Welcome to Phosphorus Forum 2025!

Session Sponsors

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Welcome Address

Jim Elser
Director
Sustainable Phosphorus Alliance

Forum Ground Rules

Expected Behavior

We expect all participants to demonstrate respect, inclusivity, and professionalism. Indeed, we strongly promote collaboration and aim to make your experience with us enjoyable and conducive to productive interactions.

Prohibited Conduct

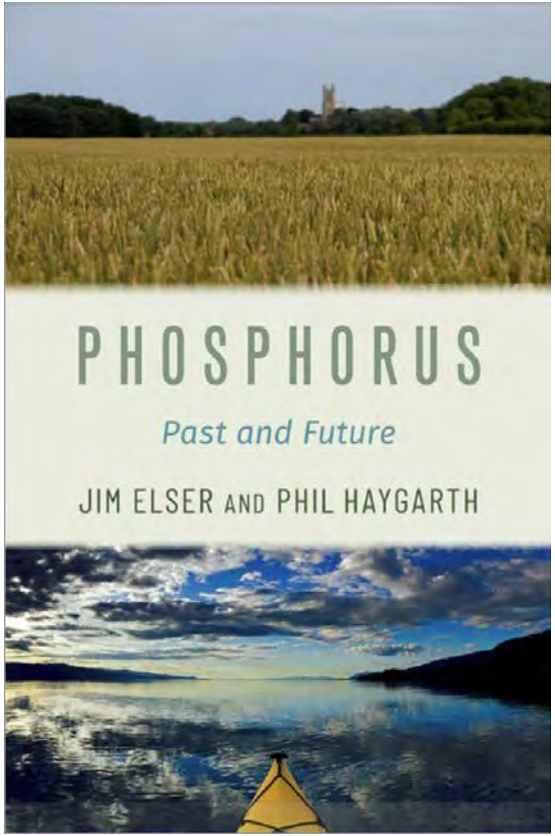
Harassment: Any unwelcome action towards another person, knowing it might cause hurt, humiliation, or intimidation. The Alliance does not permit any form of harassment, including harassment based on gender, gender expression, gender identity, race, religion, belief, nationality, ethnic origin, social origin, age, sexual orientation, marital status, disability, language, or any other reason.

Sexual Harassment: The Alliance strictly prohibits any unwelcome conduct of a sexual nature that might cause discomfort, disapproval, hurt, or humiliation. Examples include: demeaning comments about someone's sexual orientation, or gender identity, name-calling, slurs with a sexual connotation, sexual comments about appearance, clothing, or body parts, asking for sexual favors, staring in a sexually suggestive manner, unwelcome touching, inappropriate sexual gestures, sexual anecdotes/jokes, sending or sharing suggestive communications, images or videos, attempted or actual sexual assault, including rape.

Violence and Threats: All forms of physical aggression, verbal intimidation, or implied threats are prohibited.

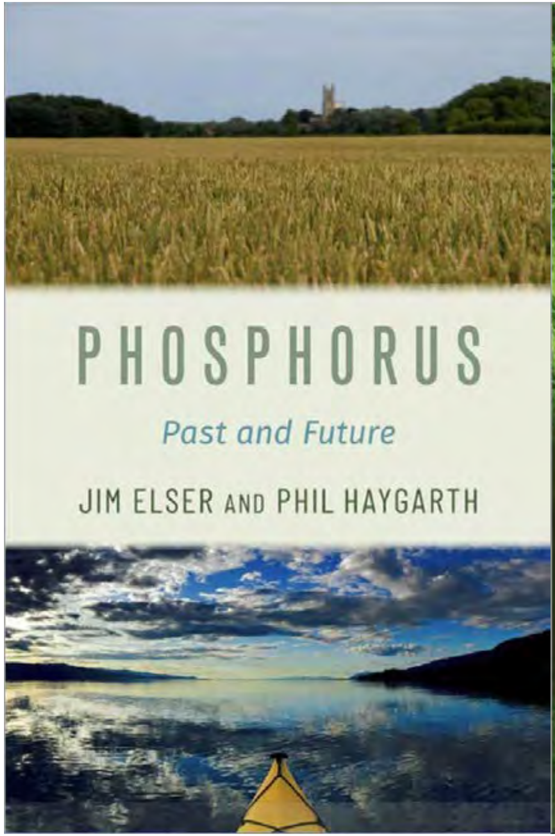
Disruptive Behavior: Sustained disruption of talks or other events will be taken seriously and may lead to removal of disruptive individuals from the venue.

Phosphorus: Such a big deal it takes a book to tell the story

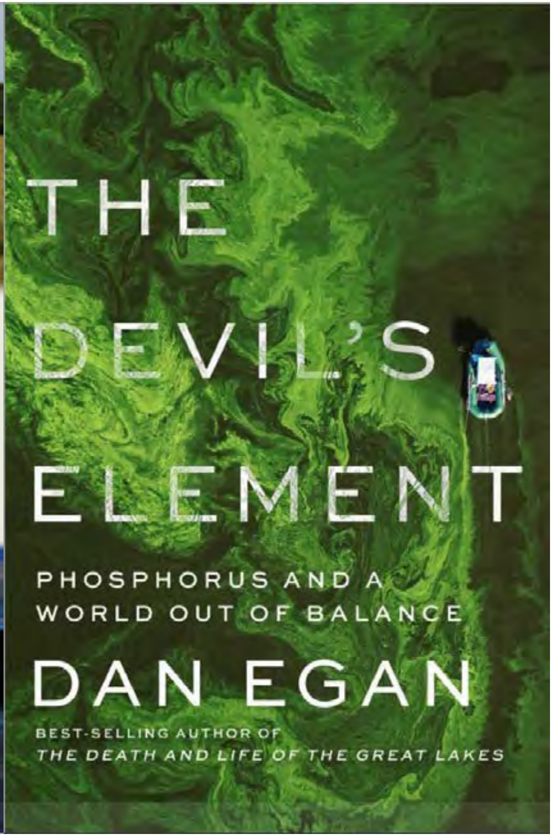


2022

Phosphorus: Such a big deal it takes 2 books to tell the story

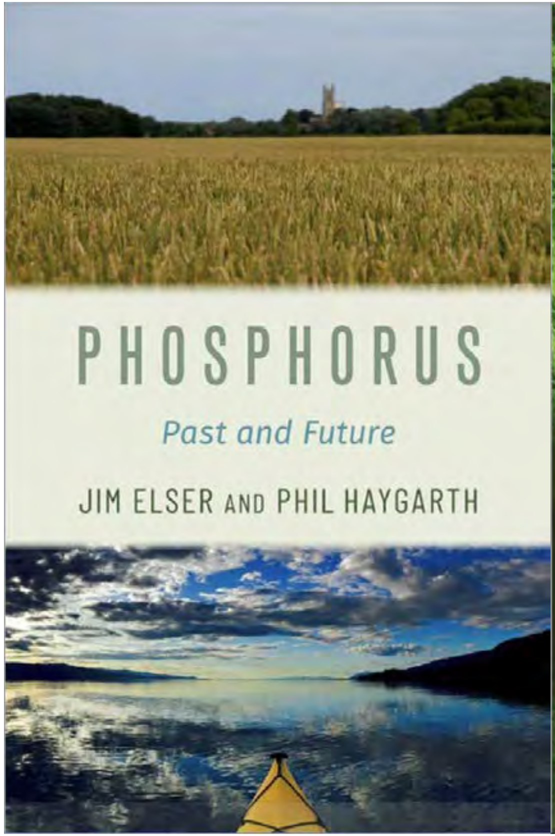


2022

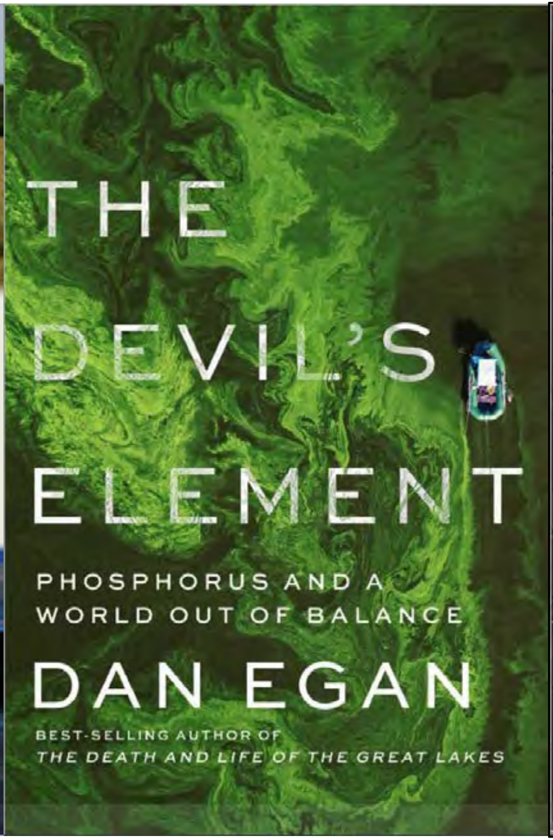


2023

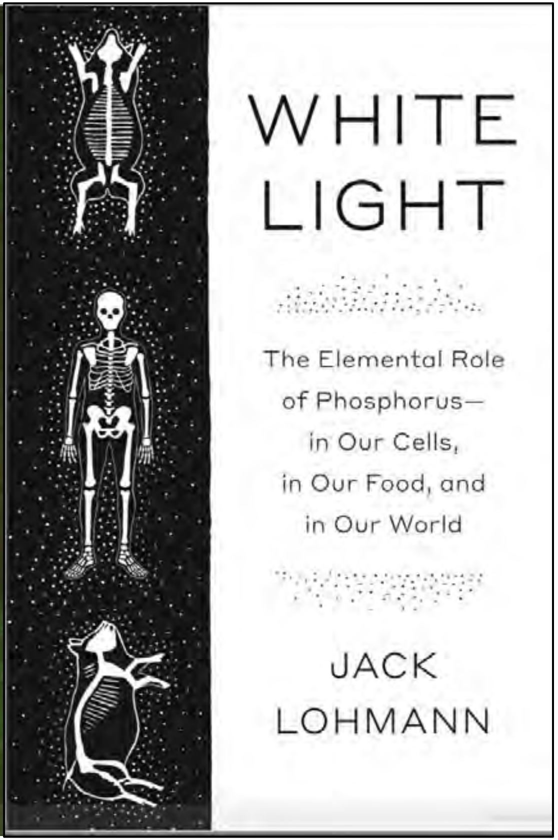
Phosphorus: Such a big deal it takes 3 books to tell the story



2022



2023

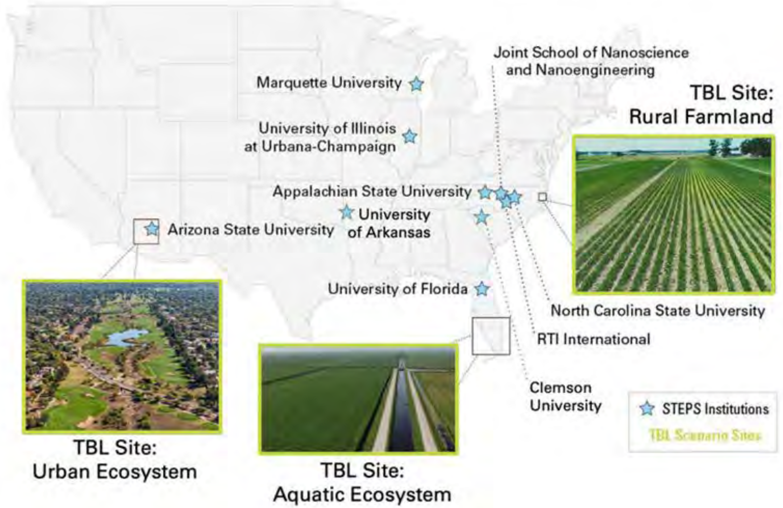


2025

Phosphorus: Such a big deal it takes a Science & Technology Center

STEPS

Science and Technologies for Phosphorus Sustainability



The STEPS 25-IN-25 Vision

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

The STEPS Mission Statement

Develop and implement convergence research on phosphorus sustainability across disciplines, scales, sectors, and communities that:

generates new knowledge across the natural, engineered, and social systems that impact the phosphorus cycle;

innovates new phosphorus sustainability solutions; and

trains a diverse group of scholars who are equipped to address complex societal challenges.

Phosphorus: Such a big deal it takes an alliance

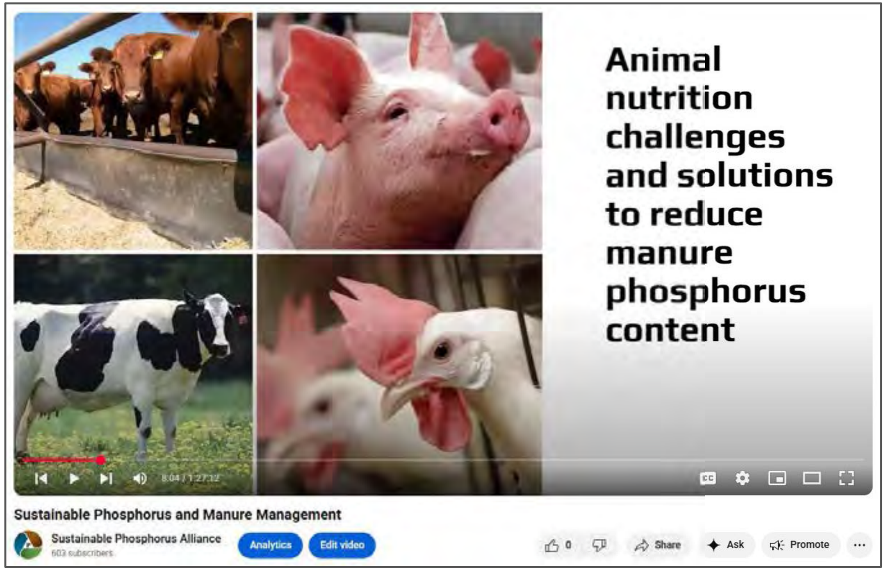
Members

47% of global fertilizer production

80% of USA fertilizer production

Partners

The Sustainable Phosphorus Alliance: what have we done lately?



Received: 27 December 2024 | Accepted: 9 May 2025
DOI: 10.1002/ael2.70022
Agricultural & Environmental Letters

RESEARCH LETTER

Radioisotopic labeling reveals inaccuracy of phosphorus use efficiency of ammonium phosphate fertilizers calculated by the difference method

Andrew J. Margenot[1,2] | Neha Chatterjee[1] | Chongyang Li[2]

[1]Department of Crop Sciences, University of Illinois Urbana-Champaign, Urbana, Illinois, USA
[2]Agroecosystem Sustainability Center, Institute for Sustainability, Energy, and Environment, University of Illinois Urbana-Champaign, Urbana, Illinois, USA

Video interviews – Phosphorus Science Now!

Matt Scholz of the Sustainable Phosphorus Alliance has conducted interviews with scientists about their work in phosphorus sustainability. Learn about their findings in these videos:

The Sustainable Phosphorus Alliance: what have we done lately?

Newly Updated!

Collection

GIS-P

A Tool for Sustainable Phosphorus Management

Sustainable Phosphorus Alliance and STEPS Center

Get started

GIS-P provides a national landscape analysis of manure and biosolids land application regulations across the United States.

1 Overview

2 Biosolids Dashboard

3 Manure Dashboard

4 Sources

The Sustainable Phosphorus Alliance: what have we done lately?

nature sustainability

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nature › nature sustainability › correspondence › article

Correspondence | Published: 17 January 2025

A critical eutrophication–climate change link

Matthew J. Scholz ✉, Daniel R. Obenour, Elise S. Morrison & James J. Elser

Nature Sustainability **8**, 222–223 (2025) | Cite this article

NATIONAL ACADEMIES Sciences Engineering Medicine

GLOBAL MENU

SHARE

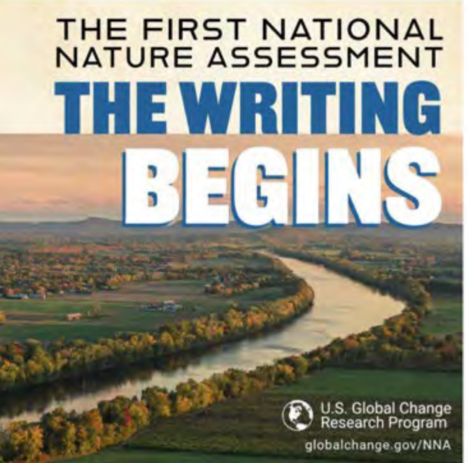
National Academies Launch Fast-Track Review of Latest Evidence for Whether Greenhouse Gas Emissions Endanger Public Health and Welfare

News Release | August 7, 2025

WASHINGTON — A new National Academies of Sciences, Engineering, and Medicine study will review the latest scientific evidence on whether greenhouse gas emissions ... welfare in the U.S.

The committee conducting the study will focus on eviden... the U.S. Environmental Protection Agency first declared ... conclusions in the committee's report will describe supporting evidence, the level of confidence in a conclusion, and areas of disagreement or unknowns.

Being released today.



Trump Killed a Major Report on Nature. They're Trying to Publish It Anyway.

The first full draft of the assessment, on the state of America's land, water and wildlife, was weeks from completion. The project leader called the study "too important to die."

Most of the 12 chapters in the report were written by teams of a dozen or so specialists.

The Sustainable Phosphorus Alliance: what have we done lately?


STATE of WISCONSIN

OFFICE of the GOVERNOR

Proclamation

PHOSPHORUS WEEK


State of North Carolina

JOSH STEIN

GOVERNOR


State of Illinois

Executive Department

Proclamation

In Witness Whereof,

Also: Arkansas

P week 2026: 6-10 April 2026   Start your planning now!

The Sustainable Phosphorus Alliance: what have we done lately?

Sustainable Phosphorus Summit (SPS)

- SPS is the world's largest convening on the topic for students, scientists, and practitioners
- To be held in **Ghana** from **30 Sept – 3 Oct 2025**
- **https://www.upcyclelakes.org/sps8africa**

2010: 1st SPS in Linkoping, Sweden

2011: 2nd SPS in Tempe,, USA

2012: 3rd SPS in Sydney, Australia

2014: 4th SPS in Montpellier, France

2016: 5th SPS in Kunming, China

2018: 6th SPS in Brasilia, Brazil

2022: 7th SPS in Raleigh, USA (hosted by STEPS)

2025: 8th SPS in Ghana

Phosphorus: Such a big deal it takes …

686

slides to tell the story…

Farm Fertilizer Emissions Management: A Risk Pricing and Capital Markets Approach

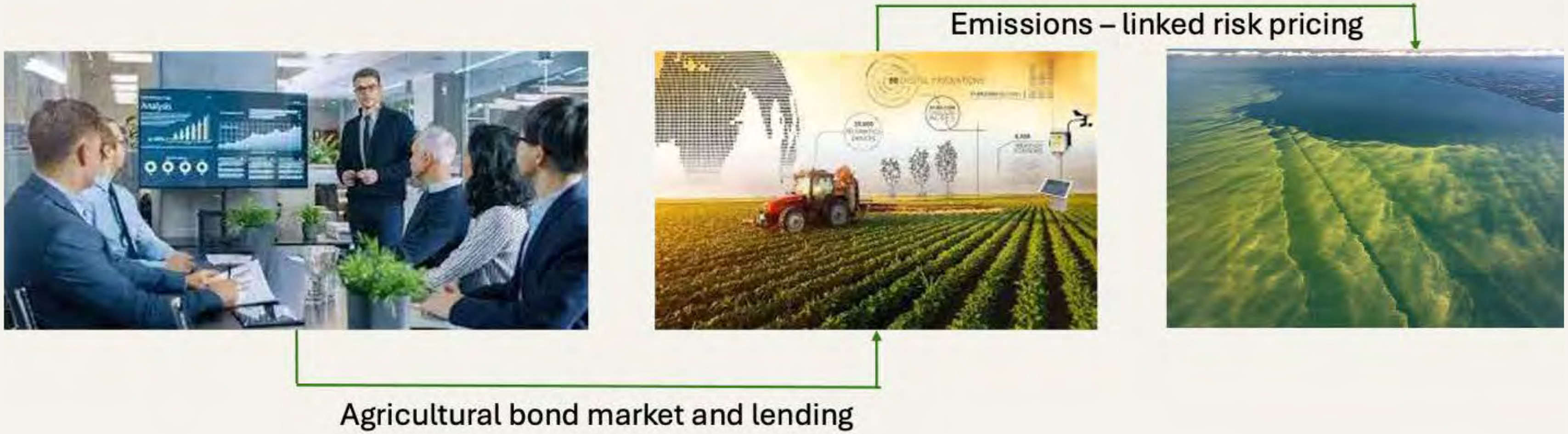
Peter Adriaens
Professor
University of Michigan

Farm Fertilizer Emissions Management:
A Risk Pricing and Capital Markets Approach

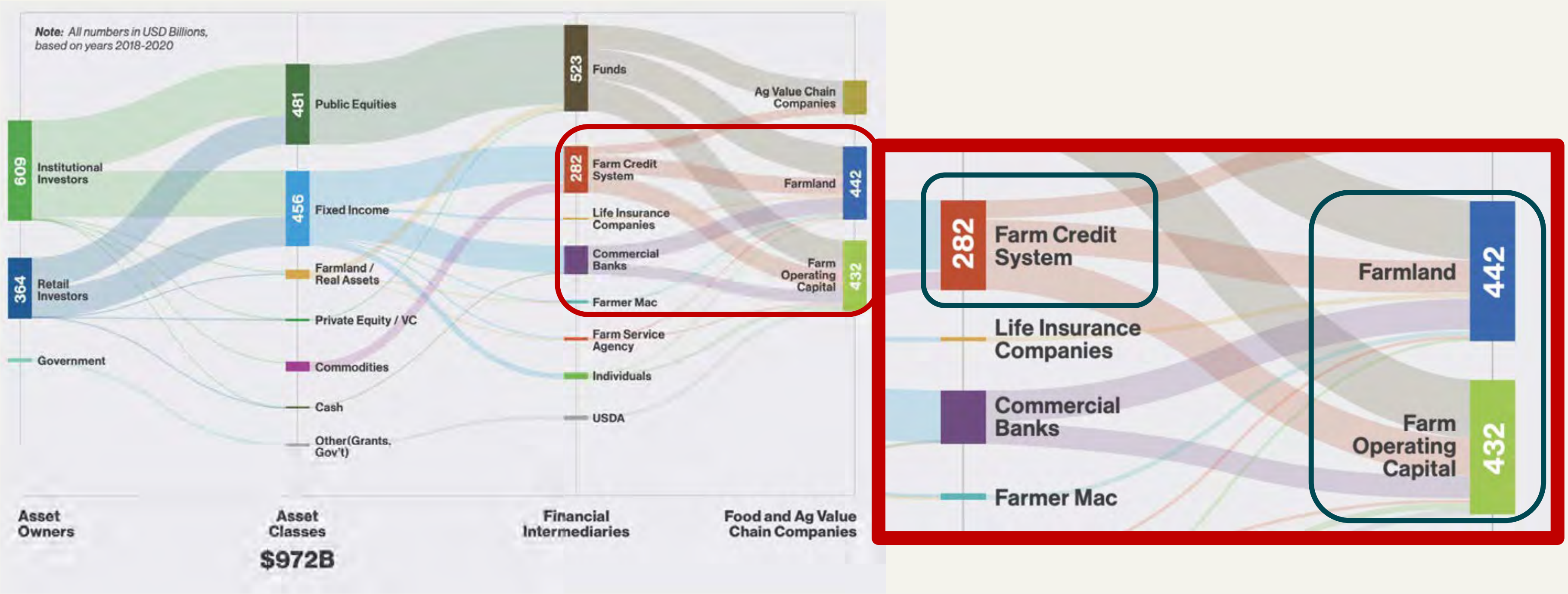
Peter Adriaens
Director, Center for Digital Asset Finance
Civil and Environmental Engineering - School for Environment and Sustainability
The University of Michigan, Ann Arbor

COLLEGE OF ENGINEERING
CENTER FOR DIGITAL ASSET FINANCE
UNIVERSITY OF MICHIGAN

Wall Street, farmers and the Great Lakes are linked

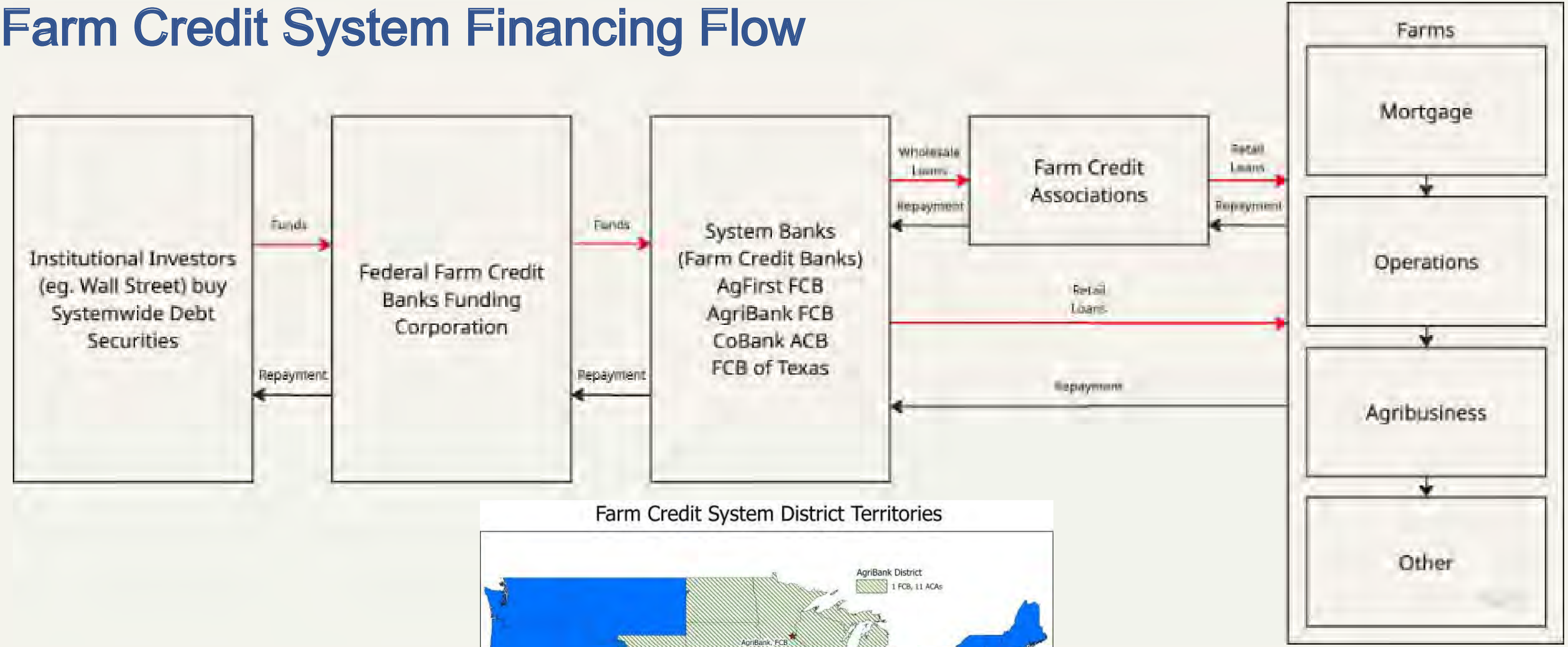


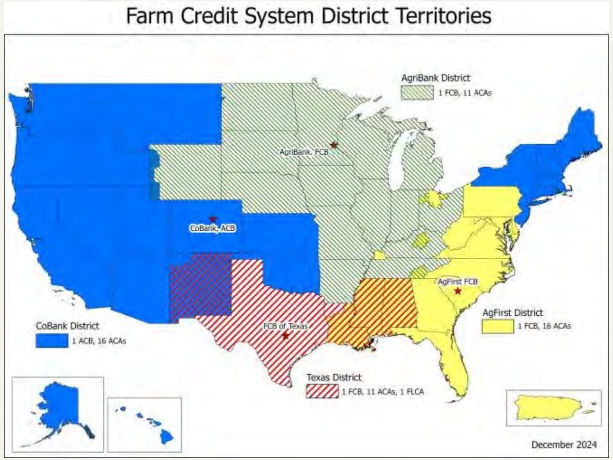
About $972B is invested in US agriculture annually - Wall Street is linked to agriculture through capital flow



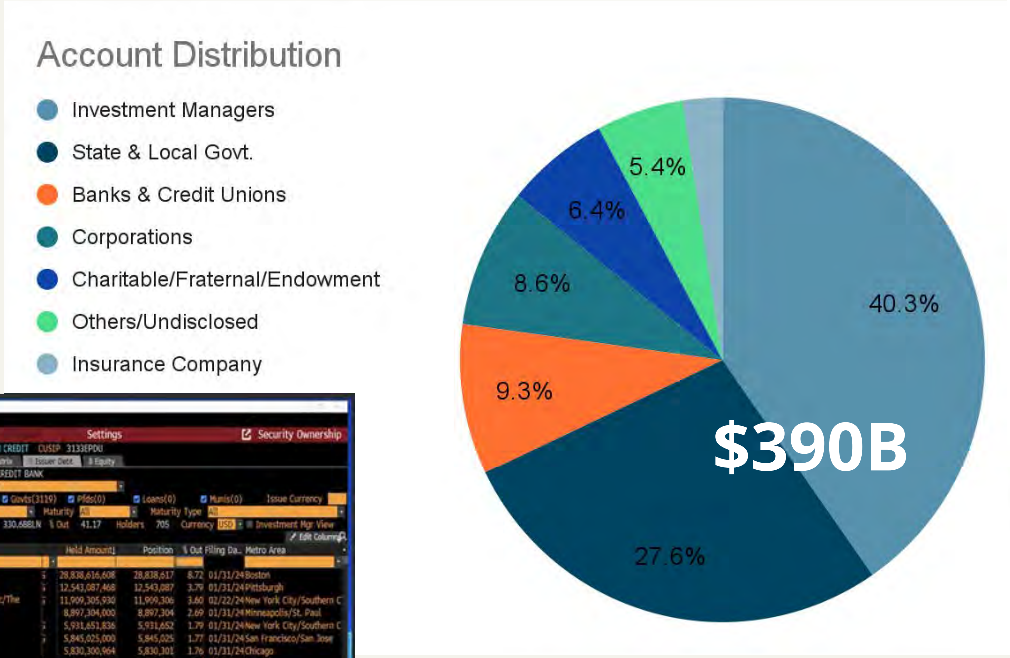
US Farmers and Ranchers in Action Report (Feb 2021): Transformative Investment in Climate-Smart Soil Agriculture

Farm Credit System Financing Flow





Approximately $390B worth of agricultural bonds were purchased by mostly US institutional investors (2022) with fiduciary req'ments



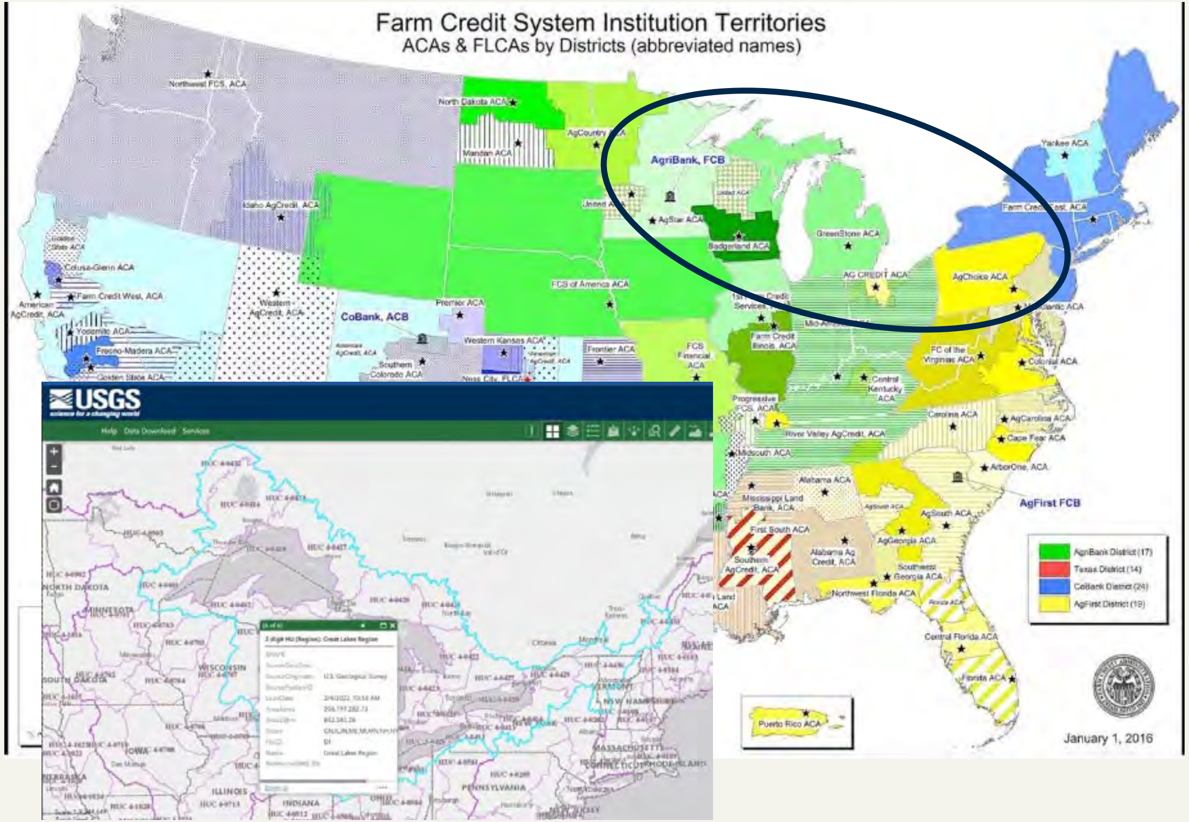

FFCB Float 02/22/24 Settings Security Ownership
FFCB Float 02/22/24 - FED FARM CREDIT CUSIP 3133EPDU
Issuer Name: FEDERAL FARM CREDIT BANK
Debt Inclusion Current Issuer
Asset Classes Corps(0) Govts(3119) Pfds(0) Loans(0) Munis(0) Issue Currency
Coupon All Maturity All Maturity Type All
Assets Held 3119 Total Debt 330.688LN % Out 41.17 Holders 705 Currency USD Investment Mgr View

	Holder Name	Held Amount	Position	% Out	Filing Da.	Metro Area
1	FMR LLC	28,838,616,608	28,838,617	8.72	01/31/24	Boston
2	Federated Hermes Inc	12,543,087,468	12,543,087	3.79	01/31/24	Pittsburgh
3	Goldman Sachs Group Inc/The	11,909,305,930	11,909,306	3.60	02/22/24	New York City/Southern C
4	US Bancorp	8,897,304,000	8,897,304	2.69	01/31/24	Minneapolis/St. Paul
5	Morgan Stanley	5,931,651,836	5,931,652	1.79	01/31/24	New York City/Southern C
6	Wells Fargo & Co	5,845,025,000	5,845,025	1.77	01/31/24	San Francisco/San Jose
7	Northern Trust Corp	5,830,300,964	5,830,301	1.76	01/31/24	Chicago
8	HSBC Holdings PLC	5,171,870,848	5,171,871	1.56	01/31/24	London
9	JPMorgan Chase & Co	5,156,229,768	5,156,230	1.56	02/22/24	New York City/Southern C
10	Invesco Ltd	4,551,736,909	4,551,737	1.38	01/31/24	Atlanta
11	Charles Schwab Corp/The	3,811,297,000	3,811,297	1.15	02/22/24	San Francisco/San Jose
12	North American Co for Life and He..	2,612,121,000	2,612,121	0.79	09/30/23	Unclassified
13	Vanguard Group Inc/The	2,309,220,492	2,309,220	0.70	01/31/24	Philadelphia
14	State Street Corp	2,306,196,248	2,306,196	0.70	02/22/24	Boston
15	Franklin Resources Inc	2,248,846,692	2,248,847	0.68	02/22/24	San Francisco/San Jose

Data Sources: Bloomberg

Represented are all outstanding bonds issued by Federal Farm Credit Banks Funding Corporation (FFCB)

Total of 7 Farm Credit Systems support 213 counties in the watershed



Data Sources:

- USGS National Map Watershed Boundary Data
- Farm Credit Administration Farm Credit Services FCS Institution Directory
- US Geological Survey Spatially-Referenced Regression on Watershed Attributes (SPARROW) model

Data Blending:

1. Determine all FCS in Great Lakes Watershed (GLW)
2. Match counties in both FCS area and GLW to integrate data points

About $100B of loans were in the Great Lakes Watershed, of which $38B related to farm business operations

GREENSTONE FARM CREDIT SERVICES, ACA
(dollars in thousands)

	2022	2021
CONDENSED STATEMENT OF CONDITION DATA		
Loans	$12,669,524	$11,492,173
Allowance for loan losses	40,889	55,056
Net loans	12,628,635	11,437,117
Investment in AgriBank		
Investment securities		
Other assets		
Total assets		

Components of Loans
(in thousands)

As of December 31	2022	2021	2020
Accrual loans:			
Real estate mortgage	$6,849,353	$6	
Production and intermediate-term	2,222,263	2	
Agribusiness	2,712,043	2	
Other	857,255		
Nonaccrual loans	28,610		
Total loans	$12,669,524	$11	

