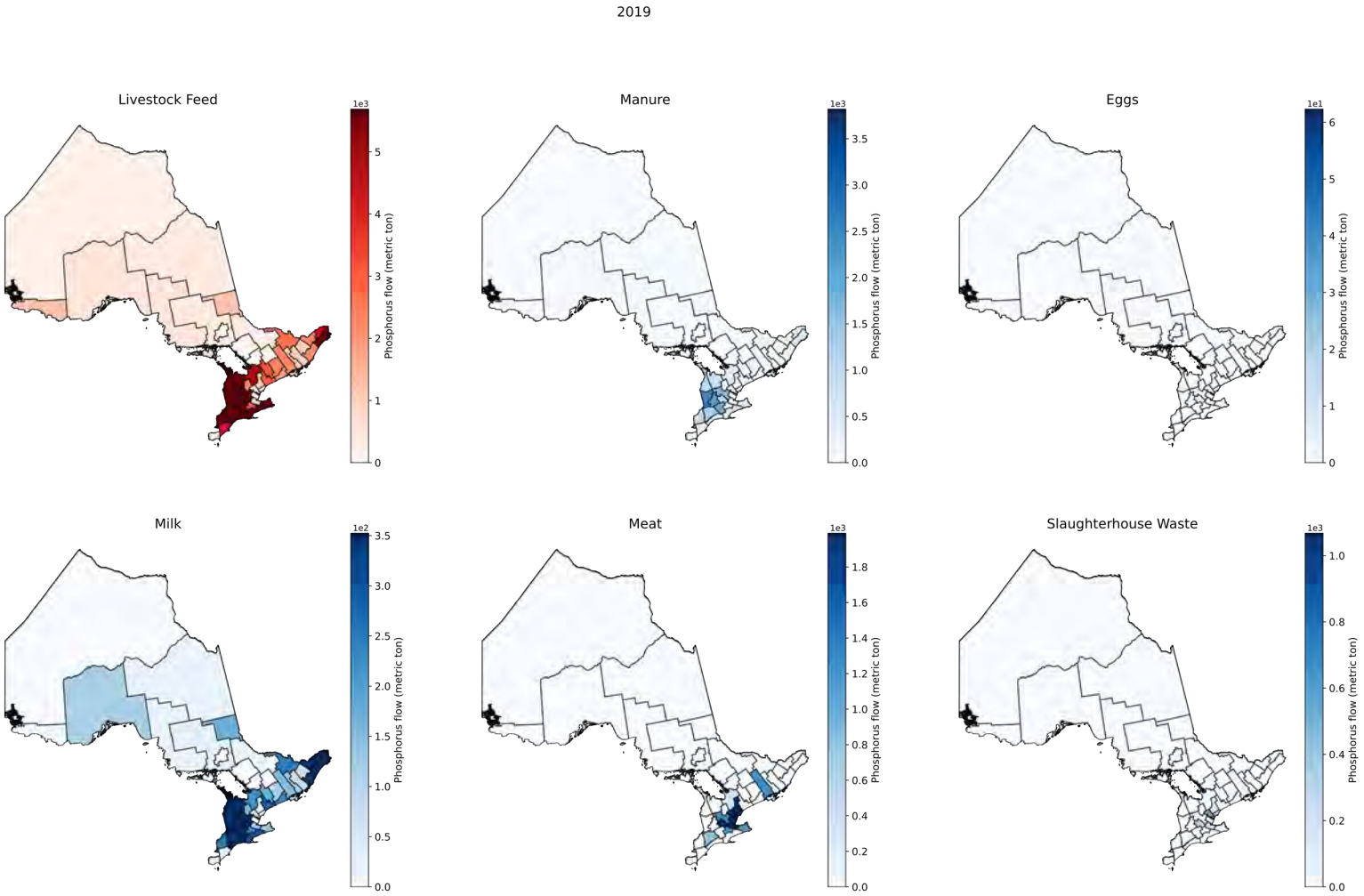
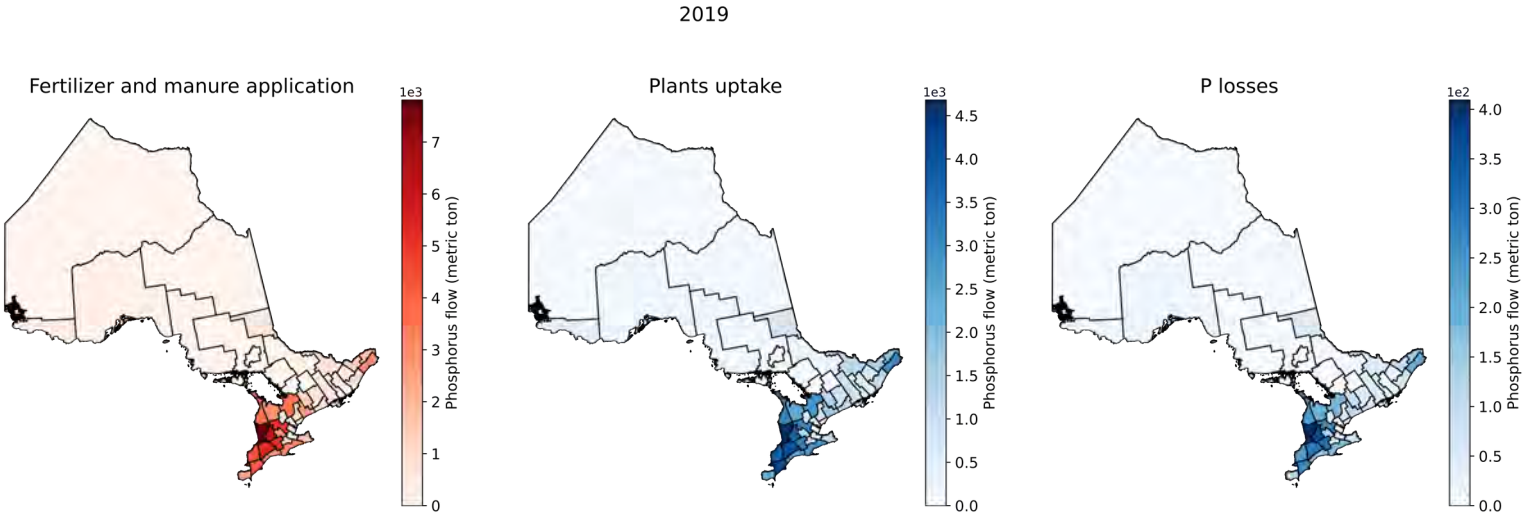


Agricultural flows

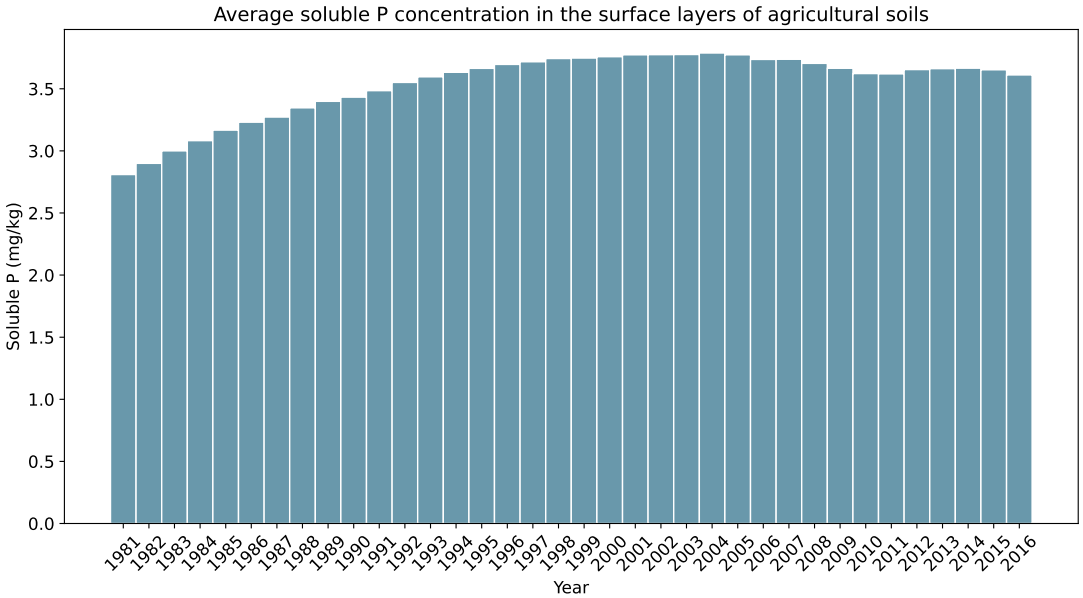
Provincial flows

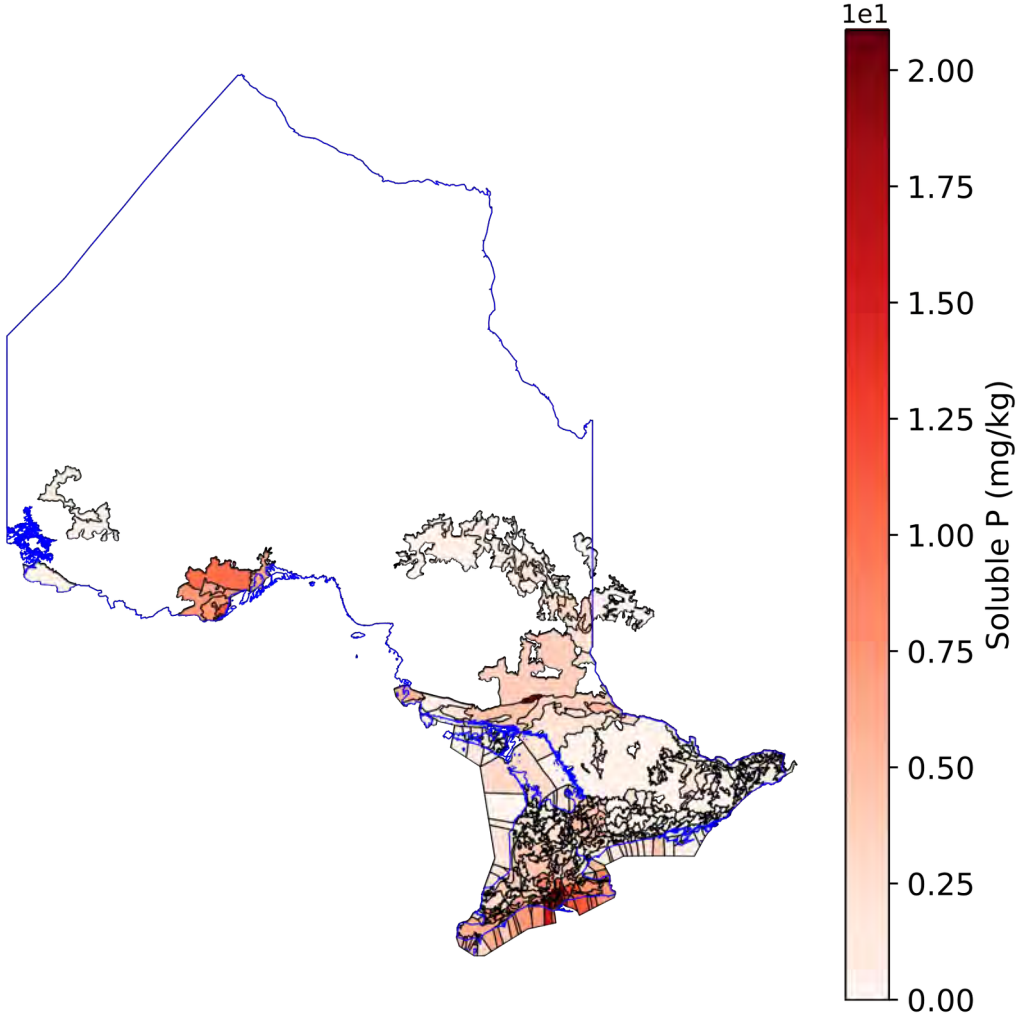


Spatial distribution:

- Overall flows
- Livestock flows
- Crop flows

Phosphorus legacy

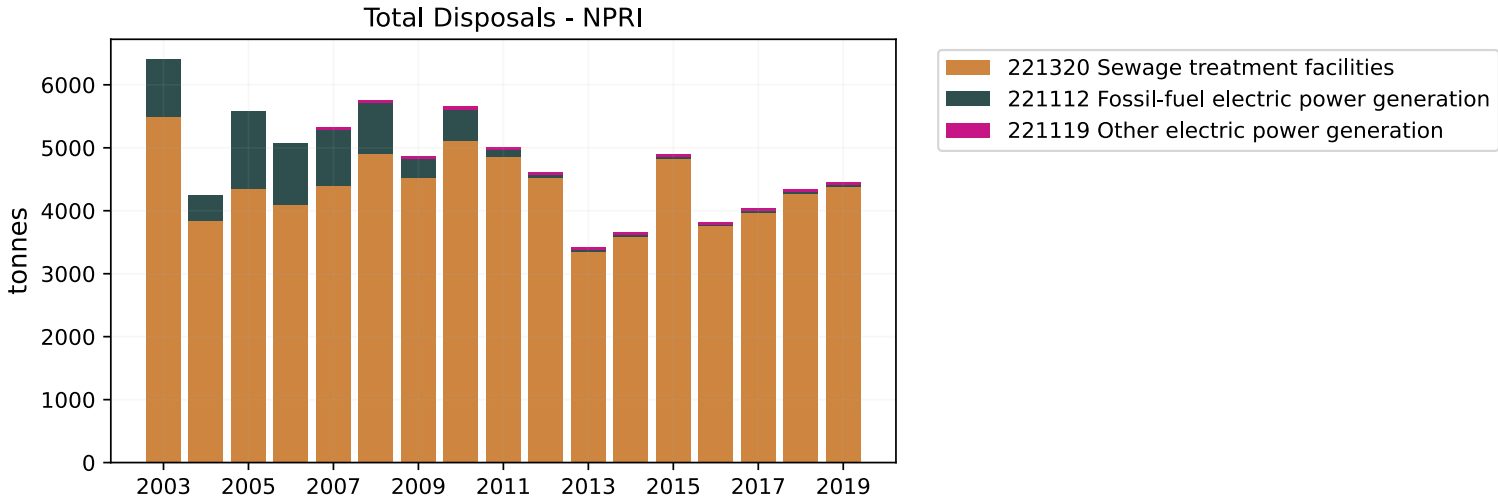


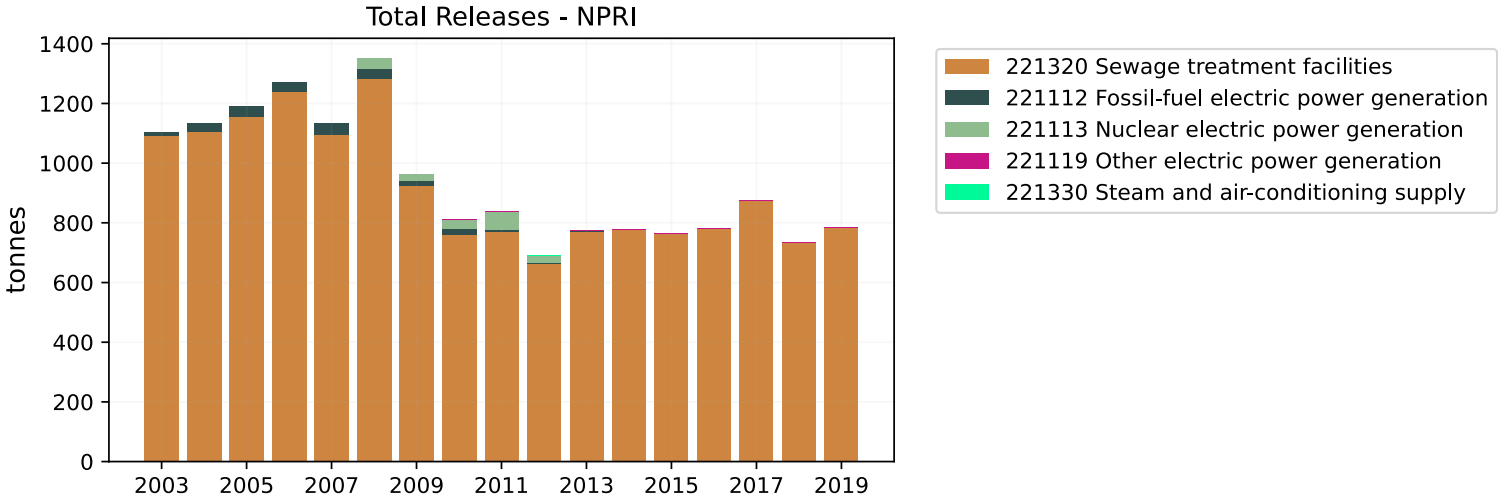


Wastewater flows

Releases and disposals

- Provincial flows
- Spatial distribution



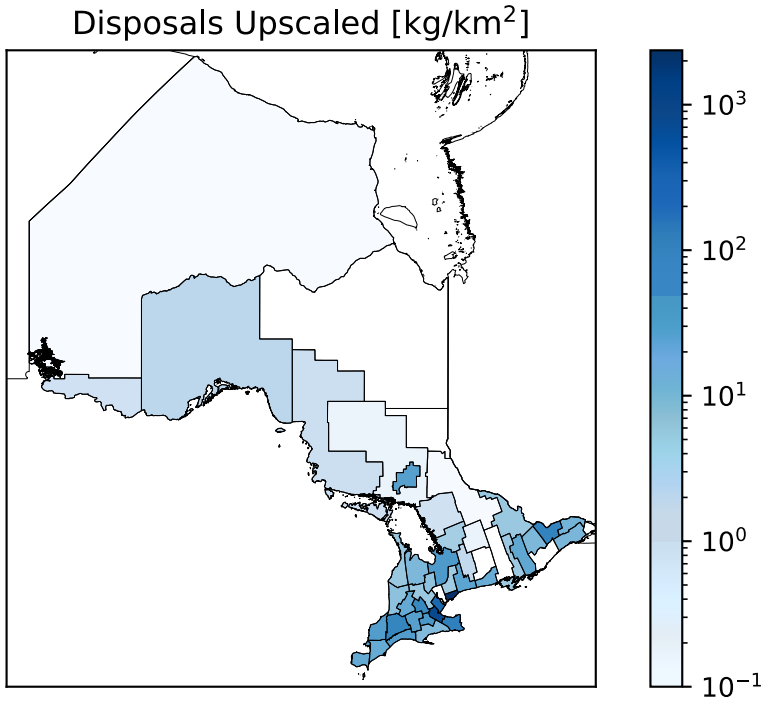


Wastewater flows

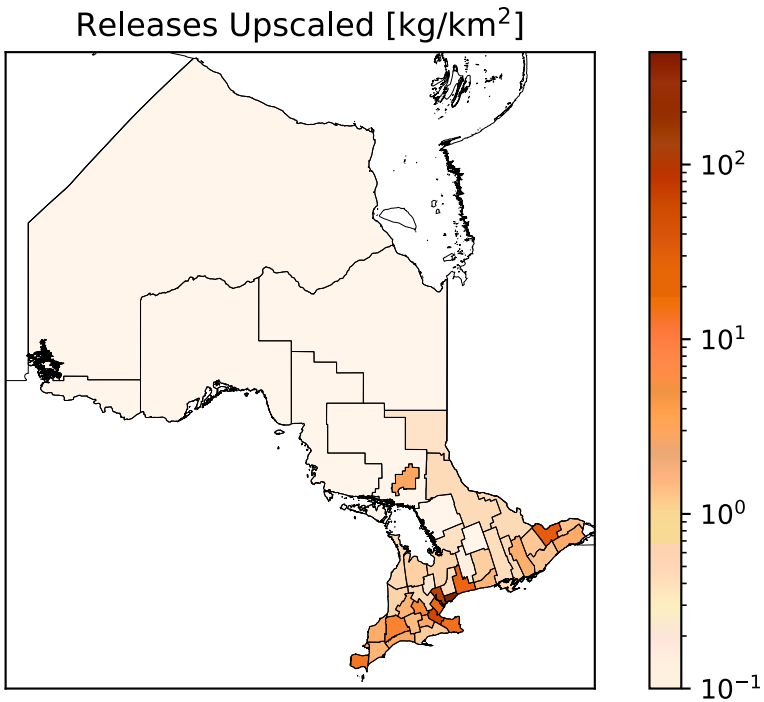
Releases and disposals

- Provincial flows
- Spatial distribution

Disposals (kg/km²)



Releases (kg/km²)

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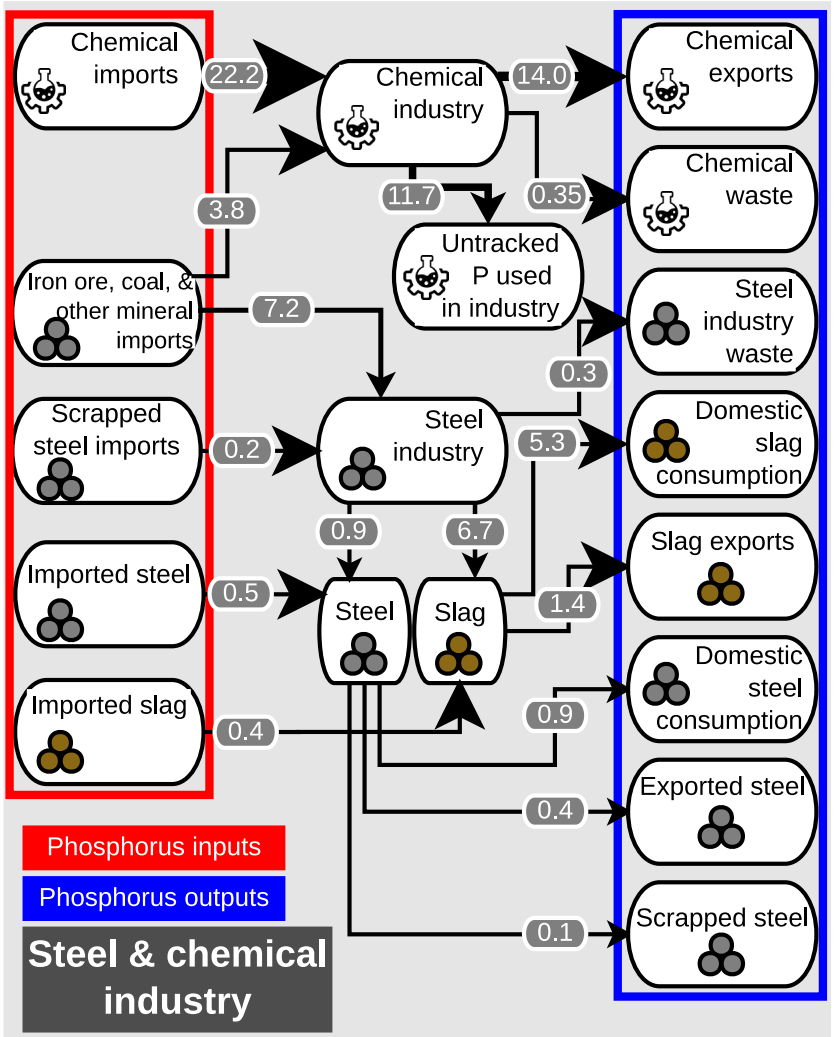
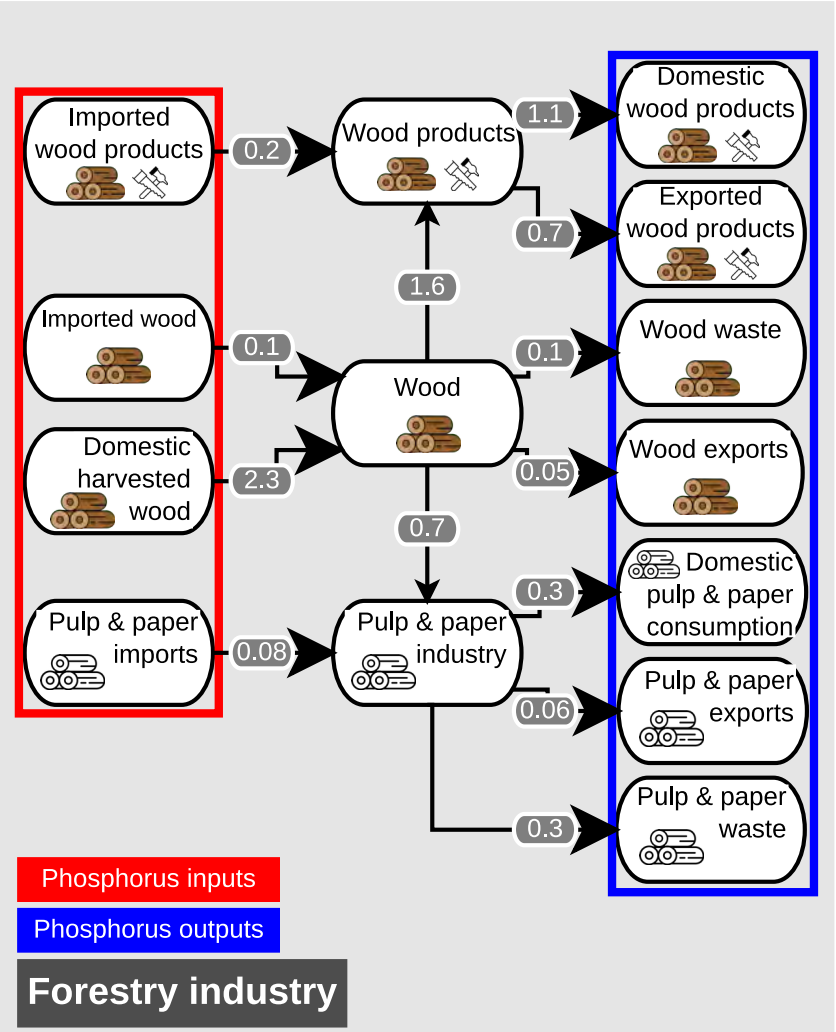
Phosphorus flows in the Economy of Ontario

