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Managing Legacy Phosphorus Loading in Agriculture & Beyond

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Managing Legacy Phosphorus Loading in Agriculture & Beyond

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Andrew Margenot
Associate Professor
University of Illinois, Urbana-Champaign

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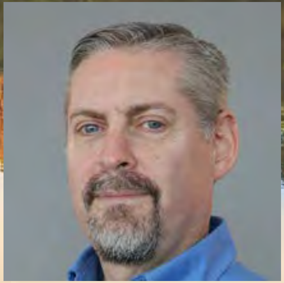
Associate Professor
University of Florida

Lauren Lurkins
Founder
Lurkins Strategies, LLC



Trevor Sample
Watershed Management
Illinois EPA

PF25

Please share your thoughts about legacy phosphorus here.

This is the same survey we sent out pre-event.

Scan the QR or use link to join

https://forms.office.com/r/taYb15r6S2

Managing Legacy Phosphorus Loading in Agriculture & Beyond

Andrew Margenot
Associate Professor
University of Illinois, Urbana-Champaign

Soil legacy P: status of and next steps in definitions, measurement and management

Andrew Margenot
Associate Professor of Soil Science

https://margenot.cropsciences.illinois.edu/

18 September 2025
Sustainable P Alliance
Raleigh, NC

Overview

- Terminology of “legacy P”
- Approaches to quantifying (estimating?) legacy P
- The mass balance problem
- Future directions to increase confidence in legacy P estimates (how much) and speciation (what type)

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PERSPECTIVE

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Plant Soil
https://doi.org/10.1007/s11104-025-07751-6

LAMBERS OPINION PAPER

Standing on the shoulders of giants – wha... from past soil chemists to address the current chal... of "legacy-phosphorus"

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Perspective

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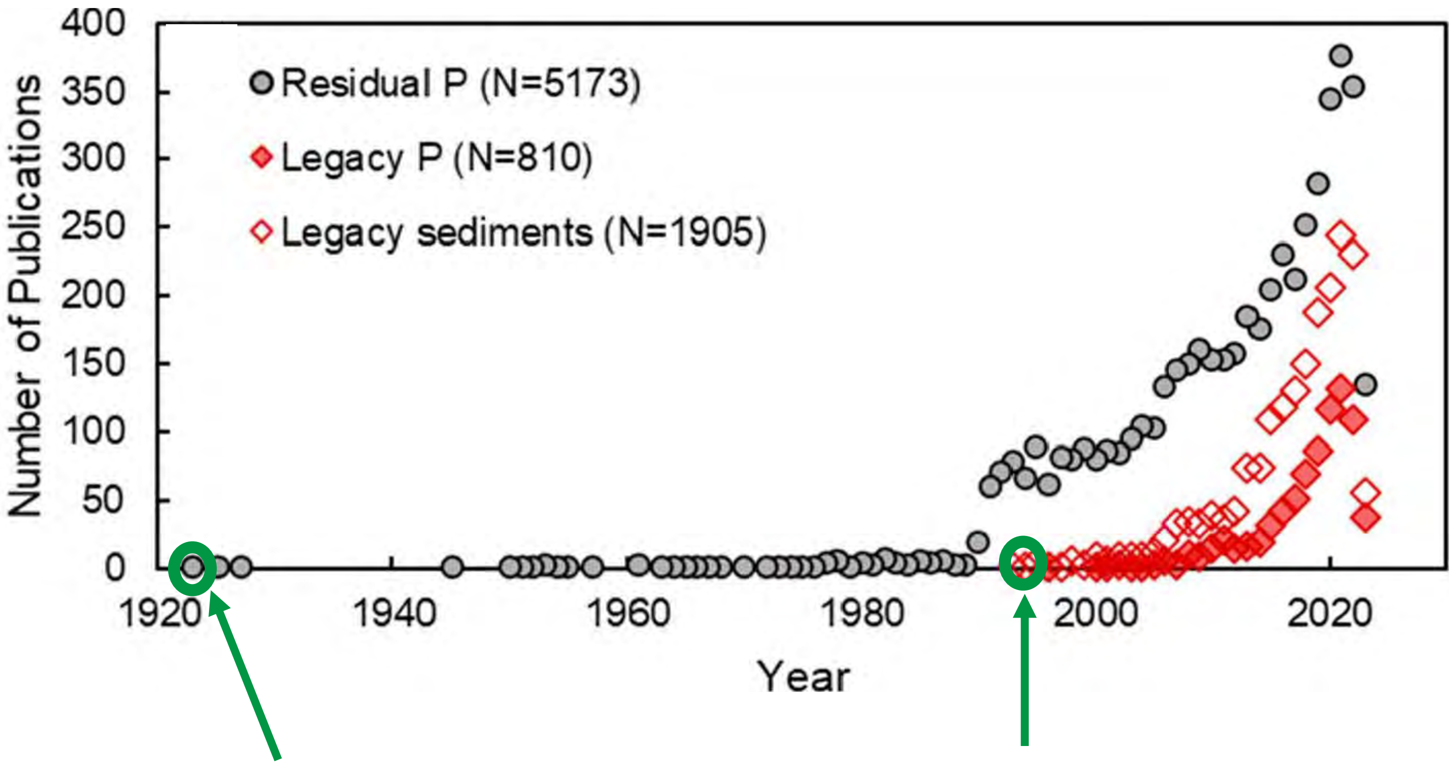
Shengnan Zhou* and Andrew J. Margenot*

Cite This: https://doi.org/10.1021/acs.est.3c04733

Read Online

...hosphorus

Historical use of “residual” vs “legacy”



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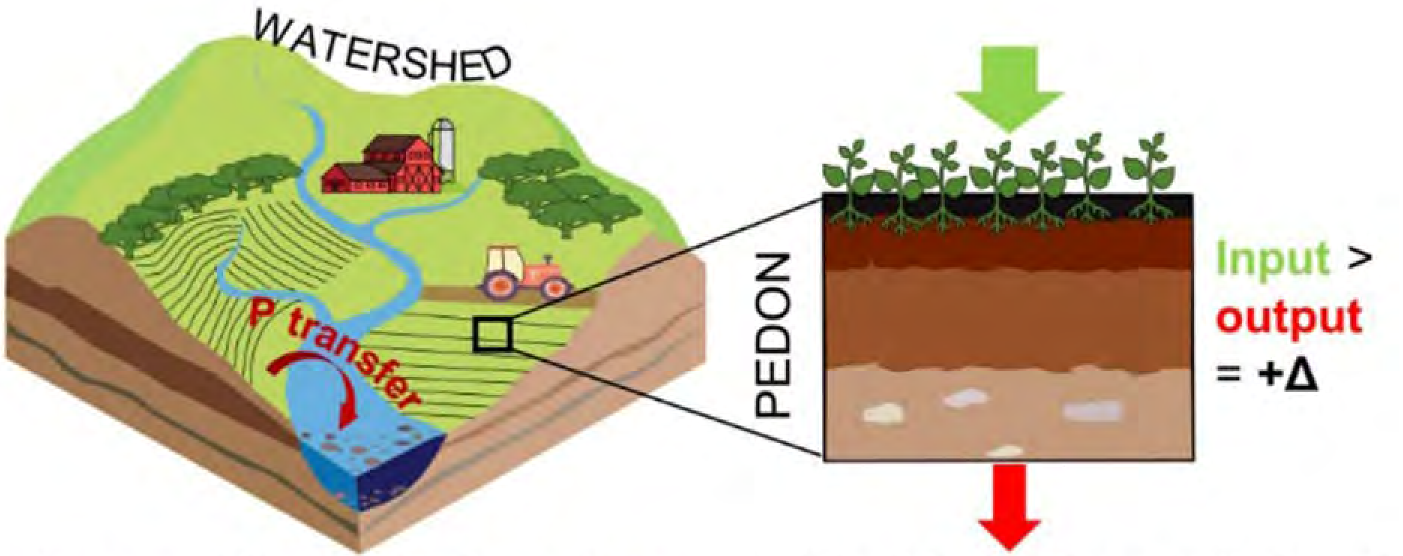
Zhou & Margenot **2023** *Environmental Science & Technology* 57:21535

P from the past: legacy P or residual P



"**Legacy P**": *mechanism of **P transfer** across watershed and impact on water quality*

"**Residual P**": *magnitude of fertilizer P remains in soil, i.e.,* **+Δ =*P input* -*P output***

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Definitions are (i) largely binary and (ii) emphasize differences in origins or impacts, and thus influence research

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Margenot et al. 2025 *Advances in Agronomy* 194: 187

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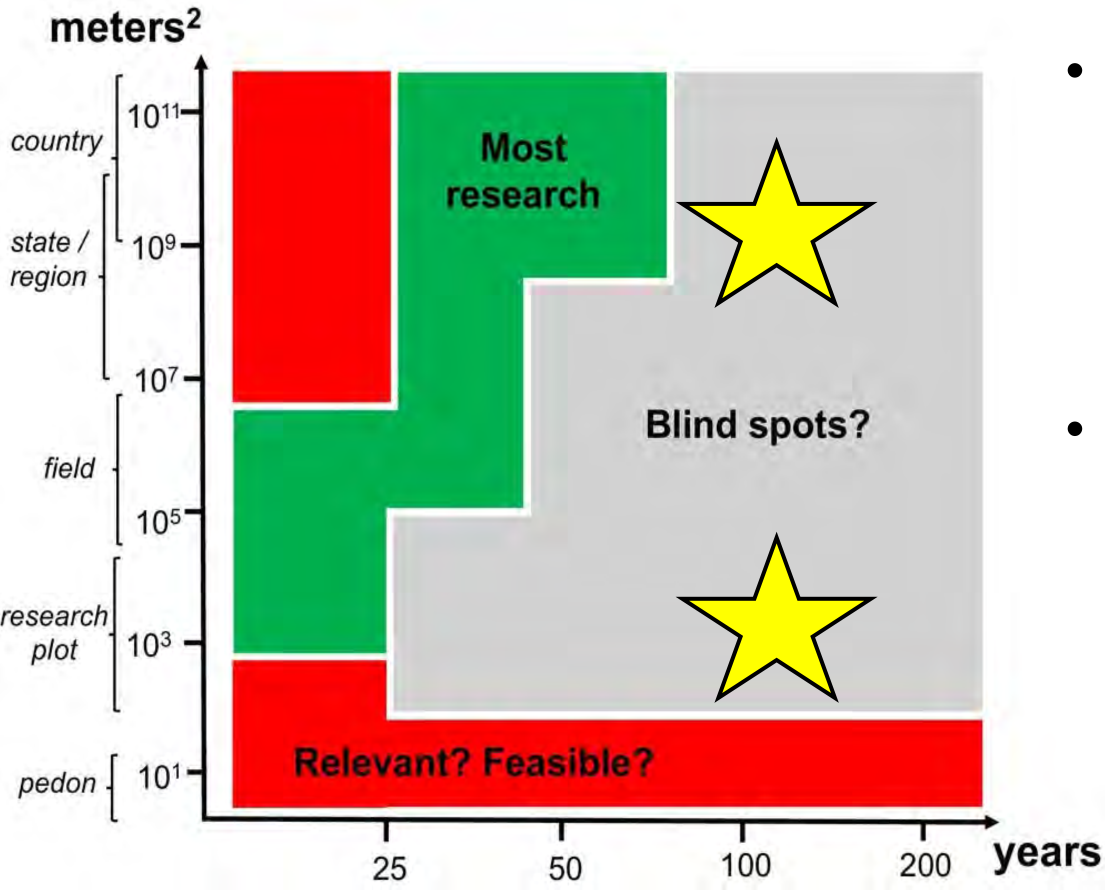

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Margenot et al 2024 *Global Change Biology* 30(6): e17376

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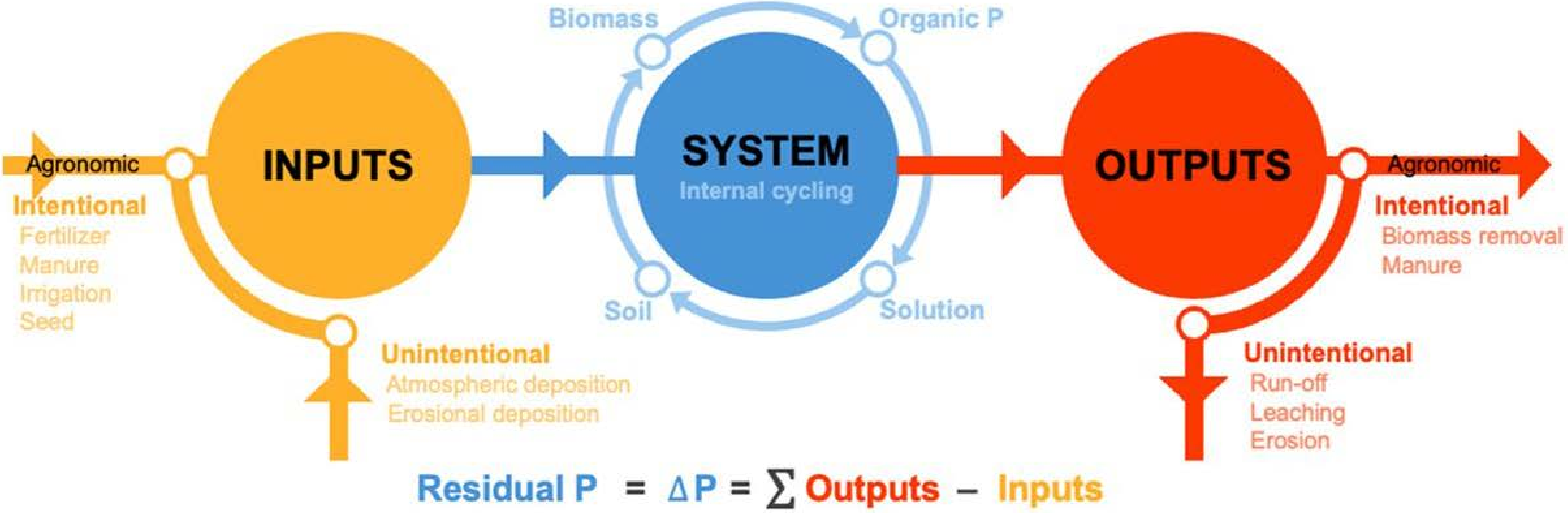

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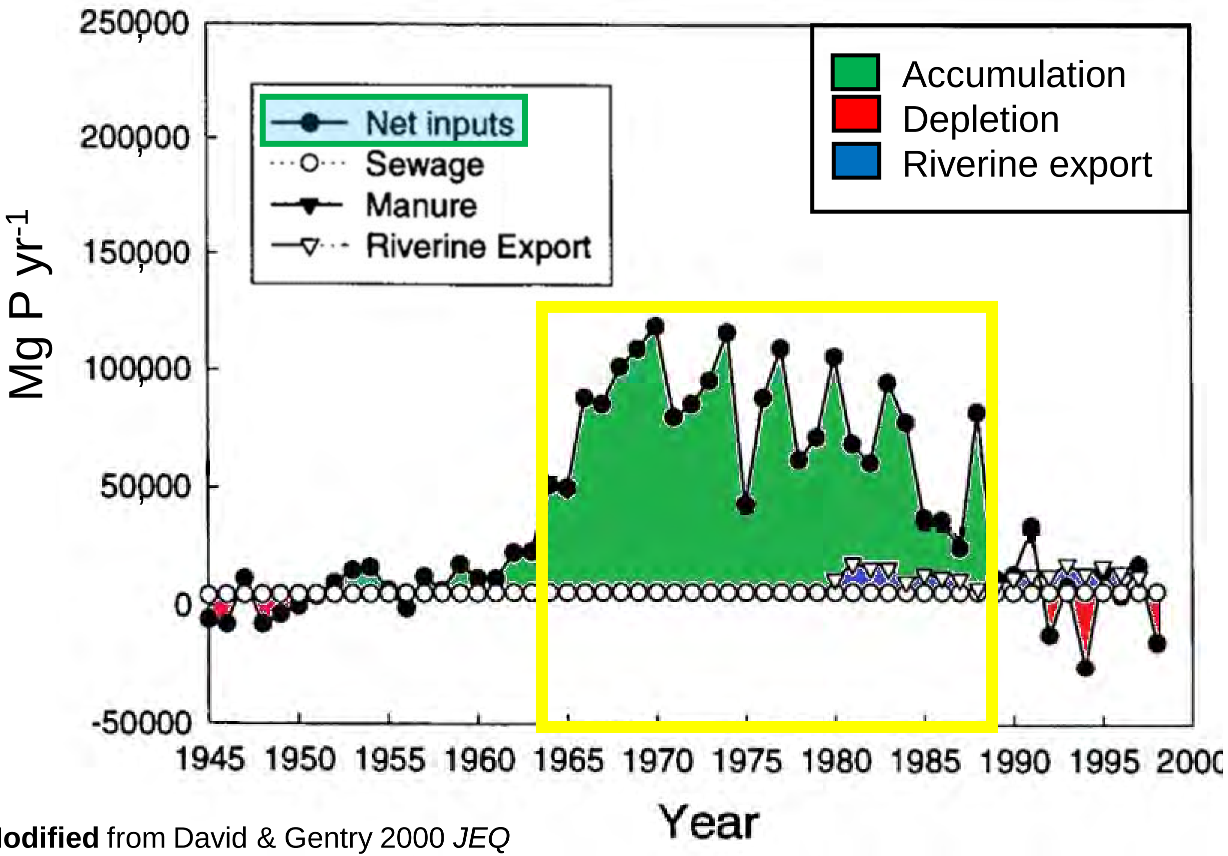

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Modified from David & Gentry 2000 *JEQ*

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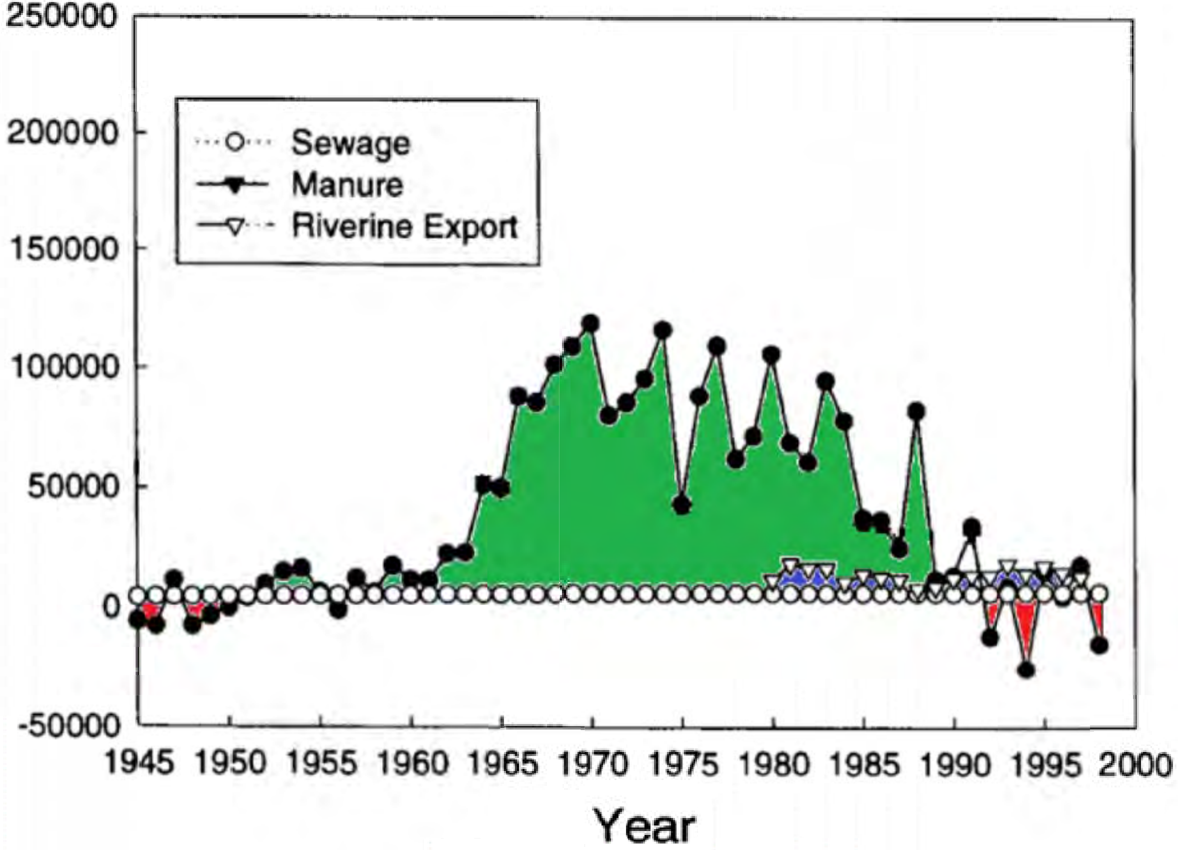
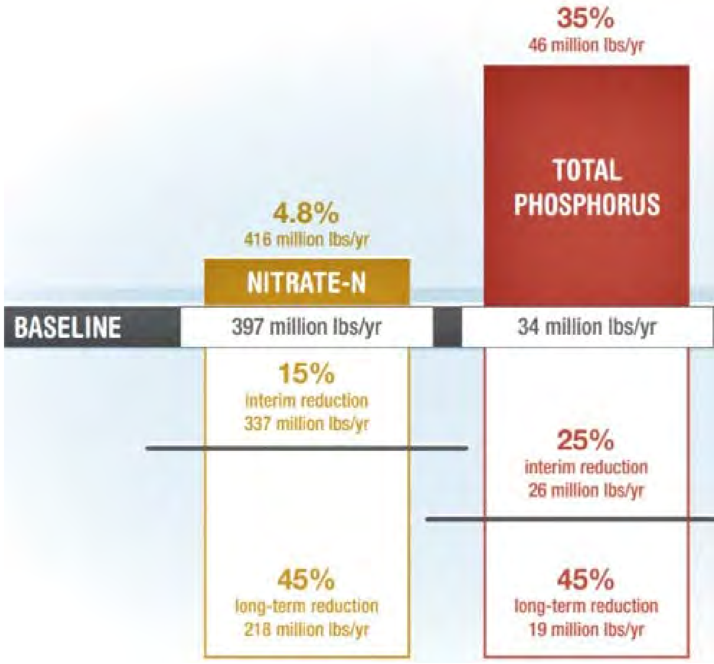


P riverine export: +35%

as a 5-year average (2017-2021)



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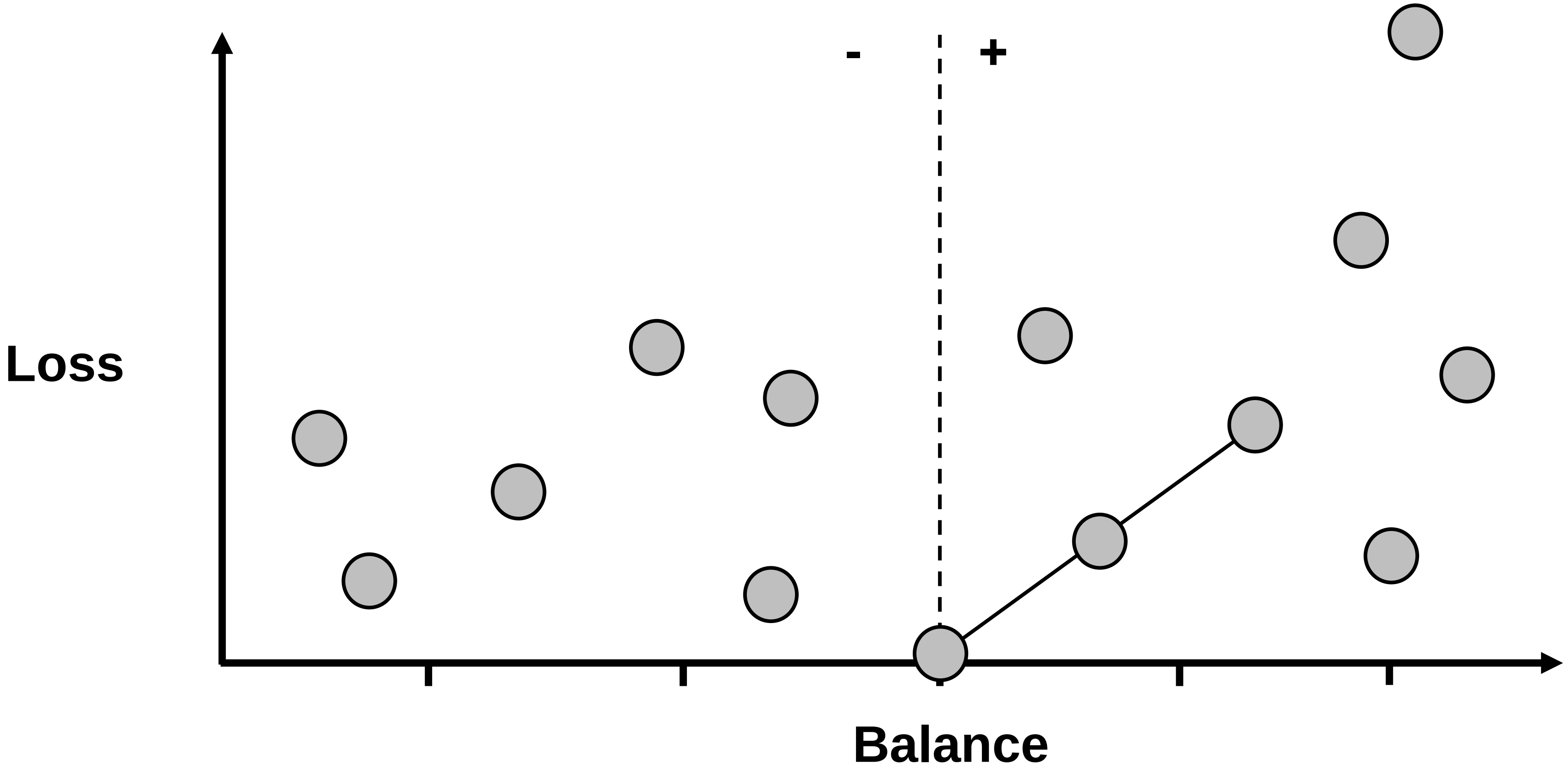

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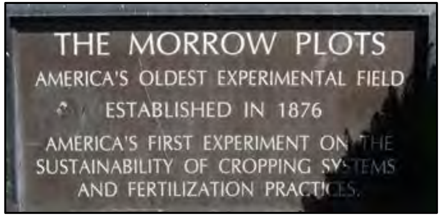

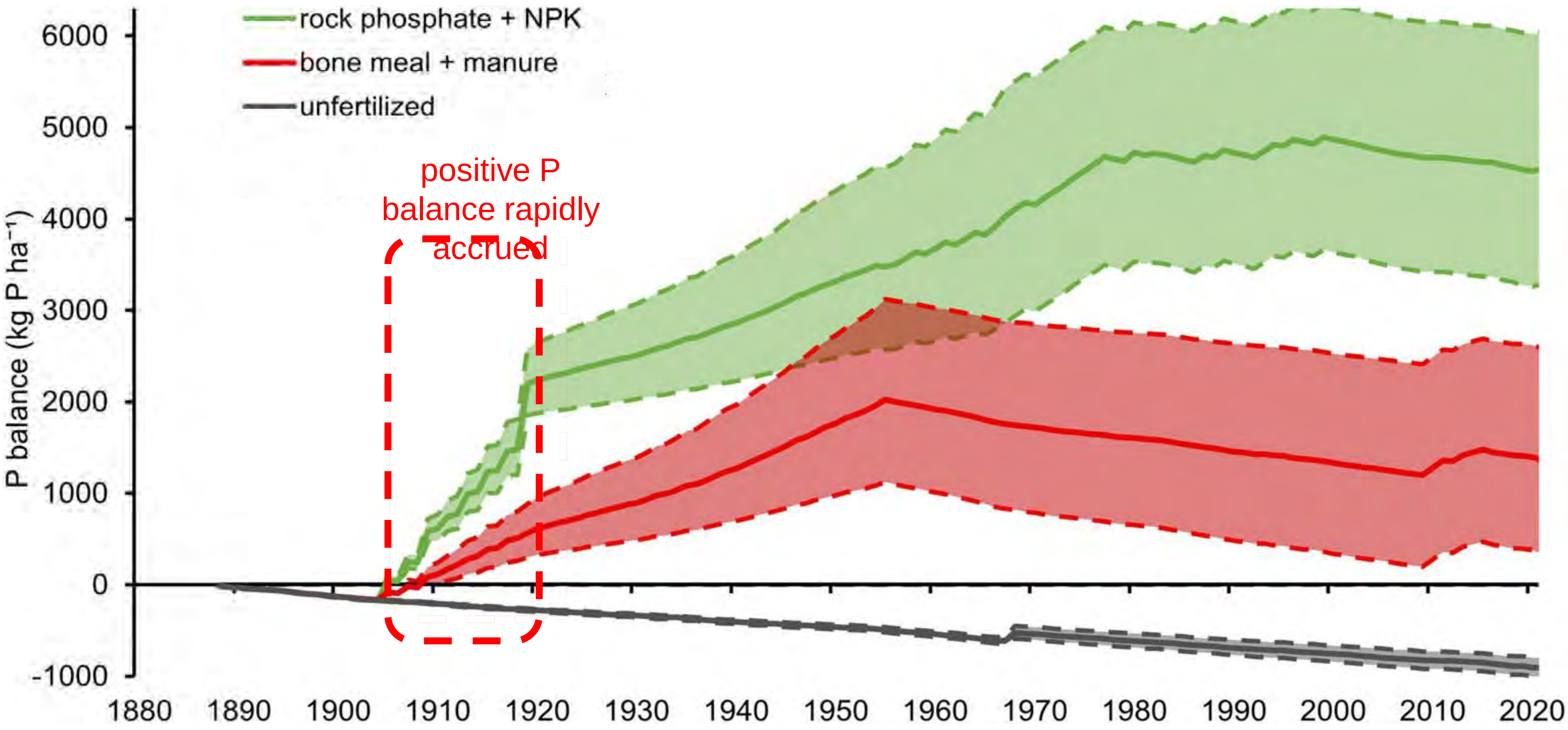

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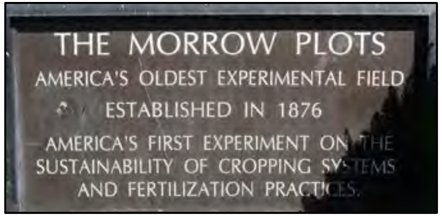

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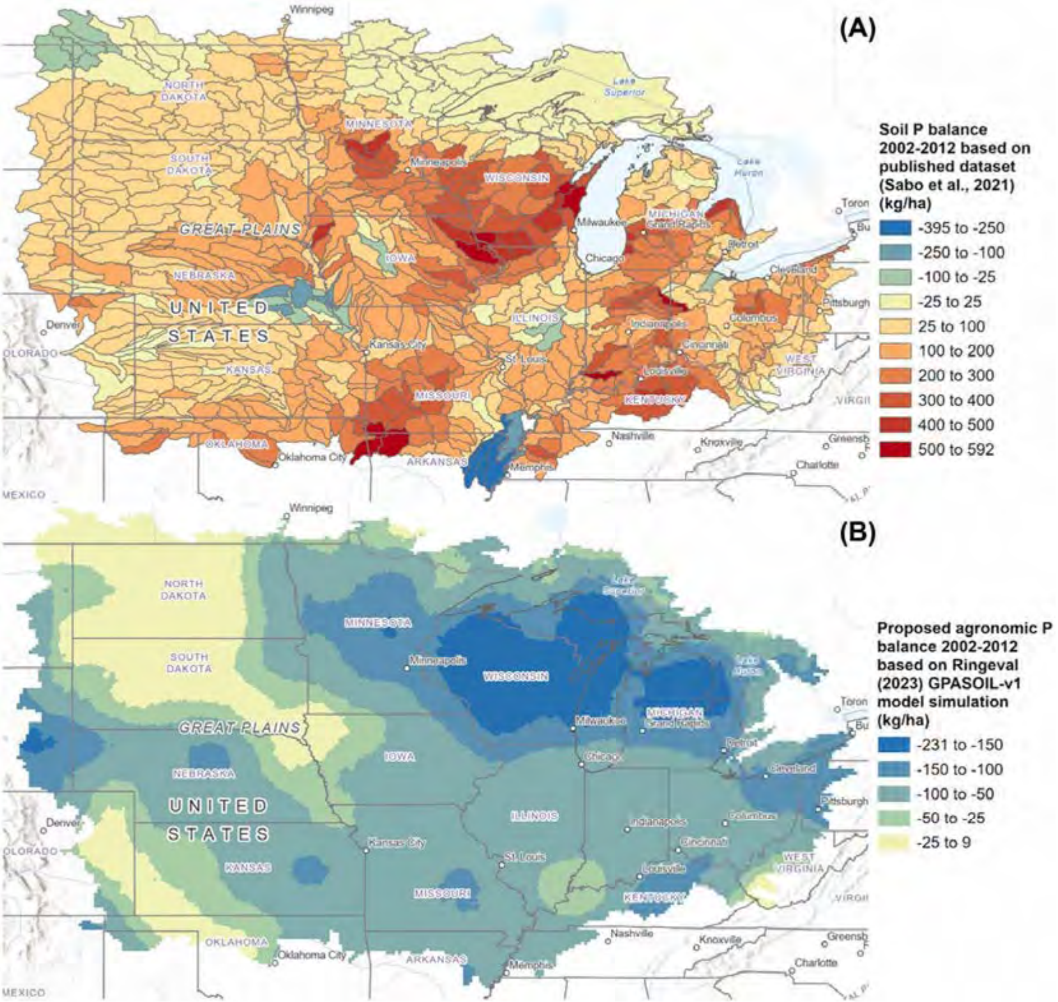
A need to improve model inputs and thus estimates



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  - (A) agronomic mass balance vs
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Margenot et al. 2025 *Advances in Agronomy* 194: 187

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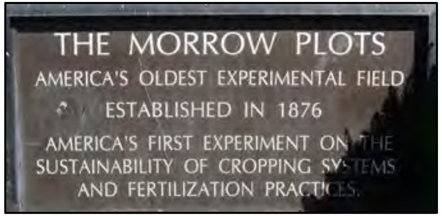
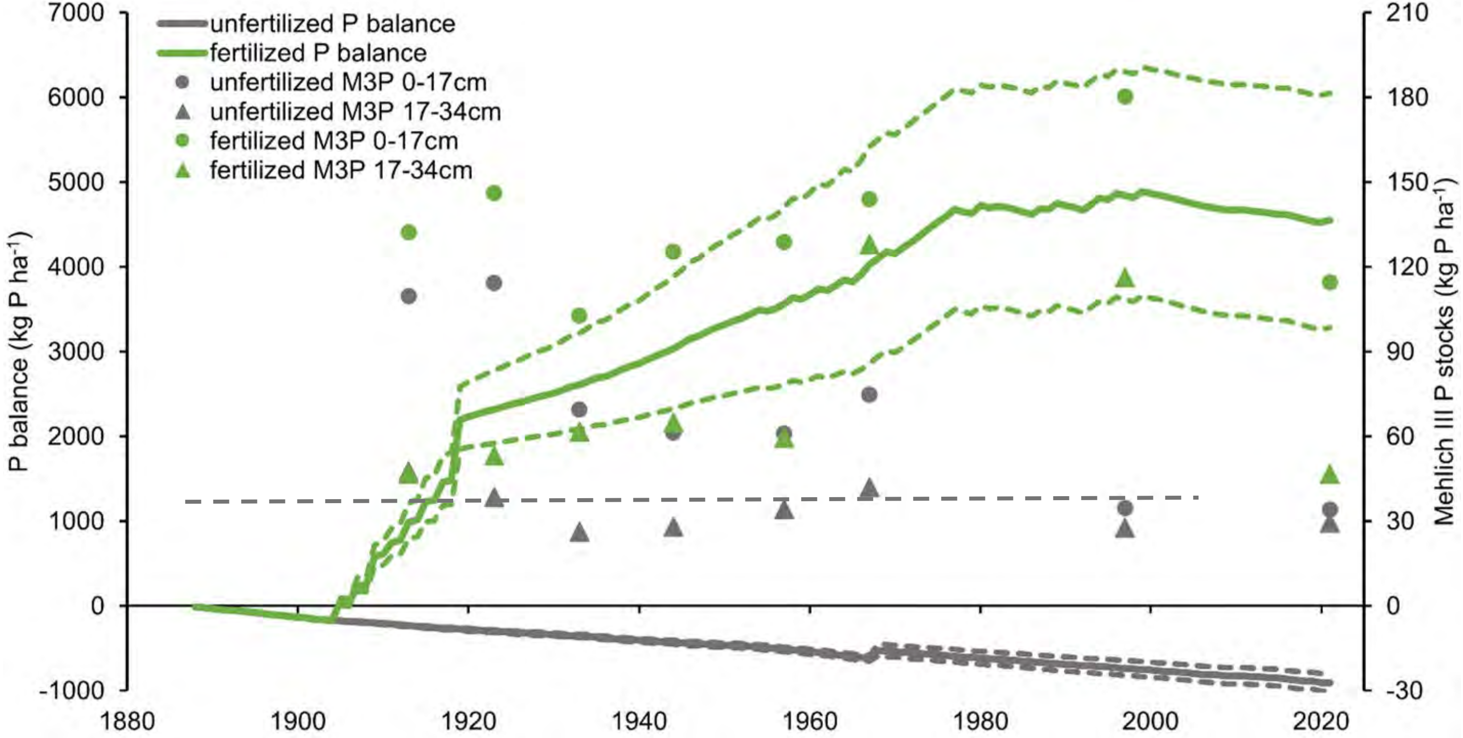
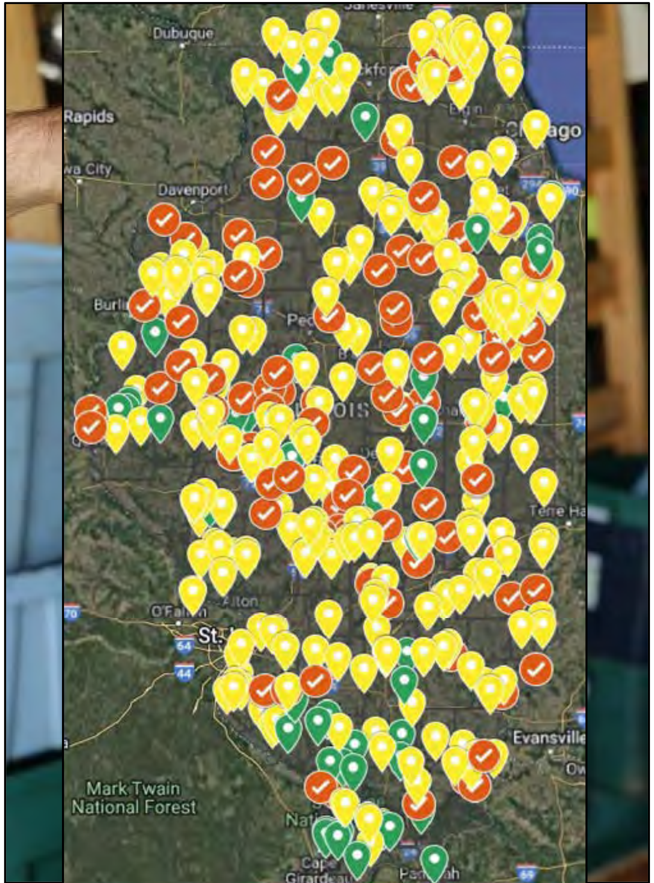


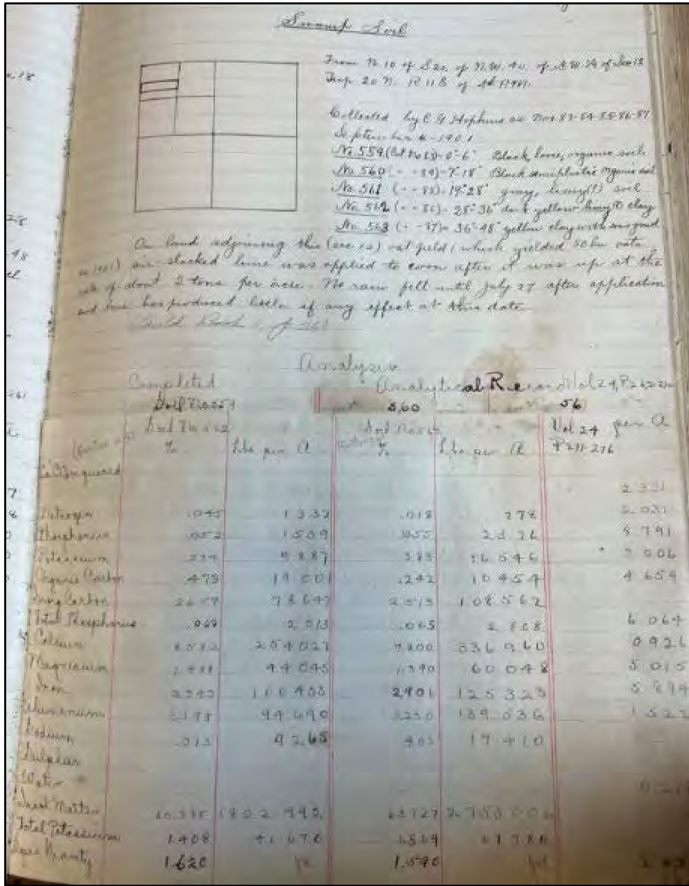
- Not quantitative, but can be qualitative:
  more residual/legacy P ~ higher soil test P



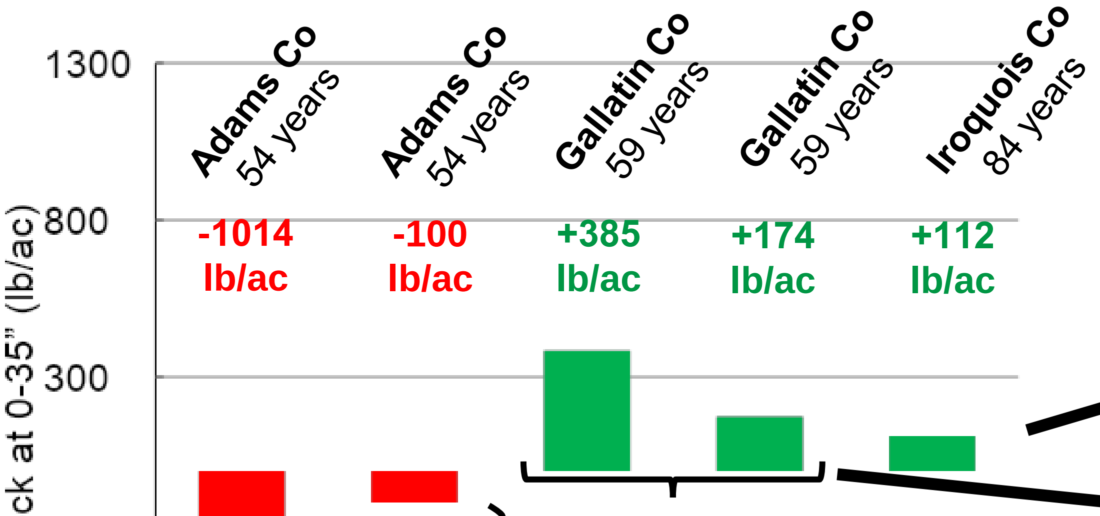
Margenot et al. 2025. *Advances in Agronomy.*

Future direction: soil monitoring networks





Example of quantifying legacy P in soils by resampling



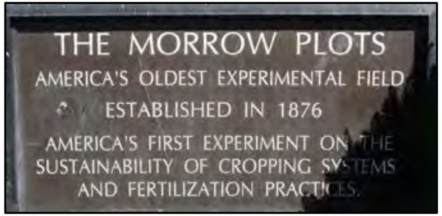
Mississippi River Valley & Le Moine watersheds

Iroquois watershed

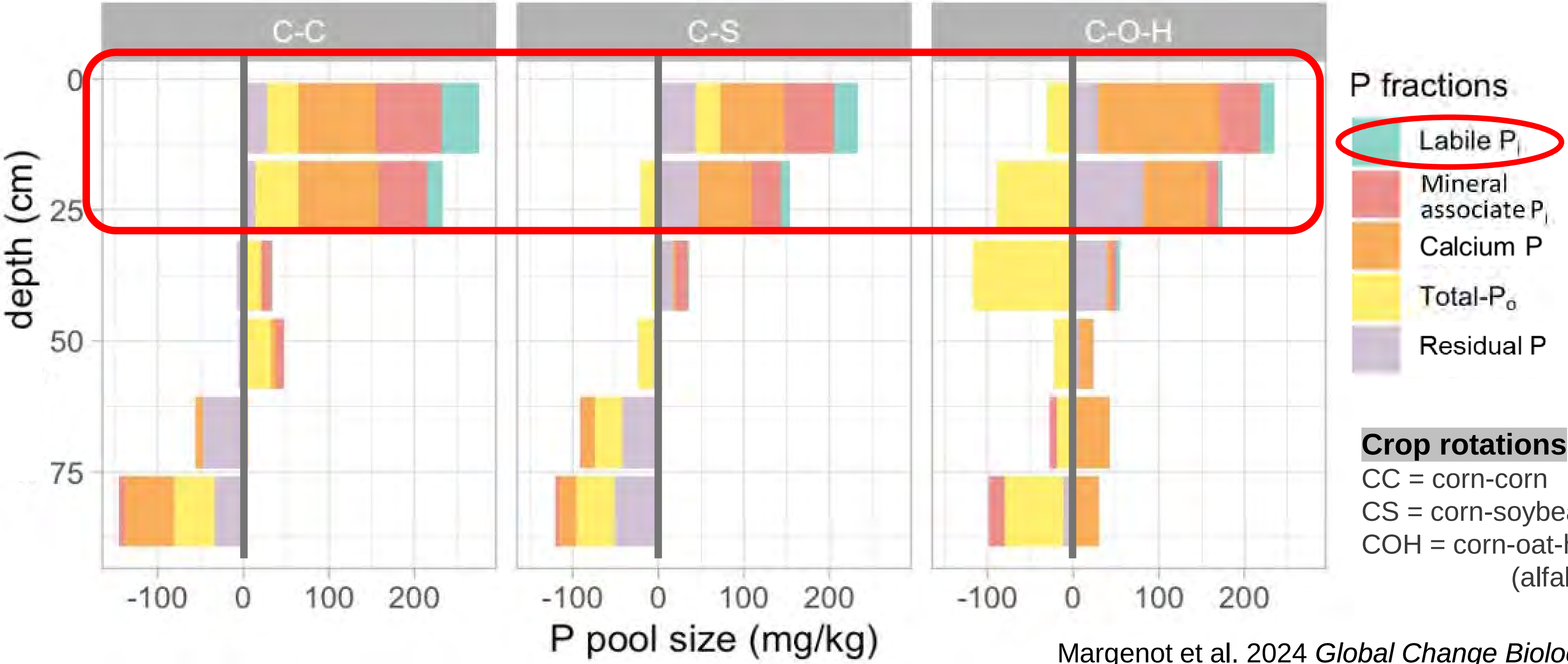
Saline watershed

Xu […] Margenot. Unpublished

Future direction: form of legacy P



- Surplus P found mostly in surface depths (0-12”)
- Surplus P exists in highly diverse forms, *including organic P*
- <10% of positive P balance ends up as labile forms: crop uptake, but also loss
- Transformation of past accumulated P inputs: a black hole



Crop rotations
CC = corn-corn
CS = corn-soybean
COH = corn-oat-hay (alfalfa)

Margenot et al. 2024 *Global Change Biology*. 30(6): e1737

Summary

- Varying definitions of "legacy P": need multiple dimensions to avoid incommensurability
- Approaches to estimating legacy P magnitudes are individually limited, but complementary
- Mass balances are most accessible approach, but require caution: precision, accuracy and implications (e.g., losses ≠ balances)
- Soil monitoring networks hold promise
- Need to improve models, from data to assumptions to ground truthing
- Key unknown: speciation (form) of legacy P given implications for agronomic use vs losses

Soil legacy P: status of and next steps in definitions, measurement and management

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18 September 2025

Sustainable P Alliance

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COLLEGE OF ACES Department of Crop Sciences

ILLINOIS

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phosphorus

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Perspective

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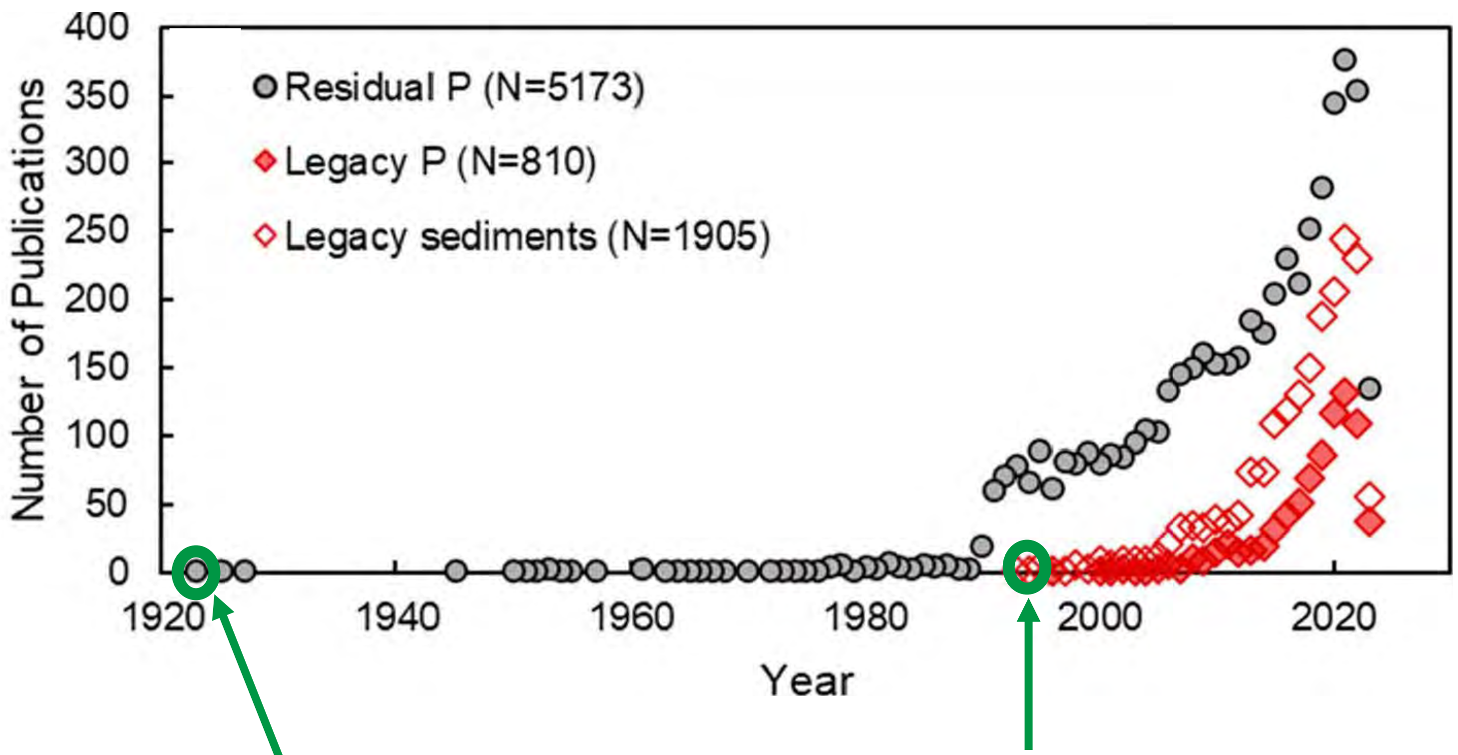

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Zhou & Margenot **2023** *Environmental Science & Technology* 57:21535

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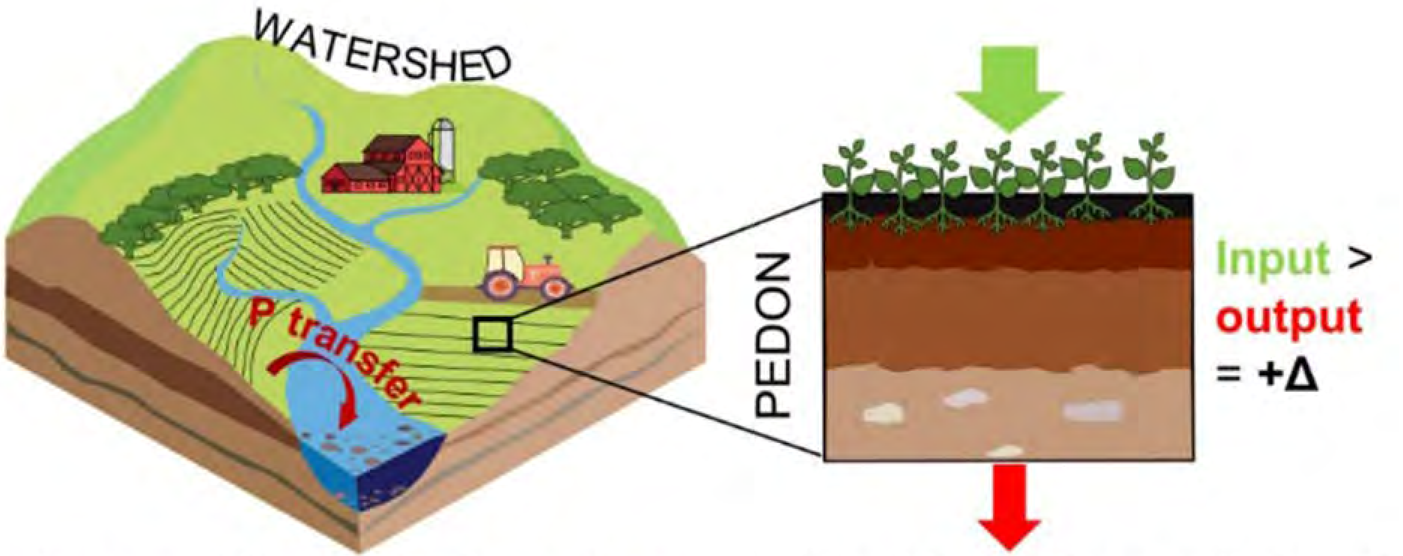

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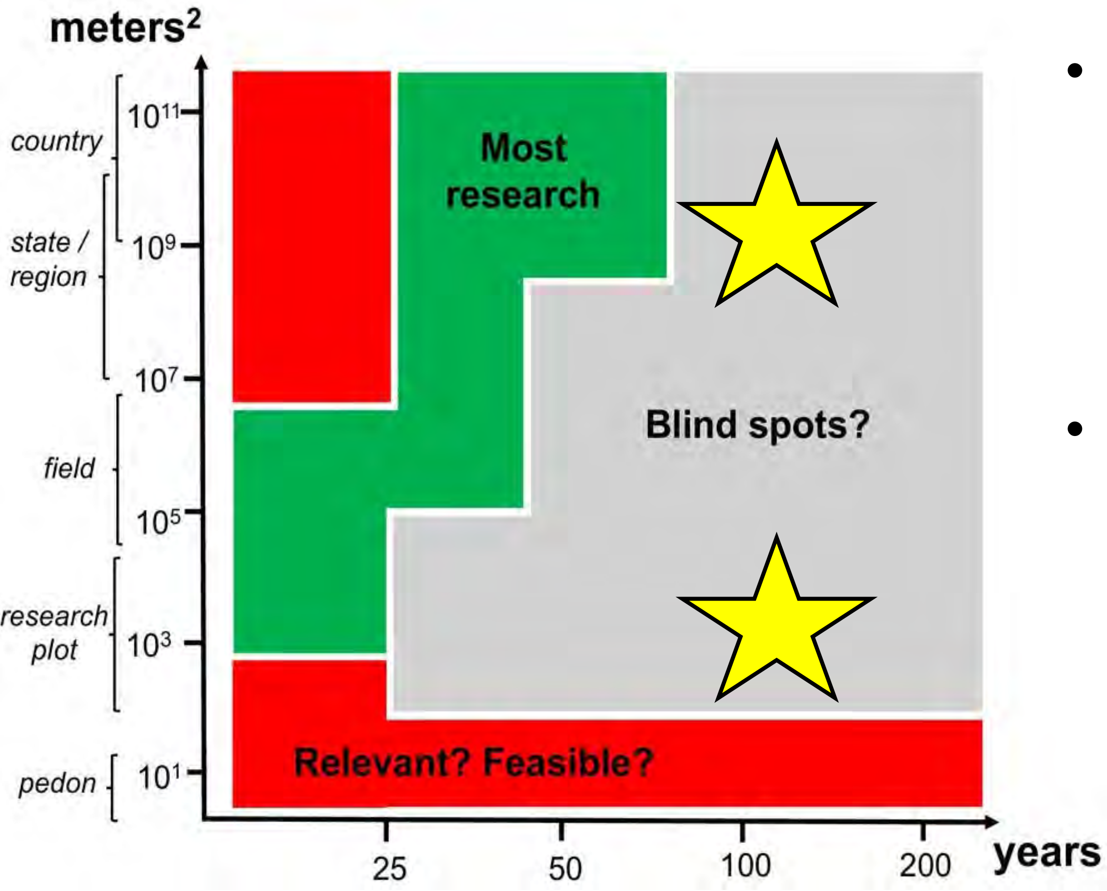

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Margenot et al 2024 *Global Change Biology* 30(6): e17376

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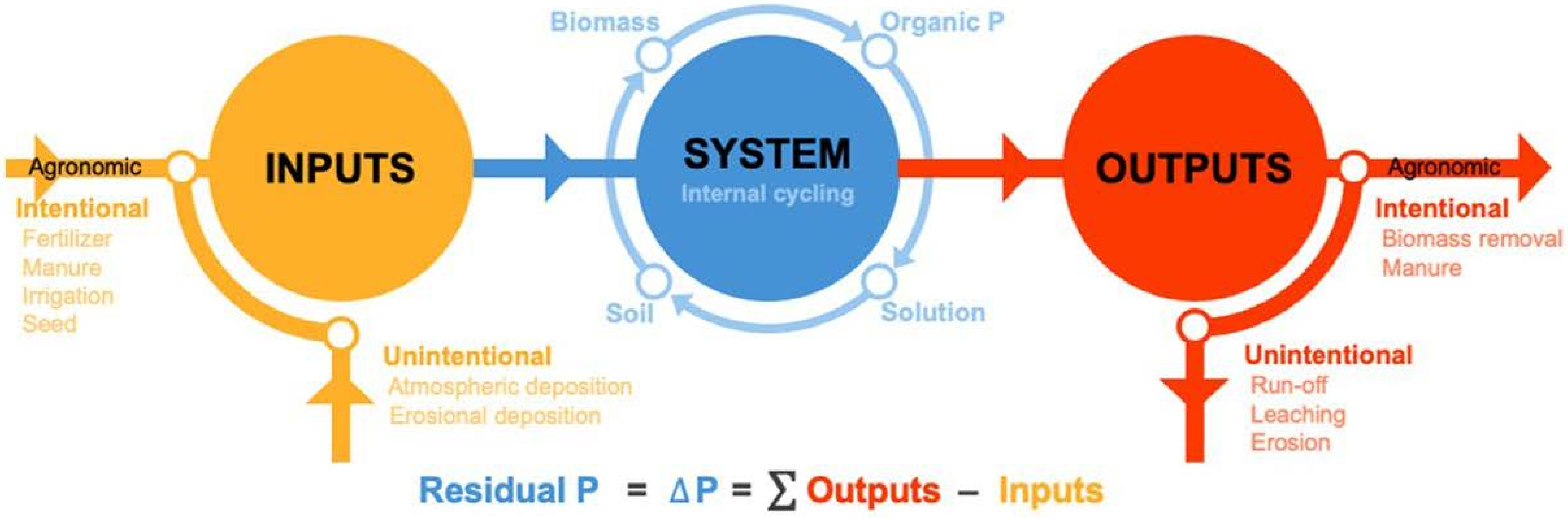

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Margenot et al 2024 *Global Change Biology* 30(6): e17376

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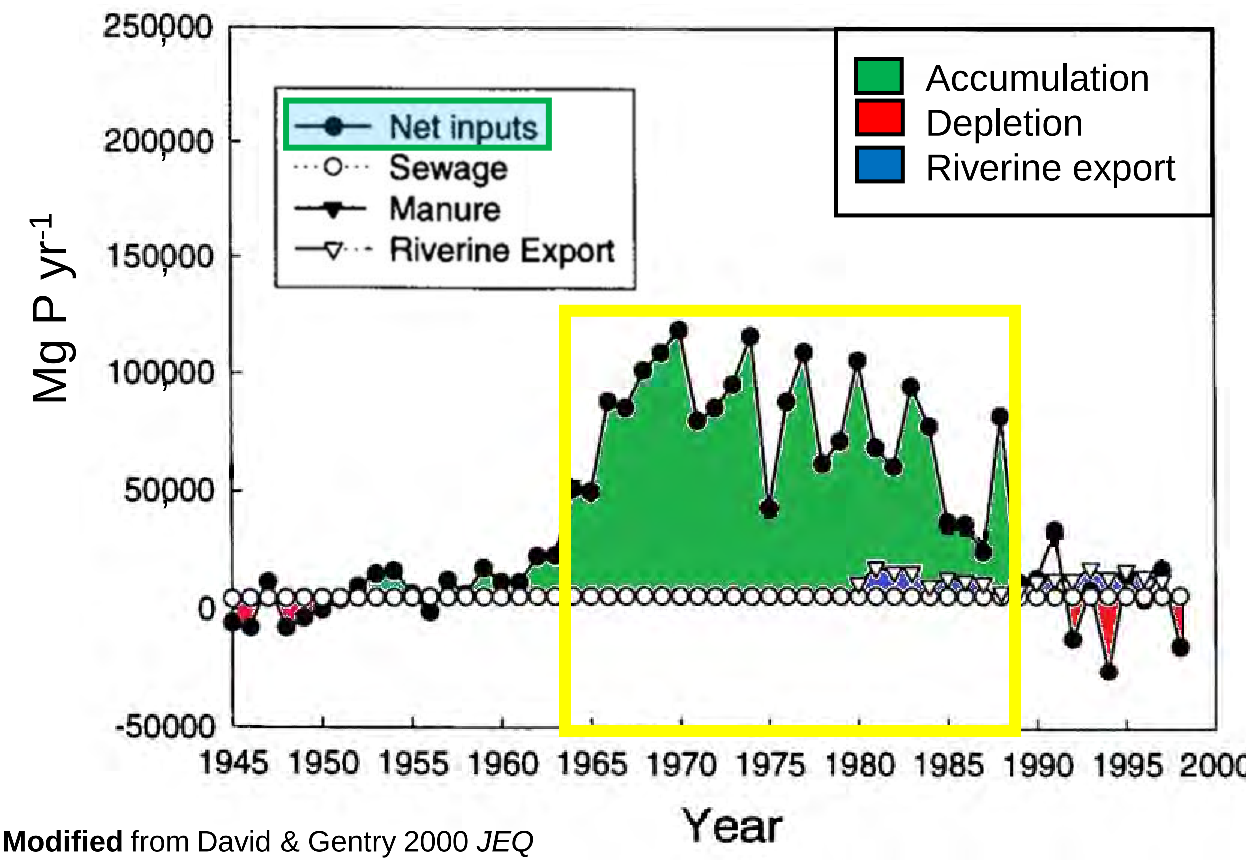

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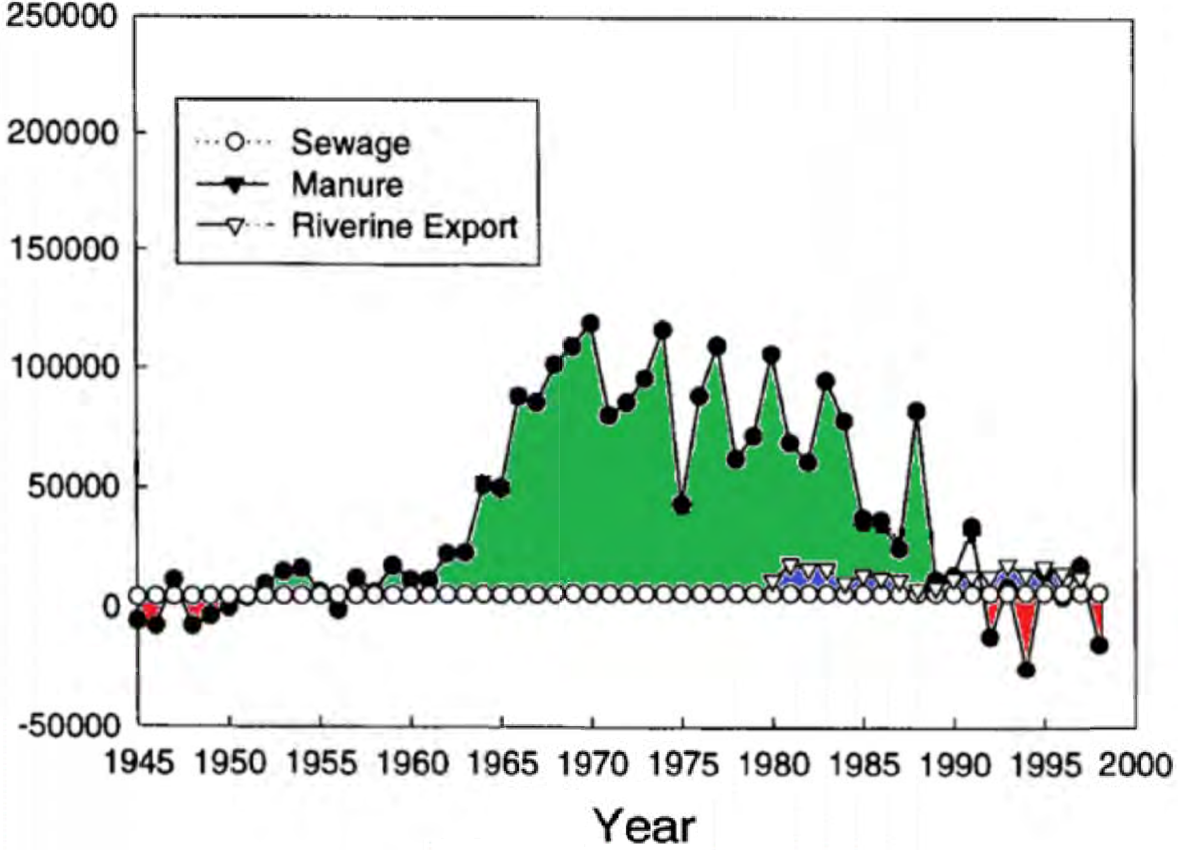