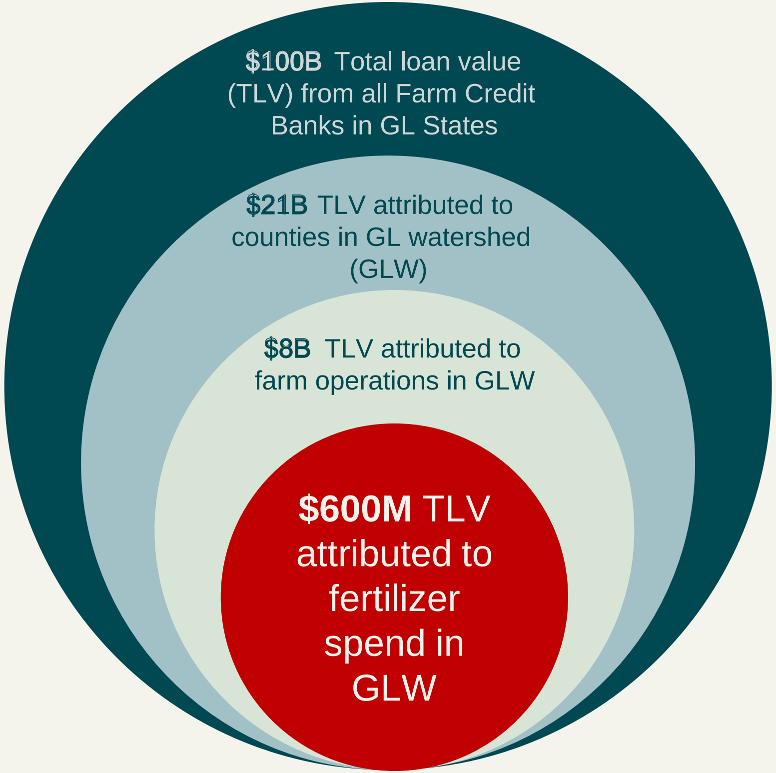
Table 1. Farm Expenditures, by Category, 2021
($ billion and percent of total)

	$ billion	percent[a]
Feed	65.2	16.6
Farm services	45.0	11.5
Livestock, poultry, and related expenses	42.4	10.8
Labor	36.8	9.4
Rent	32.0	8.1
Fertilizer, lime, and soil conditioners	29.5	7.5
Seeds and plants	22.3	5.7
Farm supplies and repairs	20.2	5.1
Agricultural chemicals	17.8	4.5
Taxes	14.7	3.7
Farm improvements and construction	14.5	3.7
Tractors & Self Propelled Machinery	17.6	4.5
Other Expenses	34.9	8.9
Total	**392.9**	**100**

Data Sources:
- FCS Annual Reports (2022)
- NASS US Farm Production Expenditure Report (2022)

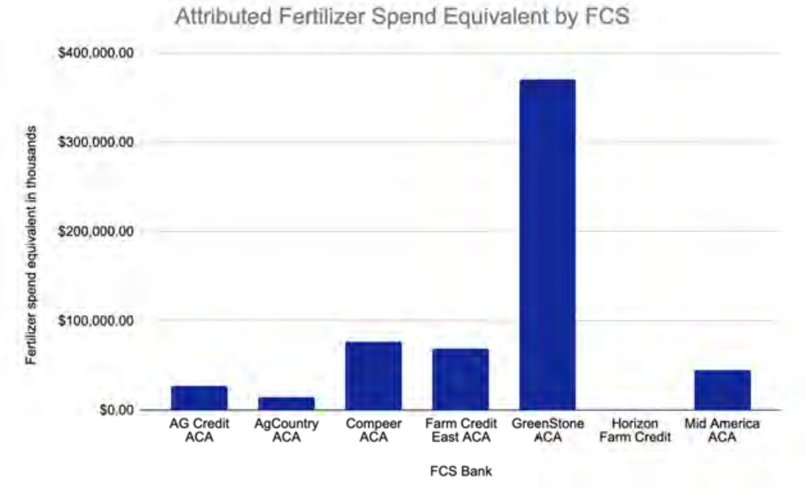
Data Blending:
1. Total loan values disaggregated to loan business and operations asset values
2. US national fertilizer spend value was then applied to estimate total loan value attributed to fertilizer spending

Total of $600M loans attributed to fertilizer spend in 2022 out of $100B total loan value (TLV) in all of the Great Lakes watershed

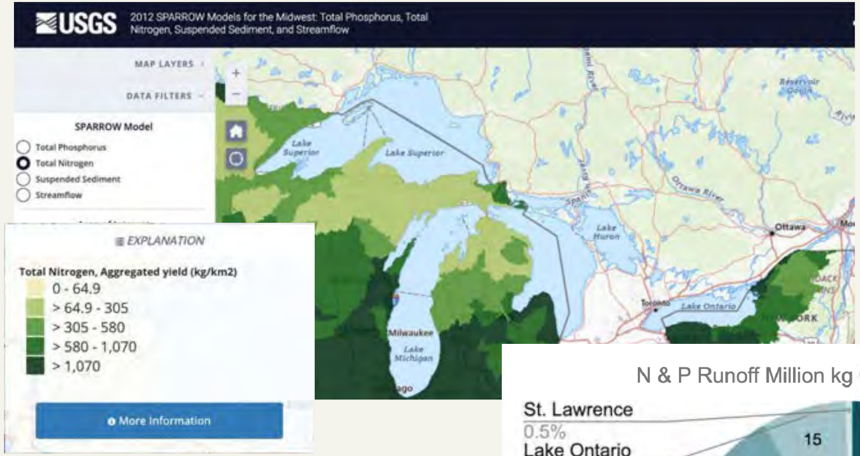


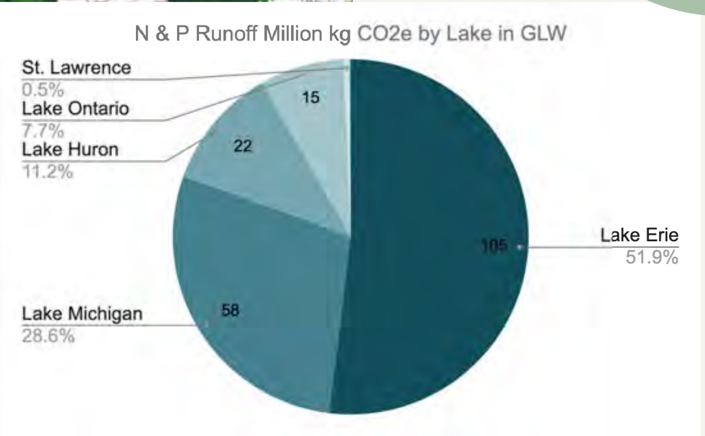
$$\sum [(ALV_{op\&agribus} / ((1/TCS) \times \%L)) \times FS] \quad (1)$$

Where: ALV= Applied Loan Value attributed to operations and agri business; TCS = total counties serviced ; %L = percentage of county that is within the Great Lakes Watershed (GLW) ; FS = National annual average fertilizer spend



There is a potential of 42M kg of N and 4M kg of P running off into the Great Lakes Watershed every year





41M kg/year total nitrogen (TN) loading potential in GLW

4M kg/year total phosphorus (TP) loading potential in GLW

Data Source:
US Geological Survey Spatially - Referenced Regression on Watershed Attributes (SPARROW) model

For every $330K in farm fertilizer financing, there may be up to 1 million kg of CO_2e in nutrient runoff into the Great Lakes

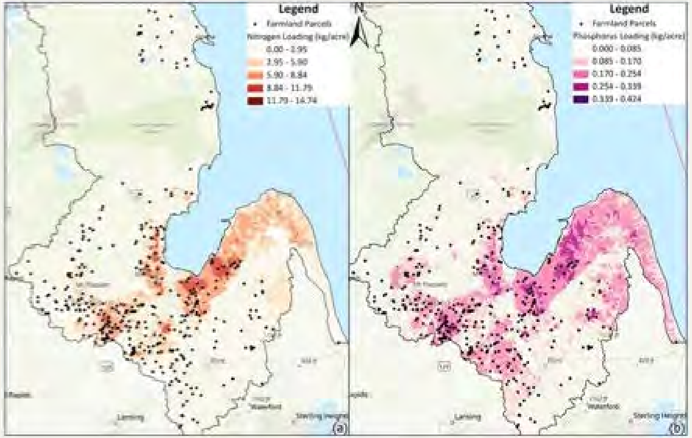
$600M Total Loan Value attributed to fertilizer spend

Conversion Source	N Rate (kg CO_2/kg N)	P Rate (kg CO_2/kg P)	GLW TN Runoff kg CO_2e	GLW TP Runoff kg CO_2e	Range of Estimated Total kg CO_2e
City of Winnipeg (South End Plant Process Selection Report)	4.62	2.7	190 M	11M	201M
International Fertilizer Society	8.798	N/A	362M	N/A	362M
Carbon Chain (Private entity)	2.6	1.7	107M	7M	114M

Challenges for determination of this CO_2e conversion

- These are 'at farm gate' conversion factors (Menegat et al., 2022)
- There is no Global Warming Potential (GWP) (IPCC AR6) for P or verified emission factor for CO_2e associated with P (Li et al., 2021)
- Further understanding how P contributes to increase CH_4 and N_2O emissions during eutrophication is needed (Ortiz-Reyes & Anex, 2018)

Externalities are not priced: The more fertilizer you use, the higher the yield and farm asset value (Data Source: Acre Value)



	Unit	Mean	Std
Dependent Variable			
Sale amount per acre	$/acre	3536.09	2301.61
Environmental Loading			
N loading	kg/acre	3.948	3.126
P loading	kg/acre	0.080	0.044
P loading (*Agricultural land)*	kg/acre	0.074	0.037
Land Productivity			
Average NCCPI	Unitless	56.99	10.54
Cultivated land % of parcel	%	0.874	0.15
Forest area % of parcel	%	0.05	0.07
Grassland area % of parcel	%	0.02	0.06
Soil organic carbon (SOC)	g/m^2	6775.625	2696.31
Root zone depth	cm	114.96	35.18
Root zone available water storage	mm	148.71	63.02
Soil loss tolerance factor	tons/acre year	4.61	0.57
Drought vulnerability	Binary	0.61	0.49
Well drained	Binary	0.17	0.38
Poorly drained	Binary	0.81	0.40
Prime farmland if drained	Binary	0.63	0.48
Not prime farmland	Binary	0.06	0.25

	Nitrogen loading		Phosphorus loading		Phosphorus loading (Agricultural land)	
	Coefficient	*p*-value	Coefficient	*p*-value	Coefficient	*p*-value
Environmental Loading						
Nitrogen loading	**75.22***	**0.099**	-	-	-	-
Phosphorus loading	-	-	**9583.78*****	**0.005**	**11680*****	**0.003**
Land Productivity						
Average NCCPI	-1.96	0.871	-5.82	0.631	-5.63	0.642
Cultivated land % of parcel	**3736.65*****	**0.001**	**3890.95*****	**0.001**	**3967.27*****	**0.001**

(Chung and Adriaens, 2023)

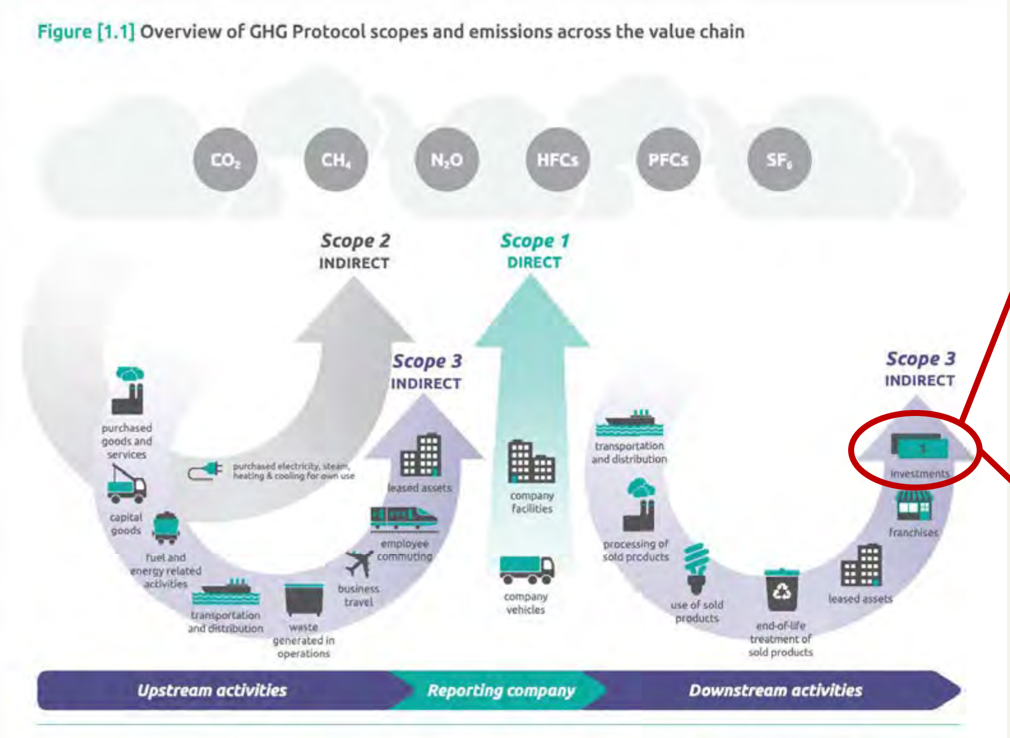
Fertilizer use is a major contributor to farm carbon emissions, and institutional investors are backing it

Fixed income (bonds) and lending support farm production

Eutrophication increases GHG emissions
(Li et al., 2021)

Intense production drives eutrophication in freshwater lakes
(Kerr et al., 2016)

Environmental externalities are not being accounted for, yet the capital flow to farms are financed emissions



Financed emissions are emissions **associated with investments and financing** by investors and financial institutions.

They are **Scope 3 emissions** and fall under the **GHG Protocol Category 15: Investments**

This is now being implemented through **IFRS S2**, which is governed by the **International Financial Reporting Standards**

(GHG Protocol, 2011) & (IFRS, 2025)

Green financing is one option to manage financed emissions

Financing Instruments

- Green/sust.-linked Bonds
- Green Insurance
- Green Investment funds
- Green Grants
- Sustainability-linked Loans

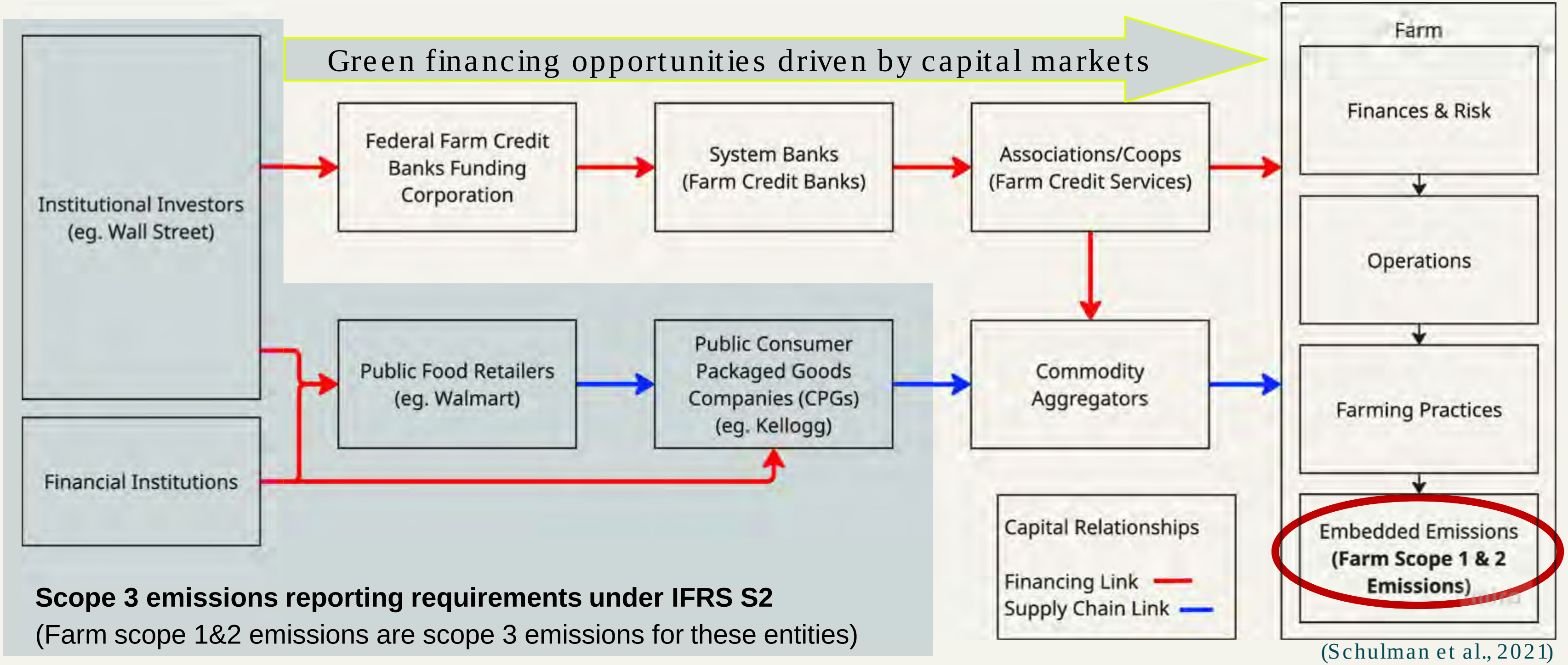
Specific Instruments for Capturing Emissions

- Carbon credits
- Carbon insets/offsets
- Carbon warrants
- Water quality accounting credits

Fiduciary Risk (investors): Green financial instruments **integrate capital and environmental performance** to capture the environmental externalities of economic growth.

(Ajayi et al., 2024)

Fiduciary risk management: Scope 3 emissions reporting and risk pricing cascades across financial supply chain



(Schulman et al., 2021)

Farmers can manage their scope 1 GHG through adopting best management practices (BMP)




But are they incentivised to do so?

Cover Cropping

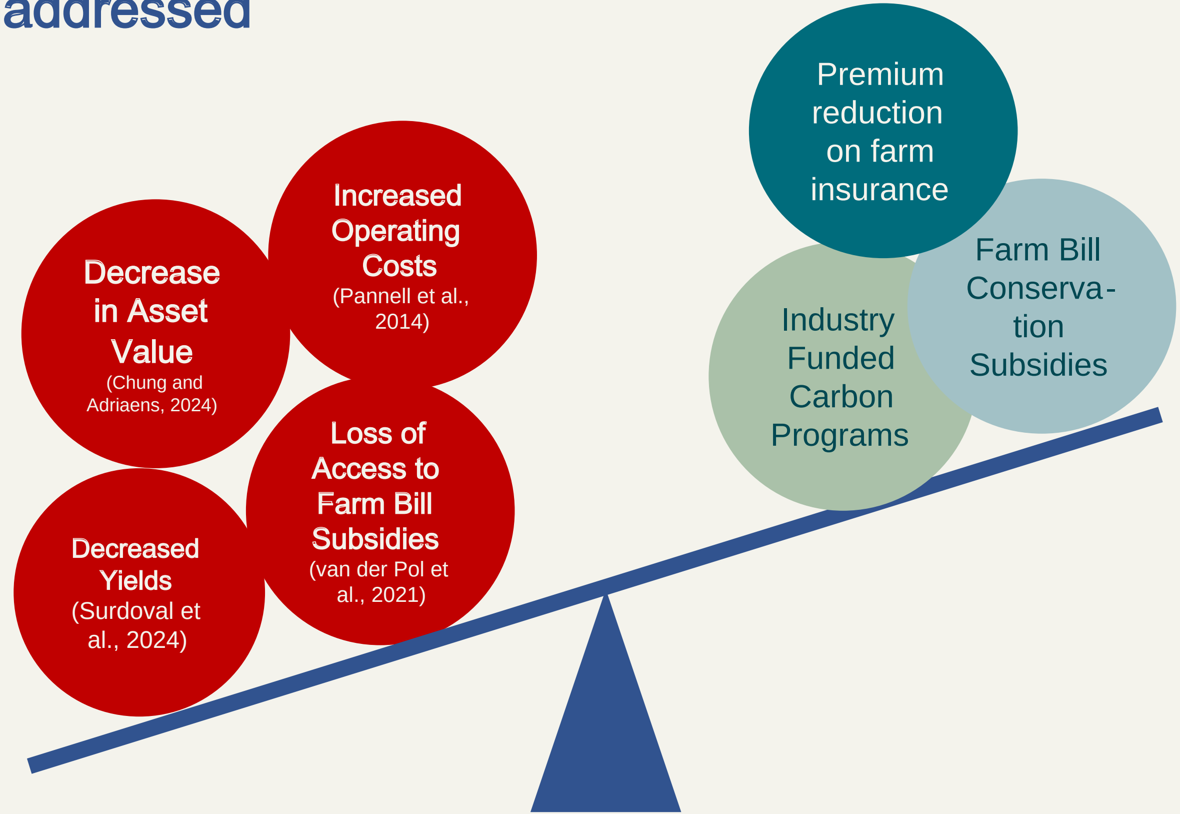
No Till/ Reduced Tillage

Precision Nutrient Management

Buffer zones and drainage

(Wilson et al., 2018)

Challenge: Financial transition risks are high for farmers and currently unaddressed



Objective

Develop and test a capital incentive stack through data monetization of fertilizer runoff to make farm income resilient

Sustainability -Linked Loans

Develop an informational framework to value farm land based on crop yield and carbon storage

Higher loan-to-value (LTV) ratio decreases interest on debt

Carbon-Based Asset Valuation

Use regression and causal machine learning models to quantify carbon stored and runoff as fertilizer – CO_2e

Runoff is scope 3 financed emissions and scope 1 operations

Parametric Transition Insurance

Actuarial models couple transition yield losses to corporate water quality benefit accounting (WQBA)

$5/acre (USDA pilot) □ pooled private insurance models (target N: $2-5/lb; P: $20-30/lb)

Capital Markets Pricing

Framework for Proof -of-Concept Deployment: Premia/Carbon

Digital Twin of the Farm

Conversion of physical entity to operational virtual copy

- Property shape file
- Hydrology
- Contamination
- Farm operations (crops, N/P application)
- Fertilizer to CO2-eq conversion

Ag. Financing Model

Capital structure of funding provenance

- Bond prospectus offered to the market
- Interbank lending rate and interest benchmark rate for loans
- Farm credit rate/credit rating

Farm P&L

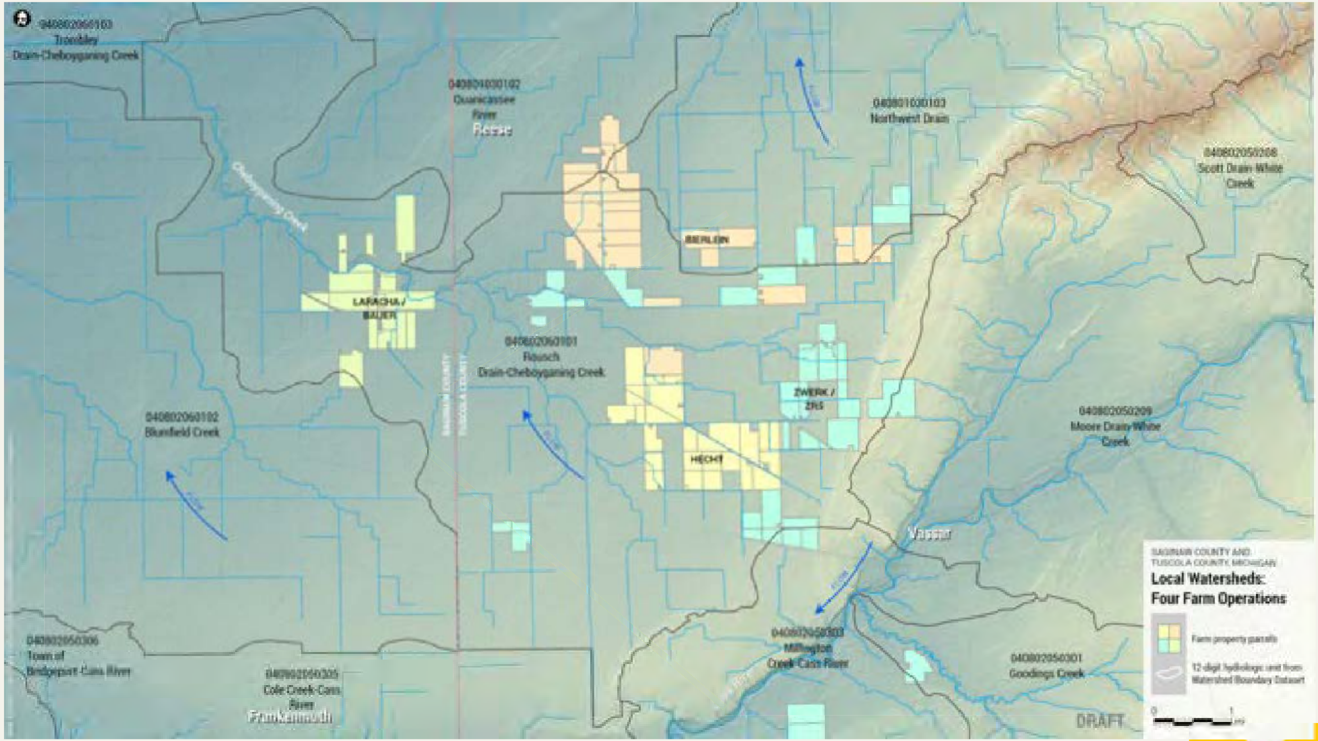
The farm's income statement and balance sheet

- Revenue - crop sales
- Cost of operations
- Form F disclosures
- Opportunity cost from not implementing regenerative practices

Scope 1 and 2 CO2e stack □ Scope 3 premium/credits □ Farm P&L benefit

Saginaw Bay Watershed Proof of Concept: Repricing Lending Risk from CO_2e in Nutrient Runoff (Sustainability-Linked Loans)

45% of land is used for agriculture
22 counties
1.4 million citizens
15,172 farms in 2022
3765 farms receive some form of government subsidy



Bay County Parcel ID	HUC8	Acres	Corn	Soybeans	Wheat	Other Crop	Agricultural N inputs (lbs/year)	Delivered N Load (lbs/year)	Agricultural P inputs (lbs/year)	Delivered P Load (lbs/year)	Carbon (MT-CO2e/year)
020-010-200-010-02	04080102	137	92%	2%	0%	1%	15934	498	3598	17	216
020-034-300-005-05	04080102	118	88%	5%	1%	1%	13368	428	3063	15	180
030-003-100-005-01	04080206	606	19%	11%	5%	4%	19727	3218	5166	69	243
030-046-200-005-00	04080206	289	93%	0%	0%	0%	33613	1534	7521	33	456
040-020-200-010-00	04080102	153	92%	3%	0%	0%	17804	557	4026	19	242
050-022-100-015-01	04080102	152	70%	26%	0%	0%	14074	552	3650	19	196
060-004-200-005-00	04080102	124	92%	8%	0%	1%	14807	451	3239	16	195
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Farmer A Profile:

Location: Bay County, Saginaw Bay Watershed
Farm Parcels: Four split amongst different sub basins
Total Acres: 1200 acres, 75% owned, 25% leased
Operations: Corn, Soy, Wheat
BMP: Cover crop & residue management

SWAT Model:

Predicts that Farmer A, could reduce N loads by 29% and 64% of P loads a year on average

Benefits of adoption

1. Have access to sustainability linked loan at a discounted rate
2. Potential carbon credit or insets from deploying BMP

Example Capital Market Benefit: Risk Pricing of Assets – Carbon -Backed Lending

		GLR	US
Wheat 2015-2024****	Unit	Per Acre	Per Acre
Yield	bushels	80.4	46.5
Price	$/bushel	5.66	5.7
Gross Revenue		455.064	265.05
Enterprise Size	planted acres	94	45
Estimated Carbon Value*	ton	2.25	2.25
Estimated Market Price of Carbon	$/ton	15	15
Potential Carbon Value		33.75	33.75
Average Operating Loan**	$	35000	35000
Loan to Value w/o Carbon		76.91	132.05
Loan to Value w/ Carbon		71.60	117.14

Green/sustainability-linked ag. bonds

Roll-up

Sustainability-Linked Credit Discount

- 1 to 2 notches on credit scale
- 25-75 basis points (bps)
- Current farm operating loan interest rate = 5.6%
- New loan: 4.9-5.3%

Financial Relationship Modeling: The Role of C -Warrants, Credits, and Carbon Asset -Backed Lending

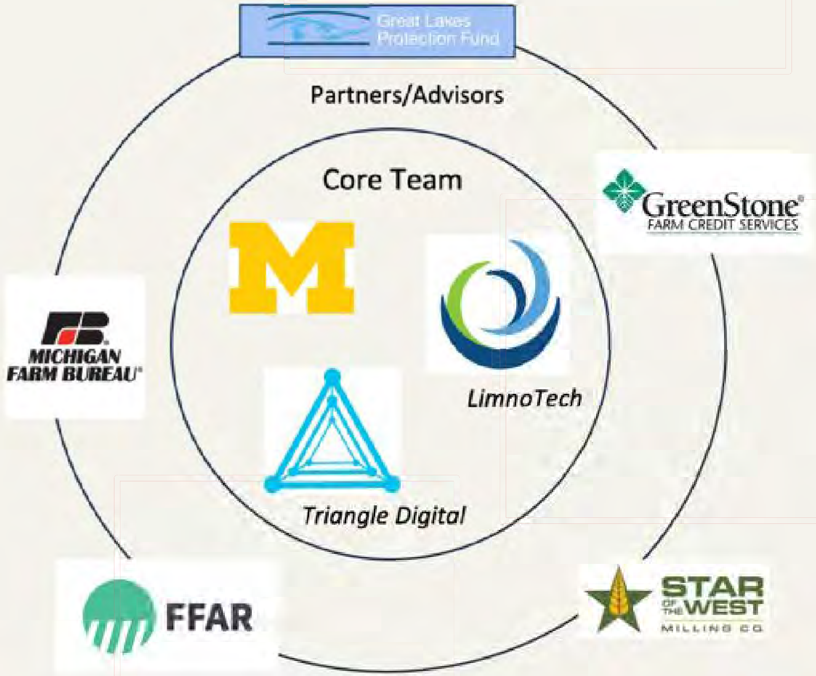
Conclusions:

1. Through the **value chain of Scope 3 financed emissions** we can attribute a **potential of 1 million kg of CO_2e for every $330,000 farm debt spent** on fertilizer a year in the Great Lakes watershed.

1. This value can be **redistributed** through **sustainability-linked financing** via the channels of debt or insurance to **incentivize the adoption of regenerative agricultural practices**.

1. The **integration** of **farm operations data with spatial data** (hydrology) enables the calculation of environmental impact of different farm operations that can **lead to the repricing of financial instruments.**

1. **Farmers** have an **opportunity to improve their financial and environmental resilience** if they are offered **sustainability-linked financing instruments.**



Thank you!

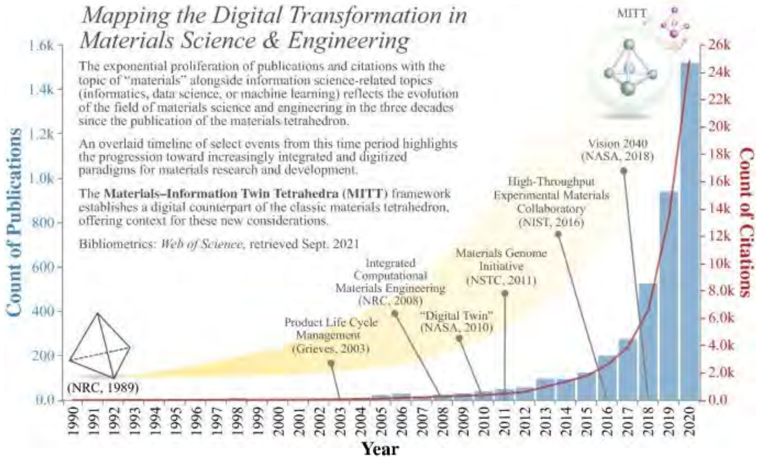
Questions?

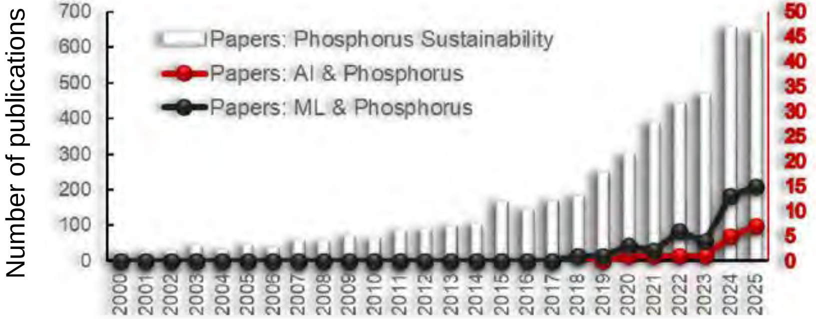
Evaluating AI Tools for Phosphorus Sustainability

Yaroslava Yingling
Associate Department Head &
Kobe Steel Distinguished Professor
North Carolina State University

Rise of AI

Data Science and Machine Learning





Deagen et al 47 MRS Bulletin (2022) 379

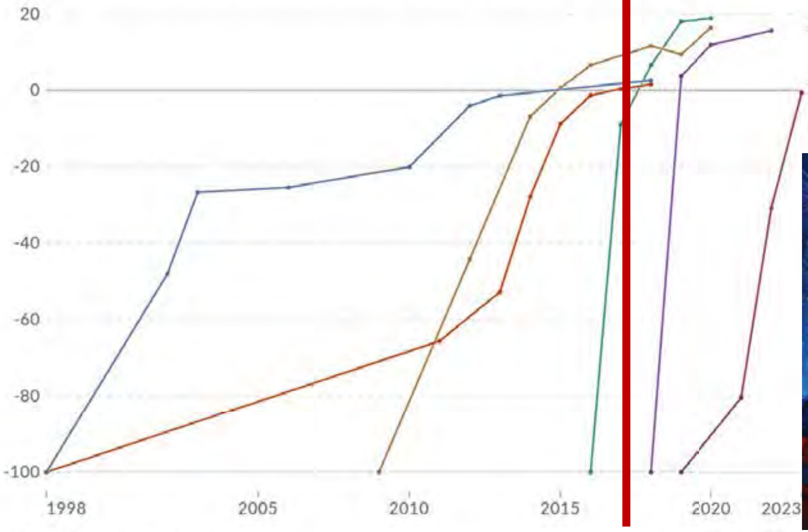
+

2017 Transformer Revolution –
Google's approach to solving NLP problems

Test scores of AI systems on various capabilities relative to human performance

Our World in Data

Within each domain, the initial performance of the AI is set to –100. Human performance is used as a baseline, set to zero. When the AI's performance crosses the zero line, it scored more points than humans.



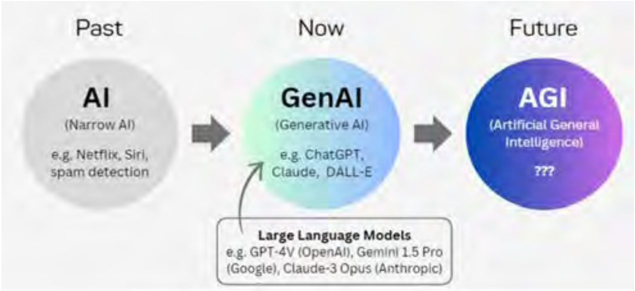
Data source: Kiela et al. (2023)

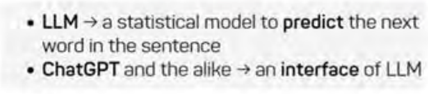
OurWorldinData.org/artificial-intelligence | CC BY

Note: For each capability, the first year always shows a baseline of –100, even if better performance was recorded later that year.

https://lifearchitect.ai/iq-testing-ai/

What are Transformers? Large Language Models?





Transformers:

AI models that process text in chunks (tokens).
Predict the next word based on context.
Use auto-regressive process → each new word depends on the words before it.

Large Language Model (LLM):

Transformers trained on huge amounts of text.
Can answer questions, write summaries, and generate human-like text.
Handle vast datasets and complex language tasks.

terns, context,

Rise in reasoning and problem-solving capabilities of LLMs, evaluated using the Massive Multitask Language Understanding (MMLU) benchmark—a test spanning 57 academic subjects such as mathematics, US history, computer science, and law.

A 3B model has read over a million books … and remembers patterns from all of them.

ChatGPT-5 model (mainstream ~**330B**) absorbs vastly more data (trillions of words from millions of books, articles, web pages, lectures, images, and code) and also generates deep insights, synthesizes new ideas, reasons across fields, and solves complex problems at near-expert levels by leveraging far more nuanced abstractions, broader context, and multi-step reasoning.

How LLM generates the Answer

- **Input Parsing:** The model breaks down your question into tokens (words or word pieces) and recognizes that you're asking for a specific **scientific fact**—a **material property**.
- **Pattern Recognition:** The LLM doesn't "look up" the answer in a database in real time. Instead, it recalls **patterns it learned during training**, from phrases like "the band gap of silicon is...“
- **Probability-Based Prediction:** The model then uses statistical modeling to **predict the most likely next words** based on: The structure of your question and the context of similar questions it has "seen" in training.
- **Limitations and Uncertainty: It doesn't "know" if that answer is true or current**—it's just highly probable based on past data. It **can make mistakes** if trained on conflicting, outdated, or low-quality information.

“What percentage of global phosphorus pollution in freshwater comes from agriculture?”

LLM-style answer:

“About 80% comes from agriculture.”