- Industrial sector

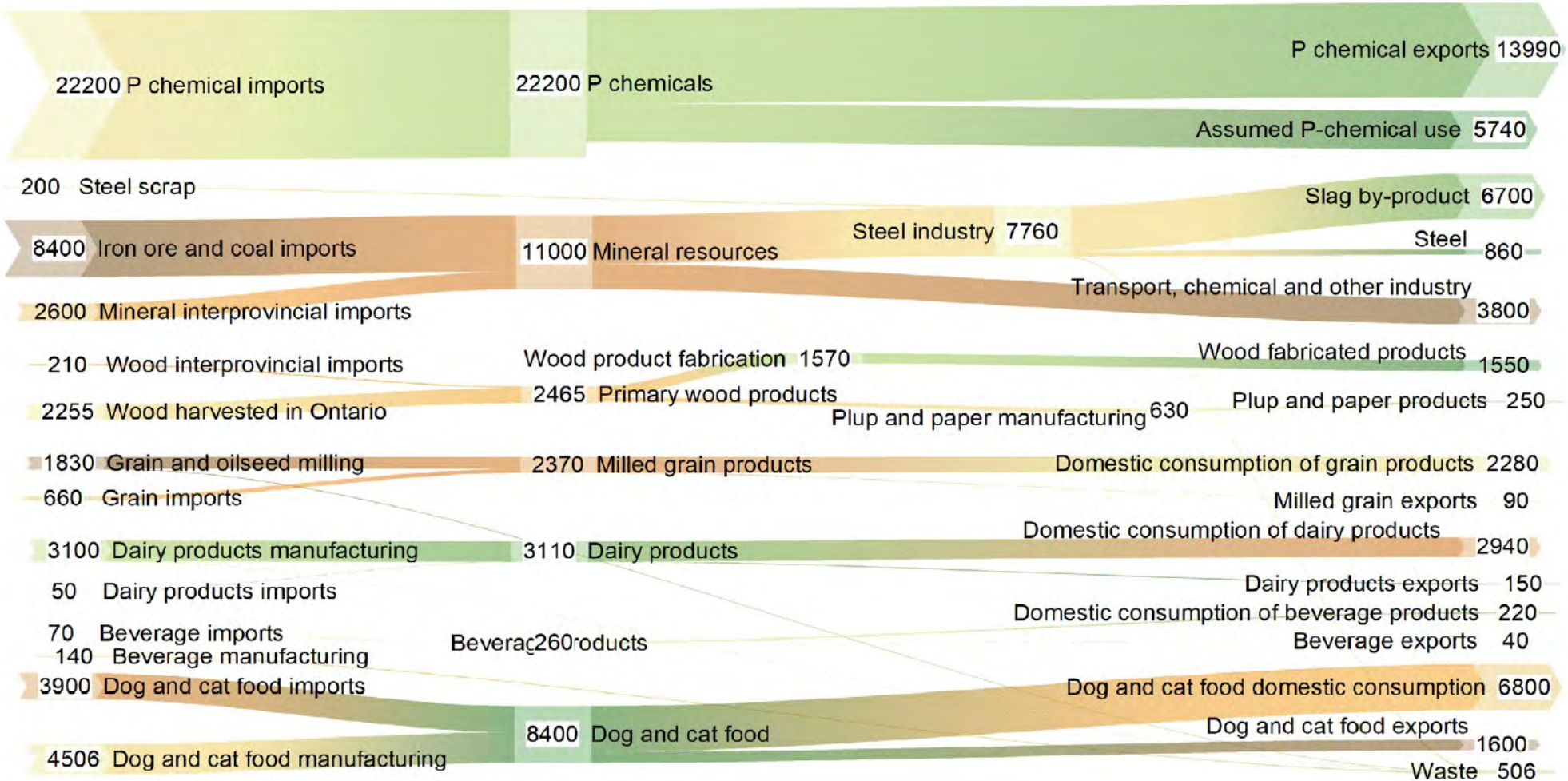
Overview


Chemical imports
22.2
Chemical industry
14.0
Chemical exports
Chemical waste
3.8
11.7
0.35
Untracked P used in industry
Iron ore, coal, & other mineral imports
7.2
Steel industry waste
0.3
Scrapped steel imports
0.2
Steel industry
5.3
Domestic slag consumption
0.9
6.7
Slag exports
Imported steel
0.5
Steel
Slag
1.4
Domestic steel consumption
Imported slag
0.4
0.9
Exported steel
0.4
Scrapped steel
0.1
Phosphorus inputs
Phosphorus outputs
Steel & chemical industry


Imported wood products
0.2
Wood products
1.1
Domestic wood products
0.7
Exported wood products
1.6
Imported wood
0.1
Wood
0.1
Wood waste
Domestic harvested wood
2.3
0.05
Wood exports
0.7
Pulp & paper imports
0.08
Pulp & paper industry
0.3
Domestic pulp & paper consumption
0.06
Pulp & paper exports
0.3
Pulp & paper waste
Phosphorus inputs
Phosphorus outputs
Forestry industry

Industrial flows (t/a)

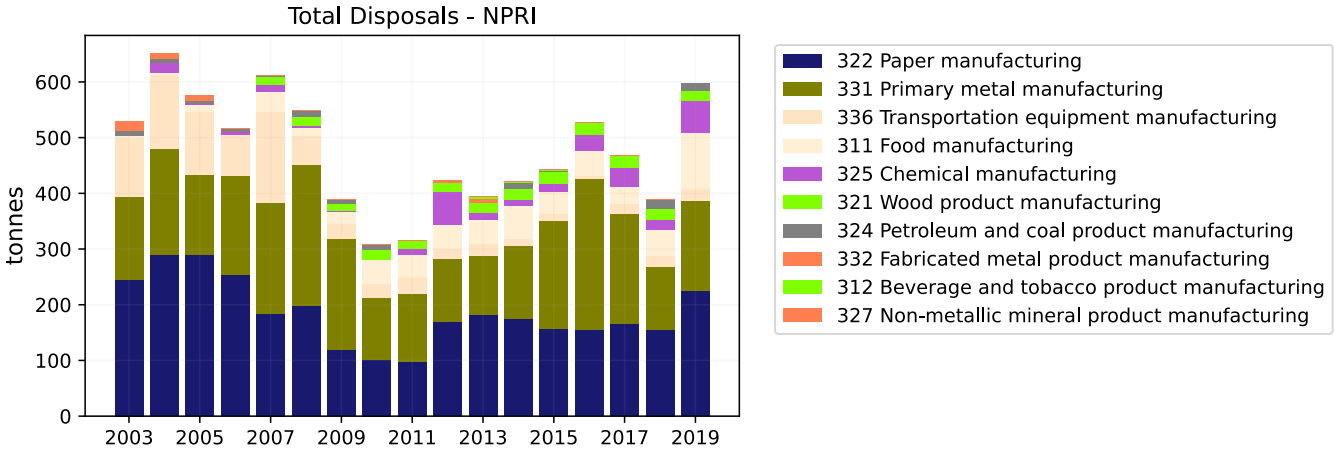
Provincial flows Spatial distribution



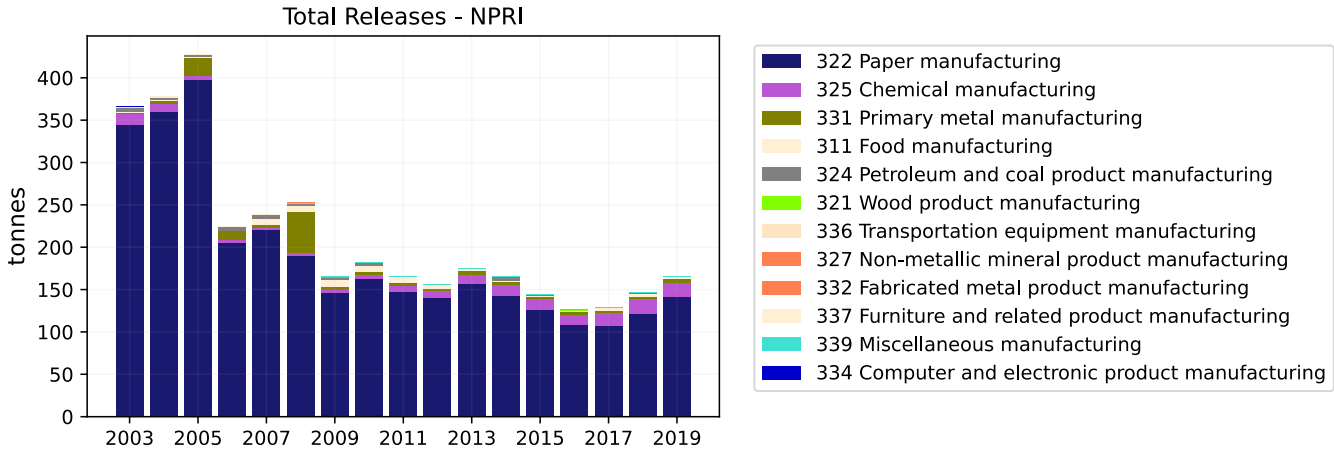
Industrial flows (t/a)