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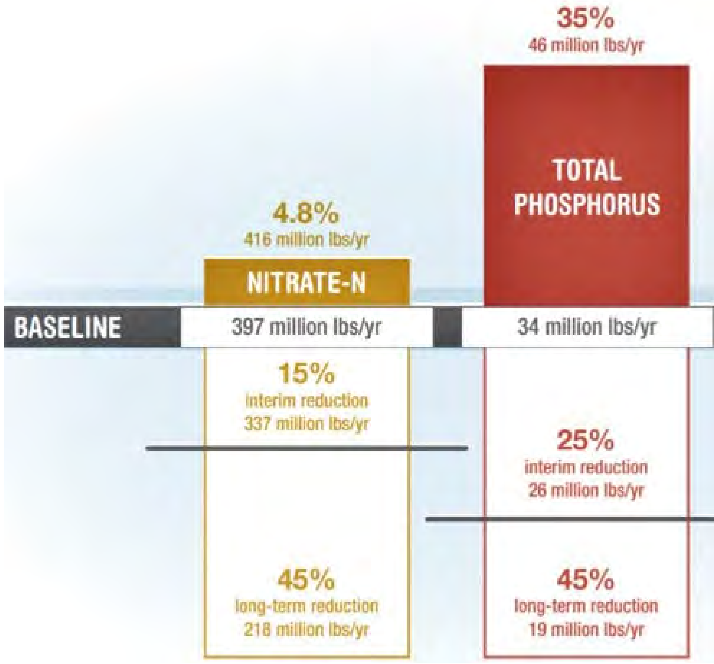

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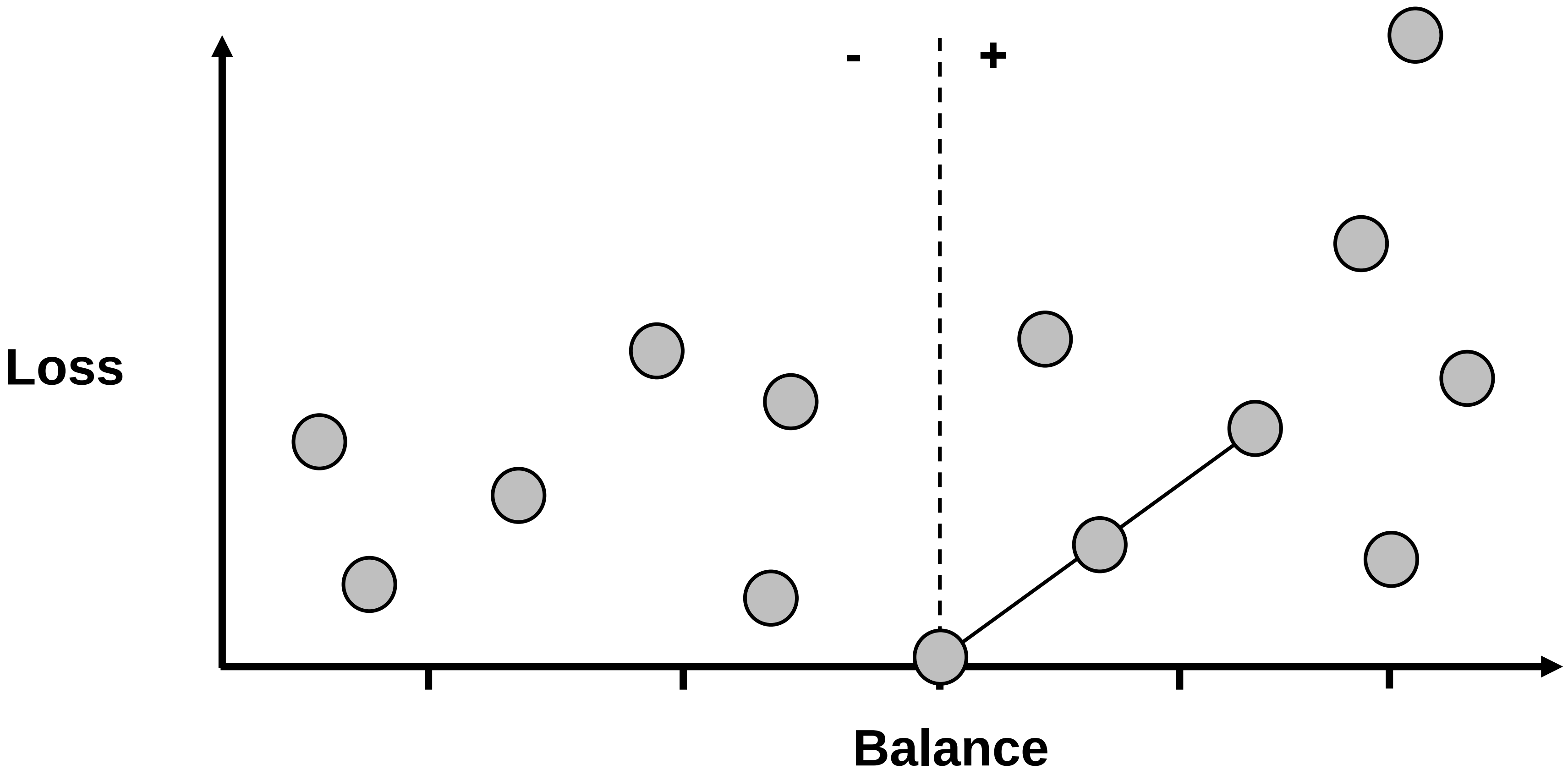

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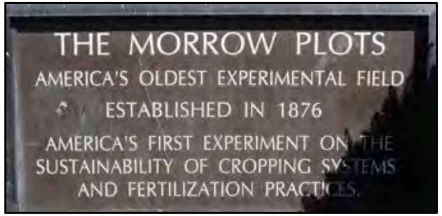

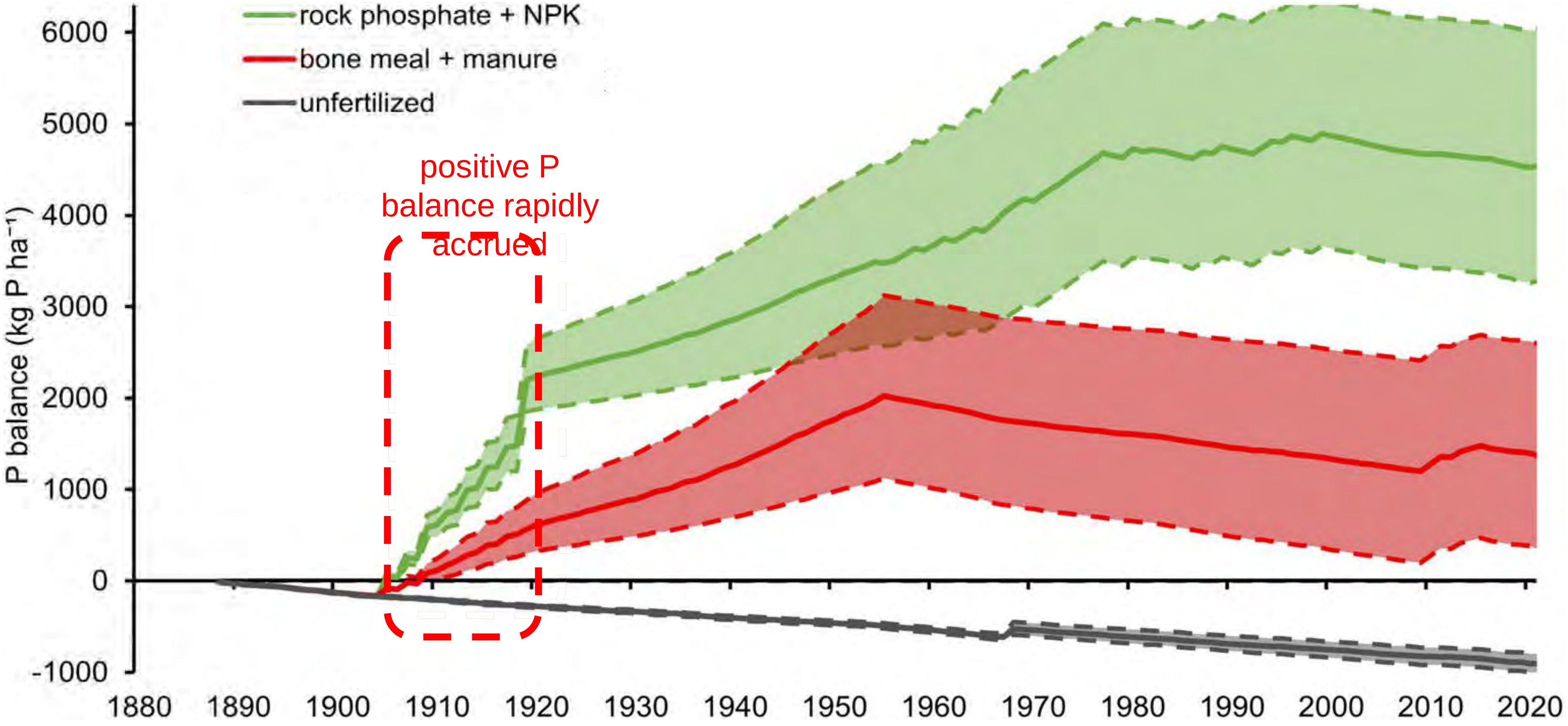

Margenot et al 2024 *Global Change Biology* 30(6): e17376

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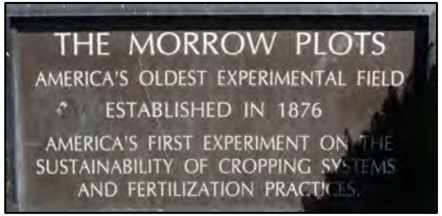

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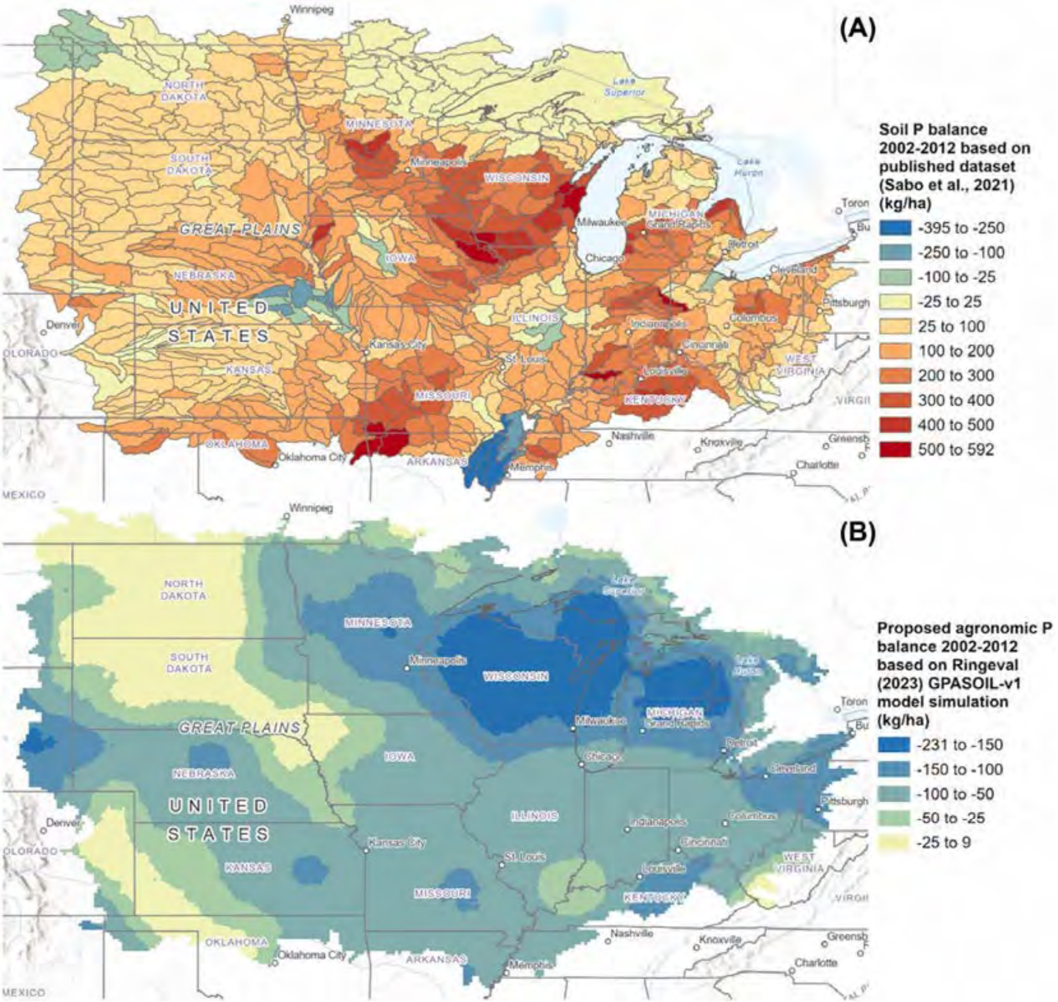

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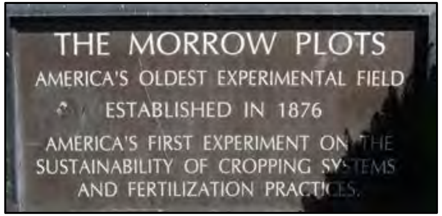
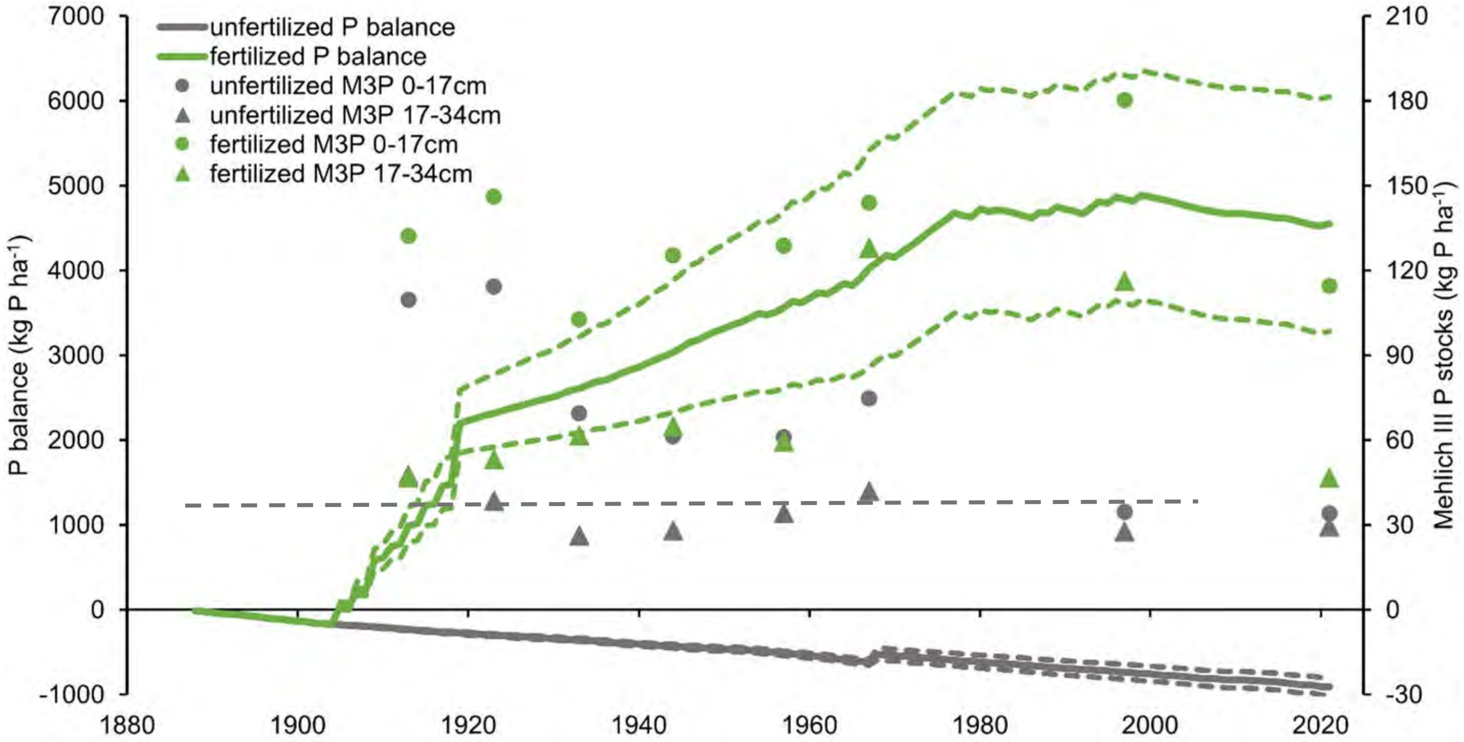
Soil test P is a poor proxy of legacy P

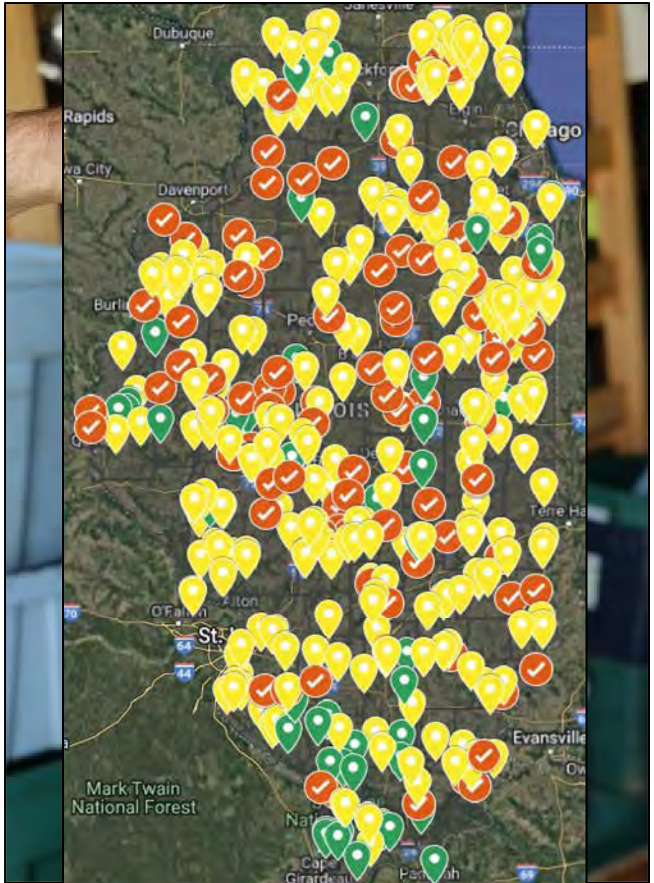
- Not quantitative, but can be qualitative:
  more residual/legacy P ~ higher soil test P

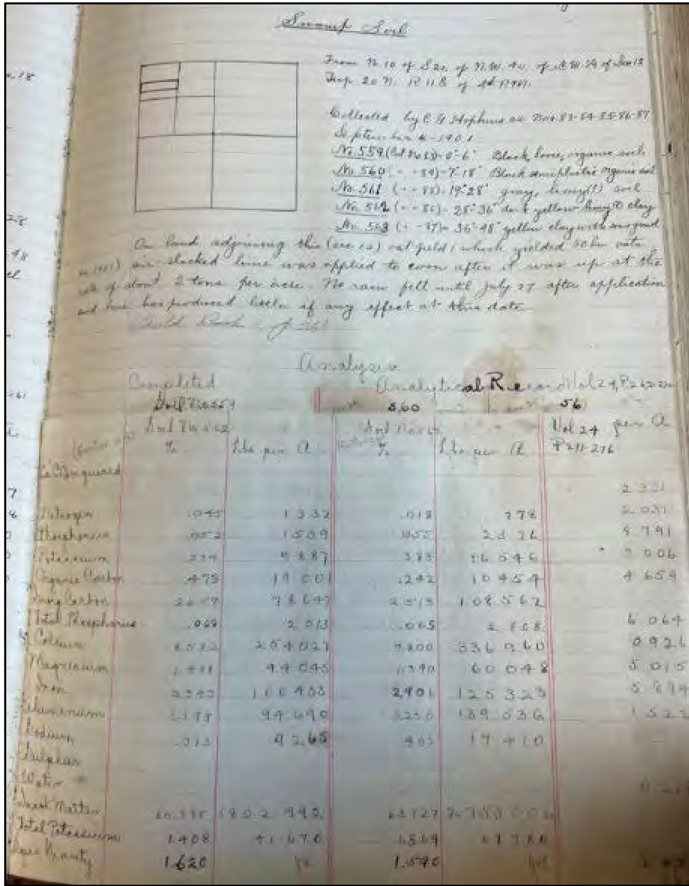




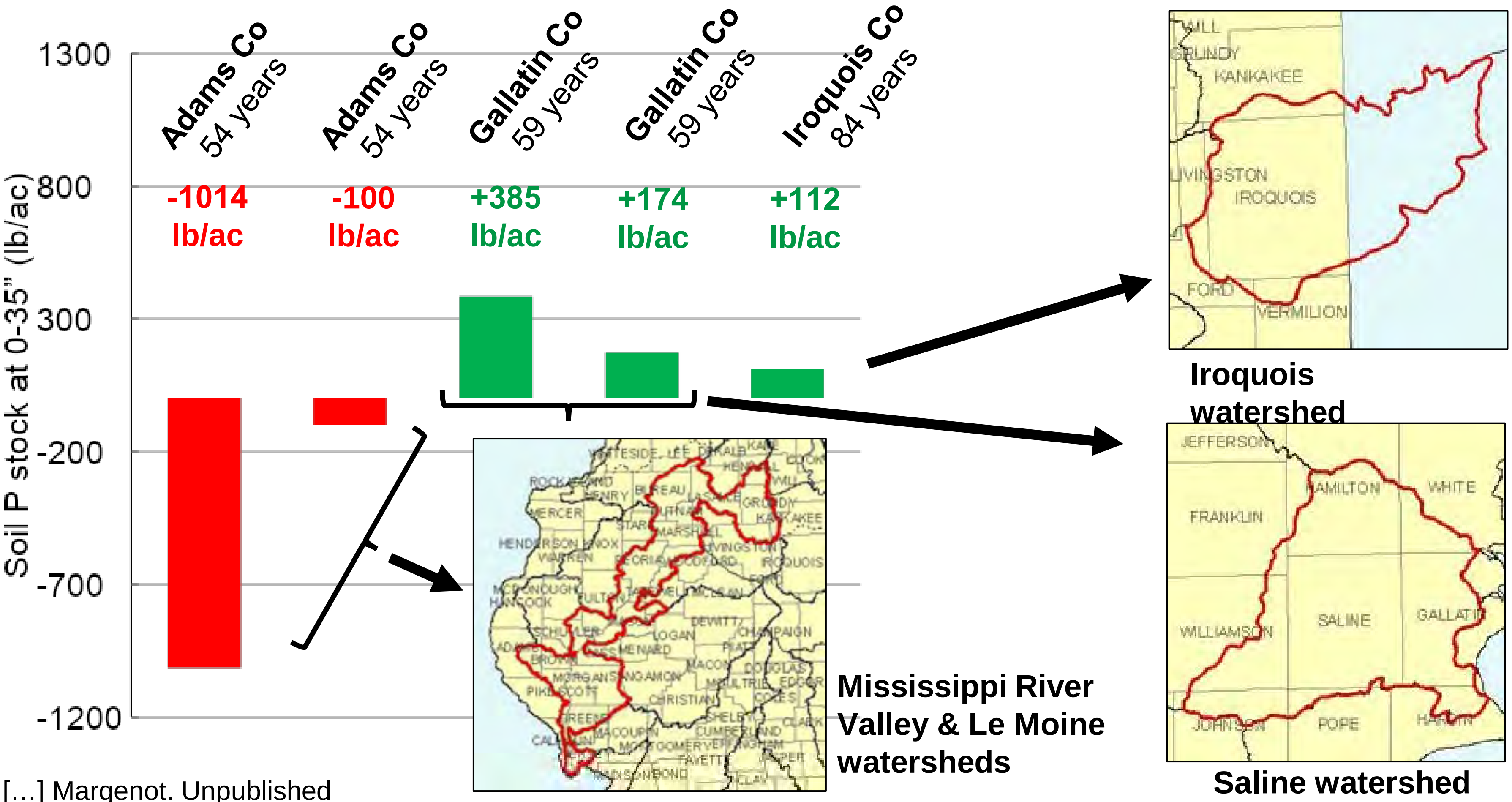
Margenot et al. 2025. *Advances in Agronomy.*

Future direction: soil monitoring networks



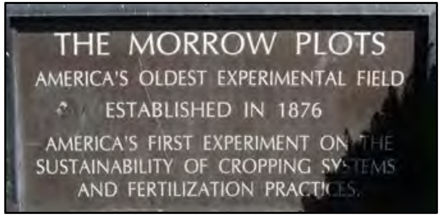


Example of quantifying legacy P in soils by resampling

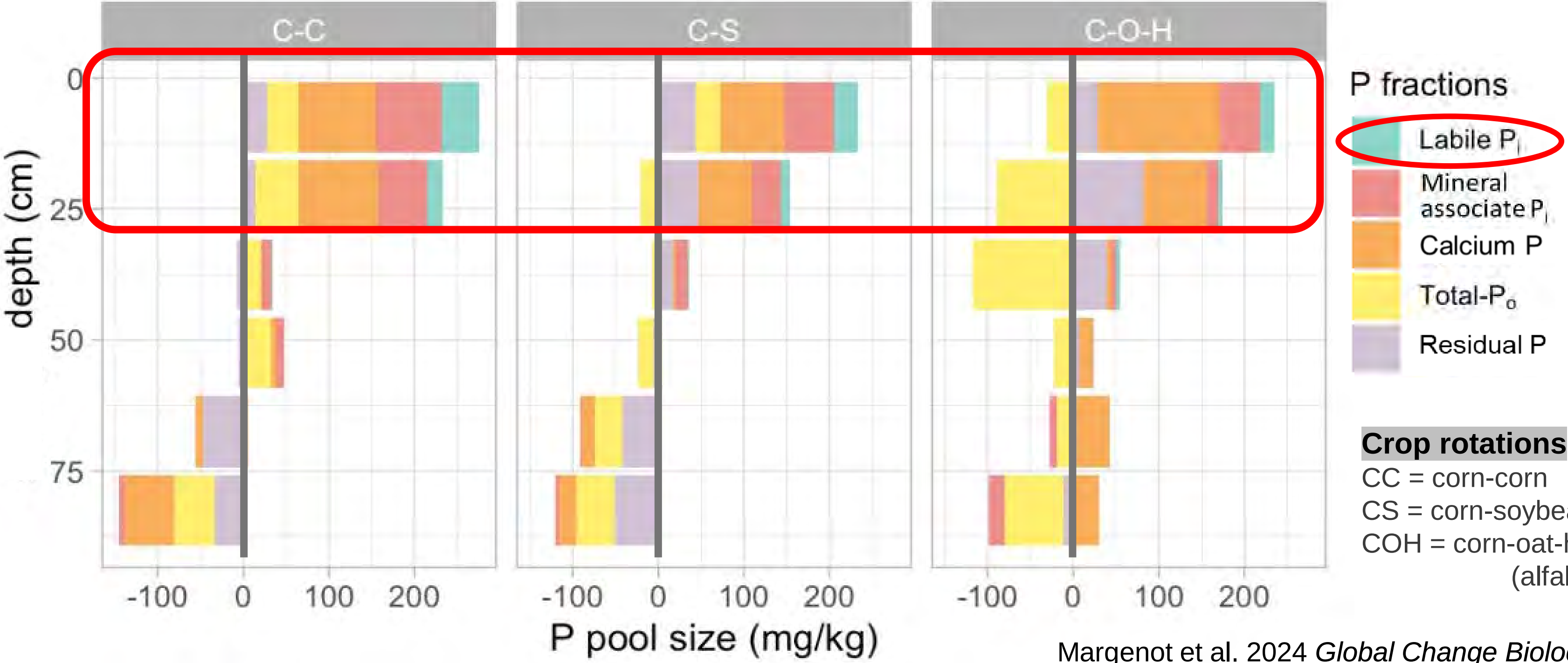


Xu […] Margenot. Unpublished

Future direction: form of legacy P



- Surplus P found mostly in surface depths (0-12”)
- Surplus P exists in highly diverse forms, *including organic P*
- <10% of positive P balance ends up as labile forms: crop uptake, but also loss
- Transformation of past accumulated P inputs: a black hole



Crop rotations
CC = corn-corn
CS = corn-soybean
COH = corn-oat-hay (alfalfa)

Margenot et al. 2024 *Global Change Biology*. 30(6): e1737

Summary

- Varying definitions of “legacy P”: need multiple dimensions to avoid incommensurability
- Approaches to estimating legacy P magnitudes are individually limited, but complementary
- Mass balances are most accessible approach, but require caution: precision, accuracy and implications (e.g., losses ≠ balances)
- Soil monitoring networks hold promise
- Need to improve models, from data to assumptions to ground truthing
- Key unknown: speciation (form) of legacy P given implications for agronomic use vs losses

Managing Legacy Phosphorus Loading in Agriculture & Beyond

Kim Van Meter
Associate Professor
Penn State University

Quantifying Legacy Phosphorus

New Datasets,
New Models,
New Pathways Forward

Kim Van Meter
Nandita Basu

LAKE ERIE

“A normal lake is knowable. A Great Lake can hold all the mysteries of an ocean, and then some.”
—Dan Egan, *Life and Death of the Great Lakes*

5-year fight removes less than 1% of phosphorus from Lake Winnipeg basin

Targeted action needed against nutrient causing toxic algae blooms, scientists and advocates say

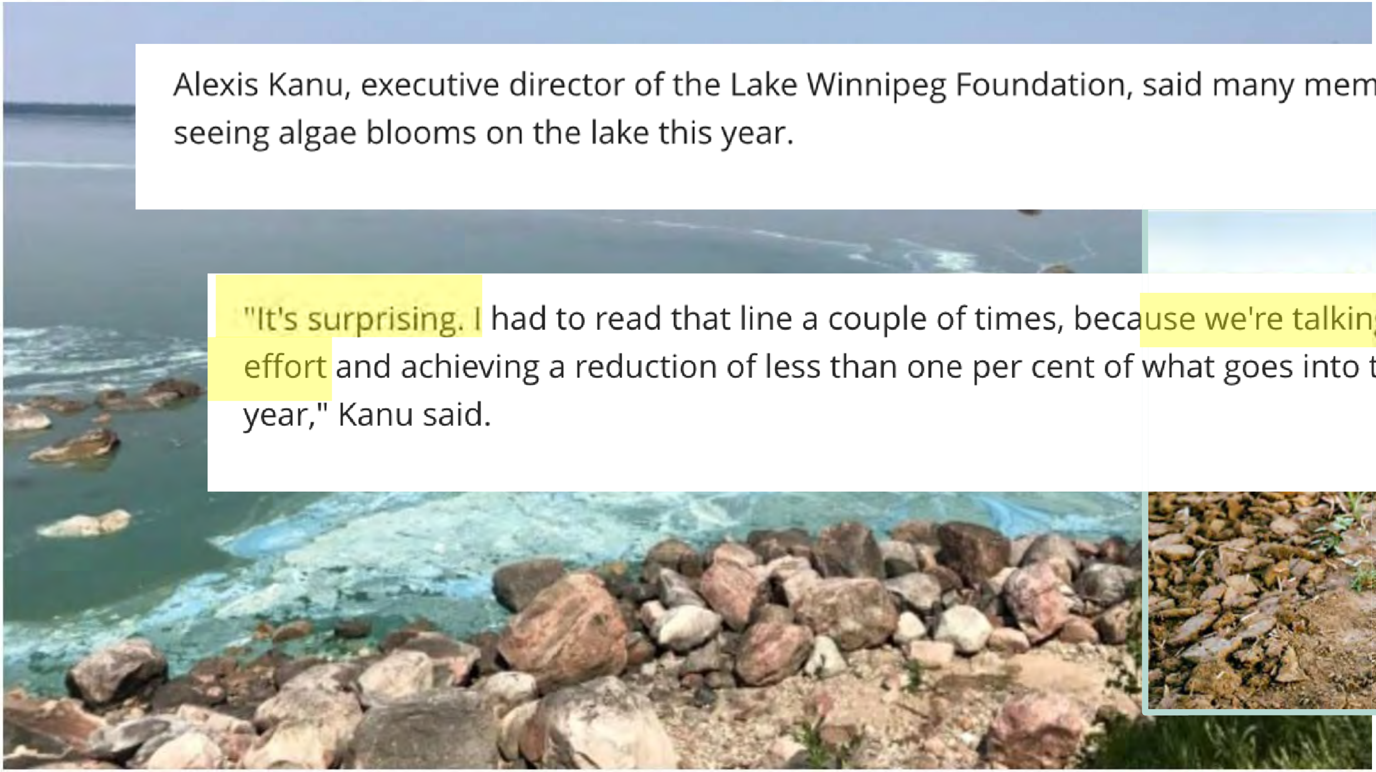
By Cameron MacLean, CBC News Posted: Sep 17, 2017 4:00 AM CT | Last Updated: Sep 17, 2017 11:02 AM CT

> "After spending $18 million, the amount of phosphorus entering the lake fell by less than 1%."
>
> *- Lake Winnipeg Basin Initiative report*

5-year fight removes less than 1% of phosphorus from Lake Winnipeg basin

Targeted action needed against nutrient causing toxic algae blooms, scientists and advocates say

By Cameron MacLean, CBC News   Posted: Sep 17, 2017 4:00 AM CT | Last Updated: Sep 17, 2017 11:02 AM CT



Alexis Kanu, executive director of the Lake Winnipeg Foundation, said many members reported seeing algae blooms on the lake this year.

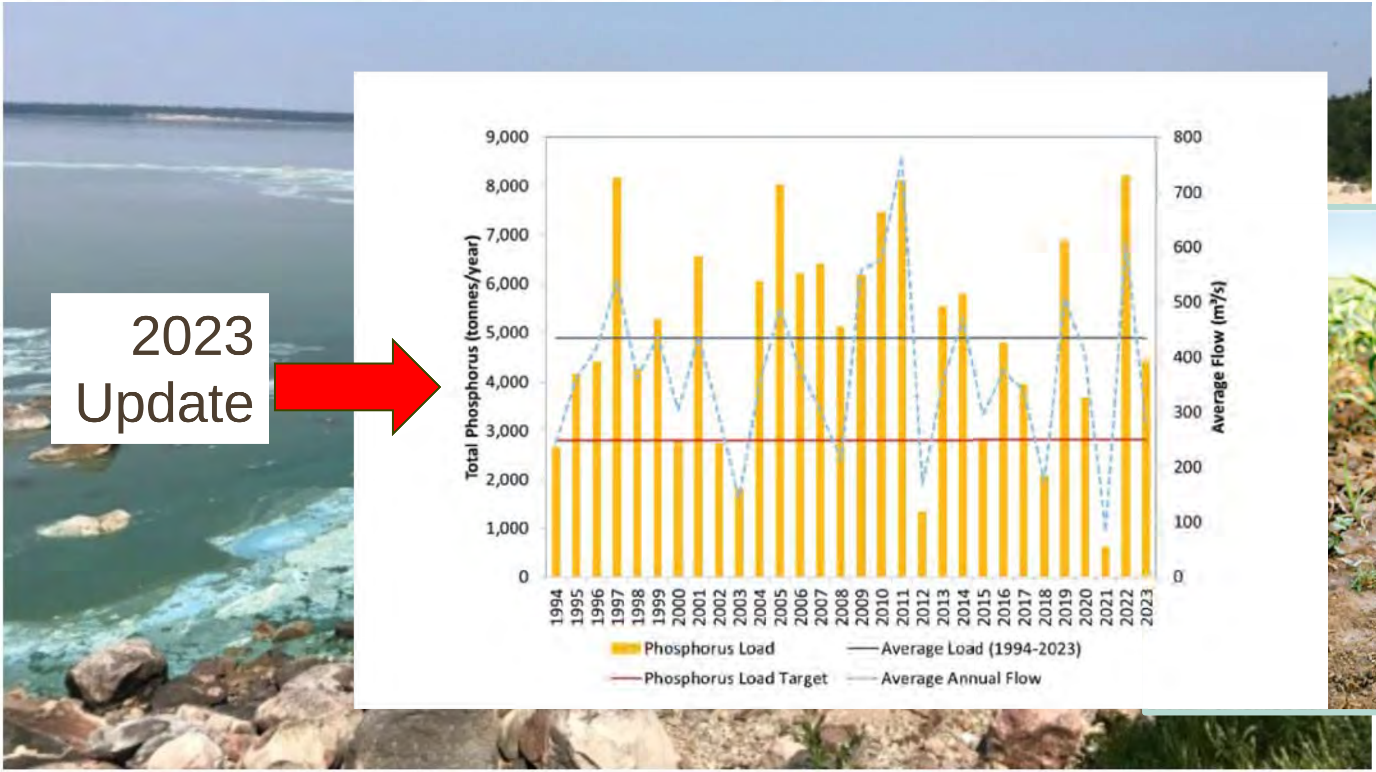
"It's surprising. I had to read that line a couple of times, because we're talking about five years of effort and achieving a reduction of less than one per cent of what goes into the lake every year," Kanu said.

5-year fight removes less than 1% of phosphorus from Lake Winnipeg basin

Targeted action needed against nutrient causing toxic algae blooms, scientists and advocates say

By Cameron MacLean, CBC News   Posted: Sep 17, 2017 4:00 AM CT | Last Updated: Sep 17, 2017 11:02 AM CT

2023 Update



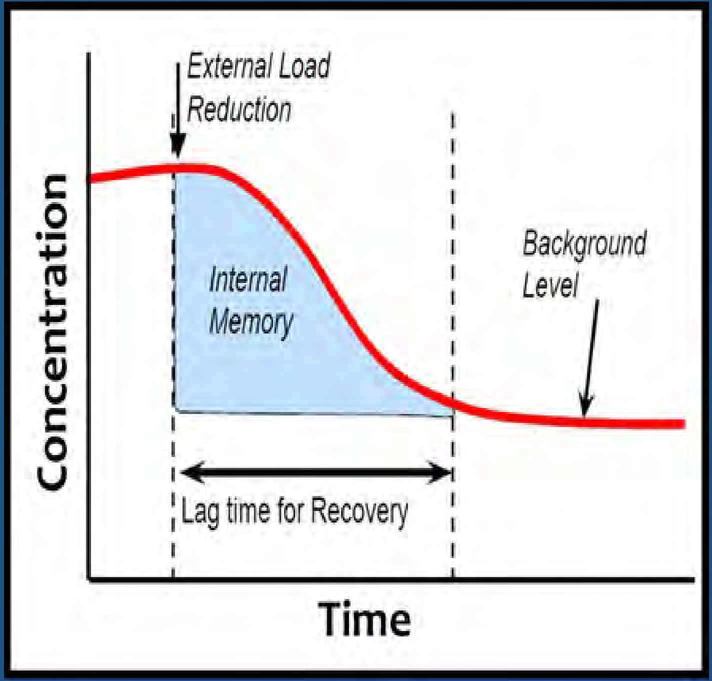
5-year fight removes less than 1% of phosphorus from Lake Winnipeg basin

Targeted action needed against nutrient causing toxic a

By Cameron MacLean, CBC News Posted: Sep 17, 2017 4:00 AM CT | Last

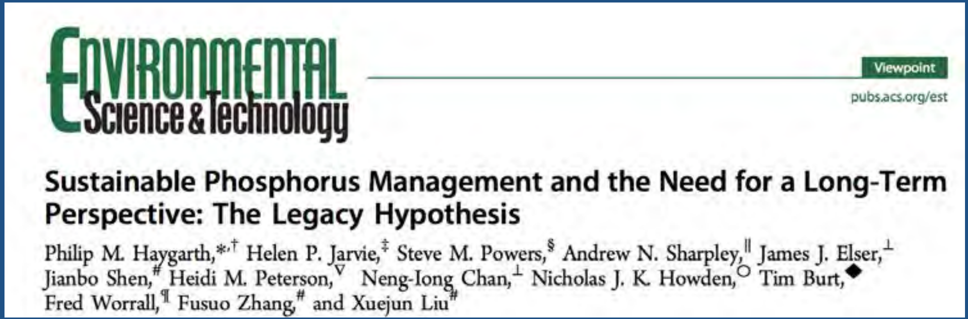
Such lack of success generates frustration

LEGACY HYPOTHESIS



adapted from Reddy et al.(2011)

Intensively managed catchments have legacy stores of nutrients that have built up over decades of fertilizer application and contribute to catchment time lags


Environmental Science & Technology

Viewpoint

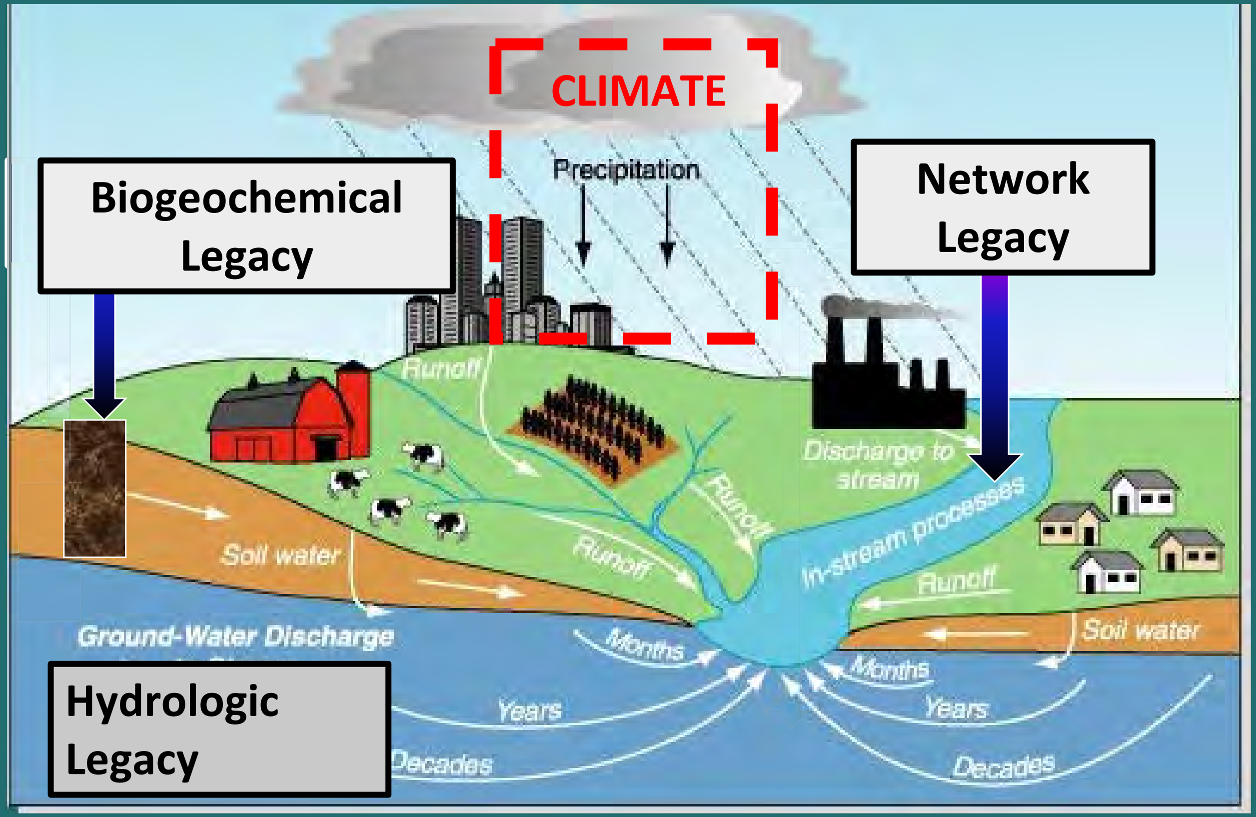
pubs.acs.org/est

Sustainable Phosphorus Management and the Need for a Long-Term Perspective: The Legacy Hypothesis

Philip M. Haygarth,*,† Helen P. Jarvie,‡ Steve M. Powers,§ Andrew N. Sharpley,∥ James J. Elser,⊥ Jianbo Shen,# Heidi M. Peterson,∇ Neng-Iong Chan,⊥ Nicholas J. K. Howden,○ Tim Burt,◆ Fred Worrall,¶ Fusuo Zhang,# and Xuejun Liu#

How long will it take for water quality to improve?

How long will it take for water quality to improve?



Stores

How much?

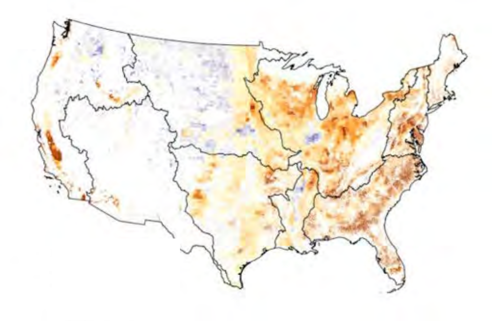
What form?

Where?

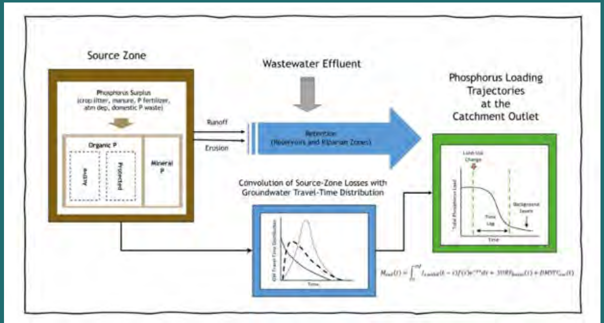
Fluxes

What are the depletion rates?

Today's Talk



TREND-phosphorus
A national-scale view



Watershed Phosphorus Modeling to Capture Legacy Accumulation and Remobilization

Stores

How much?

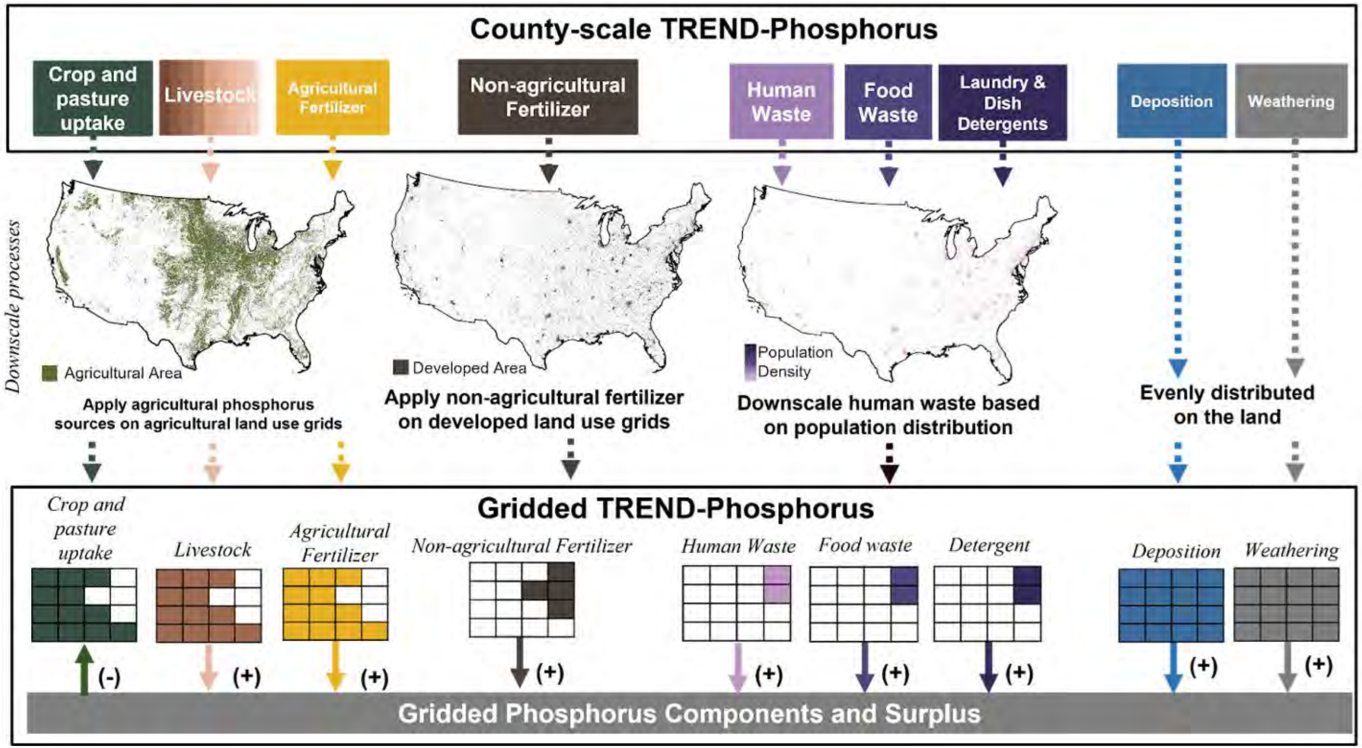
What form?

Where?

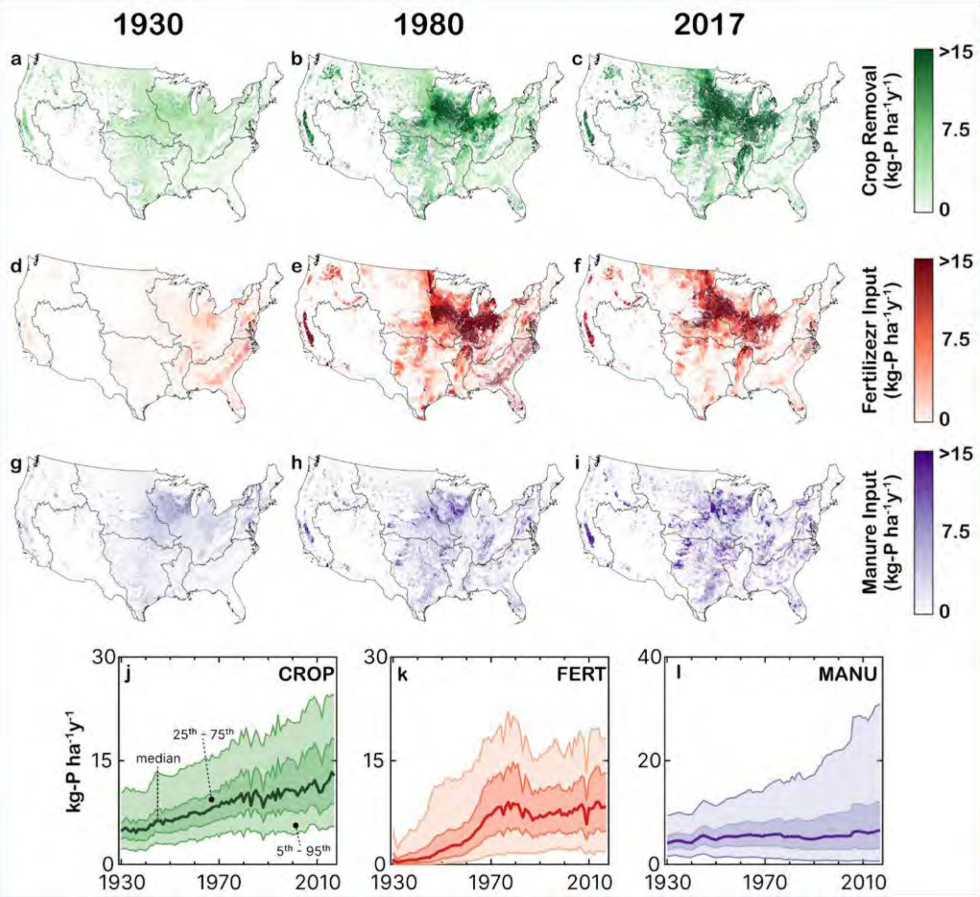
Fluxes

What are the depletion rates?

TREND-Phosphorus

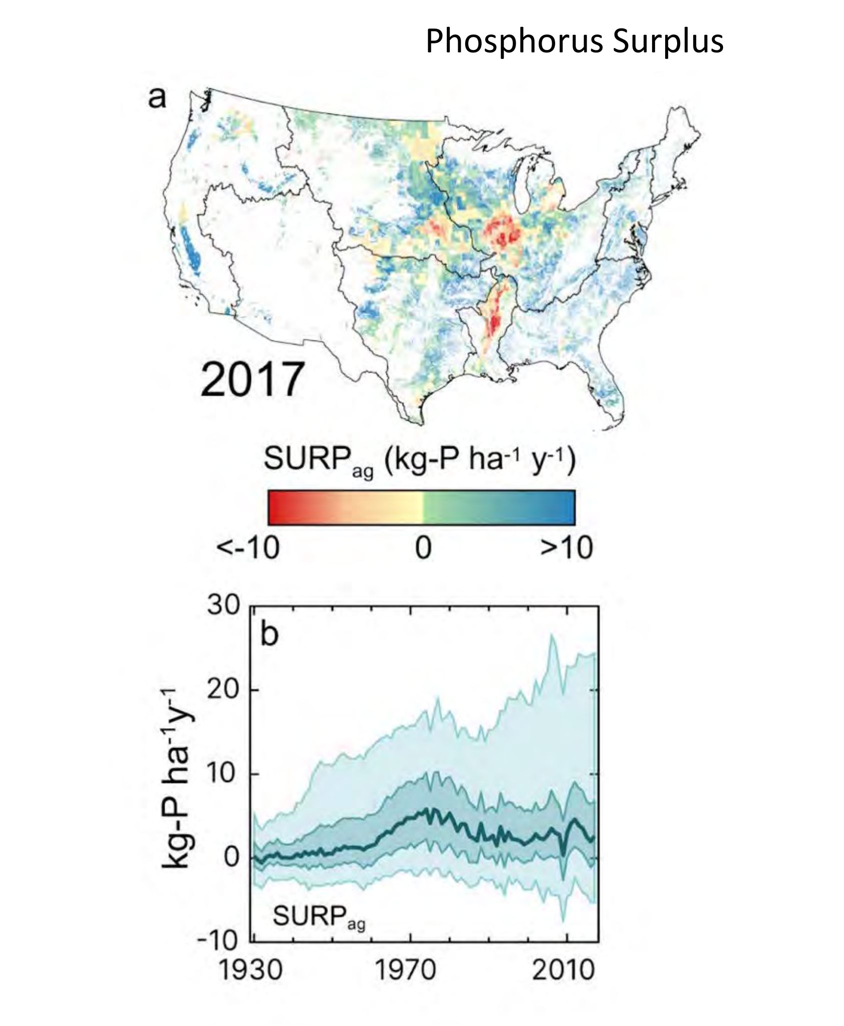


TREND-Phosphorus



Spatial patterns in phosphorus inputs

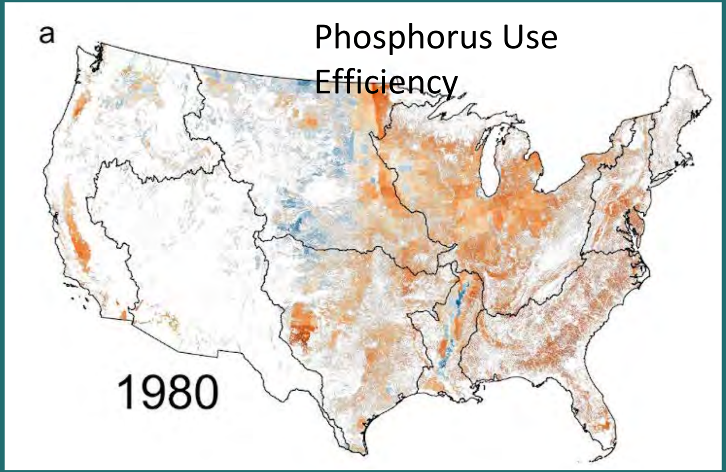
Trends in landscape Phosphorus Fluxes Over Time

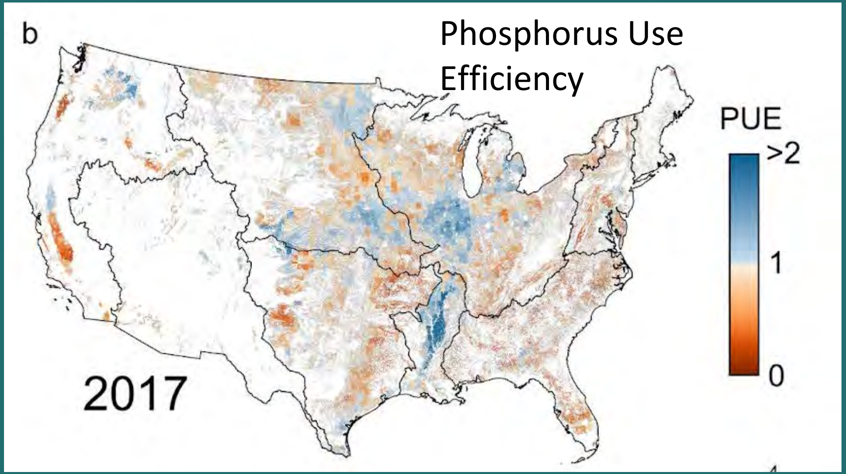


TREND-Phosphorus

- Spatial patterns in phosphorus inputs
- Trends in landscape Phosphorus Fluxes Over Time
- Phosphorus Surplus

TREND-Phosphorus

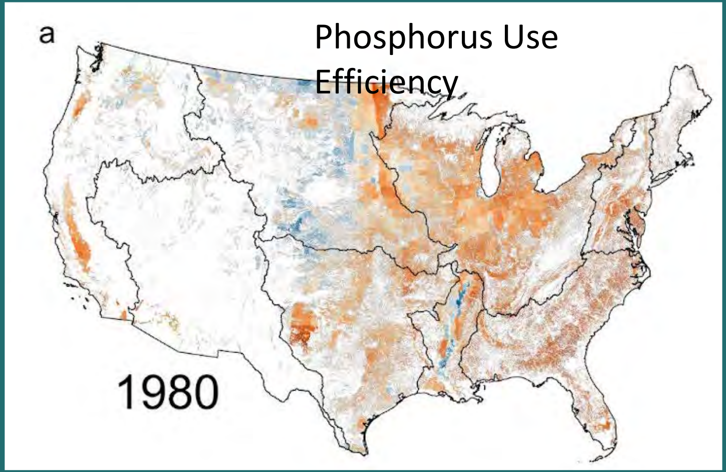


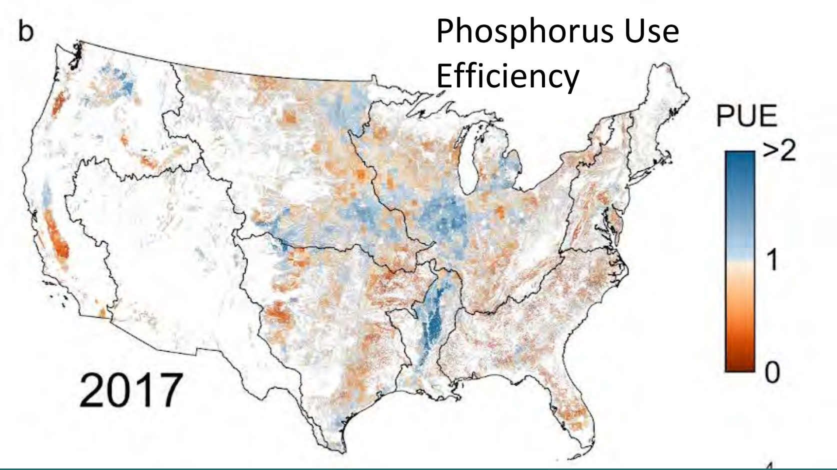


Spatial patterns in phosphorus inputs

Trends in landscape Phosphorus Fluxes Over Time

Phosphorus Use Efficiency (PUE)

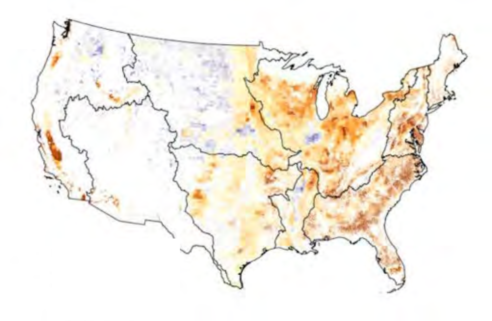




TREND-Phosphorus

- Spatial patterns in phosphorus inputs
- Trends in landscape Phosphorus Fluxes Over Time
- Phosphorus Surplus
- Phosphorus Use Efficiency (PUE)

Today's Talk



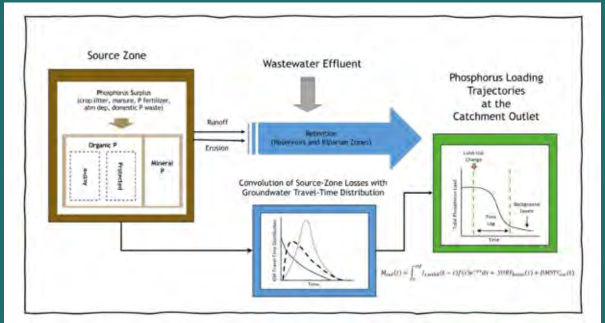
TREND-phosphorus
A national-scale view

Stores

How much?

What form?

Where?



Watershed Phosphorus Modeling to Capture Legacy Accumulation and Remobilization

Fluxes

What are the depletion rates?