-because “80%” is a commonly repeated ballpark figure across environmental discussions online

Scientific perspective:

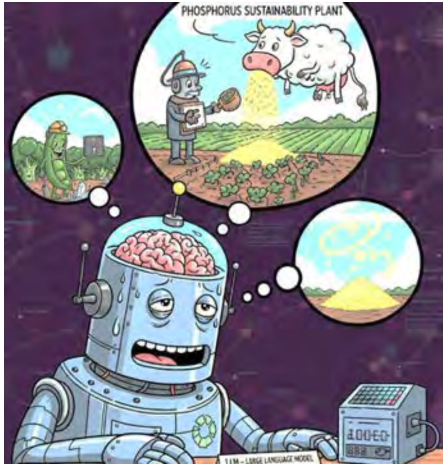
*The numbers are **much more variable***:

- Agriculture contributes ~***50–60%*** of total phosphorus loads globally on average.
- In highly industrialized regions, municipal wastewater can contribute ***30–40%*** or more.
- Local watersheds may flip the dominance (e.g., >60% from wastewater in urban basins).

- The **LLM guess**: neat, round, “probable” → **80% agriculture**.
- The **scientific truth**: messy, regional, and evidence-based → ~50–60% agriculture *globally*, but wastewater dominates in some places.

What is the rate of AI hallucinations?

Hallucination in AI refers to the generation of outputs that may sound plausible but are either factually incorrect or unrelated to the given context.



Year / Model	Hallucination Rate (varies by task)
GPT-2 / GPT-3 (2019-2021)	20–60% on factual QA tasks
GPT-3.5 (2022)	15–30% in open-domain factual tasks; ~50%+ false citations
GPT-4 (2023)	~10–20% factual hallucination in open QA; 15–25% citation errors
GPT-4o (2024)	~12–13% hallucination in composite tasks
GPT-5 (2025)	**~1–2%** hallucination on “LongFact” benchmarks; **~9–10%** in broad, mixed tasks

Human **expert** error rates often < 5% (depends on fatigue, clarity, etc.)

The rate of hallucinations in LLMs depends a lot on:

- Which model (GPT-4o, GPT-5, Gemini, Claude, etc.)
- Which task (factual Q&A, citations, math, coding, etc.)
- Which benchmark is used to measure hallucinations

GPT-5 is approaching human level in these kinds of tasks for well-defined, explicit information. Human experts are still better at interpretive or ambiguous tasks

Why General-Purpose LLMs Fall Short in Phosphorus Sustainability?

- **Fragmented Knowledge and Hallucinations**:
  - LLMs generate the *most probable* answer, not the *most accurate*.
  - Benchmarks used to evaluate hallucination rates are generic, not tailored to phosphorus science.
- **Data Quality Issues**:
  - General LLMs ingest data from podcasts, blogs, and low-quality papers.
  - This risks amplifying *“garbage in, garbage out”* for scientific use.
- **Poor Domain Adaptation:**
  - Struggle with technical specificity (e.g., phosphate forms, pH, sorbent concentration).
  - Without fine-tuning, outputs are oversimplified or inaccurate.
  - Most LLMs don’t cite sources or explain reasoning: hard for researchers and policymakers to verify answers.
  - Produce generic answers, not tailored to farmers, policymakers, or researchers.
- **Cost and Inefficiency**:
  - Training and running large models on broad corpora is expensive.
  - Domain-specific tools are smaller, cheaper, and more energy efficient.
- **Privacy and Sharing**:
  - General LLMs may share or surface sensitive data unintentionally.
  - Domain-specific models can be curated, secure, and transparent.

We need **domain-specific, evidence-grounded AI software** → optimized for trusted data, lower cost, transparency, and scientific accuracy.

How can AI help with P Sustainability?

Precision Agriculture Optimization

Goal: Achieve a 15-20% reduction in phosphorus fertilizer use.

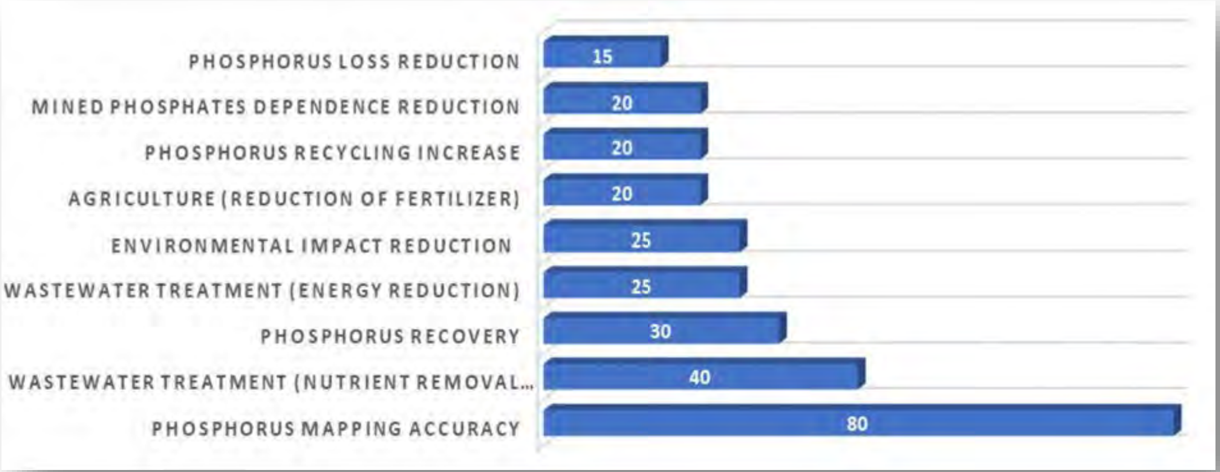
AI Role: Analyze soil data, crop needs, and environmental factors to optimize fertilizer application.

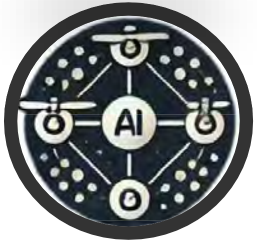
Phosphorus Recovery

Goal: Enable a 30% increase in phosphorus recovery from wastewater and other waste streams.

AI Role: Optimizes recovery processes and identifies new recovery opportunities.

Projected impact of AI tools by 2030 (%)





Phosphorus Mapping and Management

Goal: Improve soil phosphorus content prediction accuracy to over 80%.

AI Role: Uses predictive mapping and data analytics to monitor soil nutrients and plan efficient phosphorus application.

Wastewater Treatment Efficiency

Goal: Increase nutrient removal efficiency by 30-40% and reduce energy use in treatment plants by up to 25%.

- **AI Role:** Increase nutrient removal efficiency and reduces energy-intensive processes like aeration through real-time optimization.

To use AI approaches for P sustainability we need to connect data on all levels of information

Convergent AI approach

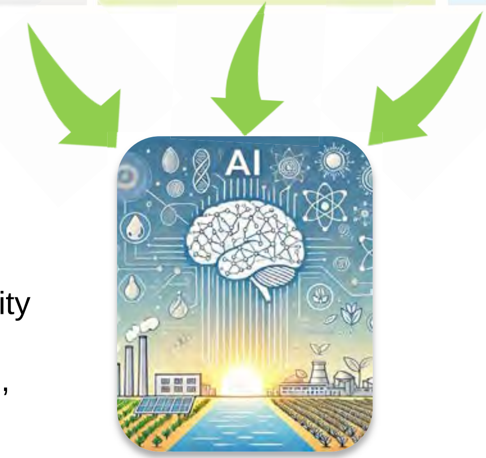
Phosphorus sustainability spans **molecular to global scales** and many disciplines.

Fragmented Data Landscape

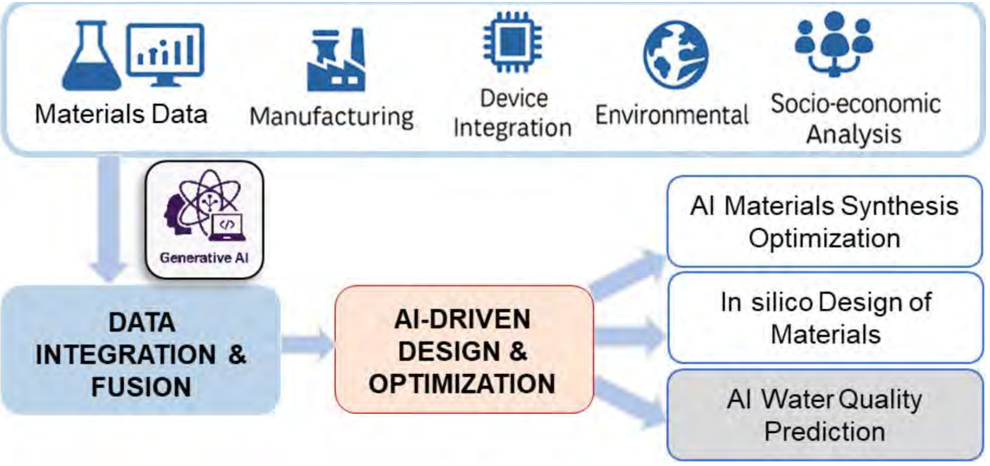
- Each scale uses different measurements, formats, and models.
- Hard to integrate insights across scales (e.g., from phosphate binding at nanoscale to farm practices to global trade).
- Traditional databases and tools don't "talk" to each other.

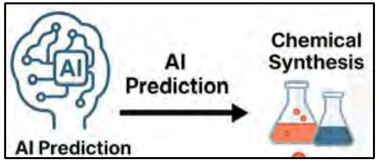
Ultimate Vision:

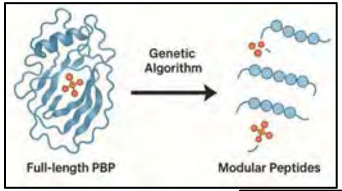
- A convergence informatics platform that integrates ALL data on P sustainability: materials, water, agricultural, policy data, ...
- AI helps bridge scales and accelerate discovery
- AI can find hidden links (e.g., how molecular adsorption impacts watershed models). Detects non-obvious correlations in sustainability outcomes.
- Democratize insights: Tailors outputs for stakeholders (researchers, farmers, policymakers).

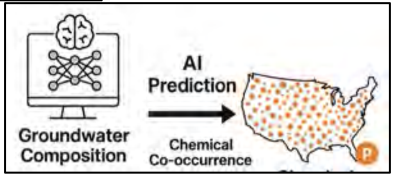


Convergence Informatics

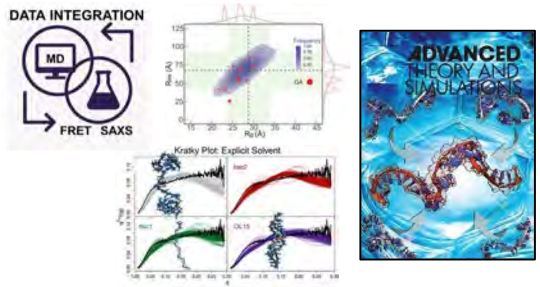




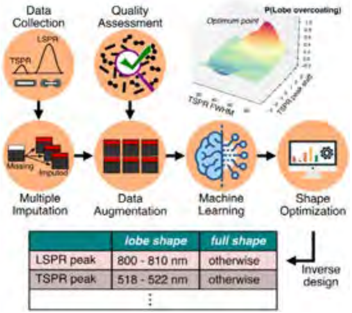




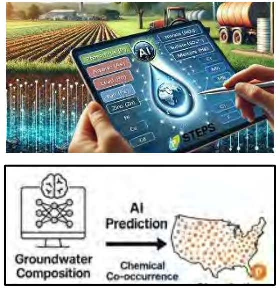
DATA INTEGRATION: STRUCTURE PREDICTION WITH MD AND EXPERIMENTS



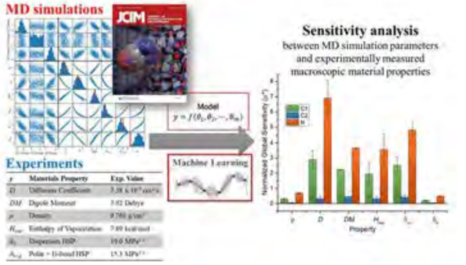
SMALL DATA



ML-BASED DATA IMPUTATION



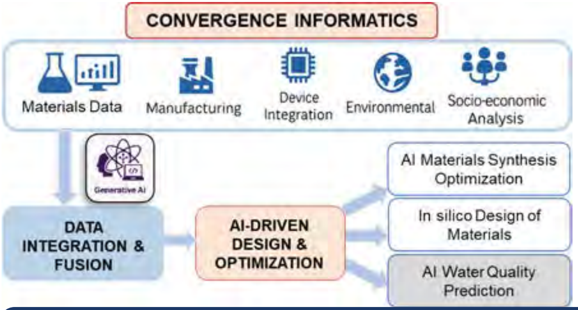
DATA FUSION: UNCERTAINTY QUANTIFICATION



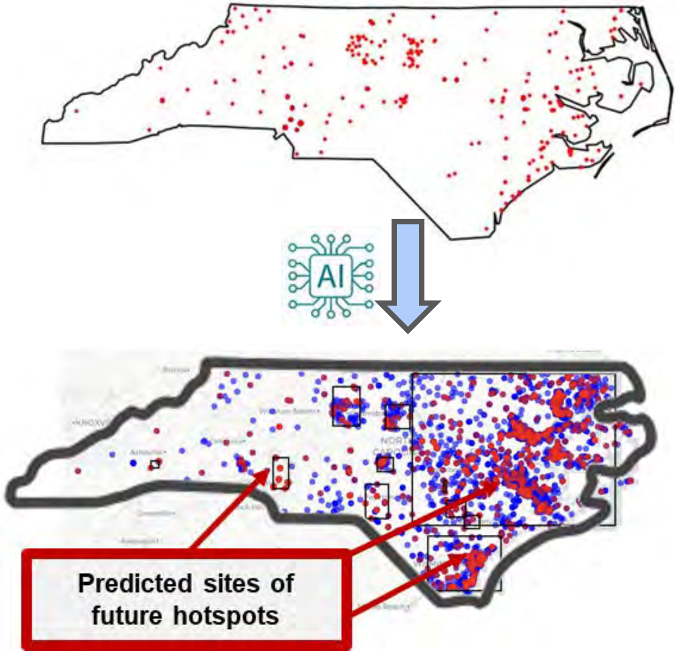
A. U. Mahmood, et al, Multiple Data Imputation Methods Advances Risk Analysis and Treatability of Co-occurring Inorganic Chemicals in Groundwater, *Environmental Science & Technology* (2024) ; T. J. Oweida et al, Resolving Structure of ssDNA in Solution by Fusing Molecular Simulations and Scattering Experiments with Machine Learning, *Advanced Theory and Simulations* 6 (2023) 2300411; J. S. Peerless, et al, Uncertainty Quantification and Sensitivity Analysis of Partial Charges on Macroscopic Solvent Properties in Molecular Dynamics Simulations with Machine Learning Model, *ACS Journal of Chemical Information and Modeling* 61 (2021) 1745-1761; K. Schatz, et al, IEEE BigData, 2023, 2965-2974

AI Predicts Highest-Risk Groundwater Sites to Improve Water Quality

Millions of Americans rely on groundwater every day, yet testing for naturally occurring pollutants like arsenic is complex and expensive.



Example: Field Data (P) concentration



Data: 140 years of sparse groundwater tests

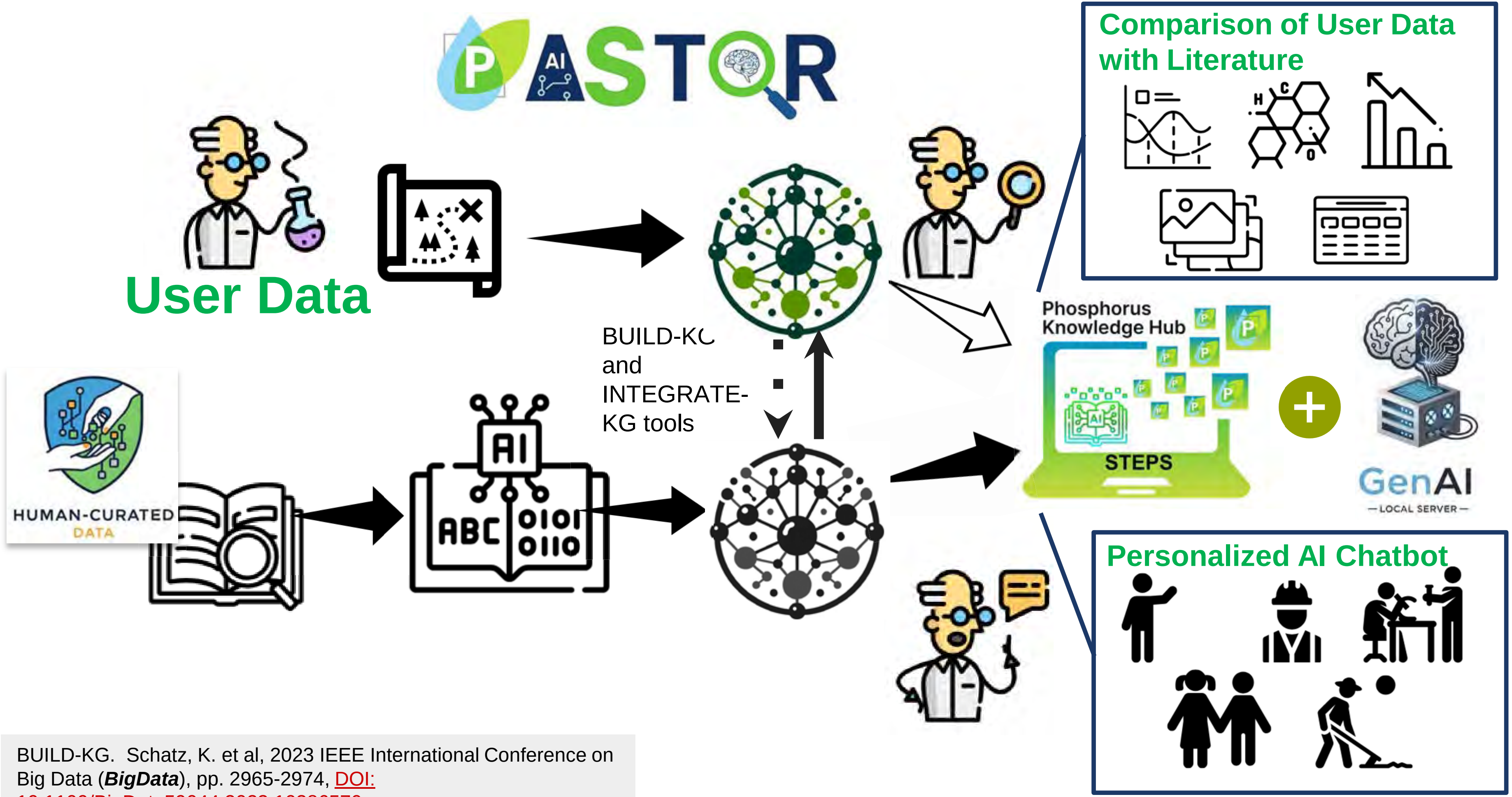
Key Results:

- AI was able to impute a complete groundwater testing dataset—filling in missing values across millions of samples.
- This enabled full-scale risk assessment without the cost and delay of physical sampling.
- The result: more accurate risk prediction, better resource allocation, and smarter decisions on where to test next.

This work was supported by the Science and Technologies for Phosphorus Sustainability (STEPS) Center, a National Science Foundation Science and Technology Center (CBET-2019435)

A. U. Mahmood, et al, Multiple Data Imputation Methods Advances Risk Analysis and Treatability of Co-occurring Inorganic Chemicals in Groundwater, *Environmental Science & Technology* (2024) ;

Phosphorus AI for Scraping, Tracking, Optimization, and Research (PASTOR)



BUILD-KG. Schatz, K. et al, 2023 IEEE International Conference on Big Data (***BigData***), pp. 2965-2974, DOI: 10.1109/BigData59044.2023.10386570

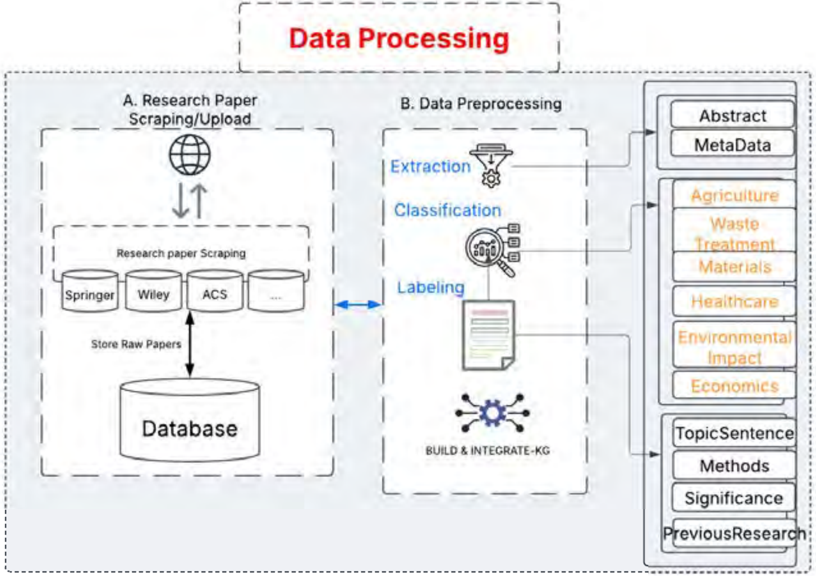
Human-curated Data

Human-curated Data is important because it filters out low-quality or misleading sources, ensuring the AI retrieves **trusted, evidence-based knowledge** instead of amplifying noise.

HUMAN-CURATED DATA

- **Keyword filter**: Title/abstract includes phosphorus terms *(e.g., “phosphorus recovery,” “phosphate removal,” “nutrient cycling”)*
- **Open-access check**: Verified through our OA detection framework
- **Expert validation**: Human-in-the-loop review for relevance
- Started from 6,556 publications ended with **3,297**
- Keyword trends: most frequent: “phosphorus” (374), “phosphorus recovery” (217), followed by “wastewater treatment” (206), “phosphorus removal” (173)

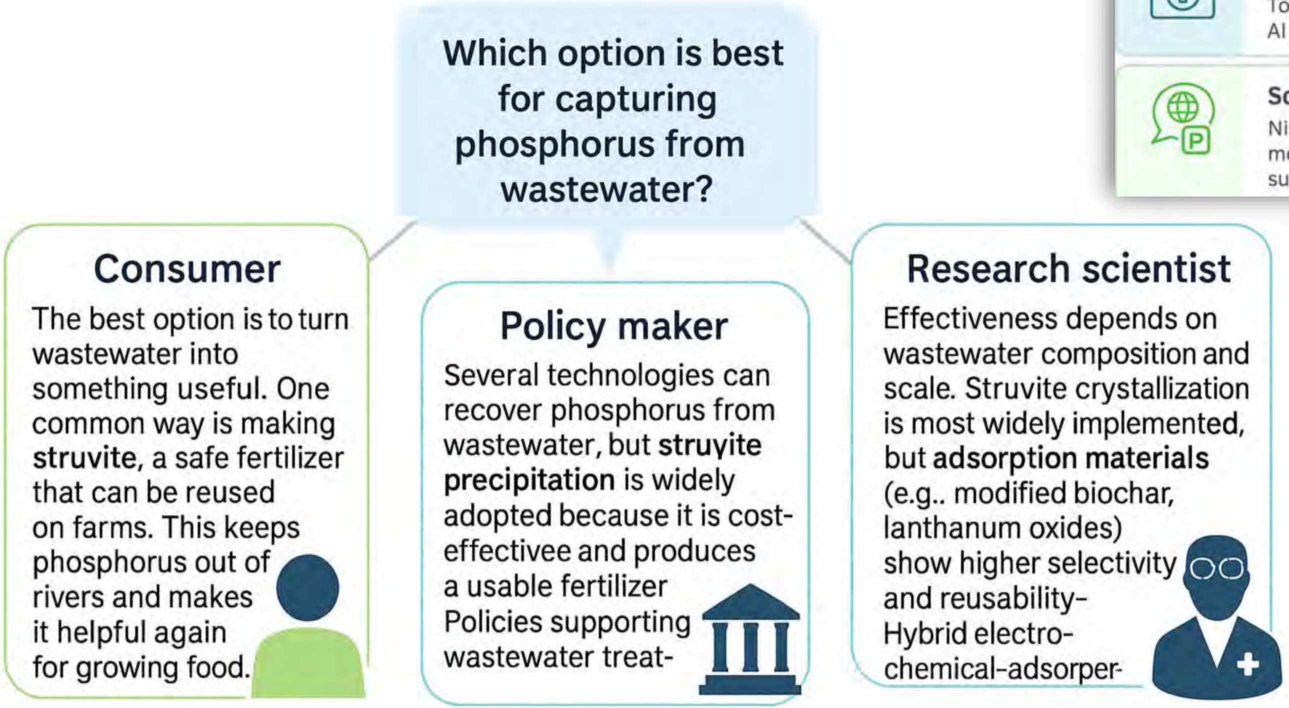
Data then extracted, classified, and labeled

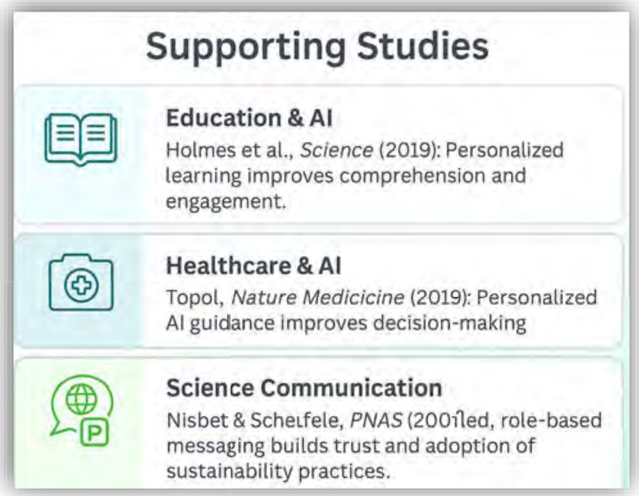


AI Personalization

AI-powered personalization can turn complex sustainability science into actionable pathways across diverse audiences

PASTOR transforms generic knowledge into role-specific, actionable insights





AI-Powered Podcasts for P Research & Accessibility

AI podcasts turn specialized phosphorus research into accessible, engaging, and shareable content — bridging the gap between experts and society.

- **Accessibility** → makes complex science understandable for non-experts through clear, spoken explanations.
- **Multimodal learning** → complements text and visuals, engaging auditory learners.
- **Wider reach** → podcasts can be shared on platforms (Spotify, Apple, YouTube), extending science communication beyond academic circles.
- **Personalization** → AI can generate podcasts tailored to a listener's role (consumer, policymaker, researcher).
- **Efficiency** → automatic conversion of papers, reports, or chatbot outputs into short audio summaries.
- **Continuous updates** → AI can produce on-the-fly podcasts summarizing new publications or data.

Justin Baker, Nathan Schunk, Matt Scholz, Ashton Merck, Rebecca Logsdon Muenich, Paul Westerhoff, James J. Elser, Owen W. Duckworth, Luke Gatiboni, Minhazul Islam, Anna-Maria Marshall, Rosangela Sozzani, and Brooke K. Mayer
Environmental Science & Technology Letters 2024 11 (6), 493-502
DOI: 10.1021/acs.estlett.4c00208

PASTOR

***P**hosphorus **AI** **S**craping, **T**racking, **O**ptimization, and **R**esearch*

The Phosphorus Knowledge Hub is a comprehensive platform designed to support phosphorus research through AI-powered tools, extensive paper collections, and collaborative features. Our platform combines traditional research methods with cutting-edge AI technology to enhance your research experience.

PASTOR Capabilities

- **Chatbot interface** → easy, conversational access to curated phosphorus knowledge
- **Trusted answers** → drawn from expert-validated, peer-reviewed sources
- **Audio podcasts** → auto-generated explanations in plain language
- **Plotting & visuals** → simple graphs to help interpret sustainability data
- **Your data, your papers** → upload personal data or documents for tailored insights
- **Personalized outputs** → guidance adapted to lifestyle, context, and choices

PASTOR empowers P-community to **learn, explore, and act** using reliable science — through chat, audio, visuals, and personal data integration.

Future: Where PASTOR is Headed

- **More ML-powered insights** → deeper integration of machine learning across scales
- **On-the-fly anomaly detection** → flag unexpected results in uploaded data or literature
- **Dynamic data fusion** → combine lab results, field data, and policy reports in real time
- **Predictive modeling** → forecast phosphorus flows under different scenarios
- **Multi-modal interaction** → richer outputs (chat + audio + plots + knowledge graphs)
- **Enhanced personalization** → role-specific dashboards for consumers, policymakers, and researchers

Example: Other **Future** PASTOR capabilities for wastewater treatment

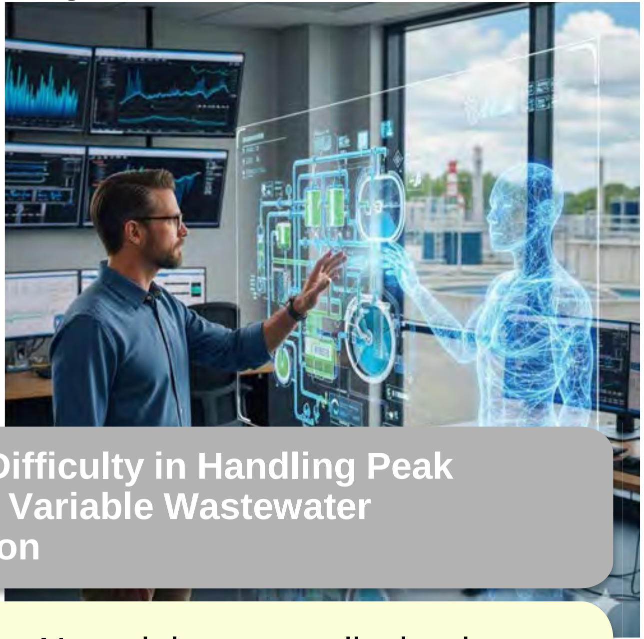
PASTOR could interact with operator, analyze data, provide real-time guidance, and simulate scenarios to improve decision-making.

Problem: Delayed Detection of Water Quality Issues

AI Solution: On the fly AI-anomaly detection can identify water quality issues immediately, enabling faster response times

Problem: Inefficient Phosphorus and Nutrient Recovery

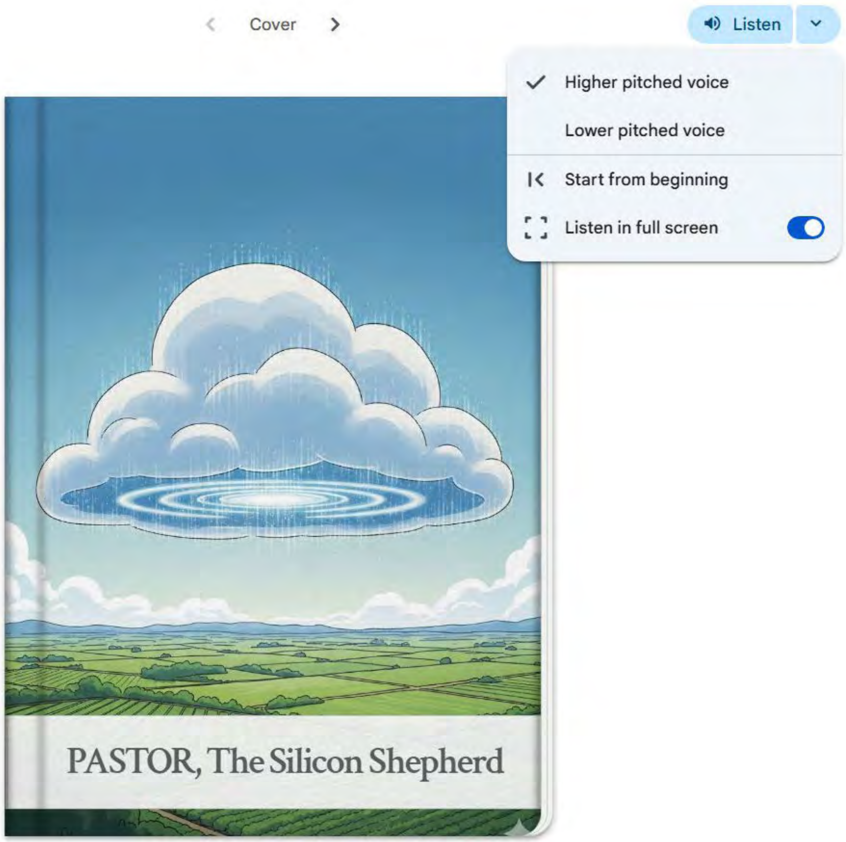
AI Solution: AI can analyze and optimize chemical usage and recovery processes, improving yield and sustainability in nutrient mining.



Problem: Difficulty in Handling Peak Loads and Variable Wastewater Composition

AI Solution: AI models can predict load fluctuations, allowing operators to prepare by allocating resources effectively and adjusting treatment parameters.

Bells and whistles: Storybooks, Podcasts, Videos, and Songs



Generate customized videos and other promo materials in less than 2 min!

Summary

With PASTOR and emerging AI tools, phosphorus research becomes faster, more accurate, and more collaborative — driving innovation for a sustainable future.

- **Accelerates discovery** – AI organizes thousands of scattered papers into structured, searchable knowledge.
- **Connects disciplines** – bridges agriculture, materials, wastewater, and policy for true systems-level insights.
- **Enhances accessibility** – tailored outputs for consumers, policymakers, and researchers.
- **Goes beyond text** – integrates data, tables, figures, and visuals for deeper understanding.
- **Continuous improvement** – human feedback + domain fine-tuning make PASTOR and other AI tools smarter over time.

This material is based upon work supported by the Science and Technologies for Phosphorus Sustainability (STEPS) Center, an NSF Science and Technology Center, under NSF Cooperative Agreement No. CBET-2019435

STEPS CI Team: A. Gulyuk, B. Allen, D. Pendyala, E. Lobaton, G. Khatri, N. Abu Zaid, S. Pinky, R. Chirkova, C. Williams, R. Lakshmi-Ratan and alumni

PF25

Please share your thoughts about AI by scanning this QR code.

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

Phosphorus Forum AI Session

Coffee Break Sponsor

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Managing Emerging Contaminants in the Circular Bioeconomy

Rebecca Muenich
Associate Professor
University of Arkansas

Janine Burke-Wells
Executive Director
NEBRA

Ivan Cooper
National Water/Wastewater Practice Leader
Civil & Environmental Consultants, Inc.

Andrew Carpenter
Soil Scientist
Northern Tilth

Emily Remmel
Senior Director of Regulatory Affairs
NACWA

PF25

Managing Emerging Contaminants in the Circular Bioeconomy

Introducing the topic

Becca Muenich, University of Arkansas
rlogsdo@uark.edu

Why Emerging Contaminants?

These farmers didn't know their land was contaminated with PFAS. Now they're suing.

Some states are ordering farms to stop selling their products after testing positive for the "forever chemicals."

Published Aug. 20, 2024

Local & State News Business Health

A forever farm is no match for forever chemicals

A fourth-generation farmer running an organic dairy farm in Fairfield lost his livelihood when his milk and lands tested hot for PFAS contamination. 'It got us good.'

Posted June 11, 2023 Updated June 11, 2023

Penelope Overton
Press Herald

Texas farmers say sewage-based fertilizer tainted with "forever chemicals" poisoned their land and killed their livestock

> The fertilizer was promoted as an environmental win-win for years. An untold number of farmers and ranchers across Texas have spread it on their land.