Provincial flows Spatial distribution

Releases



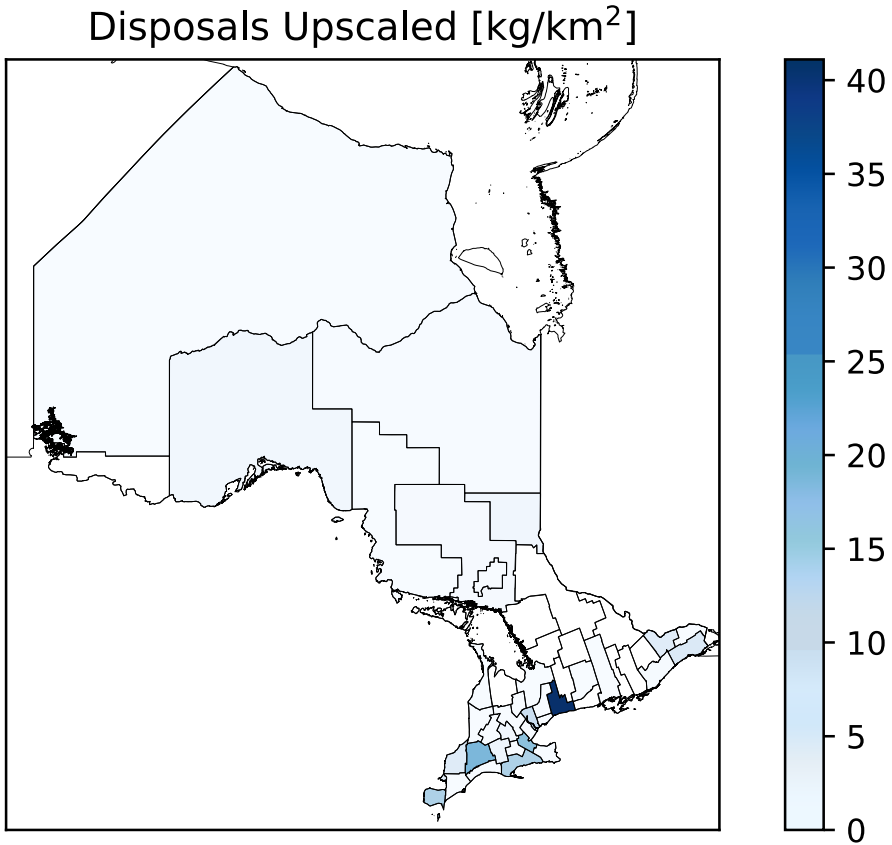
Disposals



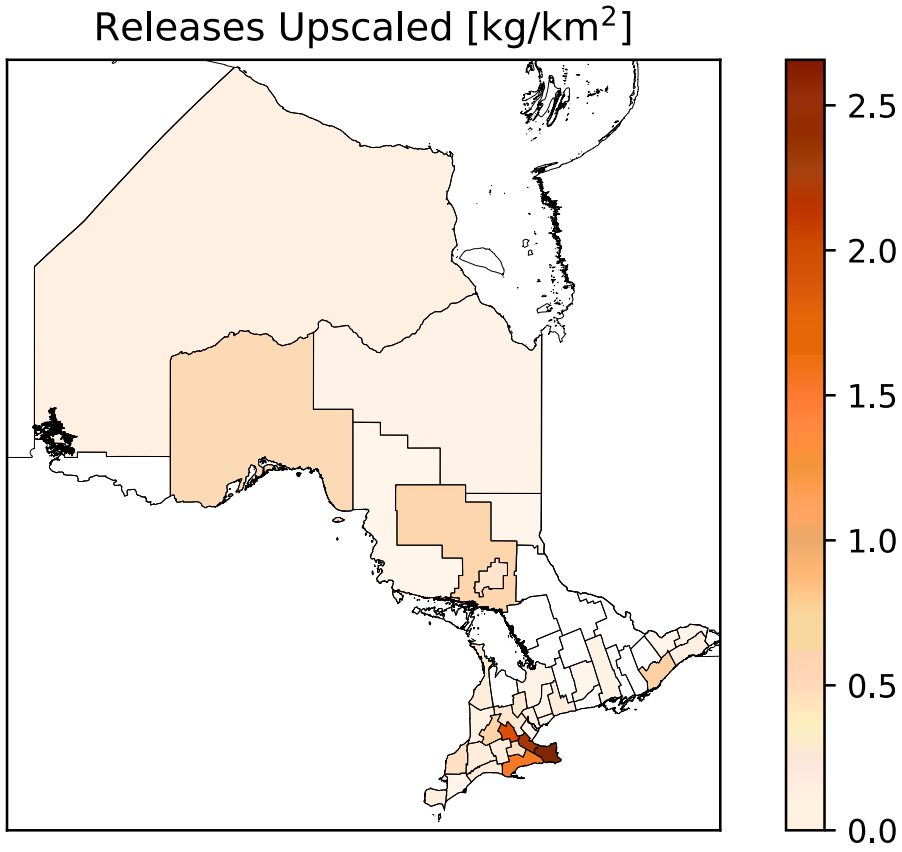
Industrial flows (t/a)

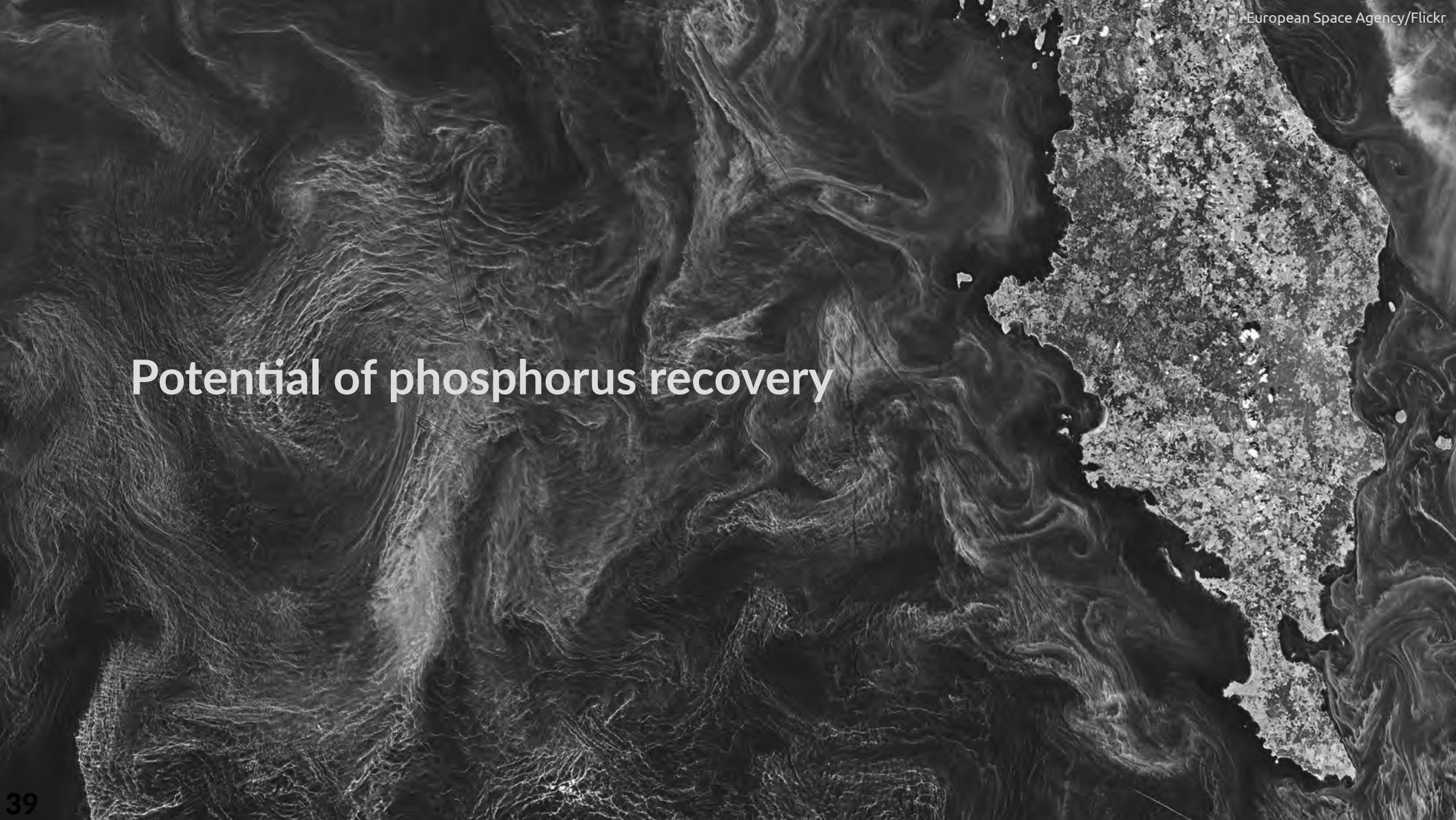
Provincial flows Spatial distribution

Disposals (kg/km²)



Releases (kg/km²)





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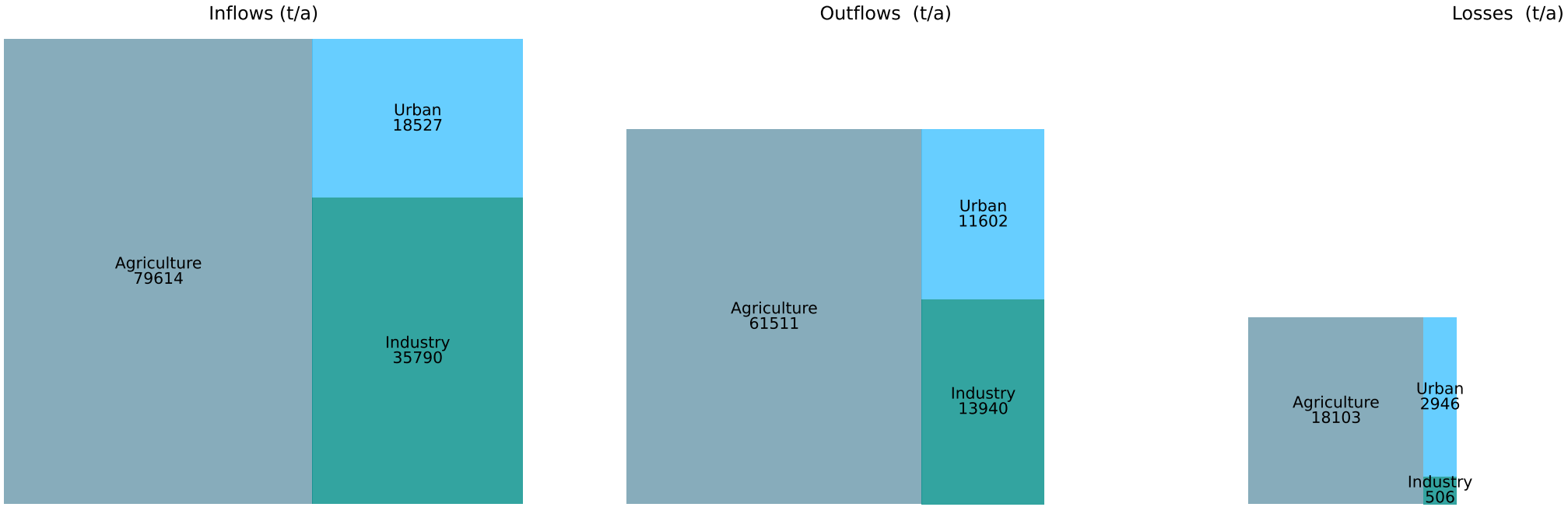
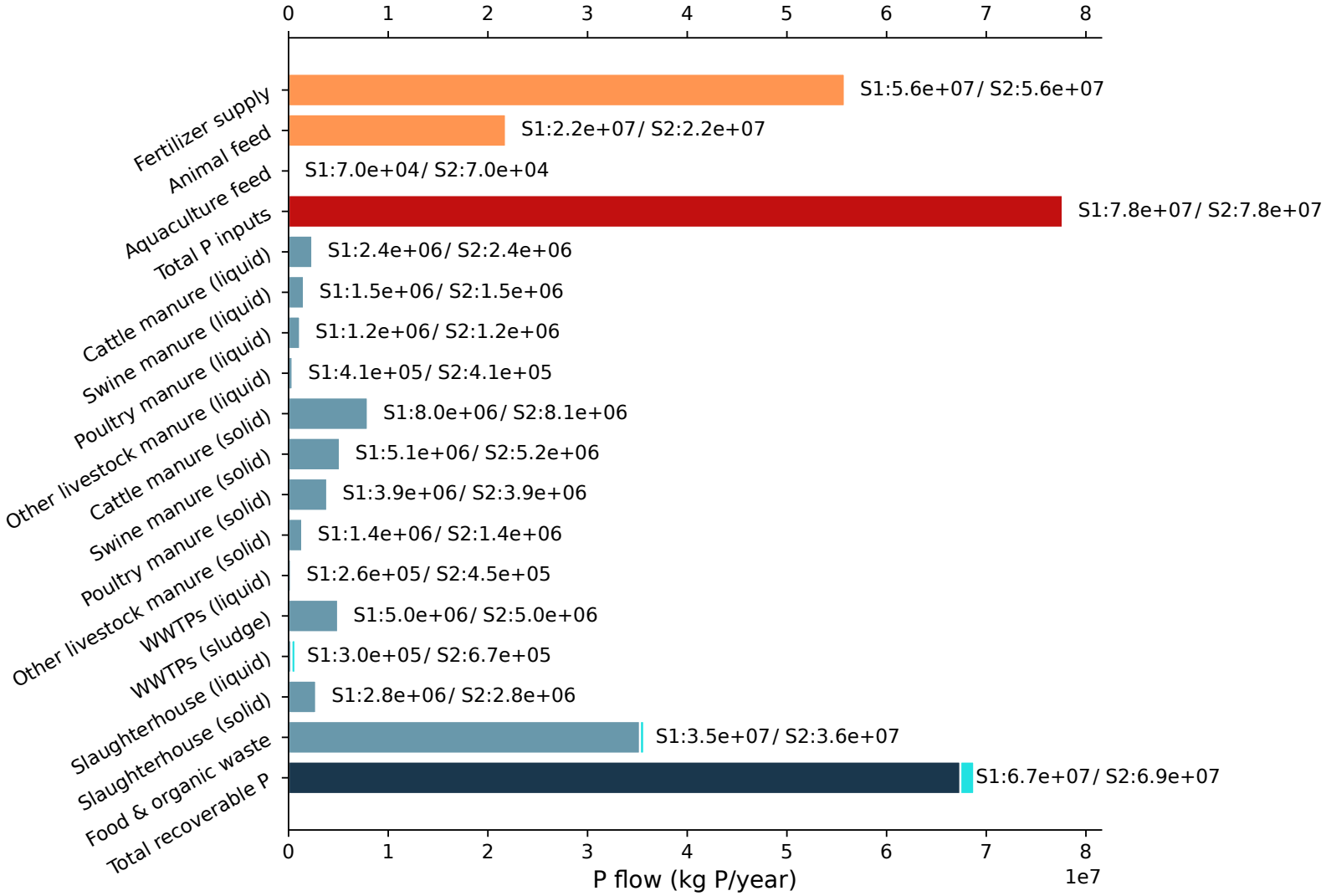
Potential of phosphorus recovery