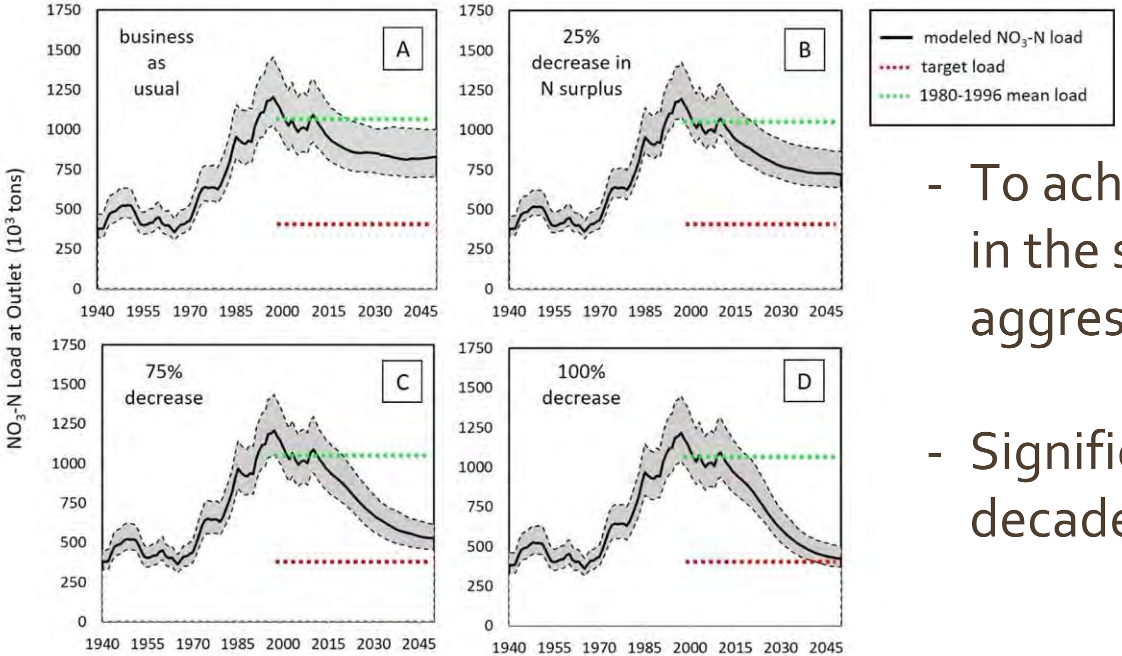
Van Meter *et al.*, *Science* **360**, 427–430 (2018)

OCEAN HYPOXIA

Legacy nitrogen may prevent achievement of water quality goals in the Gulf of Mexico

Exploration of **L**ong-t**E**r**M** **N**utrien**T** legacies (ELEMENT)

Nitrogen

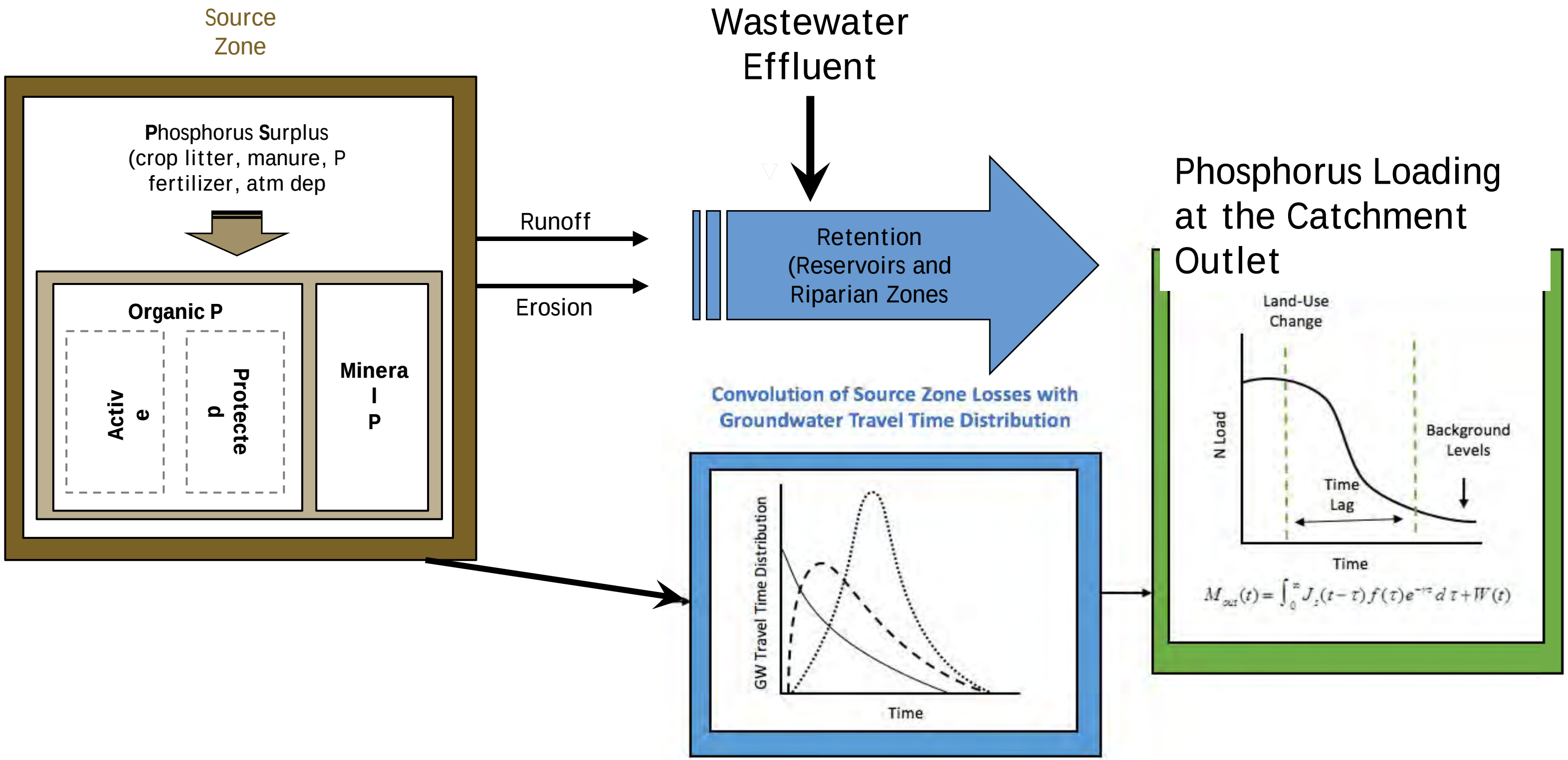


- To achieve the required 60% reduction in the size of the Gulf hypoxic zone, aggressive measures are needed

- Significant reductions could take decades to achieve

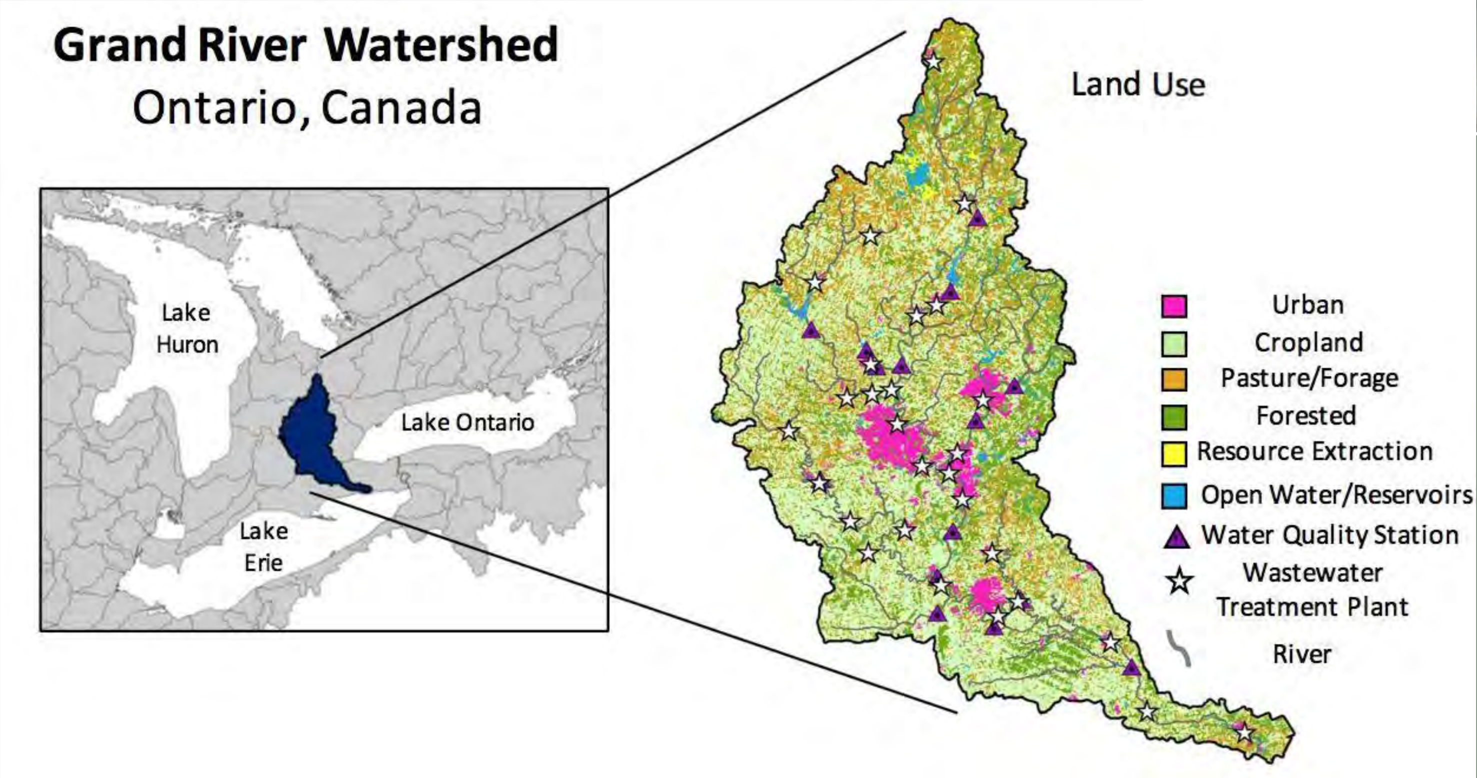
ELEMeNT
Phosphorus

Exploration of Long-tErM NutrienT legacies



Van Meter et al., 2021, *WRR*

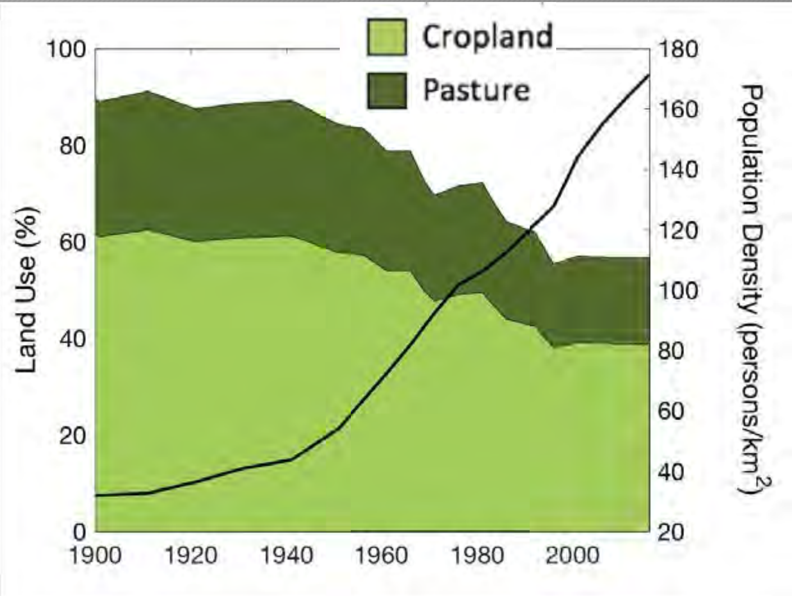
Lake Erie



Grand River Watershed
Ontario, Canada
Lake Huron
Lake Ontario
Lake Erie
Land Use
Urban
Cropland
Pasture/Forage
Forested
Resource Extraction
Open Water/Reservoirs
Water Quality Station
Wastewater Treatment Plant
River

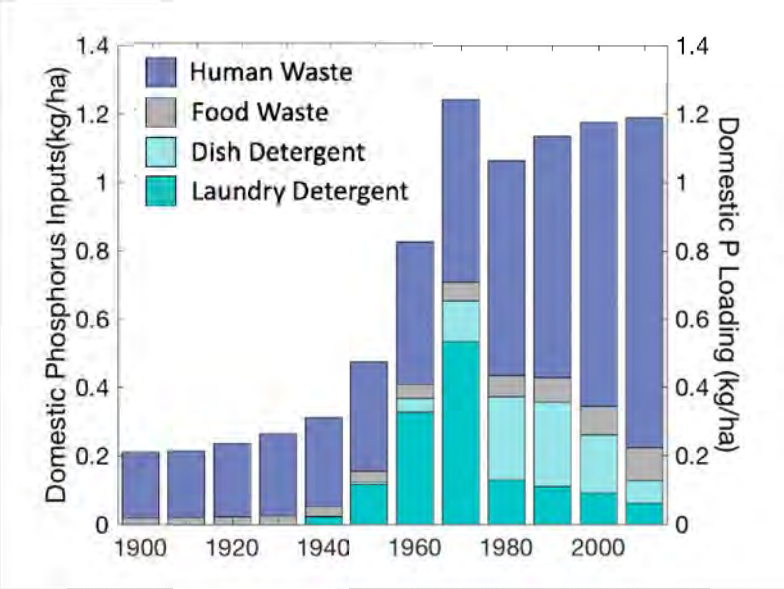
Land Use, Urbanization, and Domestic P Sources

- Land use
- Land management
- Changing Human Impacts



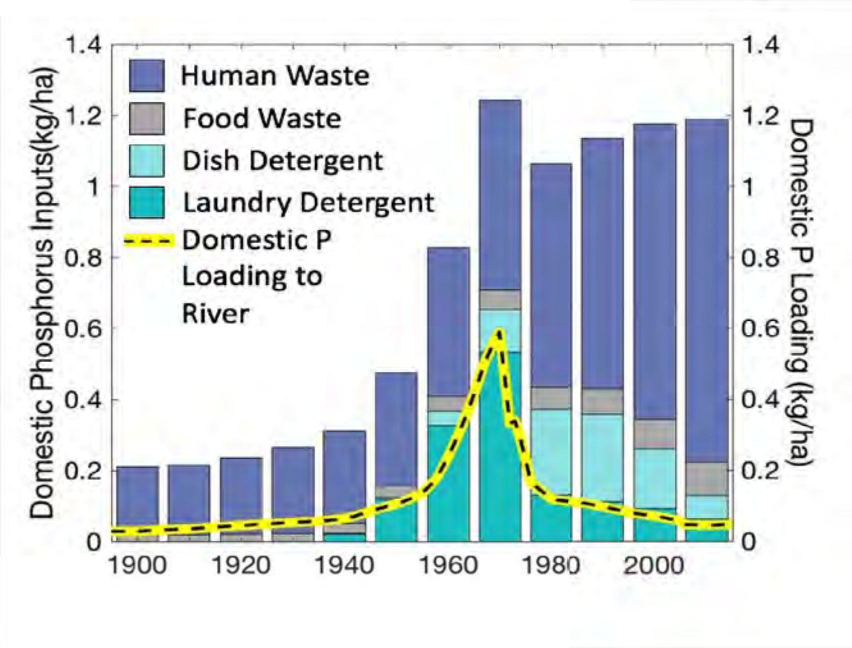
Van Meter et al. 2021, *WRR*

Domestic P Sources



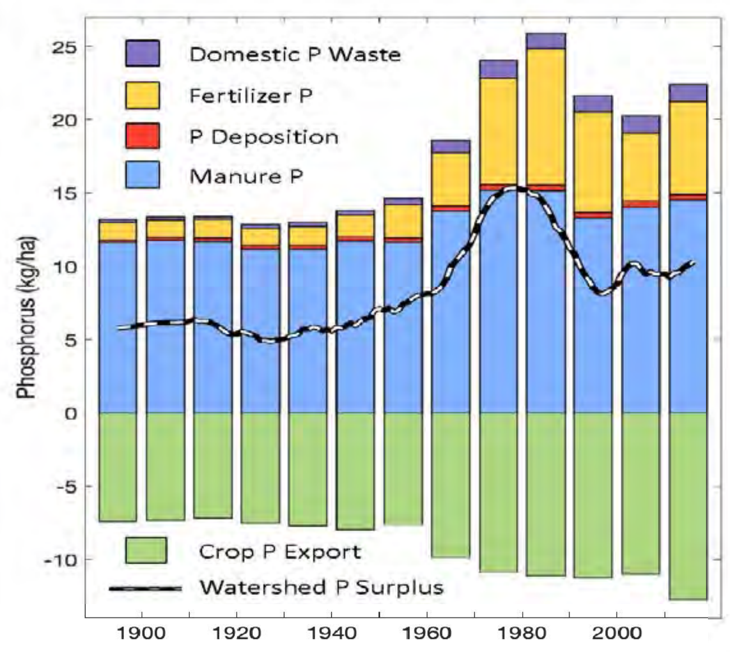
Van Meter et al. 2021, *WRR*

Domestic P Sources



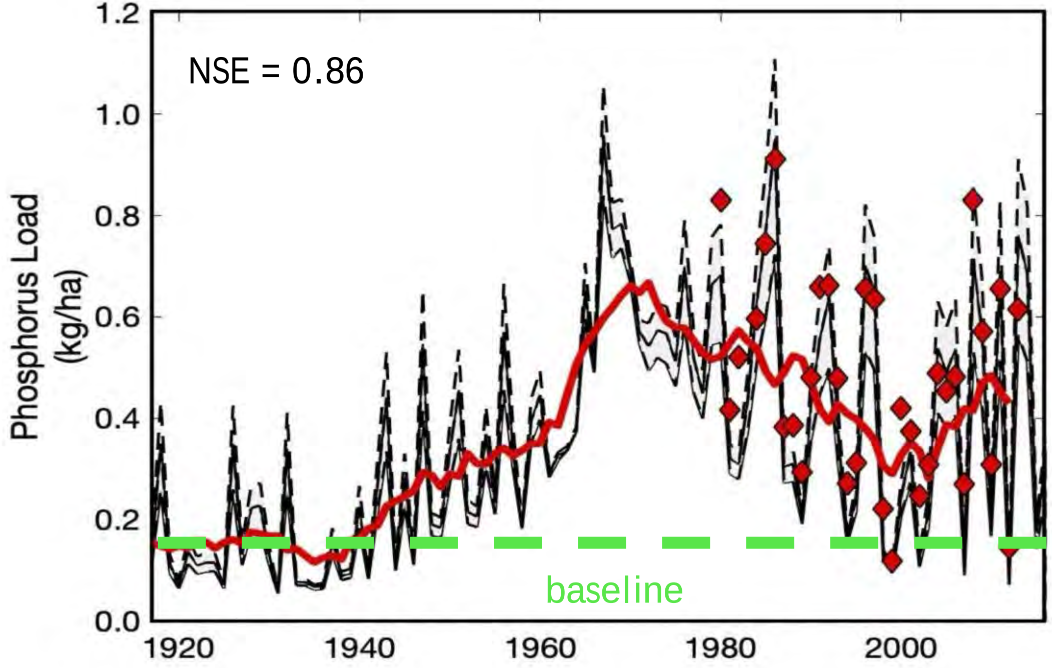
Van Meter et al. 2021, *WRR*

Watershed P Surplus Trajectories

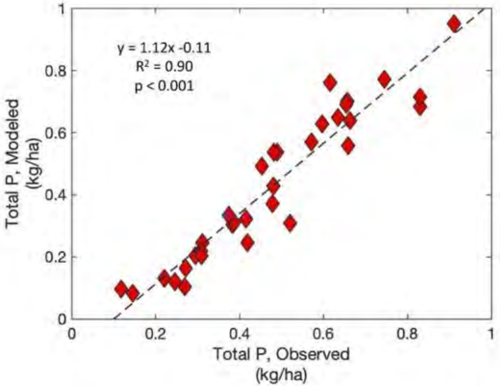


Van Meter et al. 2021, *WRR*

Total Phosphorus Loading
Grand River Watershed, Ontario

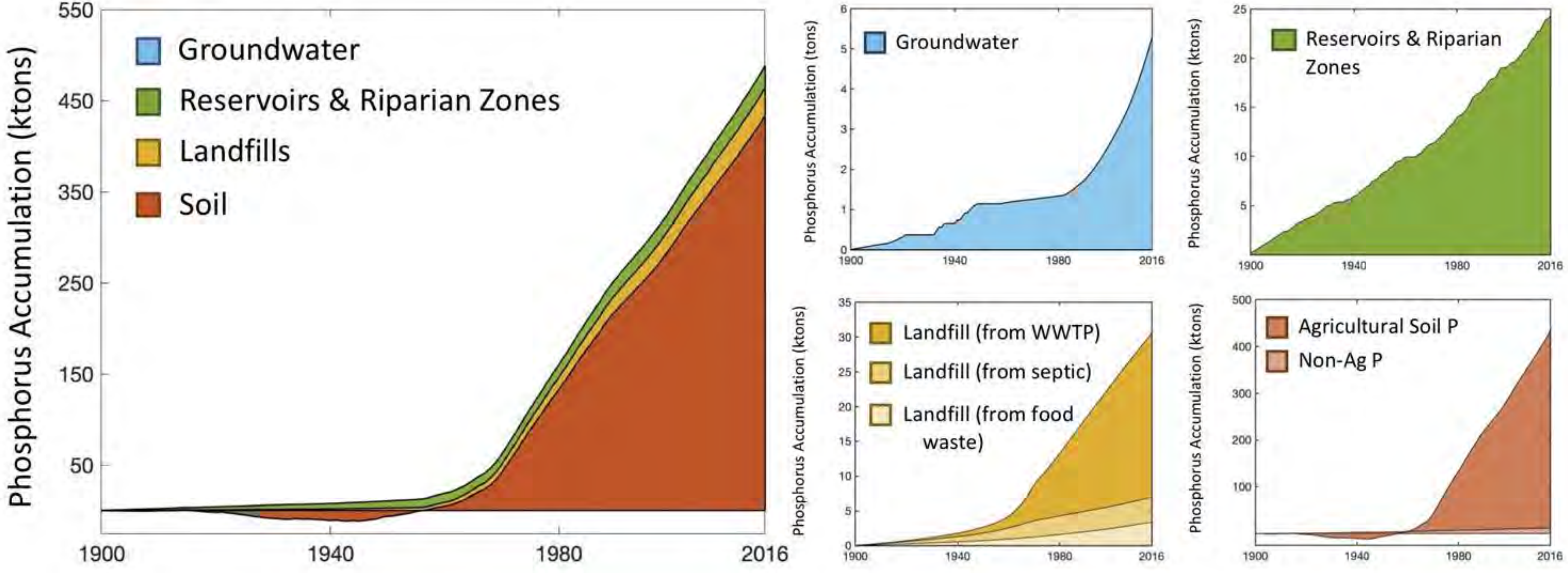


Observed vs. Modeled TP Values
1977-2011



Van Meter et al. 2021, *WRR*

Phosphorus Storage across the Land-Freshwater Continuum

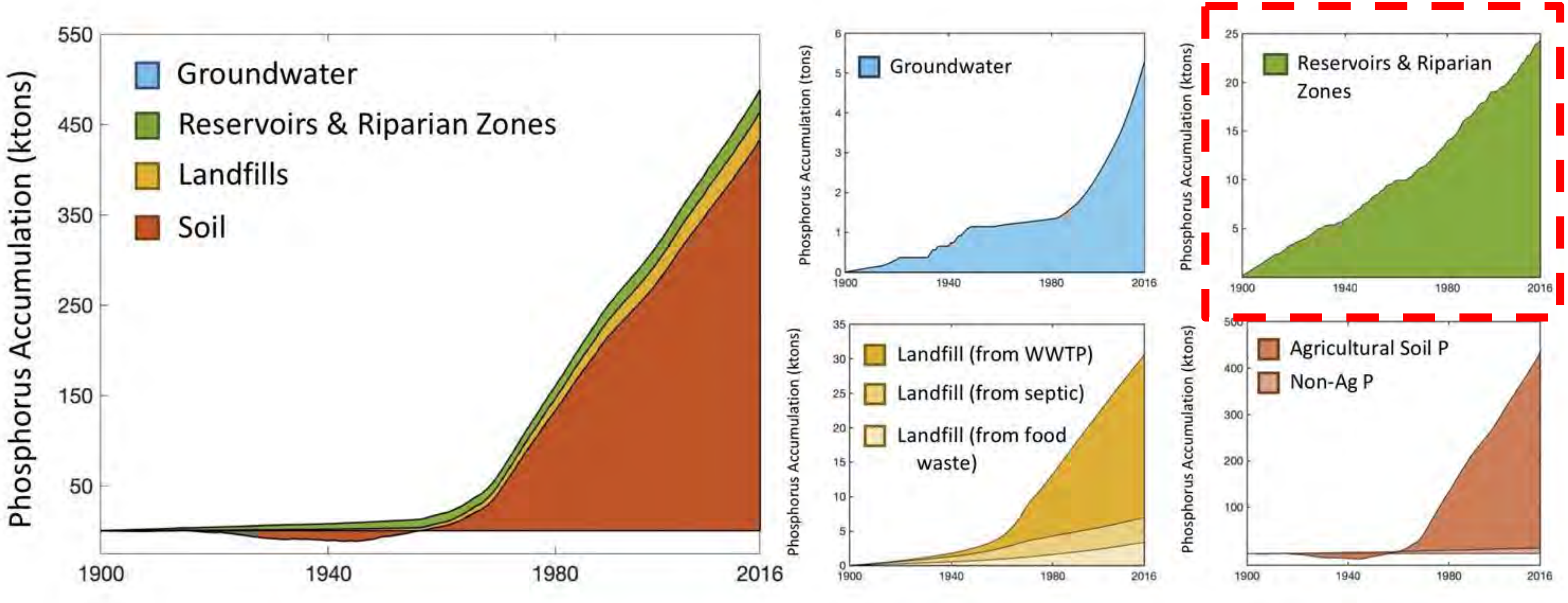


Agricultural soils have soil P levels approximately 25% higher than adjacent pristine soils

Van Meter et al. 2021, *WRR*

Phosphorus Storage across the Land-Freshwater Continuum

Since 1900, ~4% of net P inputs to the GRW have been exported to downstream waters



Agricultural soils have soil P levels approximately 25% higher than adjacent pristine soils

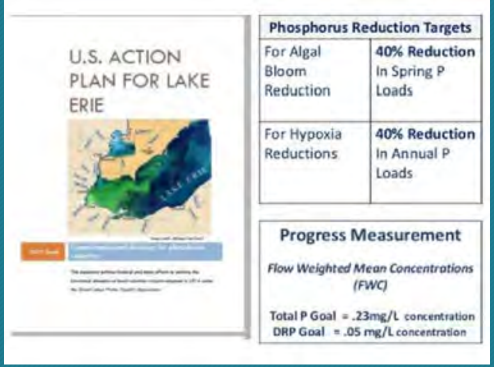
Van Meter et al. 2021, *WRR*

How long will it take for water quality to improve?

Proposed Binational Phosphorus Load Reduction Targets

Lake Ecosystem Objectives *Great Lakes Water Quality Agreement* *Annex 4, Section B*	**Western Basin of Lake Erie**	**Central Basin of Lake Erie**
Minimize the extent of hypoxic zones in the Waters of the Great Lakes associated with excessive phosphorus loading, with particular emphasis on Lake Erie	40 percent reduction in total phosphorus entering the Western Basin and Central Basin of Lake Erie – from the United States and from Canada – to achieve 6000 MT Central Basin load	

Is a 40% reduction in P loading possible under current land use?

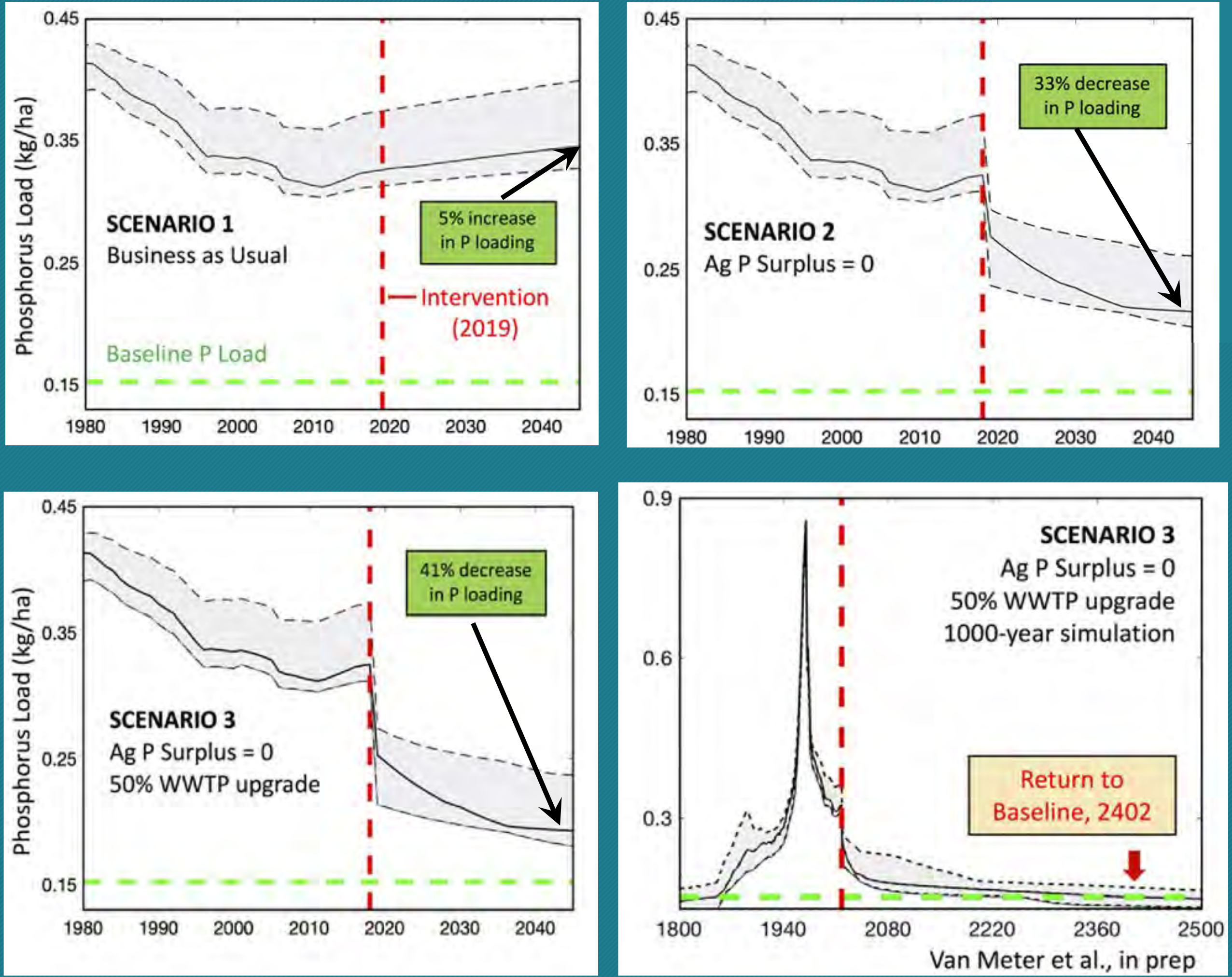


Phosphorus Reduction Targets	
For Algal Bloom Reduction	40% Reduction In Spring P Loads
For Hypoxia Reductions	40% Reduction In Annual P Loads

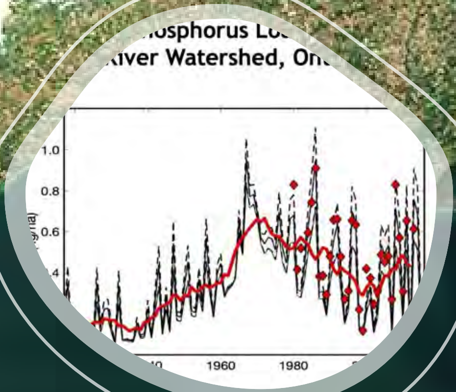
Progress Measurement

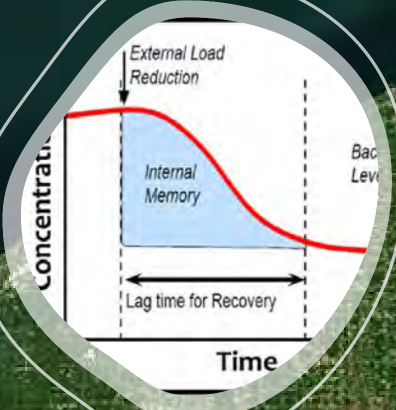
Flow Weighted Mean Concentrations (FWC)

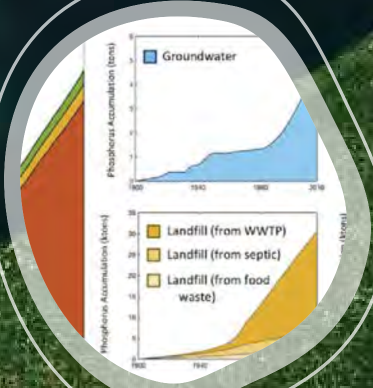
Total P Goal = .23mg/L concentration
DRP Goal = .05 mg/L concentration



Questions?


1.0
0.8
0.6
1960
1980


External Load Reduction
Internal Memory
Lag time for Recovery
Time


Groundwater
Landfill (from WWTP)
Landfill (from septic)
Landfill (from food waste)

Coffee Break Sponsor

Nutrien®

Managing Legacy Phosphorus Loading in Agriculture & Beyond

Jango Bhadha
Associate Professor
University of Florida

Slides Removed at Speaker's Request

Managing Legacy Phosphorus Loading in Agriculture & Beyond

Lauren Lurkins
Founder
Lurkins Strategies, LLC

Trevor Sample
Watershed Management
Illinois EPA

Food Waste: Feedstock for Renewable Phosphorus

Matt de la Houssaye
Commercial Director
BTS Bioenergy

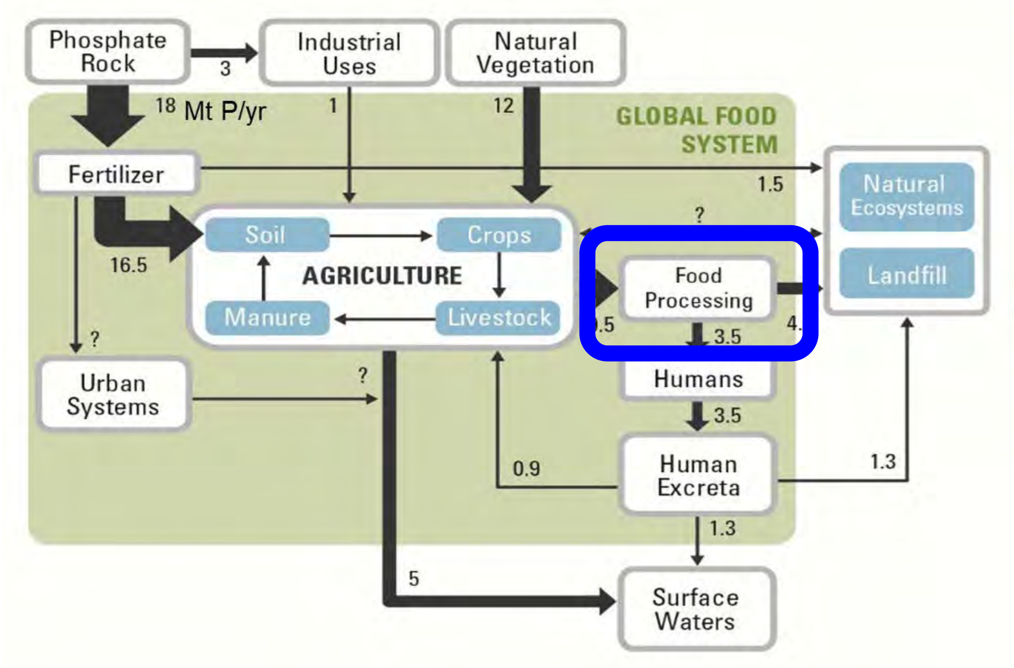
Trevor Boyer
Professor
ASU

Amir Varshovi
Founder/CEO
GreenTechnologies

Doug Call
Professor
NCSU

Christine Wittmeier
Organics Recycling Team Lead
NC DEQ

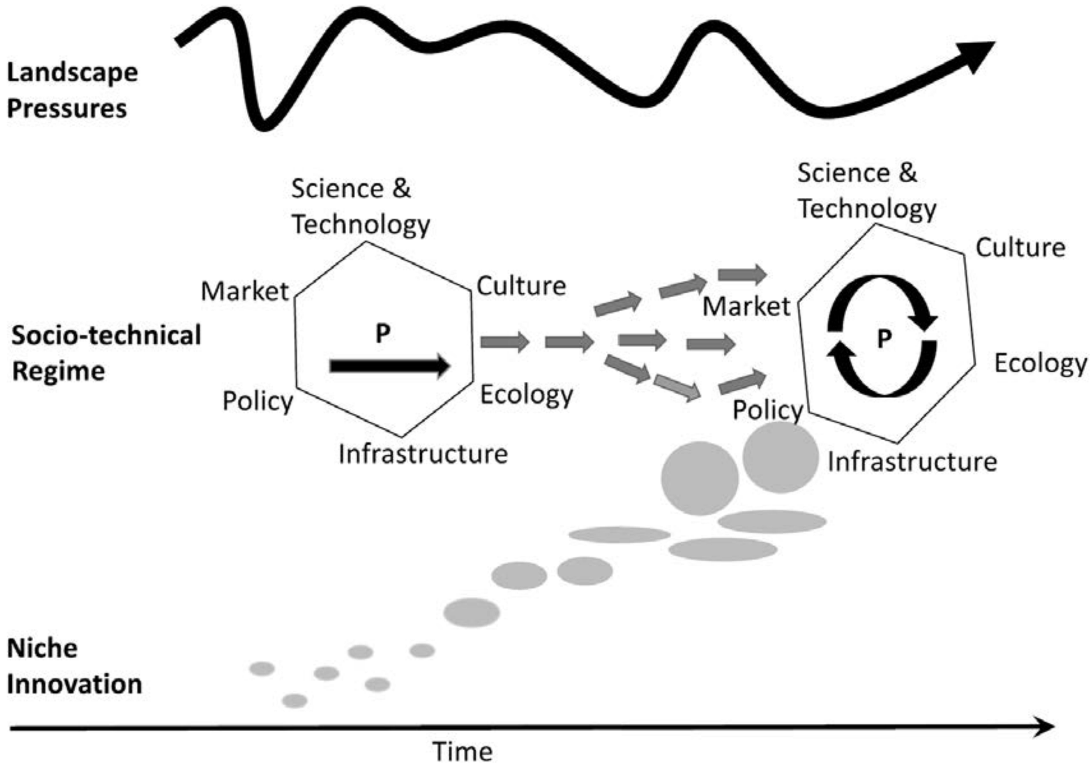
Envisioning the future of food in the context of P sustainability



Some data from Rittmann, Mayer, Westerhoff, and Edwards, “Capturing the Lost Phosphorus,” Chemosphere, 84, 846-853 (2011).
Flow diagram inspired by Cordell and White, Annu. Rev. Environ. Resour. 2014. 39:161–88.
Numbers alongside arrows represent million metric tons of P per year.

- **Increase** P use efficiency in the soil–plant continuum
- **Decrease** P pollution in agricultural runoff
- **Maximize** P recovery from waste streams for use as fertilizer
- **Improve** efficiency of P use through alternative protein sources

Transitioning from linear to circular P bioeconomy: Food waste



Peterson, Baker, Aggarwal, Boyer, Chan, 2021. Environment, Development and Sustainability

- Niche innovations include advances in anaerobic digestion and P recovery as fertilizer
- Socio-technical regime has advanced food waste collection including source separation and co-digestion
- Landscape pressures include policies to divert food waste from landfills

Food Waste: Feedstock for Renewable Phosphorus

Matt de la Houssaye
Commercial Director
BioEnergy DevCo

Slides Removed at Speaker’s Request

Food Waste: Feedstock for Renewable Phosphorus

Christine Wittmeier
Organics Recycling Team Lead
NC DEQ

Food Waste in NC

Christine Wittmeier
NC Department of Environmental Quality
Phosphorus Forum 2025| September 18, 2025

NORTH CAROLINA
Department of Environmental Quality

Division of Environmental Assistance and Customer Service (DEACS)

- Environmental Assistance Section
- **Recycling and Materials Management**
- Waste Reduction Partners
- NC DEQ Regional Offices

Recycling and Materials Management Section (RMMS)

- Non-regulatory
- Local government assistance
- Recycling business assistance
- Grants
- Statewide data, reports, studies
- Conferences, workshops, events

NORTH CAROLINA
Department of Environmental Quality

Wasted Food in NC

North Carolina generated over 2 million tons of wasted food in 2023.

48% of food waste was landfilled.

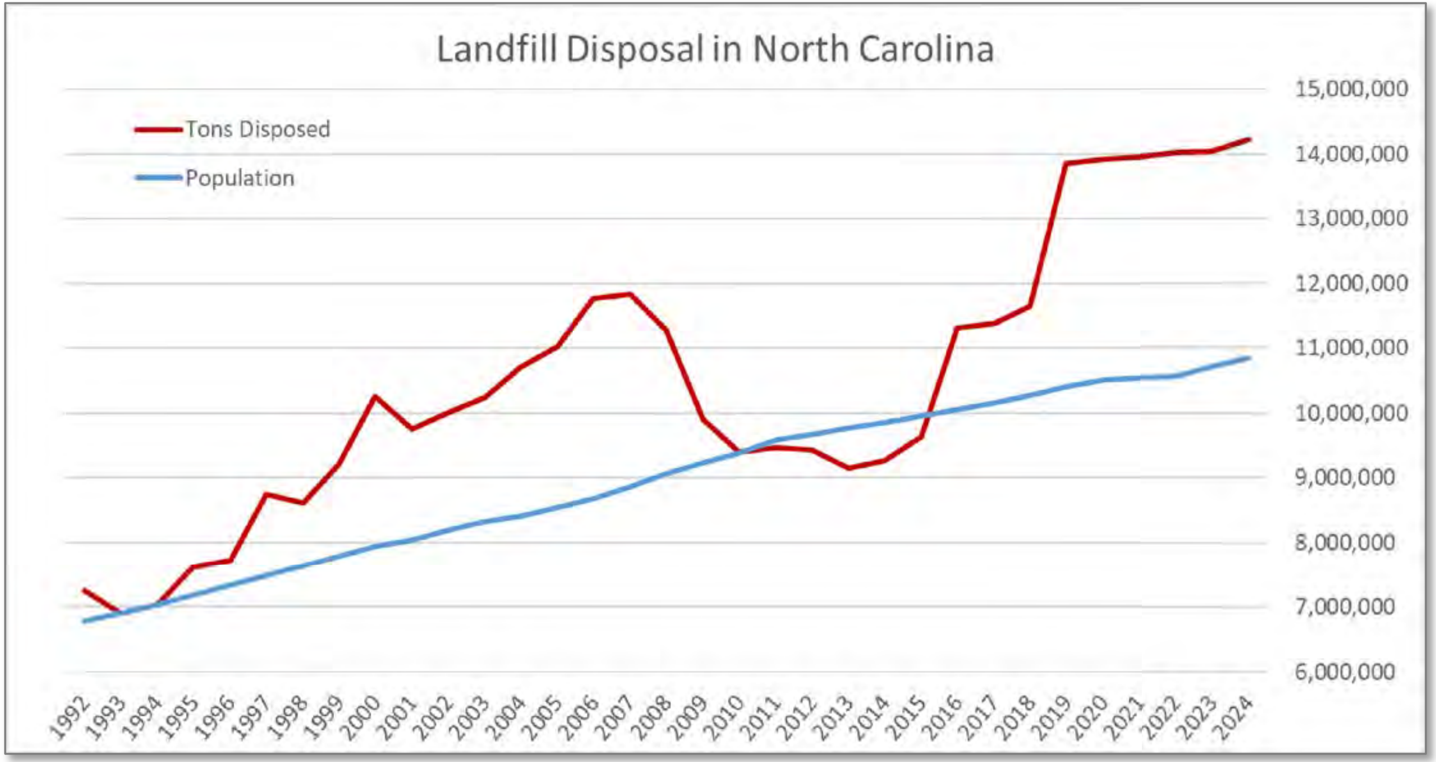
12.4 billion dollars in surplus food.

1.6 million people faced hunger in NC in 2023, 438,200 are children.

NORTH CAROLINA
Department of Environmental Quality

Source: ReFED Food Waste Monitor, Feeding America

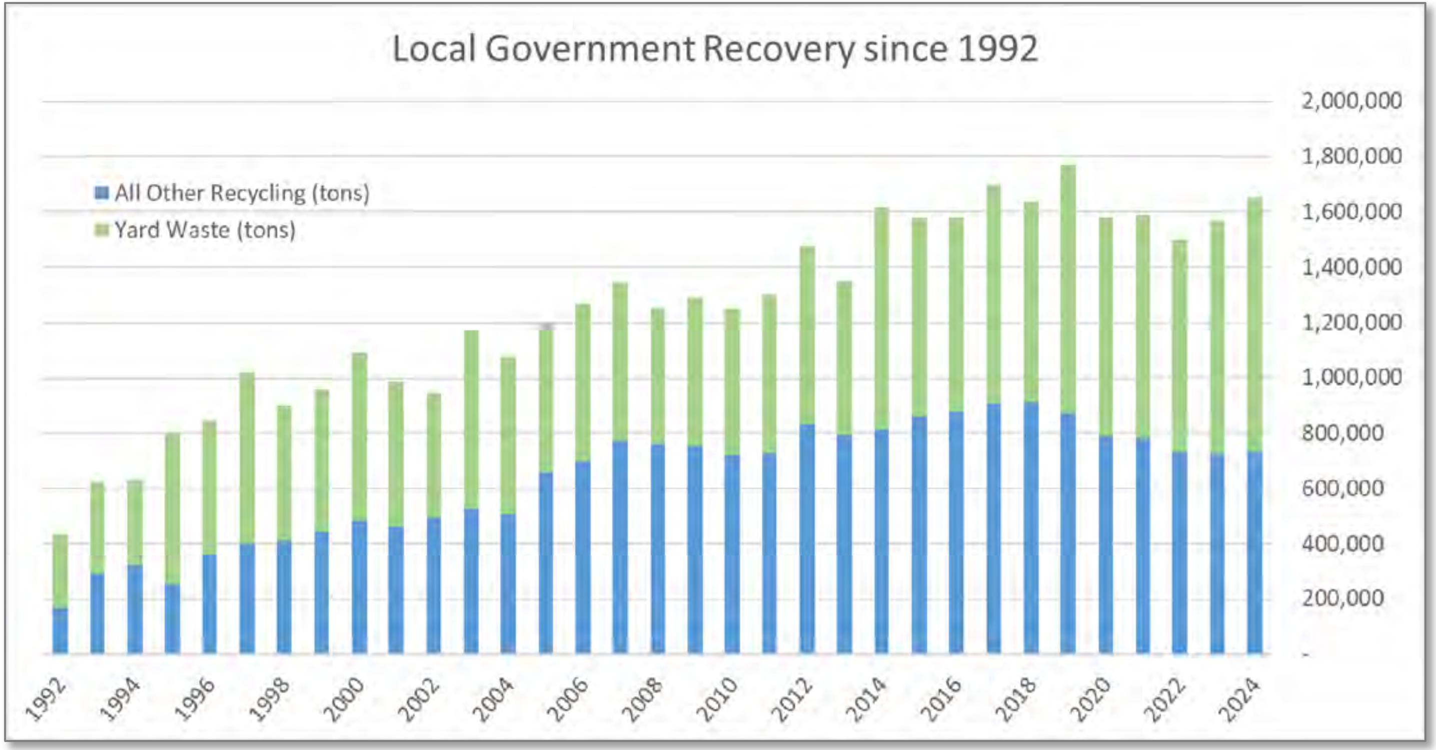
Disposal Trends



Per Capita Disposal
1992: 1.07 tons
2024: 1.31 tons

NORTH CAROLINA
Department of Environmental Quality

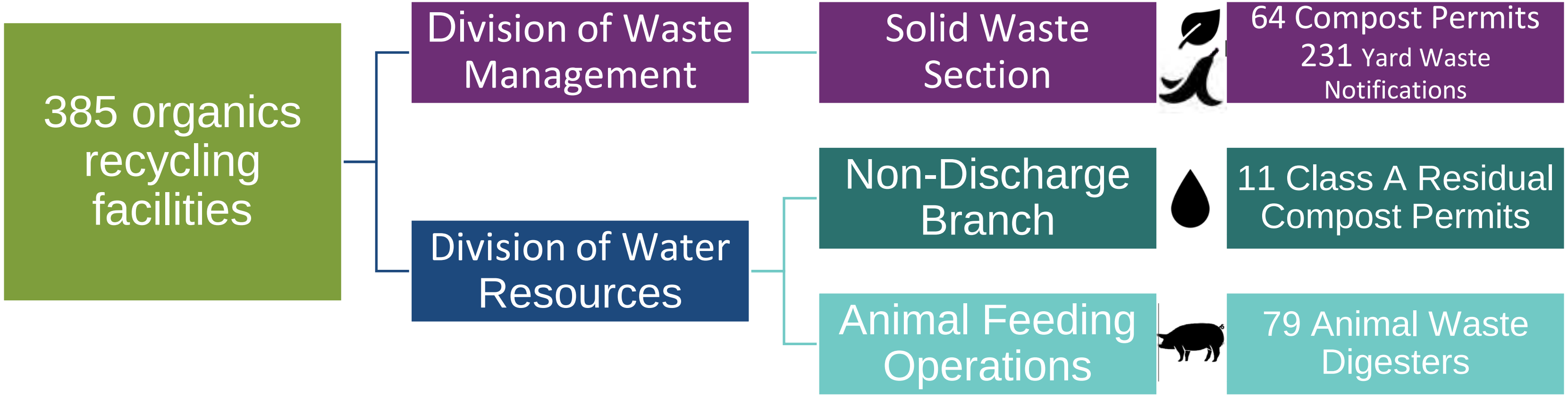
Recovery Trends



Per Capita Recycling
1992: 128 pounds
2024: 305 pounds

NORTH CAROLINA Department of Environmental Quality

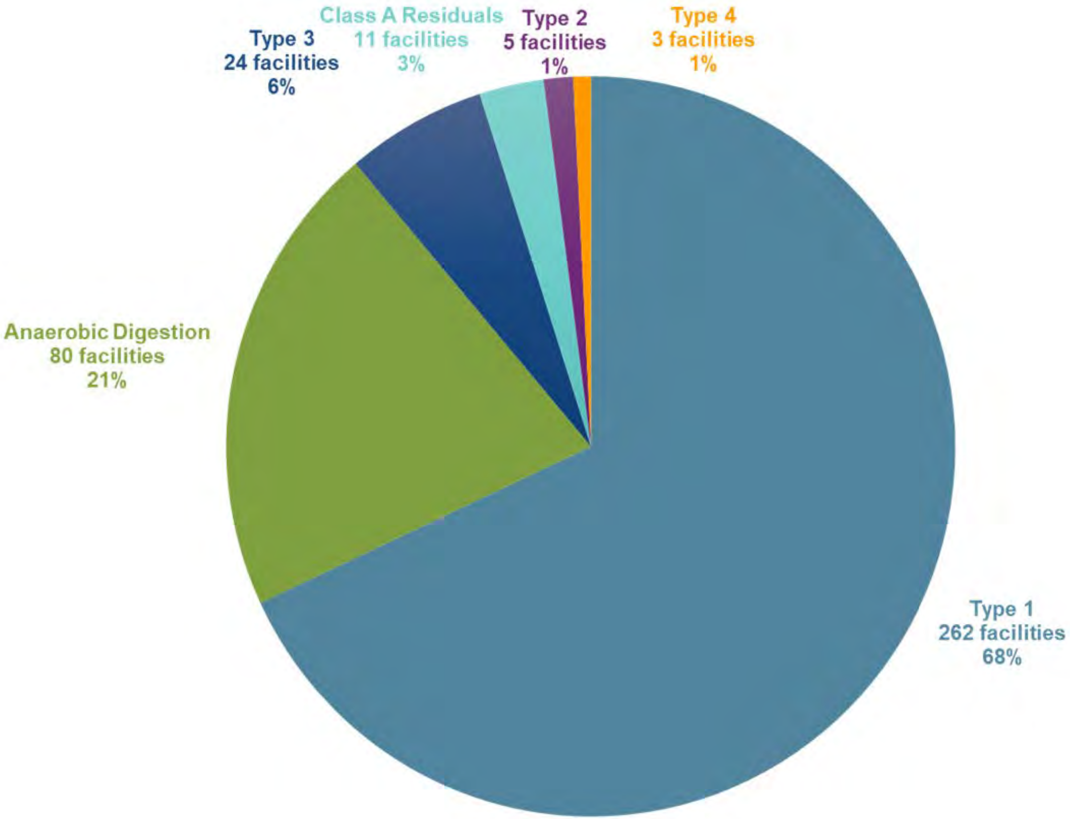
NCDEQ Permitted Facilities



*Includes facilities with an active permit but under construction / not accepting material.

*Does not include small Type 3 exempted facilities, WWTP Anaerobic Digestion or NC Department of Agriculture compost sites.

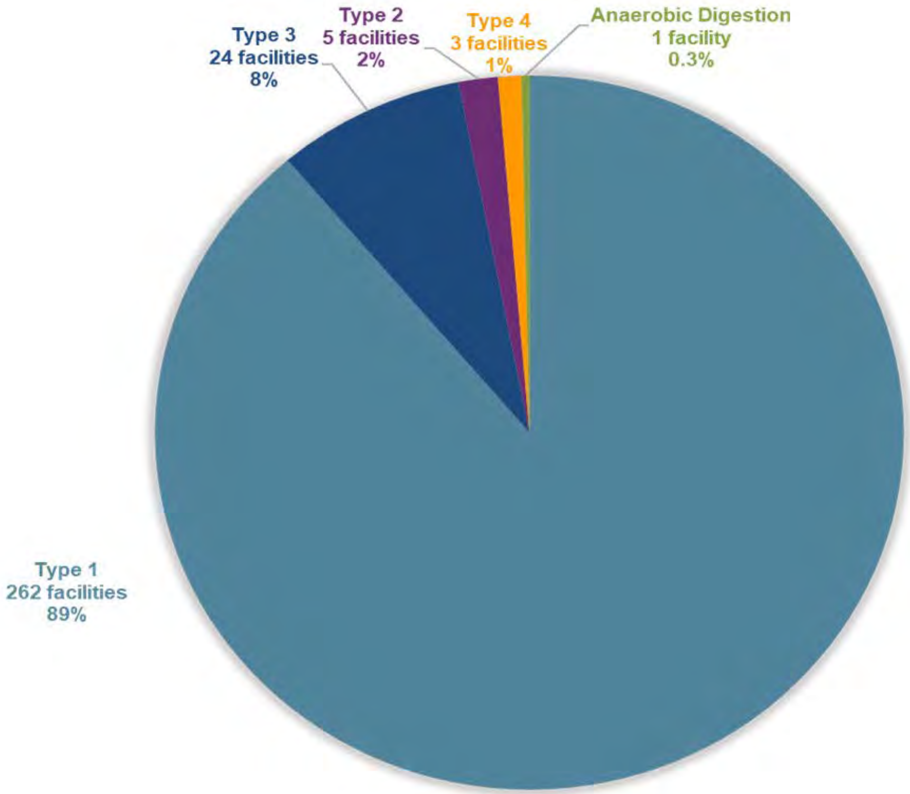
NCDEQ Permitted Facilities



Key:

- **Type 1 -** yard and garden waste, wood waste, etc. ***Including Small Type 1 YWN**
- **Type 2 -** pre-consumer meat-free food processing waste, vegetative agricultural waste, etc.
- **Type 3 –** manures, agricultural waste, meat, post-consumer source separated food wastes, etc.
- **Type 4 -** industrial solid wastes, sludges.
- **Class A Residuals -** sludges, bulking agents/amendments.
- **Anaerobic Digestion** – majority on-farm digesters, manures.

DWM Permitted Facilities by Type



Key:

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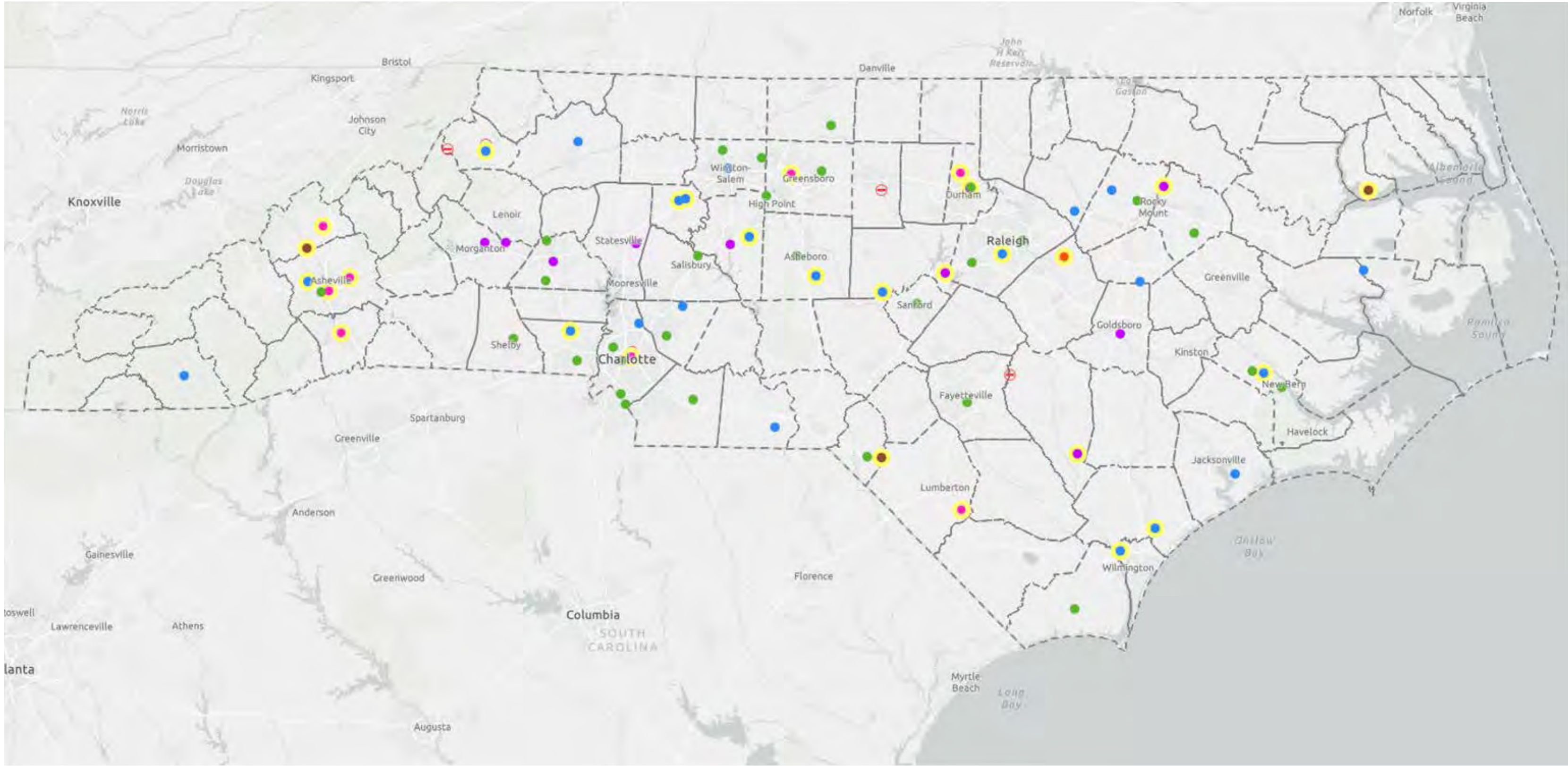
- **Type 3 –** manures, agricultural waste, meat, post-consumer source separated food wastes, etc.
- **Type 4 -** industrial solid wastes, sludges.
- **Anaerobic Digestion** – DWM co-digestion

NC Permitted Compost Facility Map

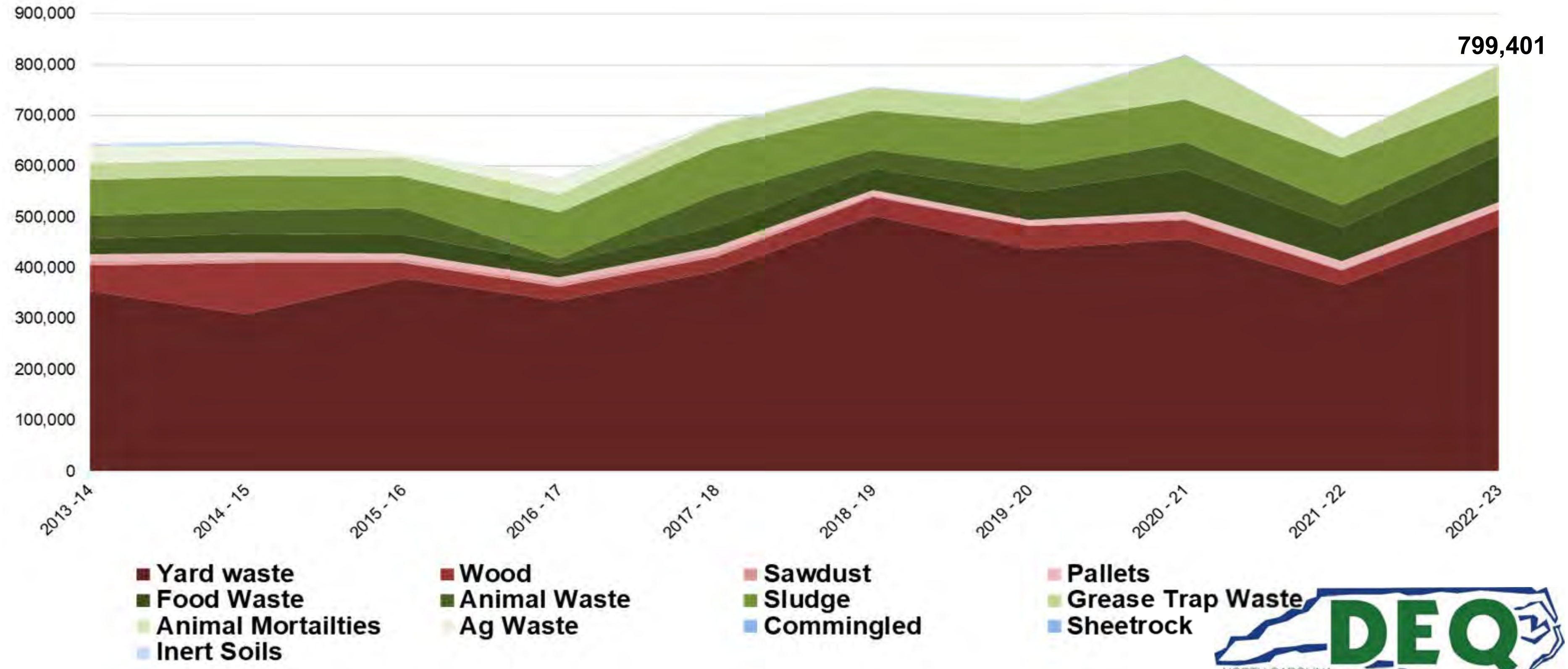


Average Tipping Fees ($ per ton)

DWM MSW Landfill vs. Compost facilities

NORTH CAROLINA
Department of Environmental Quality

Total Feedstocks Received by Category (tons)
DWM Permitted Facilities



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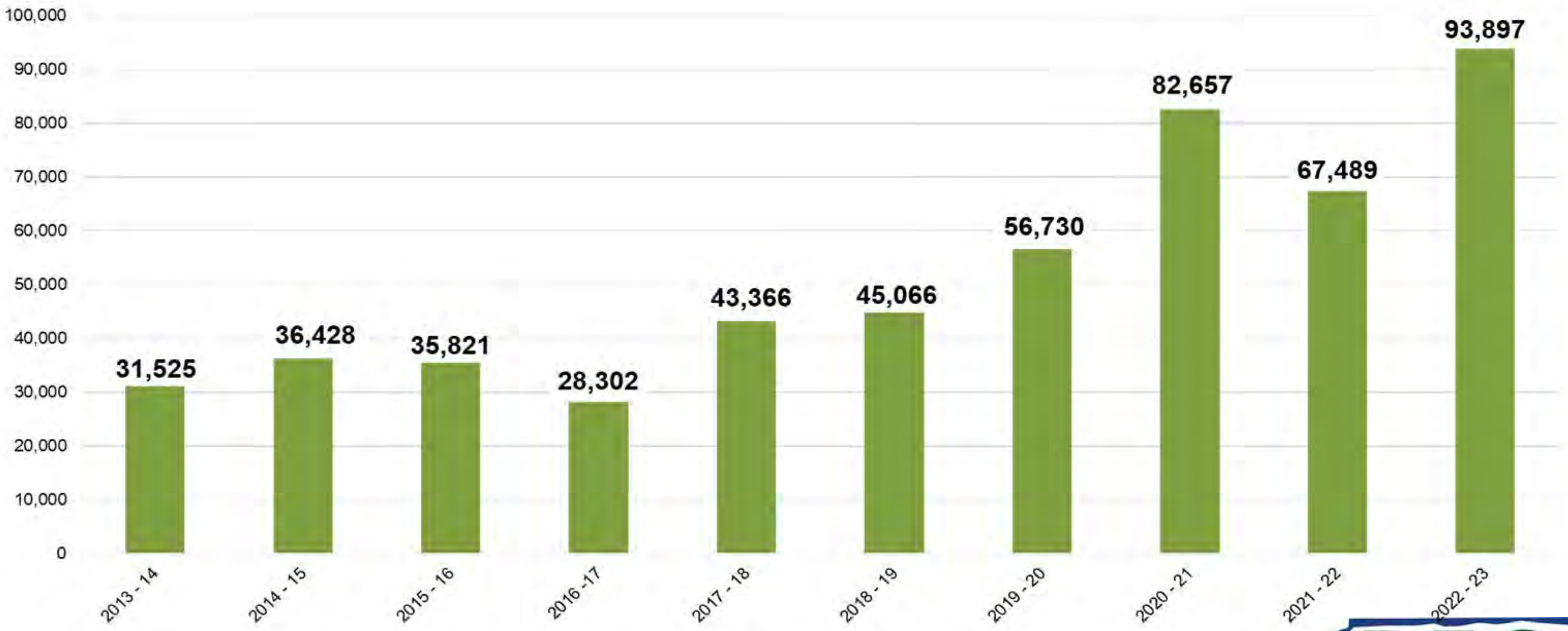
Department of Environmental Quality