BY ALEJANDRA MARTINEZ DEC. 2, 2024 5 AM CENTRAL

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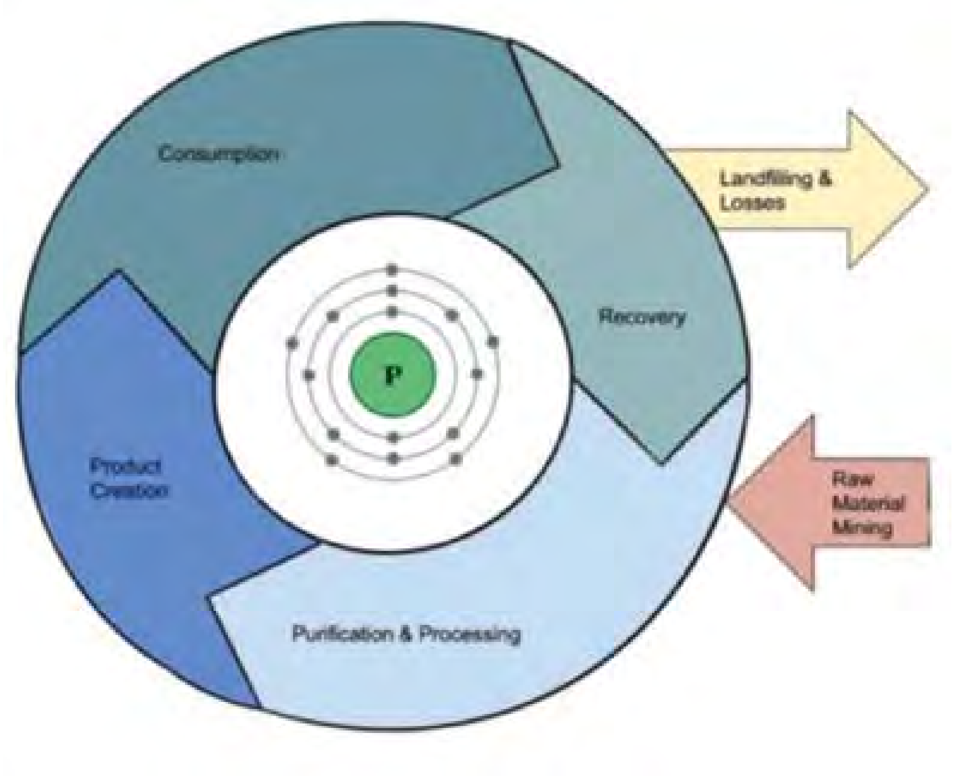
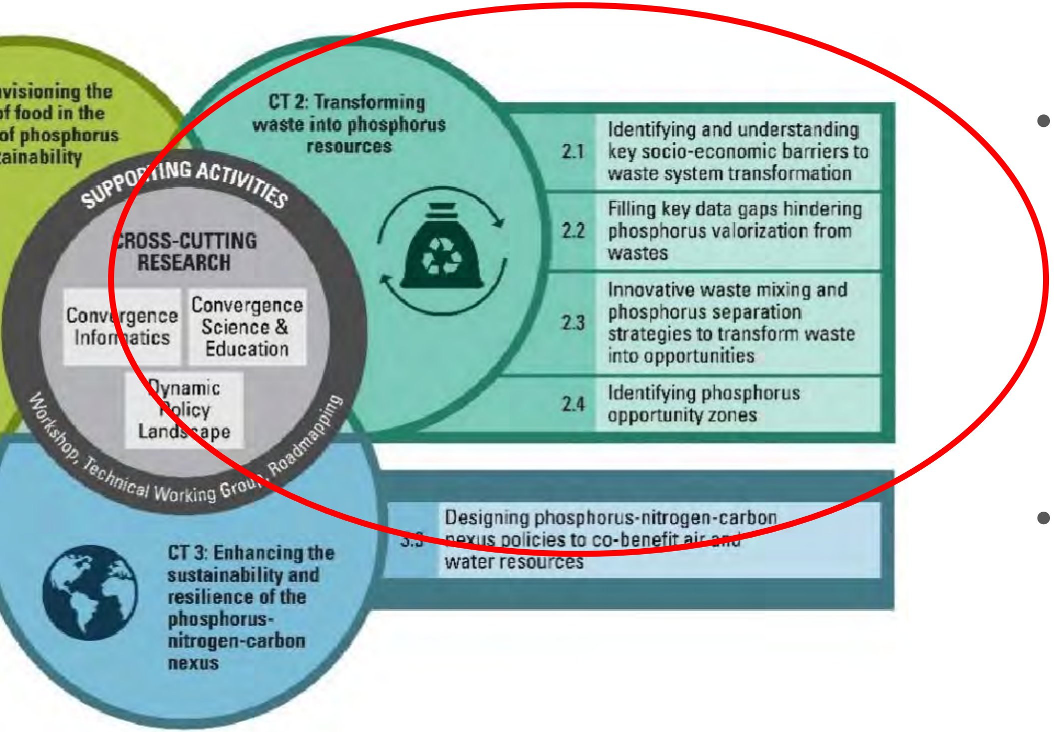
Impacts to development of a circular bioeconomy



Connection with STEPS Research

Key concern for our convergence theme of Waste valorization for a circular bioeconomy



- **Westerhoff: Fate of phosphorus and other valuable materials during application of PFAS destruction technologies applied to wastewater sewage solids or biosolids**
- **Muenich: P opportunity zones**

Topics we’ll delve into today

Scale and scope of the problem

Regulatory complexities across many emerging contaminants

Technological advances for addressing emerging contaminants

What agencies are doing to address this issue

Managing Emerging Contaminants in the Circular Bioeconomy

Janine Burke-Wells
Executive Director
NEBRA

Panel Discussion
The Phosphorus Forum

September 17, 2025

Managing Emerging Contaminants in the Circular Bioeconomy

Our "Grand Challenges"

- Soil Health
- Climate Change
- Water (quality and quantity)

The circular economy is the response to these challenges

Circular Economy Principles

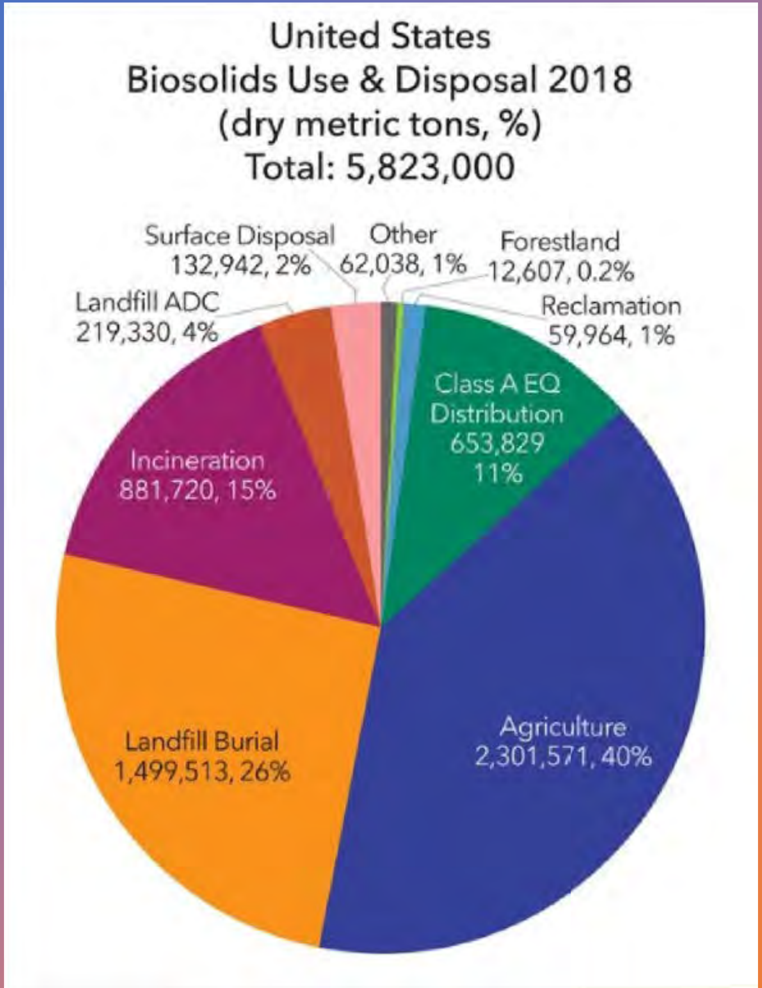
- Eliminate waste and pollution
- Circulate products and materials
- Regenerate nature

Water Environment Federation®
the water quality people®

Source: Ellen MacArthur Foundation

Why recycle biosolids?

- It's the most sustainable!
- Some proven **Benefits** include:
  - enhancing soil health
  - recycling of nutrients (macro, micro)
  - reducing chemical fertilizer use
  - improving drought resistance
  - Increasing soil carbon content
- **Concerns** include:
  - Odors
  - Over-applying of nutrients (P:N concentrations)
  - Emerging contaminants like PFAS



www.BiosolidsData.org

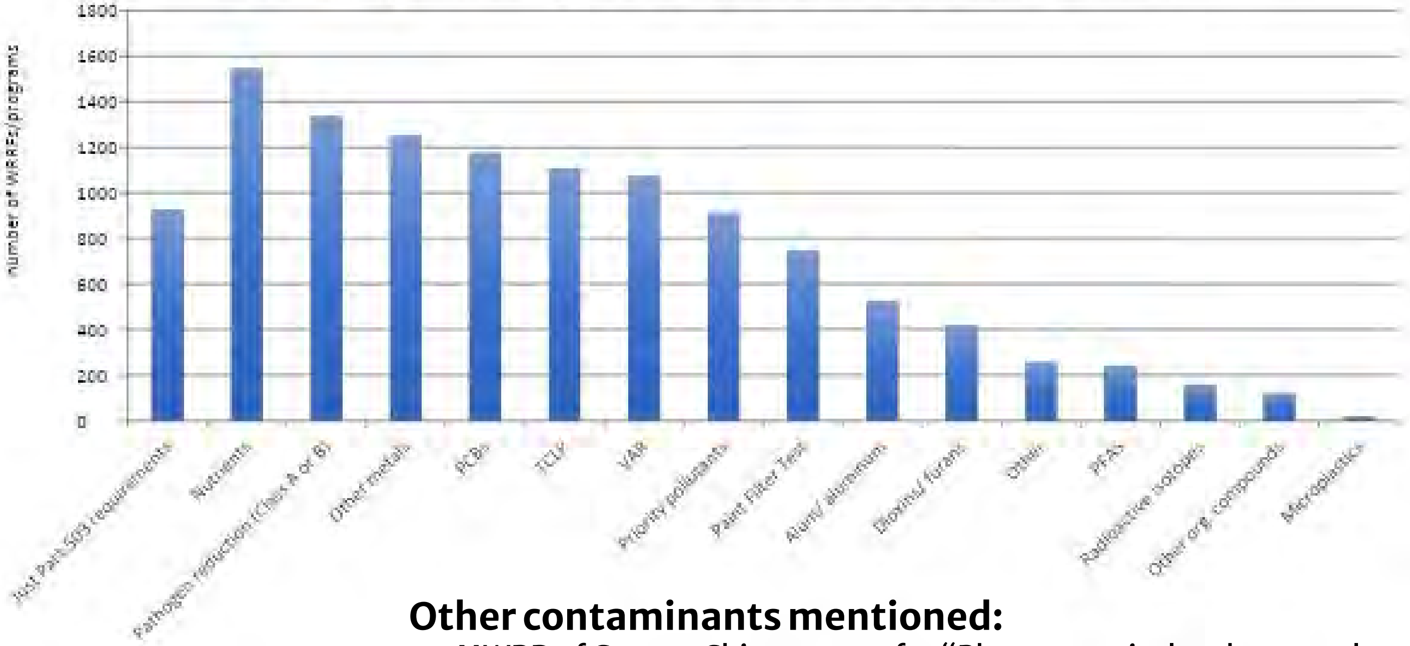
U.S. Biosolids End Use and Disposal

- About 53% of biosolids currently being recycled to soils in some way
- About 32% goes to landfill or other surface disposal facility
- 15% is incinerated

Only for biosolids, does not include other organic wastes like manures, food.

WHAT CONTAMINANTS ARE TESTED FOR?

Numbers of WRRF/programs that must test for each item, extrapolated from NBDP survey of WRRFs (n= 440). What counts is relative numbers.



Other contaminants mentioned:

- MWRD of Greater Chicago tests for "Pharmaceutical and personal care products. Analyze for list of organic compounds identified in IL soil clean up standards."
- "phenols, cyanide"
- NH WRRF: "PFAS testing is not required, but we do test on our own to confirm we are not spreading hazardous/regulated waste at our site."
- Southern TX city: "Each landfilled load tested for RCRA Non-Haz (+TCLP); ignitability, reactivity, and corrosivity, at landfill scale house"

Nutrients in Final Biosolids (n = 116)

Phosphorus %	Average (mean)	Maximum
Class A	2.3%	6%
Class B	2.0%	7%

Nitrogen %	Average (mean)	Maximum
Class A	3.4%	7%
Class B	4.8%	11%

NATIONAL BIOSOLIDS DATA PROJECT

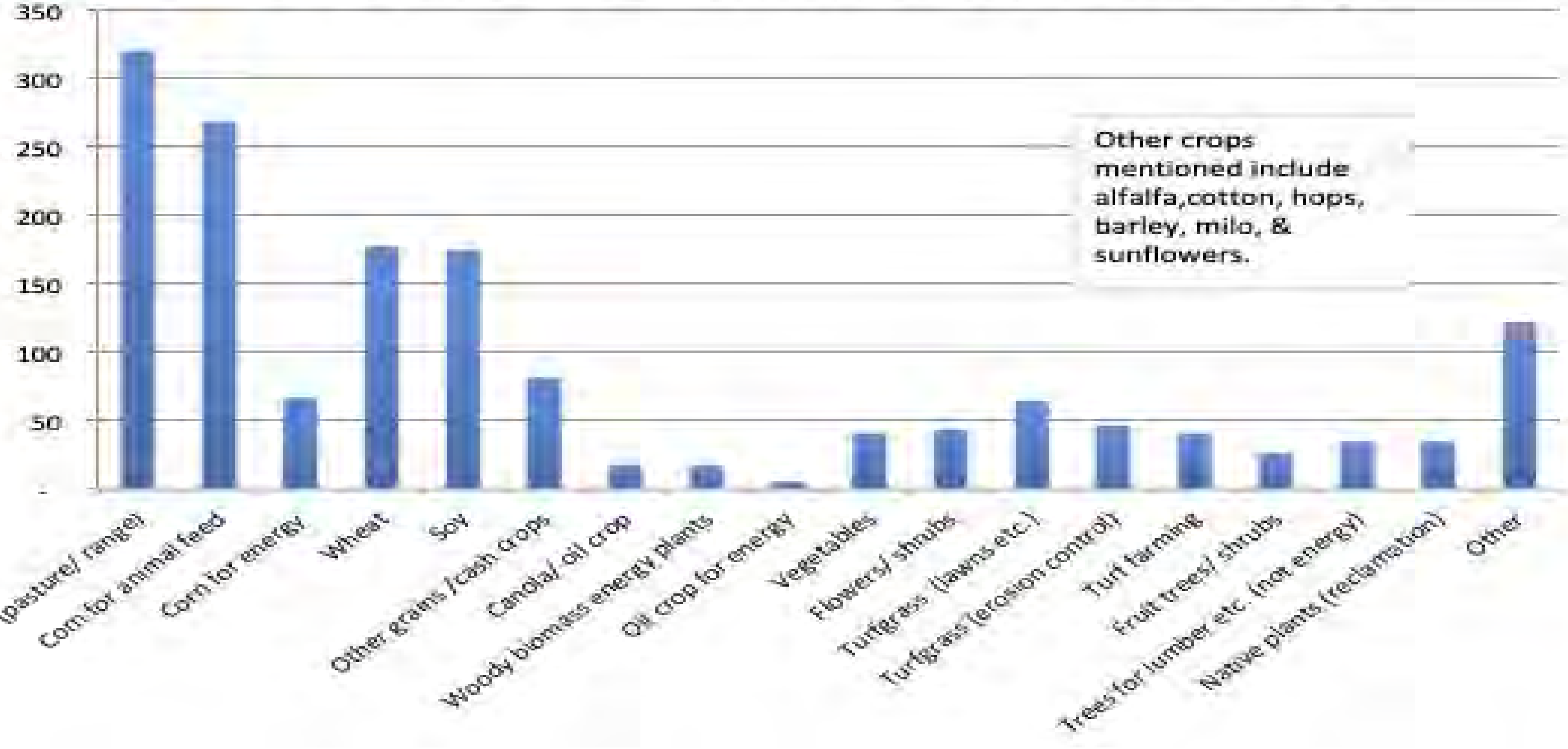
WHAT CROPS ARE GROWN WITH BIOSOLIDS?

Number of U. S. biosolids programs growing each crop

(extrapolated nationwide estimate based on 197 respondents)

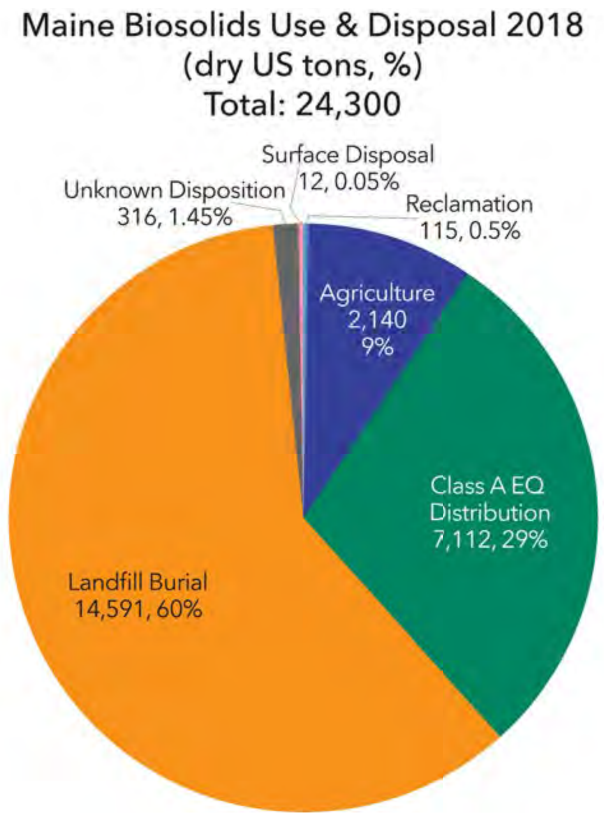
These numbers are low-end estimates.

What is accurate is the relative abundance of the different crops.



What Happened in Maine

- Major sources of PFAS related to the paper industry made their way into WRRFs
- Pulp & paper mill residuals used to contain a lot more PFAS
- First there were limits set by the regulators (2018)
- Then there was over-reaction by the legislature (2022)
- Situation is not sustainable, still no long-term solution(s)
- Major cost increases for WRRFs



www.BiosolidsData.org/Maine

Impacts on NEBRA Members, the Northeast

- Lots of legislative and regulatory activities around PFAS
- Dealing with background soil levels (approaching 1 ppb)
- Maine, Massachusetts, Vermont, and others are doing "master planning" specific to biosolids management
- Starting to see some TSS violations when outlets become unavailable
- Materials being managed further and further from the source

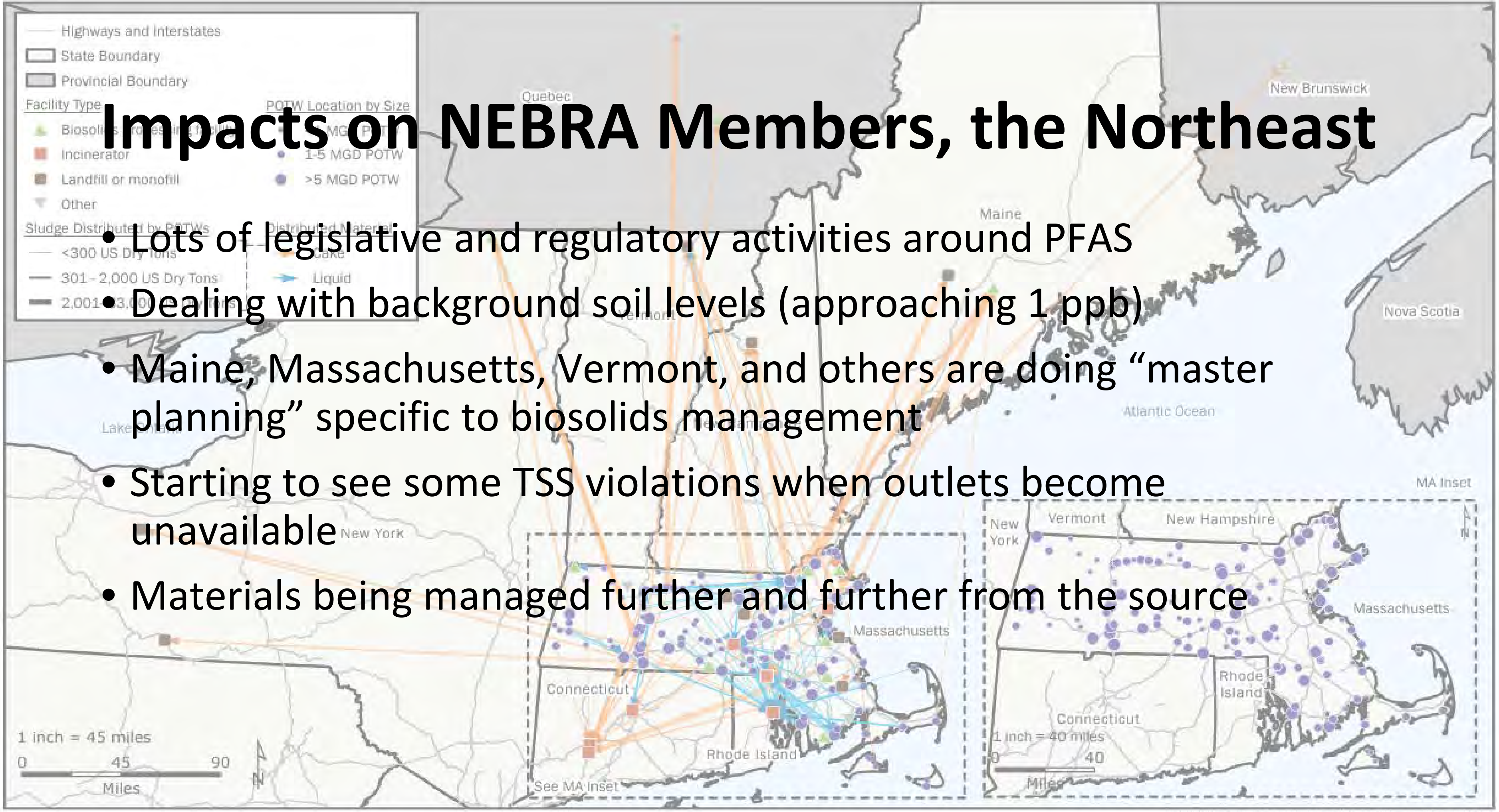


Figure ES-2. Destinations for Wastewater Sludge Produced in Massachusetts

New Technologies are needed!

Phosphorus Extraction from wastewater

- Chemical/struvite precipitation
- Membranes
- Electro-chemical processes
- Biological phosphorus removal (including enhanced BPR)

Processes for PFAS removal/destruction from solids

- Pyrolysis/Gasification (in commercial operation)
- Hydrothermal liquefaction, carbonization
- Supercritical water oxidation (P-rich minerals generated)
- Sewage sludge incineration (research ongoing, P-rich ash)

Maximizing climate benefits from biosolids management.

Unit Process	Enter "x" for all applicable processes:	Scope 1	Scope 2	Scope 3	Total	Wet tons to each unit process/day	Mg (wet) to each unit process/day	Dry metric tons to each unit process/day	Metric tons CO2e/ dry metric ton biosolids
		CO₂ equivalents (Mg/yr)							
Storage		NA	NA	NA	NA	NA	NA	NA	NA
Conditioning/Thickening	x	0	#VALUE!	117	#VALUE!	NA	NA	NA	NA
Aerobic Digestion		NA	NA	NA	NA	NA	NA	NA	NA
Anaerobic Digestion	x	4,614	#VALUE!	0	#VALUE!	NA	NA	NA	NA
Anaerobic Digestion 2		NA	NA	NA	NA	NA	NA	NA	NA
Dewatering	x	0	#VALUE!	63	#VALUE!	NA	NA	NA	NA
Thermal Drying		NA	NA	NA	NA	NA	NA	NA	NA
SFT Biodrying		NA	NA	NA	NA	NA	NA	NA	NA
Alkaline Stabilization		NA	NA	NA	NA	NA	NA	NA	NA
Composting		NA	NA	NA	NA	NA	NA	NA	NA
Composting 2		NA	NA	NA	NA	NA	NA	NA	NA
Landfill Disposal Typical		NA	NA	NA	NA	NA	NA	NA	NA
Landfill Disposal Worst case		NA	NA	NA	NA	NA	NA	NA	NA
Landfill Disposal Aggressive		NA	NA	NA	NA	NA	NA	NA	NA
Landfill Disposal CA Regulatory		NA	NA	NA	NA	NA	NA	NA	NA
Combustion		NA	NA	NA	NA	NA	NA	NA	NA
Pyrolysis		NA	NA	NA	NA	NA	NA	NA	NA
Land Application	x	-1,619	0	-1,483	-3,102	76	69	17	-0.49
Land Application 2		NA	NA	NA	NA	NA	NA	NA	NA
Transportation	x	408	NA	NA	408	76	69	17	0.66
		3,400	#VALUE!	(1,303)	#VALUE!				

Scope 1 - direct emissions
Scope 2 - purchased electricity, heat, or steam
Scope 3 - production of purchased materials and uses of end products

Screenshot

The BEAM*2024 Upd

An independent project of NEBRA and No
building on the work of the Canadian Council o

About • *How to download?*

Now available (November 2024).

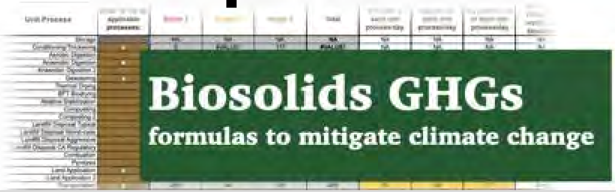
. . . with MAJOR support from:

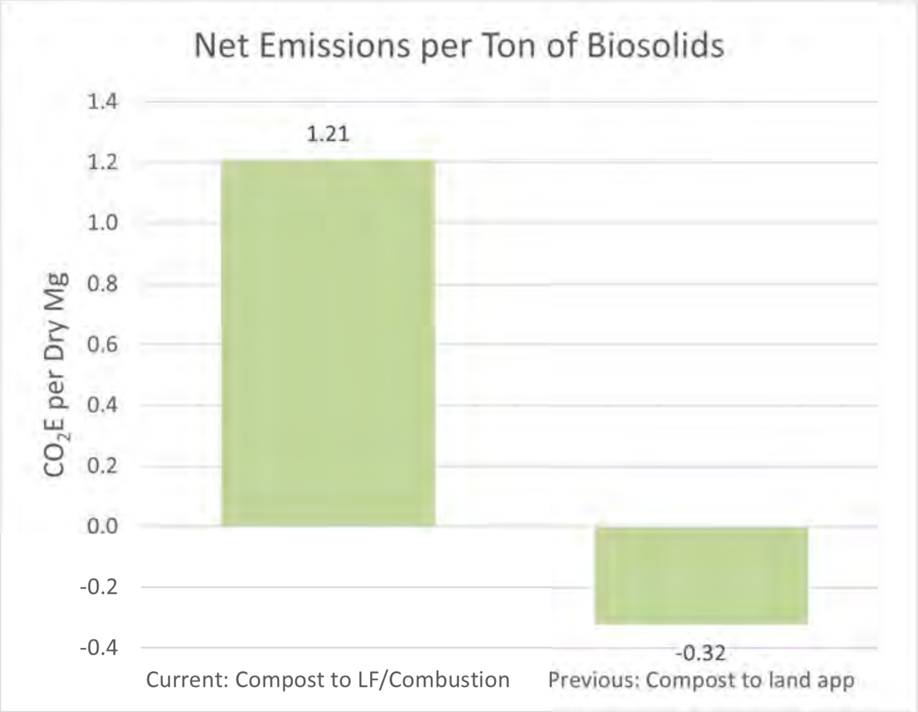
NORTHWEST BIOSOLIDS
Unearthing Sustainable Solutions

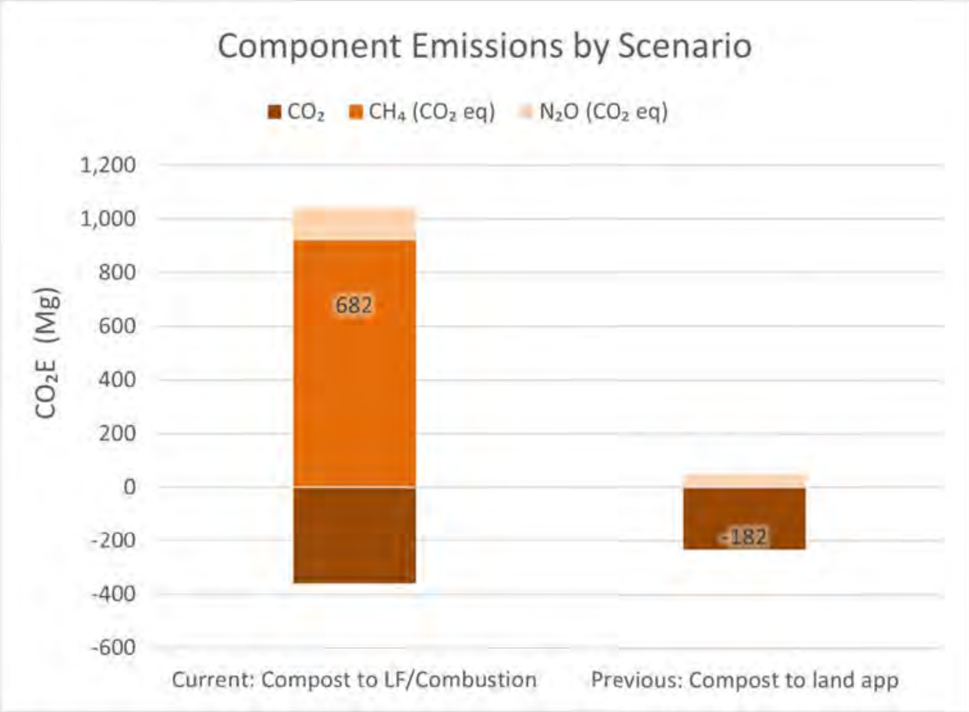
BiosolidsGHGs.org

- Spreadsheet available for download
- Supporting documents & links
  - Resources for utilities on GHG emissions & calculations
  - Standard protocols
- Space for sharing
  - results
  - tips
  - uses of data

Example BEAM Calculations & Graph *for Sanford, Maine*

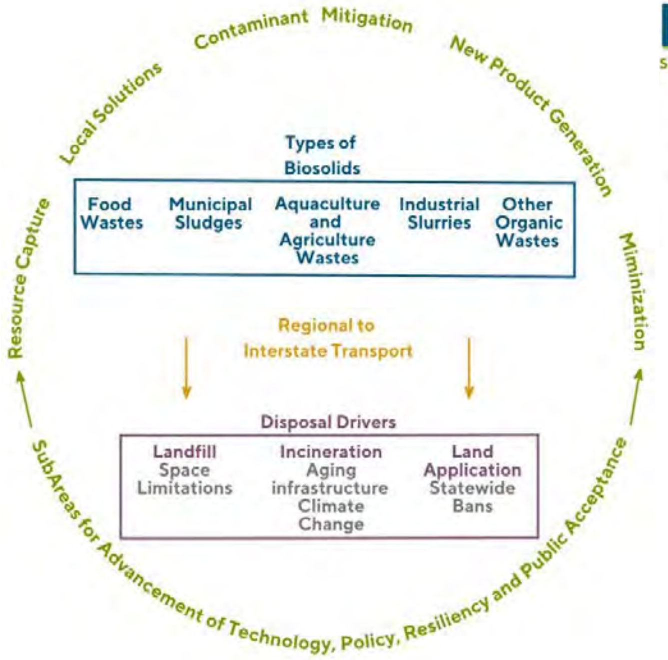






Wastewater Residuals BioHub

- Collaborative effort with regulators, utility managers and consultants – led by NEIWPCC
- Coordinating solutions to biosolids/residuals management in the Northeast
- Clearinghouse for research and new technologies, other resources



BioHub
Scan the QR code to learn more and get involved:

From Waste to Resource: Leveraging the Circular Economy Framework to Tackle the U.S. Biosolids Crisis (Abouhend, etal. 2025)*

PROBLEM

Linear Economic Models

Disposal Practices

- Landfilling
- Incineration
- Land Application

Challenges

- Shrinking Disposal Capacities
- Aging Infrastructure
- Rising Management Costs
- Greenhouse Gas Emissions
- Nutrient Runoff
- Emerging Contaminants
- Health Risks

Transition

Barriers & Pathway to a Circular Future

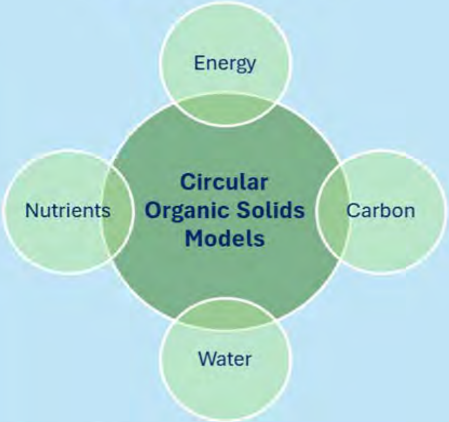
Barriers

- Regulatory Fragmentation
- Technological Gaps
- Financial Constraints

Pathway

- Technological Innovation
- Innovative Regulatory Policies
- Regional Collaboration
- Changing Mindsets & Building Support

SOLUTION



Benefits

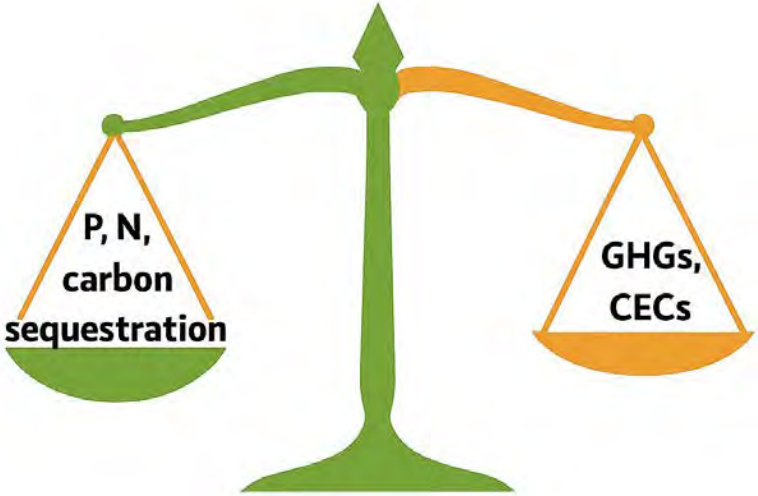
- Generate 325 Billion kWh of Electricity/Year
- Sequester 292 MMT Co_2-eq /Year
- Fully Offsets U.S. Fertilizer Demand
- Saves $ Billions In Disposal Costs

** Submitted for publication in Environmental Science & Technology, April 2025, for Circular Water Economy Special Issue*

Calculations for biosolids, manures, pulp/paper residuals, and food waste.

Managing Organic Wastes Must Balance Resource Recovery with Emerging Contaminants, Other Concerns

- Adopt a Circular Water Economy mentality
- Collaborate in earnest – the best ideas have to win!!
- Create a new regulatory paradigm; innovations in regulations/permitting needed too
- Communicate:
  - Clear, concise information about the relative risk of CECs exposure in occupational and everyday living. Language is important!



Managing Emerging Contaminants in the Circular Bioeconomy

Emily Remmel
Senior Director of Regulatory Affairs
NACWA

Disruption and Uncertainty:

Navigating the Current Regulatory PFAS Landscape

Emily Remmel, Senior Director Regulatory Affairs

Managing Emerging Contaminants in a Circular Bioeconomy
2025 Phosphorus Forum

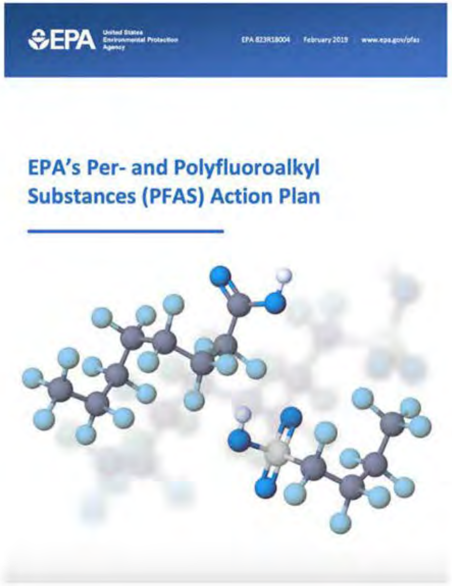
WHO ARE WE?

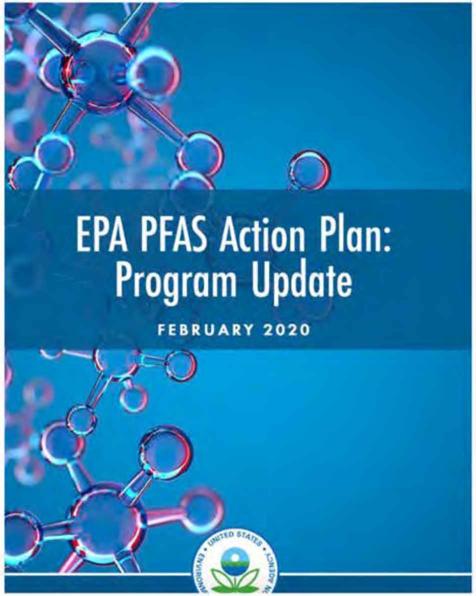
- NACWA represents ~360 public utility members of all sizes nationwide
- NACWA is on the front lines, ensuring members' voices are heard and that federal regulatory, legal, and legislative decisions are based on evidence-based science, smart engineering, and rational economic considerations

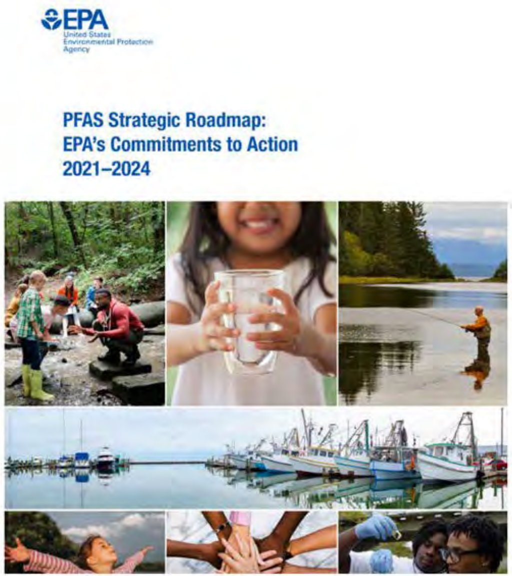

Emerging Contaminants


PFAS

PFAS Action Plans & Road Maps – By-Gone?







NATIONAL PRIMARY DRINKING WATER REGULATIONS

CLEAN WATER ACT CRITERIA: AQUATIC AND HUMAN HEALTH

BIOSOLIDS RISK ASSESSMENT

PRETREATMENT: ELG PLAN 15 AND INFLUENT STUDY

METHOD DEVELOPMENT AND MONITORING

DESTRUCTION AND DISPOSAL???