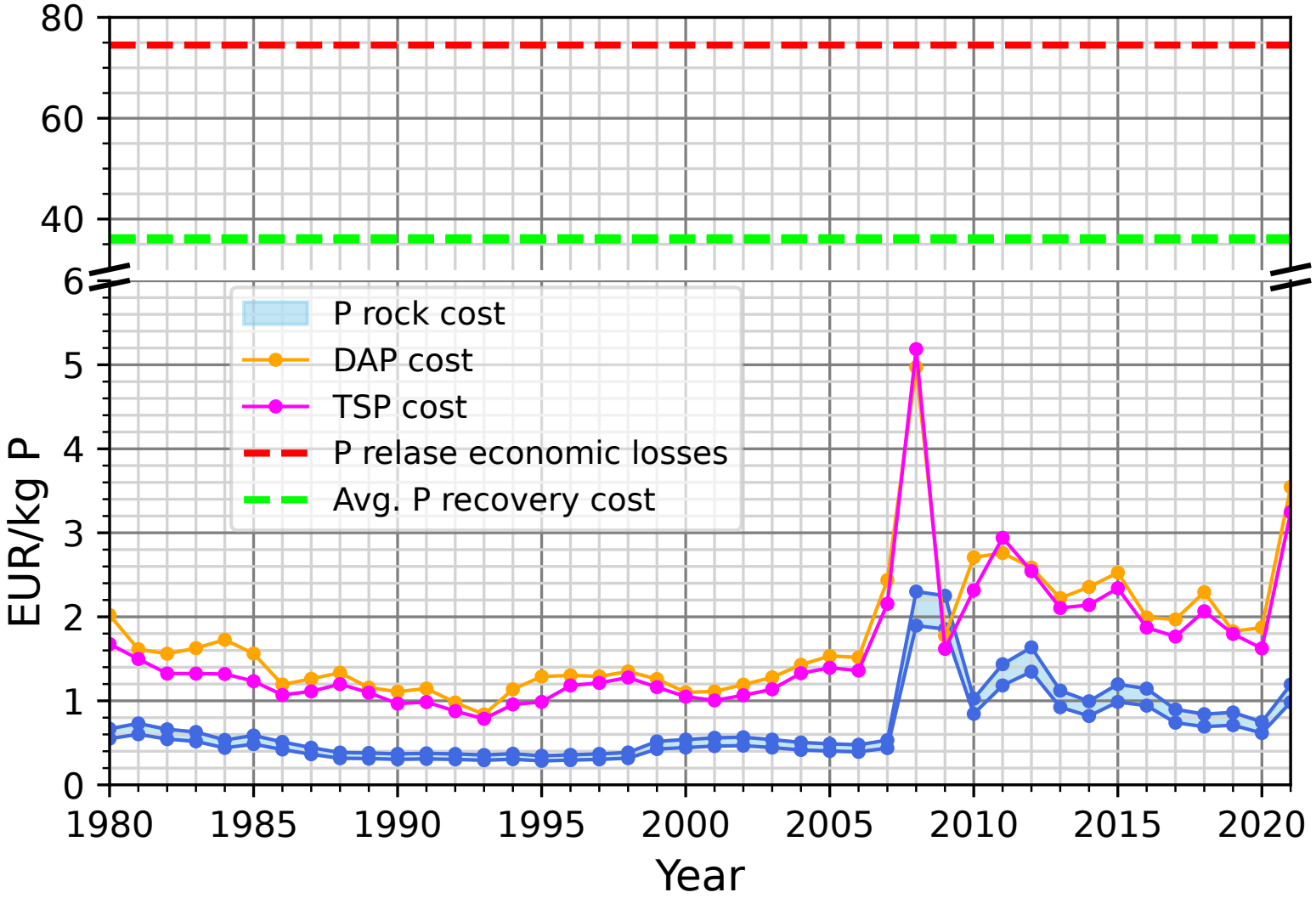
P flows overview



Potential of P recovery



Cost of P recovery



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Estimating spatial and temporal variability of Phosphorus hydrologic losses across the contiguous United States

SPS Session 2: Quantifying Phosphorus Flows and Impacts for Sustainable Nutrient Management

Presented by:

Kimia Karimi

Daniel R. Obenour

Nov 3, 2022

Center for Geospatial Analytics, NCSU, Raleigh, NC, USA

Dept. of Civil, Construction and Environmental Engineering, NCSU, Raleigh, NC, USA

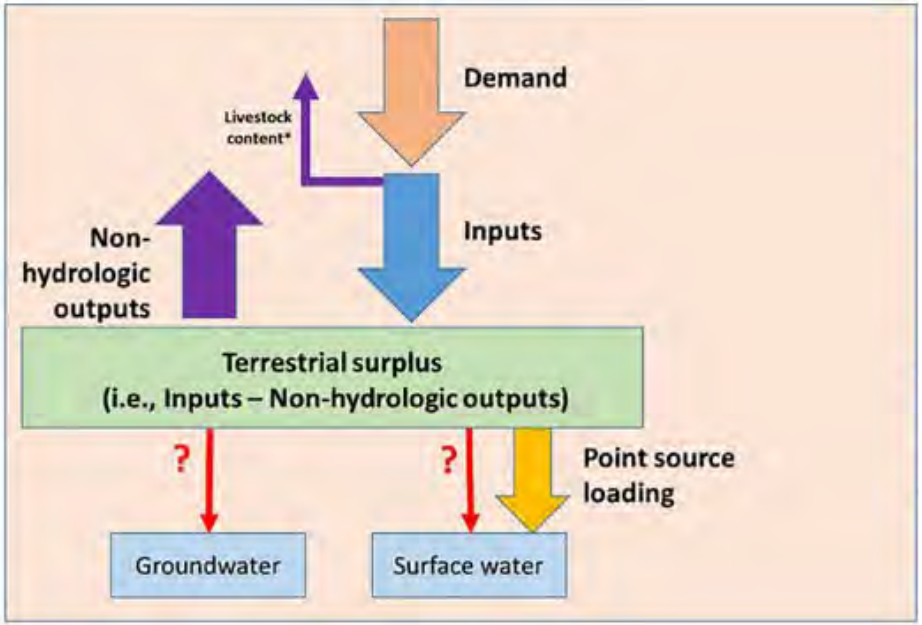
Introduction

- Excess phosphorus (P) from anthropogenic activities may subject to riverine (hydrologic) P export, causing water quality problems in lakes and coastal systems.

- Nutrient budgets have been used as a quantitative means of assessing the amount of nutrients imported to and exported from a system.

- However, at larger spatial scales, the estimates of hydrologic P losses are usually not available in the P budgets.

Introduction



Sabo et al. (2021):

- Developed an inventory of inputs and outputs of P across the United States for 2002, 2007, and 2012.
- Agricultural P inputs were the largest source of P nationwide.
- Estimates of hydrologic losses/export were not considered in the inventory.

Introduction

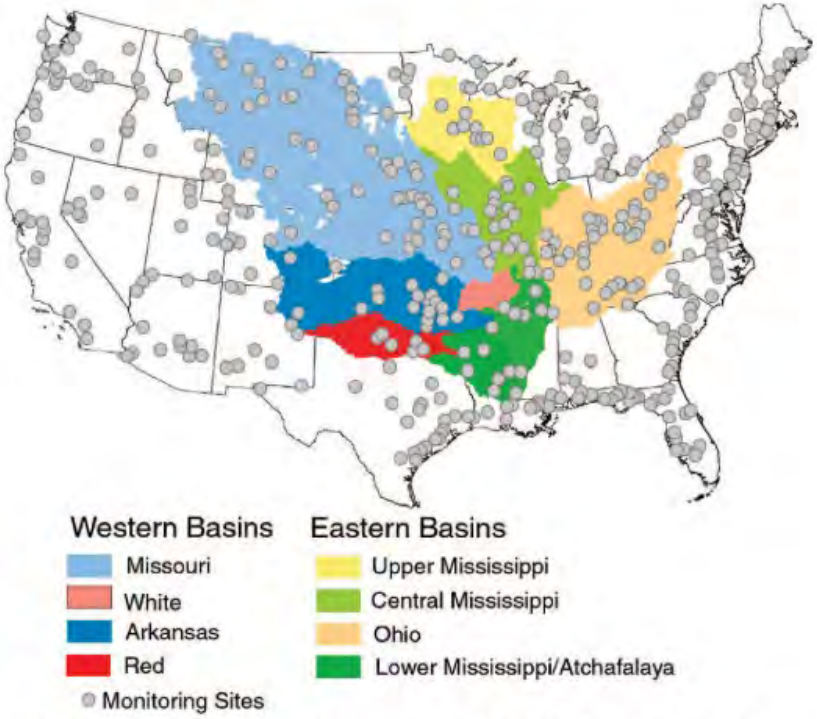


FIGURE 1. Location of the major hydrologic regions of the MARB and stream monitoring stations used to estimate the SPARROW models.