Food Waste Received (tons)
DWM Permitted Facilities



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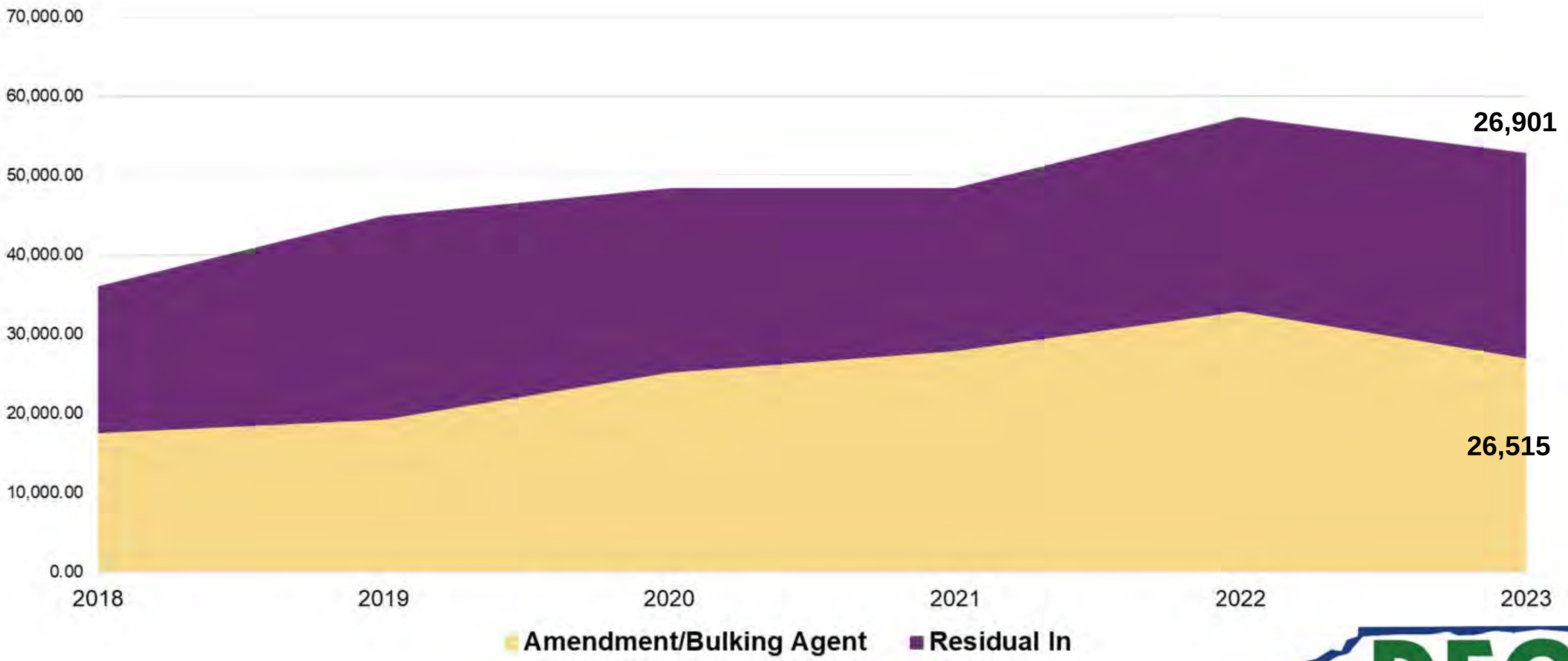
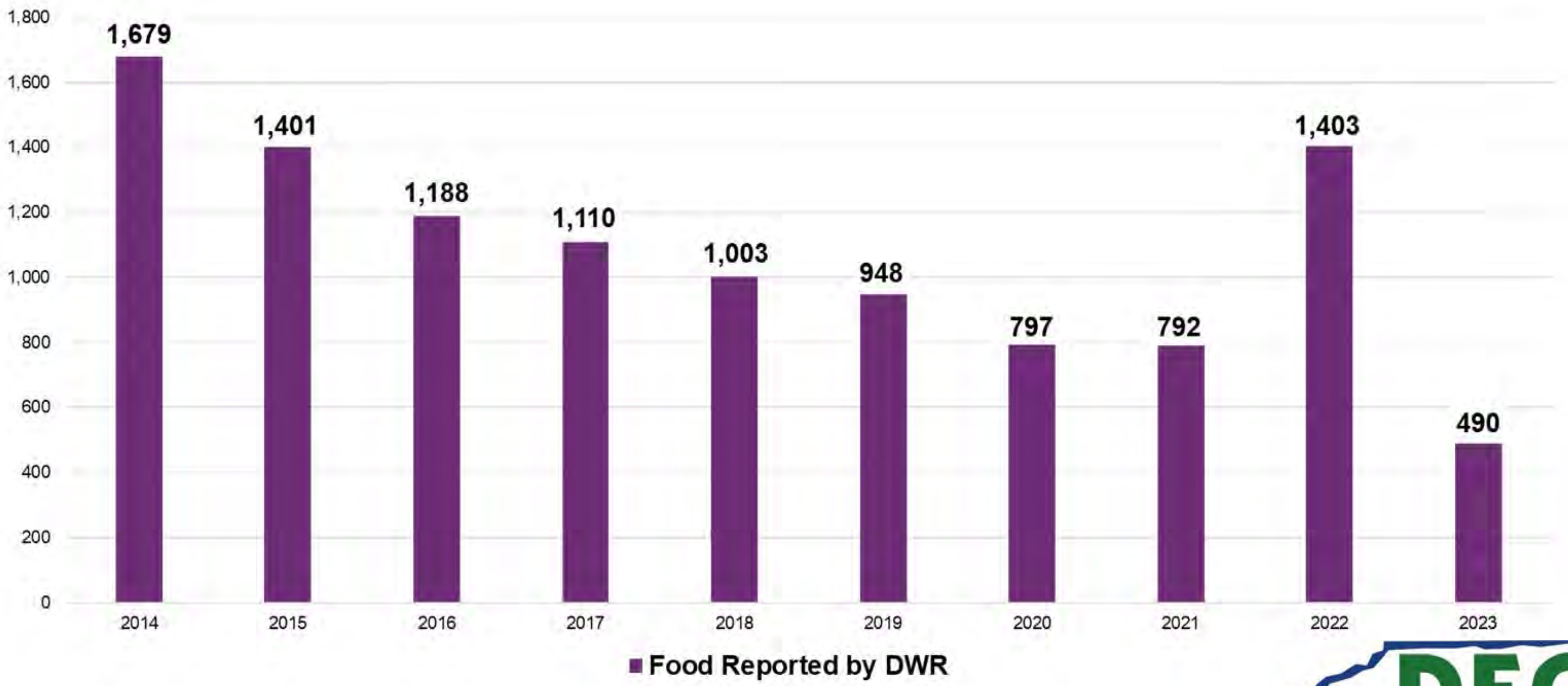
Residuals Received (dry tons)
Class A Permitted Compost Facilities



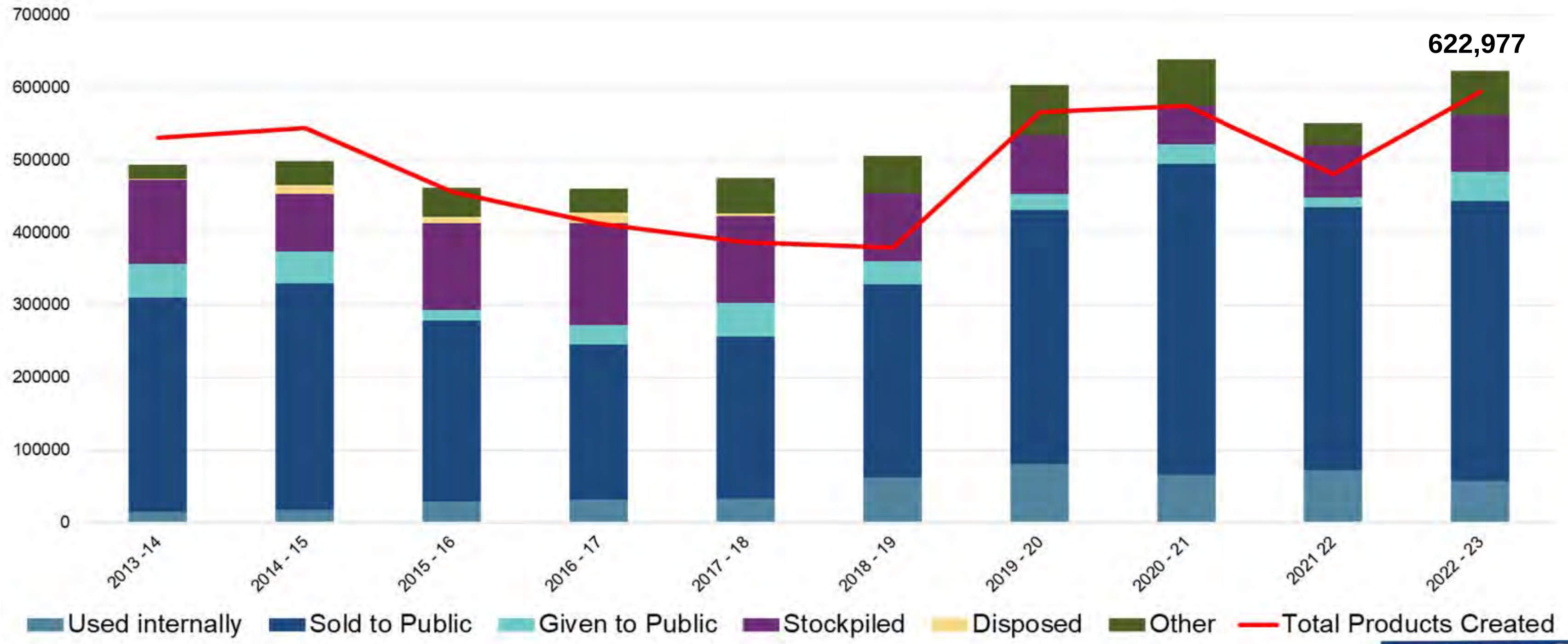
Food Waste Received (tons)

Class A Permitted Compost Facilities

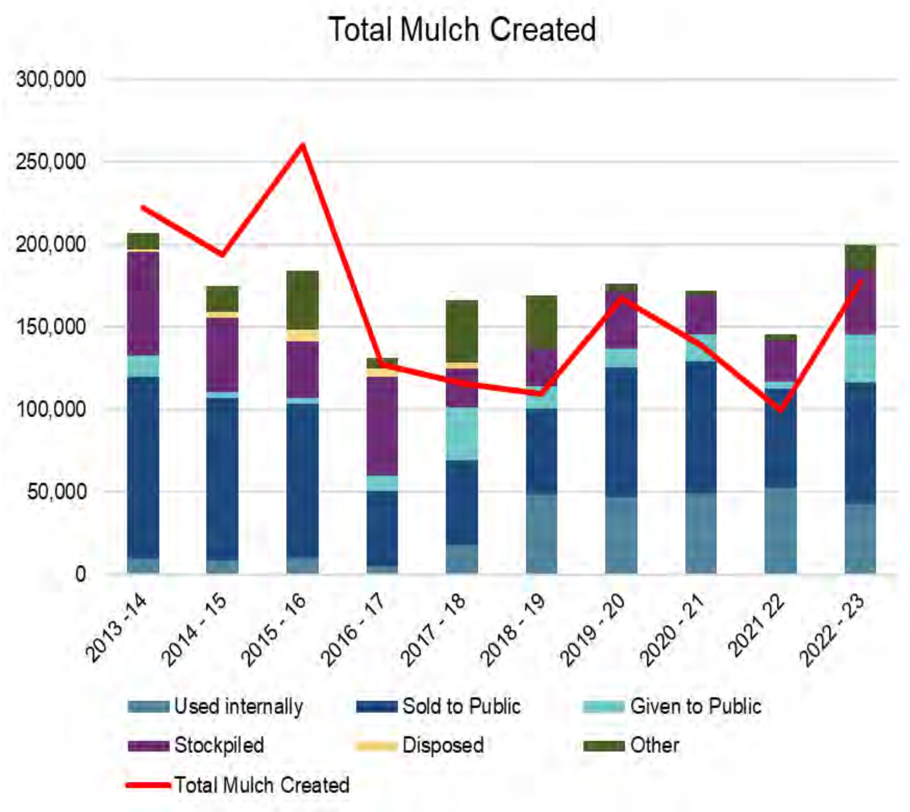


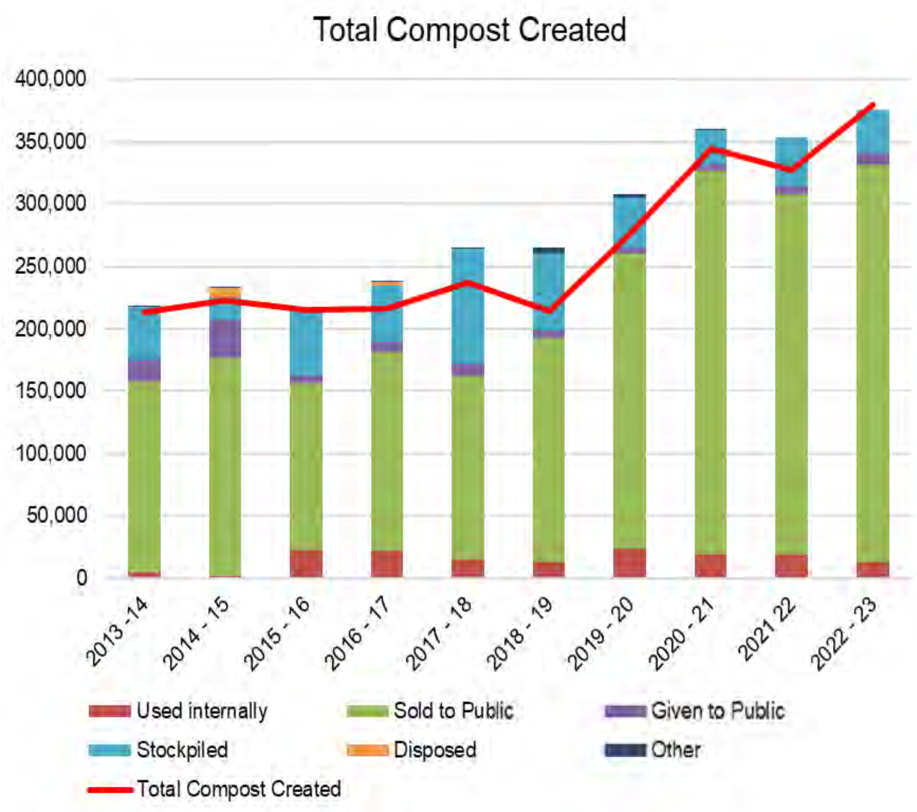
Total Products Created (tons)

DWM Permitted Facilities

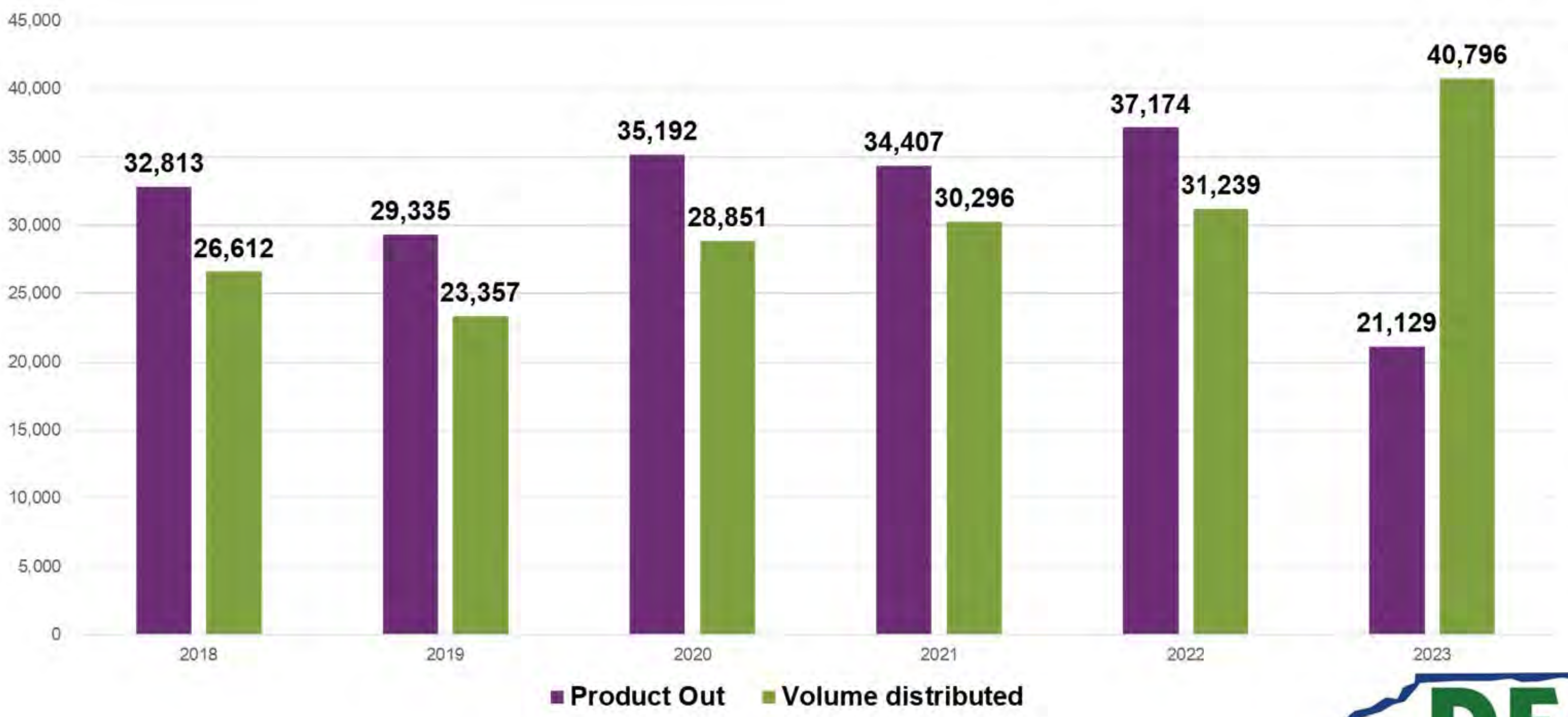


Total Products Created (tons) - Mulch vs. Compost
DWM Permitted Facilities





Total Products Created (tons)
Class A Permitted Compost Facilities



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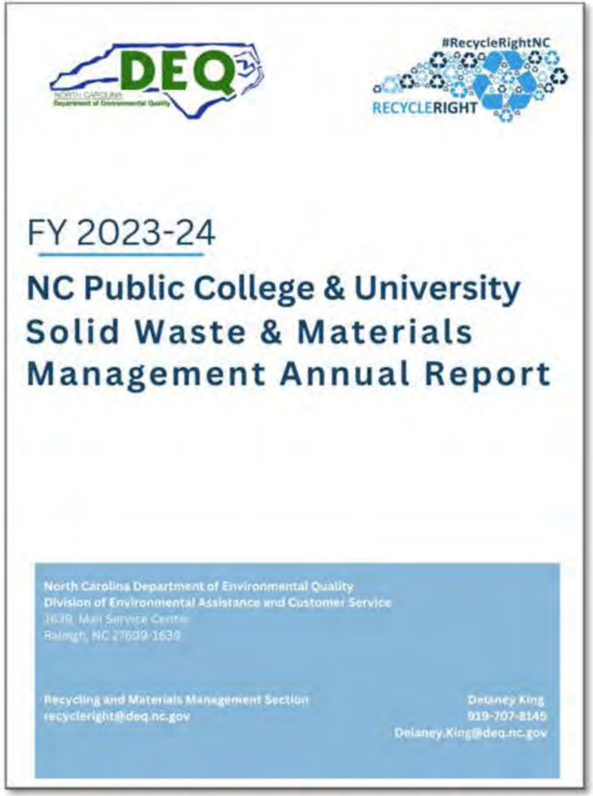
Colleges and Universities

- Improve & expand recycling programs.
- Share best management practices.
- Find markets for recyclable material.
- Provide procurement resources.
- Build food waste diversion programs.

NORTH CAROLINA Department of Environmental Quality

NC Public College & University Report


#RecycleRightNC

RECYCLERIGHT

FY 2023-24

NC Public College & University Solid Waste & Materials Management Annual Report

North Carolina Department of Environmental Quality
Division of Environmental Assistance and Customer Service
1639 Mail Service Center
Raleigh, NC 27699-1639

Recycling and Materials Management Section
recycleright@deq.nc.gov

Delaney King
919-707-8145
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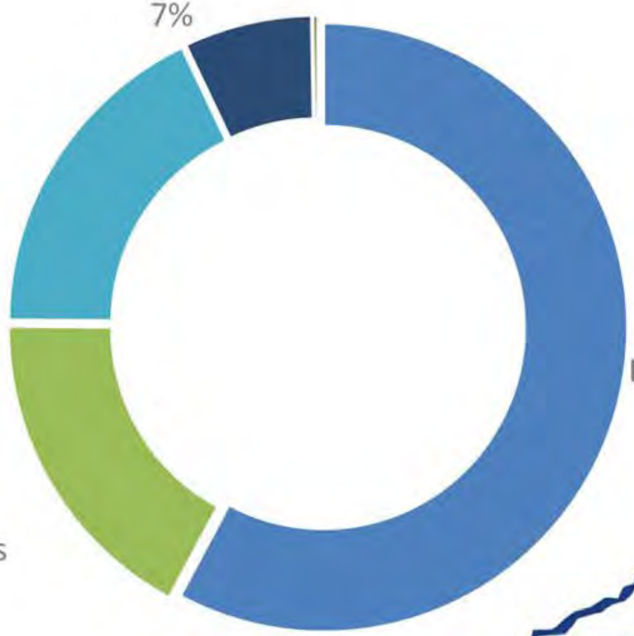
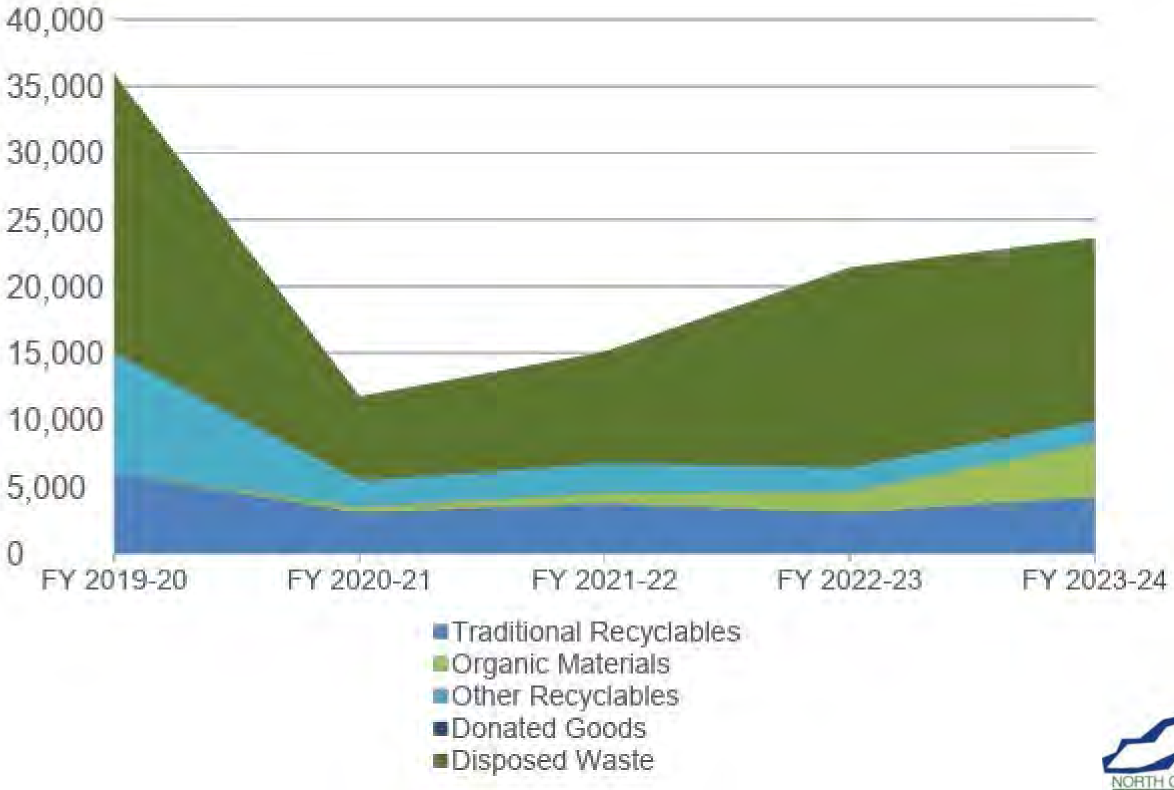
NC Public College & University Report



*Not shown: Donated Materials, 60 tons, 0%

5-Year Generation Data – Public Colleges & Universities



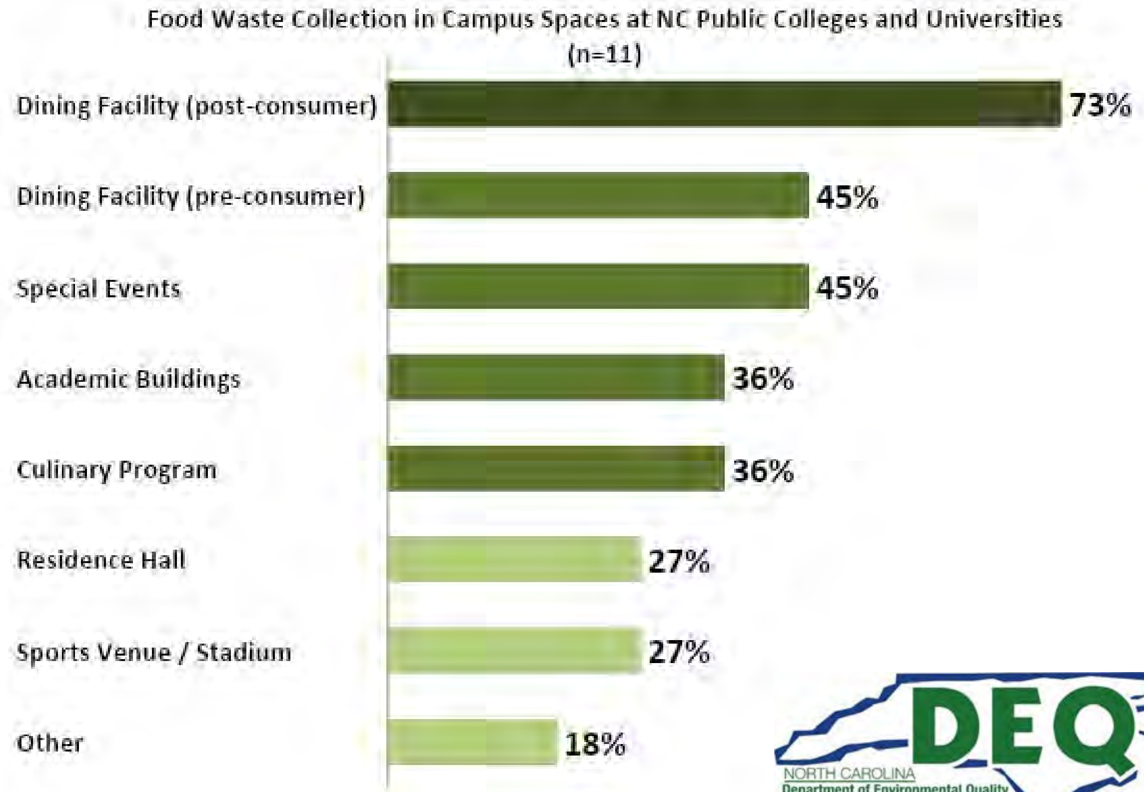
College and University Report - Organics

1,296 tons of food waste recovered

64% increase

2,584 tons of yard waste and clean wood waste

56% increase



NORTH CAROLINA Department of Environmental Quality

NC State Waste Reduction and Recycling (WRR)

- WRR provides comprehensive waste management at NC State - servicing landfill, mixed recycling, specialty recycling and organic waste streams.
- **NC State Sustainability Strategic Plan** – **70% Waste Diversion Goal**
- **Primary Services:**
  - **Front-end loading refuse service**: Landfill, comingled recycling, organics
  - **Equipment Services**: Rolloff dumpsters, C&D debris, yard waste, bulky recycling, surplus items, and more.
  - **Dearstyne Convenience Site**: C&D, yard waste, scrap metal, white goods, tires/belts, bulb/ballasts, electronics, batteries, pallets (high diversion rate from the site)
  - **Specialty Recycling**: Daily collection routes – servicing cleanout/reuse carts, E-waste, plastic film, expanded polystyrene, polypropylene, shredded paper and pallets.
  - **Compost Facility and Research Cooperative**
    - Closed loop organic waste management system – compost is utilized exclusively on campus and the lake wheeler road field labs.
    - Primary Feedstocks (all generated on campus): food waste, animal bedding (vet school), wood chips, compostable products, paper towels, greenhouse materials
    - Diverted ~2800 tons in FY 25

EPA Grant

EPA Solid Waste Infrastructure for Recycling (SWIFR) Grant

3-year project period: 2023-2026

NC Materials Management Optimization Study

- Waste Characterization
- MRF Study
- Hub & Spoke Analysis
- Market Assessments

Statewide Education Campaign

Waste Characterizations

- Spring and Fall sorts at 3 locations:
  - East: CRSWMA Landfill (New Bern)
  - Central: Greensboro Transfer Station
  - West: Watauga County Transfer Station (Boone)

- Incorporate data from local waste characterization studies.
- Final report will provide an estimate for food waste landfilled in NC.

NORTH CAROLINA
Department of Environmental Quality

Food Waste Reduction Grants

- Awarded $1,147,100 in three years.
- 36 projects:
  - 40,380 tons of food waste annually
  - 1,085,233 meals
  - Created 7 jobs

2026 RFP

Open now!

Type 2 compost facility, collection vehicle and refrigerators funded by FWR Grant.

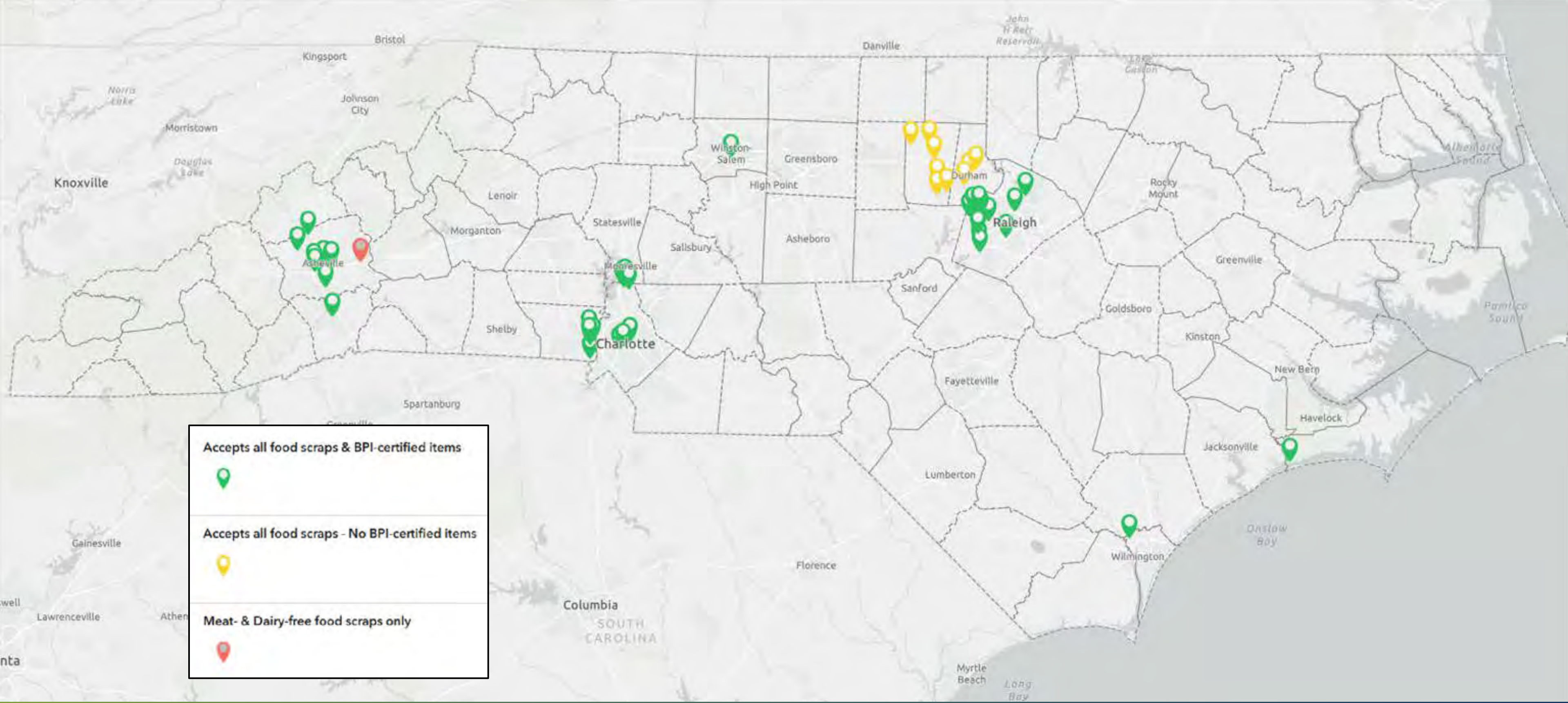
Tracking Collections & Exempted Facilities

51 Residential Food Scrap Drop-offs

~20 Food Waste Haulers

~7 Exempted Type 3 Facilities

NC Residential Food Scrap Drop-offs



Cary Composts

- Three 65-gallon carts, one 35-gallon
- Free BPI compostable bags

Total Lbs of Food Waste Collected to Date:

508,341.3

2019 Waste Characterization Study: 27% food waste to landfill

- 2022 Site 1 Convenience Center, staffed, operating hours
- 2024 site 2 park, unstaffed, open sunset – sundown
- Hauled by Compost now 3/week
- Composted at Brooks Composting Facility, Goldston NC

Cary's Good Hope Farm - Preserving agricultural roots

Earned 25 tons of finished compost to date in Garden Partner program with hauler
=10% of total weight of food scraps collected

Local farmers

- Sales, CSA
- Donation
- Training

Carync.gov/GoodHopeFarm

Customized Outreach Design

Use the Food NC

USE THE Food NC
FOOD WASTE STOPS WITH ME

DEQ
NORTH CAROLINA
Department of Environmental Quality

Thank you!

Christine Wittmeier

Organics Recycling Team Lead

Christine.wittmeier@deq.nc.gov

919-707-8121

#RECYCLERIGHTNC

RECYCLERIGHT

USE THE FoodNC

FOOD WASTE STOPS WITH ME

DEQ

NORTH CAROLINA
Department of Environmental Quality

Coffee Break Sponsor

Nutrien®

Food Waste: Feedstock for Renewable Phosphorus

Doug Call
Professor
NCSU

Characterizing and Recovering Phosphorus After Anaerobic Treatment of High-Strength Organic Waste Streams

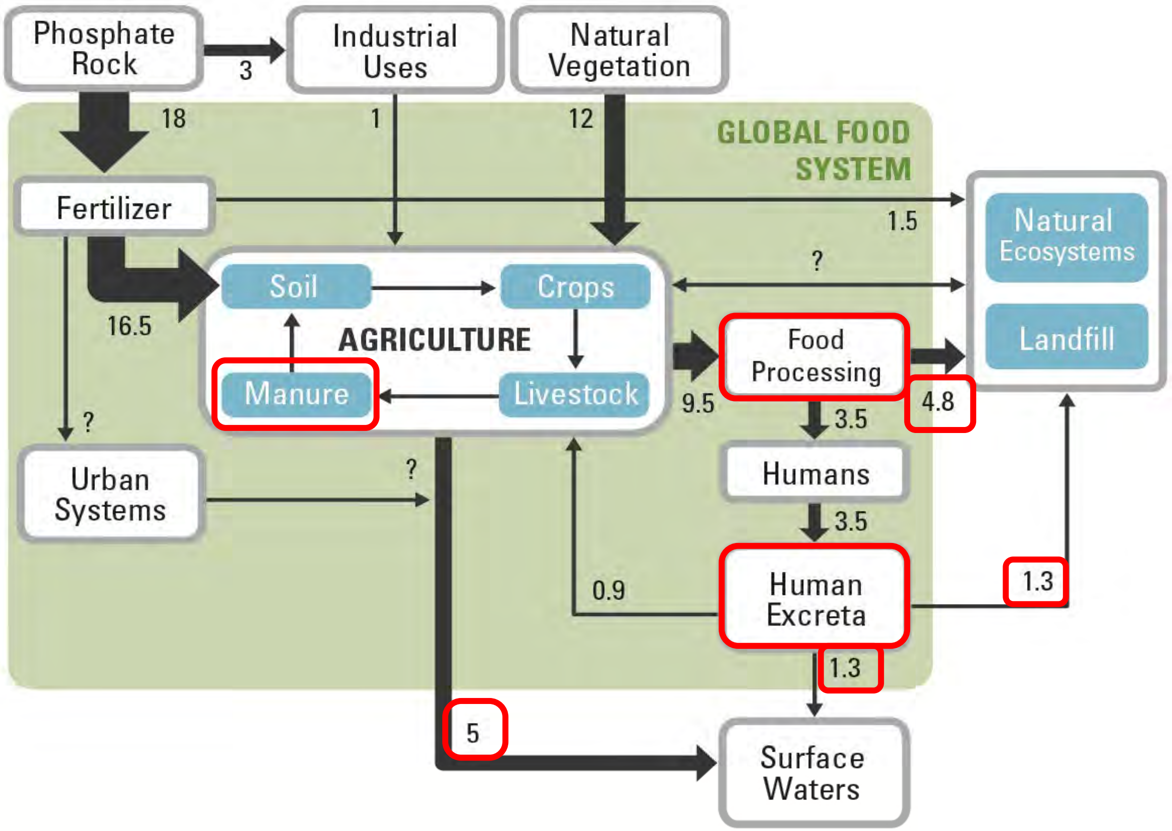
Doug Call[1], Maheen Mahmood[2], Jenny Ding[1], Joshua Boltz[3], Bruce Rittmann[2]

[1]Civil, Construction, and Environmental Engineering, NC State
[2]Biodesign Swette Center for Environmental Biotechnology, Arizona State
[3]Woodard and Curan

NC STATE UNIVERSITY

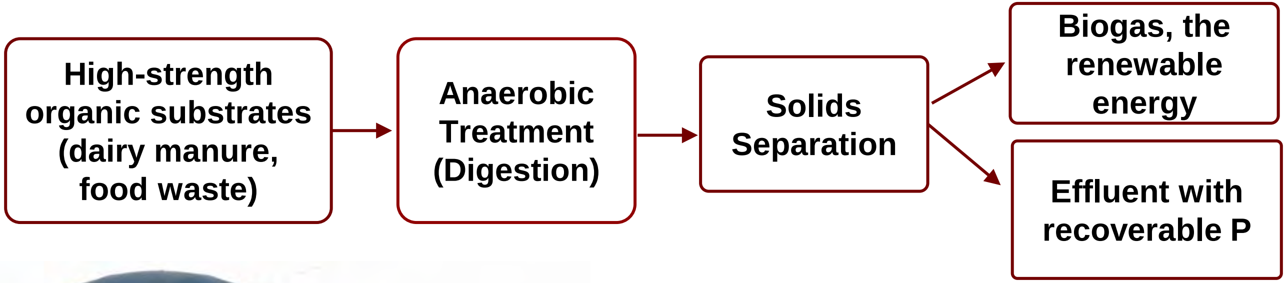
ASU

Roughly 50% of P is lost through organic waste streams



[www.cidrap.umn.edu] [www.scientificamerican.com]

Anaerobic treatment of these waste streams is ideal for recovering P along with methane (CH_4) as renewable energy



[www.biocycle.net]

Potential for multiple benefits

- Released inorganic and organic phosphorus
- Economic benefits of recovered methane
- Biosolids reduction (less to landfill)
- Improved soil health (as a soil amendment)

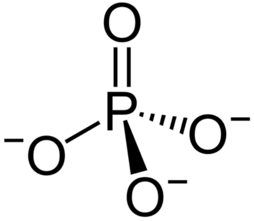
STEPS is addressing two important questions related to the anaerobic digestion of P-containing organic wastes:

1. What forms of P are generated during anaerobic treatment of organic wastes?

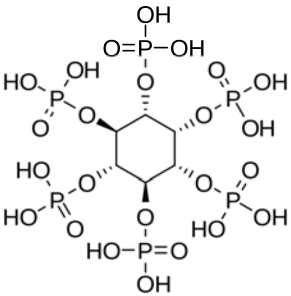
2. How can we recover P released during anaerobic treatment?

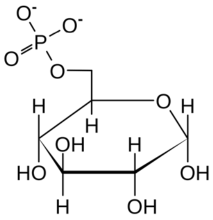
P in organic wastes can be present in many different forms

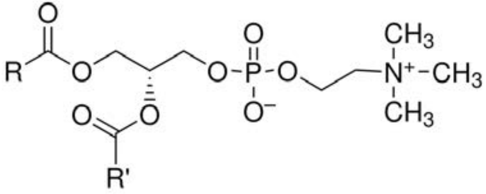
PO_4^{3-}



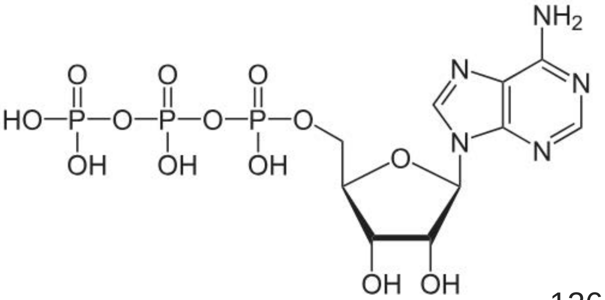
Orthophosphate
(or just phosphate)



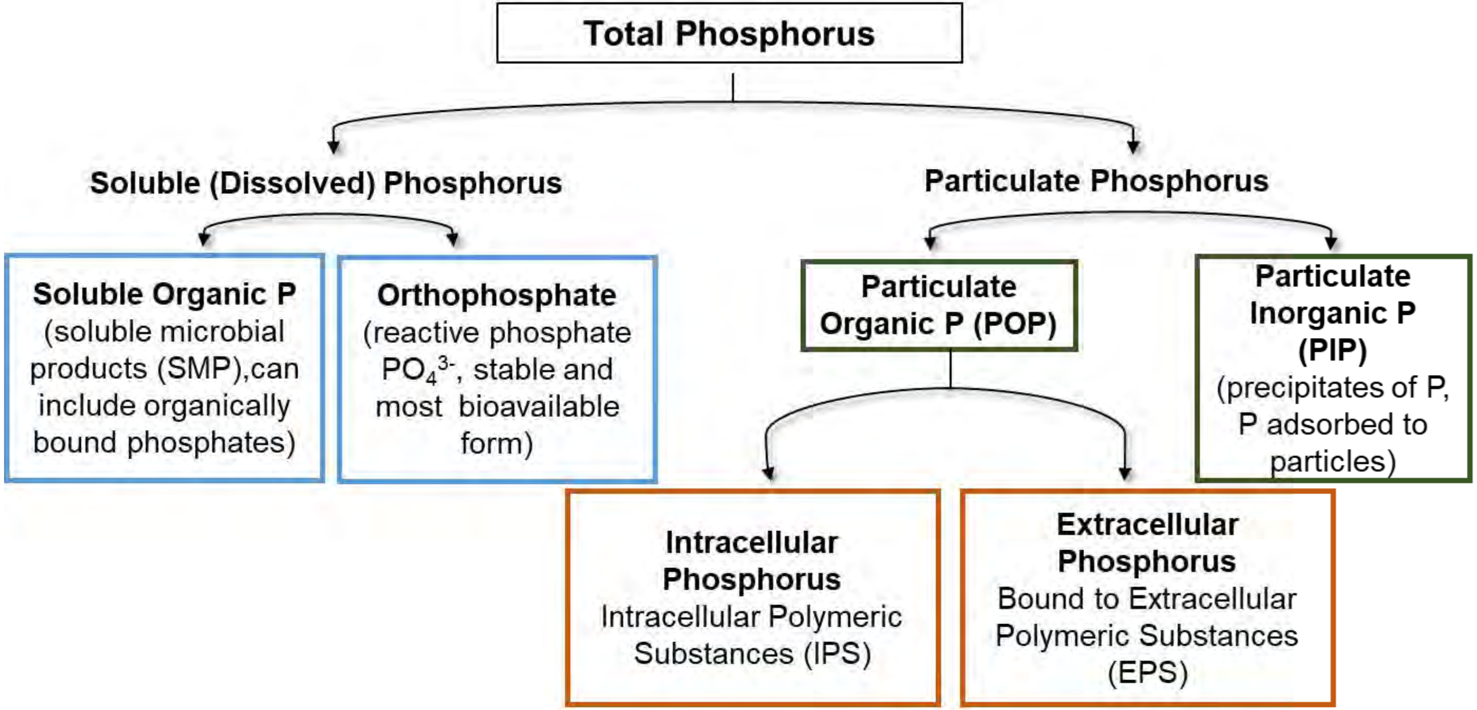




R, R' = fatty acid residues



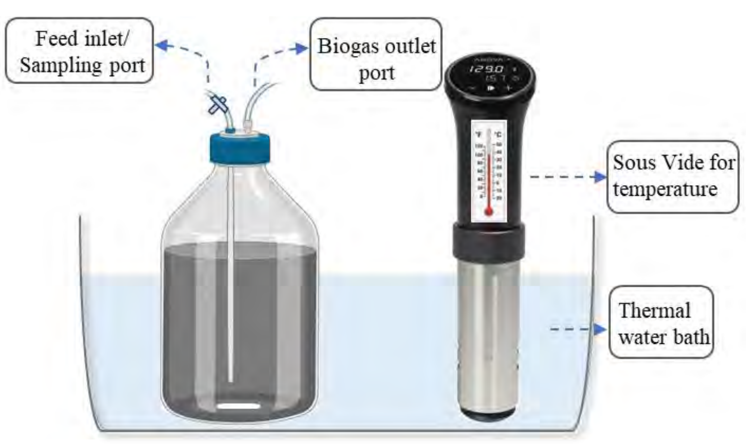
Why does phosphorus speciation matter? It influences how we recover it



We conducted lab-scale tests to determine P speciation with complex and defined sources of organic P

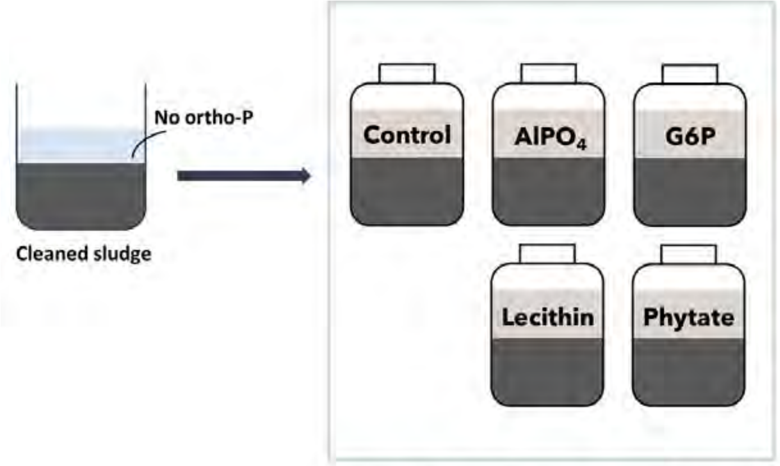
Method # 1

Bench-scale anaerobic reactors operated with dairy waste with varying hydraulic retention times □ understand how anaerobic treatment affects P speciation.



Method # 2

Batch tests to study non-reactive P transformation to ortho-P □ understand impacts of anaerobic treatment on generating reactive P.

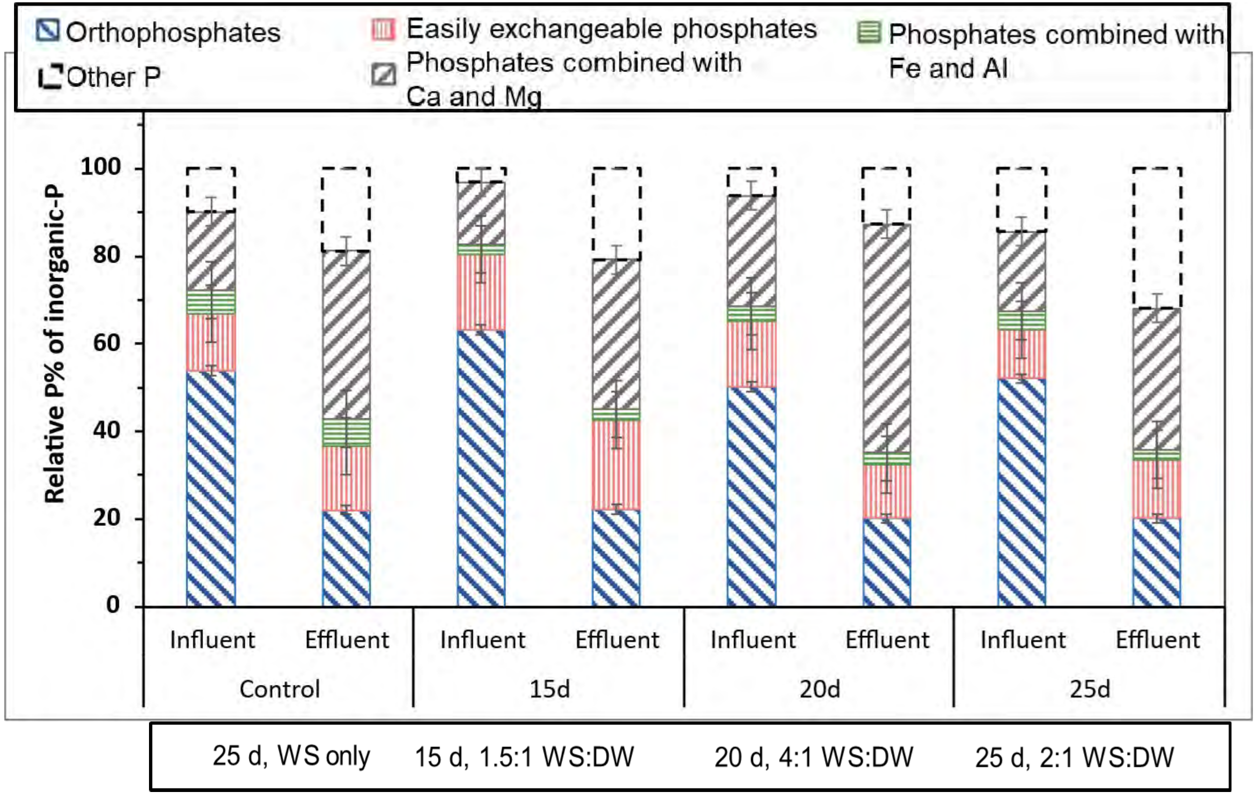


Introducing P source to cleaned sludge

Orthophosphate was not the predominant P species in the effluent of the dairy waste-fed anaerobic bioreactors

Speciation of P in effluents after anaerobic treatment of wastewater sludge (WS) with dairy waste (DW).

Most of the P was in inorganic solids and "other", which was likely organic P.

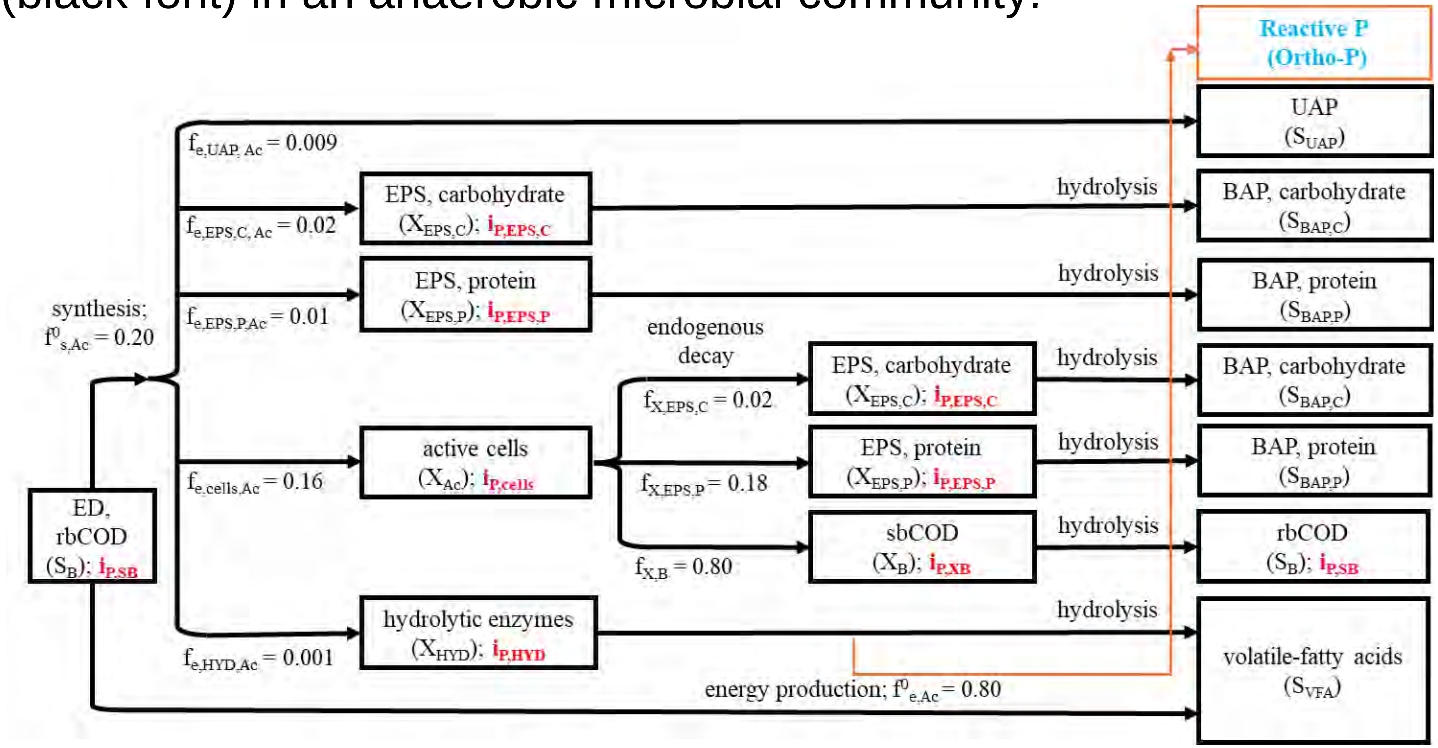


Hydraulic Retention Time (days, d),

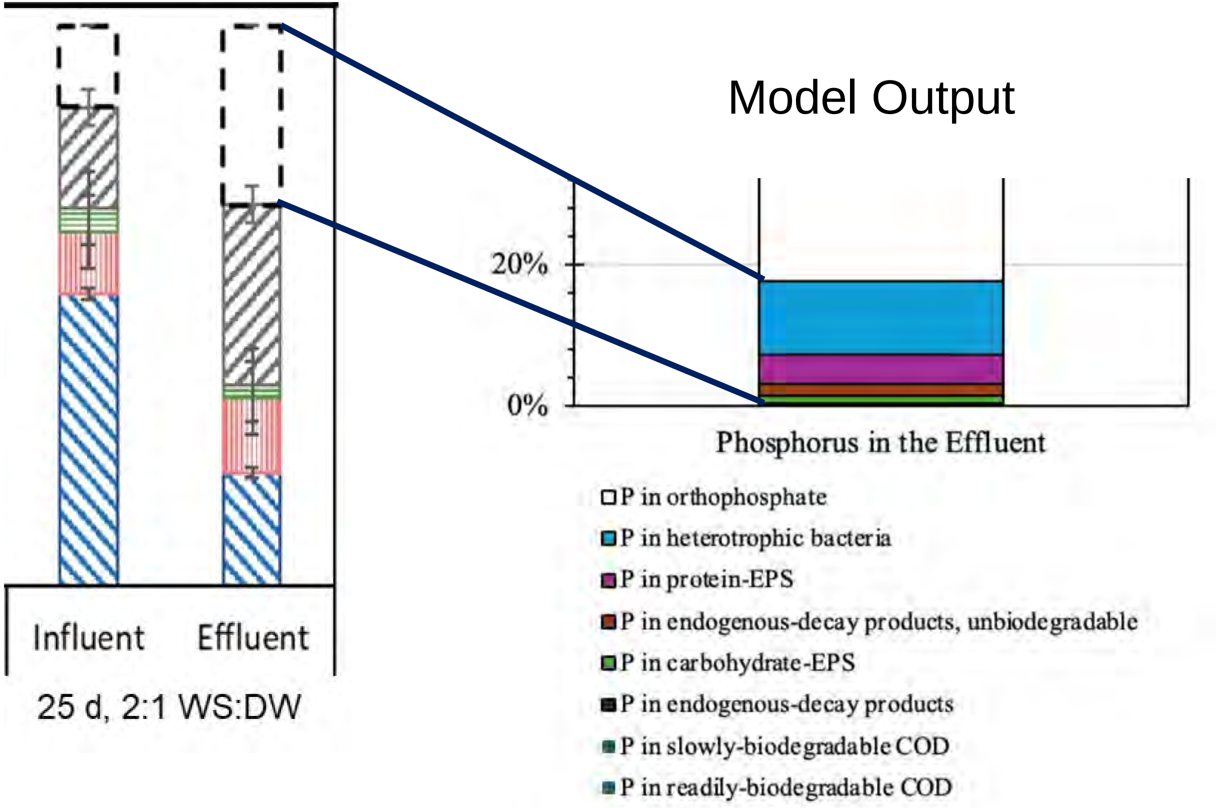
[Mahmood and Rittmann, In preparation]

We developed mathematical models that linked P and electron flows in the anaerobic bioreactors

The models show P flows (P fractions in red font) link to electron flows (black font) in an anaerobic microbial community.

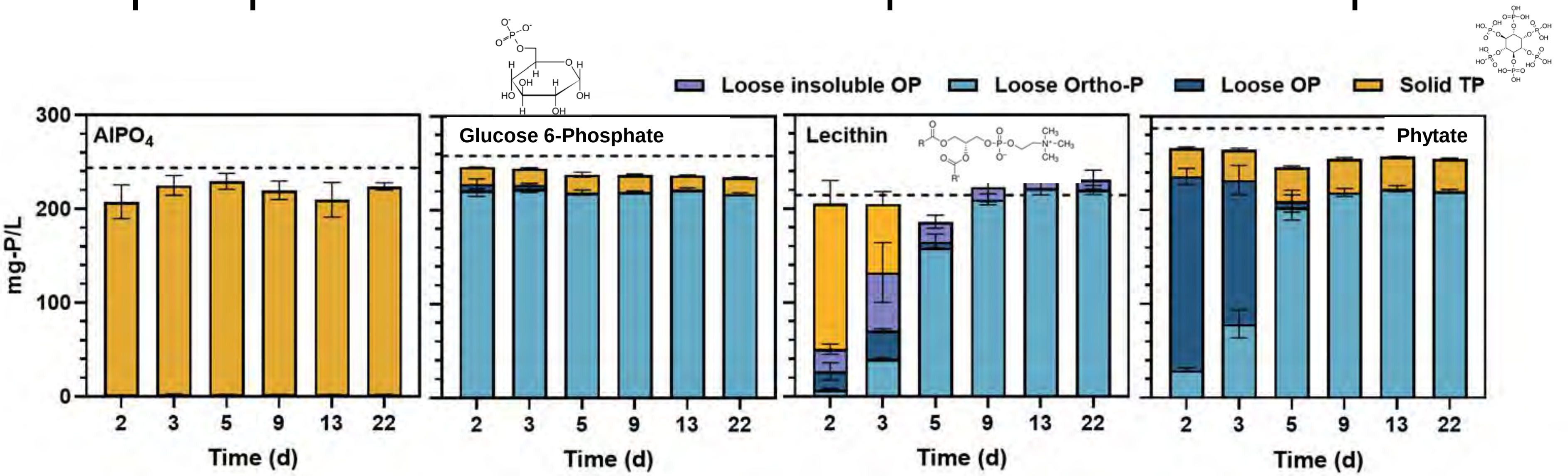


The model predicted that about 20% of total P would be organic, which agreed well with our experimental results



The model predicted that organic P was dominated by P in bacteria, protein-based EPS, and nonbiodegradable endogenous-decay products.

Most P in defined P compounds was released as orthophosphate. The release rate depended on the compound



- Very little insoluble inorganic P ($AlPO_4$) could be solubilized.
- Depending on the form of non-reactive P, the speciation of P in the bioreactors varied.

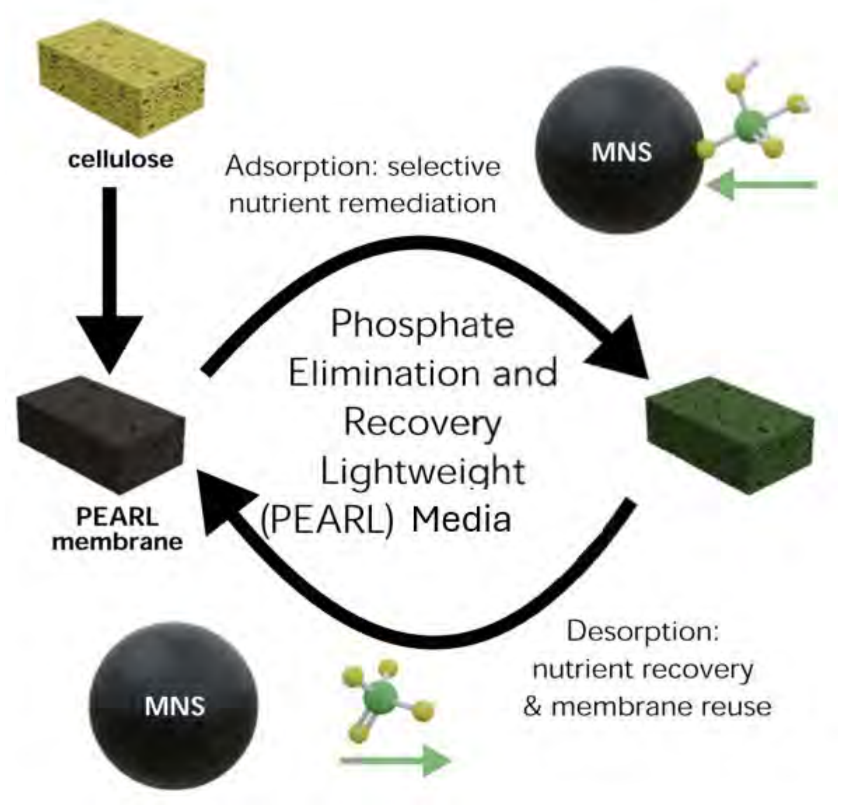
*Loose insoluble OP, Loose OP: partially bioavailable, requires alkaline extraction (e-g NaOH)
*Loose Ortho-P: Ortho-P, readily bioavailable form of P
*Solid TP: P bound to metals or minerals (Al, Ca, Mg), requires acid extraction

STEPS is addressing two important questions related to the anaerobic digestion of P-containing organic wastes:

1. What forms of P are generated during anaerobic treatment of organic wastes?

2. How can we recover P released during anaerobic treatment?

PEARL membrane recovery of ortho-P



(PEARL Media) : Dip coated in Fe_3O_4 nanoparticle coating, 6.5-16% coating by mass

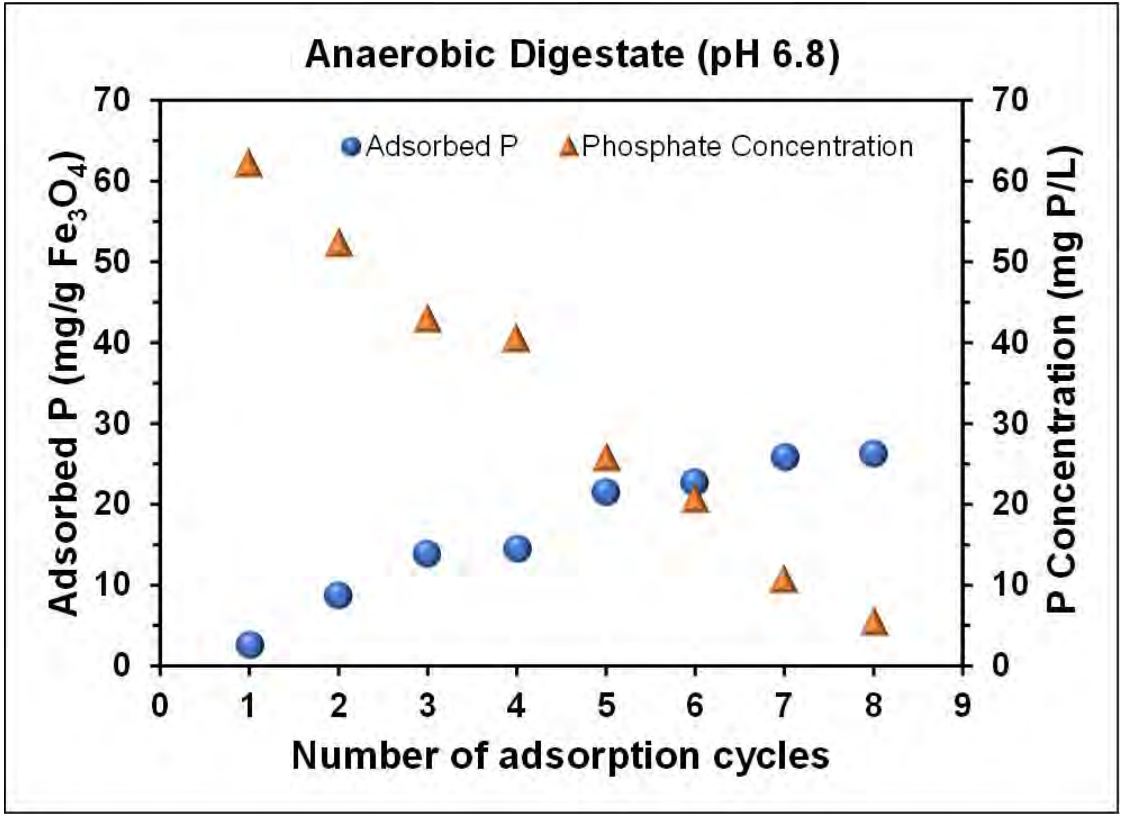
Electrostatic Attraction

$\equiv Fe{-}OH + H^+ + H_2PO_4^- \rightarrow \equiv Fe{-}OH_2^+ \rightarrow H_2PO_4^-$

Ligand Exchange

$\equiv Fe{-}OH + H^+ + H_2PO_4^- \rightarrow \equiv Fe{-}H_2PO_4 + H_2O$

The PEARL membrane shows promise for P adsorption from anaerobic digestates



Lowering the pH helped reduce the number of adsorption cycles needed.