Comprehensive Environmental Response, Compensation & Liability Act (CERCLA)

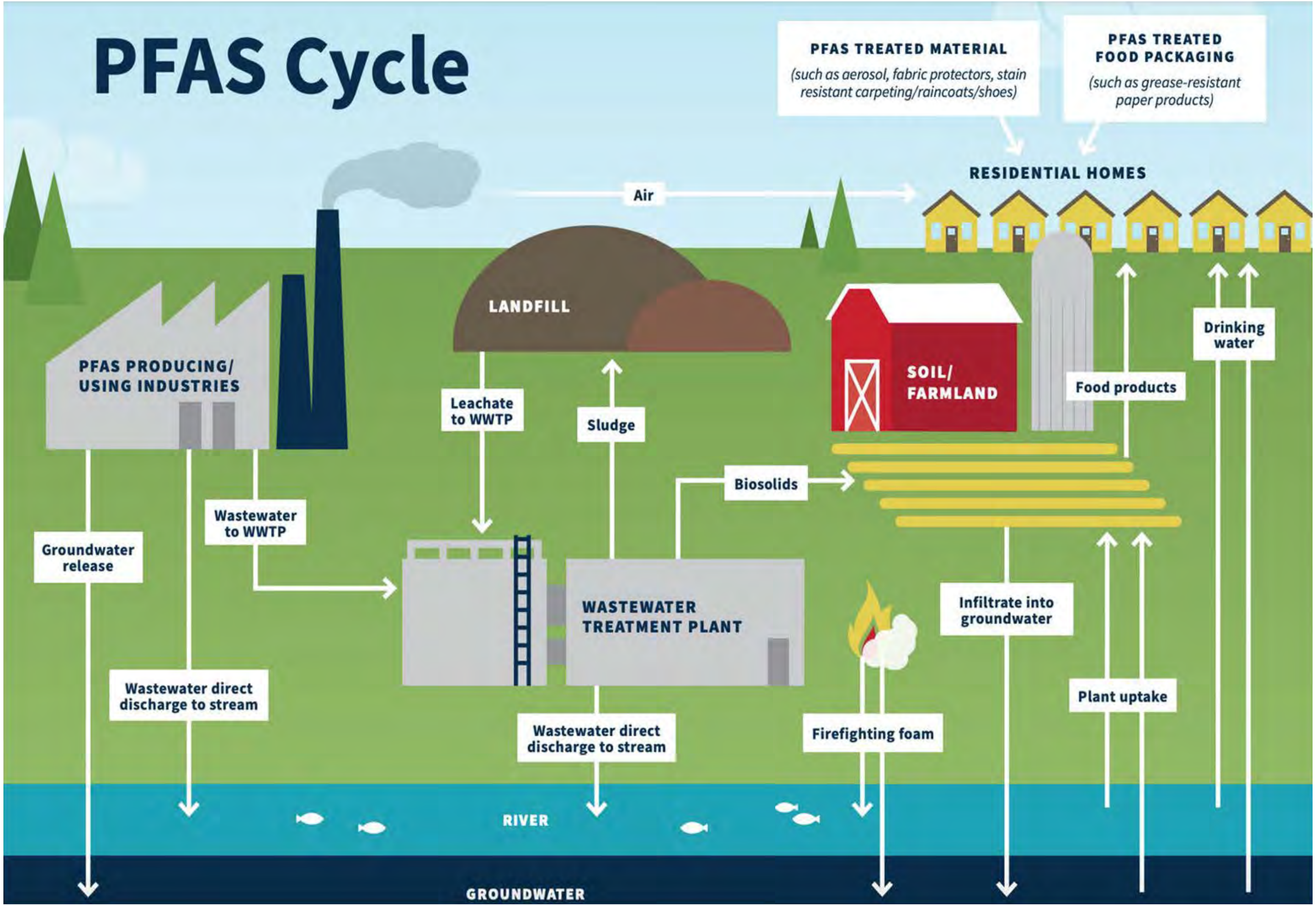
Sept. 2022 - EPA proposed designating two PFAS (PFOA and PFOS) as "hazardous substances" under Section 102(a) of CERCLA

April 2023 – Agency took comment on whether to also designate: (1) any of the following 7 PFAS – PFBS, PFHxS, PFNA, HFPO-DA (GenX), PFBA, PFHxA, or PFDA; (2) precursors to PFOA, PFOS, or any of the 7 proposed PFAS; and/or (3) categories of PFAS

April 2024 – EPA finalized PFOA and PFOS designations while publishing corresponding enforcement discretion memo aimed at shielding POTWs, MS4s, community water systems, farmers land-applying biosolids, publicly owned/operated municipal solid waste landfills, publicly owned airports, and local fire departments from PFAS remediation costs

Spring/Summer 2025 - Litigation

CERCLA Hazardous Substance Designation Effective on July 8, 2024



PFAS Cycle
PFAS TREATED MATERIAL
(such as aerosol, fabric protectors, stain resistant carpeting/raincoats/shoes)
PFAS TREATED FOOD PACKAGING
(such as grease-resistant paper products)
RESIDENTIAL HOMES
Air
LANDFILL
PFAS PRODUCING/ USING INDUSTRIES
SOIL/ FARMLAND
Drinking water
Food products
Leachate to WWTP
Sludge
Biosolids
Wastewater to WWTP
Groundwater release
WASTEWATER TREATMENT PLANT
Infiltrate into groundwater
Wastewater direct discharge to stream
Plant uptake
Wastewater direct discharge to stream
Firefighting foam
RIVER
GROUNDWATER

What are the Costs?

Minnesota Report, June 2023

- Removing and destroying PFAS from water and biosolids leaving Minnesota's wastewater treatment facilities could cost between $14 billion and $28 billion over 20 years
- PFAS can be bought for $50 - $1,000 per pound (according to MPCA estimates), but costs between $2.7 million and $18 million per pound to remove and destroy from municipal wastewater, depending on facility size
- Small wastewater treatment facilities would face per-pound costs over six times greater than large facilities, due to economies of scale
- New "short-chain" types of PFAS are more difficult and up to 70% more expensive to remove and destroy compared to old "long-chain" PFAS

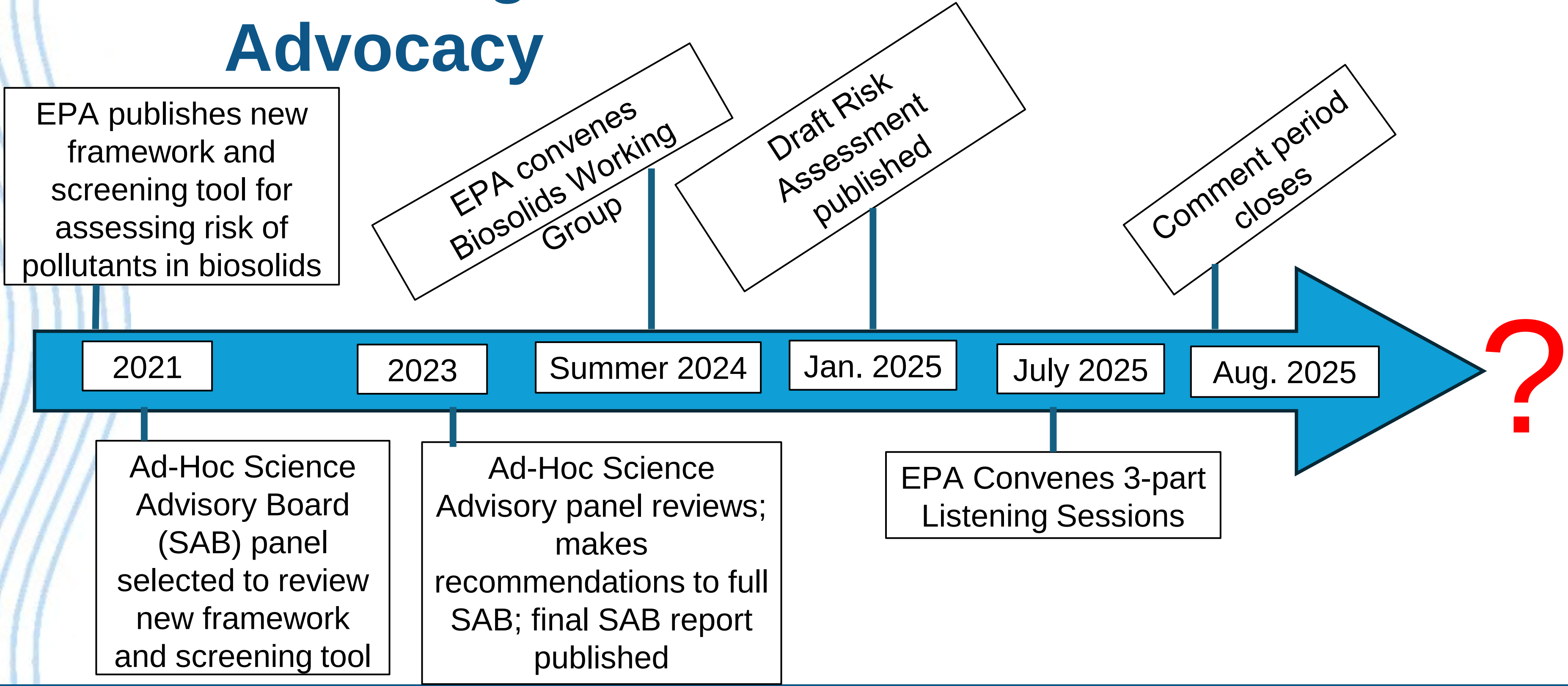
Draft Human Health Criteria for PFAS

- Concentrations that are not expected to cause adverse human health effects
- For combined water and fish/shellfish consumption:
  - PFOA – 0.0009 ppt
  - PFOS – 0.06 ppt
  - PFBS – 400 ppt
- Current method quantification levels for PFOA and PFOS range from 1 to 4 ppt (Method 1633)
- States may incorporate criteria into their water quality standards

Biosolids PFOA/PFOS Risk Assessment

- Will provide risk levels as numeric values for a variety of potential exposure pathways (e.g., 1 in 10,000)
- Risk levels developed using very conservative/hypothetical assumptions about "typical farm family"
  - Assumed continual application each year for 40 years
  - Assumed 1 ppb PFOA/PFOS starting concentration
- First time a biosolids risk assessment released w/out proposed Part 503 changes or management considerations or cost/treatment considerations
- Assessment will not look at relative risk of other fertilizers like artificial fertilizers or manure

The Long Game of Biosolids Advocacy



The Long Game of Biosolids Advocacy

Administrator Zeldin Announces Major EPA Actions to Combat PFAS Contamination

April 28, 2025

Contact Information
EPA Press Office (press@epa.gov)

Source: EPA Press Office, https://www.epa.gov/newsreleases/administrator-zeldin-announces-major-epa-actions-combat-pfas-contamination

The Long Game of Biosolids Advocacy

Administrator Zeldin Announces Major EPA Actions to Combat PFAS Contamination

April 28, 2

Contact

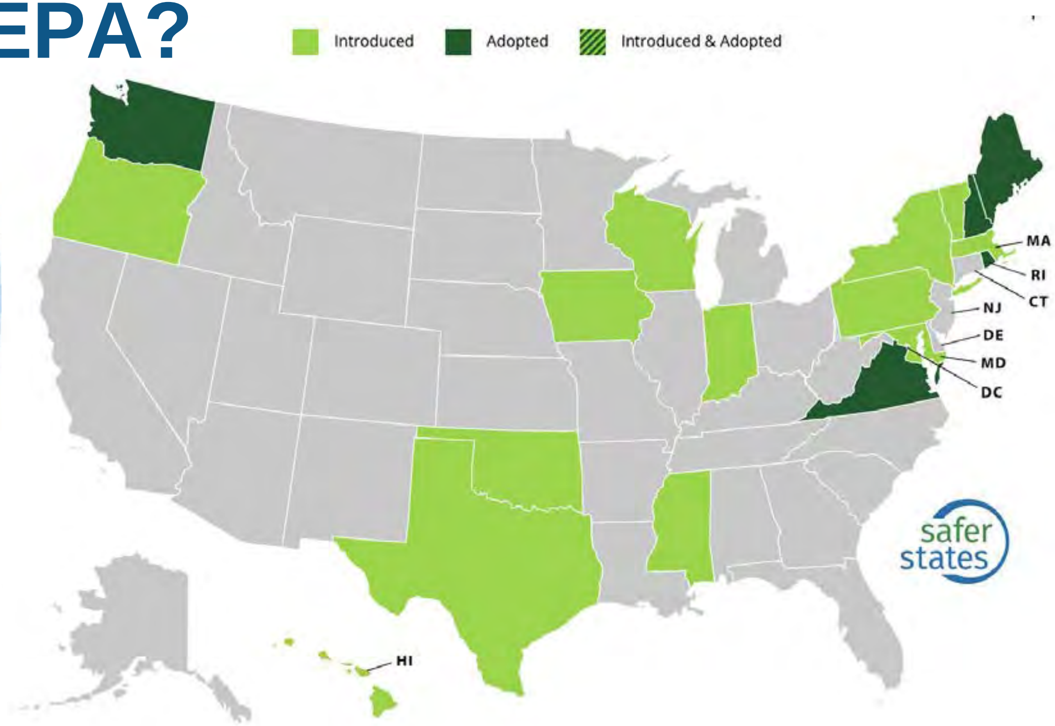
EPA Press

Building Partnerships

- Advance remediation and cleanup efforts where drinking water supplies are impacted by PFAS contamination
- Work with states to assess risks from PFAS contamination and the development of analytical and risk assessment tools
- Finish public comment period for biosolids risk assessment and determine path forward based on comments
- Provide assistance to states and tribes on enforcement efforts
- Review and evaluate any pending state air petitions
- Resource and support investigations into violations to hold polluters accountable

Source: EPA Press Office, https://www.epa.gov/newsreleases/administrator-zeldin-announces-major-epa-actions-combat-pfas-contamination

State Legislative Biosolids Activity – A Response to EPA?



5 states have adopted 8 policies & 13 states have introduced policies

Most states focusing on testing and analysis and establishing programs for management of biosolids or conduct studies of PFAS in biosolids (WA, VA, RI, NH)

Other states following Maine's prohibition or looking directly at EPA's draft risk assessment as a means for establishing a 1ppb limit (AKA a de facto ban on land application) (MD, TX, OK, NY)

Source: Safer States Bill Tracker (accessed July 3, 2025; refined for biosolids/sludge legislation) https://www.saferstates.org/bill-tracker/?toxic_chemicals=PFAS&issue_sectors=Biosolids/Sludge

PFAS Everywhere

TIME

HEALTH • ENVIRONMENTAL HEALTH

Now We Need to Worry About Harmful 'Forever Chemicals' in Our Toilet Paper Too

In case you're counting, the average American will go through 26 kg (57 lbs) of toilet paper in a single year. Multiply that by the 332 million people in the U.S. and you get more than 19 billion pounds of waste paper being flushed away annually.

SOURCE CONTROL CAN WORK

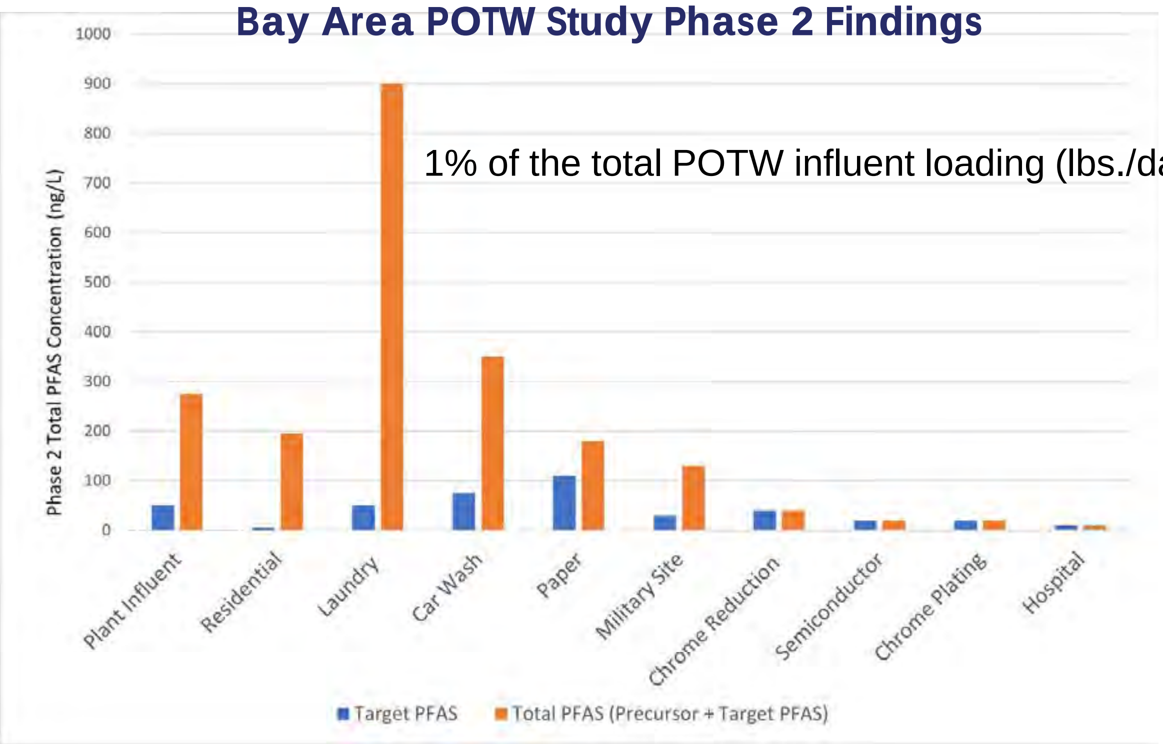
Michigan Industrial Pretreatment Program Initiative

Table 1. Identified Industrially Impacted Solids: 2017 to 2021 PFOS Results

WWTP	IPP	Significant Sources	2017/2018 Biosolids PFOS (µg/kg)	2021 Biosolids PFOS (µg/kg)	PFOS Reduction Since IPP Initiative
WWTP #50	Yes	Yes	983	140	85.8%
WWTP #14	Yes	Yes	1060	120	88.7%
WWTP #57	Yes	Yes	1680	33	98.0%
WWTP #54	Yes	Yes	161	74/180	54%/-11%
WWTP #92	Yes	Yes	2150	113	94.7%
WWTP #69	Yes	Yes	160	NS	N/A

Takes time and effort. Communication with the public is key. You will still have PFAS hits due to domestic sources, but industrial pretreatment programs can reduce PFAS concentrations in biosolids.

Domestic Sources – California Study



1% of the total POTW influent loading (lbs./day)

Domestic Sources – California Study

At most Bay Area treatment plants, more than 95% of flows are from residential and commercial customers. Phase 2 results indicate that residential areas may contribute PFAS at concentrations similar to plant influent, **which means that residential users may be the dominant source of PFAS to many treatment facilities**. PFAS is found in many consumer products, including textiles, household chemicals, cosmetics, and food packaging, at concentrations several orders of magnitude higher than those found in this study, as shown in Figure 5. **This source of PFAS can only be controlled by removing or reducing the amount of PFAS found in consumer products.**

(emphasis added)

Managing Emerging Contaminants in the Circular Bioeconomy

Andrew Carpenter
Soil Scientist
Northern Tilth

PFAS IN SOIL AMENDMENTS; WHAT I'VE LEARNED TO DATE AND WHAT I DON'T KNOW

PHOSPHORUS FORUM 2025

BY

ANDREW CARPENTER

OF NORTHERN TILTH, LLC

Environmental Media and Consumer Products PFAS levels

PFOA/PFOS Product Comparison	PFOA	PFOS
	µg/kg (parts per billion) – dry wt.	
Microwave popcorn bags[a]	6 - 290	Not available
Concealer cosmetic[b]	2,335.0	ND
Furniture, apparel, bedding (max)[c]	22.5	2.1
Dental Floss[a]	3.0	Not available
Body lotion[b]	3.5	ND
US Household Dust (2001)[d]	142.0	201.0
Soil Background Levels (VT 2019)[e]	0.5	1.0
US Blood Serum Levels (1999-2000)[f]	5.2	30.4
US Blood Serum Levels (2017-2018)[f]	1.4	4.3
Yard Waste Bags[g]	0.8	0.2
US Compost Containing Food Waste[h]	4.7	1.7
US Compost without Food Waste[h]	0.3	1.9
ME, NH & VT Biosolids Compost[i]	12.0	8.7

[a] Begley et al (2005), *Perfluorochemicals: potential sources of and migration from food packaging.*

[b] Danish EPA (2018). *Risk assessment of fluorinated substances in cosmetic products.*

[c] Rodgers et al (2022). *How Well Do Product Labels Indicate the Presence of PFAS in Consumer Items Used by Children and Adolescents?*

[d] Strynar and Lindstrom (2008). *Perfluorinated compounds in house dust from Ohio and North Carolina, USA.*

[e] Zhu et al (2019), *PFAS Background in Vermont Shallow Soils.*

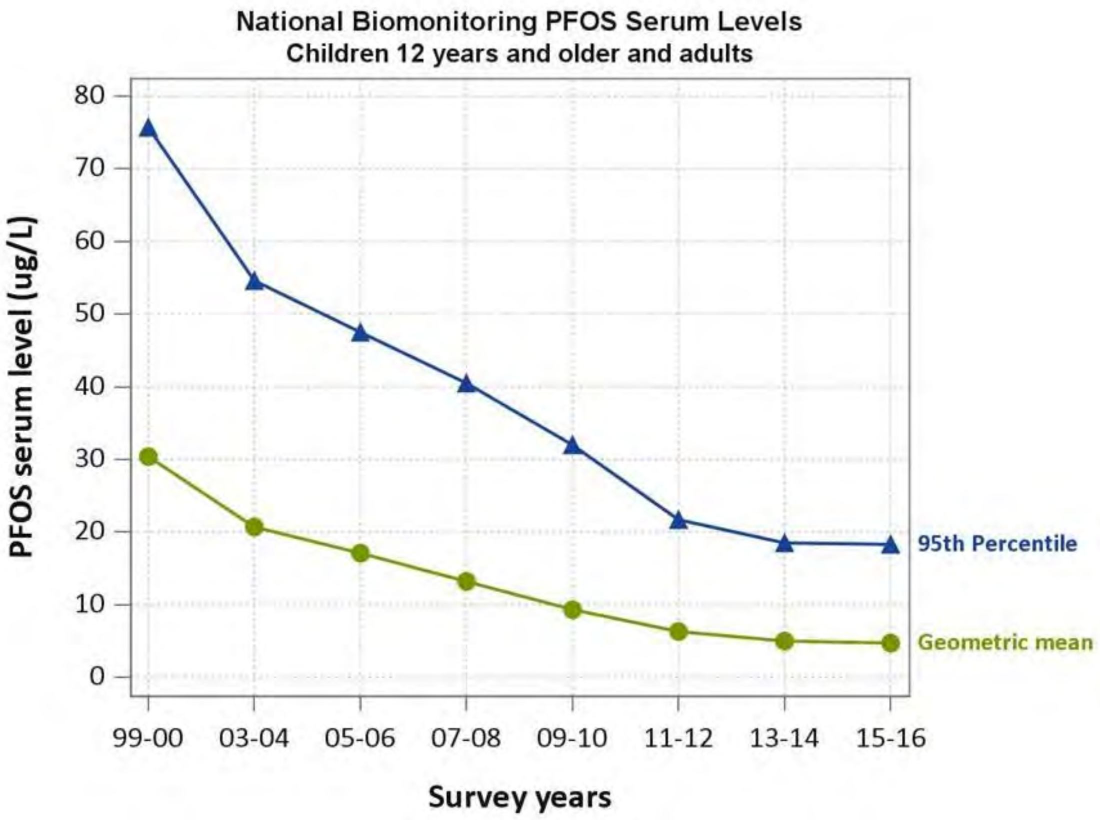
[f] US Center for Disease Control (CDC). *National Report on Human Exposure to Environmental Chemicals.*

[g] Minnesota Pollution Control Agency, June 2022: *Testing for PFAS in yard waste bags.*

[h] Choi et al (2019), Lazcano et al (2020), as presented in US EPA Report August 2021: *Emerging Issues in Food Waste Management - Persistent Chemical Contaminants.*

[i] Based on data sets from the Maine DEP (from 2019) and the New Hampshire DES (from 2022) and from the Vermont DEC (from 2022) including a total of 33 analyses of biosolids compost.

Why are we concerned about PFOS?



We are all exposed to PFOS.

Source:
National Report on Human Exposure to Environmental Chemicals – US CDC:
https://www.cdc.gov/exposurereport/index.html

Farms on which Northern Tilth Identified High Levels of PFAS Contamination

- Organic vegetable farm that purchased land from a farm that had used biosolids in the early 1990s
  - Extremely high soil and drinking water levels
  - The farmers have extremely high blood serum levels of both PFOS and PFOA
- Organic diversified farm that purchased land from a farm that had used biosolids in the early 1990s
  - Extremely high milk levels
  - Milk had been tested randomly off-the-shelf by the MDACF one year earlier and it did not have a PFAS problem at that time
  - ***Further testing identified hay from another farm with very high levels of PFOS which at this point seems to be the source of high PFOS in milk***
- Organic vegetable farm adjacent to farm that applied biosolids in the early 1990s
  - Extremely high irrigation water levels and high drinking water levels
  - To date soils appear to only be impacted by recent use of irrigation water

Soil Loading Rates

Soil Loading with Food Waste Compost or Digestate with relatively high PFOS level

	Units	
Solids content (%)	%	25%
Bulk Density	$\#/Y^3$	1450
Application Rate	wet tons/ac	20
Application Rate	dry tons/ac	5.0
soil bulk density	$\#/Y^3$	2,400
soil moisture content	%	75%
dry mass of soil	dry tons/acre-inch	121
Depth of plow layer	inches	8
dry mass of plow layer	dry tons/acre	968
ratio of soil to soil amendment	dry weight	194
Parameter of Interest*		PFOS
Concentration in Soil Amendment	ug/kg	5.20
amount of PFAS compound added to soil	#/acre	0.00005
amount of PFAS compound added to soil	g/ac	0.0236
Initial soil concentration*	ug/kg	0.5
amount of PFAS compound in soil	#/acre	0.00097
amount of PFAS compound after 1 application	#/acre	0.00102
Soil concentration after 1 application	ug/kg	**0.53**
change in soil conc. after 1 application	ug/kg	**0.027**

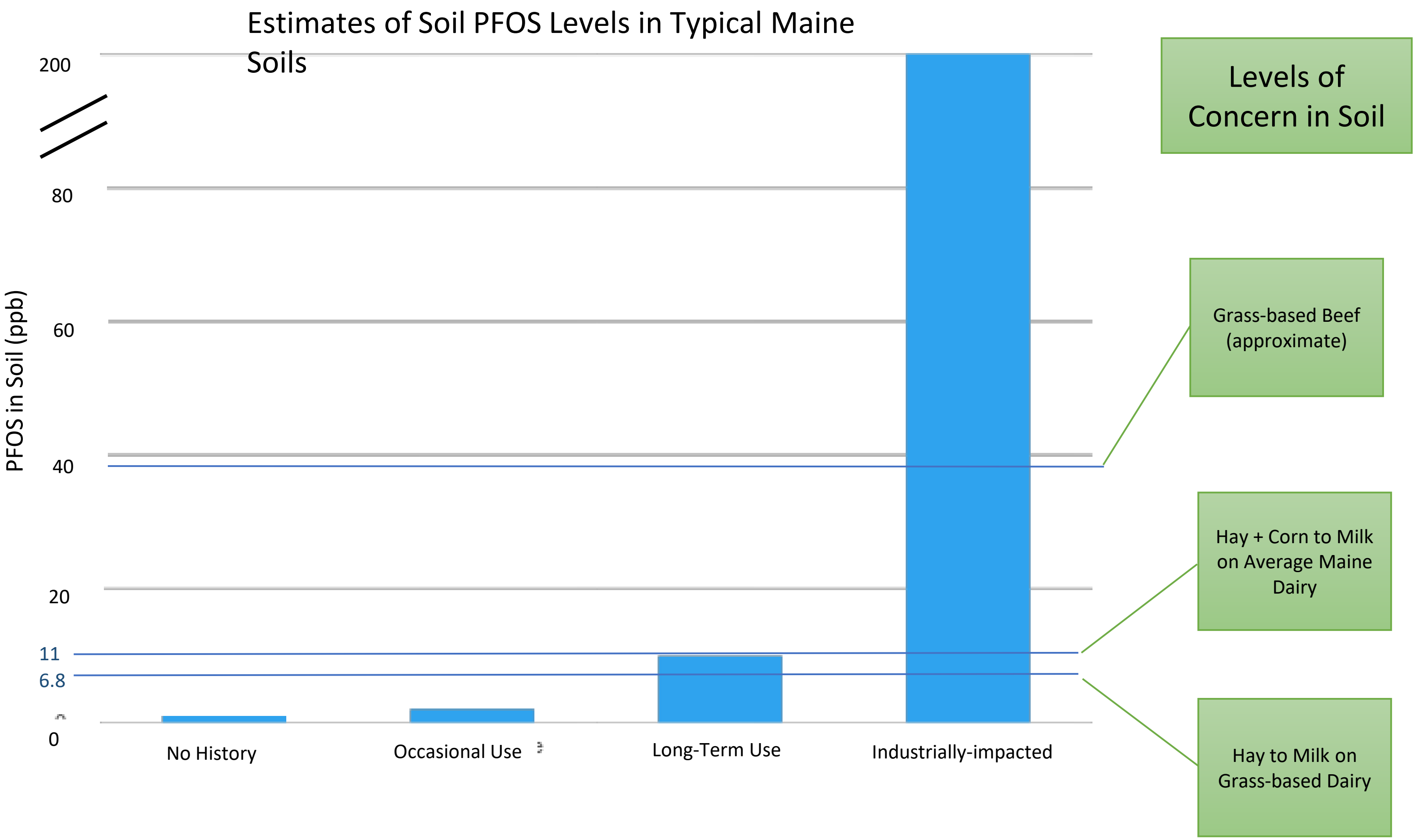
Soil Loading from Highly Contaminated Farm Field in Maine

	Units	
Solids content (%)	%	30%
Bulk Density	$\#/Y^3$	1450
Application Rate	wet tons/ac	176
Application Rate	dry tons/ac	52.8
soil bulk density	$\#/Y^3$	2,400
soil moisture content	%	75%
dry mass of soil	dry tons/acre-inch	121
Depth of plow layer	inches	8
dry mass of plow layer	dry tons/acre	968
ratio of soil to soil amendment	dry weight	18
Parameter of Interest*		PFOS
Concentration in Soil Amendment	ug/kg	7000
amount of PFAS compound added to soil	#/acre	0.7
amount of PFAS compound added to soil	g/ac	335.6
Initial soil concentration*	ug/kg	0.5
amount of PFAS compound in soil	#/acre	0.00097
amount of PFAS compound after 1 application	#/acre	0.740
Soil concentration after 1 application	ug/kg	**382.3**
change in soil conc. after 1 application	ug/kg	**381.8**

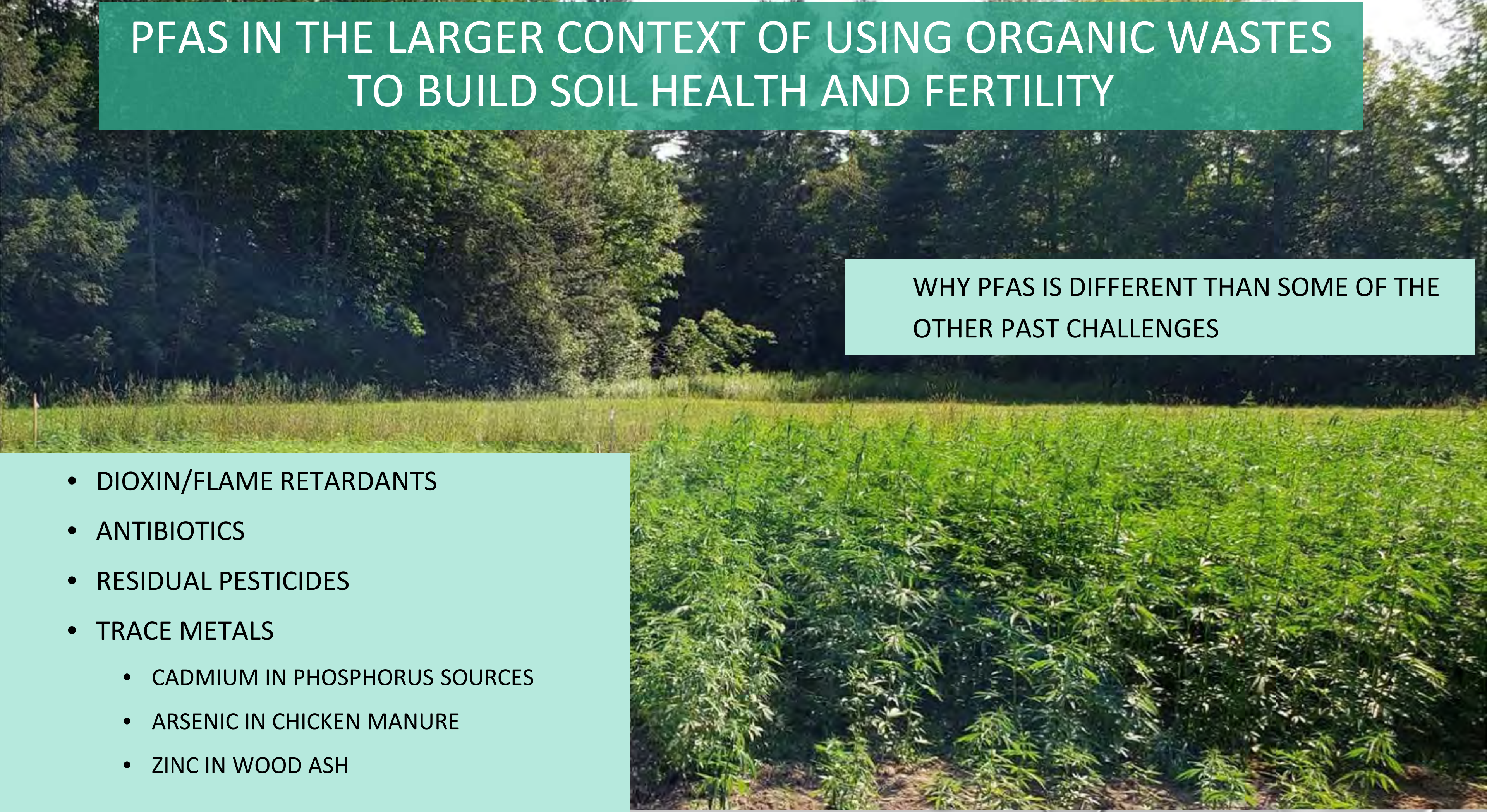
Contemporary Biosolids PFAS Levels

Individual State Records Summarized by Northern Tilth - DO NOT QUOTE, CITE OR DISTRIBUTE									
Materials Analyzed	PFBA	PFPeA	PFHxA	PFHpA	PFHxS	PFOA	PFOS	PFDA	Net FOSAA
	ug/kg dry wt.								
New Hampshire Biosolids Median (2018-2022)	1.4	1.7	2.4	0.98	1.8	1.7	8.3	2.6	3.6
Maine Biosolids Median (2019)	no data	no data	no data	no data	no data	3.8	22.9	no data	no data
Massachussetts Biosolids Median (2020-2021)	1.7	1.4	1.8	0.9	1.2	1.0	6.3	1.2	no data
Michigan Biosolids Median (2018 - outliers removed)	4.5	1.4	1.9	1.3	1.3	2.7	12.7	3.9	
New Hampshire Biosolids Max (2018-2022)	31	16	53	7.9	73	27	390	22	35
Maine Biosolids Max (2019)	no data	no data	no data	no data	no data	46	120	no data	no data
Massachusetts Biosolids Max (2020-2021)	31	17	69	9.1	9.1	61	69	4.3	no data
Michigan Biosolids Max (2018 - outliers removed)	10	42	28	15	2.0	25	161	48	
no data	Not analyzed in the comparison datasets								

4 Very Rough Groupings, meant to provide sense of scale; these are not precise numbers



PFAS IN THE LARGER CONTEXT OF USING ORGANIC WASTES TO BUILD SOIL HEALTH AND FERTILITY



WHY PFAS IS DIFFERENT THAN SOME OF THE OTHER PAST CHALLENGES

- DIOXIN/FLAME RETARDANTS
- ANTIBIOTICS
- RESIDUAL PESTICIDES
- TRACE METALS
  - CADMIUM IN PHOSPHORUS SOURCES
  - ARSENIC IN CHICKEN MANURE
  - ZINC IN WOOD ASH

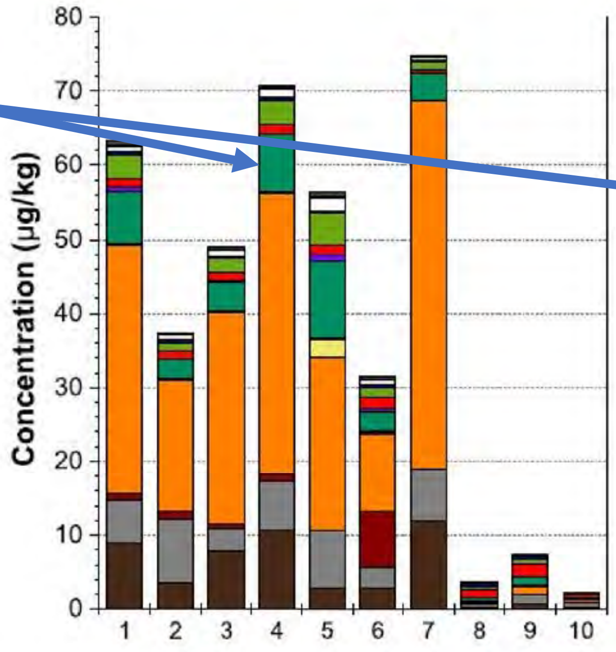
Pfas in non-biosolids compost

Environmental Science & Technology Letters

Letter

From Choi et al. 2019. *Perfluoroalkyl acid characterization in U.S. municipal organic solid waste composts. – supporting data provided by Dr. Linda Lee, Purdue University*

Note that the PFOA level in several of these non-biosolids composts would be higher than the Maine screening standard of 2.5 ppb)



	Description
1	Municipal solid waste
2	Municipal solid waste and wood products
3	Residential and commercial food and yard waste, compostable food serviceware products
4	Residential and commercial food and yard waste, compostable items
5	Mixed food waste (residential, local grocers, restaurants, and commercial food handling facilities) and yard waste
6	Residential food and yard waste, & compostable food serviceware
7	Food waste, horse manure, wood shavings, coffee grounds and lobster shells, &compostable food serviceware
8	Leaves and grass waste from municipalities
9	Residential back yard compost bin
10	Leaves

source	PFOA conc. (ug/kg dry wt)
1	6.88
2	2.54
3	3.58
4	7.85
5	10.31
6	2.73
7	3.64
8	0.48
9	1.05
10	0.47

Figure 1. PFAA concentrations quantified (micrograms per kilogram oven-dried, <2 mm) in the comp ... contribution (percent) of each PFAA to the total PFAAs quantified for composts 1−10 (right).