Alexander et al. (2008):

- Developed a SPARROW model to characterize P delivery to the Gulf.
- Stations across the CONUS were used but the export coefficients were specific to the Mississippi river basins.
- Watersheds with predominantly urban and agricultural sources have the highest predicted nutrient yields.

Research questions

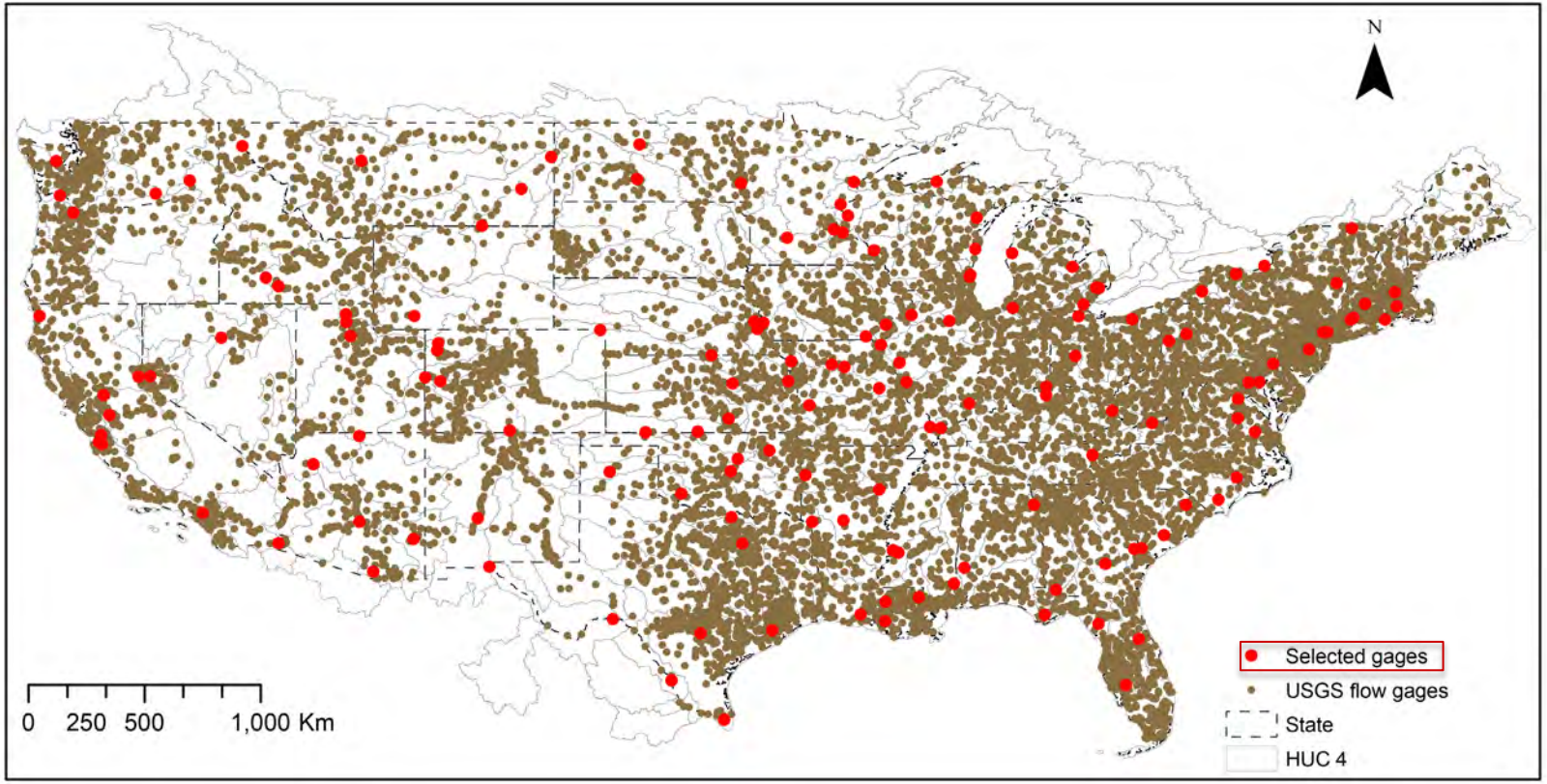
- How do hydrologic losses vary over space and time?
- Are hydrologic losses consistent with P inventories?
- What factors explain anomalies in P losses?

Approach

1. Estimate hydrologic losses of P (P loads) using flow and concentration data.

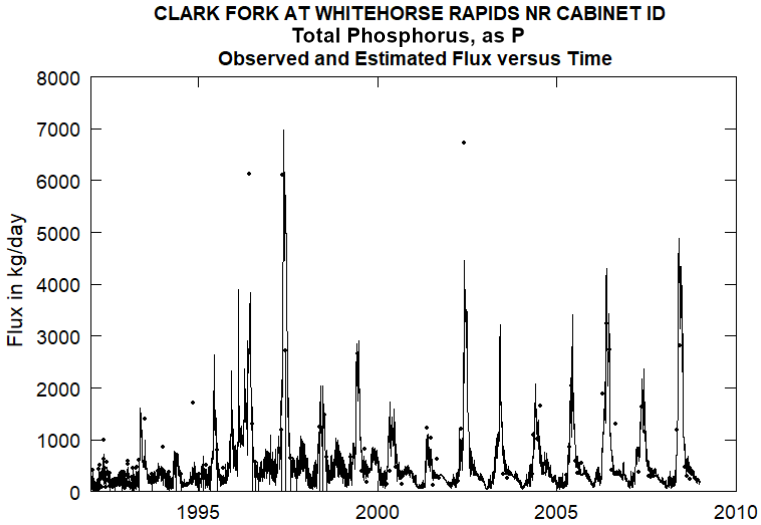
2. Develop a predictive model to identify potential drivers of spatio-temporal variability of P loads.

1- Selected sites

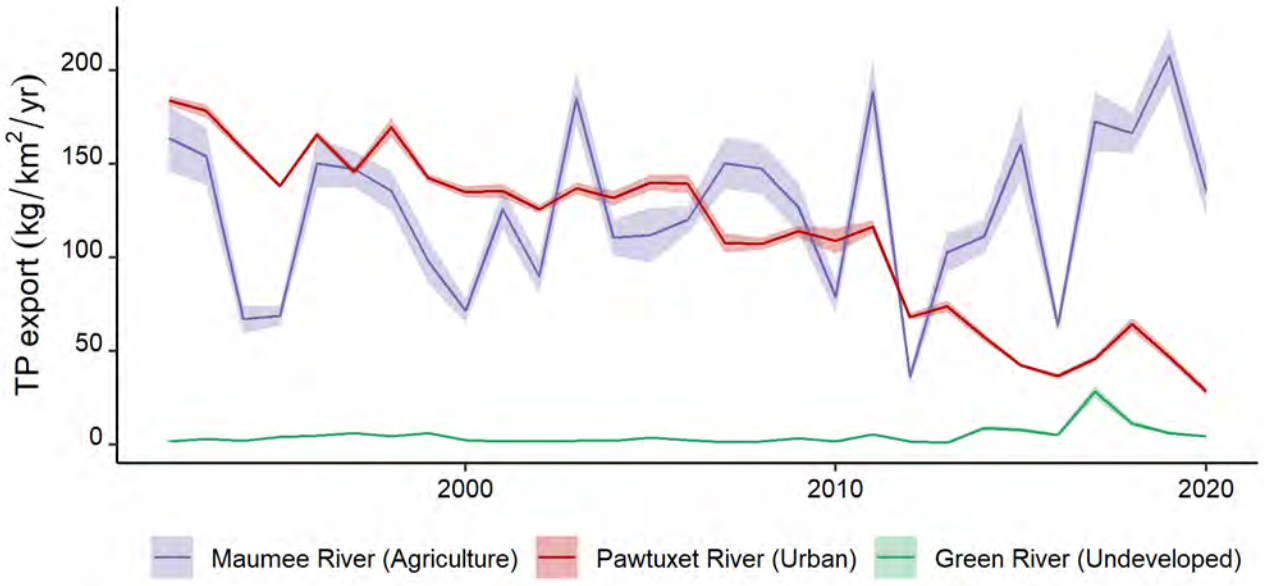


Estimating annual P loadings

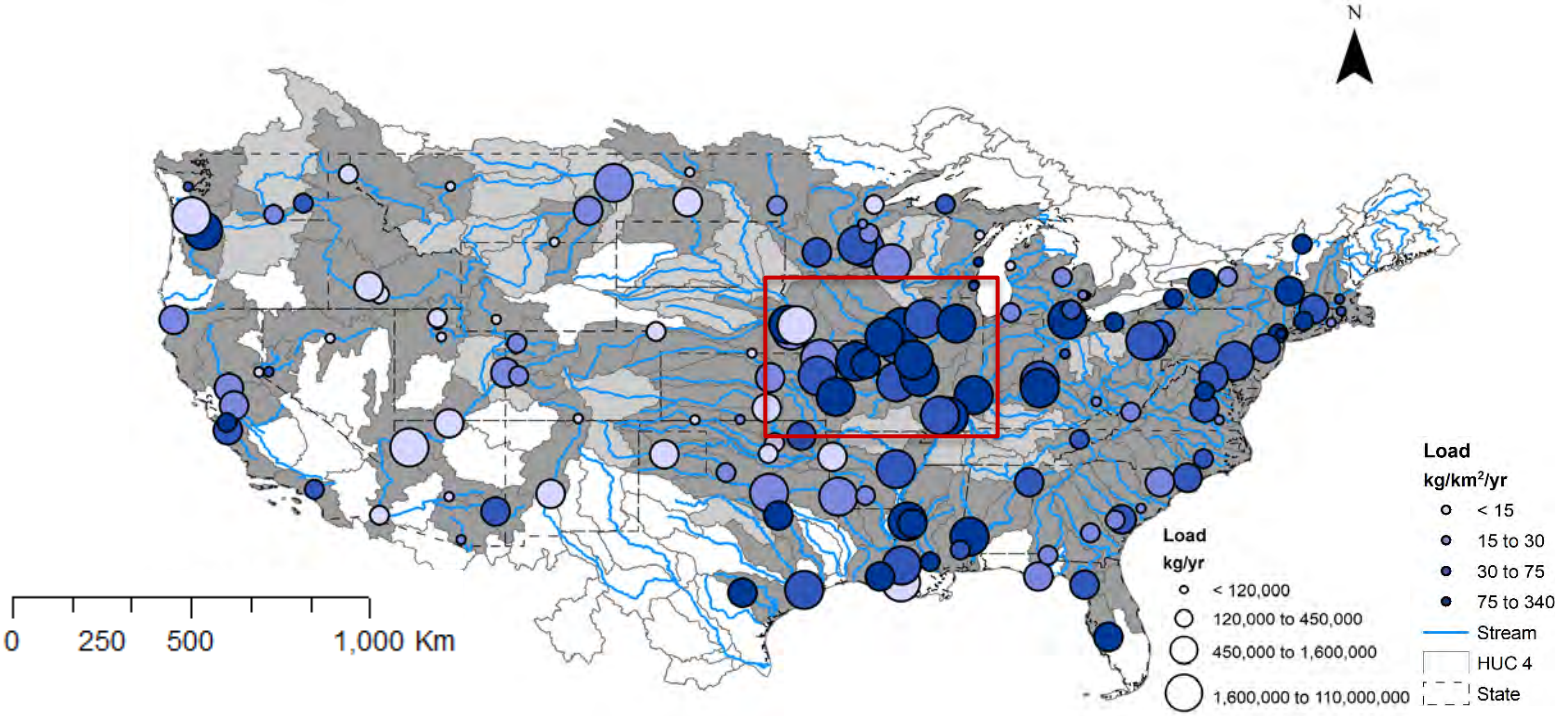
- Weighted Regression on Time, Discharge, and Season (WRTDS; Hirsch et al. 2010).
- It determines unique regression coefficients for each estimation date.