Multiple adsorption cycles can effectively remove over 90% of phosphate.

Desorption efficiency increases with increasing pH [e.g., from 54% (pH 9) to 63% (pH 10)]

STEPS is addressing two important questions related to the anaerobic digestion of P-containing organic wastes:

1. What forms of P are generated during anaerobic treatment of organic wastes?

A mix, but mostly P bound to metals and organics

2. How can we recover P released during anaerobic treatment?

Iron-coated “sponges” show promise for multiple P adsorption/desorption cycles applied to anaerobic digestates

Characterizing and Recovering Phosphorus After Anaerobic Treatment of High-Strength Organic Waste Streams

Doug Call[1], Maheen Mahmood[2], Jenny Ding[1], Joshua Boltz[3], Bruce Rittmann[2]

[1]Civil, Construction, and Environmental Engineering, NC State
[2]Biodesign Swette Center for Environmental Biotechnology, Arizona State
[3]Woodard and Curan

This work was funded by the NSF Science and Technologies for Phosphorus Sustainability (STEPS) Center

NC STATE UNIVERSITY

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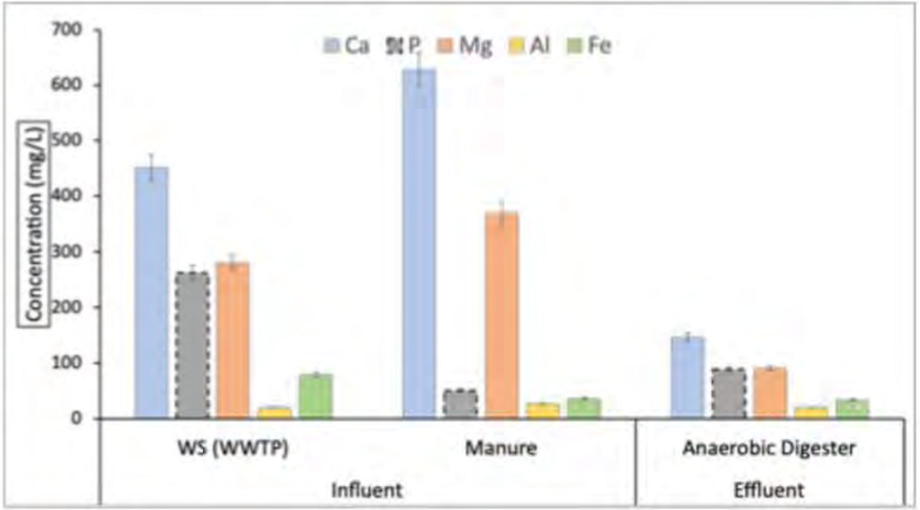
Dairy Waste : Cow Manure (Casa Grande Dairy Farm, Casa Grande, AZ)



Elemental Analysis of Waste Sludge (WS), Cow Manure and anaerobic digestate after anaerobic digestion

Post-it Stack

Voting Stars

Parameter	Unit	Dairy Waste	Sludge	Inoculum
TS	%	4.5-5	3.5-4	2-3
VS	%	58-70	75-80	66-70
TCOD	g/L	55.5-69	55-56	22.5-25
SCOD	g/L	14.4-21.3	7.38-7.42	0.85-0.98
pH	-	7.67-7.8	5.55-6.5	7.1-7.5

Reactor	HRT (d)	Amount fed (mL/d)	Co-substrate Ratio (WAS:DW)
25 d, WS only	25	20	-
15 d, 1.5:1 WS:DW	15	33.3	1.5:1
20 d, 4:1 WS:DW	20	25	4:1
25 d, 2:1 WS:DW	25	20	2:1

Food Waste: Feedstock for Renewable Phosphorus

Amir Varshovi
Founder/CEO
GreenTechnologies

Slides Removed at Speaker’s Request

Food for thought

What is the P footprint of lunch?

OPEN ACCESS
IOP PUBLISHING ENVIRONMENTAL RESEARCH LETTERS

Environ. Res. Lett. 7 (2012) 044043 (10pp) doi:10.1088/1748-9326/7/4/044043

The role of diet in phosphorus demand

Geneviève S Metson[1], Elena M Bennett[1,2] and James J Elser[3]

[1] Department of Natural Resource Sciences, McGill University, 21,111 Lakeshore Road, Sainte Anne de Bellevue, QC, Canada
[2] McGill School of Environment, McGill University, 3534 University Street, Montreal, QC, Canada
[3] School of Life Sciences, Arizona State University, Tempe, AZ 85287-4501, USA

- **Calculations:** Required feed quantities for animal production, feed composition and P contained in feed, P required for feed-crop production
- **Output:** Conversion factors from crop or animal product to mined P requirements by food groups, i.e., P footprint

P footprint based on diet

Food group	Dry matter and phosphorus coefficient	Phosphorus use efficiency	Conversion factor (kg P (kg of crop or animal)$^{-1}$)
Cereals	0.003	1.03	0.0029
Starchy roots	0.0004	1.26	0.0003
Sugars	0.0005	2.19	0.0002
Pulses	0.0002	0.53	0.0004
Tree nuts	0.003	0.47	0.0068
Oil crops	0.004	1.57	0.0025
Vegetables	0.0004	0.30	0.0013
Fruits	0.0002	0.33	0.0005
Stimulants	0.004	0.50	0.0076
Bovine meat	0.003[a]	0.63	0.0612
Mutton and goat meat	0.001[a]	0.45	0.0094
Pig meat	0.003[a]	0.64	0.0316
Poultry meat	0.004[a]	0.74	0.0192
Eggs	0.003[a]	0.74	0.0126
Milk	0.003[a]	0.60	0.0043

The Journal of Nutrition 153 (2023) 2137–2146

American Society for Nutrition

JN THE JOURNAL OF NUTRITION

journal homepage: https://jn.nutrition.org/

Perspectives

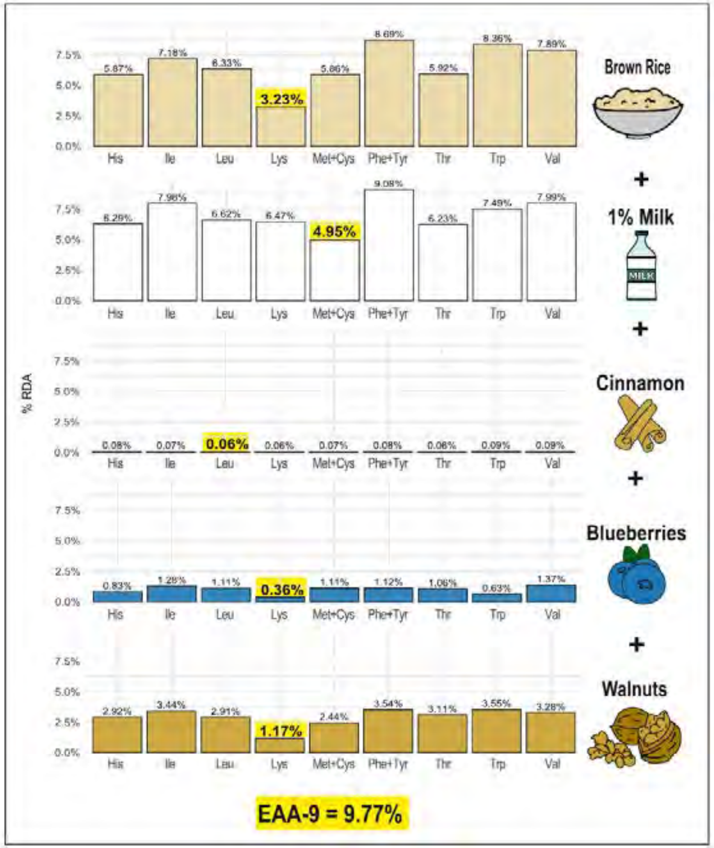
Perspective: Developing a Nutrient-Based Framework for Protein Quality

Shavawn M. Forester[1,*], Emily M. Jennings-Dobbs[1], Shazia A. Sathar[2], Donald K. Layman[3]

[1] *Nutrient Institute LLC, Reno, NV, United States;* [2] *WISEcode, Reno, NV, United States;* [3] *Department of Food Science and Human Nutrition, University of Illinois at Urbana-Champaign, Urbana, IL*

- Proteins are made of amino acids; your body breaks down the proteins you eat into amino acids, which the body uses
- Amino acids are categorized as "essential" from diet, or "non-essential," which the body can produce

Adjusting P footprint based on protein quality



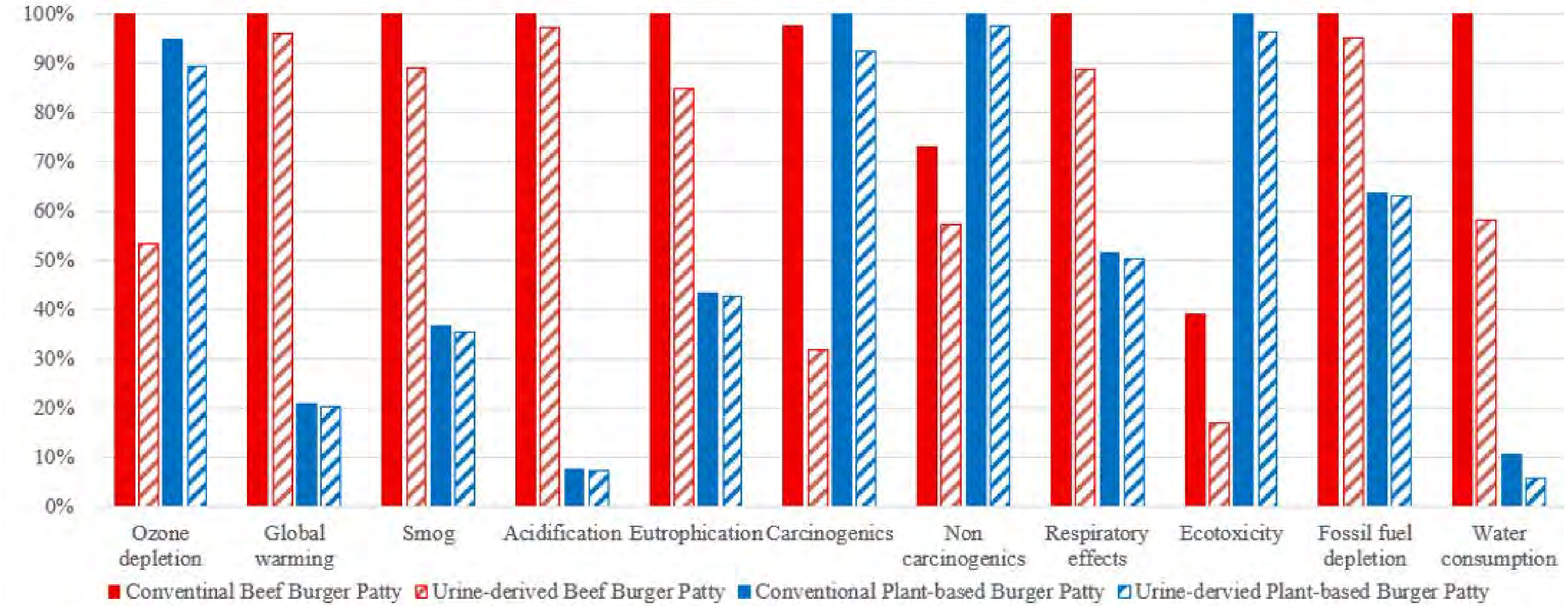
- P footprint is a measure of **protein quantity**
- For precision diet, also need to consider **protein quality**
- Protein quality can be quantified by measuring types and amount of essential amino acids
- Different foods contain essential amino acids to different extents

P footprint and protein quality of lunch

Food	kg P applied to produce kg of product	Protein Digestibility Corrected Amino Acid Score	kg digestible protein/kg P applied
Herb Baked Chicken Breast	0.0192	0.93	15
Smoked Beef Brisket	0.0612	0.92	4
Black Beans	0.0004	0.7	10
Brown Rice	0.0029	0.72	7
Seasonal Fresh Vegetables	0.0013	0.65	15

Credit: Matt Scholz

What is the impact of P recovery on P footprint impacts?



- **P recovery** can decrease the environmental impact of food with high P footprint (Evans et al., under review)

Evaluation & Adoption of Novel Plant Nutrition Products

This session is sponsored by

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Evaluation & Adoption of Novel Plant Nutrition Products

Fred Nichols
Chief Sales & Marketing Officer
Huma

Vinayak Shedekar
Assistant Professor
The Ohio State University

Sarah Lyons
Scientific Project Manager
FFAR

David Emerman
Chief Community Officer
Ohio EPA

Jason Haegele
Marketing & Innovation Manager
ICL

The Efficient Fertilizer Consortium

Advancing Enhanced Efficiency Fertilizer Products & Practices Through Applied Research

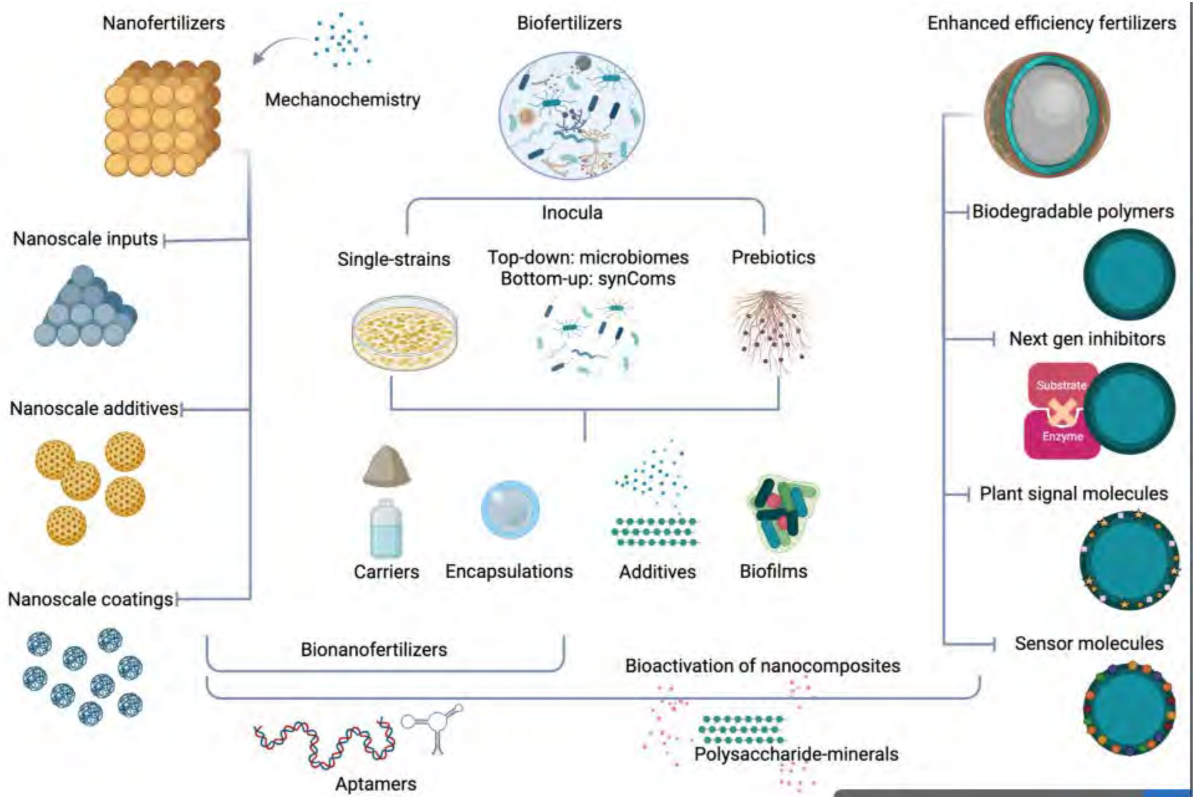
Dr. Sarah Lyons

Foundation for Food & Agriculture Research

So Many Options, So Little Time (and Data)

- Many promising technologies, but limited standardized and independent evaluation

- Low farmer adoption due to high cost, lack of experience and uncertainty of effectiveness



Maaz et al., 2023; https://foundationfar.org/wp-content/uploads/2023/08/EFC-White-Paper-1.pdf

Efficient Fertilizer Consortium

- A public-private partnership that funds research to:
  - Advance enhanced efficiency and novel fertilizer products and practices that improve nutrient use efficiency and decrease environmental impact
  - **Establish common protocols for field trials**
  - Conduct field trials across diverse systems to ground industry claims and generate better guidance for farmers

Efficient Fertilizer Consortium

Field Trial Guidelines for Evaluating Enhanced Efficiency Fertilizers

- **Agronomic performance and environmental impact** of EEFs
- Consistency in experimental design, data collection and data analysis for large-scale impact and end-user confidence

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ORIGINAL ARTICLE
Agricultural Soil and Food Systems

Field trial guidelines for evaluating enhanced efficiency fertilizers

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Assigned to Associate Editor Steve Culman

Abstract
There are many fertilizer additives and alternatives that aim to increase plant nutrient use efficiency and reduce nutrient losses to the environment, here referred to collectively as enhanced efficiency fertilizers (EEFs). However, there is often insufficient published scientific field trial results across a variety of locations, climates, soils, cropping systems, and management scenarios to prove their efficacy and conditions

Next Steps & Opportunities

- Funding international field trials evaluating EEFs using the *Field Trial Guidelines*
- Executive Committee meeting this fall to discuss next round of projects & next steps for the consortium

- *Please contact me with interest in partnering and/or funding opportunities:*
- Dr. Sarah Lyons, slyons@foundationfar.org

Evaluation & Adoption of Novel Plant Nutrition Products

Jason Haegele
Marketing & Innovation Manager
ICL

How were fertilizers developed in the past?

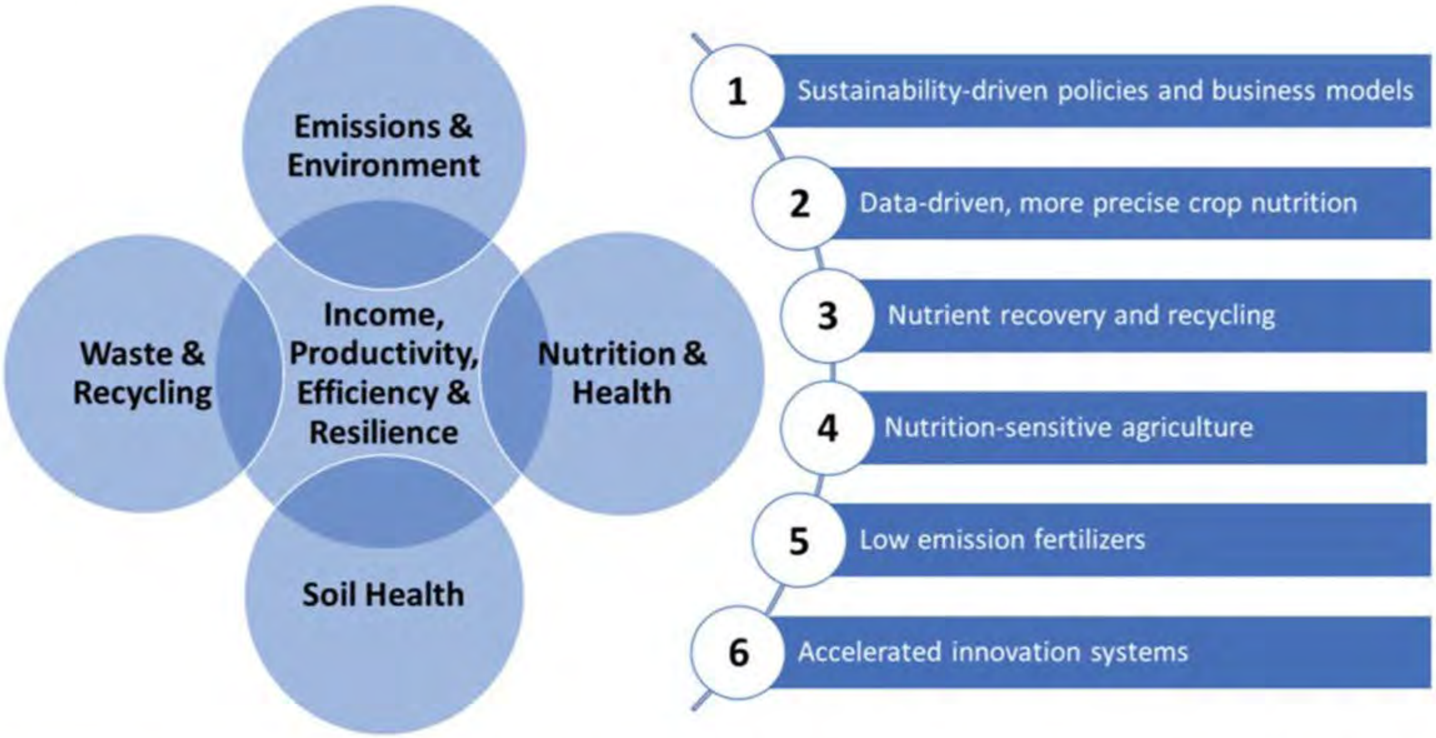
What is the needed nutrient analysis?

Which are the most appropriate nutrient sources?

Combine into a finished product

A New Paradigm for Plant Nutrition

Modern plant nutrition must solve for more problems and outcomes than just increased yield



Dobermann, A. et al. (2023). A New Paradigm for Plant Nutrition. In: von Braun, J., Afsana, K., Fresco, L.O., Hassan, M.H.A. (eds) Science and Innovations for Food Systems Transformation. Springer, Cham. https://doi.org/10.1007/978-3-031-15703-5_19

The future of fertilizer product development and testing

A new paradigm for plant nutrition will require:

- New approaches that do not rely solely on combining individual nutrients, but rather **combinations of novel technologies**, a broader range of nutrient sources, and complementary biology

- Solving for a broader range of non- yield-based outcomes will require **reliable and consistent methods** to screen candidate product concepts and validate the target characteristics

- Undifferentiated, less efficient commodity fertilizers will be with us for the foreseeable future. The attractiveness of relatively low-cost commodity plant nutrients in an economically volatile world requires **a solid value proposition demonstrated through scientifically valid, local testing** (soil types, cropping systems, climate, etc)

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Distribution models impact the economics and dynamics of fertilizer product adoption

Manufacturer
↓
Grower

Manufacturer
↓
Local distributor/retailer
↓
Grower

Manufacturer
↓
Wholesale distributor
↓
Local distributor/retailer
↓
Grower


Bringing new products to market
Early-stage product ideation
R&D
(formulation, product characterization, etc)
Controlled environment testing
Market development trials in local environments
Product Launch
Ongoing trials with customers
5
4
3
2

Examples of recent ICL innovations

Promoting agricultural productivity and environmental stewardship

- PURALOOP, an eco-friendly product, is crafted from 100% SSA (sewage sludge ash) and MGA phosphoric acid, providing a sustainable phosphorus source with performance comparable to traditional fertilizers

- eqo.x introduces the market's first coated controlled release fertilizer (CRF) for urea, designed to meet upcoming European fertilizer standards (effective 2026) with faster degradation

- BIOZ offers targeted biostimulant products to enhance crop yields, tailored for optimal productivity by boosting various aspects of crop growth and performance

These products are examples of global ICL innovations and may not be currently available in the US

PURALOOP

ICL's recycled P fertilizer

ICL

PURALOOP

Agronomic advantages

Essential nutrient phosphorus (P) source for all crops

P in phosphate form as taken up by plants

High P-bioavailability

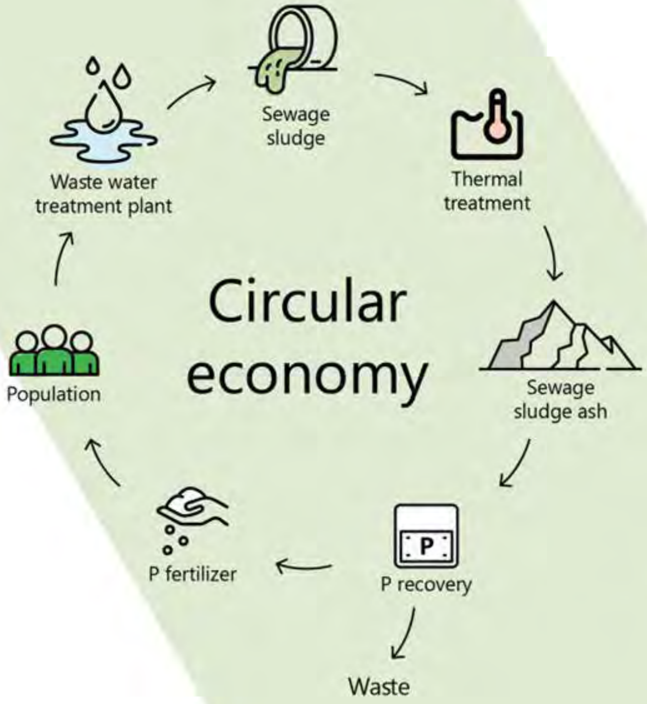
Granular product, easy and uniform spread on the fields

Contains some macronutrients (like K, Mg, Ca, S), and small amounts of micronutrients

In agronomic trials, PURALOOP shows similar performance to conventional P fertilizers

Sewage sludge ashes
Raw material

- Phosphorus (P), which is a valuable plant nutrient, can be recovered from sewage treatment plants
- Sewage sludge is a mud-like residue resulting from wastewater treatment
- Sewage sludge ashes (SSA) is the by-product produced during the combustion of dewatered sewage sludge in an incinerator
- Sewage sludge ashes are rich in phosphorus content, ranging between 4 to 9%



- SSA is an important source of P, globally it accounts for 4Mt P (0.3 Mt in Europe)
- Although farmers can spread SSA directly on their fields, plants are not able to make much use of the P in it (it is not in available form for root uptake)
- Sewage sludge contains organic compounds such as drugs that are dangerous for crops and humans. Combustion removes these compounds
- By acidulating the SSA with phosphoric acid in Amfert process for producing PURALOOP, the P becomes in available form like in the TSP fertilizer

PURALOOP
Agronomic trials

Level 1: Pot trials in Gilat research station in Israel

Maize plants in 10 L pot filled with low P sandy soil (from the Besor area). All pots but the negative control received similar dose of P in a rate of 50 mg/kg. N was applied with irrigation water at concentration of 50 mg/l

The six treatments were:
- Negative control: no P fertilizer
- Negative control + AMF: no PK fertilizer with mycorrhiza
- PURALOOP PK 0-32-2
- PURALOOP PK 0-32-2 + AMF
- PURALOOP PK 0-5-40
- TSP (positive control)

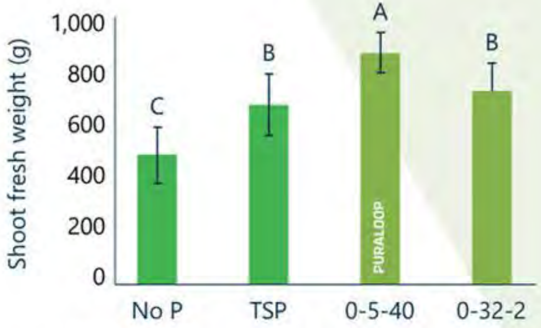
All nutrients but the negative control supplied at the same rate, K as KCl, Ca as $CaCl_2$ and Mg as $MgSO_4$.

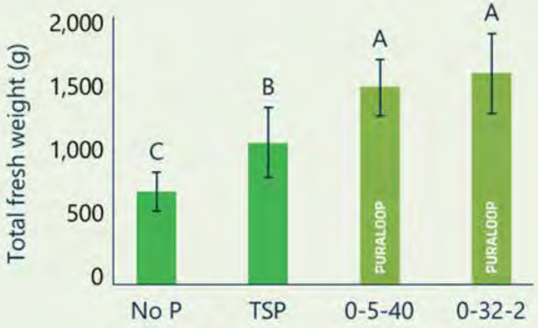
ICL

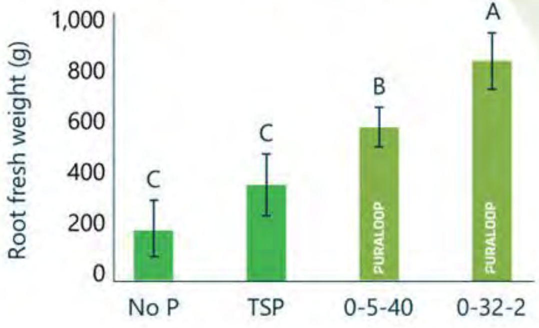
PURALOOP
Agronomic trials

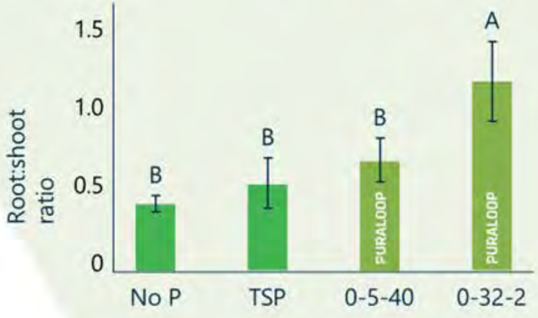
Preliminary results

Level 1: Pot trials in Gilat research station in Israel









- Adding P to the soil significantly increased Shoot and root fresh biomass and total fresh biomass
- PURALOOP 0-5-40 had the highest shoot biomass
- PURALOOP 0-32-2 had the highest root fresh biomass
- The total plant biomass with PURALOOP products was higher than with TSP

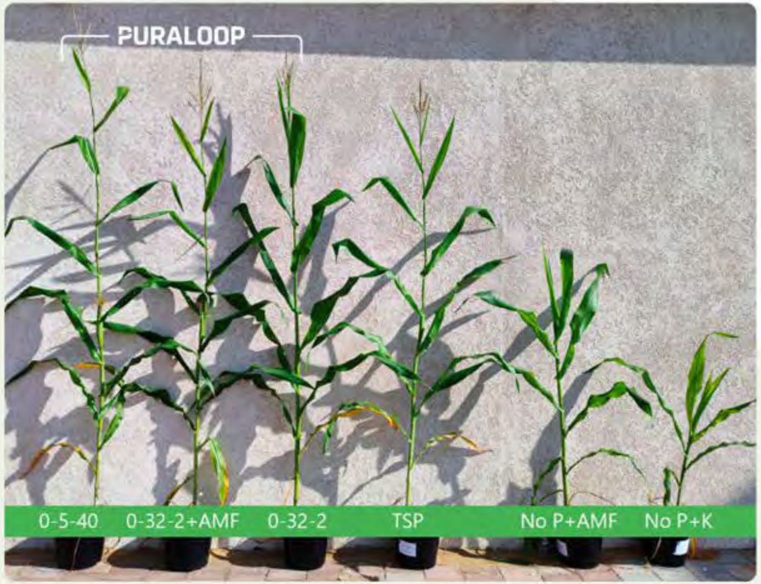
PURALOOP
Agronomic trials

Level 1: Pot trials in Gilat research station in Israel

Preliminary results

All plants that received P had normal appearance, comparable to the field (~2 m in height), while P deficient plants were retarded

Plants that received P (regardless of the P source) had normal and developed flowering (male and female) while in the P deficient treatments flowering was delayed



Evaluation & Adoption of Novel Plant Nutrition Products

Fred Nichols
Chief Sales & Marketing Officer
Huma

How Farmers Make Decisions

EVALUATION & ADOPTION OF NOVEL PLANT NUTRITION PRODUCTS


B2B buyers go through
70% of the sales cycle
before ever contacting a
sales person.

To Buy or Not to Buy

THE JOURNEY:

1 — Spark Interest

2 — Conduct Research

3 — Seek Validation

4 — Assess Price & Value Relationship

5 — Contact Retailer/Rep

6 — Set Up Test Plot

7 — Evaluate Performance

8 — Decide to Apply to Commercial Acres

1 SPARK INTEREST

How are Farmers Introduced to Products?

- **Farmers are Curious by Nature**
- **Often Driven by a Need**
  - May need to tell them they need it
  - Pests, nutrient deficiency, plant health issues, reduce labor
- **Events can Trigger**
  - Product performance issues, stuck on a yield plateau, warranty expires, machine paid off, gains/loses more land
- **Can Occur in Many Places**
  - Trade show, a coffee shop, field day, reading an article or seeing/hearing an ad, riding in combine

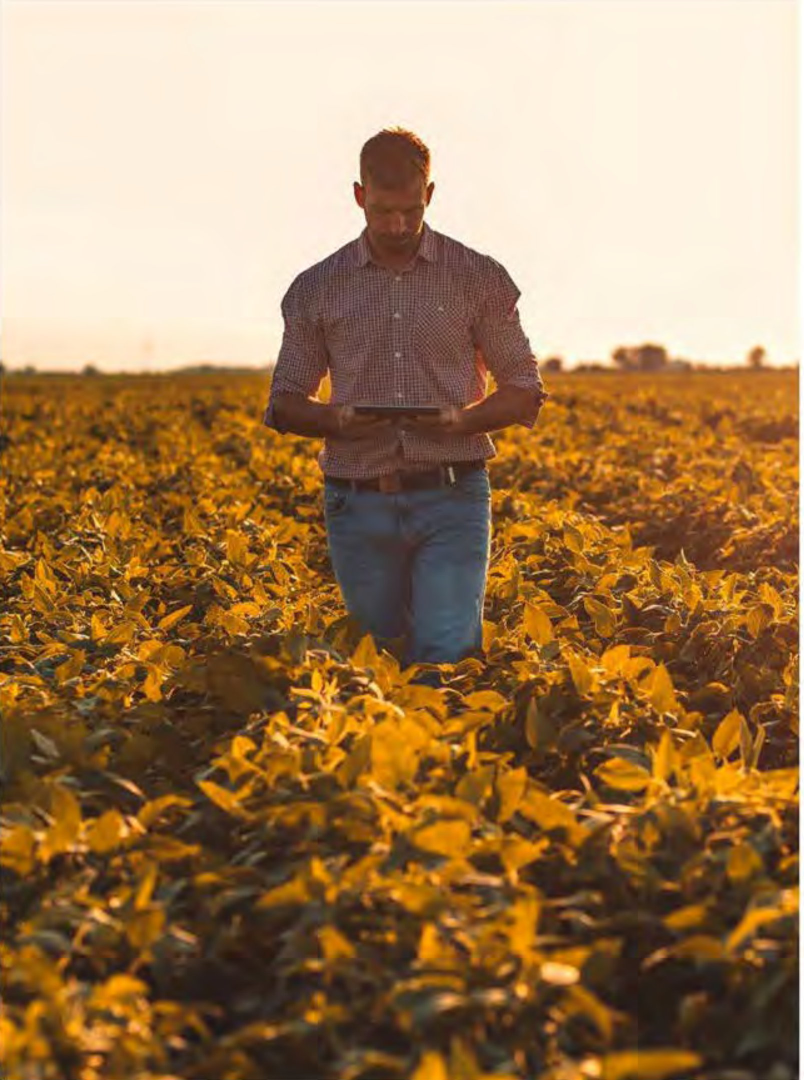
Questions Farmers Always Ask

1 — Will it **make me money**?

2 — Will it **save me money**?

3 — Will it **save me time**?

Value propositions must address at least one, preferably more, of these factors.
Safety, convenience, environmental/regulatory issues are also factors.



How to Make Them Money

- Increase Production
- Improve Quality
- Premiums
- New Market & Revenue Stream
- Market Access
- Add Value to Current Assets
- Help Them Make Better Decisions

How to Save Them Money

- Lower Price
- Reduce Input Costs
- Reduce Labor
- Improve Effectiveness of Other Products

How to Save Them Time

- Improve Efficiency
- Spread Out Workload
- Automation
- Combine & Eliminate Trips Across the Field

Willing to Pay More if it Saves Them Time

- Farming Is Labor Intensive & Reliable Labor is Scarce and/or Expensive
- Time Crunch is Amplified during Busy Seasons (Planting, Spraying, Harvest, Calving)
- Many Younger Farmers are Looking for a better Work-life Balance
- More Time for a Second/Primary Job

2 CONDUCT RESEARCH

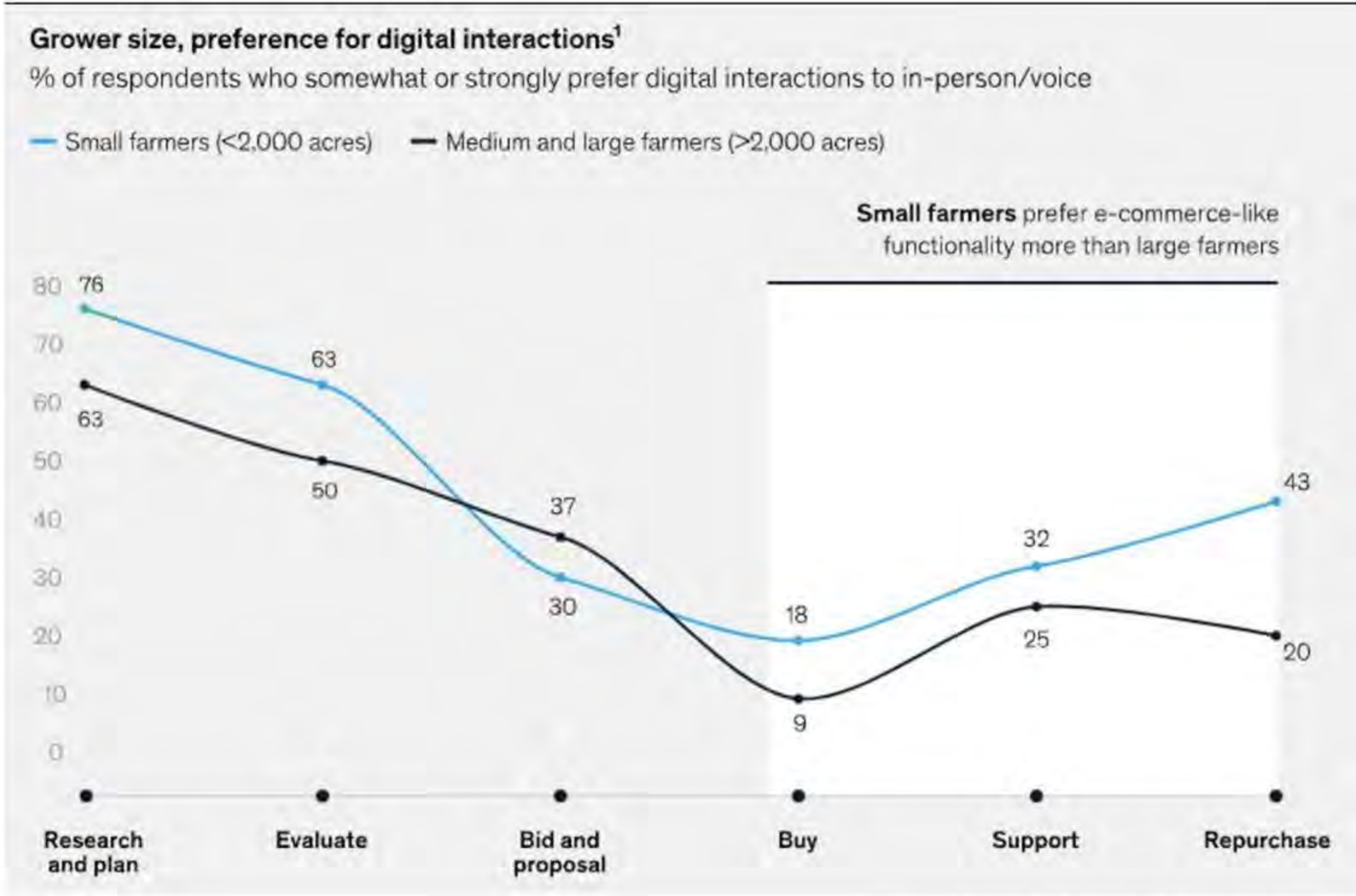
There's No 'Silver Bullet' for Reaching Farmers

- Trade Publications
- Farm-focused Radio (NAFB)
- Search Engine
- Social Media
- TV & Radio
  (Sports, News, Ag-related)
- On-line Trade Publications
- Digital Programmatic
- E-newsletters
- E-mail
- Direct Mail
- Outdoor
- Text
- Trade Shows

Over 66% of Farmers prefer digital interaction

over human interaction early in the buying cycle.

Grower Engagement Preference Varies by Stage in Buying Journey



2022 McKinsey Study Based off of 800 Growers

Any Change Farmers Make to their Operation Affects their Entire Operation

When marketing to farmers,

always take an enterprise approach.

3 VALIDATION

A Farmer's Most Trusted Source of Information is Other Farmers

64% turn to friends & peer farmers for buying advice,

61% turn to an agronomist

Farmers have an '**Inner Circle**' to help validate decisions

KEY INSIGHT

- **Trusted Advisors Can Include:**
  - Fellow Farmers
  - Retailers
  - Seed Dealer
  - Loan Officer
  - Equipment Dealers
  - Consultant
- **On-line search, social media, and Ag media can also play a role**

Farmers who participate in associations often get on these boards to learn from each other. They are also deemed as highly credible by other farmers.

4 PRICE & VALUE RELATIONSHIP


3:1 ROI
Will get a farmer interested

Specialty Growers are **Driven by Quality** & more willing to Invest in their Crop

- Directly Driven by Consumers & Retailers
- They Grow High Value Crops with Higher Margins
- Taste
- Eye-appealing Produce... Beautifully Colored, Shaped & Textured Appearance
- Shelf Life… Long-lasting Freshness And Firmness on the Inside with Longer Storage/Shelf Life… Longer Harvest Intervals
- Efficiency, Labor & Production still Important

Commodity Growers Live by Cost per Acre

- They Get Paid by Delivering the most Grain for the Least Amount of Money
- All Inputs – Equipment, Labor, Technology, Cash Rent – are Amortized Across Total Acres Covered, to end up a Cost/Ac
- Fertilizers, Insecticides and Yield Enhancers are more Tangible to Measure; Herbicides can be more Subjective
- Application Rates are Subject to Scrutiny

Premiums from Regen Ag practices & lower CI scores

can be game changers.

Farmer Math

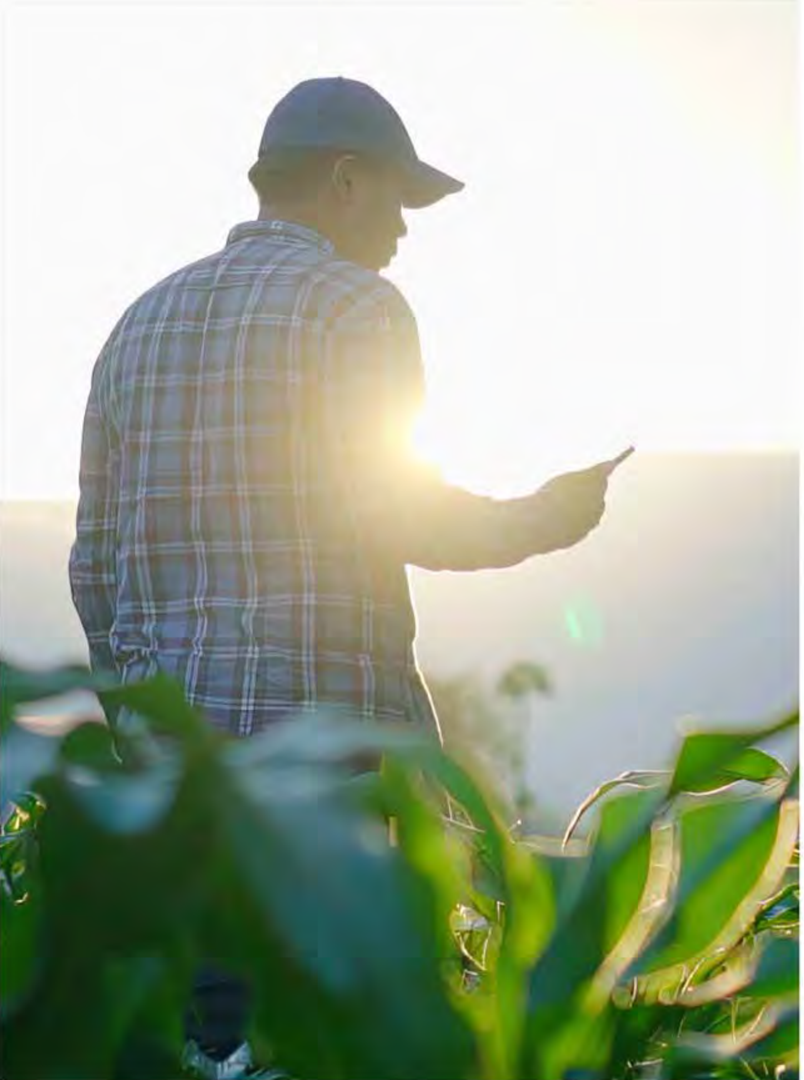
"If a new phosphorus product costs $15/ac (plus $7/a application cost), I'm paying $22/ac

… if can conservatively yield an additional 8 bushels more corn (at $4/bu), I can net $10/ac

… that means I make money even after paying interest.

...provided I do not need to change anything in my operation.

5 CONTACT REP



Farmers are Shrewd Negotiators

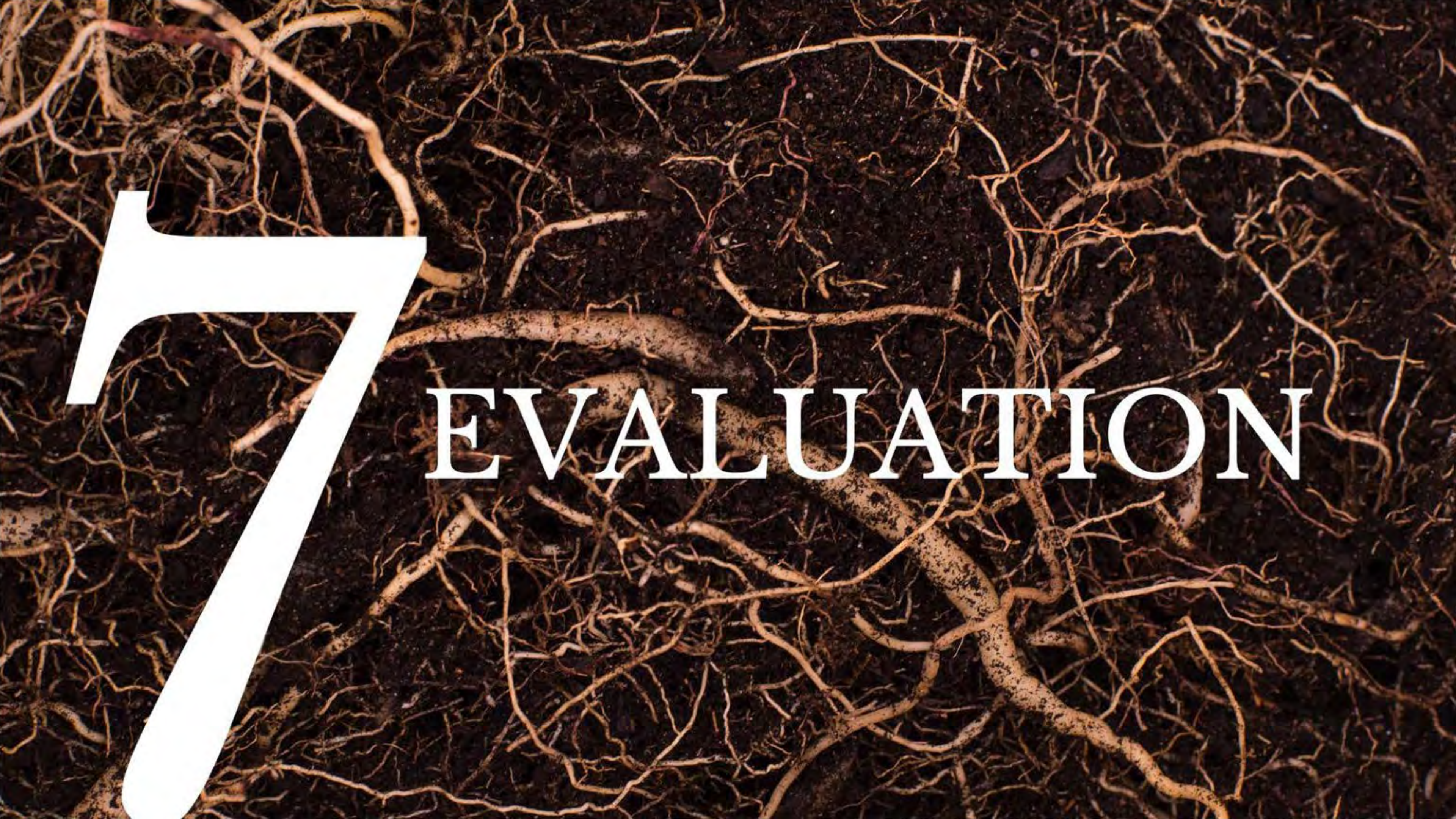
Once they have done some homework and sought validation, and the product has received a degree of legitimacy in their mind, they will contact a sales rep, or retailer, to ask questions about the product and get a price.

They often place a perceived value on something before they ever talk to a rep.

6 CONDUCT A TEST

On Farm Research

- More Growers are Devoting Sections of their Farms to on-farm Research Plots
- Younger Farmers & Large Farmers most Likely
- They May “Try Out” a Product on a Specific Field or Plot
- They Should Plant Untreated Checks in the Field for Comparison, but Sometimes this Does Not Happen
- During this Trial Period Sales Reps should stay in Frequent Contact, Monitor Season-long Progress, as Farmers can “Plant It & Forget It”



7 EVALUATION

How Farmers **Measure Success**

- This is Easier Done with Some Products than Others
- Yield is Always the Ultimate Measure & Difficult to Downplay
- But ROI Drives Decisions
- Progressive Growers look Beyond the Scales. They Evaluate their Crop Throughout the Season & look for Key Events in the Plant's Life
- Continual Follow Up by a Rep and/or Company is Vital, to Continuously Remind Growers of these Events

8 DECISION

To Buy or Not to Buy

If the product proves itself in a test plot, the ROI is favorable and the impact on the operation is manageable, the grower will likely adopt the product on a large portion of their commercial acreage.

But beware – products are always being evaluated.

Product performance, cost/value relationship and service must always be maintained, compared to alternatives. Now more than ever.

Coffee Break Sponsor

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Evaluation & Adoption of Novel Plant Nutrition Products

David Emerman
Chief Community Officer
Ohio EPA

David Emerman,
Chief Community Officer

H2Ohio TAP

Environmental Protection Agency

Ohio Environmental Protection Agency

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Technology Assessment Program (TAP)

ScottsMiracle-Gro

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Sea Grant
Ohio Sea Grant College Program

Owens Corning

CWA
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Alliance for the Great Lakes

The Nature Conservancy

Ohio | Department of Agriculture | Department of Natural Resources | Environmental Protection Agency | Lake Erie Commission

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HDR

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Myerholtz Family Farms

The Nature Conservancy

Ohio | Department of Agriculture | Department of Natural Resources | Environmental Protection Agency | Lake Erie Commission

Evaluation & Adoption of Novel Plant Nutrition Products

Vinayak Shedekar
Assistant Professor
The Ohio State University

Slides Removed at Speaker’s Request

Diagnosing & Responding to Enhanced Biological Phosphorus Removal Upsets

Doug Call
Professor
NCSU

JB Neethling
Wastewater Treatment & Effluent Management Director
HDR

Roland Cusick
Associate Professor
University of Illinois, Urbana-Champaign

Tom Solon
Process Optimization & Planning Manager
ReWa

Diagnosing & Responding to Enhanced Biological Phosphorus Removal Upsets

JB Neethling
Wastewater Treatment & Effluent Management Director
HDR

Phosphorus Removal and Recovery Strategies

JB Neethling, PhD, PE

HDR

September 18, 2025

Agenda

- Phosphorus Removal vs. Phosphorus Recovery
- Enhanced Biological Phosphorus Removal
- Phosphorus Recovery

P removal vs P recovery

Phosphorus Removal

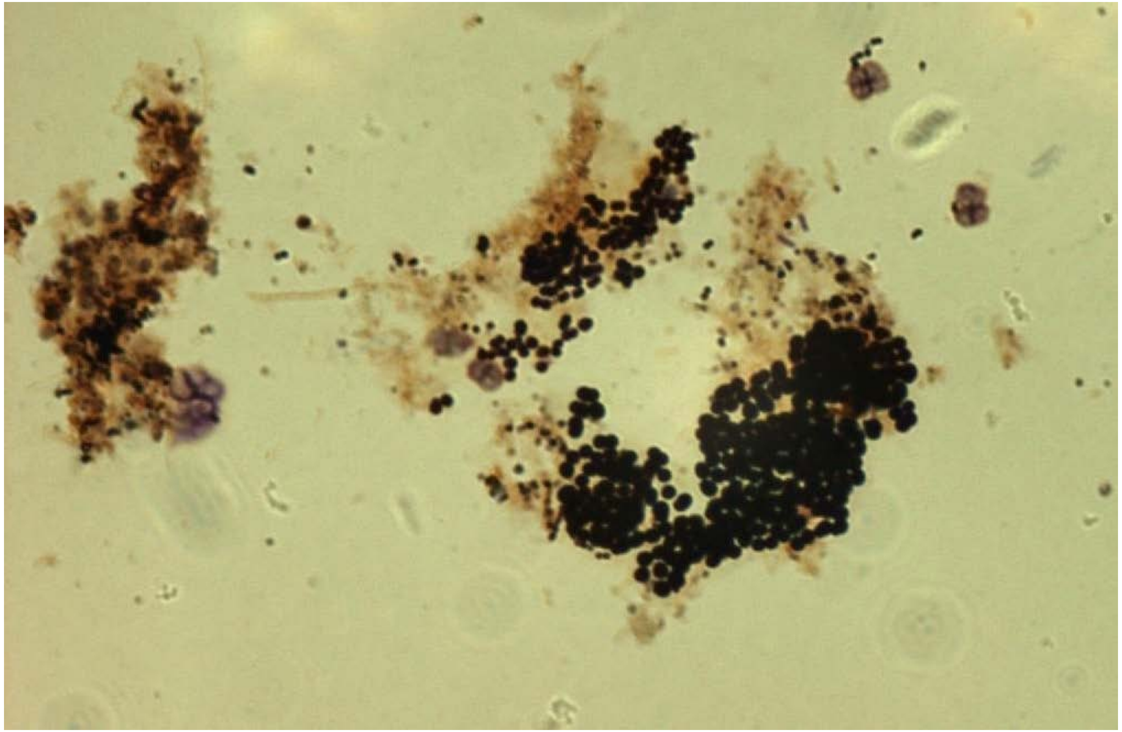
- Remove P from wastewater to discharge into receiving water
- Removed P goes to:
  - Solids processing Residuals
    - Land application
    - Landfill
    - Compost, etc.