PFAS in Fairground Compost

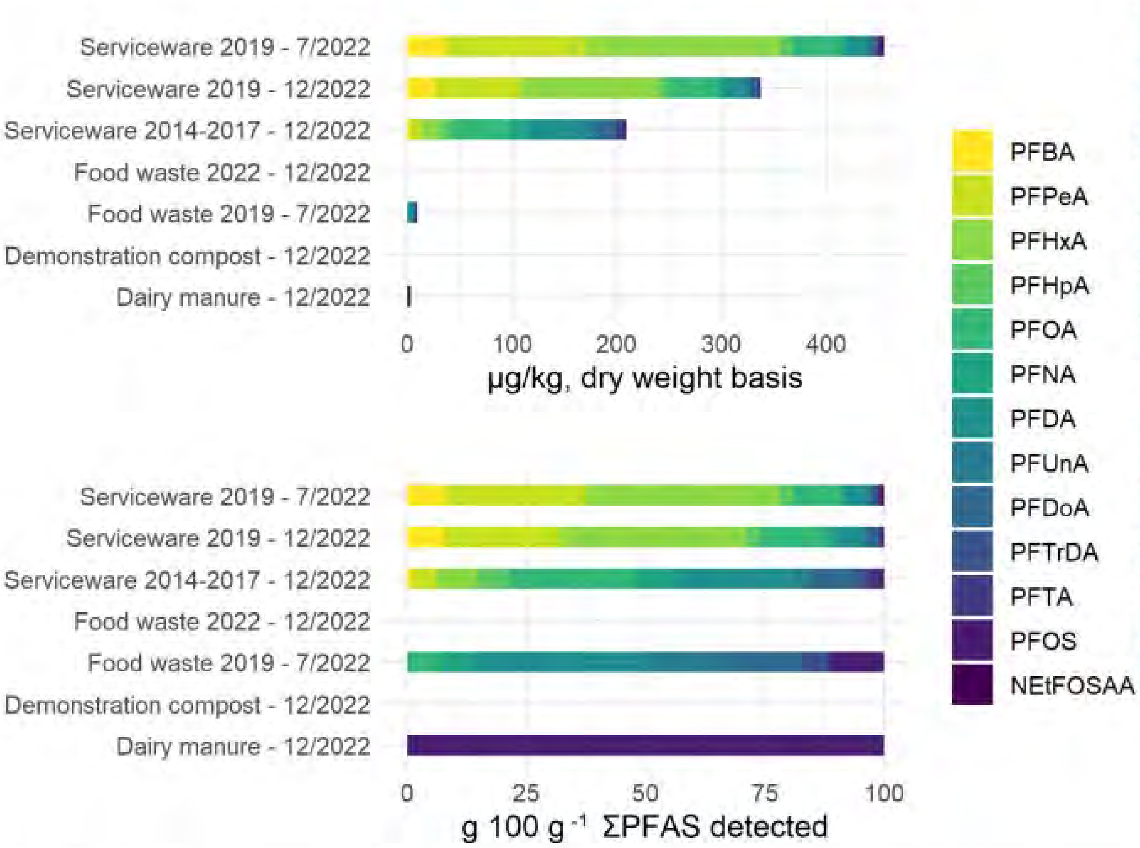


FIG. 1. Analysis of 28 PFAS compounds from compost and manure samples, each a composite of ten representative subsamples, presented on µg/kg dry weight basis and as a proportion of Σ PFAS detected. PFPeA and PFOA values in 07/22 sampling of Serviceware 2019 compost should be considered estimated, as they were re-extracted on dilution, with the method required holding time exceeding in order to quantitate the results within the calibration range. Detailed results are available in Table SI in the supplementary material.[34]

Evidence of compost contamination with per- and polyfluoroalkyl substances (PFAS) from "compostable" food serviceware

Cite as: Biointerphases 18, 030501 (2023); doi: 10.1116/6.0002746
Submitted: 4 April 2023 · Accepted: 18 May 2023 ·
Published Online: 6 June 2023

Caleb P. Goossen,[1,a] Rachel E. Schattman,[2] and Jean D. MacRae[3]

AFFILIATIONS

[1]Maine Organic Farmers and Gardeners Association, P.O. Box 170, Unity, Maine 04988
[2]School of Food and Agriculture, University of Maine, 5722 Deering Hall, Orono, Maine 04469
[3]Department of Civil and Environmental Engineering, University of Maine, 5711 Boardman Hall, Orono, Maine 04469

Note: This paper is part of the Biointerphases Special Topic Collection on Per- and Polyfluoroalkyl Substances (PFAS) at the Interface of Biological and Environmental Systems.

[a]**Electronic mail:** cgoossen@mofga.org

PFAS in digestate

Sample	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFOS	PFDA
	Units = µg/kg (ppb)						
Food waste slurry	<5.00	<2.50	<1.25	<1.25	<1.25	<1.25	<1.25
Food waste digestate	<32.0	<3.69	<1.85	<1.85	<1.85	<1.85	<1.85
Separated solids	<1.55	<0.774	<0.387	<0.387	<0.387	**0.789**	<0.387

- 2023 data from foodwaste/manure digestion project
- Food waste slurry is the slurry coming directly from depack machine going into digester
- Separated solids are constantly recycled as bedding, and may represent the PFAS that might build up over time.
- We sampled these same materials from the same location in 2021 for only PFOA and PFOS and found the same results

Background Levels in New England Soils

	VT 2019 Study	ME 2022 Study
PFBA	--	0.137
PFPeA	--	0.098
PFHxA	0.230	0.219
PFHpA	0.190	0.085
PFOA	0.390	0.394
PFNA	0.160	0.145
PFDA	0.095	0.078 (non-urban)
PFUnA / PFUnDA	0.074	0.073
PFOS	0.680	0.275 (non-urban)
PFBS	0.130	--
PFHxS	0.120	--
PFDS	0.092	--

All units are ng/g (parts per billion). Values shown are median values.

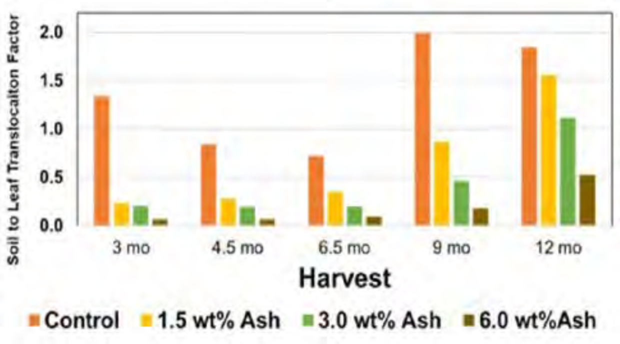
Options for farms that do have high PFAS levels on agricultural soils

- Phytoremediation has almost no potential (for the compounds of greatest concern)
- In-Situ destruction in soil has very limited potential and as of yet is unproven
- Changing crop types has been the most useful tool available for contaminated farms in Maine

Using Biochar and High Carbon Ash to Reduce Uptake of PFAS in Grasses

Research conducted by:
Andrew Carpenter, Northern Tilth
Romy Carpenter, Northern Tilth
Dr. Linda Lee, Purdue University
Elijah Openiyi, Purdue University

Research funded by Maine NRCS Conservation Innovation Grant



PFAS PRECURSORS AND TRANSFORMATIONS

CLOSING REMARKS

- Returning our organic matter-based wastes to the soil to build soil health and reduce negative climate impacts is imperative
- Findings related to PFAS in soil amendments derived from organic waste have led to a regulatory scramble to address public concerns, which has resulted in a patchwork of regulatory responses while we simultaneously have a shifting target of determining actual risks related to PFAS in soil amendments
- Working upstream to both ban these compounds in commercial and industrial uses and identifying potential feedstocks that have aberrantly high levels of PFAS is an effective strategy for addressing the issue
- **<u>There is a need to distinguish between low level detections of PFAS in compost and soil amendments and the levels that can cause a concern from exposure pathways (drinking water, agricultural products, etc.)</u>**

Managing Emerging Contaminants in the Circular Bioeconomy

Ivan Cooper
National Water/Wastewater Practice Leader
Civil & Environmental Consultants, Inc.

Technology Overview of PFAS Treatment

Ivan Cooper, PE, BCEE

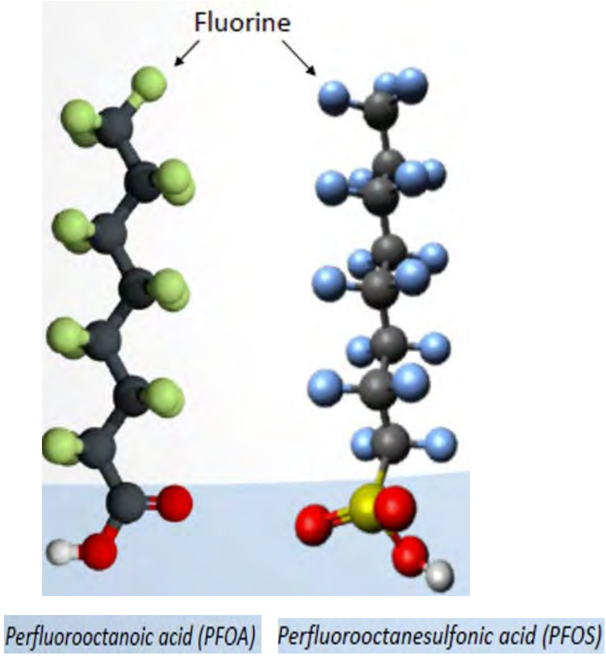
Civil & Environmental Consultants, Inc

Charlotte, NC

September 17, 2025

Agenda – PFAS Treatment

- Emerging Contaminants
- Regulations/Timing
- Operational Considerations
  - Construction
  - Operations
  - Utilities
- Costs
- Summary



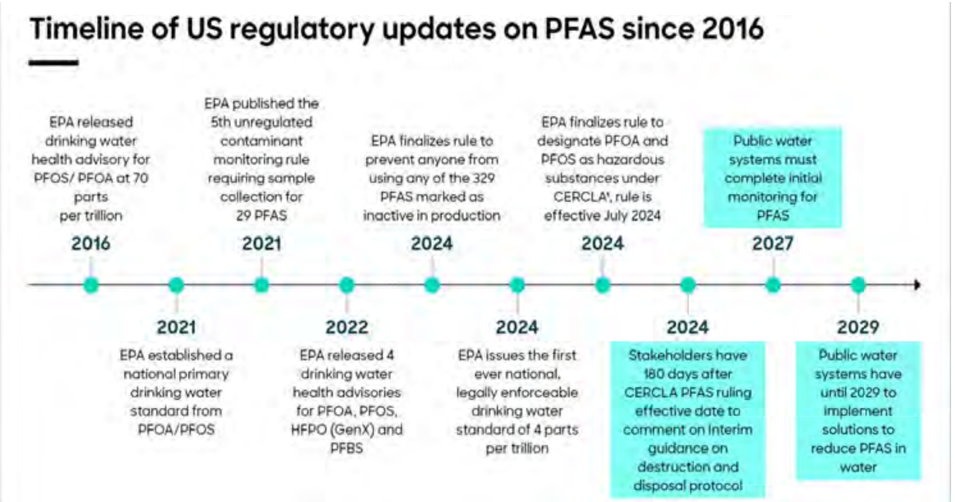
Ref: EPA

Emerging and Non-Conventional Contaminants

- 1,4 Dioxane
- Microplastics
- 6PPD- Quinone
- PPCP (Human and Animals- “CAFO”)
- Cyanotoxins
- Phenols
- PCBs, and of course,
- PFAS

PFAS Regulatory Timing

- Federal
  - RCRA EPA Proposed Rule – On Hold
    - *Definition of Hazardous Waste Applicable to Corrective Action for Releases from Solid Waste Management Units* and *Listing of Specific PFAS as Hazardous Constituents*
  - CERCLA July 8, 2024 Liability, Cleanup, Release reporting, Transactional Practice – Compliance 2031 or later?)
  - EPA Landfill Study ~ 4 years (EPA Plan 16 EFGs)
  - SDWA – NPDW Regulations -Water systems on-line ~ 3 years (Maybe 2031 or later!), partial rescind
  - NDAA, other laws, other agencies
    - Sec 318 Intentionally Added PFAS Haz substances, Manufacturers under CWA– rollback?; Sec 319 – AFFF – rollback?
  - Policy Reversal under Trump Administration – Rollbacks = Uncertainty
- States
  - Possibly more aggressive than Feds
  - Eliminating intentionally added PFAS
  - Local Permits/Actions –
    - Limiting or banning discharge
- Litigation- Multiple lawsuits v. EPA, Private parties
- Innocent receiver concerns
- Start Planning Now!



Current PFAS Treatment Processes

- Few Process are single unit operations
- Commercial Status – **Full Scale** / **Limited** / **Developing or Laboratory**

Segregation – Adsorptive	Segregation- Physical Chemical	Destructive
Activated Carbon Granular Colloidal Ion Exchange Polymers Modified bentonite Mixed Media NanoSorb	Reverse Osmosis/Nano/Ultra Foam Fractionation Deep Well Injection Cementitious encapsulation Aqueous Electrostatic Concentrator (AEC)	Supercritical Oxidation Electrochemical Plasma Thermal Photochemical Oxidation/Reduction Persulfate Sonolysis UV Permutations Pyrolysis Mechanochemical Degradation Hydrothermal Alkaline - HALT

PFAS Treatment Operational Concerns

- Flexibility
  - Changing regulations means new equipment – how to adjust?
- System Costs
  - Replacement media, backwash or other waste, residuals disposal
- Training
  - Can staff work with equipment – finding new staff?
  - Operator certification
- Operator Friendliness
  - Frequency of operator actions
  - Monitoring/Flow volumes
  - SCADA or Phone Apps
  - Media accessibility/changeouts – storage onsite and delivery issues
  - Tools needed
  - Testing
- Ease of Installation
  - Tanks or inside a building
  - Piping changes – welding or plastic
- Adaptability
  - How flexible is each process to continual changes in treatment requirements/New permit limits?

Current PFAS Liquids Treatment Technologies
(Usually Treatment Trains)

- Separation/Physical Technologies
- Most Amenable to Leachate Treatment
  - Activated Carbon
  - Resin
  - Mixed Media
  - RO
  - Deep Well
  - Evaporation
  - Foam Fractionation

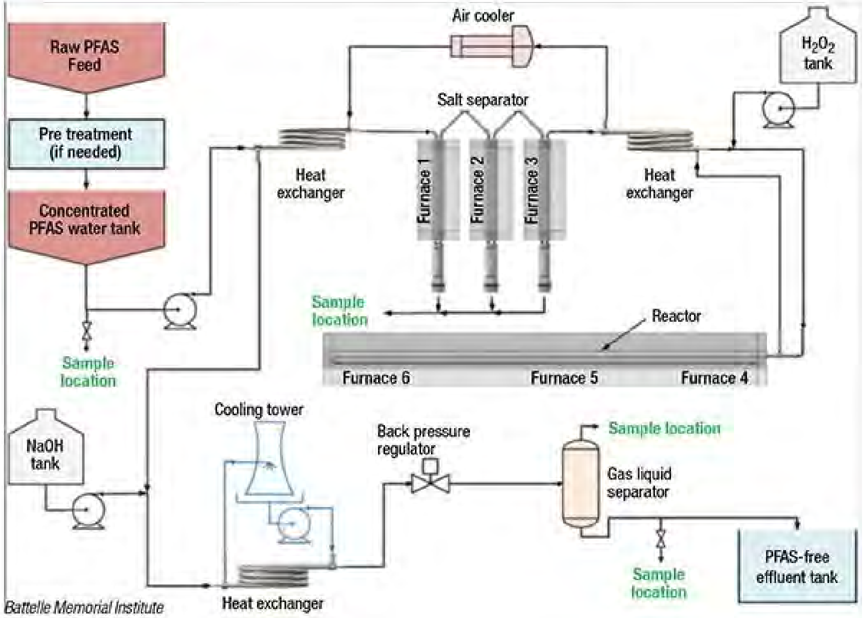
GAC

Source: Australian DOD 2018

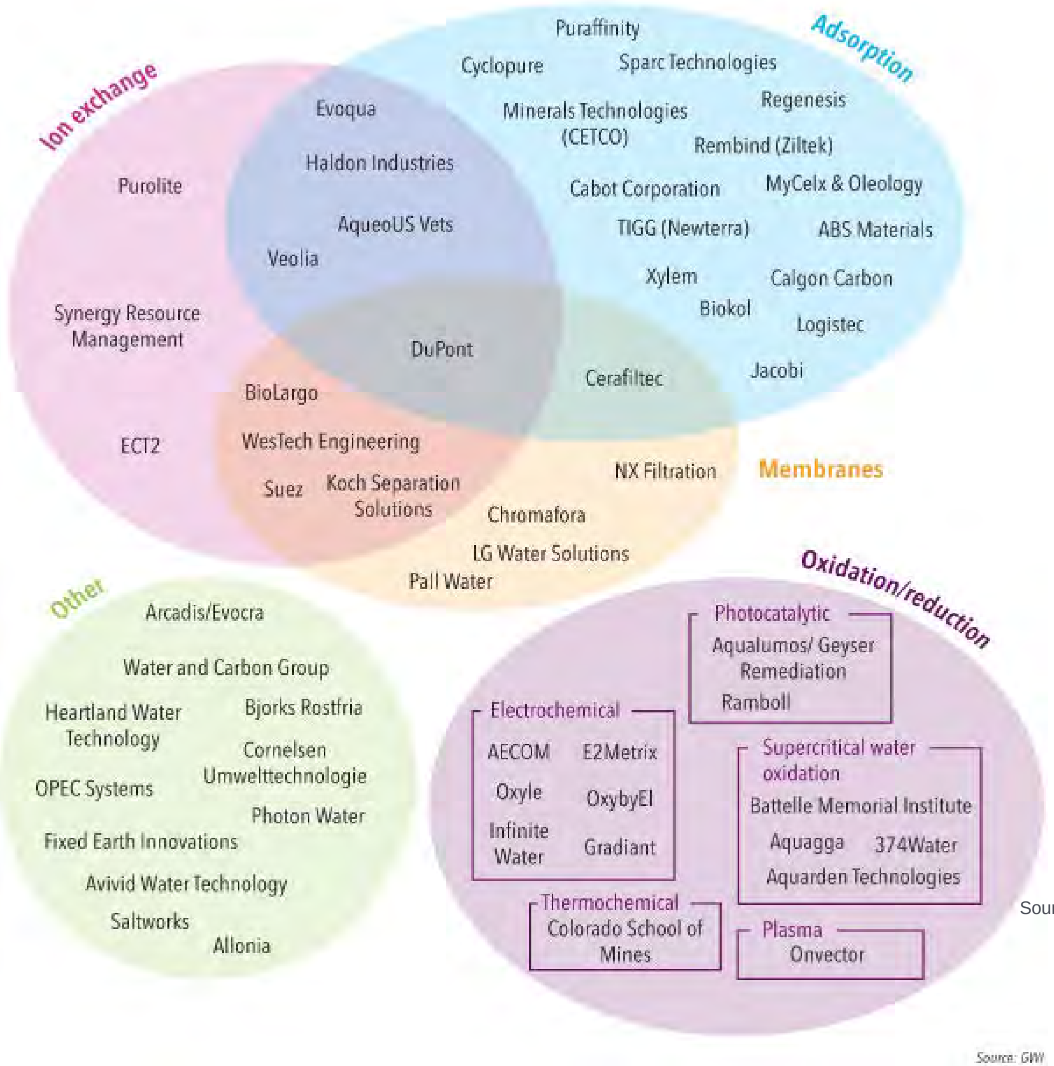
Source: NH Business Review 2018

PFAS Residuals Technologies

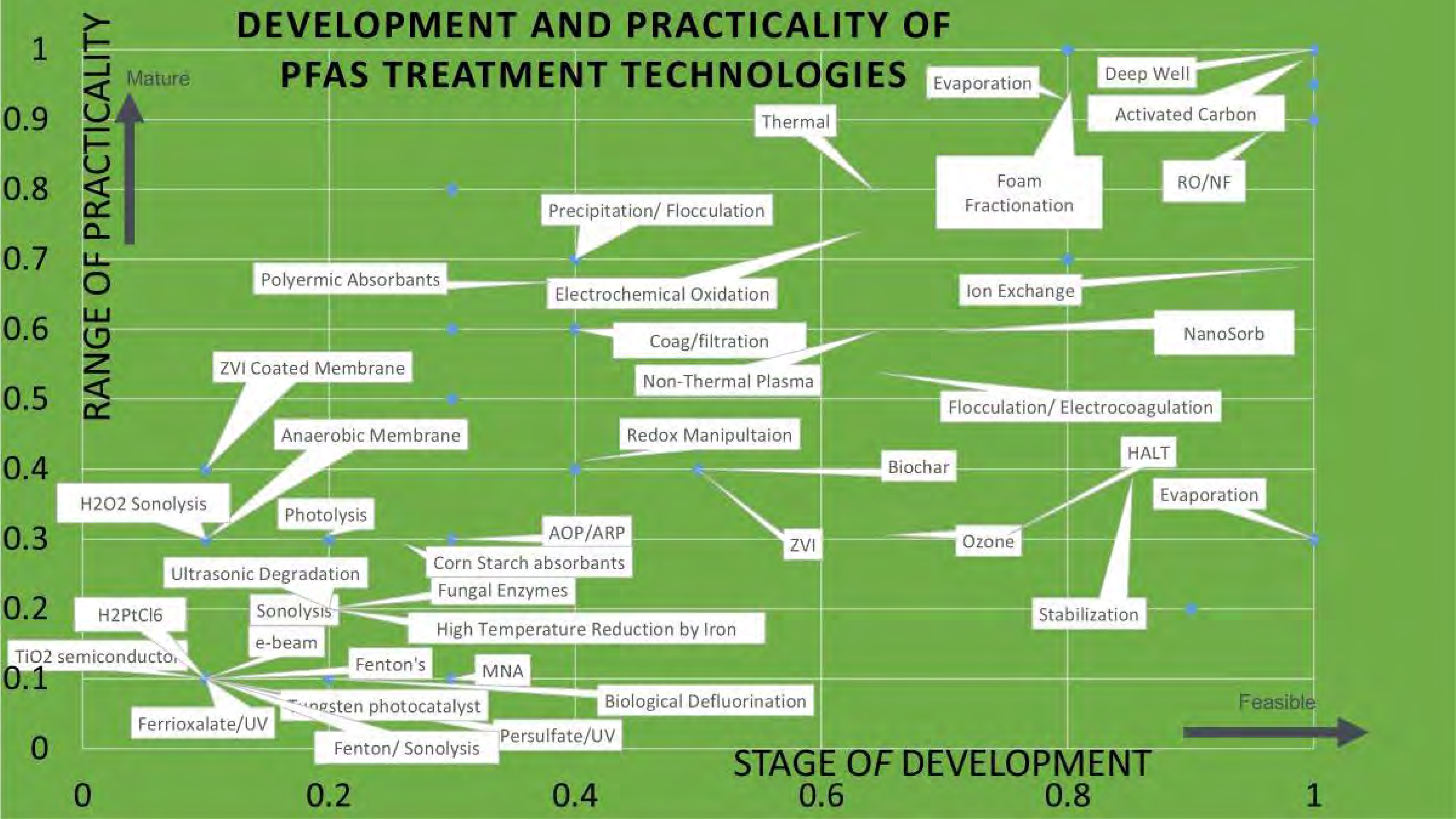
- Destruction
  - Incineration
  - Plasma
  - SCWO (Supercritical Water Oxidation)
  - ElectroChemical Oxidation
  - Deep Well Injection
  - HALT (Hydrothermal Alkaline Treatment)
- Stabilization/Solidification
  - Cementitious S/S
    - Encapsulation (In totes or vessels)
    - Holcim/ADC
  - Return to the landfill
  - Hazardous Waste Landfill Haul and Dispose



Current PFAS Market Players



Source: PFAS treatment market concentrates on waste reduction and total destruction, GWI, May 2021


DEVELOPMENT AND PRACTICALITY OF
PFAS TREATMENT TECHNOLOGIES
RANGE OF PRACTICALITY
Mature
STAGE OF DEVELOPMENT
Feasible
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
Evaporation
Deep Well
Activated Carbon
Thermal
Foam Fractionation
RO/NF
Precipitation/ Flocculation
Polyermic Absorbants
Electrochemical Oxidation
Ion Exchange
NanoSorb
Coag/filtration
Non-Thermal Plasma
ZVI Coated Membrane
Flocculation/ Electrocoagulation
Anaerobic Membrane
Redox Manipultaion
Biochar
HALT
H2O2 Sonolysis
Evaporation
Photolysis
AOP/ARP
ZVI
Ozone
Corn Starch absorbants
Ultrasonic Degradation
Fungal Enzymes
Sonolysis
H2PtCl6
High Temperature Reduction by Iron
Stabilization
e-beam
TiO2 semiconductor
Fenton's
MNA
Biological Defluorination
Ferrioxalate/UV
Persulfate/UV
Fenton/ Sonolysis

Comparison of PFAS Treatment Technologies

Readiness Factor	Treatment Criteria
5	The technology is highly suitable for the category
4	The technology is appropriate
3	The technology is adequate with minor improvements
2	Greater attention is required
1	The issue defined in the category should be carefully addressed before implementation

Journal of Hazardous Materials 481 (2025) 136685

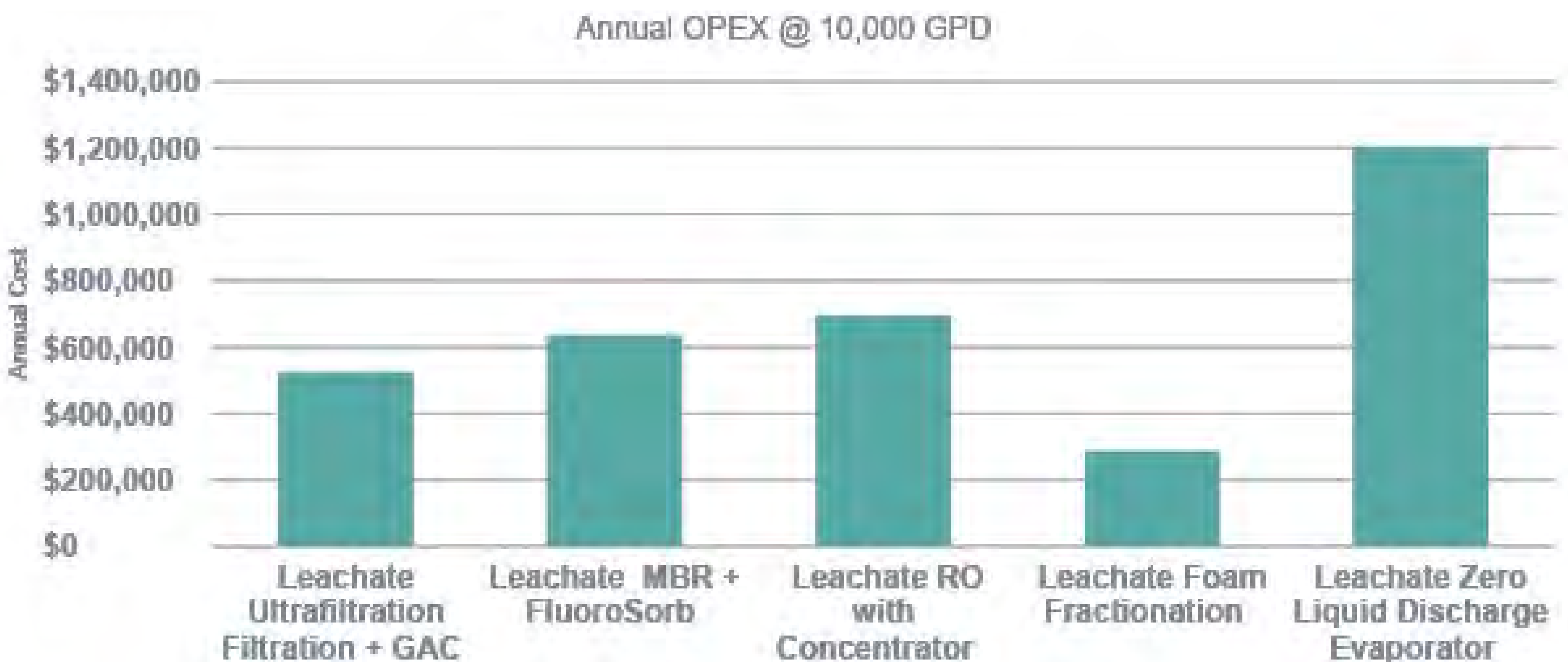
Technology	GAC	IX	RO	Foam Fract.	EO	SCWO	HALT	Plasma
Type	Separation	Separation	Separation	Concentration	Degradation	Degradation	Degradation	Degradation
CAPEX ($-$$$$)	$$	$$	$$$$	$$	$$$	$$$$	$$$$	$$$$
OPEX ($-$$$$)	$$$	$$$	$$$$	$	$$	$$$	$$	$$$
*Applicability for Landfill Leachate**	1	2	3	5	4	4	4	5
Level of Technological Readiness	5	5	5	2	3	2	1	1
Energy Consumption	5	5	3	4	3	1	2	1
Chemical Addition	5	5	5	4	1	2	2	3
Treatment Capacity	5	5	4	4	3	2	2	1
Long-chain PFAS Removal	4	5	5	5	5	5	4	5
Short-chain PFAS Removal	1	5	5	1	2	5	4	1
Gas Emissions	5	5	5	5	3	1	2	2
Aqueous Byproducts	5	5	4	5	3	3	4	3

Technological capability of different processes for PFAS treatment in complex landfill leachate matrices.

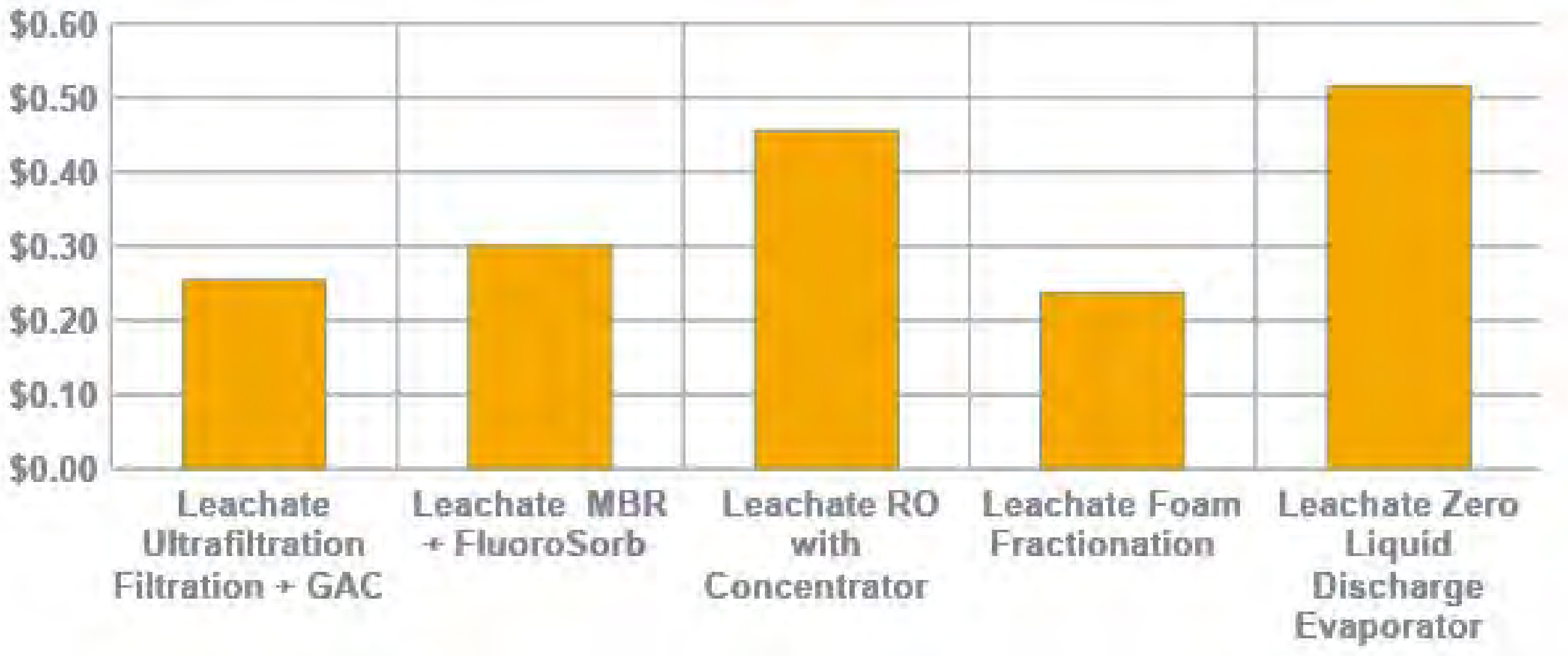
Cost Opinion of Possible PFAS Treatment Alternatives

Major Process Description	Treatment Flow Rate	Low CAPEX Less 50%	Mid - CAPEX	High CAPEX Plus 100%	Annual OPEX	Treatment System Life Cycle Cost - Present Worth	Mid opinion annual Capital Recovery Factor (CRF) = 0.087185	Combined Annualized Cost, CRF + OPEX	Treatment Cost/Gal
Clarification/Filtration GAC and Ion Exchange Discharge to WWTP	10,000 gpd	$2,101,000	$4,202,000	$8,404,000	$294,000	$7,600,000	$366,000	$660,000	$0.0739
Foam Fractionation, Solidification, Solids to LF Discharge to WWTP	10,000 gpd	$1,856,000	$3,712,000	$7,424,000	$217,000	$6,200,000	$324,000	$541,000	$0.0606
Reverse Osmosis/Ion Exchange, Direct Discharge	10,000 gpd	$2,558,000	$5,115,000	$10,230,000	$348,000	$9,100,000	$446,000	$794,000	$0.2175

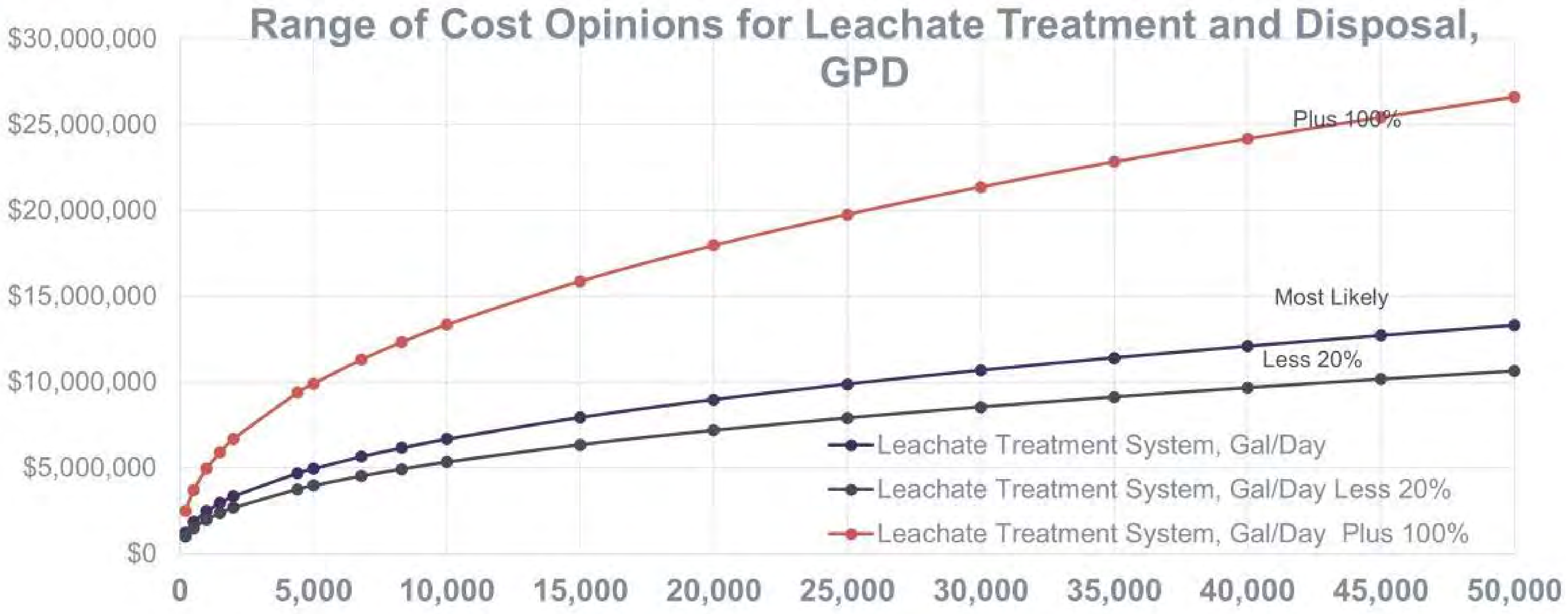
Annual OPEX @ 10,000 GPD



Landfill Leachate PFAS Treatment and Disposal Cost/Gal (CAPEX and OPEX) @ 10,000 GPD



CAPEX Impact of Size on Costs Based on Foam Fractionation



Treatment Challenges

- Carboxylates (ex. PFOA) harder to remove than Sulfonates (ex. PFOS)
- Longer chain easier to remove/destroy than shorter chain
- Many technologies focus on longer chain, shorter chain problematic
- Many technologies require multi step processes
  - time to permit & construct!!!
- Mixtures, precursors, co-contaminants means more testing
- More testing and operations time
- Limited field-scale examples
- Energy intensity means more costs
- Life cycle costs?