WRTDS TP load estimate



Mean WRTDS estimates



2- Model development

$$Ln(load) = x\beta + \varepsilon$$

observed load (kg/km^2/yr)

predictor variables

regression coefficients

residuals (kg/km^2/yr)

Model variables

Gross Anthropogenic P Input (GAPI):

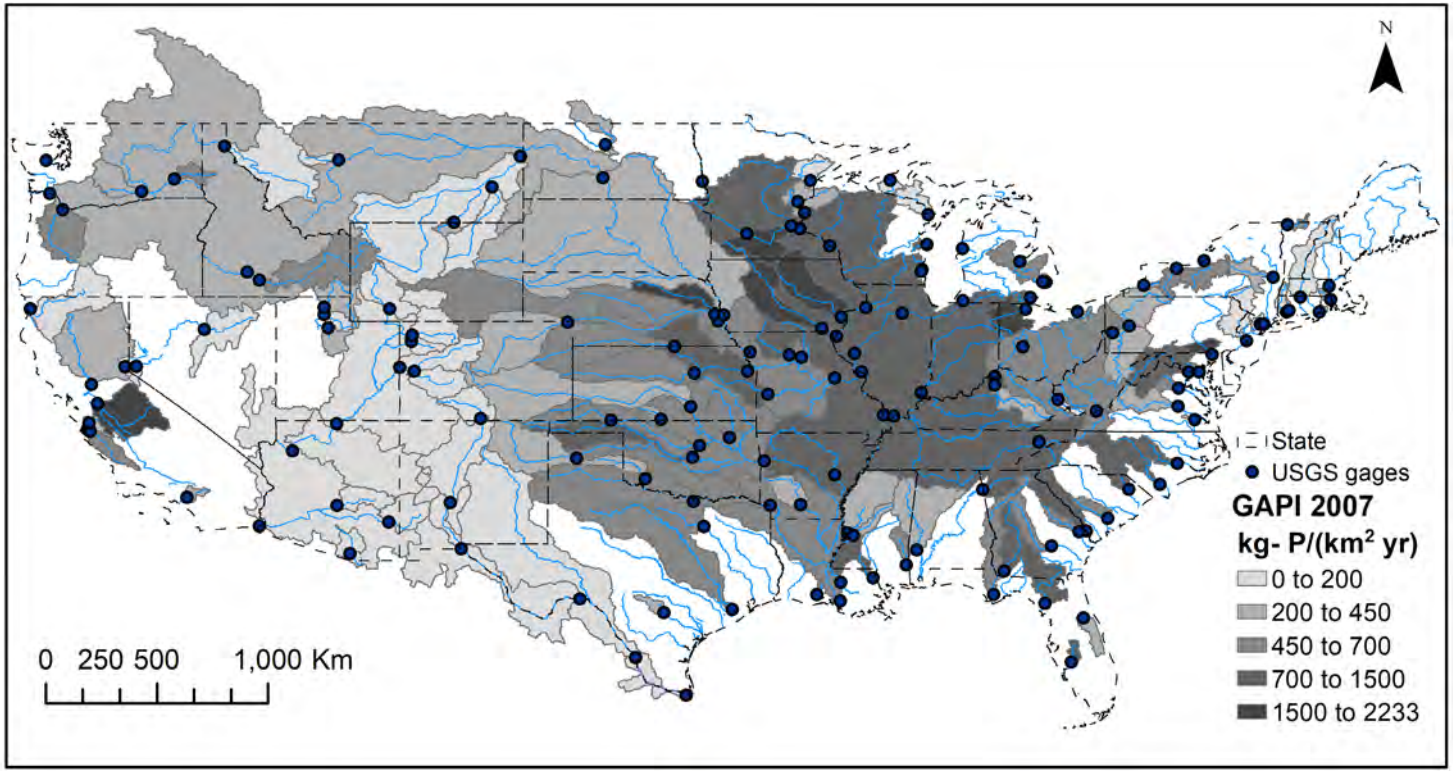
GAPI= [ag inputs: agricultural fertilizer + livestock waste + pesticides and herbicides] – ~~[crop removal]~~ + [point source] + [urban fertilizer] + [atmospheric deposition] (kg/yr)

Precipitation (mm)