Phosphorus Recovery

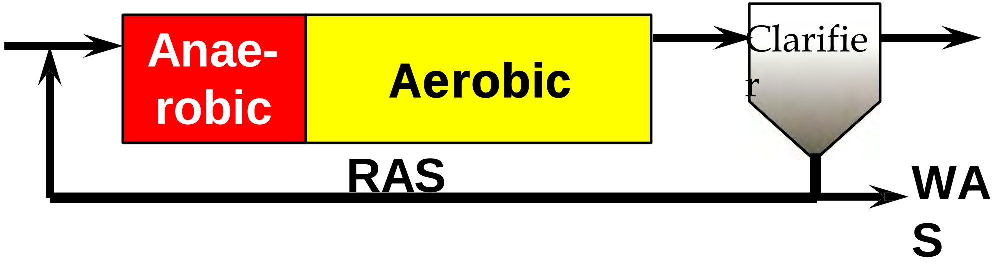
- Recover removed phosphorus in a useable form
- Recovery process aim to:
  - Extract PO4 and precipitate into marketable product
  - Concentrate in biosolids to land apply beneficially
    - P/N ratios are not typically attractive
    - Some regions have limitations on P applied to land

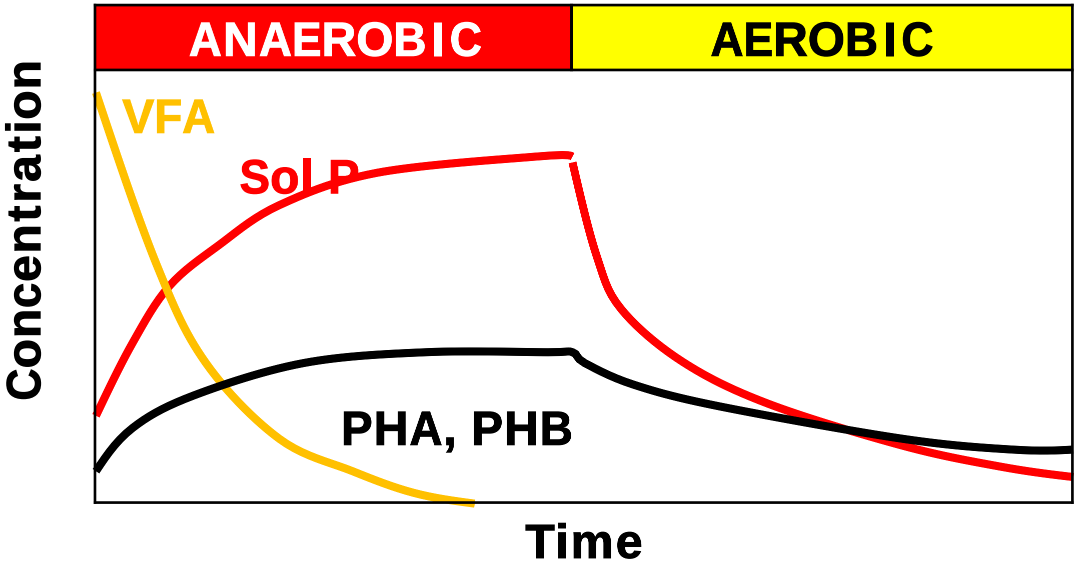

Phosphorus Removal

Neisser Stain shows polyphosphate granules



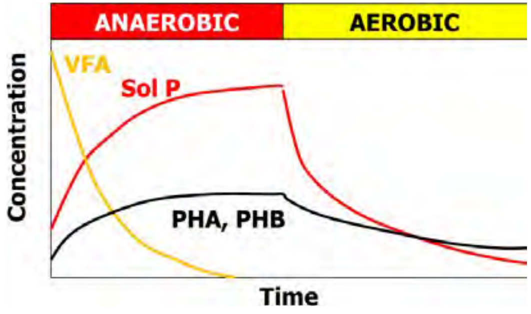
EBPR AO Process Configuration – BOD only

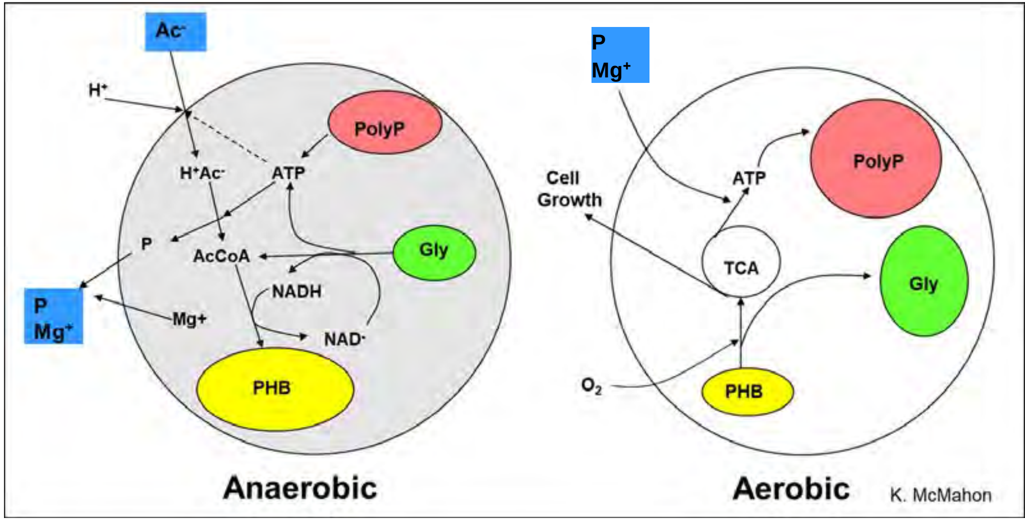




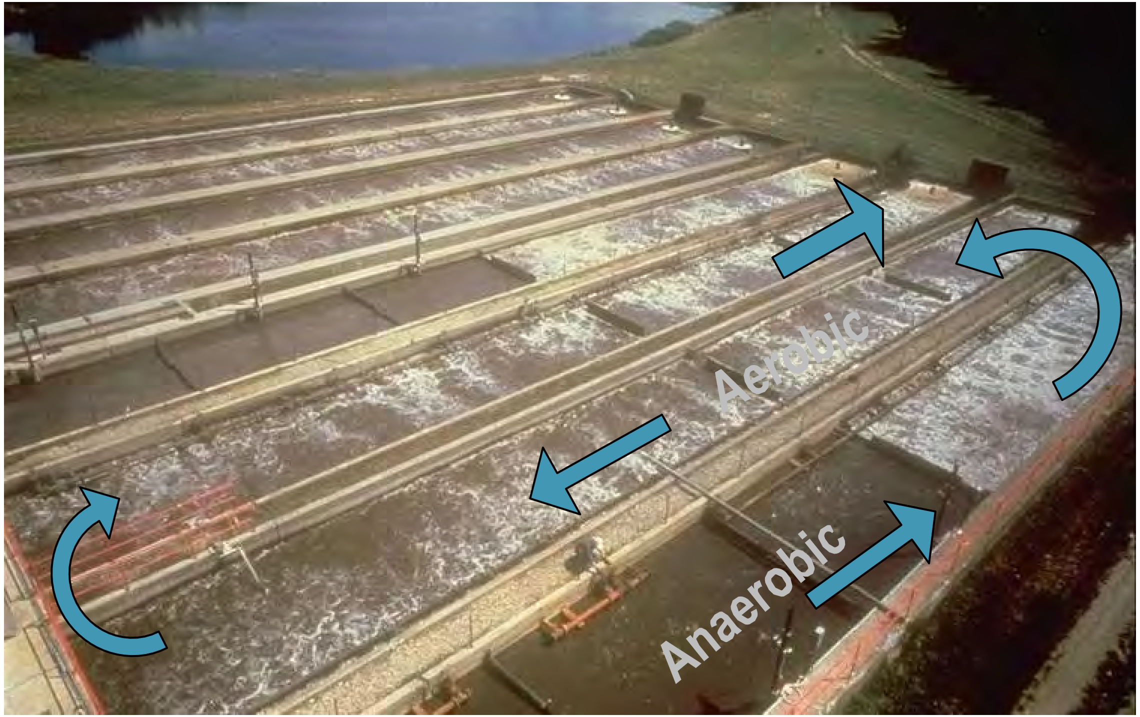
EBPR Requirements

- Anaerobic/aerobic sequence
- Anaerobic zone
  - Supply readily biodegradable organics and VFAs in anaerobic zone
  - Release P and Mg
  - Store PHB's
  - No free or bound oxygen (nitrate)
- Aerobic zone
  - DO and PHB grow cells
  - Take up P and Mg
  - Store P as polyP

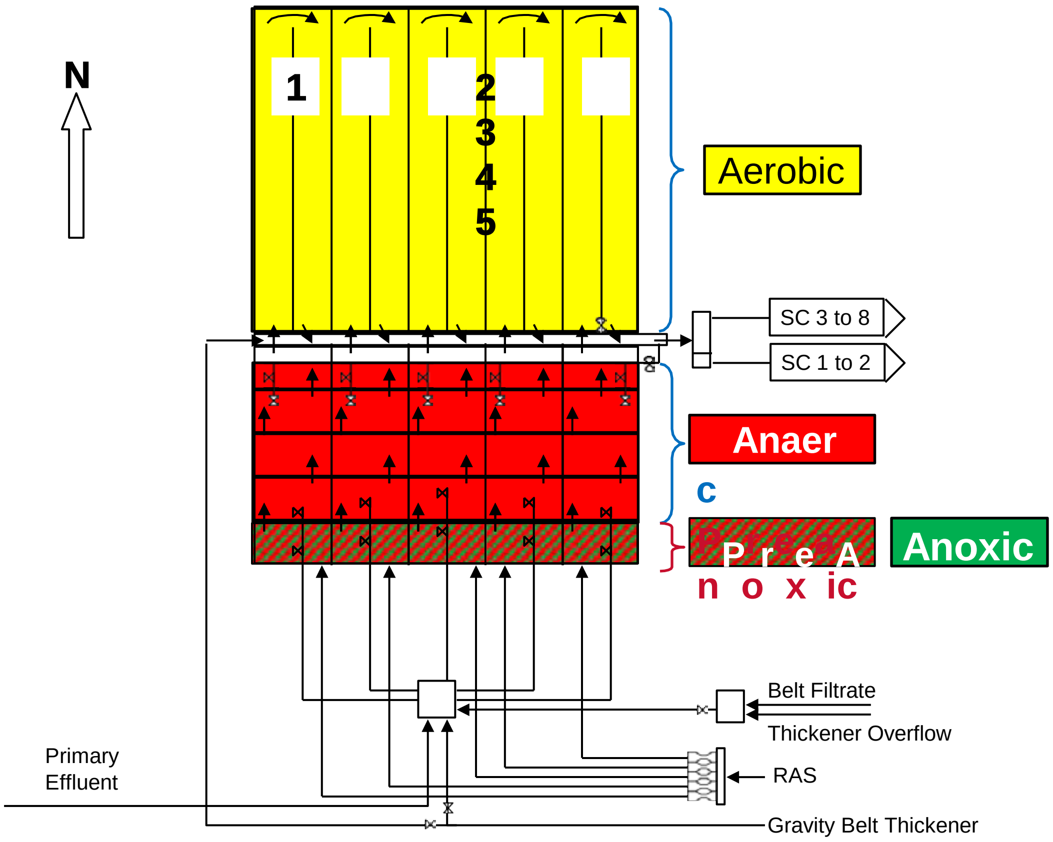




Pontiac, MI. AO process for P removal

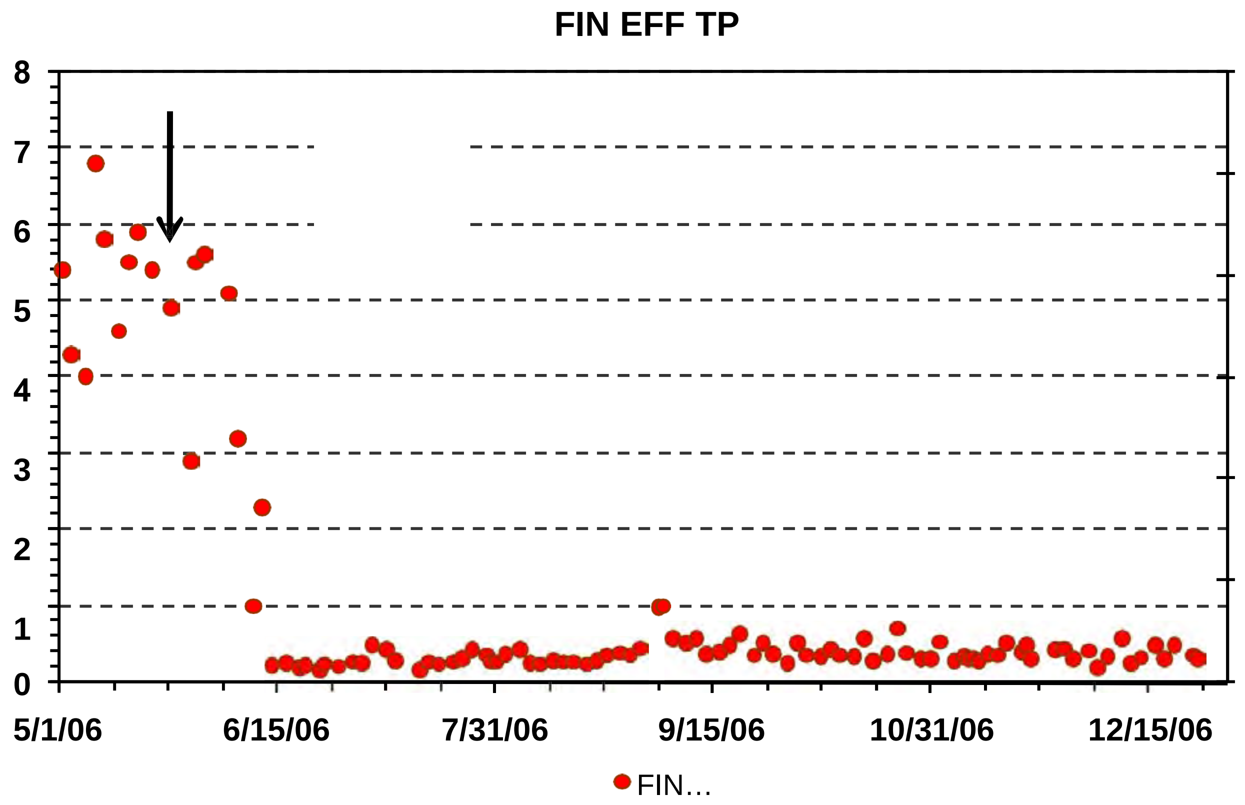


Empire Layout – P removal

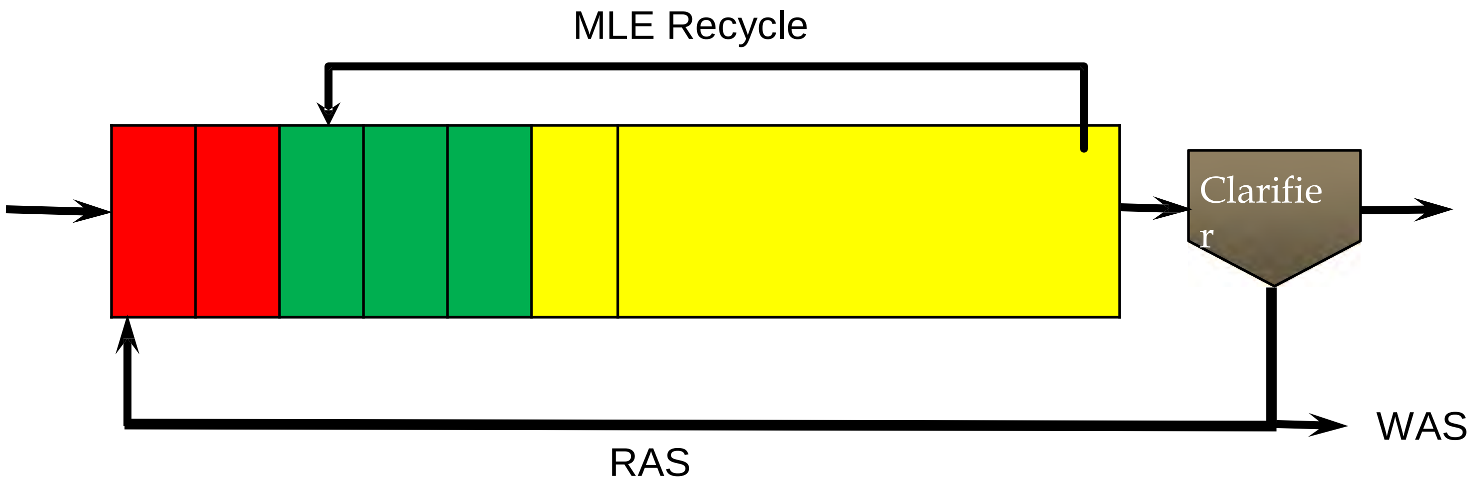


Anoxic/Anaerobic Tank 3

Startup of BioP at Empire – about 3 weeks



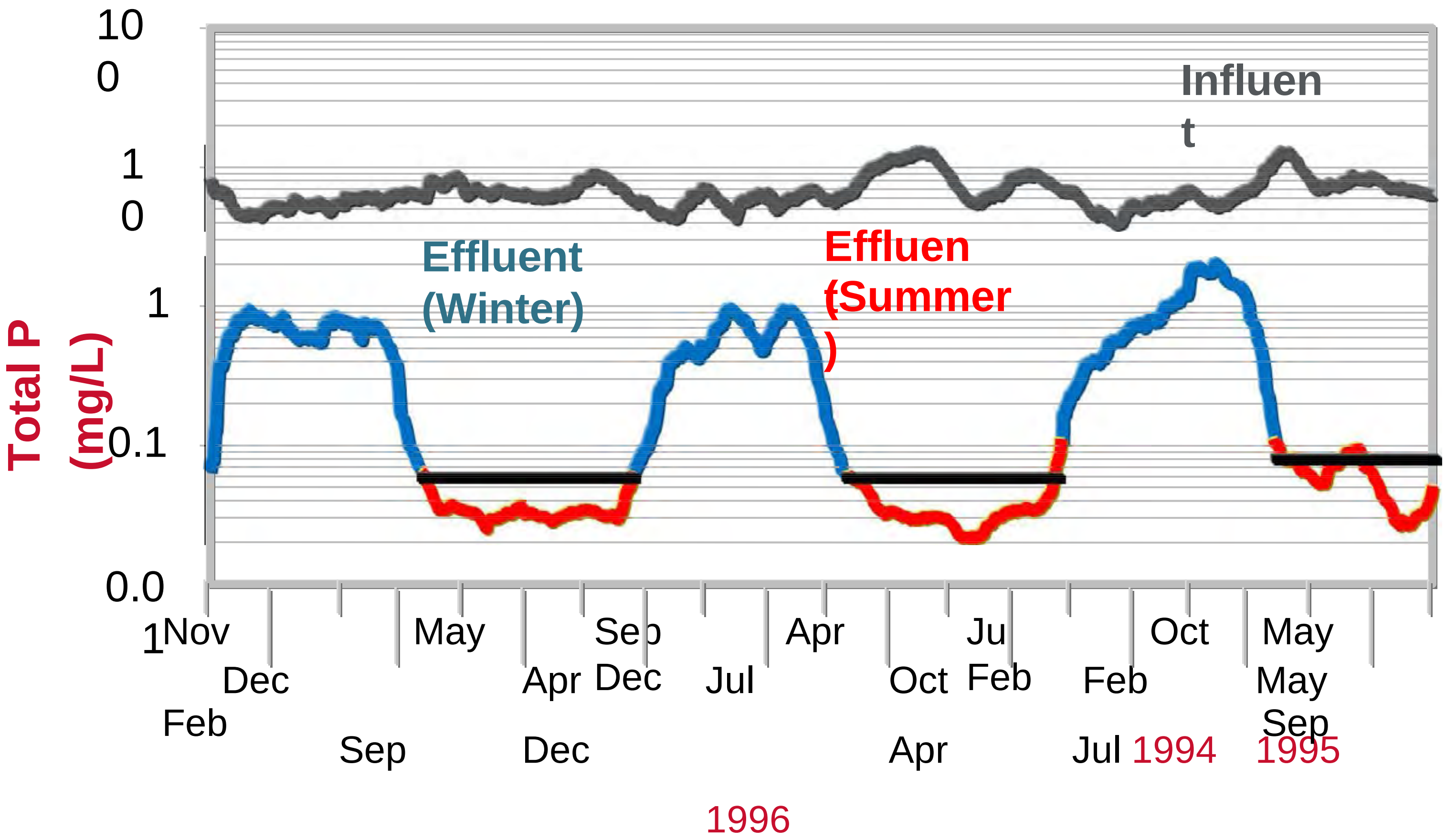
CWS Durham Process (Summer – 3 stage Phoredox)



CWS Durham Aeration Basin

Permit limit: 0.07 mg P/L median during summer (1994)

Durham AWWTP -- Phosphorus (‘94-’97)



Challenges with EBPR

EBPR Challenges

- Struvite formation
  - Precipitants form on equipment, pipes, any surface
- Solid Dewaterability
  - Deterioration of cake in dewatering

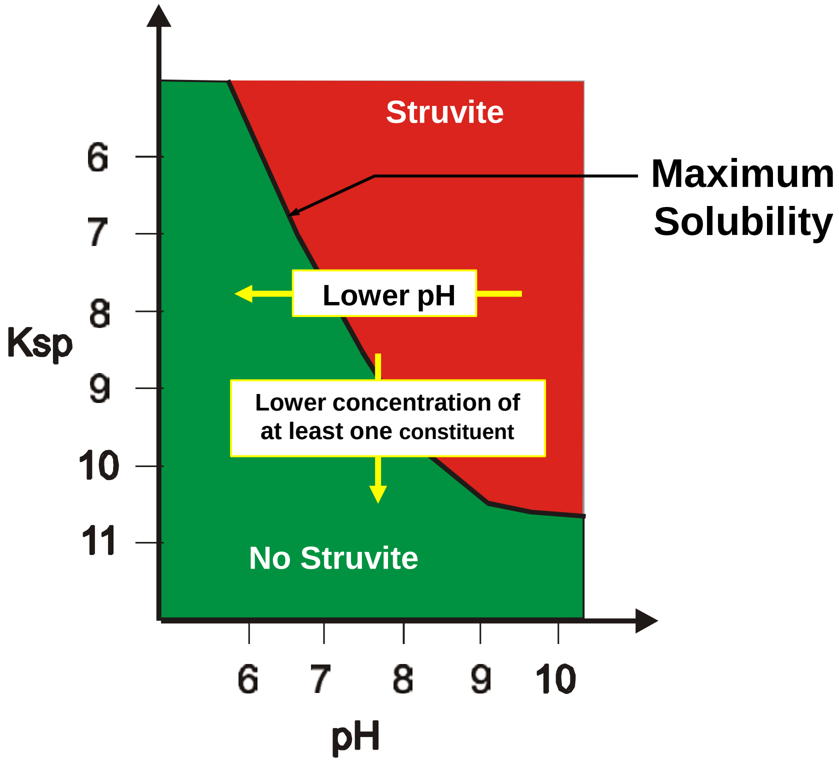
Struvite - MAP

Magnesium Ammonium Phosphate

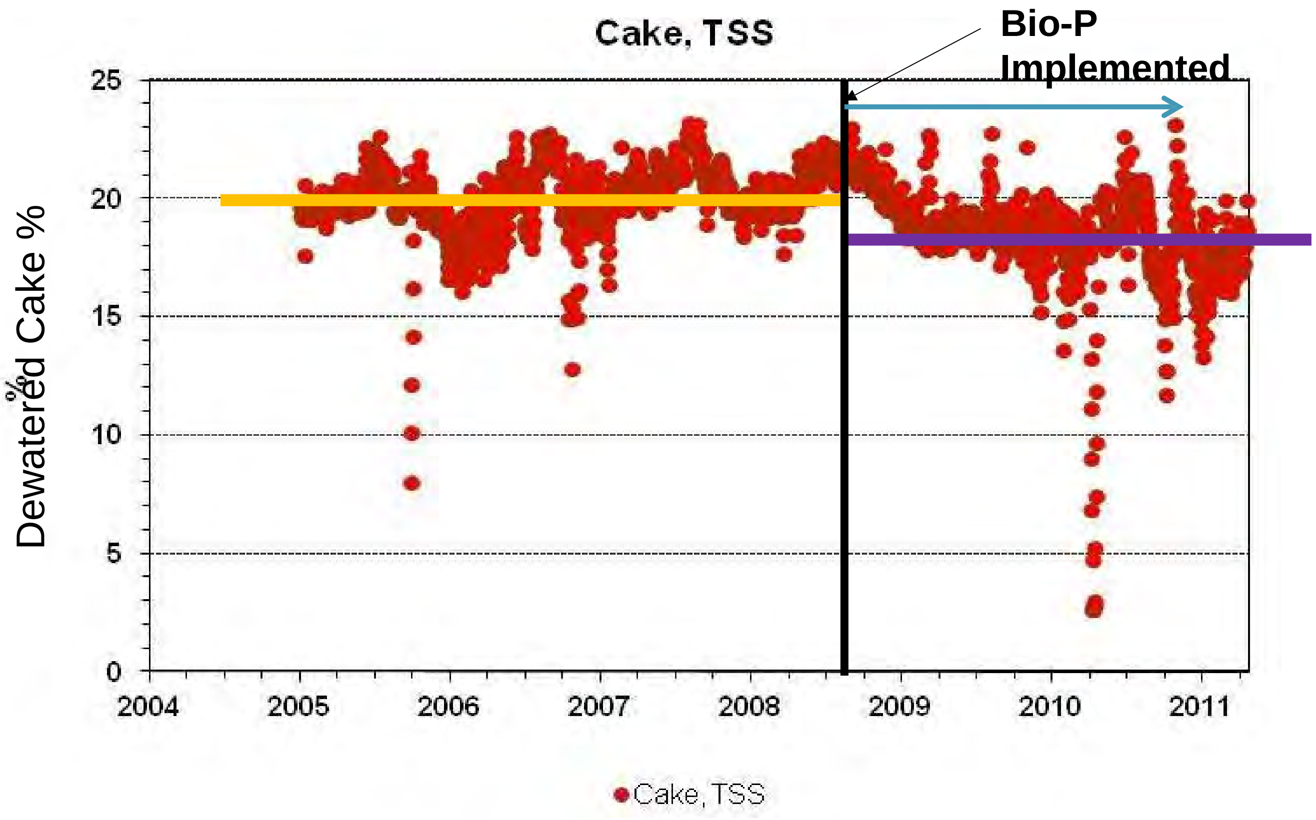
Struvite Control Strategies – Prevent Struvite Formation and Deposition

- Dilution – add dilution water to reduce concentrations below precipitation
- Lower the pH
- Struvite inhibitors – chemical, proprietary chemicals and electric/magnetic device

$[Mg^{++}].[NH4^{+}].[PO_4^{3-}]$



Impact of Bio-P on Dewaterability



Theories on Why Bio-P Impacts Dewaterability

- Impact of phosphate on protein molecule
- Ratio of monovalent to divalent ions
- Controlled struvite formation can increase cake%

Conclusion

Struvite Recovery – Controlled precipitation and harvesting of P-rich crystals

From Problems
Problems

To Solutions
Solutions

Enhanced Biological Phosphorus Removal

- Conditions to grow PAO's
  - Readily degradable organics (ex. VFA) from influent or "manufactured" on site
  - Sequential exposure to anaerobic and aerobic (or anoxic) conditions
  - Many process options to create right growth conditions
- Limit variations if growth conditions
  - Steady/consistent feed composition
  - Limit variable influent concentration swings
  - Slug loads leads to variable performance/effluent quality – "Don't Kick the Bucket"
- Effluent phosphorus concentrations below 0.1 mg/L is achievable with advanced technologies if influent flow and load remain consistent

Potential Treatment Costs Savings from P-Recovery

- Reduced coagulant use
- Reduced alkalinity supplementation
- Reduced cake hauling
- Reduced dewatering polymer (with SPR)
- Reduce struvite mitigation cost
- Reduce agronomic P load of biosolids
- Revenue from product sale

Phosphorus Removal and Recovery Strategies

HDR

18 September 2025

Diagnosing & Responding to Enhanced Biological Phosphorus Removal Upsets

Tom Solon
Process Optimization & Planning Manager
ReWa

Improving Efficiency and Resiliency of Phosphorus Removal at Mauldin Road WRRF

ReWa
renewable water resources

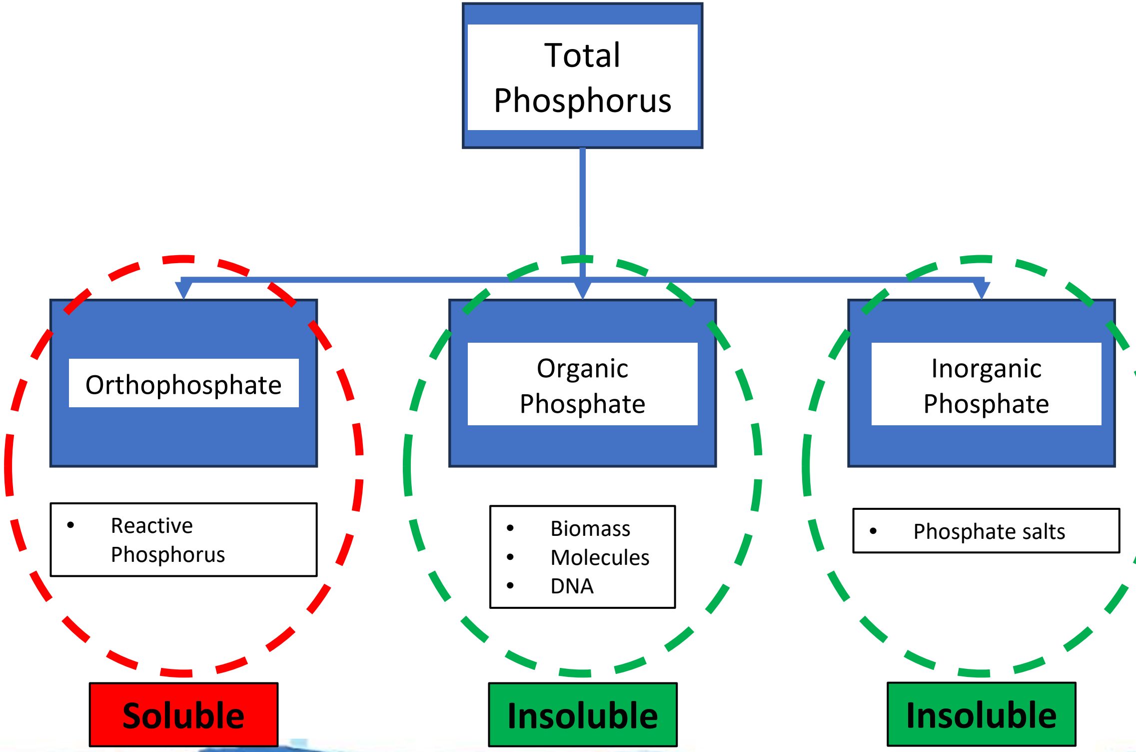
Agenda

- Phosphorus removal in water resource recovery facilities (WRRFs)
- Mauldin Road Overview
- Mauldin Road Phosphorus removal
- Operational improvements
- Dewatering and capital improvements

ReWa renewable water resources

Phosphorus removal

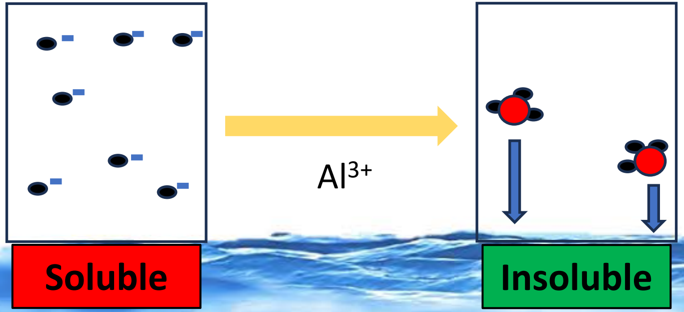
- Three major forms of phosphorus in domestic wastewater
- Ortho P:TP ratio is typically 50-80%
- Ortho P must be made insoluble to be removed using physical processes
- Two major processes to achieve this goal
  - Chemical coagulation
  - Biological phosphorus removal



Phosphorus removal

Chemical

- Strong negative (anion) charge keeps Ortho-P soluble
- Metal salts (cation) are added to neutralize Ortho-P charge
- Charge neutralization facilitates coagulation and allows for physical separation process



Phosphorus removal

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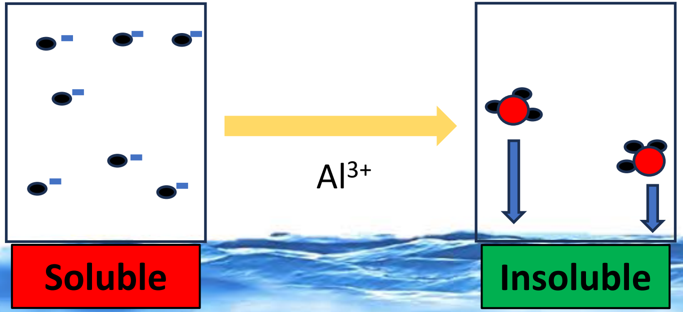
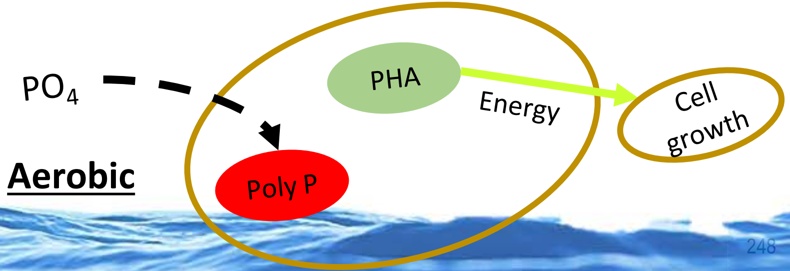
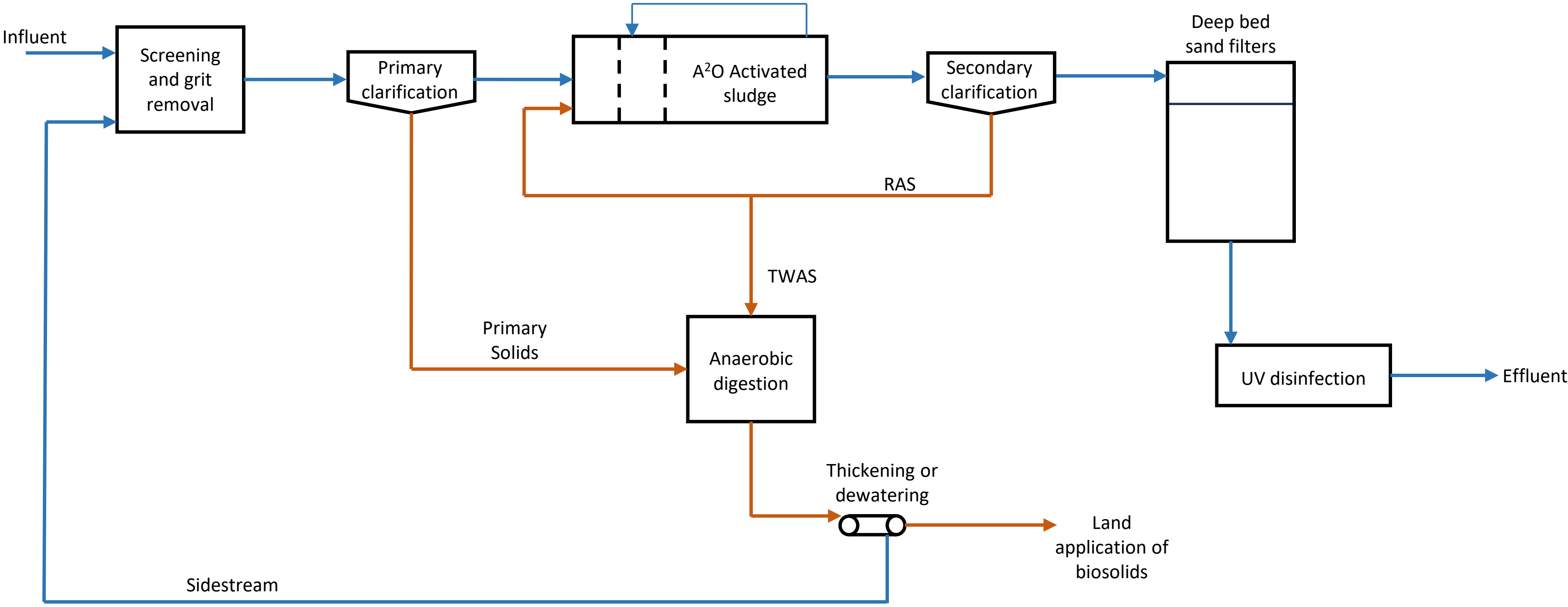


Biological

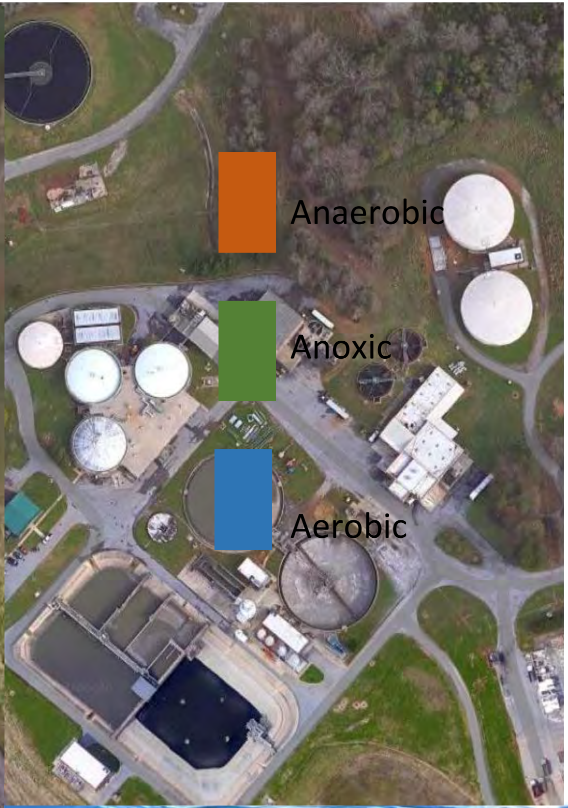
- Alternating metabolic conditions facilitates the growth of polyphosphate-accumulating organisms (PAO)
- **Anaerobic**: PAOs use a polyphosphate to store VFAs intracellularly.
- **Aerobic:** PAOs consume stored VFAs and uptake "extra" phosphorus to replenish polyphosphate stores



Mauldin Road flow diagram and overview

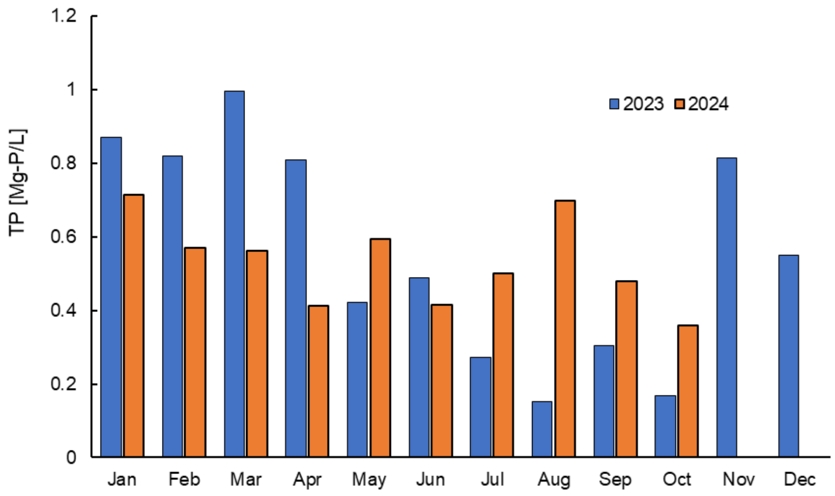


Mauldin Road- A2O



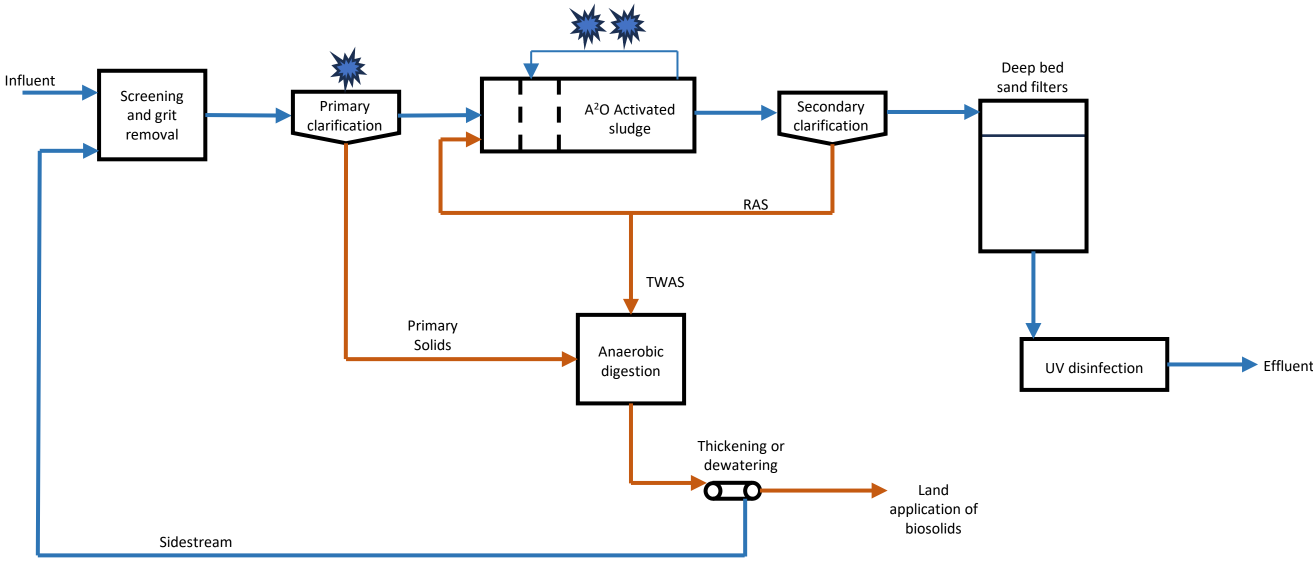
Mauldin Road Performance

- Current Permit
  - Flow: 29 MGD
  - TP: 1.3 mg-P/L monthly average
  - TN: MR
  - Sampled 7 days per week
- 2024 Performance
  - Average daily flow: 18.69 MGD
  - TP: 0.54 mg-P/L
  - TN: 12.03 mg-N/L
- Challenges
  - Currently liquid land apply but transitioning to cake application.
  - Seasonal variation
  - NPDES under review with potential to be significantly lower TP limit.



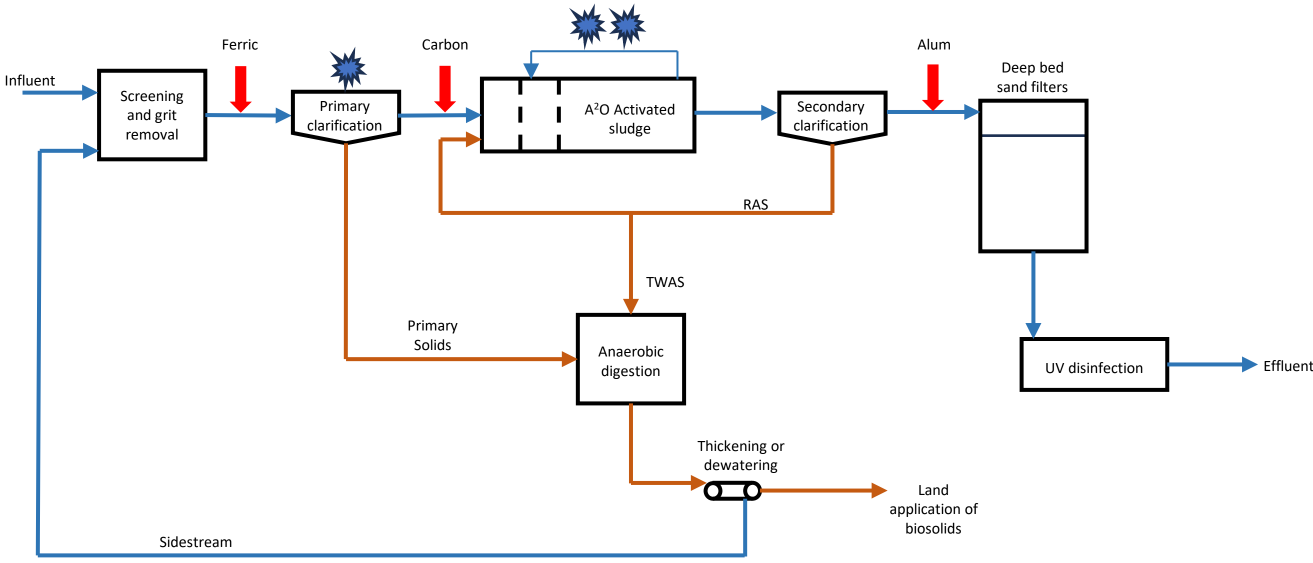
Mauldin Road: P-removal

- Mauldin Road influent TP
  - 6-10 mg/L
- “Free” TP removal at Mauldin Road
  - Primary clarification removes settleable TP (5-10%)
  - Biomass growth in activated sludge consumes TP (10-20%)
  - Enhanced biological TP removal (EBPR) can remove remaining depending on influent carbon.



Mauldin Road: P-removal

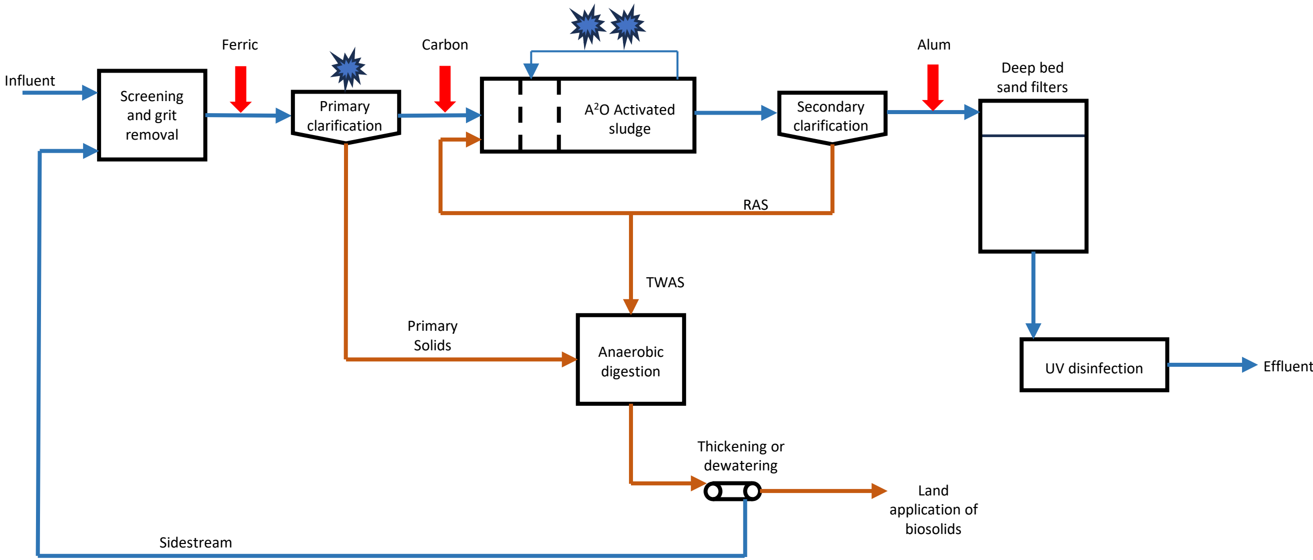
- EBPR is an unstable process and does not always remove enough TP.
- “Not free” backup TP removal at Mauldin Road
  - Addition of carbon to secondary treatment to improve EBPR.
    - Juice waste or acetic acid
  - Alum addition to remove ortho P in deep sand bed filters
  - Ferric addition to primary clarification to increase settable TP



Mauldin Road: Optimization

Optimization projects:

1. Primary clarifier operation
2. Alum feed optimization
3. Juice tank CIP project



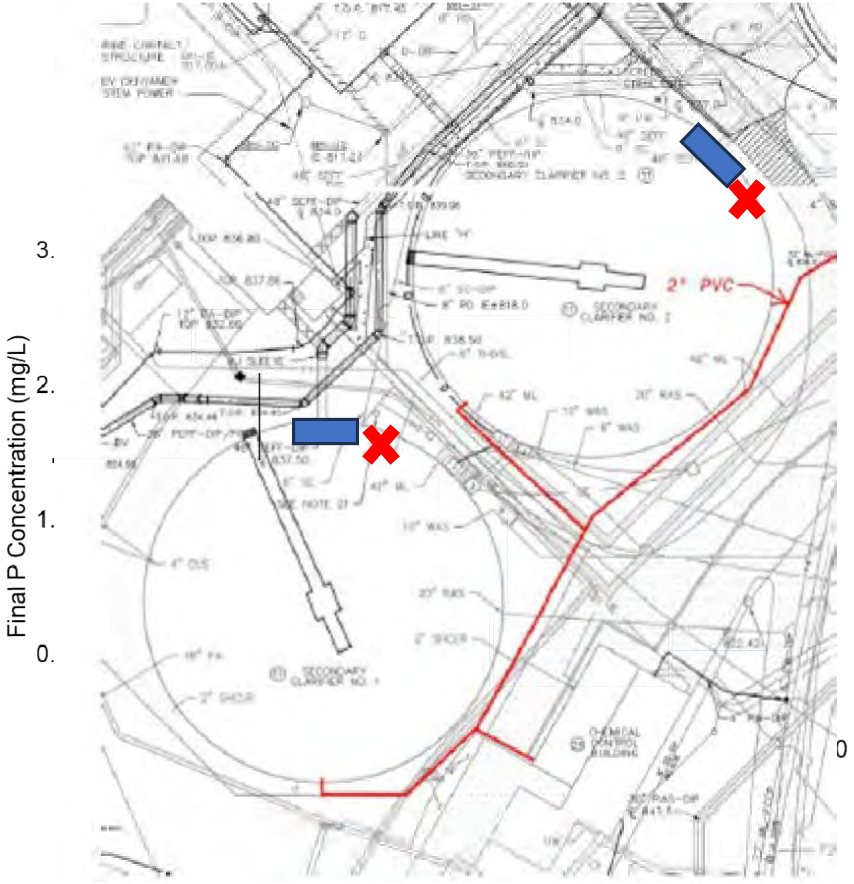
Primary clarifier operation

- Primary clarifiers remove settleable solids
- Operators can control solids residence time in the clarifier by altering the blanket depth
- Longer residence time improves fermentation and VFA generation
- Blanket depth shown to be correlated to EBPR performance
- Historical data analysis changed future clarifier operation

Alum feed optimization

Alum is fed at secondary clarifier effluent to turn soluble Ortho-P into insoluble aluminum phosphate.

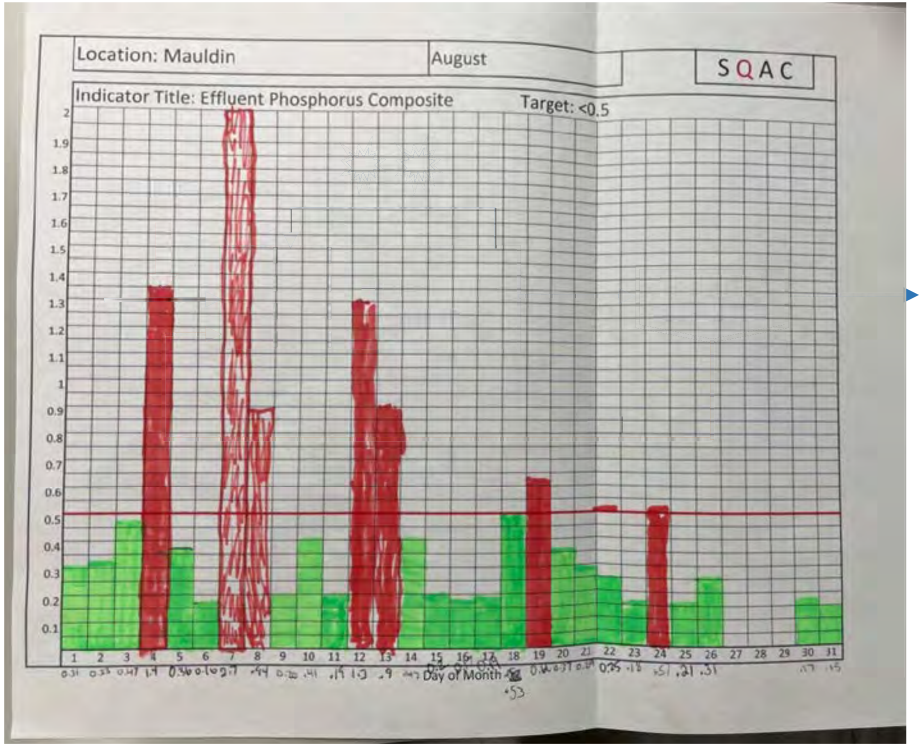
1. Conducted jar testing to determine dose required
2. Replaced oversized pump
3. Changed alum feed point
4. Conducted follow up dose testing
5. Capital project to rehab alum system



Juice feed CIP and operation

Additional carbon can be fed prior to secondary treatment to improve EBPR

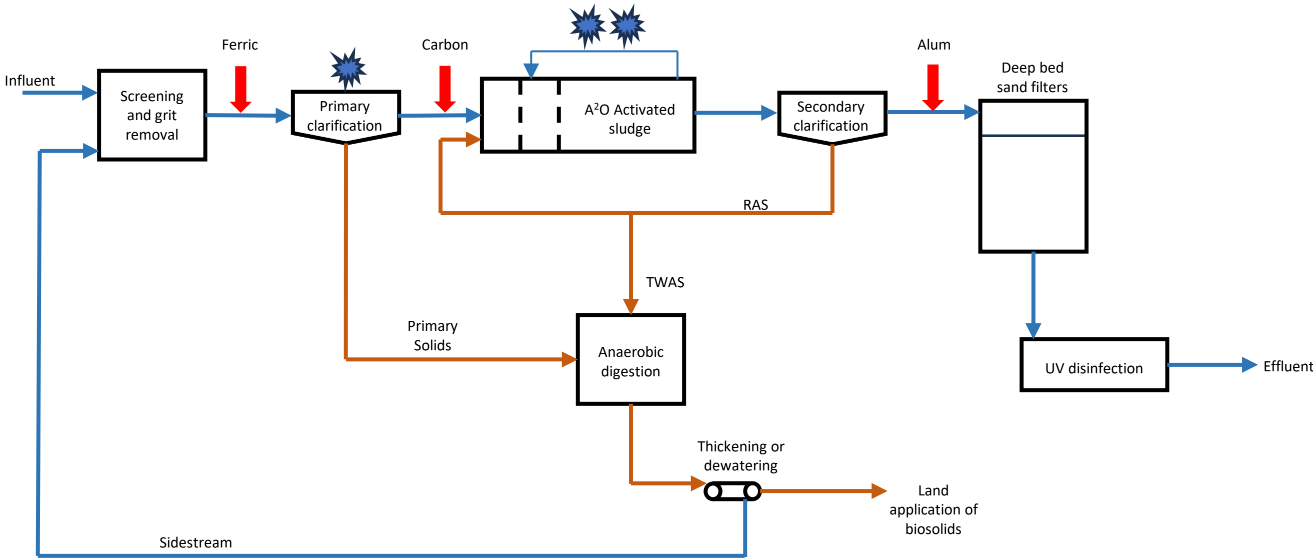
1. Conducted capital project to rehabilitate gravity thickener tank
2. Characterized juice waste to understand strength
3. Developed tracking system to determine juice dosing



Mauldin Road: Future optimization projects

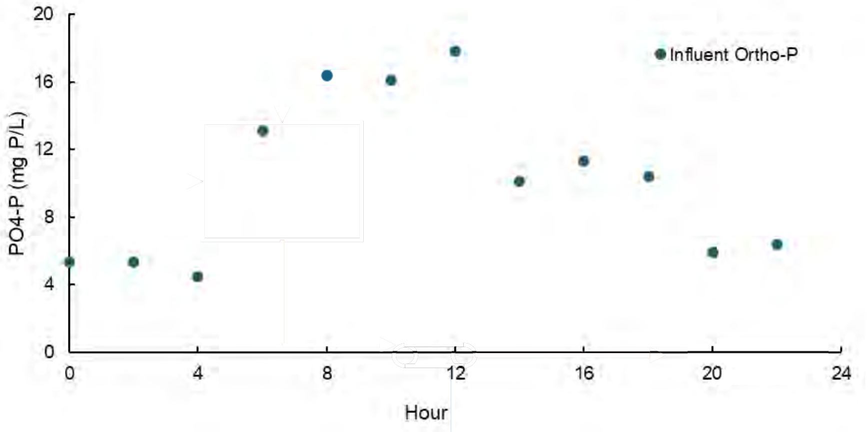
Future projects:

1. Develop process to trial beneficial wastes
2. Integrate solids fermentation into juice tank process (primary or WAS)
3. Optimize operation based on microbial study conducted by NC State



Transitioning to land application of Cake

- Mauldin Road is currently transitioning from land application of liquid biosolids (3-4%) to cake land application (18-20%)
- P loading from sidestream will significantly increased
- Hazen and ReWa partnered to build a dynamic BioWin model to understand how loading will impact EBPR process
- Hazen will recommend best strategy to mitigate EBPR overloading risk
  - Centrate EQ
  - Centrate treatment
  - Do nothing



Final Thoughts

1. EBPR is not a one size fits all treatment technology
    a. Many factors will impact the reliability of EBPR
2. Characterize the flow of phosphorus and carbon to create the best improvement strategy
3. Optimize **all** P-removal processes to ensure a robust and efficient treatment system
    a. Take an operations first approach to improvement
4. Leverage creative solutions to improve the stability of EBPR such as external carbon and/or fermentation

Coffee Break Sponsor

Diagnosing & Responding to Enhanced Biological Phosphorus Removal Upsets

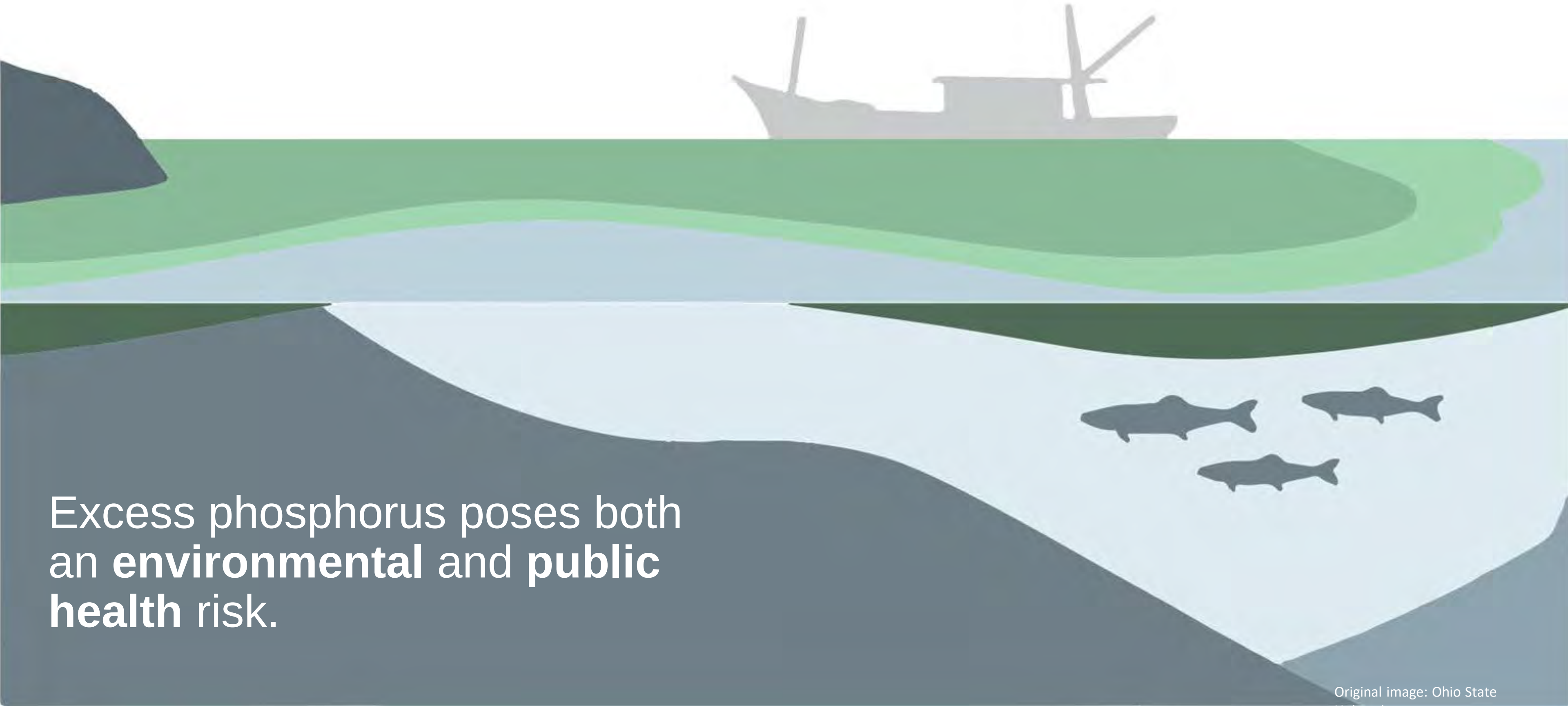
Roland Cusick
Associate Professor
University of Illinois, Urbana-Champaign

Developing modeling tools to understand the benefits of sidestream phosphorus precipitation

Ro Cusick
Pronouns: they/them
Associate Professor
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

2025 Phosphorus Forum
September 18th, 2025

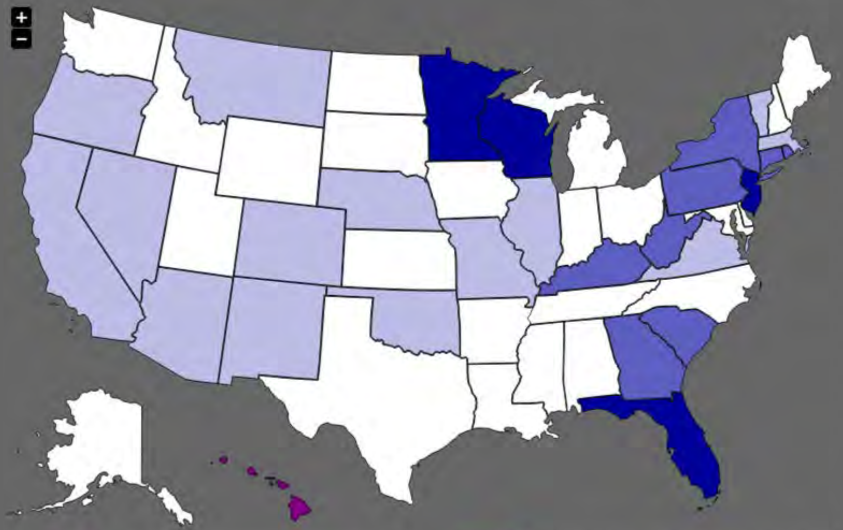
I ILLINOIS


Excess phosphorus poses both an **environmental** and **public health** risk.
Original image: Ohio State

NPDES nutrient discharge limits have created incentive for P recovery at Water Resource Recovery Facilities (WRRFs)

States with Total Nitrogen or Total Phosphorus Criteria

1998 | 2008 | 2013 | 2014 | 2015 | Current | 2016* | 2017* | 2018* | 2019*



(white)	District of Columbia
(purple)	American Samoa
(purple)	Commonwealth of Northern Marianas
(purple)	Guam
(blue)	Puerto Rico
(purple)	US Virgin Islands

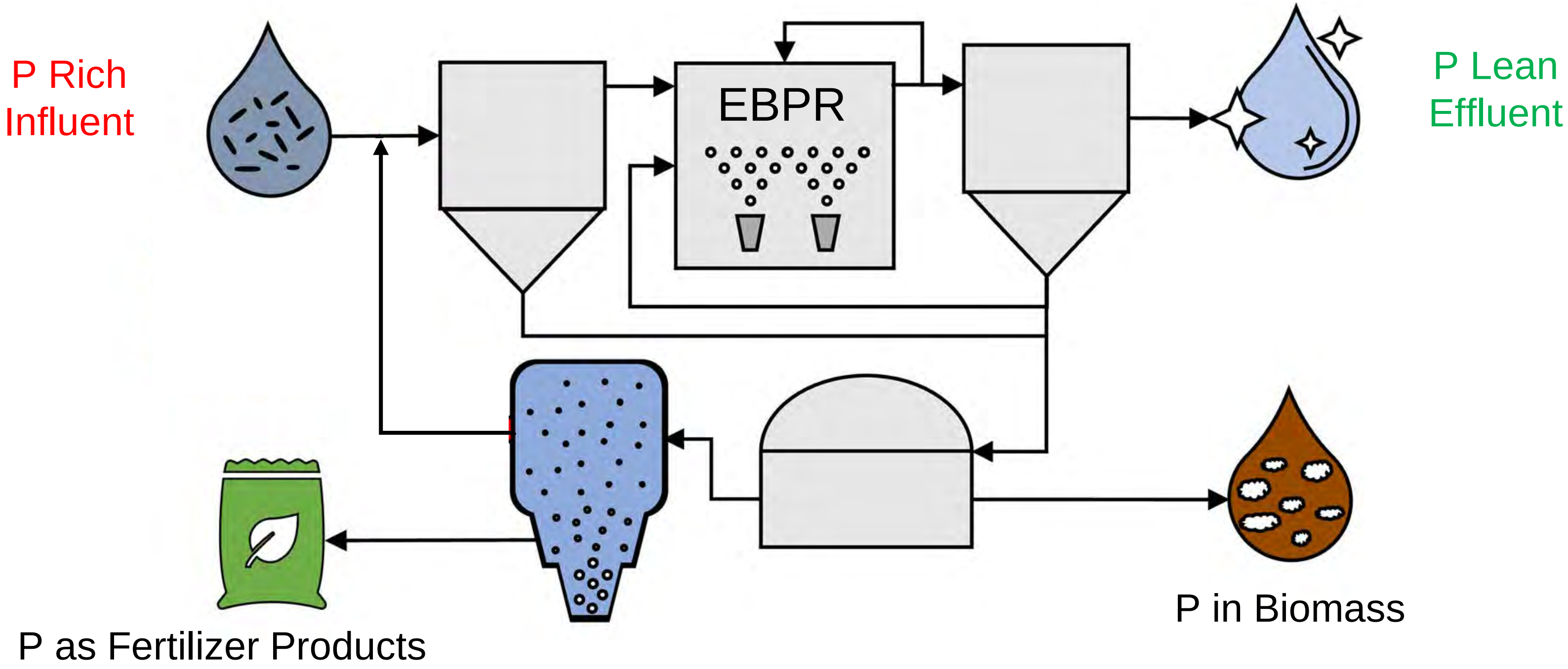
Level 5	Complete set of N and P criteria for all watertypes**
Level 4	2 or more watertypes with N and/or P criteria
Level 3	1 watertype with N and/or P criteria
Level 2	Some waters with N and/or P criteria
Level 1	No N and/or P criteria

* Progress expected by December 31st of the selected year based on milestone information provided by the state or territory.

** "Watertypes" on the national maps and tables within this webpage refers to three watertypes: *lakes/reservoirs, rivers/streams, and estuaries*. Criteria for additional watertypes are included under the State/Territory Details tab.