Questions?

Ivan A. Cooper, PE, BCEE

Civil & Environmental Consultants, Inc.

3701 Arco Corporate Drive
Charlotte, NC 28273
704-226-8074
icooper@cecinc.com

Operational Issues

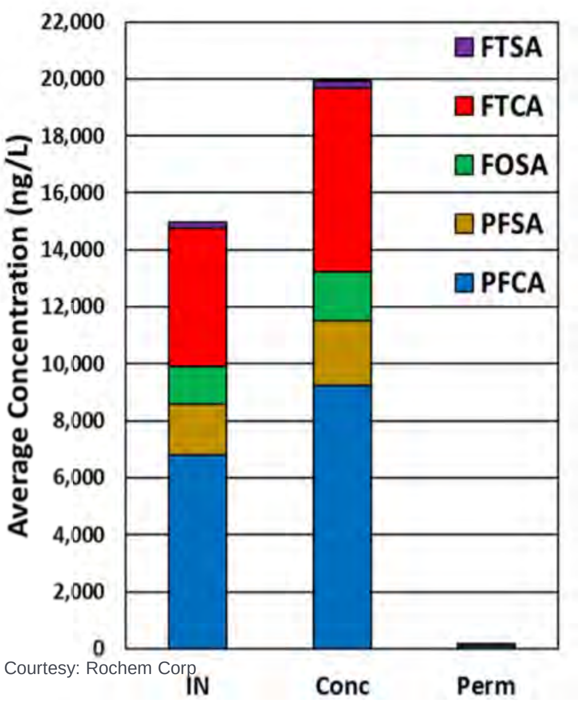
Technology	Pros	Cons
Granular Activated Carbon	• Effective for Long Chain PFAS • Simple to Operate • Simple to Change Media (Service) • Can be reactivated and reused • Many vendors/suppliers • Relatively temperature insensitive • Treated flow for dust control	• Needs RSSCT Test to evaluate breakthrough • Large Quantities of spend media • Needs good pretreatment - Ultrafiltration, biological treatment (Pretreatment requires treatment waste disposal) • Short chains PFAS breaks through quicker • After saturation, needs changeout - can be frequent • Washout of media, especially after changeout, contains PFAS. Therefore, need backwashing after changeout • Flow sensitive to prevent channeling/rat-holing • Activated carbon may become fouled biologically reducing effectiveness. May need to bleed bleach • Specialized equipment to prevent dust generation and uniform distribution in tanks • Can be resource intensive over long times for testing and replacements

Operational Issues

Technology	Pros	Cons
Ion Exchange Ion Exchange Resin 	• Can remove most compounds, GenX • Short detention time compared to other adsorbents • Lasts longer than Activated Carbon, so less frequent changeout or regeneration • Relatively temperature insensitive	• Needs Pretreatment and often Post treatment • Other constituents interfere – iron, chlorides, TSS, etc. • When will breakthrough occur? • Regeneration at site of offsite, or disposal. • If regenerated, results in concentrated PFAS stream • Biological fouling • Add bleach – may cause some IX to foul or become “blocky” – Gel types • Replacement media very costly

Reverse Osmosis Leachate Process Flow

- Membrane Based Separation Process- 99.9% removal +/-
- Separates Water from Organic and Inorganic Compounds.
- Effluent for reuse or disposal.
- What to do with Reject???
  - Recirculation returns the contaminants to the landfill.
  - Solidification
  - Evaporation – Crystallization
    - Heat needed
    - Air Emissions
  - Other –
    - Electrochemical Oxidation
    - Plasma



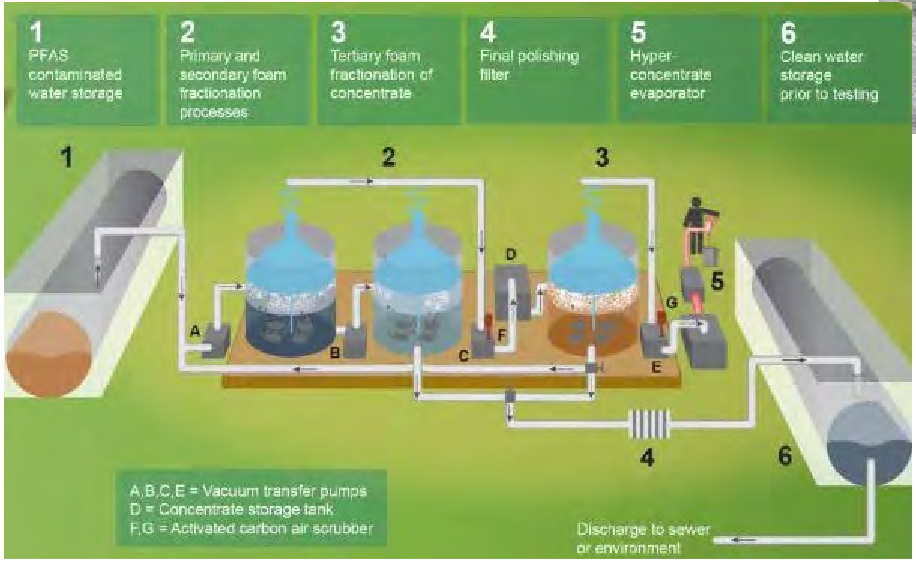
Courtesy: Rochem Corp

Operational Issues

Technology	Pros	Cons
Reverse Osmosis, NF	• 2 or 3 stage very effective • Robust monitoring available • Some Mfg. do not require pretreatment (filters on skid) • Membranes last years • Permeate reuse on site for dust control	• Requires high pressures – big amp draw • Problems with high TDS – permeate percentage reduced • Generates large amounts of reject to manage • Fouling - Cleaning frequency/chemicals • Requires housing in a building • Depends on membranes, may not remove all PFAS • May need to be chained with other technologies

Foam Fractionation

- Removal of six Massachusetts PFAS to below drinking water standards

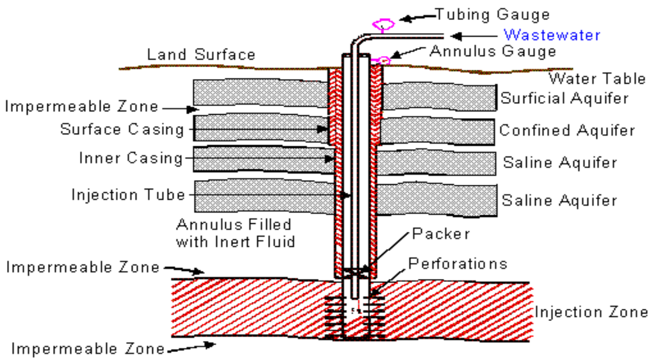


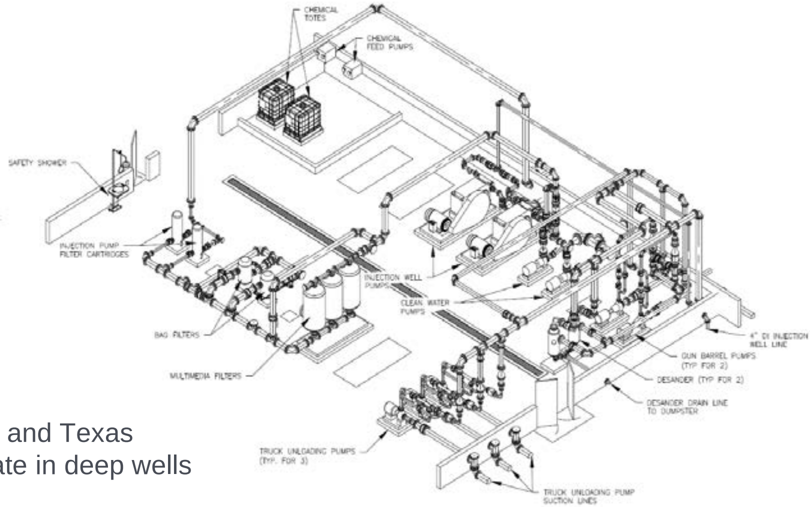
Operational Issues

Technology	Pros	Cons
Foam Fractionation	• Commercially available • Internet support for process monitoring and changes • Comes in 40-foot containers • Can be located outdoors • Low operating costs • Low volume concentrate –needs solidification/destruction	• Pretreatment recommended • Incomplete removal of all PFAS • Skimming and disposal of foam • Residual concentrated PFAS disposal/destruction • Possible additional treatment of FF leachate/combined treatment • Reactor plugging by fluoride salts • Vary operational parameters by aeration rate, pH, temp. salinity, surfactants, stability, quality foam

Deep Well Injection

- Depends on Geology, Receptors, Seismicity
- Long, Expensive Permit Time
- Pretreatment/Filtration, Ion Removal
- High Pressure Pumps





Sites in Michigan and Texas
dispose of leachate in deep wells

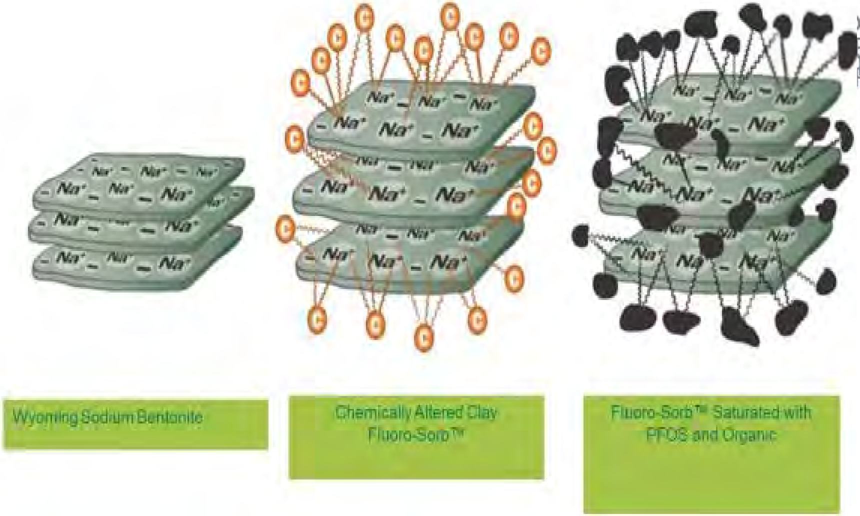
Operational Issues

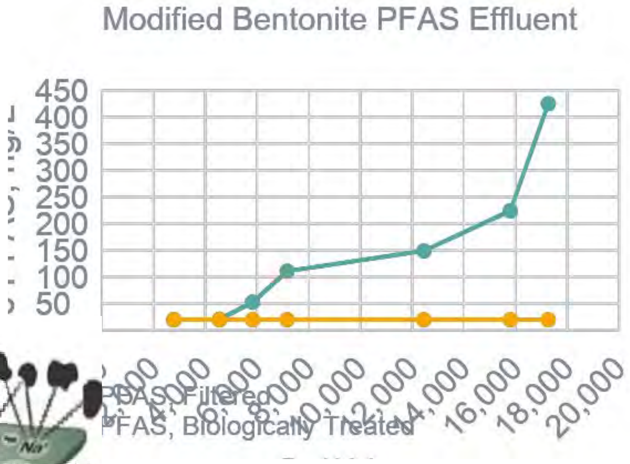
Technology	Pros	Cons
Deep Well Injection	• Others manage disposal • O&M may be low	• Limited locations • Permitting • Pretreatment to prevent clogging formation • Manage pretreatment residuals • CAPEX Can be costly • Manage hauling trucks

Surface Modified Bentonite
(Adsorbent)

- 3 minute EBCT

FLUORO-SORB® 200 adsorbent





Courtesy: Cetco

Operational Issues

Technology	Pros	Cons
Surface Modified Bentonite (FluoroSorb)	• Commercially available • Monitor flow and pressures • Clay plates separate and give longer life • Longer bed life than activated carbon • Research active – improvements coming!	• Pretreatment recommended • Focus on PFAS, no removal other constituents • Better at removal of long chain than short chain • PFHxS, others often bleeds through • Static bed versus fluidized bed installation • Replacement of media • Treatment of expended media • May bleed PFAS if not stabilized • Possible post-treatment of leachate

Evaporation

Courtesy: Heartland

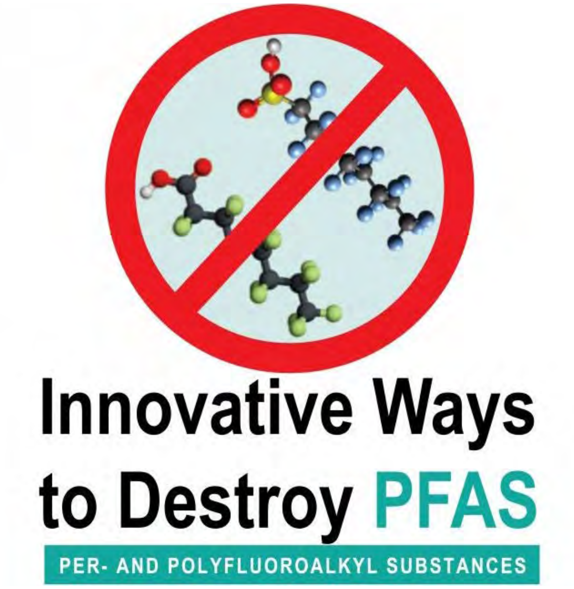
Courtesy Encon Evaporators

Operational Issues

Technology	Pros	Cons
Evaporators	• Mature designs • Passive/Active designs • Significantly reduces volumes • May be candidate for residuals or entire leachate flow • Can be cost effective	• Costly • Significant design/construction time • Large energy consumption • Needs concentrate management • May not remove all PFAS • Some may be emitted in exhaust • Visual plume maybe objectionable • Public perception

Residuals Technologies

- Destruction
  - Incineration
  - Plasma
  - SCWO (Supercritical Water Oxidation)
  - ElectroChemical Oxidation
  - HALT (Hydrothermal Alkaline Treatment)
  - Deep Well Injection
- Stabilization/Solidification
  - Cementitious S/S
    - Encapsulation (In totes or vessels)
    - Holcim/ADC
  - Return to the landfill
  - Hazardous Waste Landfill Haul and Dispose



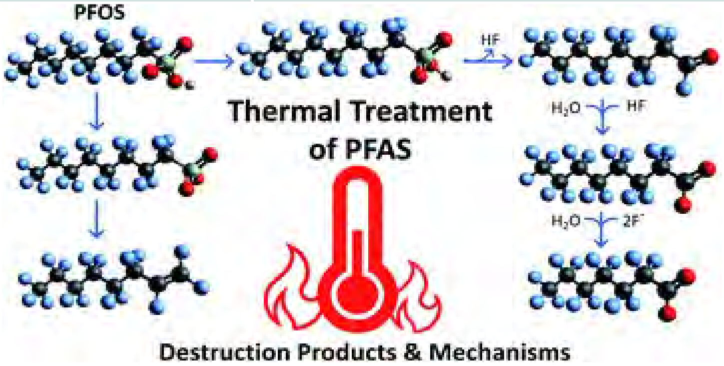
Incineration

- EPA – 99.99% destruction at 1,400 deg C at 1 second detention time
- DOD banned for a time

Courtesy Heartland Heliostorm

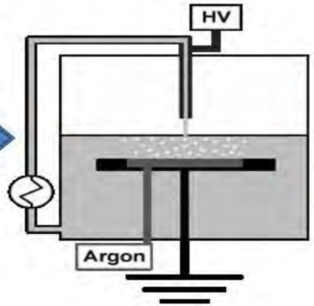
Operational Issues

Technology	Pros	Cons
Incineration	• Monitor flow, turbulence, temperature • Possible complete PFAS destruction • Ship to offsite incineration • Mobile vendors can make periodic visits to manage stored concentrate to avoid costly construction • Heartland's Heliostorm operates at 3,000 deg C – more complete destruction?	• Pretreatment • Startup/shutdown procedures • Long time to permit/construct • Fuel usage • Visual emissions/public concerns • Possible recombining to other larger molecules • Public concerns • Expensive to install, operate, maintain

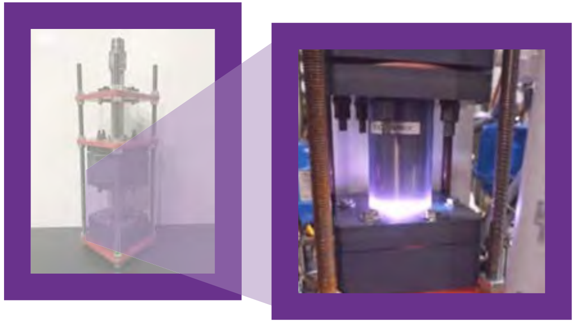


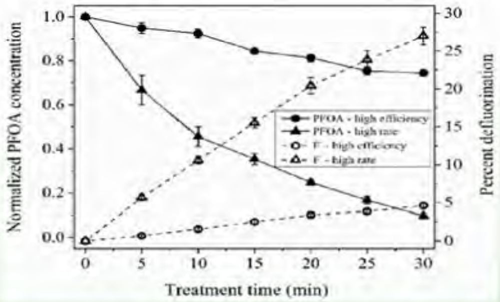
Plasma Destruction

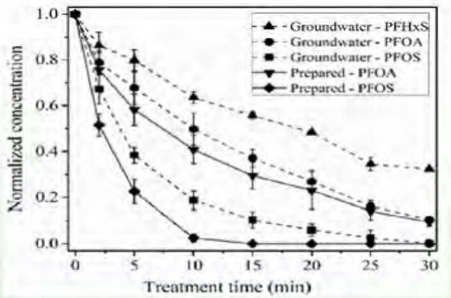
Bench-scale enhanced contact plasma reactor



Plasma produces aqueous electrons and H radicals which are capable of chemically degrading PFASs





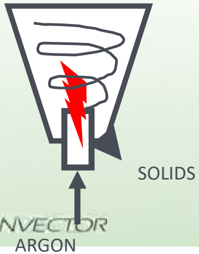


Major byproducts: fluoride ions, fluorinated gases and shorter-chain PFAAs

Plasma hydrocyclone
Water enters tangentially at the top, spins down, then exits at the center top forming a reverse vortex tornado flow.

Cyclonic separation of solids

Recirculation of plasma carrier gas (argon)



Operational Issues

Technology	Pros	Cons
Plasma Destruction	• Monitor flow and pressures • Daily operations may be minimal • Best used for small volumes of concentrated PFAS removed by other processes (i.e., Foam Fractionation) • Possible complete PFAS destruction	• Under development • May not remove or destroy all PFAS • Long term operation requirements unknown • Treat off-gas (Caustic or Carbon?) • Power - Free and hydrated electrons in plasma (reductive reactants) break C-F bonds due to their very high energy (50 to 100 eV)

Supercritical Water Oxidation (SCWO)

- Water above 705°F and 3,200 lbs/in^2 - Rapidly destroys PFAS
- >99.99% removal under 10 seconds or less
- If organics, no additional fuel needed
- Creates HF – needs neutralization

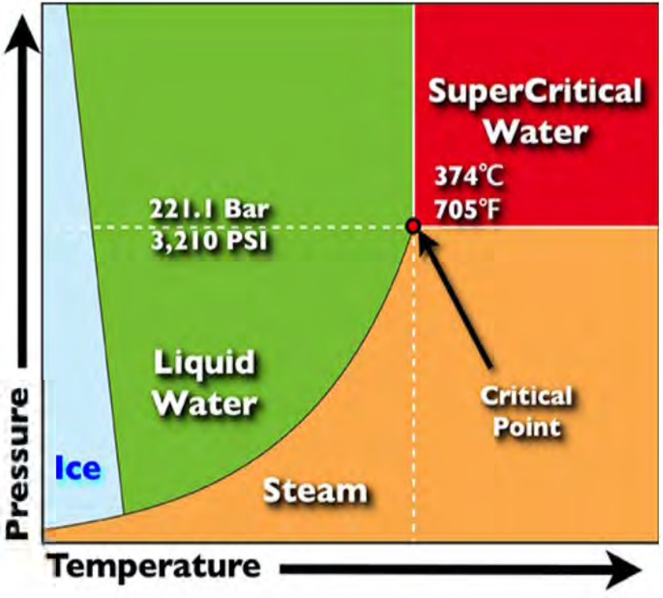


Figure 1. *SCWO reactions occur above the critical point of water. Image credit: Jonathan Kamler.*

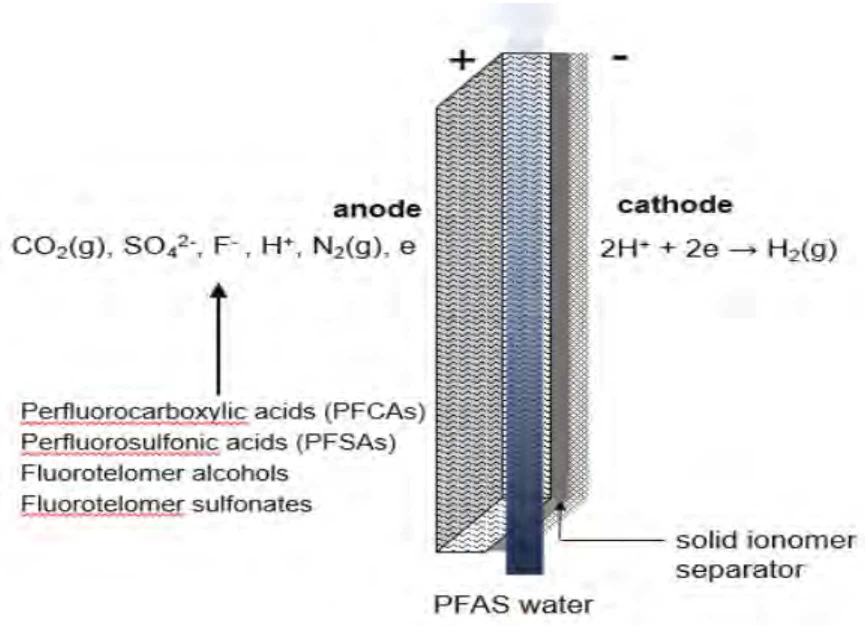
EPA, Jan 2021

Operational Issues

Technology	Pros	Cons
Supercritical Water Oxidation (SCWO)	• Monitor flow and pressures, gas emissions • Daily operations may be minimal • After initial Temp/pressure, may not require more energy • Best used for small volumes of concentrated PFAS removed by other processes (i.e., Foam Fractionation) • Possible complete PFAS destruction – results in inert ash • Several vendors available	• Limited Suppliers • Costly to run – depends on waste stream • Corrosive gases - HF -Treat off-gas (Activated Carbon?), sequestering with calcium • Long term operation requirements unknown • May not removal all PFAS • Materials of construction • High Pressure/temperature • High energy - Free and hydrated electrons in plasma (reductive reactants) break C-F bonds due to their very high energy (50 to 100 eV)

Electrochemical Oxidation

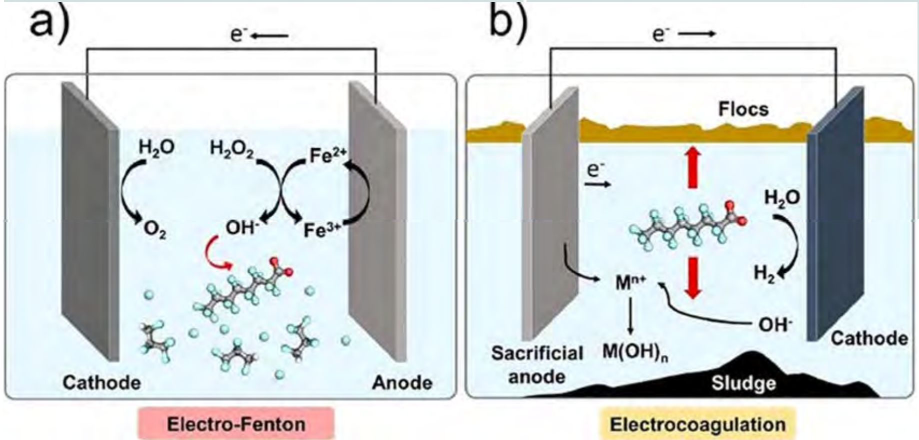
Various Equipment designs



- Several Vendors
  - ECT2; Aclarity; Sanexen; Siemens; OXbyEL; others
- Power Requirements:
  - 0.125 - 0.5 kwh/gallon
  - 6 volts produces free electrons
- Electrode materials
  - Titanium; boron doped diamond
- Single pass v. multiple pass
- Destroys ammonia too!

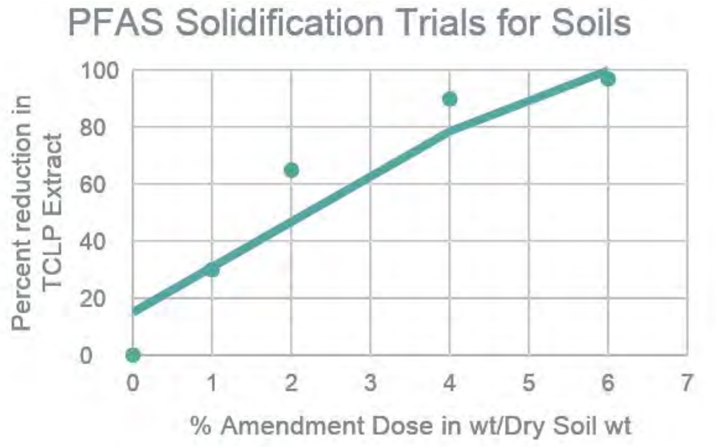
Operational Issues

Technology	Pros	Cons
Electrochemical Oxidation	• Monitor flow and power feeds, gas emissions • Daily operations may be minimal • Operates at ambient temperature • Small footprint • Several vendors available	• May need pre and post treatment may be required • Long term operation requirements unknown • Replacement materials – Expensive electrodes • Generates toxic products, HF, Perchlorates formed ?– removal control • Long processing time for PFAS destruction • Power requirements



Leachate Residuals PFAS Stabilization

- CEC Solidification of SAFF
- 0.6:1 TCLP 99.9% retention all PFAS



Tests by Dan Cassidy, Western Michigan University - 6% dose Fluoro Sorb achieved < 70 ppt [PFOA+PFOS] in leachate in all soils using TCLP Test.

Techniques:
Mixture of generic S/S amendments known to sorb PFAS*:
Powdered activated carbon (PAC),
Iron oxide (Fe_2O_3) powder,
Montmorillonite clay,
Ground-granulated blast-furnace slag (GGBFS), and
Portland cement (PC)
Fluoro Sorb

Disposal:
Landfill
Alternate Daily Cover

[PFOS] = **14,000 -** 100,000 ng/Kg
[PFAS] = 2,500 – 17,000 ng/Kg

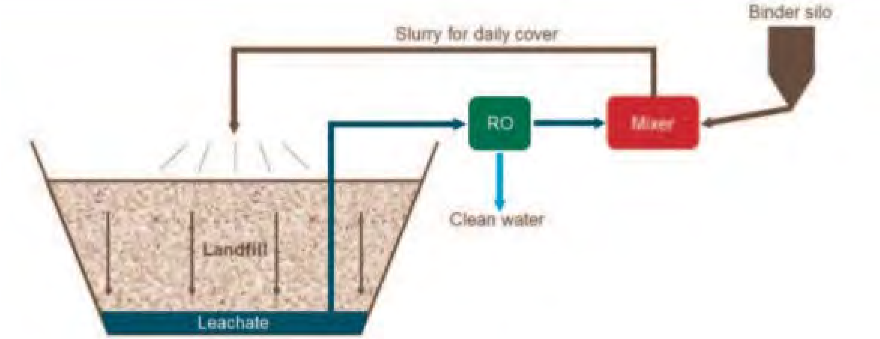
Tested with Fluoro Sorb from Cetco

Fixation of Residuals

(Holcim/Lafarge)

- Proprietary cement binder
- No free liquid (Paint Filter Test)
- Friable for use as Alt Daily Cover

MAR- Enviroset	As Received Results	SPLP Results
Sand	ppt (ng/L)	ppt (ng/L)
PFNA	800	11
PFOS	4,900	63
PFOA	1,500,000	390
NY State- Enviroset		
Sand		
PFNA	500	ND
PFOS	5,900	ND
PFOA	2,400	ND



Operational Issues

Technology	Pros	Cons
Solidification	• Possible disposal back to Landfill • ADF or in blocks • Simple, everyday type operation	• Does not destroy PFAS, but reduces mobility and leachability • Tests to confirm no release • May not be effective on all PFAS • Volume and weight - Mass takes up airspace • Time to cure before disposal • ADC proposed – not commercially used • Possibly costly based on volume of solidification materials

Questions?

Ivan A. Cooper, PE, BCEE

Civil & Environmental Consultants, Inc.

3701 Arco Corporate Drive
Charlotte, NC 28273
704-226-8074
icooper@cecinc.com


PF25
Questions?


PF25
Reception

New Developments & Initiatives

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New Developments & Initiatives

Amarjit Basra
Chief Scientist
OCP North America

Jango Bhadha
Associate Professor
University of Florida

Dan Obenour
Associate Professor
NCSU

Anna-Maria Marshall
Associate Professor
of Sociology and Law
University of Illinois,
Urbana-Champaign

Mamou Ehui
Executive Director
Global Phosphorus
Institute

Brian Bohman
Agronomic Science &
Innovation Manager
OCP North America

Jeff Costantino
Communications Director
ReFED

Stephanie Kulesza
Associate Professor,
NCSU
SERA-17

Gerald Steiner
Consultant
UWK-Danube University

New Developments & Initiatives

Brian Bohman
Agronomic Science & Innovation Manager
OCP North America

Understanding Phosphate Fertilizers:
Sources and Agronomic Considerations

Brian Bohman, Ph.D.

17 September 2025

OCP North America

Reliable Products.
Reliable Partners.

Outline

01
Production of Phosphate Fertilizers

02
Review of Key Phosphate Fertilizers

03
Phosphate Innovation

04
Agronomic Considerations

Production of Phosphate Fertilizers

OCP Group: Mission

STEWARDS

A century-long legacy as stewards of **70% of the world's phosphate** reserves.

GLOBAL LEADER

Global leader in sustainable phosphate-based solutions, dedicated to transforming **agriculture** and **food security** for a growing global population.

EXPERTS

Accomplishing goals by leveraging extensive experience and cutting-edge technologies to **enhance crop productivity** while **bolstering environmental resilience**.

Global Phosphate Resources

- Global phosphate rock production has significantly increased in line with demand for growing agricultural and industrial uses
- Current estimates of reserve life ~350 years demand consideration of methods to enhance efficiency of phosphate production and usage

Figure 1-3: World phosphate rock production, 1900-2021

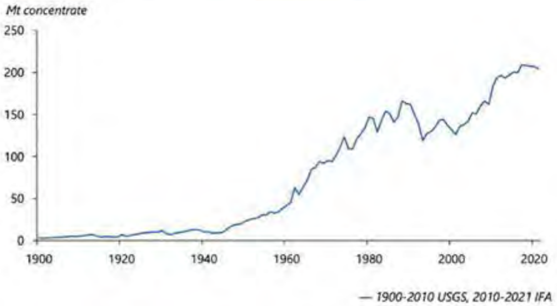


Figure 4-1: Cropland P_2O_5 demand projections to 2050

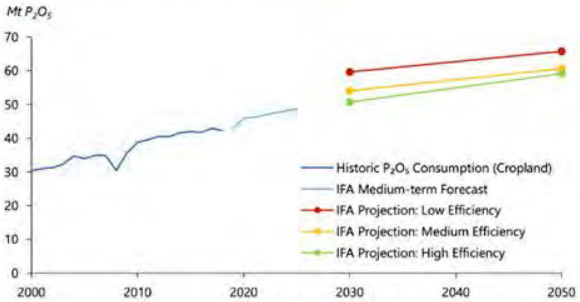
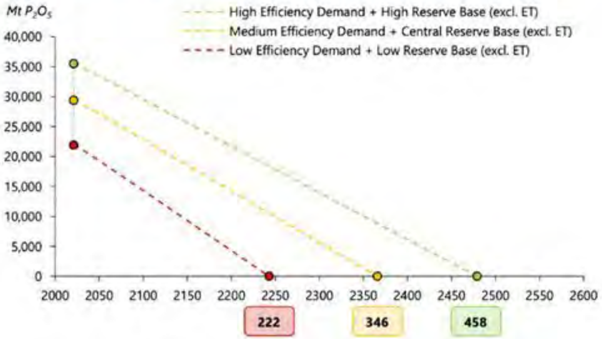


Figure 2: Depletion of the reserve base (technically recoverable using current technology)

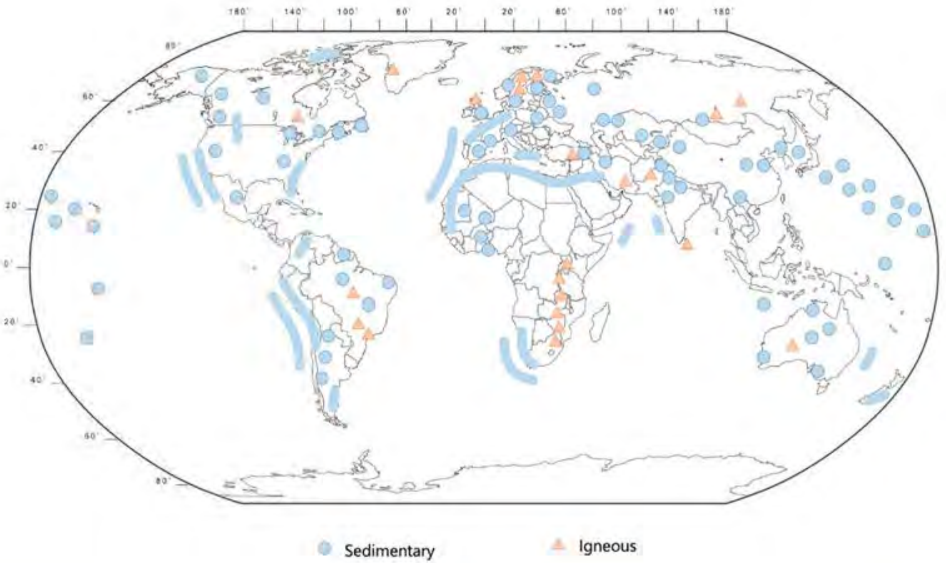


Argus (2023)

Global Phosphate Resources

- *Sedimentary* phosphates (85%)
  - Formed by marine sediments
  - Surface mining
  - Lower production costs
  - Higher impurities
  - Higher raw grade
- *Igneous* phosphates (15%)
  - Formed by magma
  - Deep mining
  - Higher production costs
  - Lower impurities
  - Lower raw grade

Figure 1-4: Distribution of phosphate occurrences (after Pufahl & Groat, 2017)[4]



Stewart et al. (2005)
Argus (2023)

OCP Group: Industrial & Mining Infrastructure

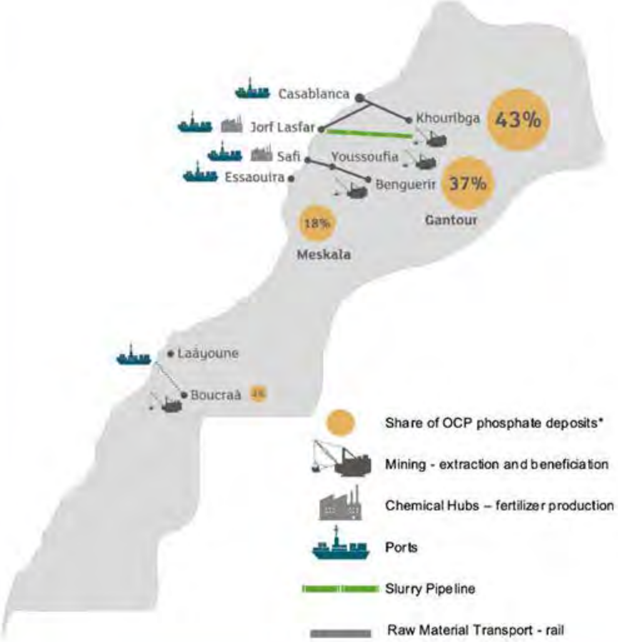
As the steward of the world's largest phosphate reserves, OCP oversees a sizeable industrial and mining infrastructure.