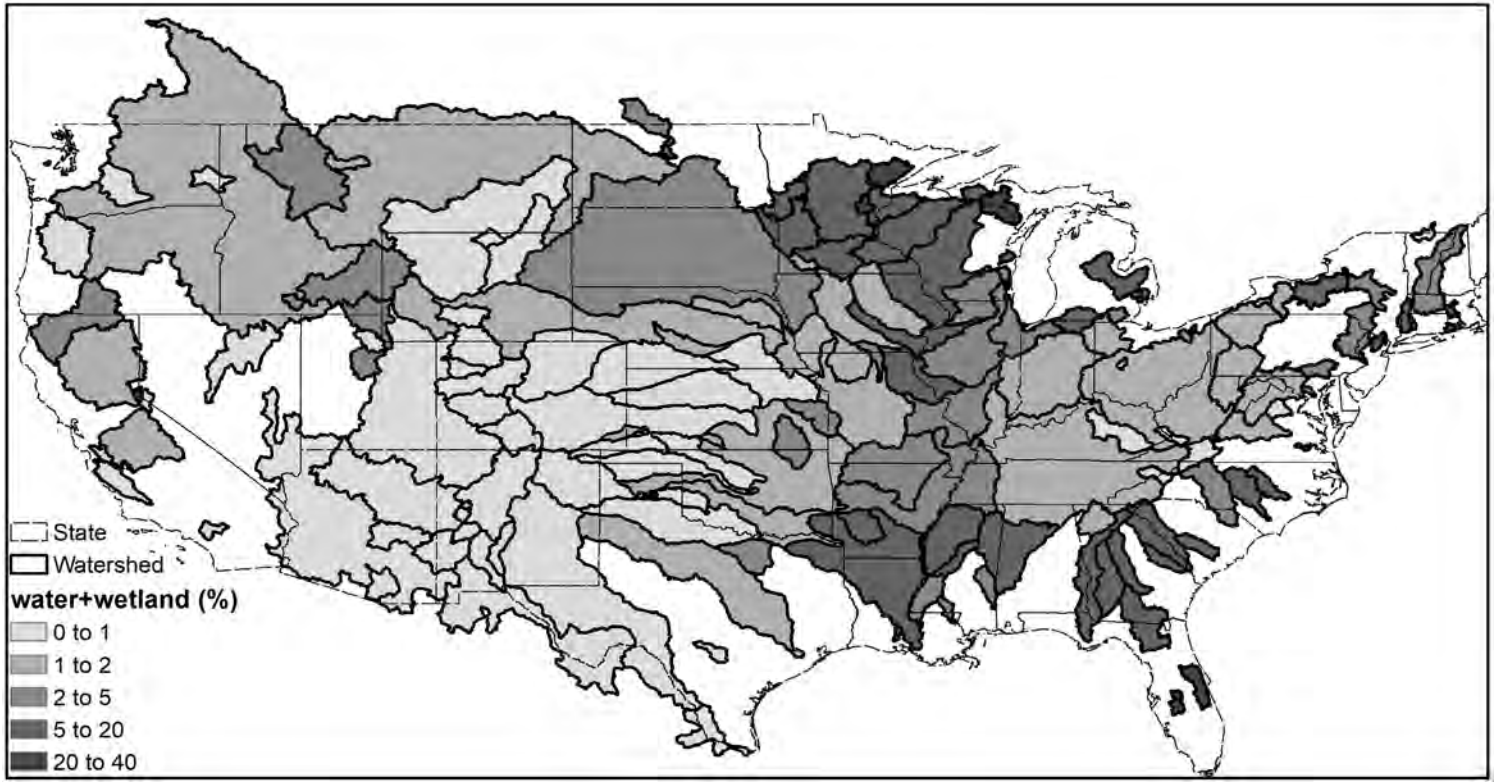
Water and wetland fraction

Ecoregions

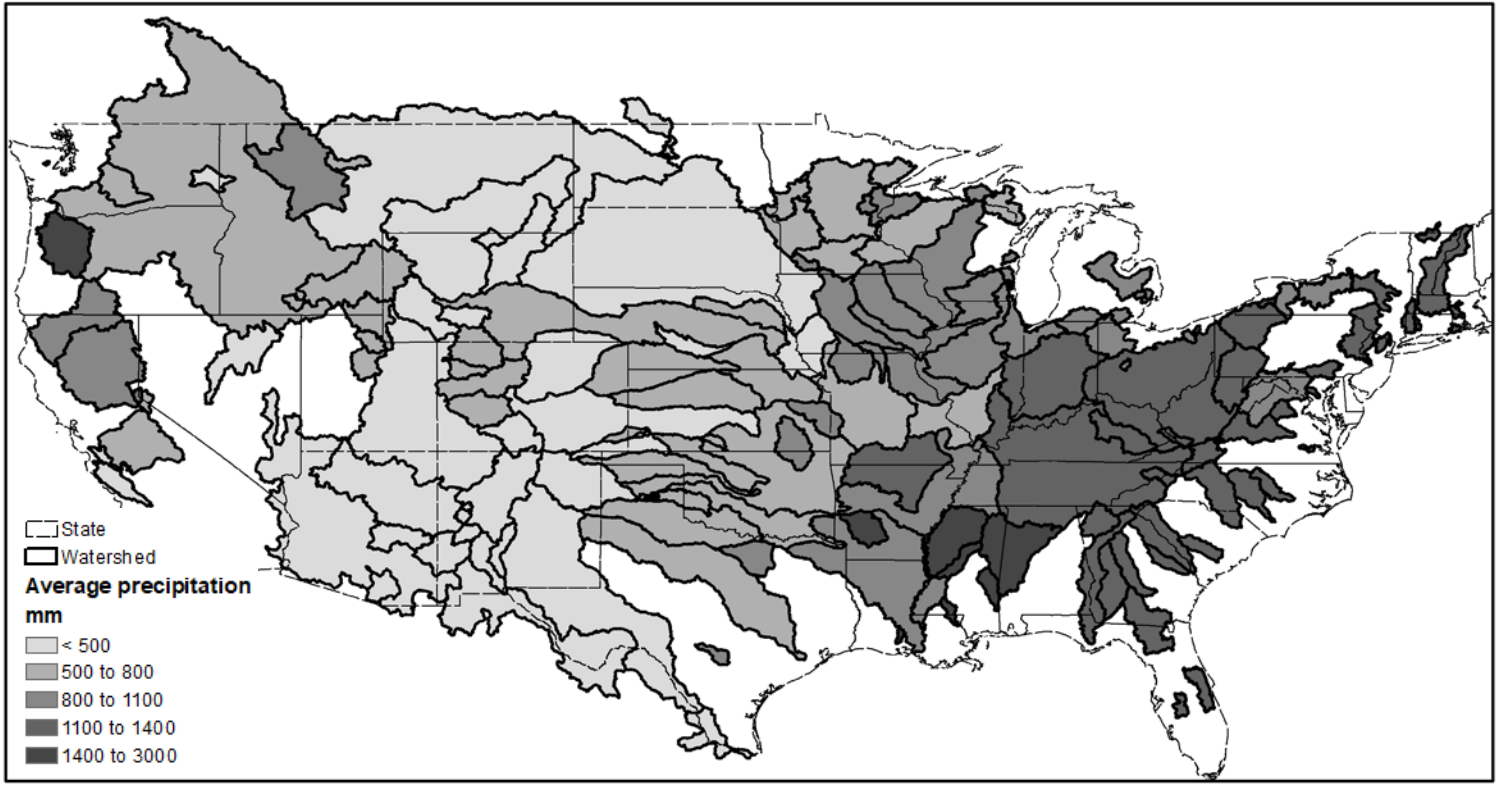
Variables: GAPI



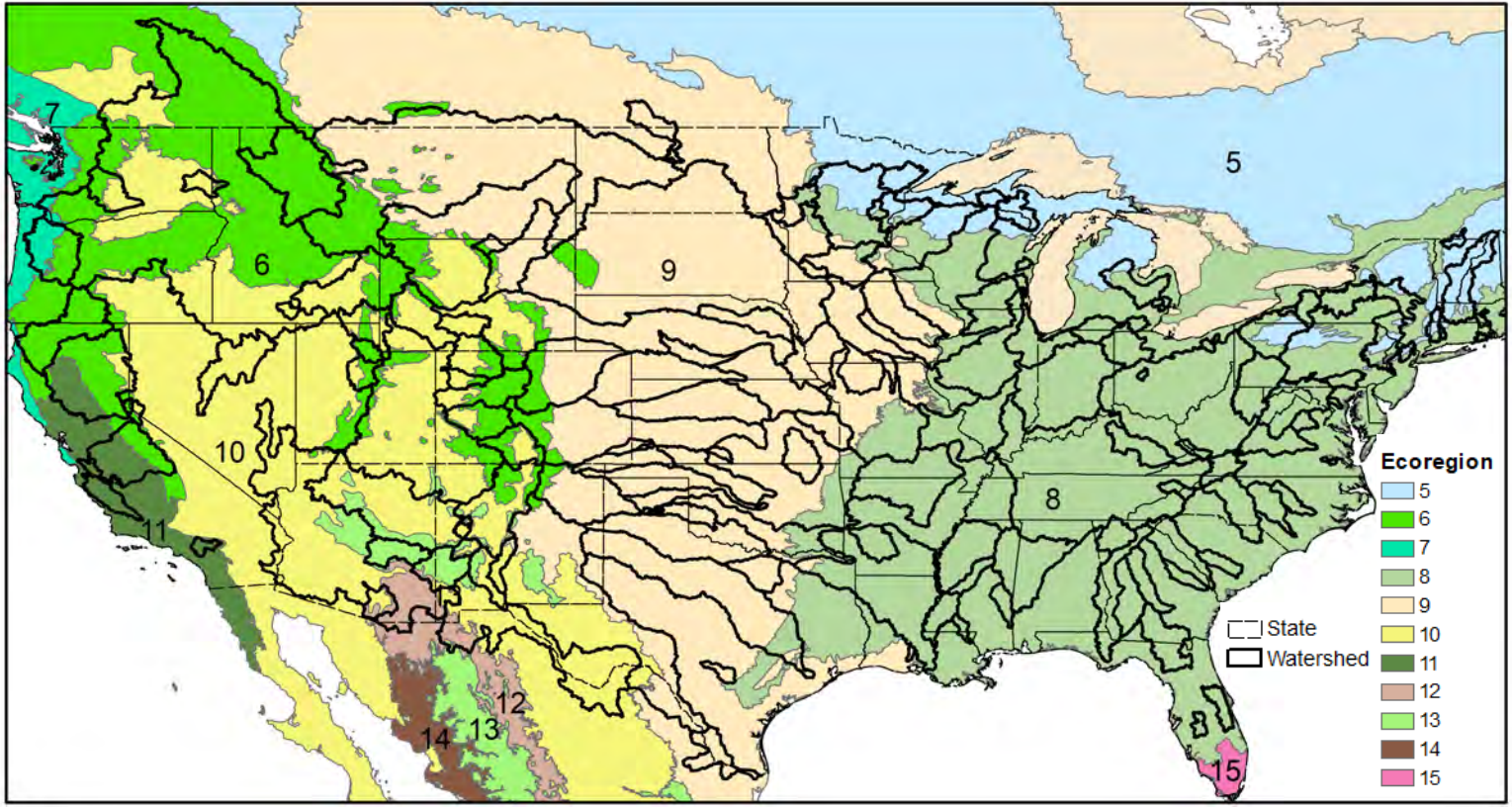
Variables: Water and wetland fraction



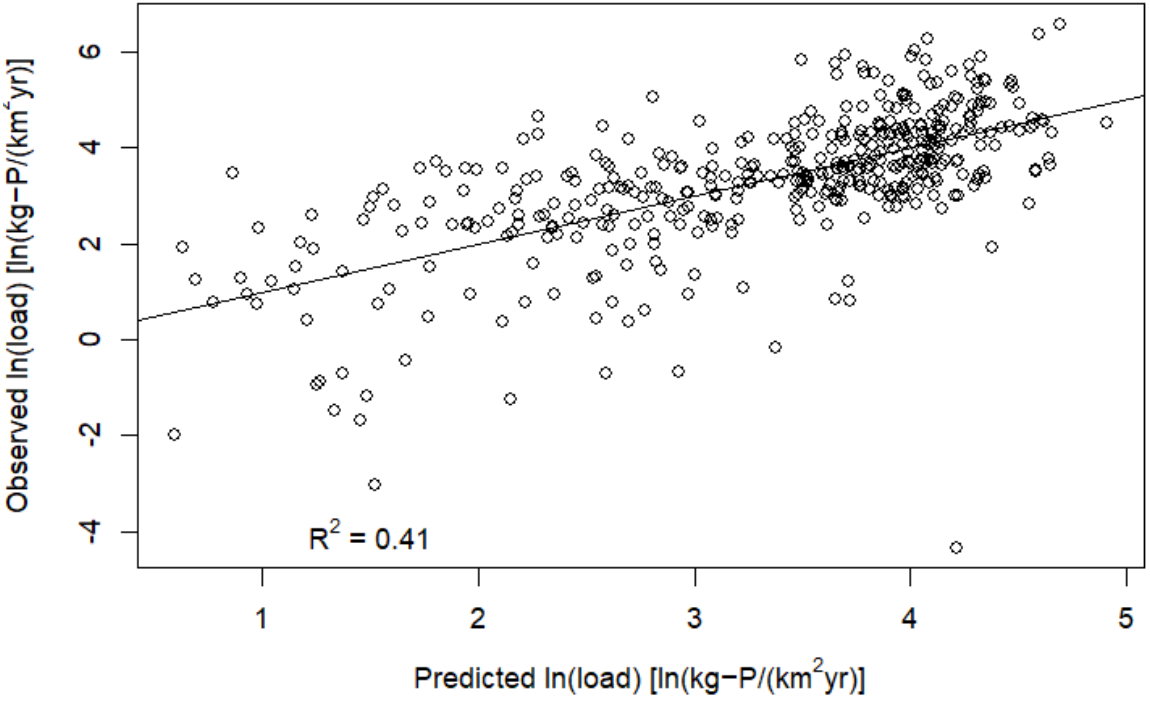
Variables: Precipitation



Variables: Ecological regions of North America



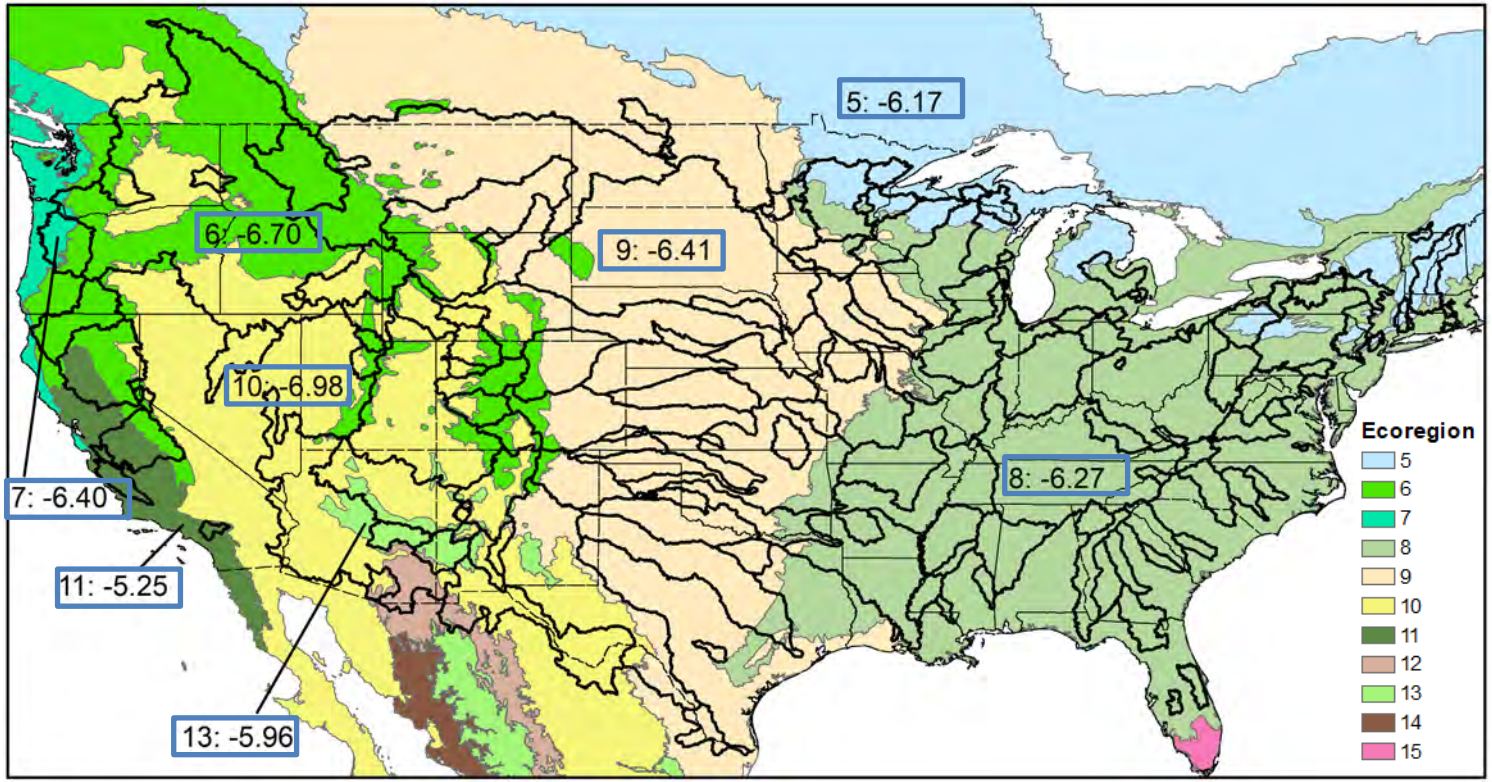
Model development



Predictor	Coef.	p-value	Relative importance
log(GAPI/area)*	0.28	2.07e-5	0.08
log(precipitation)**	1.24	4.01e-12	0.16
log(water + wetland)	-0.11	0.0517	0.02
eco region 5	-6.17		0.15
eco region 6	-6.70		
eco region 7	-6.40		
eco region 8	-6.27		
eco region 9	-6.41		
eco region 10	-6.98		
eco region 11	-5.25		
eco region 13	-5.96		

*ln(kg-P/(km²yr)
**ln(mm)

Ecoregions intercept



Preliminary results

- Hydrologic losses range from 1% to 64% of GAPI across the catchments and years.
- On average, the largest areal P losses occur in Mid-Atlantic and Great Lakes.
- Precipitation and ecoregions are the major predictors of P hydrologic losses.

More data to consider

- Soil P
- Long term P surplus
- Population/land use
- Waterbodies
- Extreme precipitation

Next steps

- Develop datasets for all years from 1997-2017.
- Explore covariate relationship change with different ecoregions (through hierarchical modeling).
- Estimate hydrologic losses on HUC8 scale.
- Integrate hydrologic losses with new P source data being developed to create a more comprehensive national P budget.

References

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Acknowledgments

Center for Geospatial Analytics

STEPS
Science and Technologies for Phosphorus Sustainability

- Water quality portal: https://www.waterqualitydata.us/
- USGS: https://waterdata.usgs.gov/nwis
- PRISM: https://prism.oregonstate.edu/
- LAGOS: https://lagoslakes.org/the-lagos-database/
- Land use: http://dx.doi.org/10.3133/ds948

Questions:

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