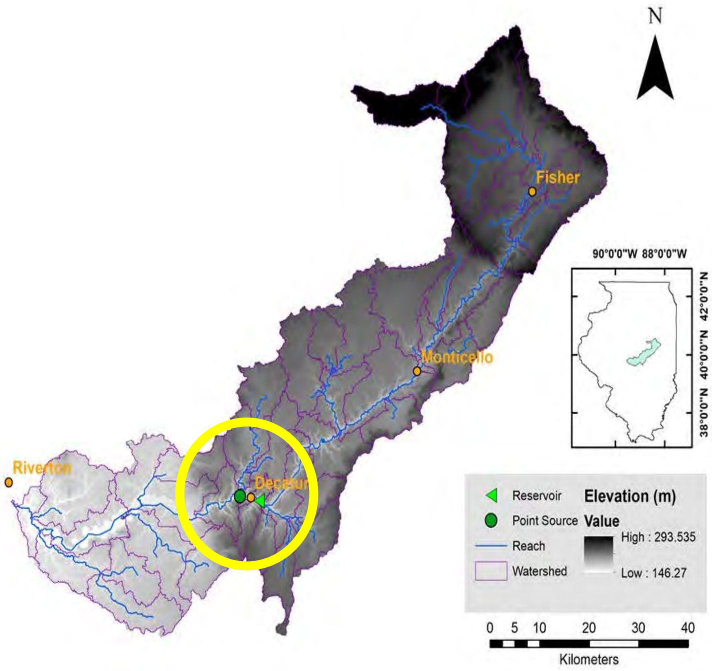
epa.gov

Coupling Enhanced Biological Phosphorus Removal (EBPR) to Struvite precipitation enables P recovery at WRRFs

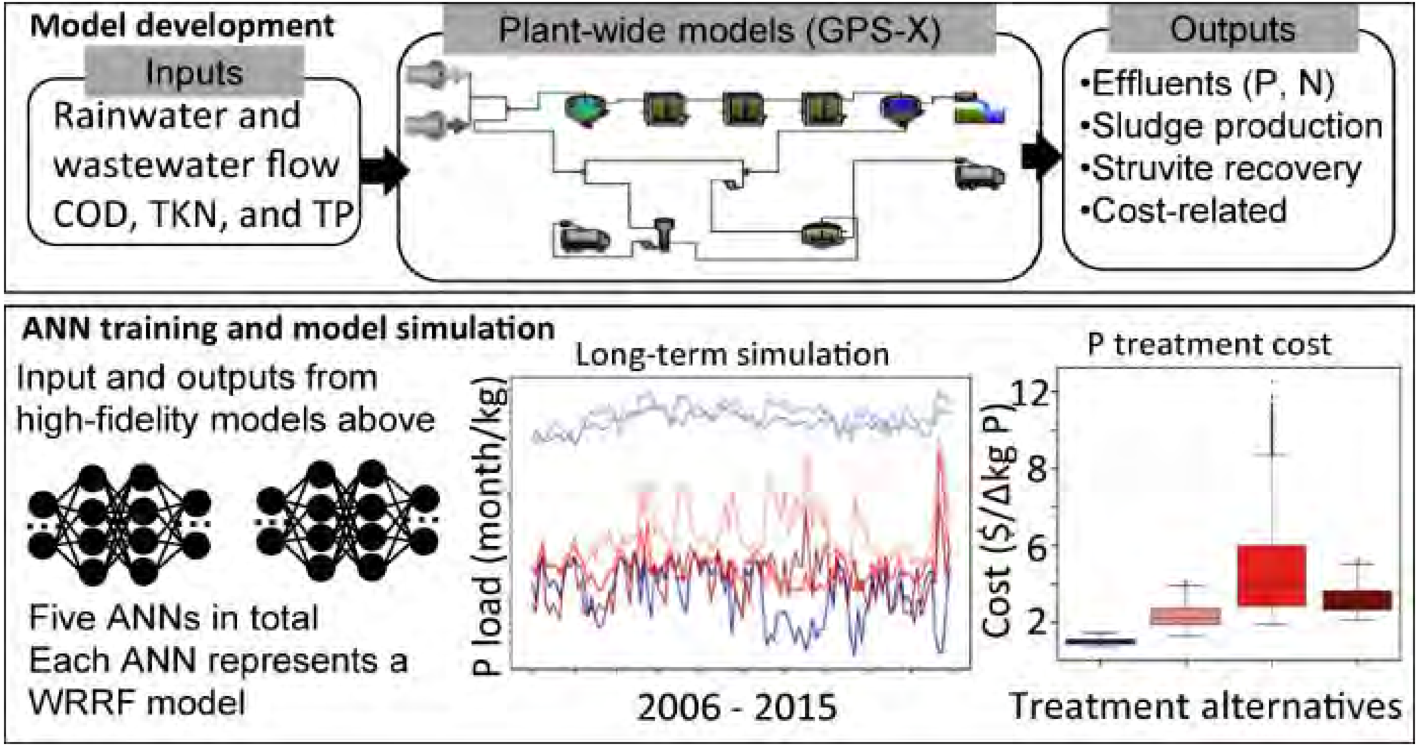


SDD is the primary point source in the Upper Sangamon Watershed

Sanitary District of Decatur



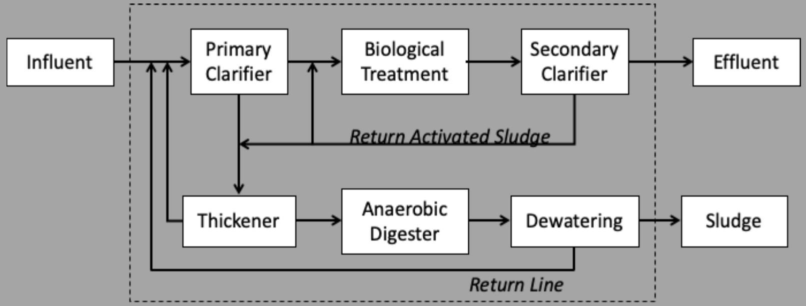
We developed Surrogate ANN Models for different SDD Treatment Scenarios to quantify the benefits of sidestream Struvite



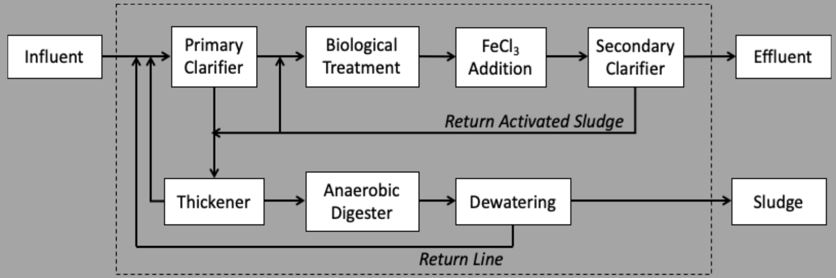
S. Li et. al, *ES&T Eng.* 2021

Simulated Wastewater Treatment and Nutrient Recovery Layouts

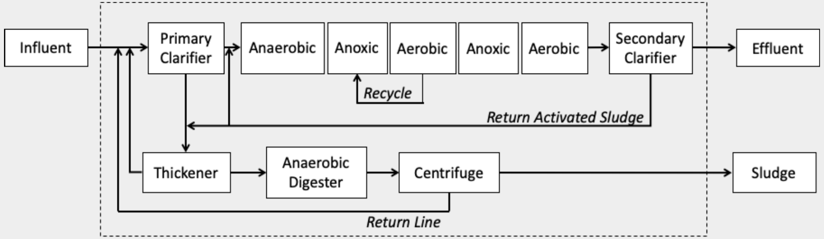
Activated Sludge (AS)



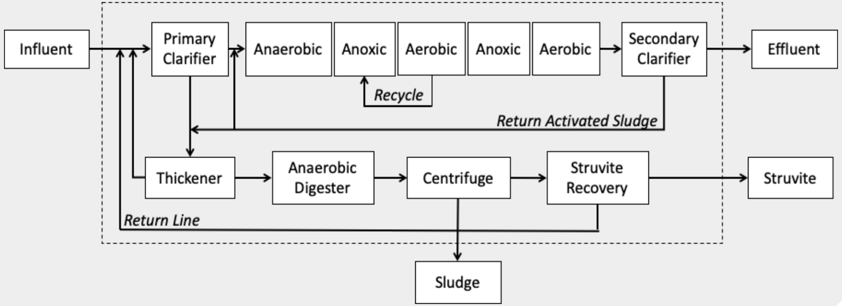
Activated Sludge with Chemical Precipitation (ASCP)



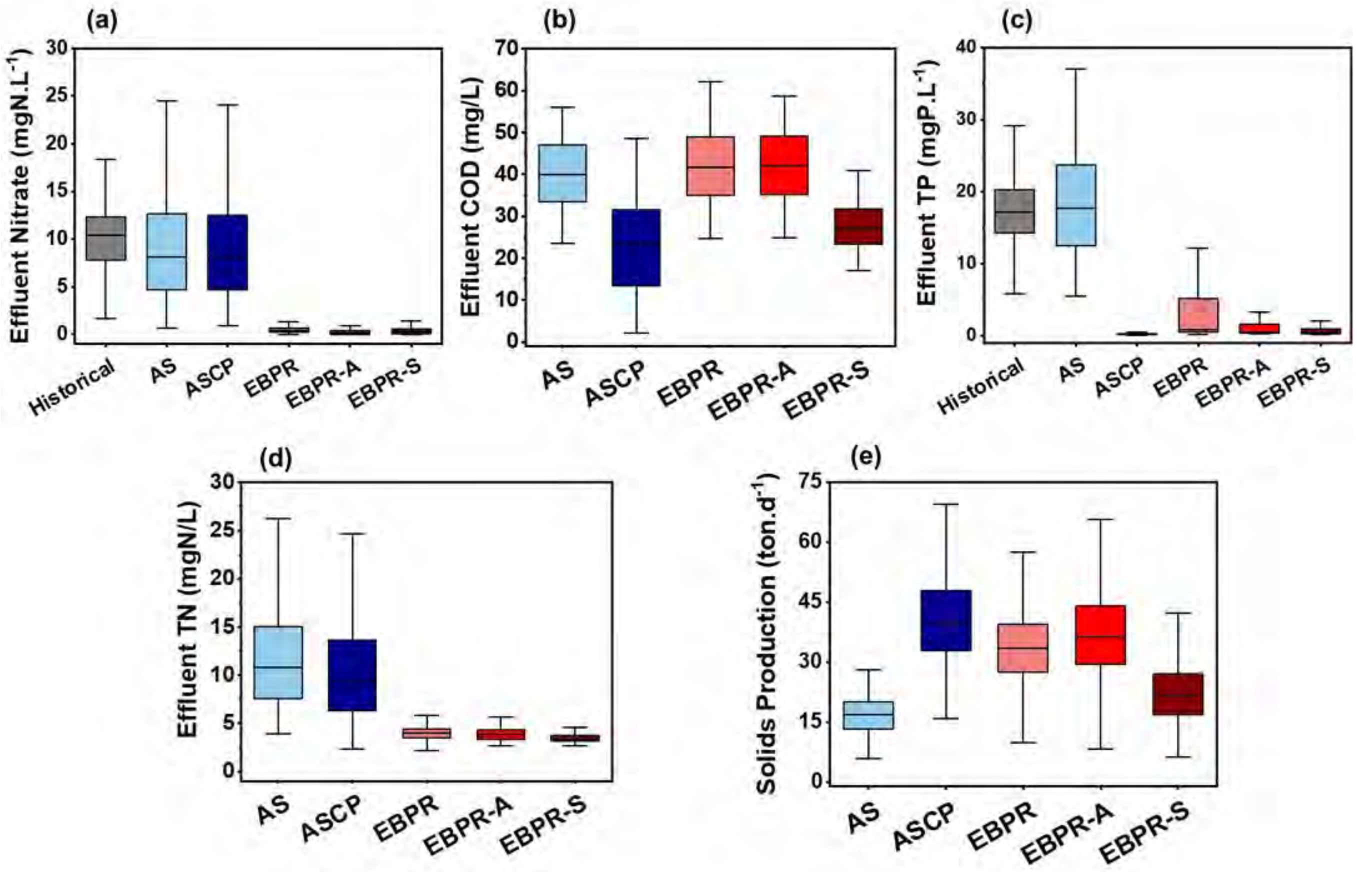
Modified-Bardenpho Enhanced Biological Phosphorus Removal (EBPR)



Modified-Bardenpho Enhanced Biological Phosphorus Removal with Struvite Recovery (EBPR-S)

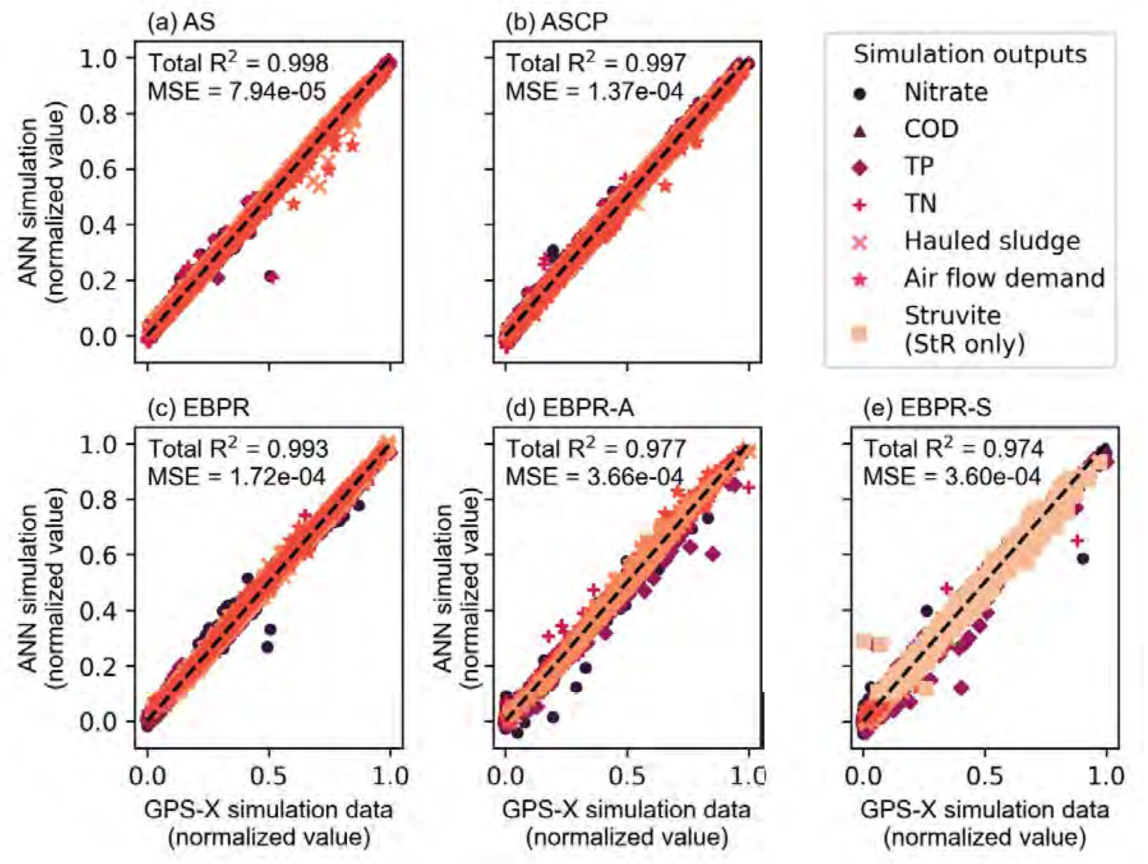


Plantwide simulation results highlighted the benefits of sidestream P



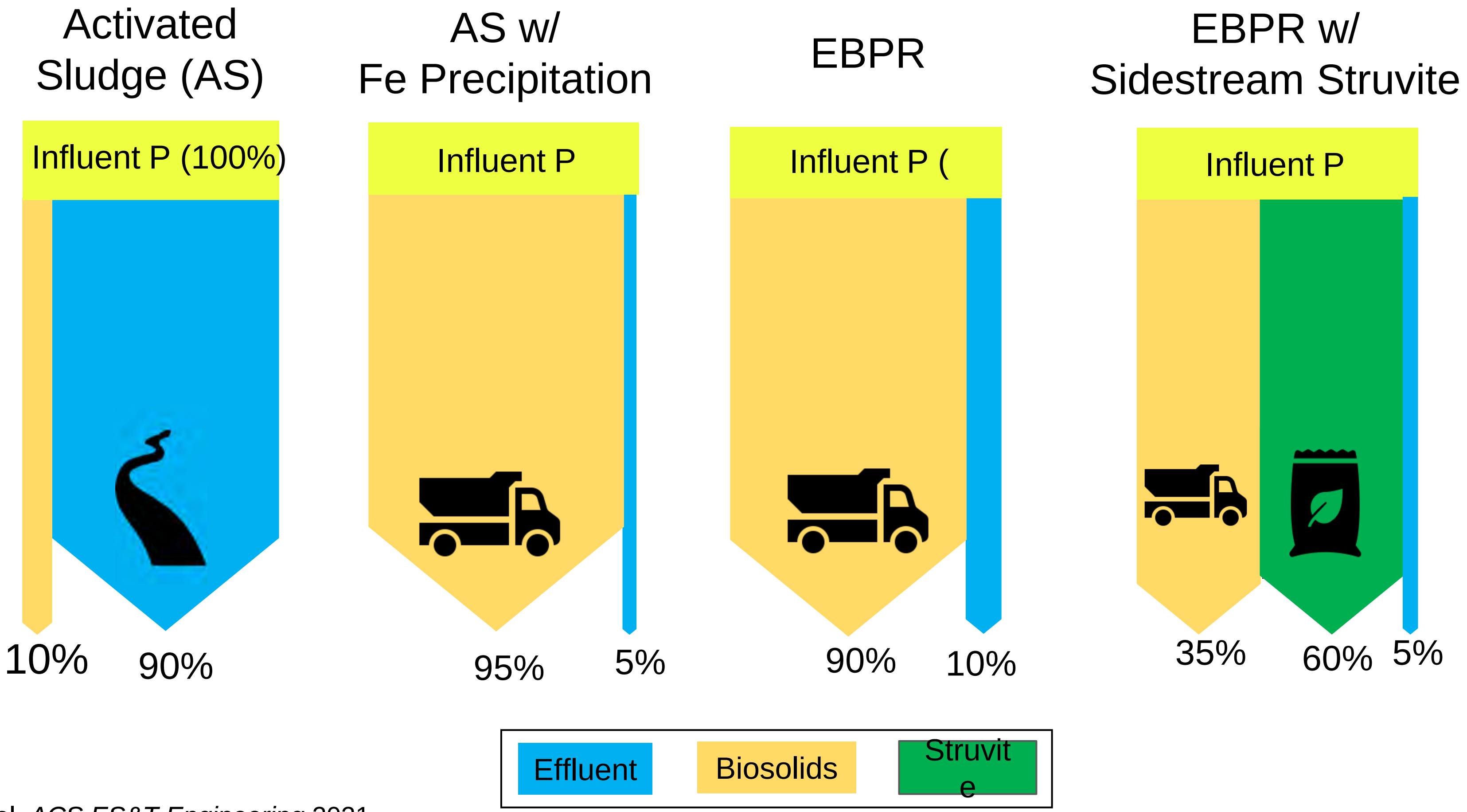
S. Li et. al, *ES&T Eng.* 2021

Trained ANNs were accurate surrogate models for each plant layout



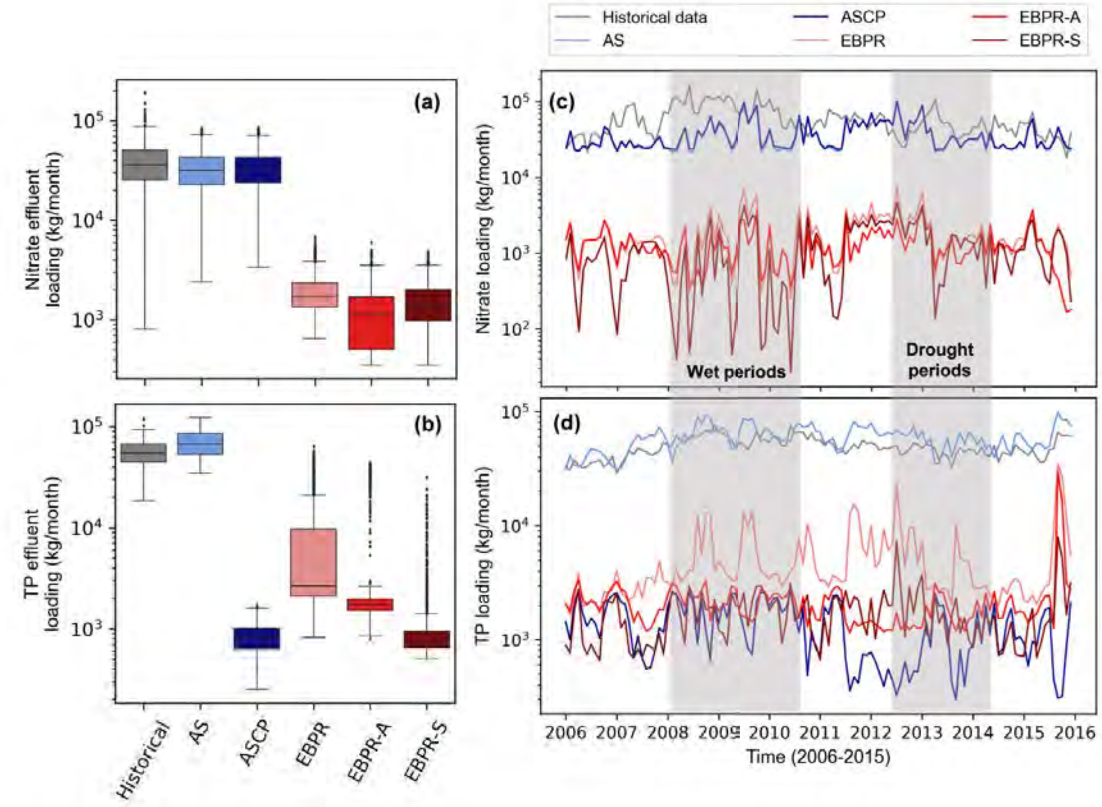
S. Li et. al, *ES&T Eng.* 2021

Plantwide models indicate that the majority of influent P can be recovered as struvite

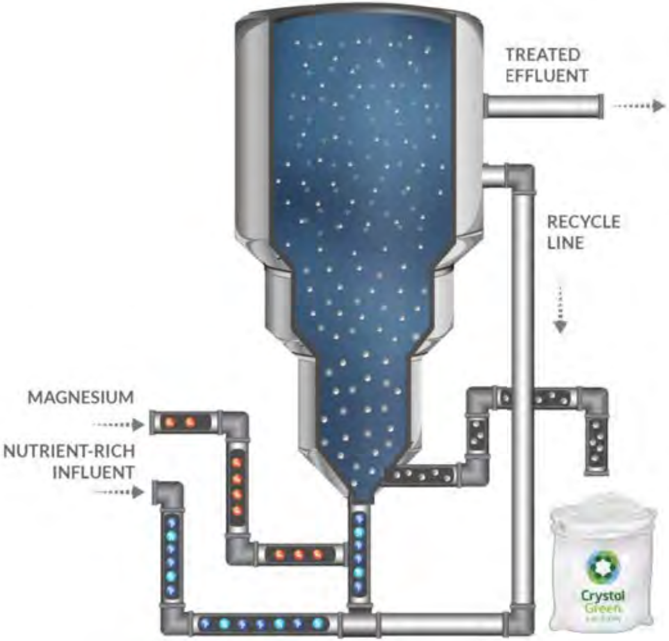


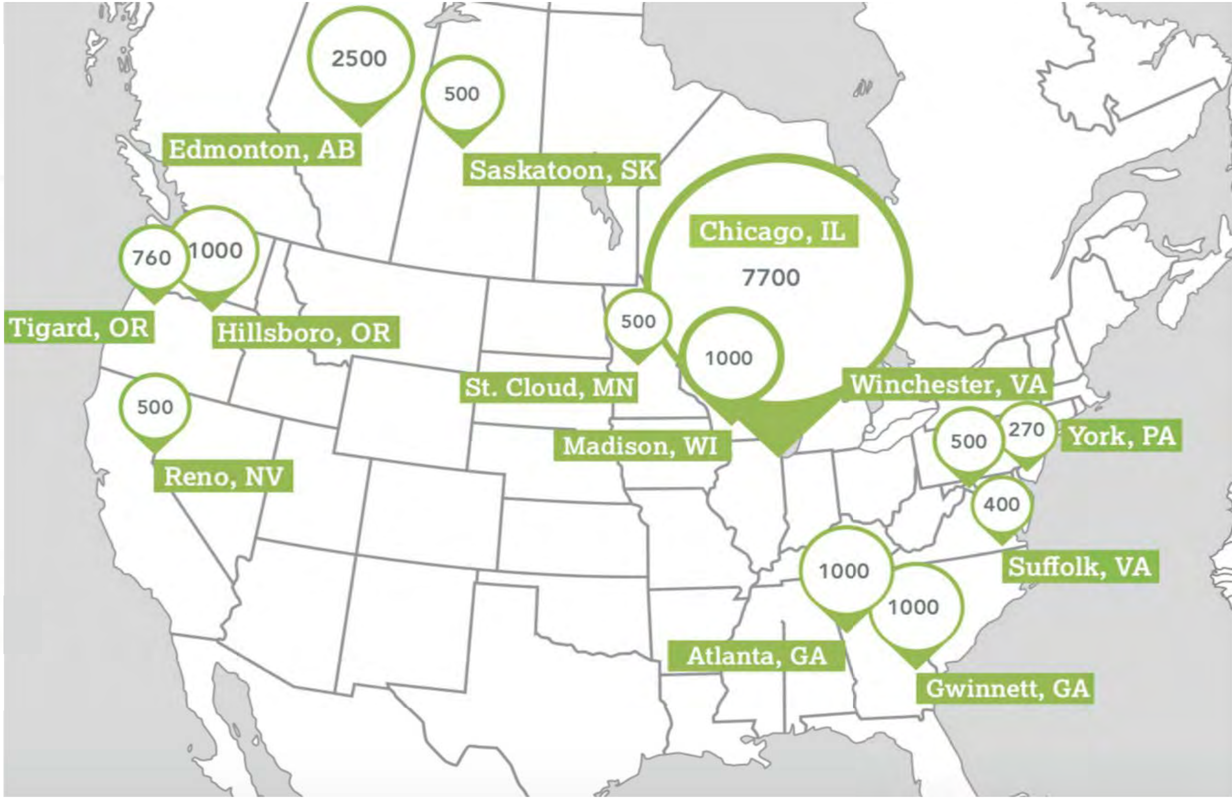
S. Li et al. *ACS ES&T Engineering* 2021

Long-term simulation with ANNs indicates that EBPR-S is most stable and effective for both N and P removal



S. Li et. al, *ES&T Eng.* 2021

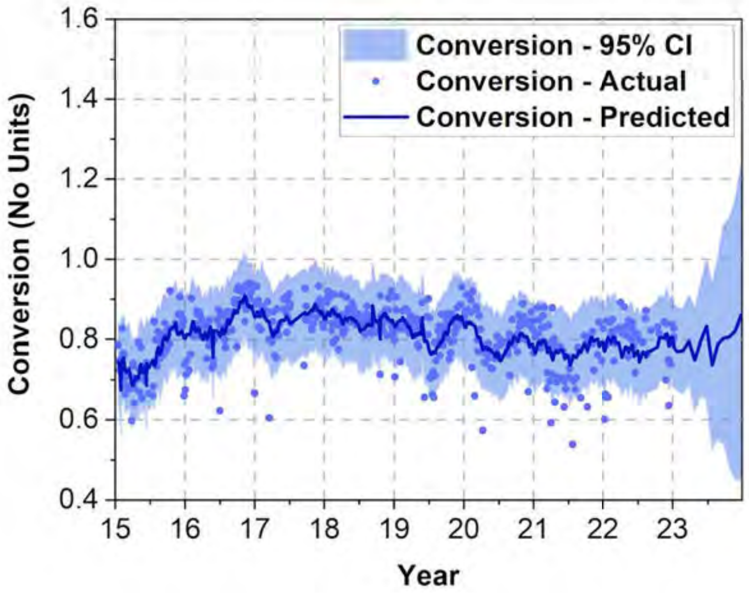

TREATED
EFFLUENT
RECYCLE
LINE
MAGNESIUM
NUTRIENT-RICH
INFLUENT
Crystal
Green

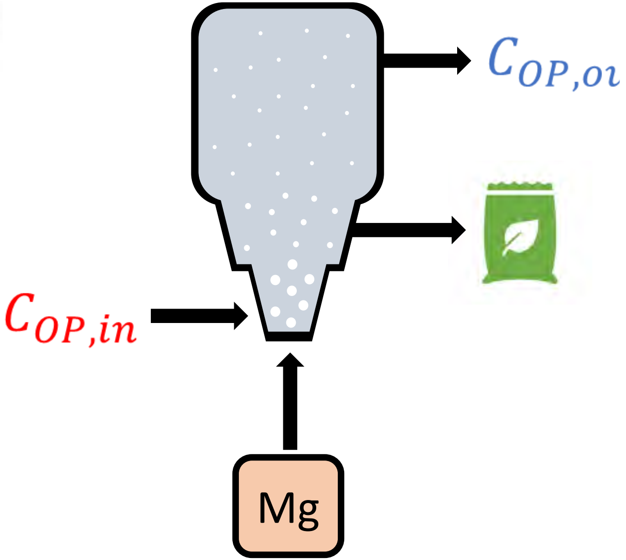

2500
Edmonton, AB
500
Saskatoon, SK
760
1000
Tigard, OR
Hillsboro, OR
Chicago, IL
7700
500
1000
St. Cloud, MN
Winchester, VA
500
Reno, NV
Madison, WI
500
270
York, PA
400
Suffolk, VA
1000
1000
Atlanta, GA
Gwinnett, GA

Reactor Performance: Conversion (P Removal)

% of soluble P converted to a solid form

$$Conversion = \left(\frac{C_{OP,in} - C_{OP,out}}{C_{OP,in}}\right) * 100$$

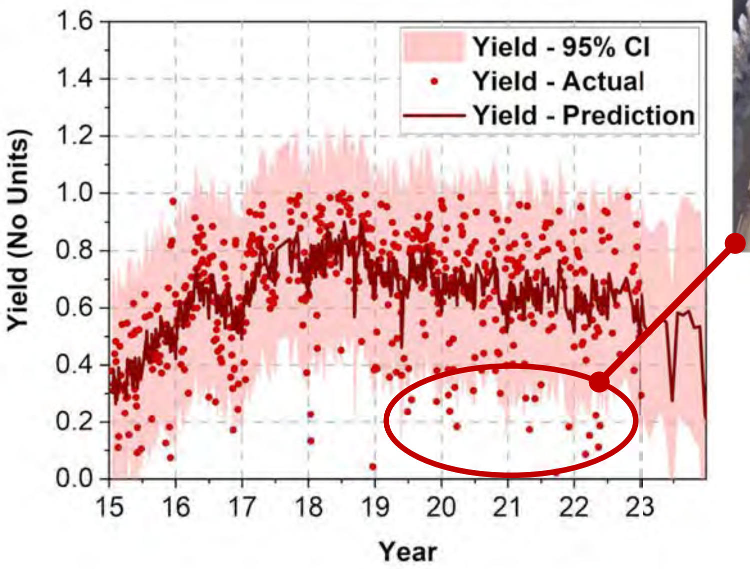


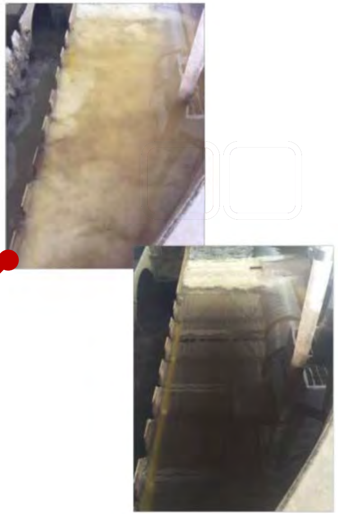


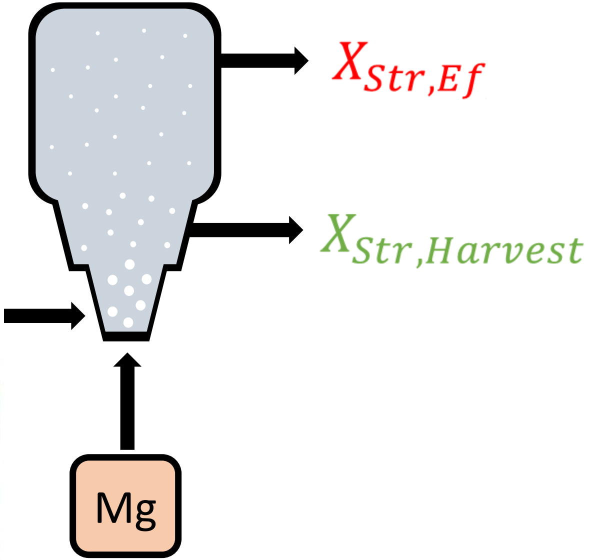
Reactor Performance: Yield (P Recovery)

$$Yield = \left(\frac{X_{Str,Harvest}}{X_{Str,Eff} + X_{Str,Harvest}}\right) * 100$$

Captured struvite relative to total struvite formed







Low Struvite yield is frequently reported for pilot and full-scale reactors

% Conversion	% Yield	Reference
DNR	8-82	Cubbage (2011)
90*	60-83	Cullen (2013)
28-71	38-80	Grooms (2015)
60 - 80	14-54	Hardy (2016)
80*	12-48	Kucek (2017)

*Estimated

Cullen, N.; Baur, R.; Schauer, P. Three Years of Operation of North America's First Nutrient Recovery Facility. *Water Sci Technol* **2013**, *68* (4), 763–768. https://doi.org/10.2166/wst.2013.260.

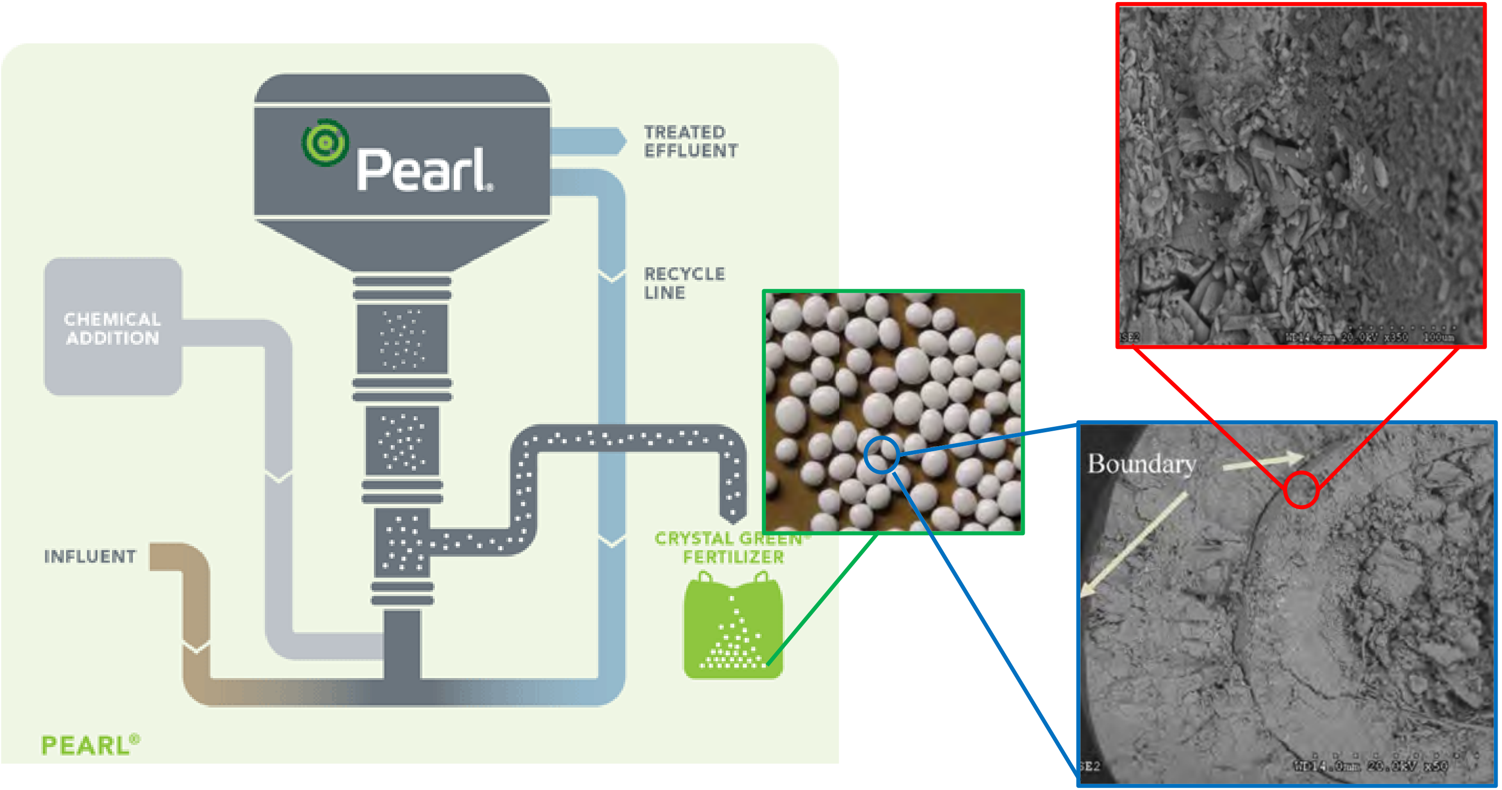
Cubbage, L.; Bilyk, K.; Stone, A.; Pitt, P.; Flowers, L.; Dano, J.; Balzer, W.; Bott, C.; Dharas, A.; Britton, A. A Green Alternative for Dissolved Nutrient Recovery in Wastewater Sidestreams; Water Environment Federation, 2011; Vol. 2011.

Hardy, S.; Brown, B.; Nguyen, V.; McCallum, E.; Latimer, R.; Bullard, M.; Harris, R.; Lan, J. C.; Richards, T. Nutrient Recovery at the F. Wayne Hill Water Resources Center: Wasstrip Design and Full Scale Start Up. In *Proceedings of the Water Environment Federation*; Water Environment Federation, 2016; Vol. 2016.

Grooms, A.; Reusser, S.; Dose, A.; Britton, A.; Prasad, R. Operating Experience with Ostara Struvite Harvesting Process. In *Proceedings of the Water Environment Federation*; Water Environment Federation, 2015; Vol. 2015.

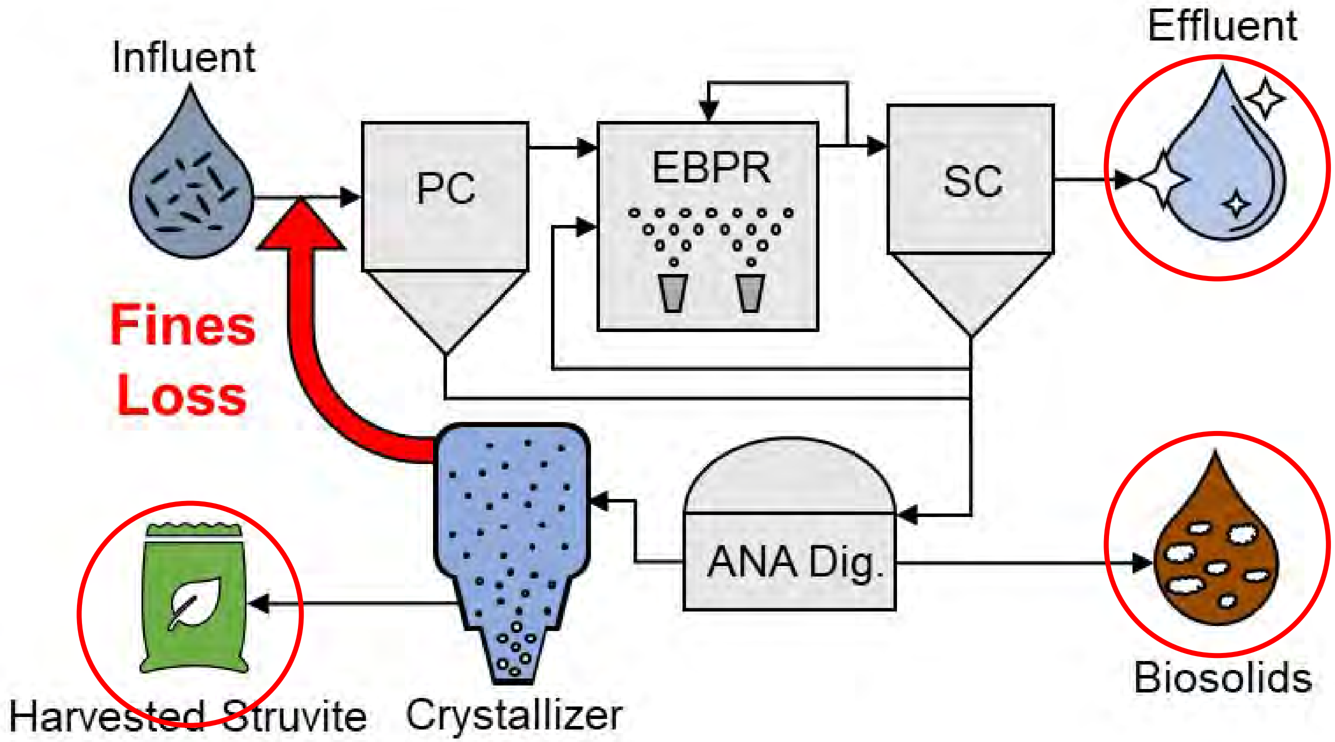
Kucek, L. A.; Grooms, A. L.; Ericson, W. A. Phosphorus Recovery at the Madison MSD: Turning Lemons into Lemonade; Water Environment Federation, 2017.

Pelletized aggregates are actually aggregates of fine struvite crystals

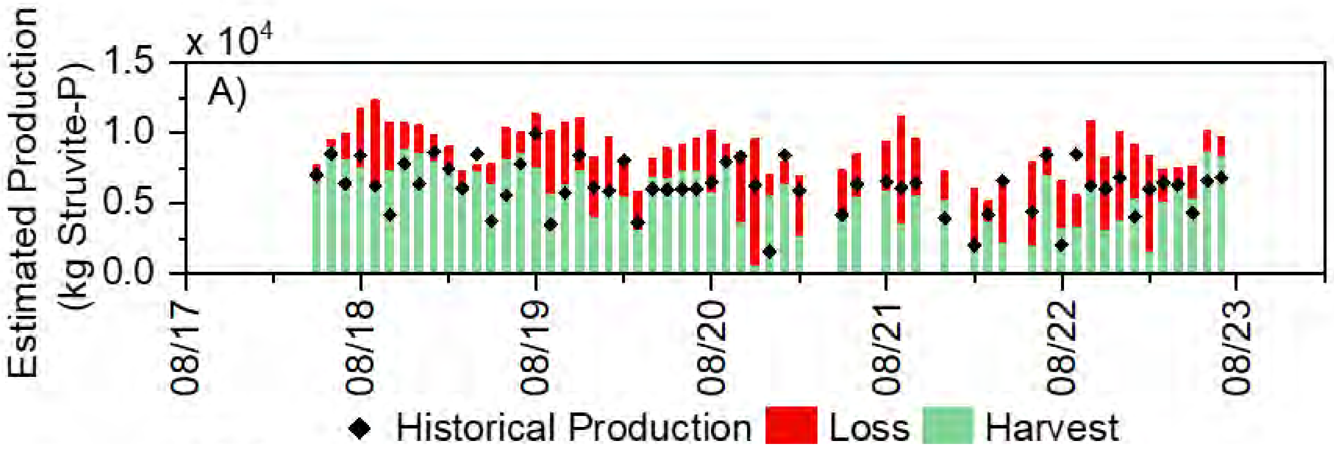


Grain boundaries indicate that solution composition changes can impact crystallization and agglomeration

How Does Fines Loss Impacts Plantwide P Distribution?

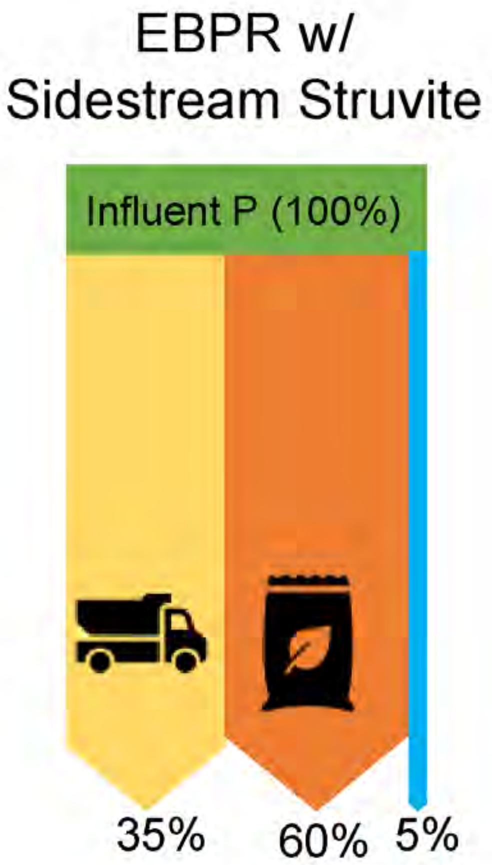


Low Yield events can impact of Mainline P Treatment

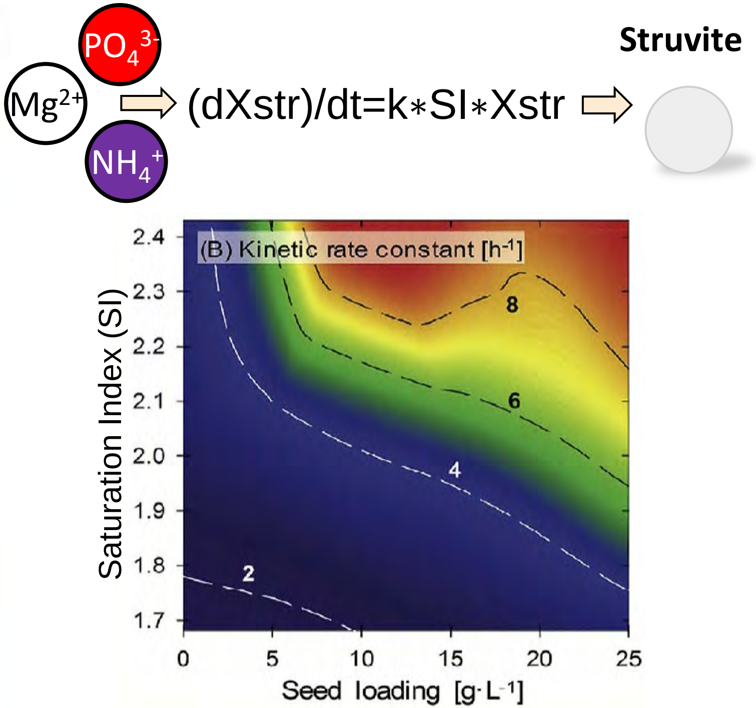


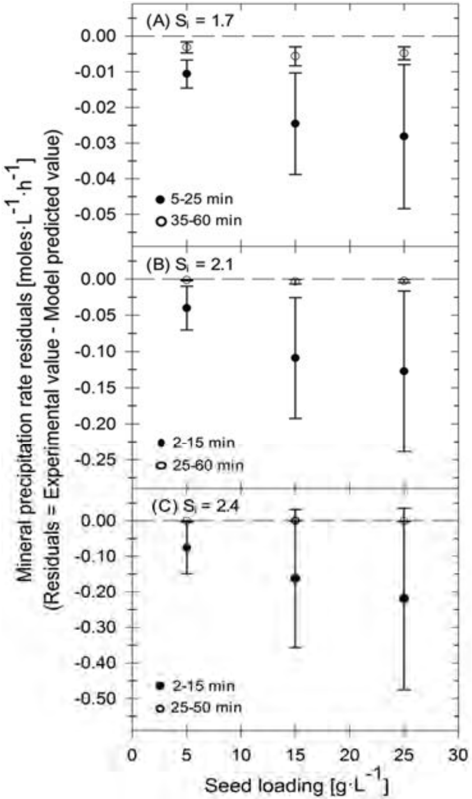
Aguiar et al. (in revision)

Current Precipitation Models Neglect Particle Size



ASM Style Models

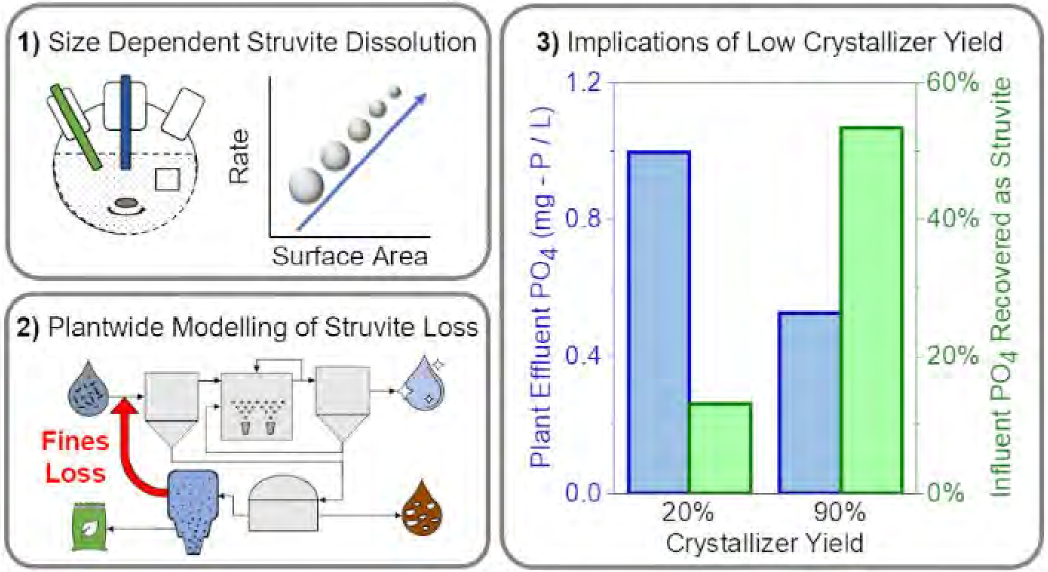




Mass based model is violated under realistic conditions

Agrawal, Guest, and Cusick. *Wat. Res.* (2018)

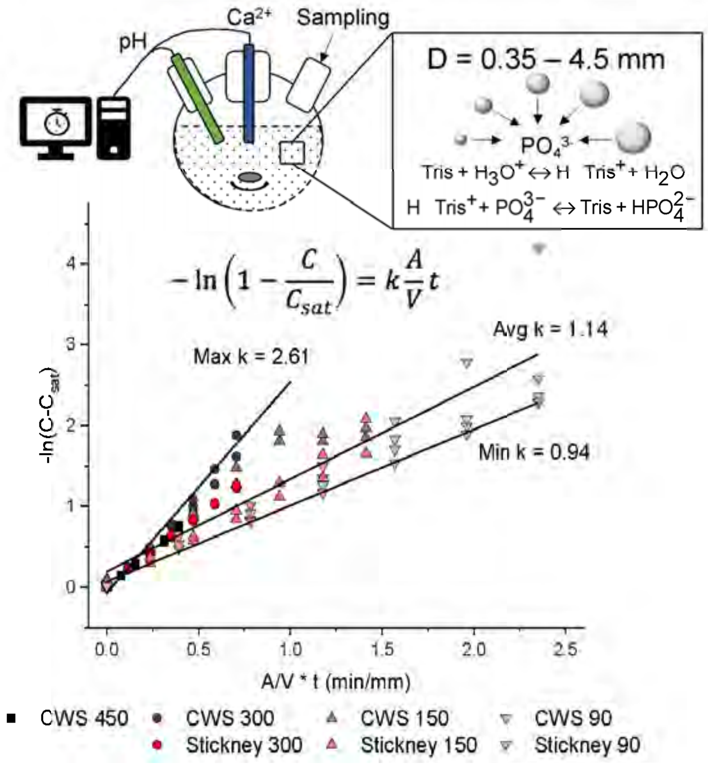
Modeling the plantwide impacts of side stream recovery

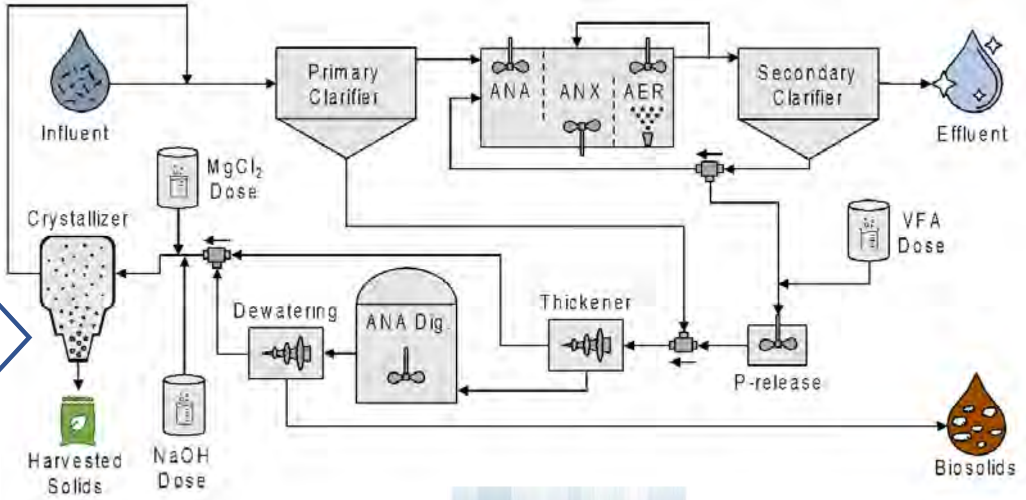


S. Aguair et al. *ES&T Engineering* 2022

Integrating particle population balance models into plantwide simulators helps to quantify size dependent impacts of struvite loss

Struvite Dissolution Kinetics



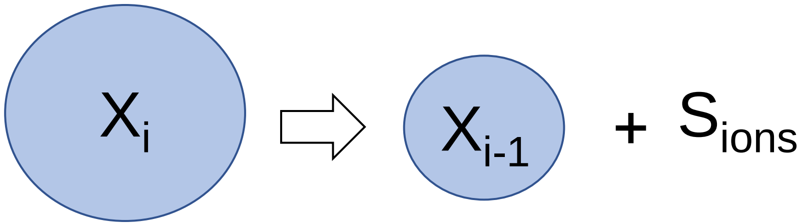


SUMO

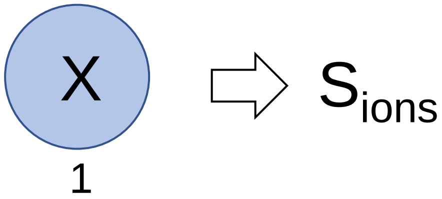
S. Aguair et al. *ES&T Engineering* 2022

SUMO PSD SETUP - Generalized Functions

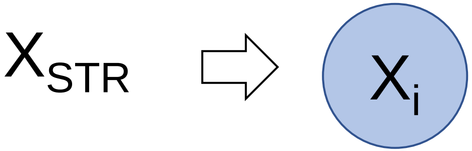
Particle to Particle Dissolution



Particle to Solubles Dissolution



State Variable Conversion



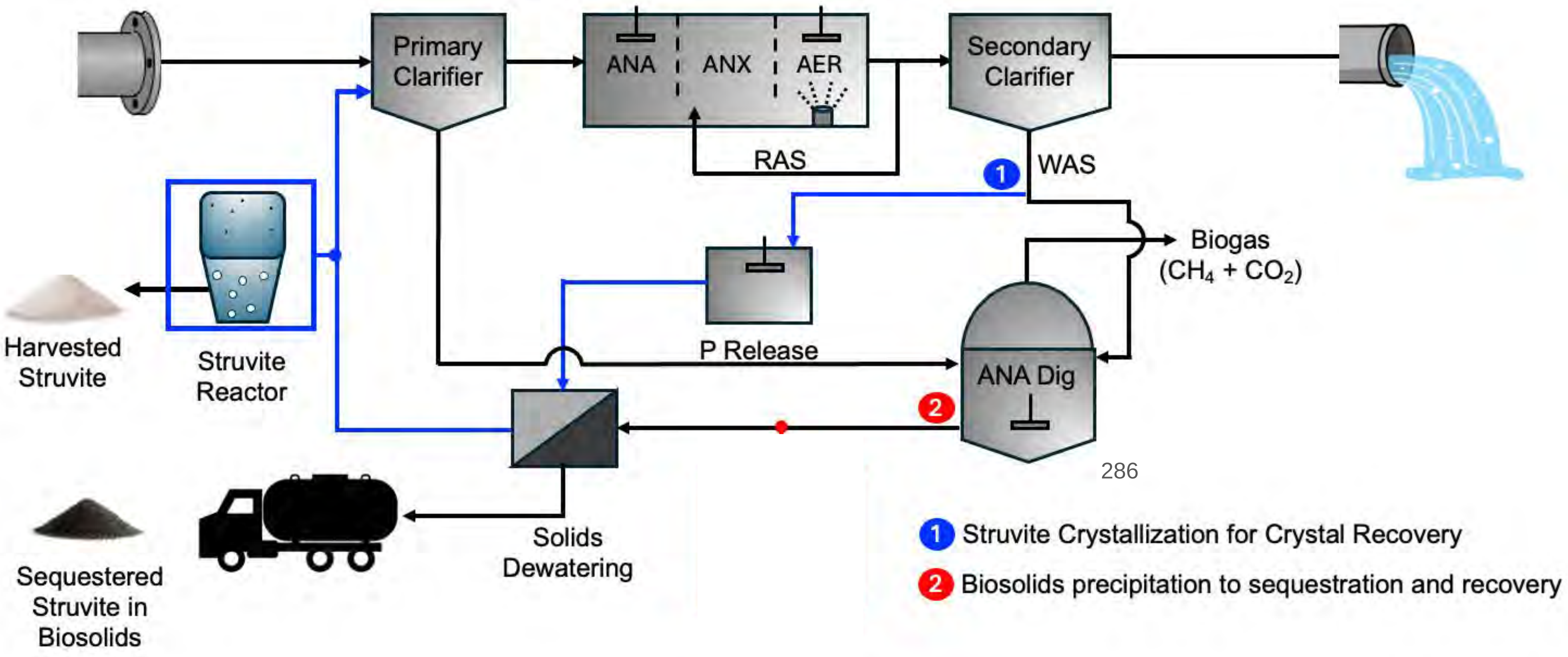
<u>User Inputs</u>

- N – Number of particles
- Size Range

Incorporating PSD revealed the impact of struvite size and yield on dissolution rate and effluent quality

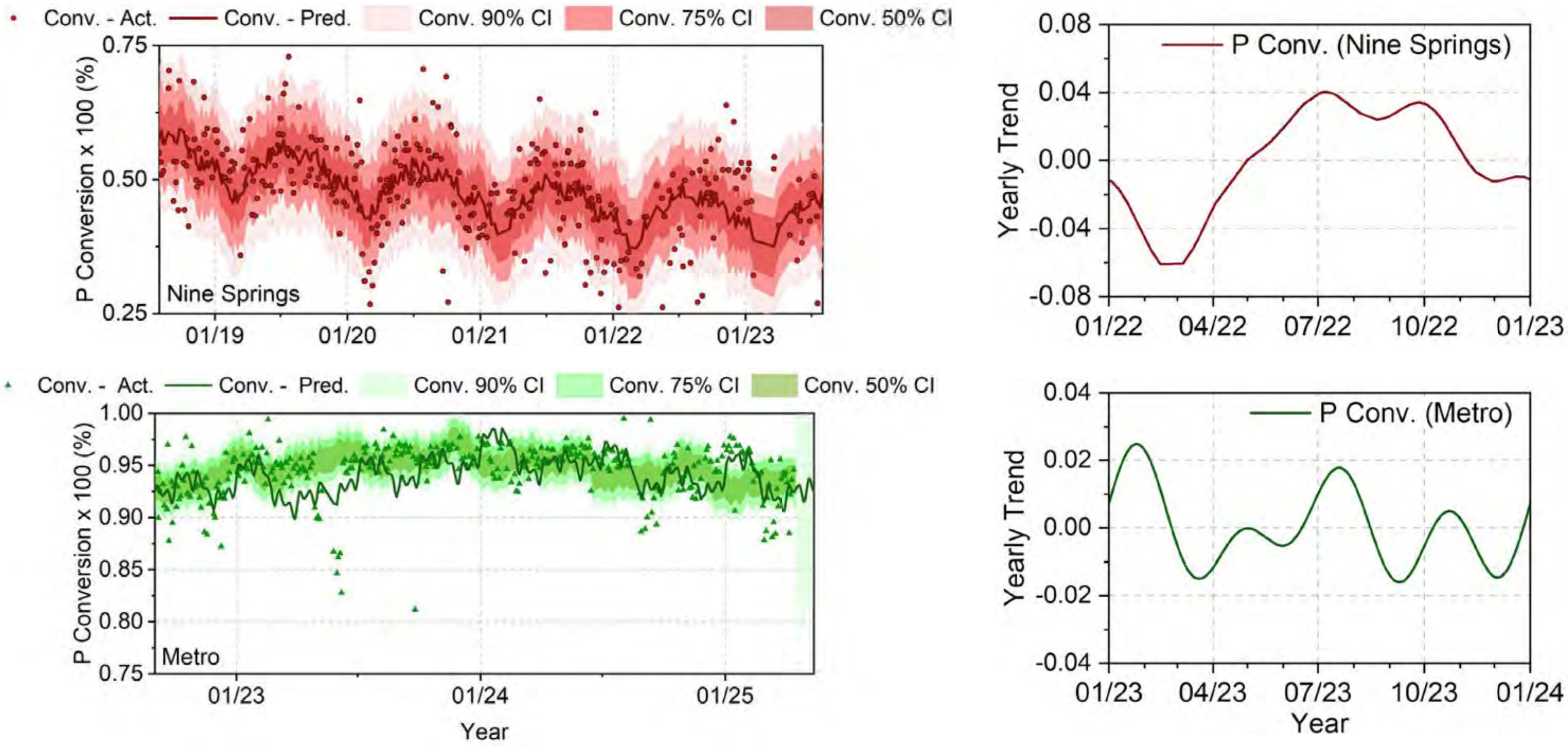
S. Aguair et al. *ES&T Engineering* 2022

Which approach to struvite precipitation is best for the utility?

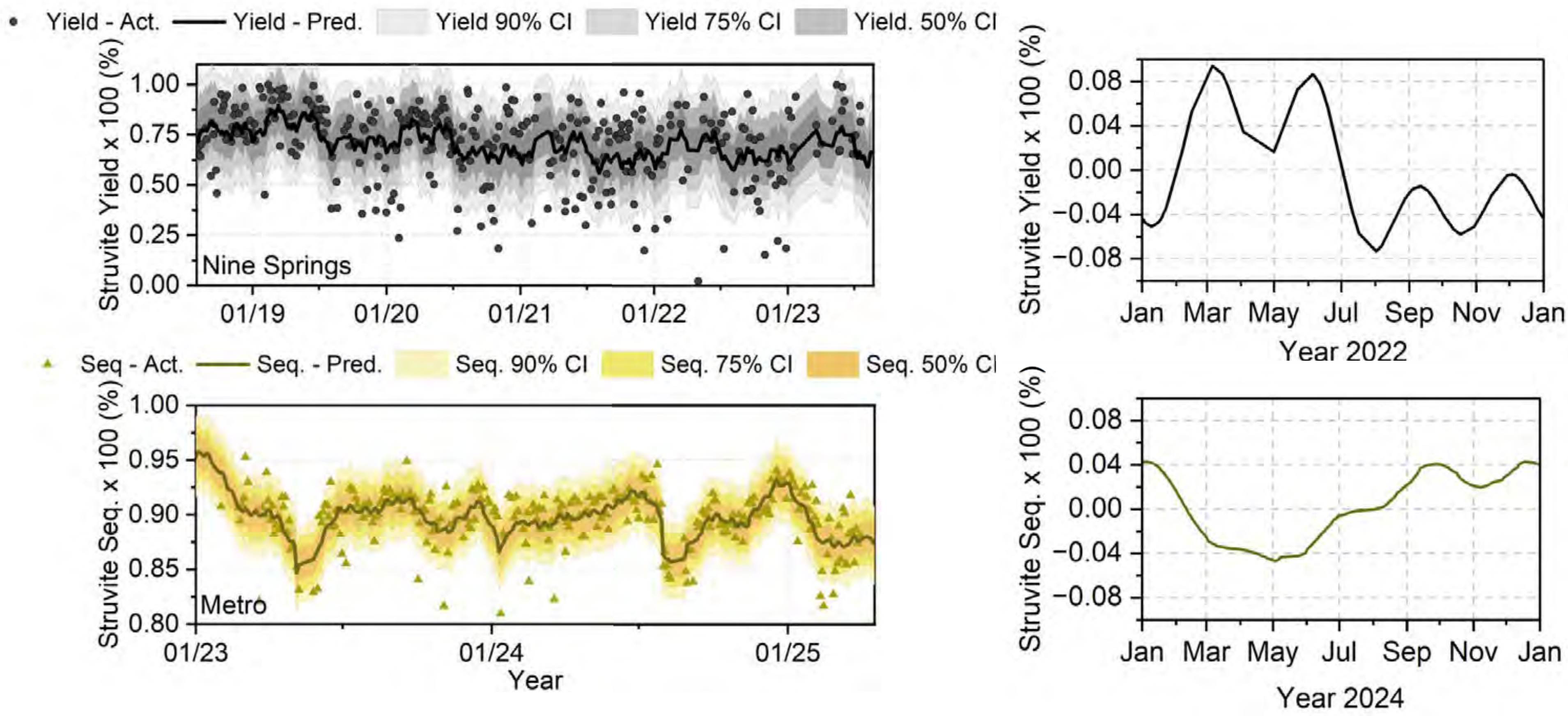


R. Puri et al (in prep)

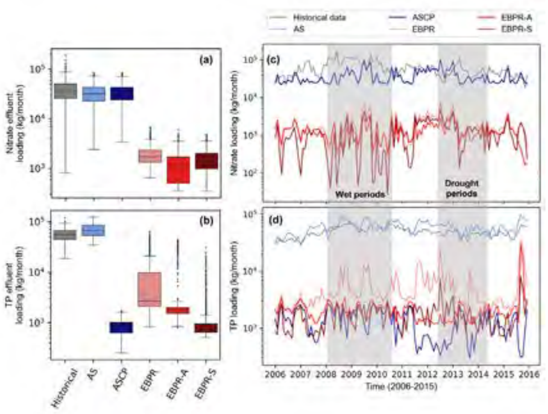
Biosolids precipitation appears to maintain higher conversion



Biosolids precipitation also appears to reduce struvite loss

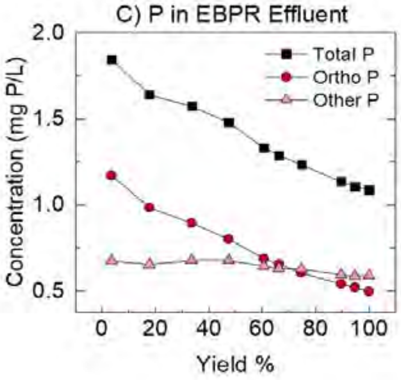


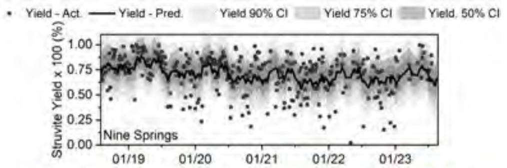
Conclusions

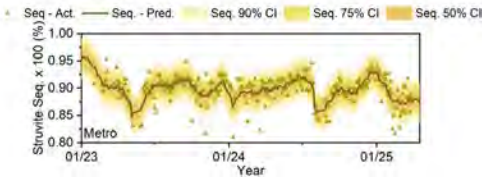


Sidestream P removal can improve WRRF performance and resilience

Struvite reactor yield is can have a strong influence on EBPR performance







Biosolids precipitation may provide more plantwide benefits than crystal recovery

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- STEPS Science and Technologies for Phosphorus Sustainability
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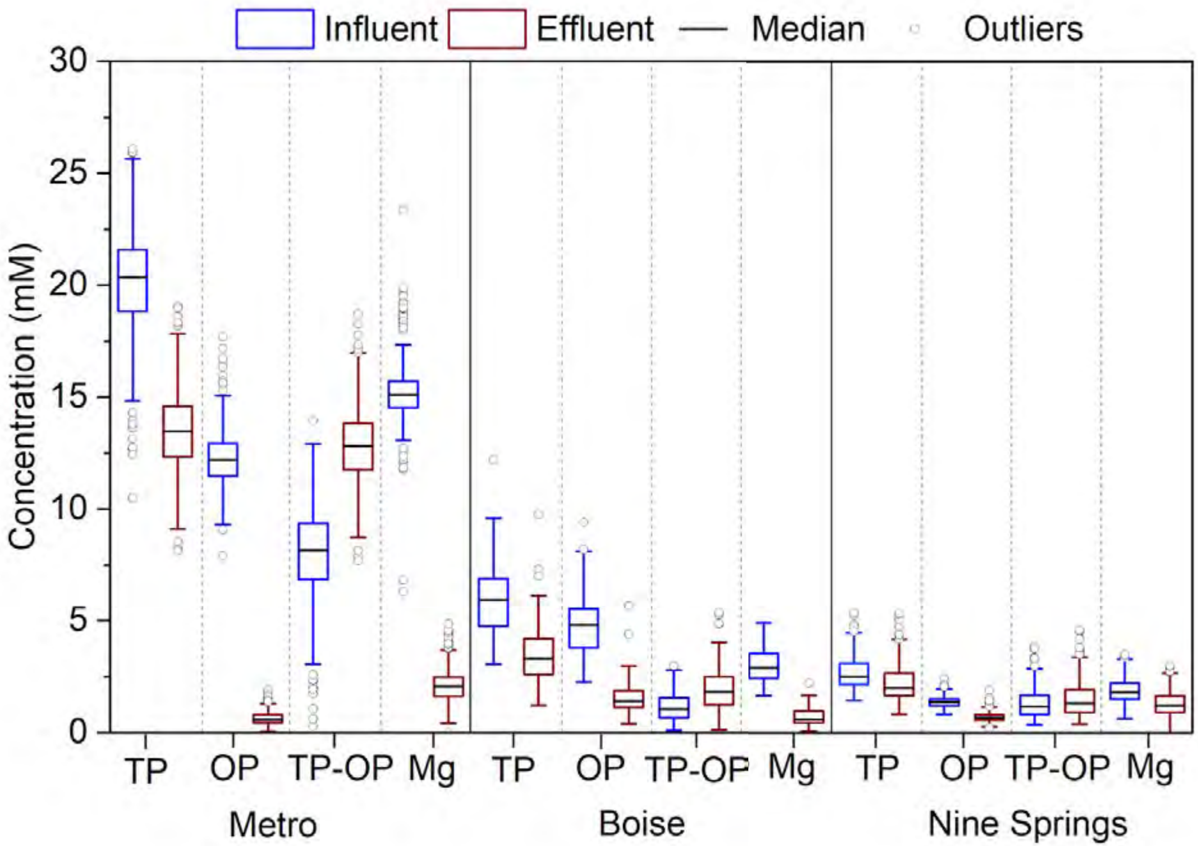
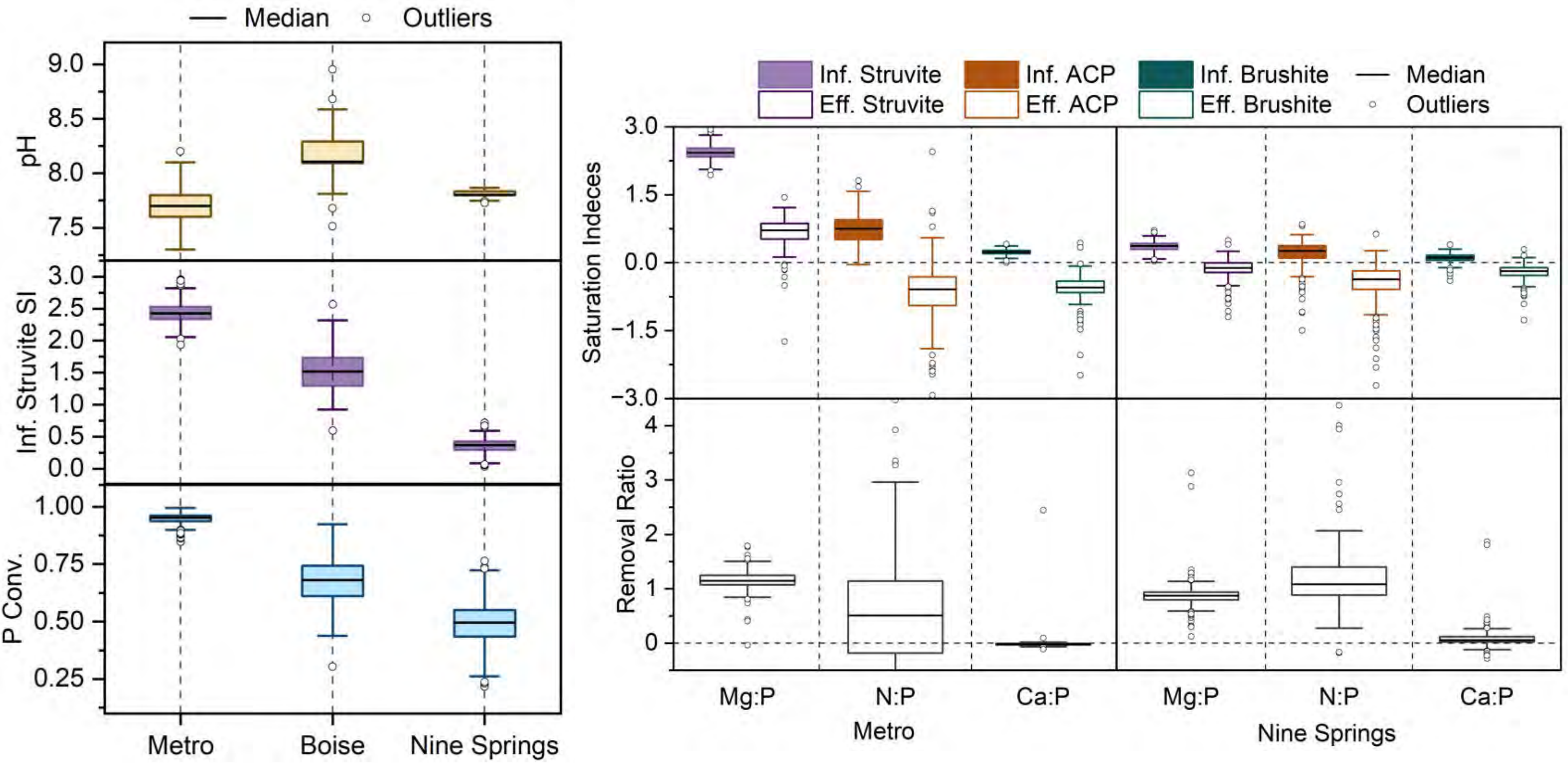


Influent
Effluent
Median
Outliers
Concentration (mM)
30
25
20
15
10
5
0
TP
OP
TP-OP
Mg
Metro
Boise
Nine Springs



Median
Outliers
pH
Inf. Struvite SI
P Conv.
Metro
Boise
Nine Springs
Inf. Struvite
Eff. Struvite
Inf. ACP
Eff. ACP
Inf. Brushite
Eff. Brushite
Median
Outliers
Saturation Indeces
Removal Ratio
Mg:P
N:P
Ca:P
Mg:P
N:P
Ca:P
Metro
Nine Springs


PF25
Questions?

Diagnosing & Responding to Enhanced Biological Phosphorus Removal Upsets

Doug Call
Professor
NCSU

Using DNA and RNA sequencing tools to understand EBPR upsets

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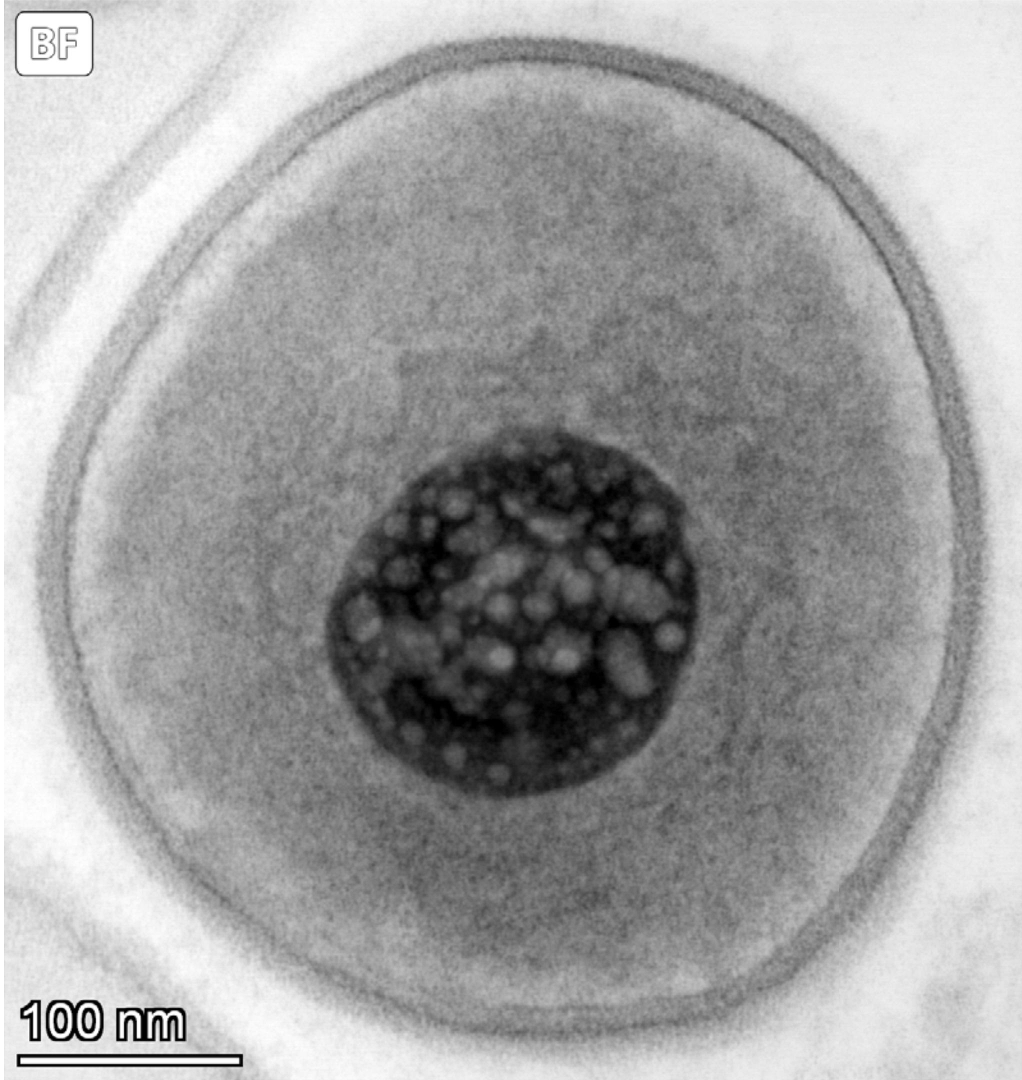
NC State

Jessica Deaver, PhD
Dept. of Civil, Construction, and Environmental Engineering,
NC State (*Current: Principal Scientist at Hazen & Sawyer*)
Tom Solon
Renewable Water Resources (ReWa)
Amy Grunden, PhD
Dept. of Plant & Microbial Biology, NC State

NC STATE UNIVERSITY



Many water resource recovery facilities experience unstable EBPR, sometimes for reasons unknown

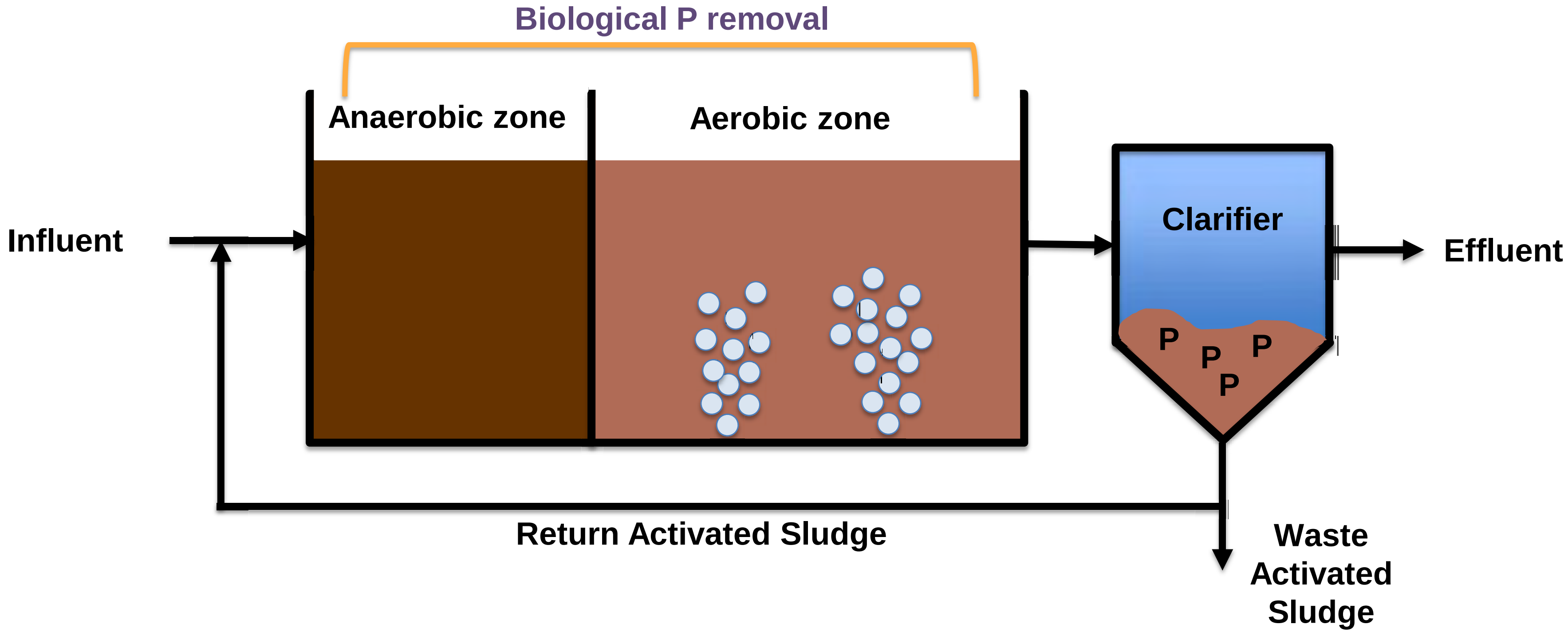
Stakeholder feedback from interviews led by Ashton Merck and Jessica Deaver:

"…The bugs, you think they're going to work, and for the reasons that are completely mysterious, they decide one [day] to stop working…"

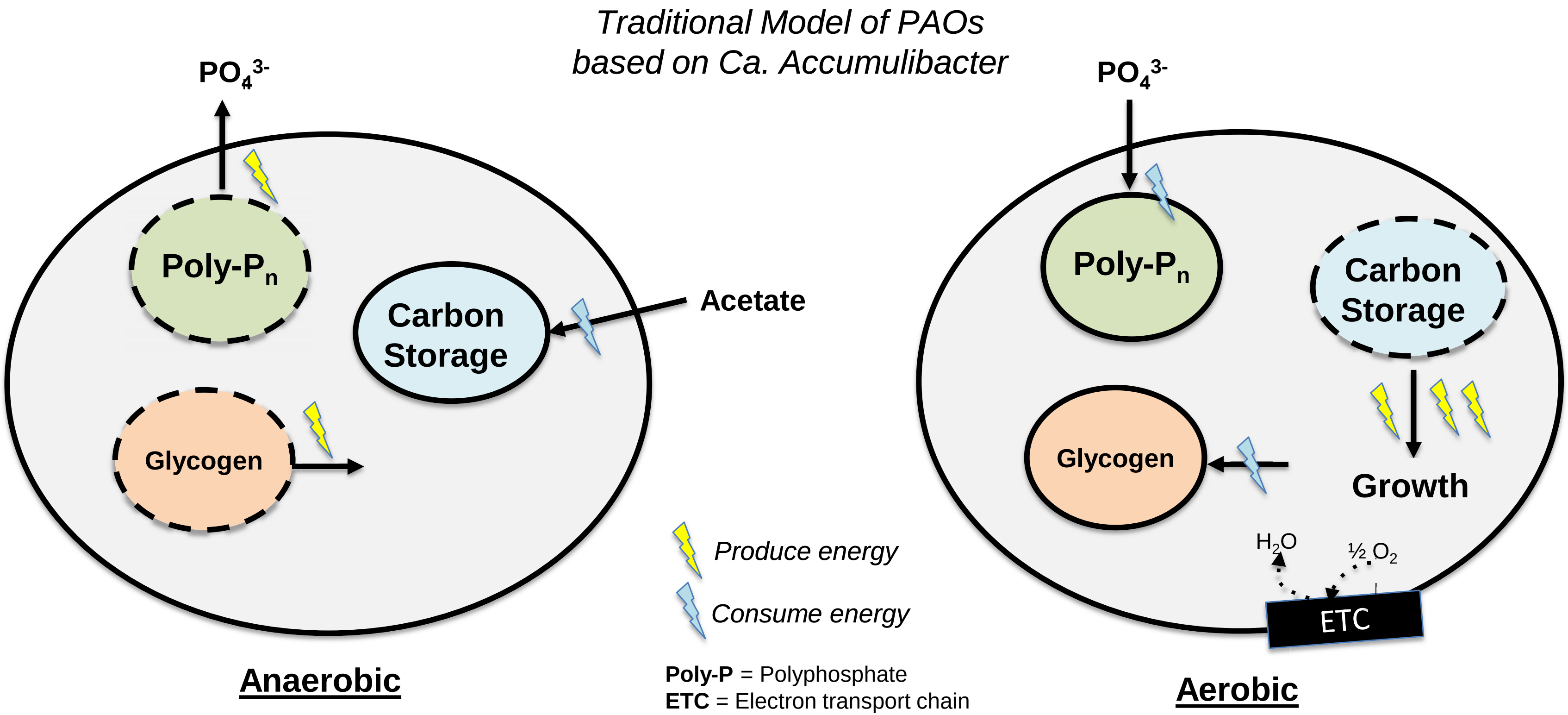
"You've got this working population of bugs, and we really think they can do great. But we kind of have no clue as to what they need to be happy."

[Merck et al. *Soc. Nat. Res.* 2025]

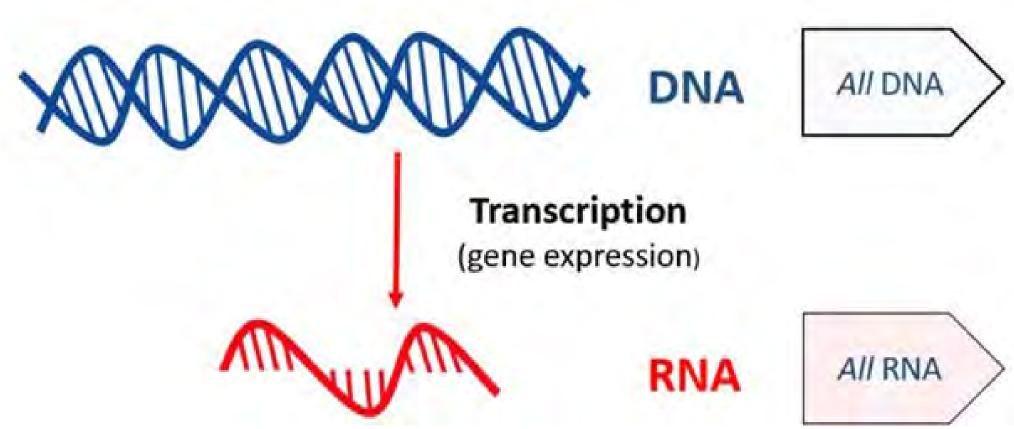
In EBPR, having the right conditions in the anaerobic and aerobic zones is critical



Phosphorus accumulating organisms (PAOs) undergo cycling of P and carbon during EBPR



DNA and RNA sequencing of PAOs can help us understand “who” is there and “what” they are doing



Metagenomics

Metatranscriptomics

How is this useful?

More sequences of gene X recovered suggests that more of the protein that gene X encodes is present.

[http://laundregen564s17.weebly.com/]

Metagenomics: Make multiple separate puzzles from a single mixture of all of the puzzle pieces

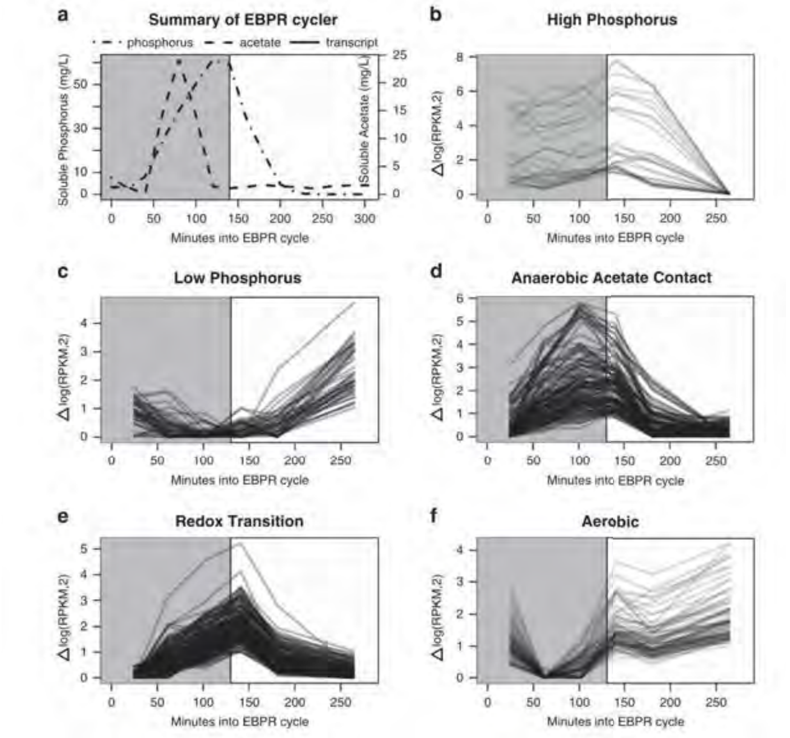
Sequencing has helped us identify who the predominant PAOs are and how they cycle gene expression in ***stable*** systems

Globally, **3 main PAO genera** – known so far:

- *Ca. Accumulibacter*
- *Azonexus* (formerly Dechloromonas)
- *Ca. Phosphoribacter* (formerly Tetrasphaera)

Ca. Accumulibacter exhibits cyclical gene expression in stable lab-scale reactors

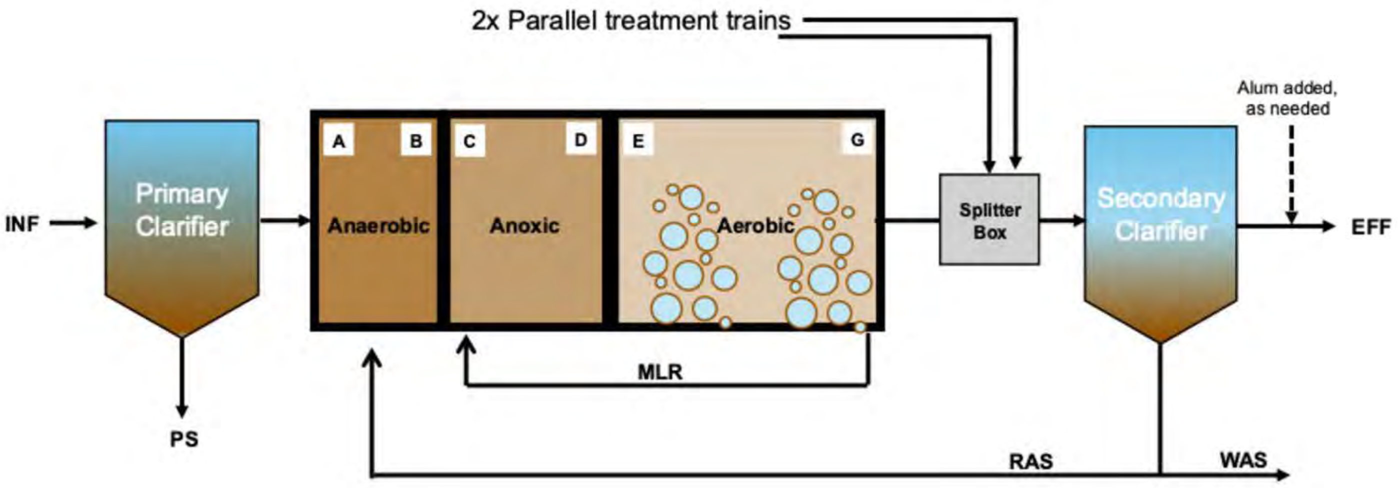
We do not understand what happens in unstable systems



Ca. Accumulibacter cyclical gene expression in lab-scale reactor fed acetate

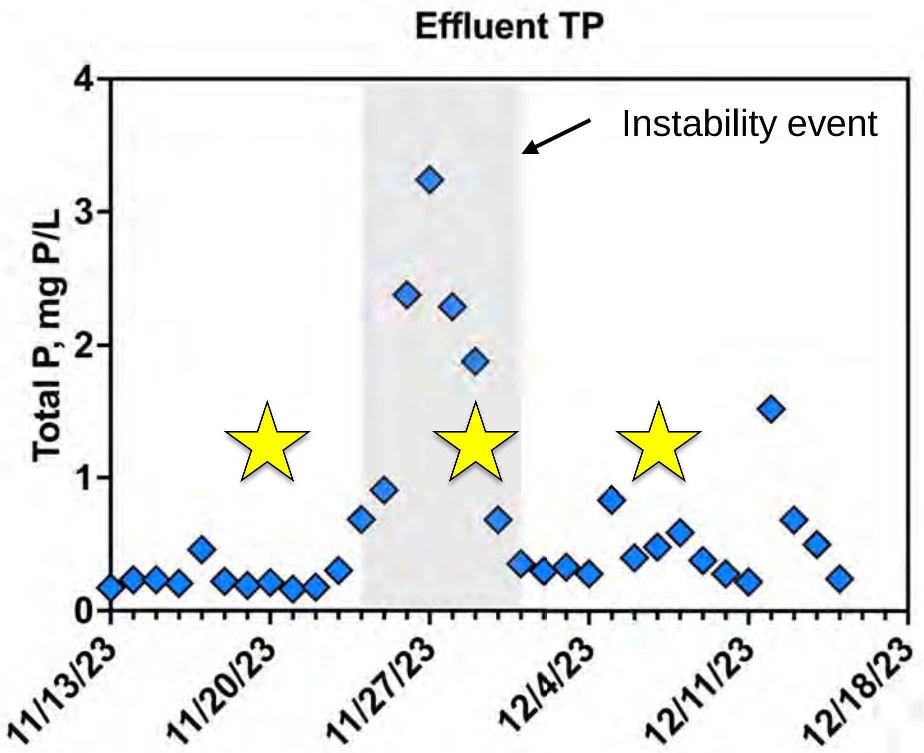
Dueholm et al. *Nat Commun* 2022, **13**:1908.

We partnered with a full-scale facility to study PAO gene expression levels when EBPR becomes unstable



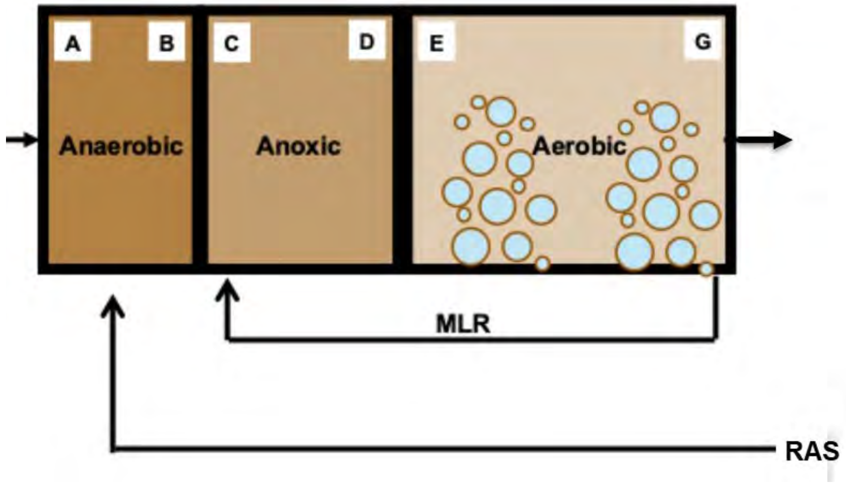
- **15-20 MGD facility**
- **Southeast United States**
- **A2O – N + P removal**
- **10-day solids retention time**
- **Supplemental carbon**

We collected samples for DNA and RNA sequencing before, during, and after an instability event



Instability defined as effluent TP > 1 mg-P/L

Samples collected on 3 days:
(11/20, 11/29, and 12/6) at locations A-G



[Deaver et al., Under review]

There were no major changes to other water quality parameters that were recorded during the instability event

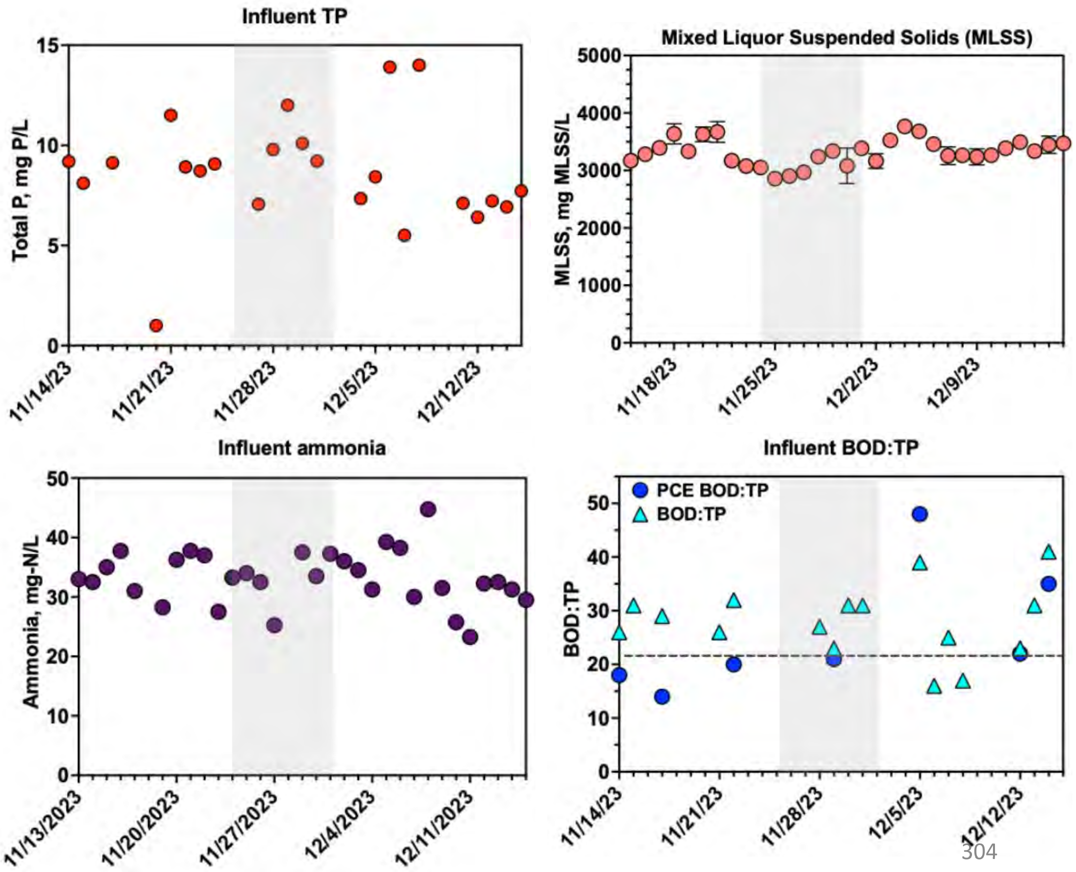
Consistent influent TP

Consistent winter targeted **MLSS** concentrations

Consistent BOD:TP for this facility

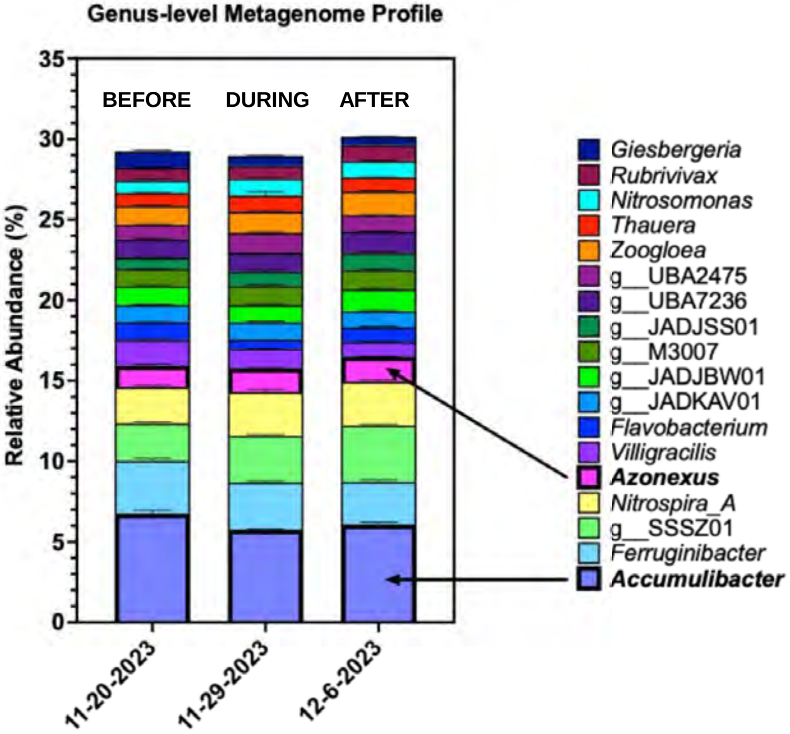
Other parameters not indicative of a problem

Water **temperatures decreasing**

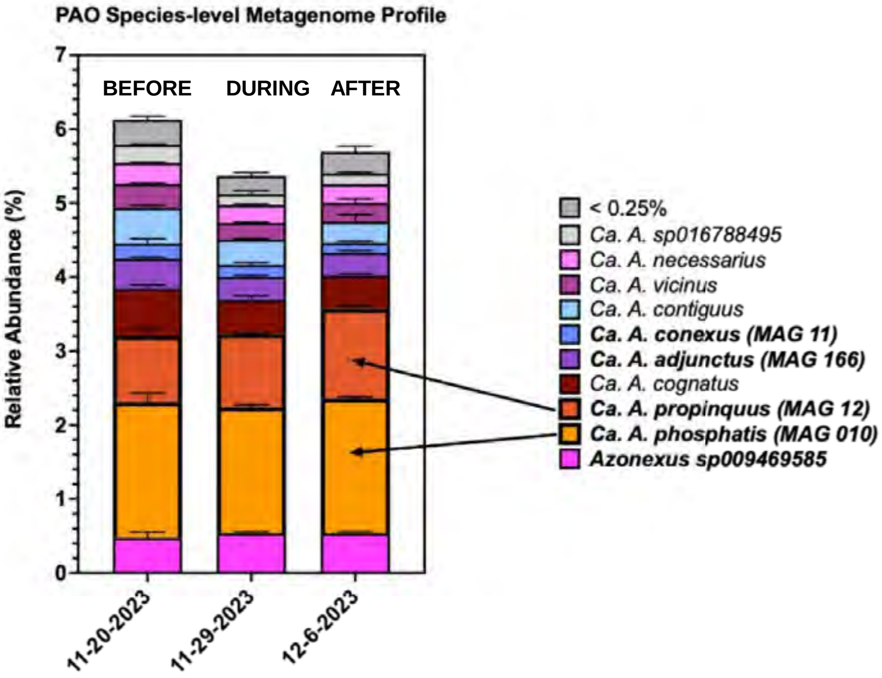


[Deaver et al., Under review]

The *Ca. Accumulibacter* **genus** was ~6% of all genera; Two of the *Ca. Accumulibacter* **species** were in high abundance



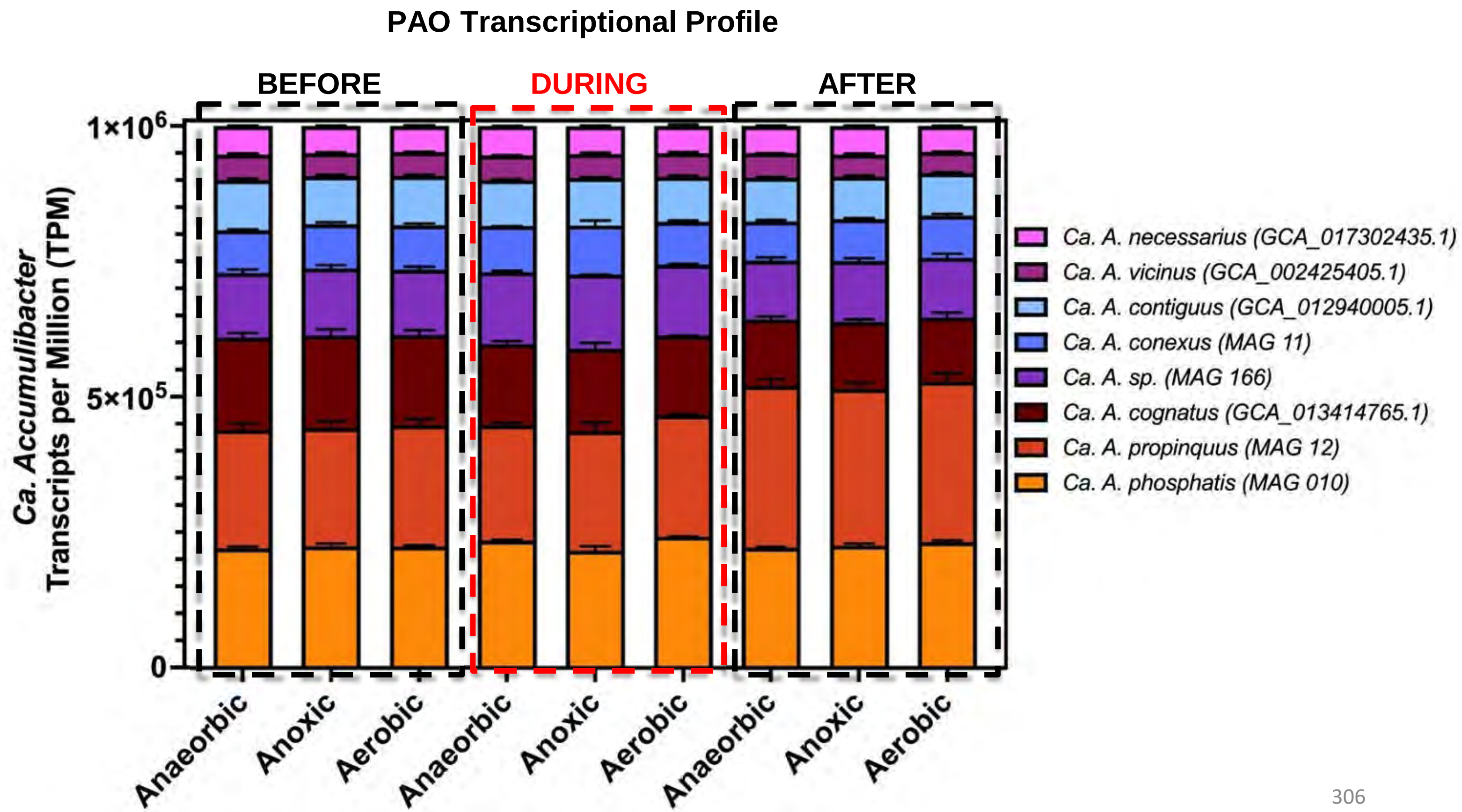
Ca. Accumulibacter is ~6% of the total microbial community



Two *Ca. Accumulibacter* species present in the highest relative abundance

[Deaver et al., Under review]

Those two *Ca. Accumulibacter* **species** were also the most "active"



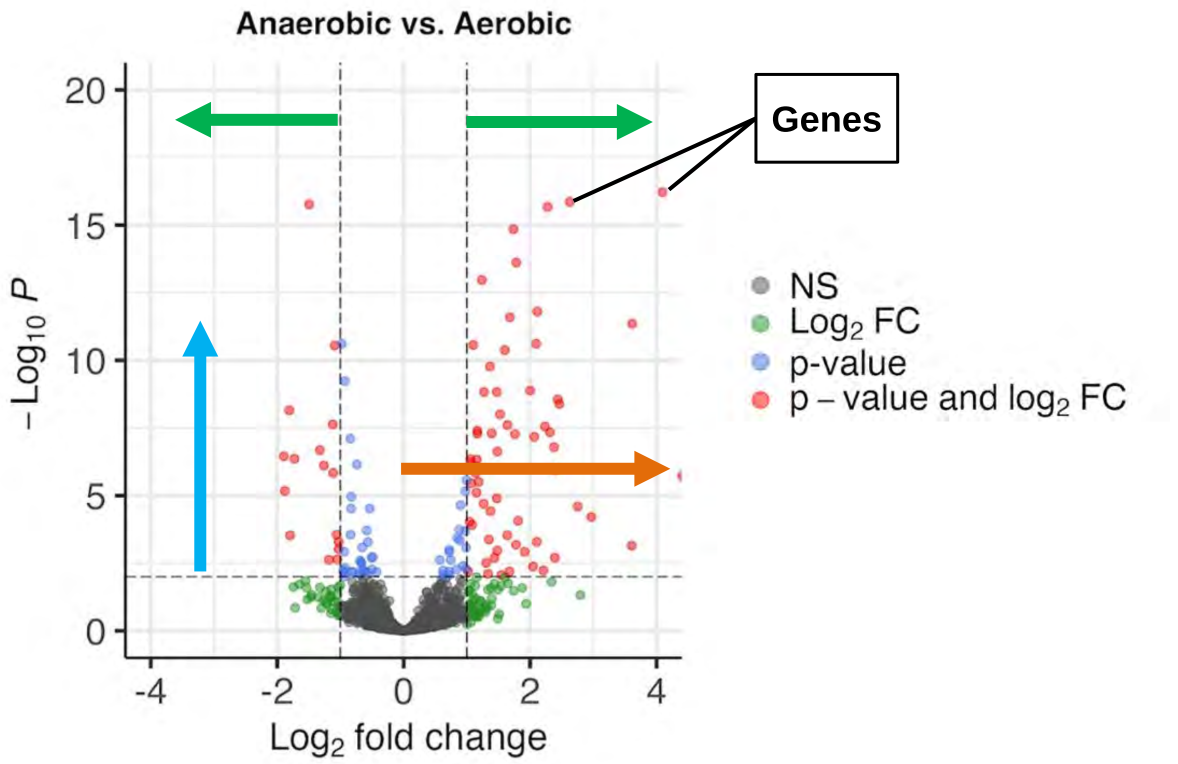
[Deaver et al., Under review]

Volcano plots allow us to visualize significant changes in gene expression between two conditions (e.g., anaerobic vs aerobic)

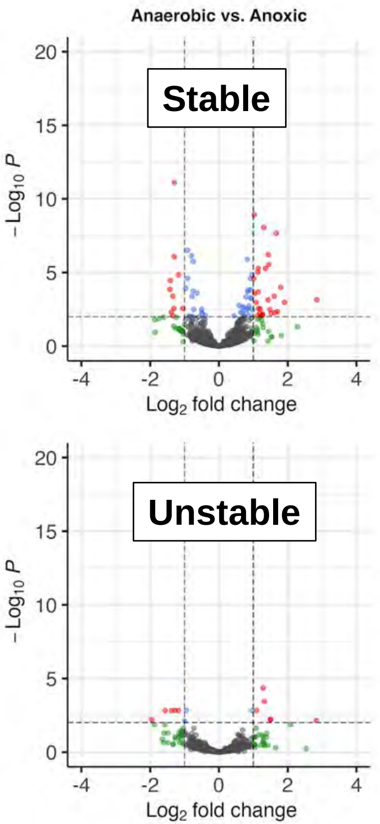
Significantly differentially expressed

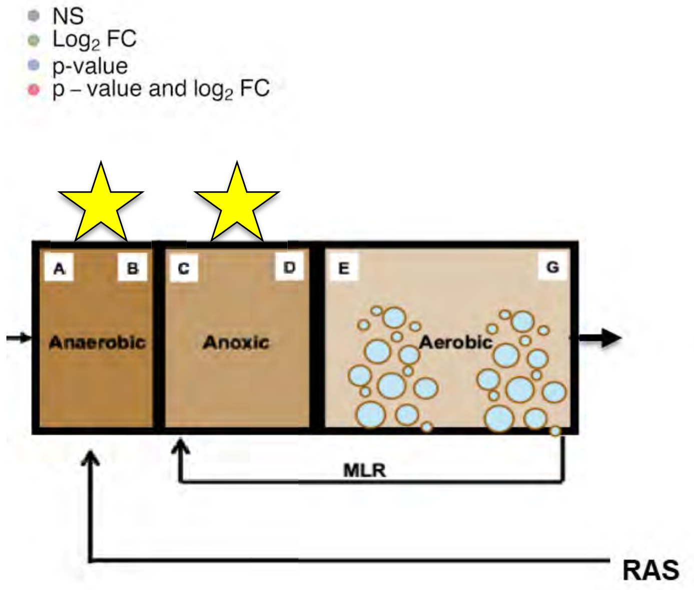
> + 1 log2(fold change)

+ log2(fold change) = higher anaerobic zone expression



There were noticeable differences in peak expression across the basins between the stable and unstable periods





[Deaver et al., Under review]

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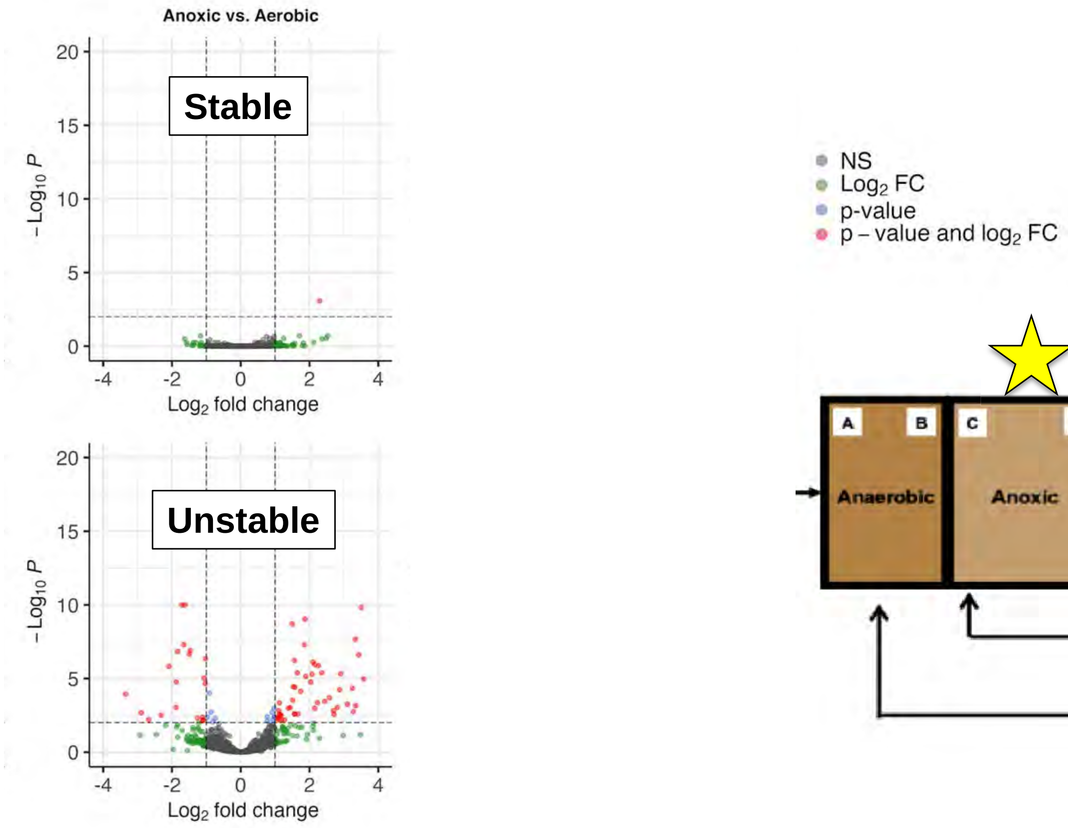

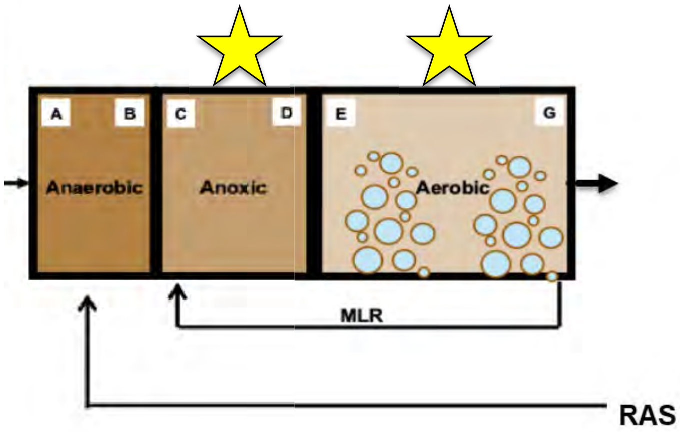

[Deaver et al., Under review]

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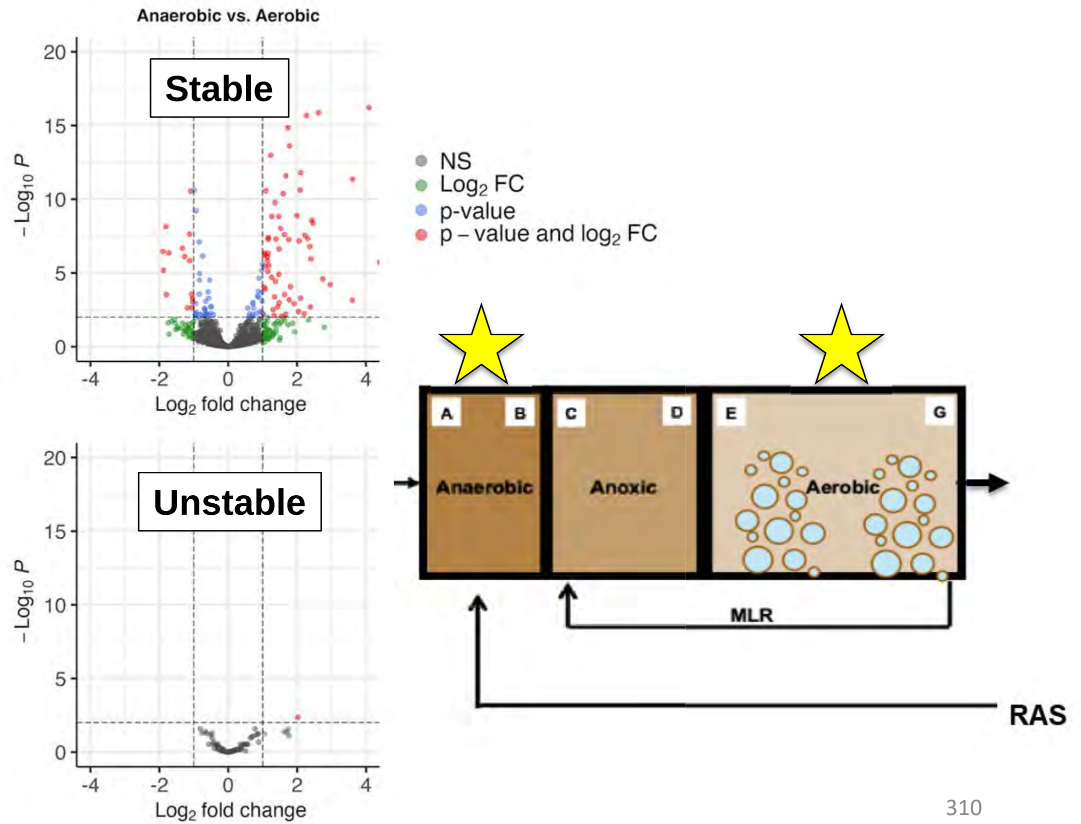
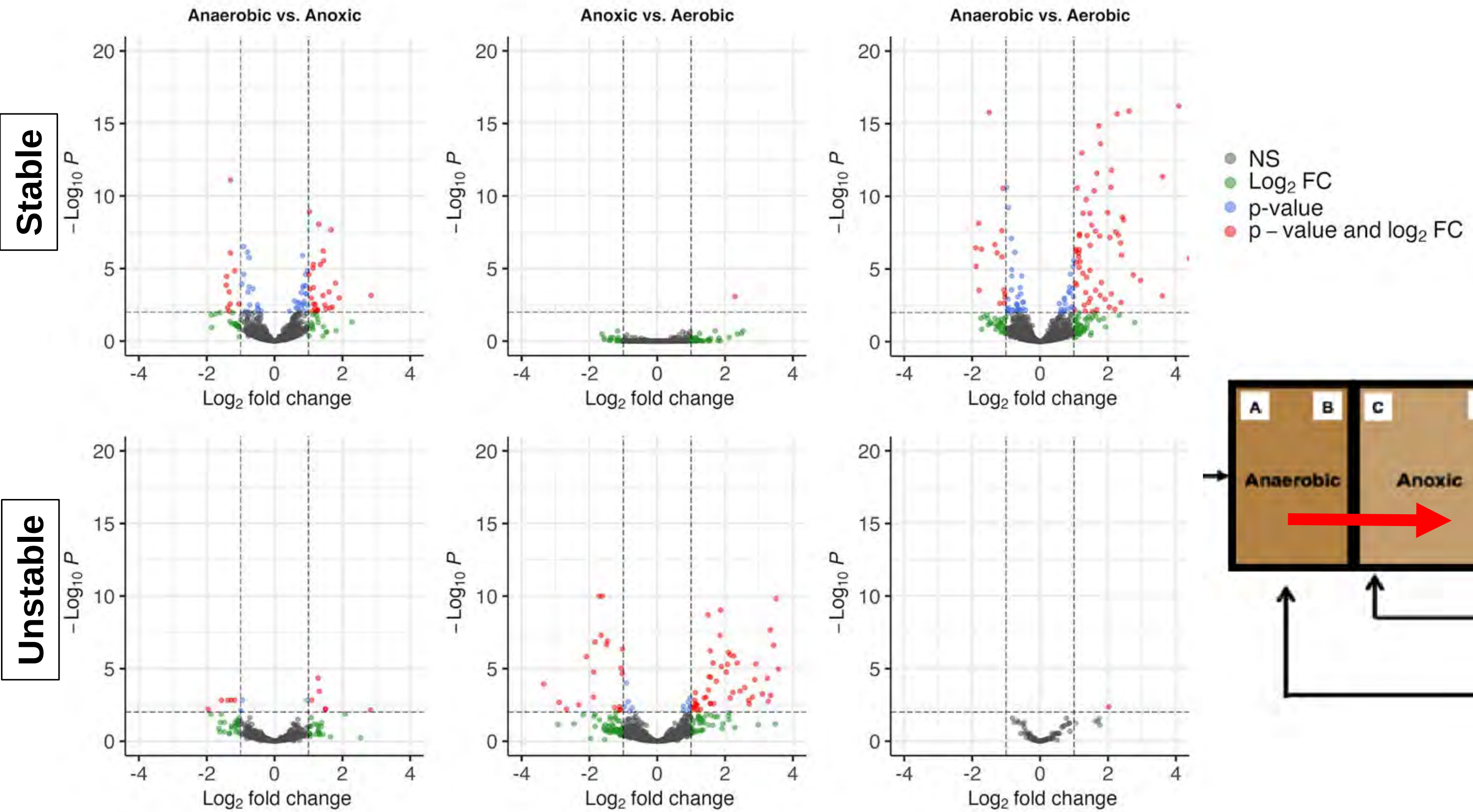
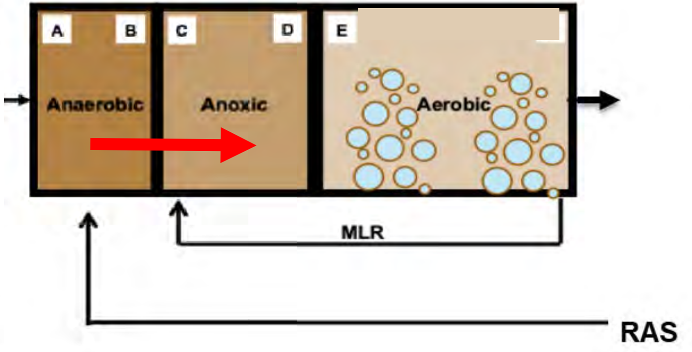


[Deaver et al., Under review]

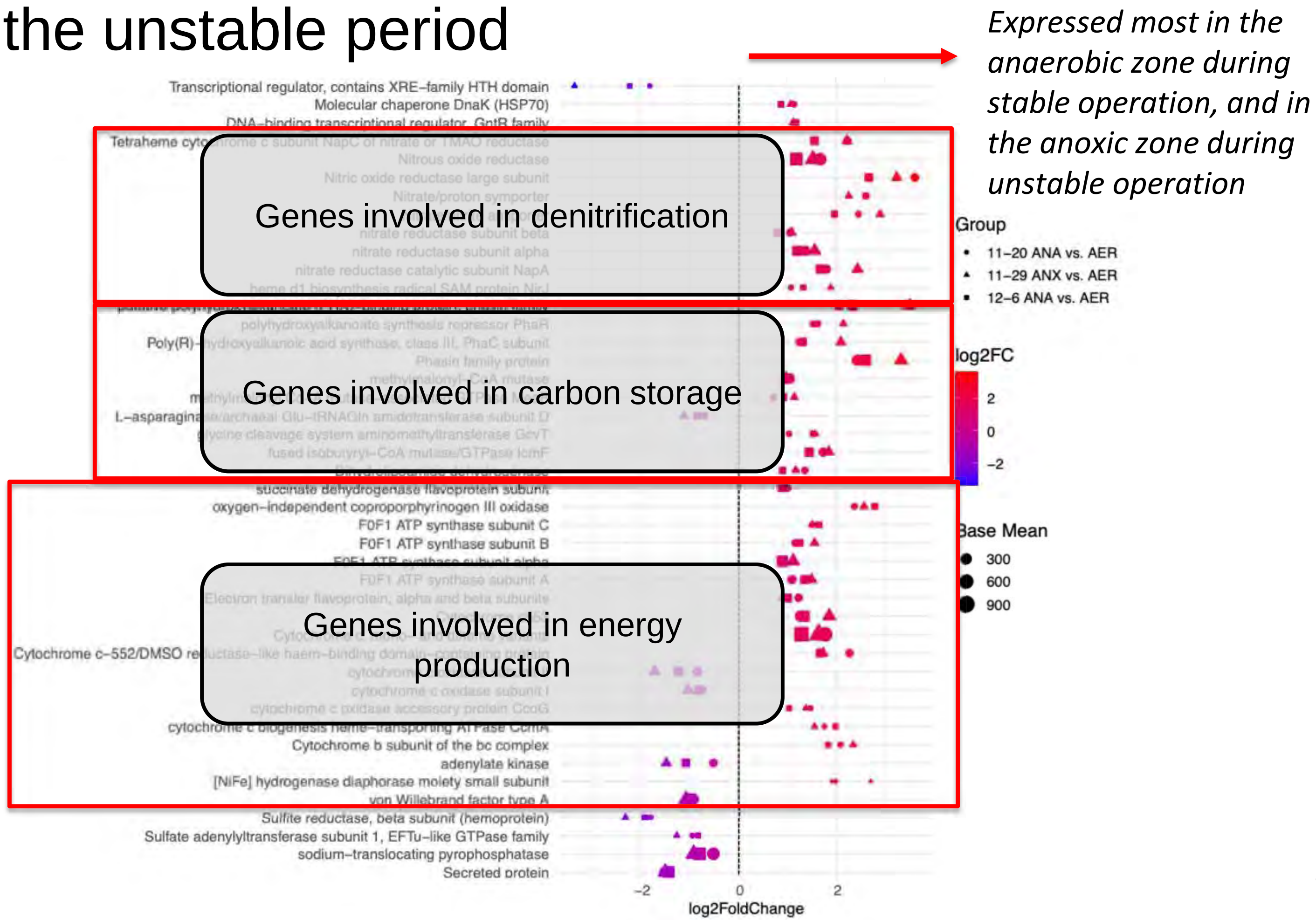
Peak gene expression shifted from the anaerobic to the anoxic zone during the unstable period





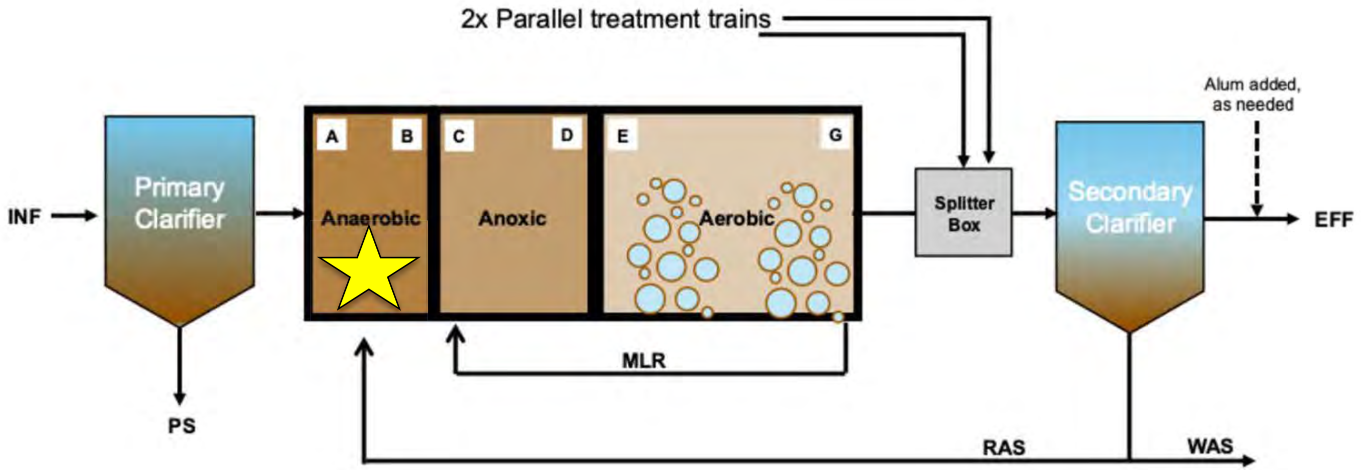
[Deaver et al., Under review]

Peak gene expression shifted from the anaerobic to the anoxic zone during the unstable period



[Deaver et al., Under review]

Our results suggest that disruption to the gene expression cycles likely resulted in delayed P removal



- Disruption in typical gene expression patterns suggests anaerobic zone disturbance led to biological phosphorus instability event
- We hypothesize anaerobic zone impacts include either 1) depth of anaerobic conditions or 2) VFA composition changing (or both)
- Future studies should include an evaluation of VFA composition and anaerobic zone optimization

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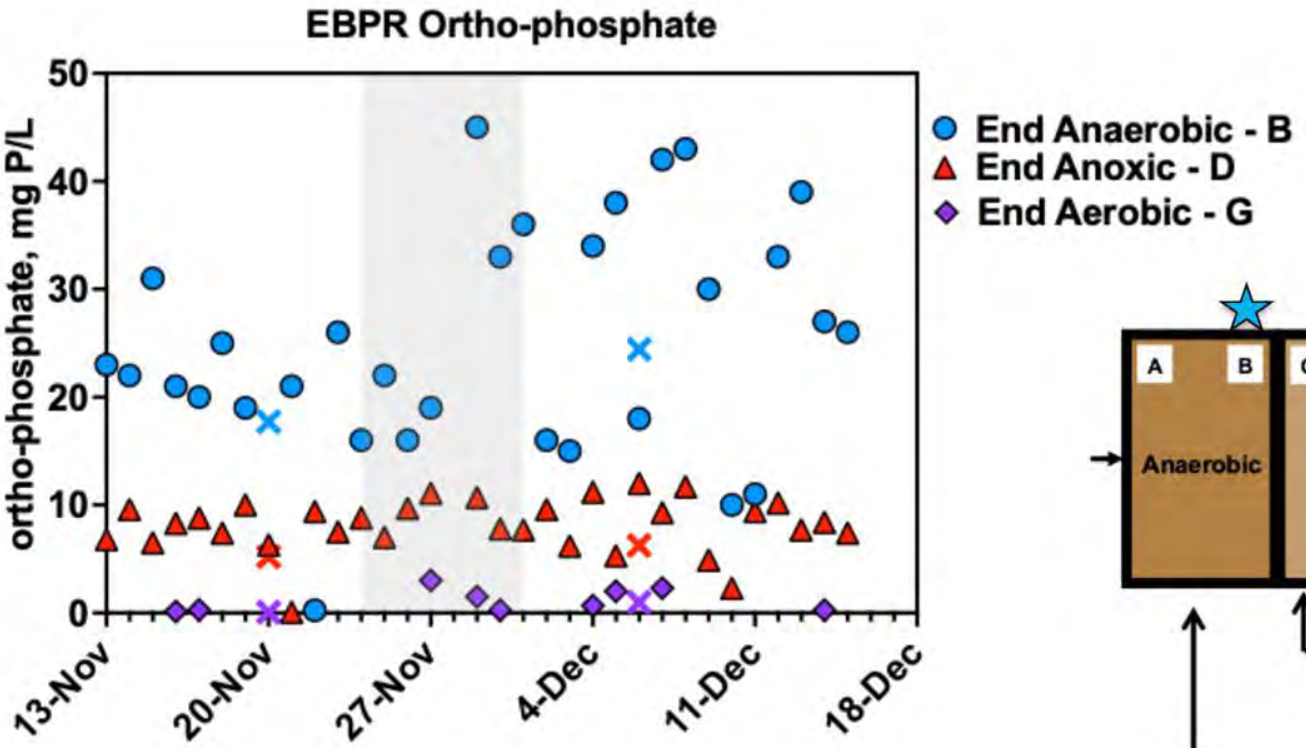
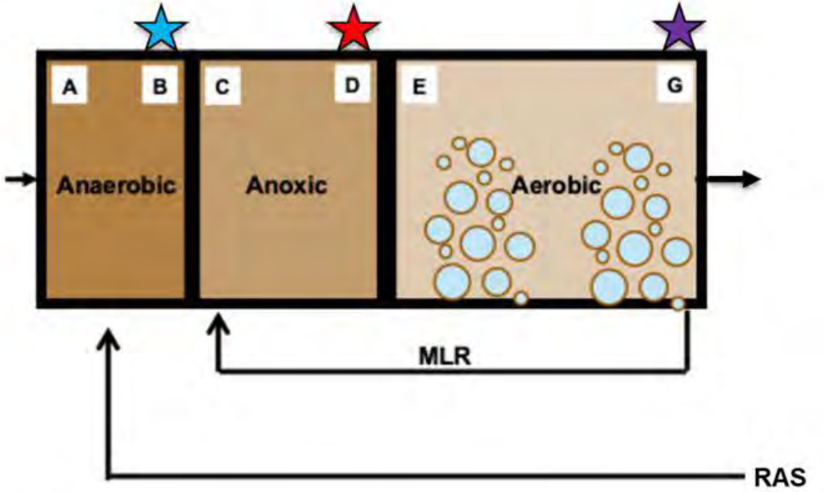
Jenny Ding
(Graduate Students)

Ho Wa Chu
Fiona Reed
(Undergraduate Students)



EBPR Ortho-phosphate
ortho-phosphate, mg P/L
0
10
20
30
40
50
13-Nov
20-Nov
27-Nov
4-Dec
11-Dec
18-Dec
End Anaerobic - B
End Anoxic - D
End Aerobic - G



A
B
C
D
E
G
Anaerobic
Anoxic
Aerobic
MLR
RAS