Global Phosphate Rock Reserve Estimates - billion tons*

~70% of currently known global phosphate reserves located in Morocco

~50bn tons of economically exploitable phosphate reserves

200+ years of global consumption at current demand levels



*Sources: US Geological Survey (USGS) and International Fertilizer Development Center (IFDC)

Mining: Sedimentary Phosphates

Phosphate-rich ore is extracted from layered sedimentary rock, by sequentially removing layers of low-grade and high-grade ore

Rock layers were formed over millions of years by P-rich ocean sediments

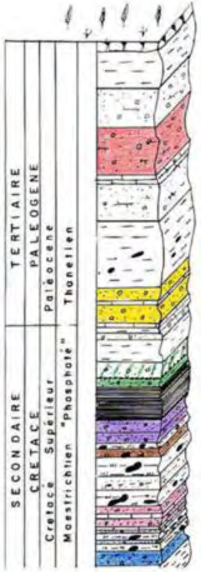
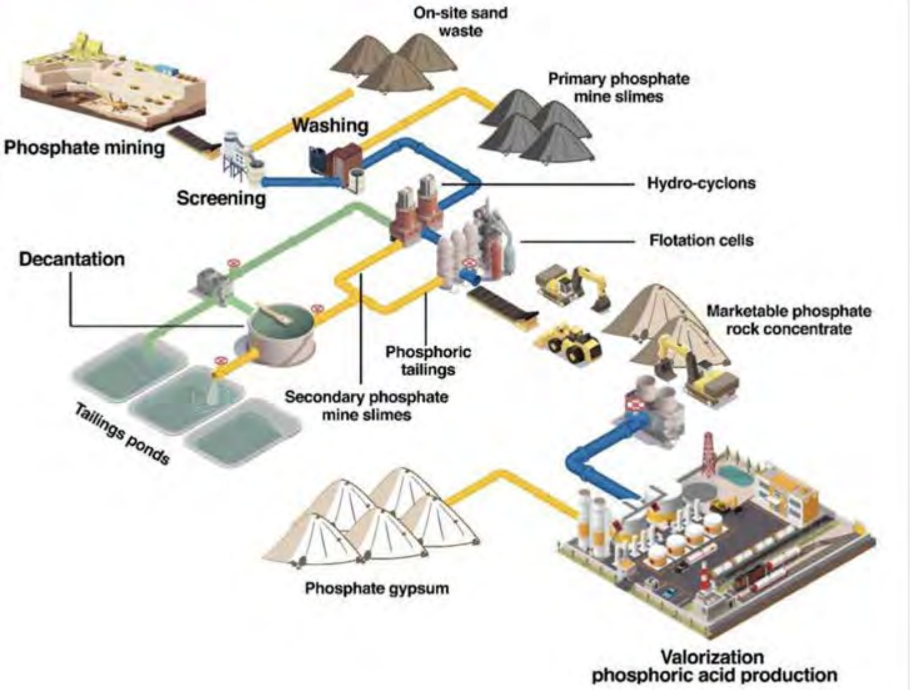


Fig. 7 : La coupe lithologique moyenne du gisement de Ben guérir (documents OCP)

(including fossils!)

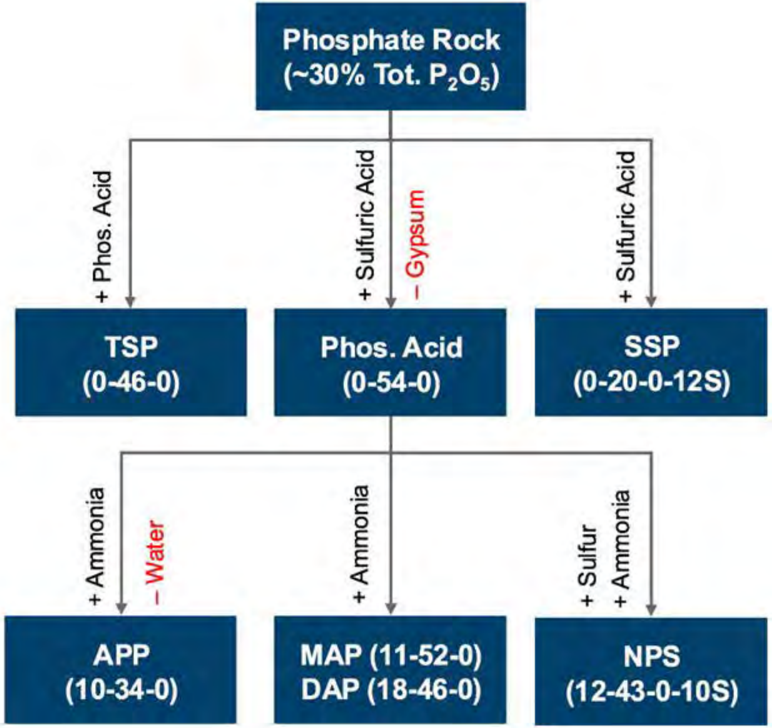
Initial Processing: Sedimentary Phosphates

High-grade phosphate rock is mechanically separated from other low-grade materials, and transported for subsequent processing



End Product Processing

Various chemical processes are used to transform phosphate rock into industrial or fertilizer products



Historical Phosphate Use and Production

- Superphosphates were the original high analysis P fertilizer; global use peaked in 1970s
- Dramatic rise in total production driven by ammoniated phosphates, due to reduced production cost/complexity relative to superphosphates
- Global P fertilizer use remains dominated by ammoniated phosphates over superphosphates

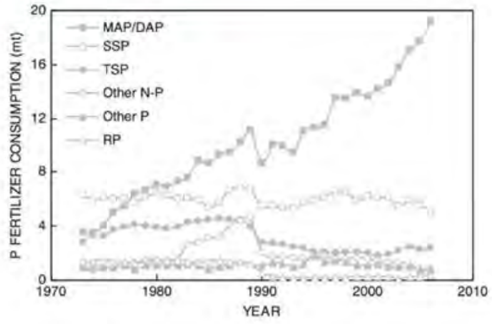


Figure 5-25
World use of common P fertilizers in metric tons of P. MAP/DAP, diammonium phosphate/monoammonium phosphate; SSP, single superphosphate; TSP, triple superphosphate; RP, rock phosphate used for direct application.
(Adapted from International Fertilizer Industry Association, 2009.)

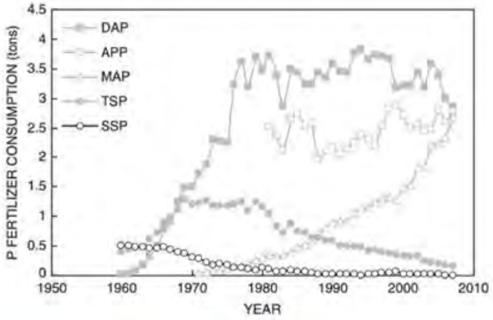


Figure 5-26
Use of common P fertilizers in the United States. DAP, diammonium phosphate; APP, ammonium polyphosphate (also includes other N-P fertilizer); MAP, monoammonium phosphate; TSP, triple superphosphate; SSP, single superphosphate.
(USDA ERS, 2009.)

Havlin et al. (2014)

Review of Key Phosphate Fertilizers

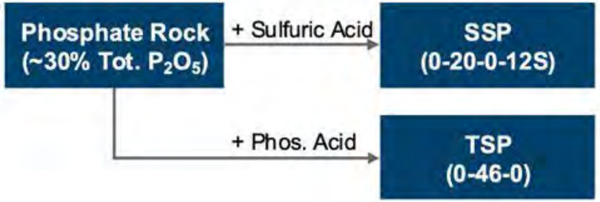
Phosphate Rock

- Phosphate rock is an apatite mineral with impurities varying by source
- Rock can be beneficiated to ~30% total P_2O_5
- Has very low water solubility, and requires acidic soil conditions (pH <5.5) to dissolve phosphate
- Qualifies as an organic fertilizer

Phosphate Rock (~30% Tot. P_2O_5)

- $Ca_{10}(PO_4)_{6-z}(CO_3)_zF_{2+0.4z}$
- **pH**: 8
- **Total P_2O_5**: 28-35%
- **Available P_2O_5**: ~3% (citrate-soluble)

Superphosphates



- SSP was first commercial mineral fertilizer
- TSP was first “high analysis” phosphate, due to acidulation with phosphoric acid instead of sulfuric acid (i.e., no gypsum)

Single Superphosphate (0-20-0-12S)

- $Ca(H_2PO_4)_2 \cdot H_2O + 2CaSO_4$
- **pH**: 2

Triple Superphosphate (0-46-0)

- $Ca(H_2PO_4)_2 \cdot H_2O$
- **pH**: 3

Ammoniated Phosphates

Phosphate Rock (~30% Tot. P_2O_5) → + Sulfuric Acid / – Gypsum → Phos. Acid (0-54-0) → + Ammonia → MAP (11-52-0) DAP (18-46-0)

- High total analysis grade (N + P_2O_5) with good granule characteristics
- Agronomically similar performance with regional preference in use

Monoammonium Phosphate (11-52-0)

- $(NH_4)H_2PO_4$
- **pH**: 4

Diammonium Phosphate (18-46-0)

- $(NH_4)_2HPO_4$
- **pH**: 8

S-Enhanced Phosphates

- Various techniques used to create sulfur-enhanced phosphates including
  - Co-granulation
  - Coating
  - Partial acidulation
- Two forms of S can be used for co-granulation
  - Sulfate-S: plant-available
  - Elemental-S: slow-release

TerraTek 10S (12-43-0-10S)

- $NH_4H_2PO_4 + (NH_4)_2SO_4 + S$
- **S**: 5% Sulfate; 5% Elemental
- **pH**: 5

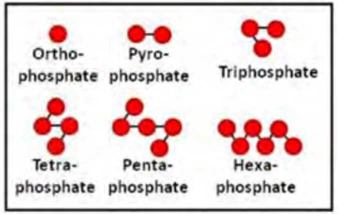
Polyphosphates

Phosphate Rock (~30% Tot. P_2O_5) → + Sulfuric Acid / – Gypsum → Phos. Acid (0-54-0) → + Ammonia / – Water → APP (10-34-0)

- Fluid fertilizer composed of two phosphate forms
  - Orthophosphate (~33%) immediately plant-available
  - Polyphosphate chains (~67%) plant-available w/in weeks
- Good as starter; mixes/stores well

APP (10-34-0)

- $[(NH_4)PO_3]_x$
- **pH**: 6



Comparative Phosphate Analysis

Fertilizer	N (%)	P_2O_5 (%)	K_2O (%)	S (%)	Ca (%)	Mg (%)	pH	Water Solubility
Phosphate Rock	0	~3*	0	0	~30	0	8	V. Low
SSP	0	20	0	12	30	0	2	High
TSP	0	46	0	0	15	0	3	High
MAP	11	52	0	0	0	0	4	High
DAP	18	46	0	0	0	0	8	High
NPS (TerraTek S10)	12	43	0	10	0	0	5	High
APP	10	34	0	0	0	0	6	High

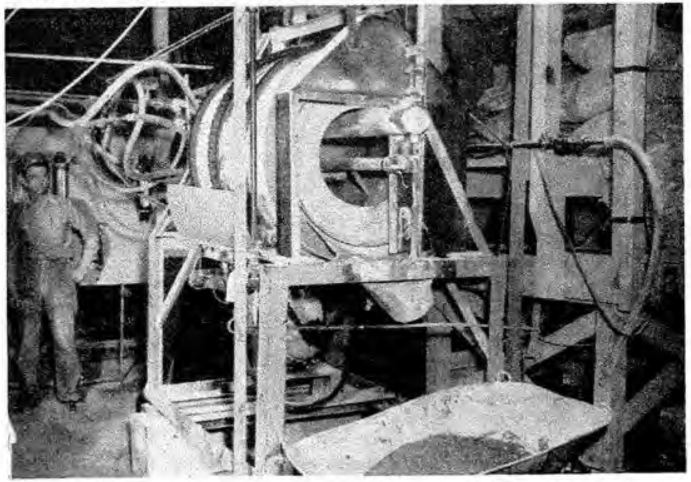
* Total P_2O_5 of ~30%

Phosphate Innovation

Phosphate Production Technologies

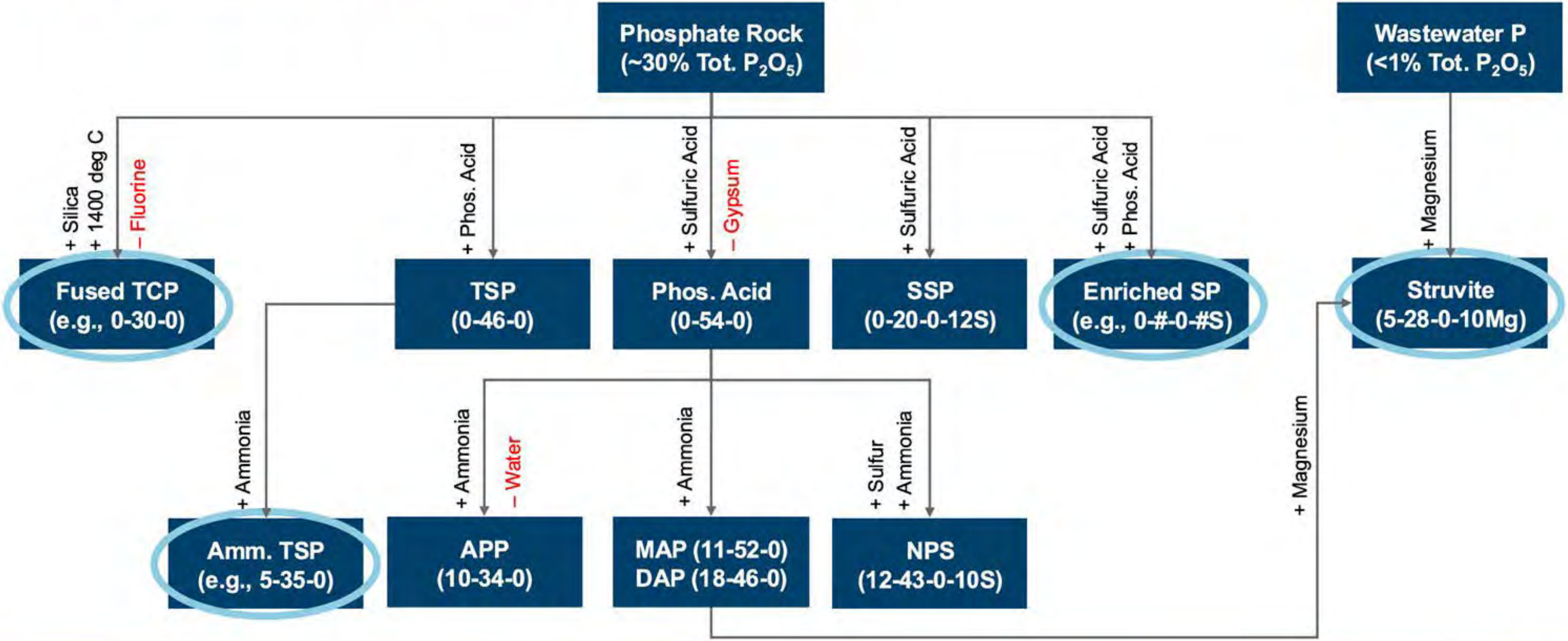
- Many key phosphate technologies were developed at TVA NFDC in 1930-1970s, including ammoniated phosphate production
- Various technologies that were historically developed may have applications of renewed interest
- In recent decades, phosphate fertilizer technology has shifted from the public to the private sector leading to new innovations

TVA's continuous ammoniator for superphosphates and fertilizer mixtures.



Yates et al. (1954)

Potential Phosphate Innovations



Fused Tricalcium Phosphate

Phosphate Rock (~30% Tot. P_2O_5)	+ Silica + 1400 deg C – Fluorine	Fused TCP (e.g., 0-30-0)

- Early process (circa 1930s) from TVA leveraging energy intensive nitrate production infrastructure dating back to WWI era
- Widely adopted by growers in the Tennessee Valley and became a bridge to adoption of improved phosphates
- Eventually deprecated in favor of more efficient production processes and higher analysis phosphates

Fused Tricalcium Phos. (e.g., 0-30-0)

- $3(Ca_3(PO_4)_2) + CaSiO_3$
- **Citrate Soluble P_2O_5**: >90%

TVA, 2020
Hignett, 1946

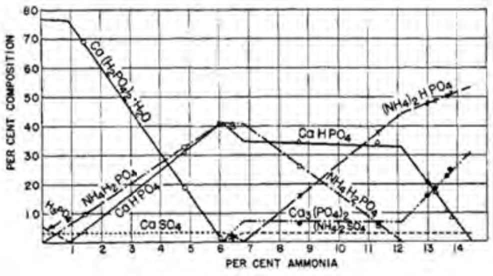
Ammoniated Superphosphates

Phosphate Rock (~30% Tot. P_2O_5) → + Phos. Acid → **TSP (0-46-0)** → + Ammonia → **Amm. TSP (e.g., 5-35-0)**

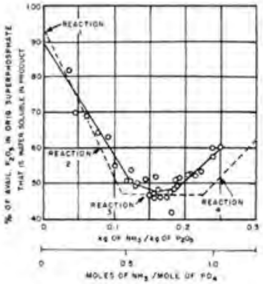
- Precursor technology to producing ammoniated phosphates (e.g., MAP/DAP) dating to the 1930s
- Ammoniation of superphosphates will reduce water- and citrate-soluble P_2O_5 by evolving new phosphate species (e.g., MAP, DCP, DAP, TCP, etc.)
- Fully ammoniated superphosphate (i.e., 5-6% N, no MCP remaining) is chemically compatible with urea

Ammoniated TSP (e.g., 5-25-0)

- $NH_4H_2PO_4 + CaHPO_4 + NH_4HPO_4 + Ca_3(PO_4)_2$



Composition of Products Obtained on Ammoniated Double Superphosphate at 100 deg C in a Closed Vessel



Effect of Ammoniation on Water Solubility of P_2O_5 in Triple Superphosphates

White et al., 1935
Hignett, 1985

Enriched Superphosphates

Phosphate Rock (~30% Tot. P_2O_5) → + Phos. Acid + Sulfuric Acid → **Enriched SP (e.g., 0-33-0-6S)**

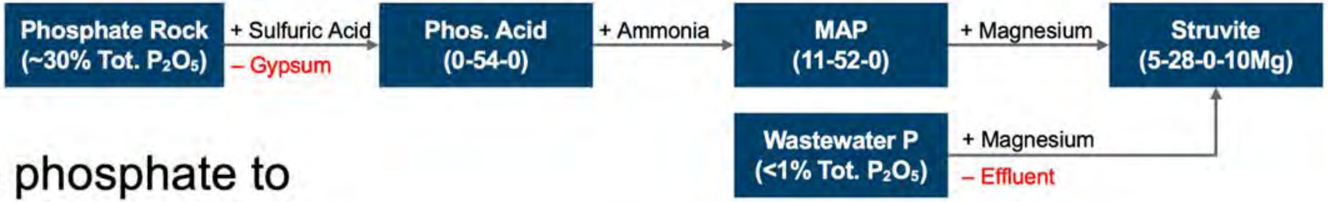
- Transition technology bridging between SSP and TSP paradigm
- Provides calcium sulfate (i.e., gypsum) source with differential solubility/availability than ammonium sulfate or elemental sulfur
- Modifying ratio of phosphoric and sulfuric acids can tailor the product to meet the specific P:S ratio required for a specific crop/geography

Enriched SP (e.g., 0-33-0-6S)

- $Ca(H_2PO_4)_2 \cdot H_2O + CaSO_4$

Yates et al., 1953
Hignett, 1985

Struvite



- Emerging alternative phosphate to recycle P from waste streams; can also be produced via MAP
- Low water-soluble P_2O_5 content due to low solubility of ammonium magnesium phosphate mineral
- Remaining citrate-soluble P_2O_5 is considered plant available under acidic soil conditions (e.g., rhizosphere)

Struvite (5-28-0-10Mg)

- $NH_4H_2PO_4 \cdot 6H_2O$
- **Water Soluble P_2O_5**: <1%
- **pH**: 9

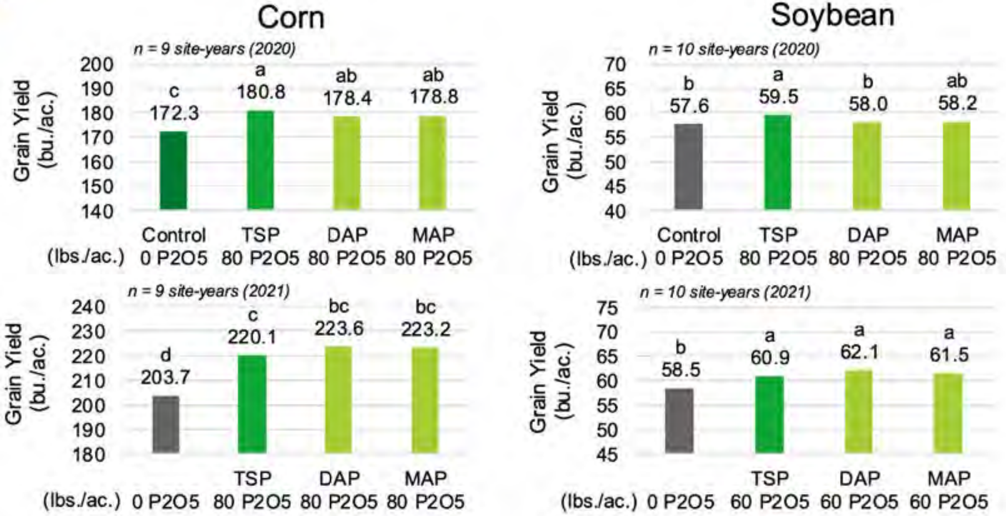
Degryse et al., 2016
University of Arkansas, 2023

Agronomic Considerations

Agronomic Considerations

Agronomic Equivalence

- Phosphate source comparisons trials are required to confirm equivalence across soil, crop, etc.
- E.g., TSP was demonstrated across 32 site-years in corn and 24 site-years in soybean to have equivalent agronomic performance to MAP/DAP

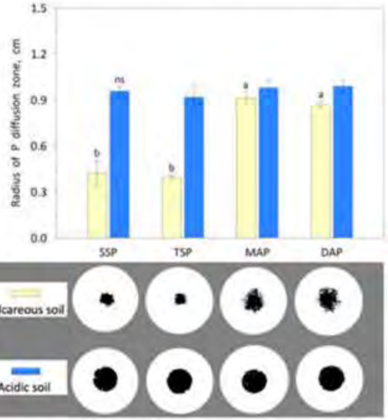


3rd Party Trials in 2020 – 2022 across Corn Belt locations (IA, IL, IN, SD, NE) in P responsive (4 – 35 ppm Bray P1) and acidic/neutral (5.1 – 7.8 pH) soils

Agronomic Considerations

Soil pH

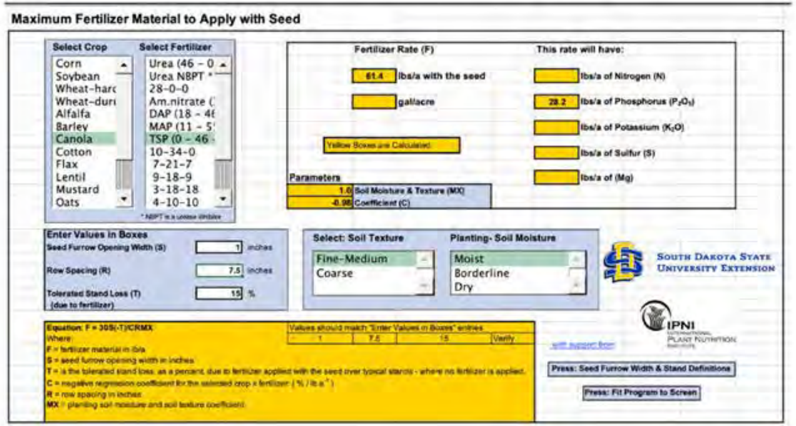
- Phosphate solubility and diffusion can be affected by soil pH



McLaughlin, 2018
Clark and Gelderman, 2024

Seed Safety

- Sensitivity to soluble salts from seed-placed fertilizers varies by crop and phosphate source



Agronomic Considerations

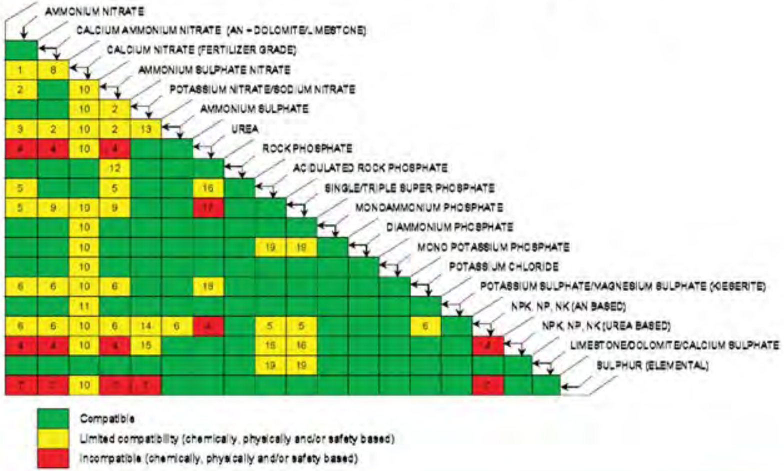
Nitrogen Losses

- Fall-applied ammoniated phosphates have significant potential for N losses

*“**only about one-third of N applied in the fall** as ammoniated phosphates at typical rates **is available to the next year’s corn crop** in Corn Belt mollisols. Colder, drier fall to spring conditions may increase this proportion, while warmer, wetter conditions would be expected to lower availability.”*

Blending Compatibility

- Superphosphates are not compatible to blend with urea



Fernandez et al., 2010
European Fertilizer Manufacturers Association, 2006

Thank You!

b.bohman@ocpna.com
(651) 307-8298

OCP North America

New Developments & Initiatives

Mamou Ehui
Executive Director
Global Phosphorus Institute

Gerald Steiner
Consultant
UWK-Danube University

Global Phosphorus Institute (GPI)

Role, Vision, Action and Strategic Perspectives

Dr Mamou EHUI | Dr Abdellah EL HOUARI | Dr Gerald STEINER

📍 Phosphorus Forum 📅 NC; September 17th, 2025

Why Phosphorus Matters

Phosphorus is a **non-substitutable element**, essential to all life and to global food production.

Yet its use and access remain uneven across geographies.

Global disparities:

- In some regions, **overapplication** leads to nutrient runoff and environmental degradation.
- In others, notably parts of the Global South, **underapplication** contributes to poor yields, land degradation, and food insecurity.

The African context reveals a critical paradox:

- Over **60% of agricultural soils** are phosphorus-deficient.
- Yet Africa holds **80% of global phosphate rock reserves**, while remaining import-dependent for fertilizers and processed phosphates.

→ This mismatch between **availability and accessibility** defines what we call the **Phosphorus Paradox**.

Governance and Leadership

GPI is guided by a multi-tiered governance model that includes:

- A **Board of Directors** providing institutional oversight
- A **Scientific Committee**, chaired by Dr. Terry L. Roberts, ensuring research quality and neutrality
- An **Executive Director** (in post since January 2025), supported by a dedicated scientific and administrative team

Ongoing governance restructuring is underway to better align GPI with its expanding global scope and partnerships.

Our Vision & SD2030 (2025–2030)

- **Goal: sustainable phosphorus for food security, environment, efficiency.**
- **Five pillars guide delivery and measurement via a Theory of Change.**
- **Focus on influence, facilitation, and sustained engagement.**

 |

What We Do

GPI serves as a **neutral knowledge broker**, a convener of dialogue, and a technical catalyst for improved phosphorus-related practices and policies.

P1. Knowledge production & consolidation (flagship & technical reports, knowledge hub, strategic research and disgnostics).

P2. Innovations & solutions (roadmaps, pilots, fellowship).

P3. Policy engagement & advocacy (promoting context specific solutions through dialogues, briefs, factsheets, events-COPs).

P4. Knowledge packaging & outreach (website, media, multimedia).

P5. Institutional development & strategic partnerships (regional and global).

Current Flagships include

- The **GPI Knowledge Hub**
- A **global phosphorus flow analysis** in collaboration with GTAP/Purdue
- The **African Platform on Sustainable Phosphorus**
- **The Pilot Fellowship Program**
- A series of **Phosphorus Fact Sheets and " did you know? "on** over 12 priority topics..
- **Governance & operations framework**; partnership dashboard.

Africa Platform for Phosphorus for Food Security

- Launched Sept 3 (Dakar) with six partners to connect policy, science, industry & farmers.
- Complements AFSH-AP, SIA, CAADP; avoids duplication via joint workplans & MoUs.
- Inclusive governance – modalities to be discussed.
- Sustainability- modalities to be discussed.

Work with us

- Co-produce data, reports, and dashboards; share legacy projects into the hub.
- Co-design pilots (affordability, circularity, water-quality hotspots).
- Join policy dialogues; align standards across regions.
- Partner on fellowships.

Prospects for mid- and long-term security of phosphorus supply

Prospects for mid- and long-term security of phosphorus supply

- Background : Concerns about possible future phosphate scarcity.
- Study performed by the Td Lab Sustainable Mineral Resources at UWK - Danube University, Austria
- Study main deliverables (a report backed by a summary paper in the **RCR journal**

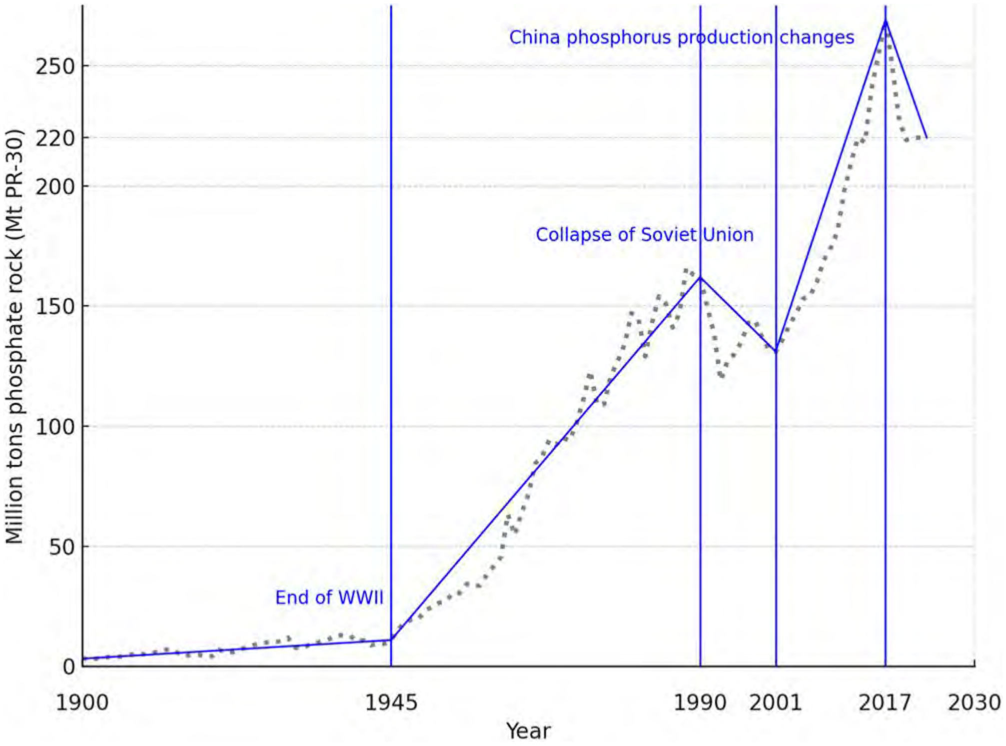
Contents lists available at ScienceDirect
Resources, Conservation & Recycling
journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling

The dynamics of increasing mineral resources and improving resource efficiency: Prospects for mid- and long-term security of phosphorus supply

Roland W. Scholz [a,b,*], Friedrich-Wilhelm Wellmer [c], Michael Mew [a], Gerald Steiner [a,d]

[a] *Danube University Krems, University for Continuing Education, Faculty for Business and Globalization, Transdisciplinarity Laboratory Sustainable Mineral Resources (SMR Td-Lab), Krems, Austria*
[b] *Swiss Federal Institute of Technology, Department of Environmental Systems Sciences, Zurich, Switzerland*
[c] *Academy of Geosciences and Geotechnology Hannover, Germany*
[d] *Complexity Science Hub, Vienna, Austria*

Historic trends of phosphorus consumption/demand (in million tons phosphate rock)



Prospects for mid- and long-term security of phosphorus supply

- **The fallacy of Mineral Reserves lifetime according to current static method- R/C (Reserves/Consumption):**

Phosphate reserves : **320 years** (Argus-IFA study, April 2023)

- Iron reserves: **54 years**.
- Zinc reserves: **17 years**
- Copper reserves: **36 years** in 1970 (till 2006), revised to **43 years** in 2000 (till 2043) and currently the estimation is **32 years** (till 2056)

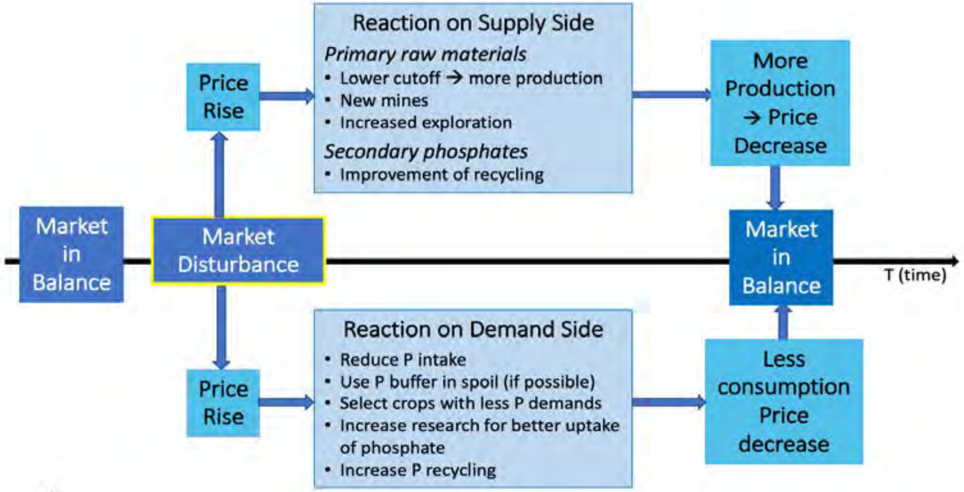
→ **Reserves increase with additional prospecting and demand development**

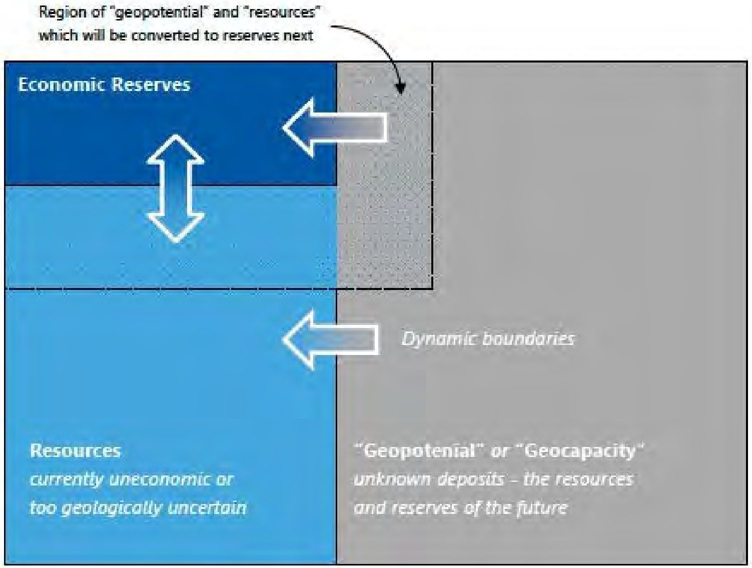
When resources become reserves

Resources become Reserves when technological advancements occur, and prices increase: current resources **R/C is 1,300 years.**

The feedback control cycle of P-demand and supply

- Reserves are a genuine dynamic geo-economic/geo-social entity: As prices rise
  - Stocks (reserves/resources) increase, you can mine lower ore grades, deeper etc.
  - Technology develops (faster)
  - Recycling increases

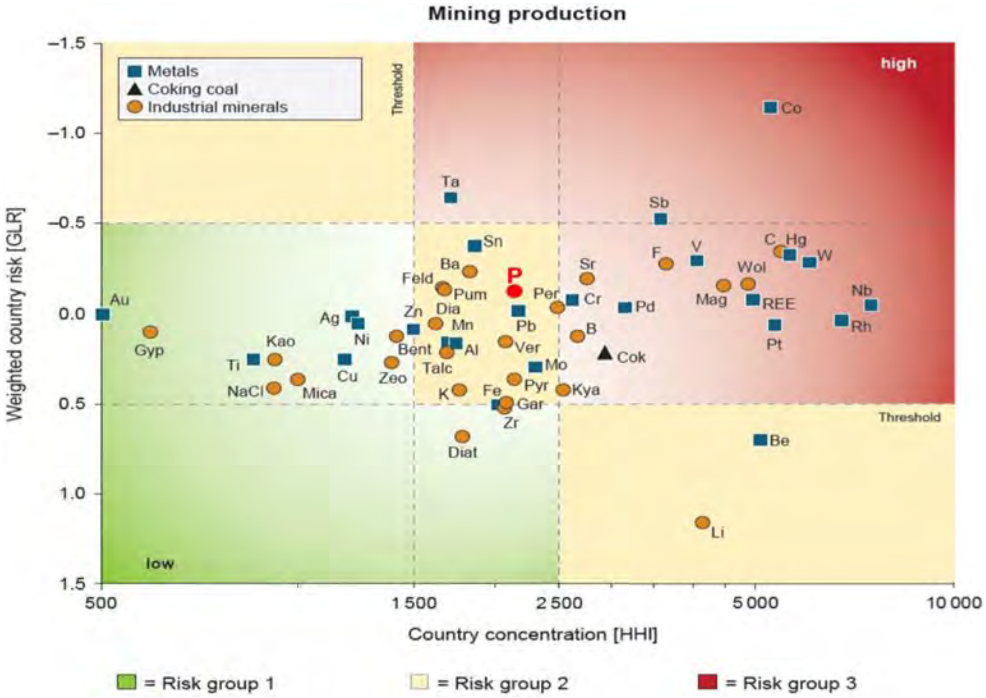




Geographical distribution of Phosphate Reserves and production

No more concentration of mining and production than for other minerals

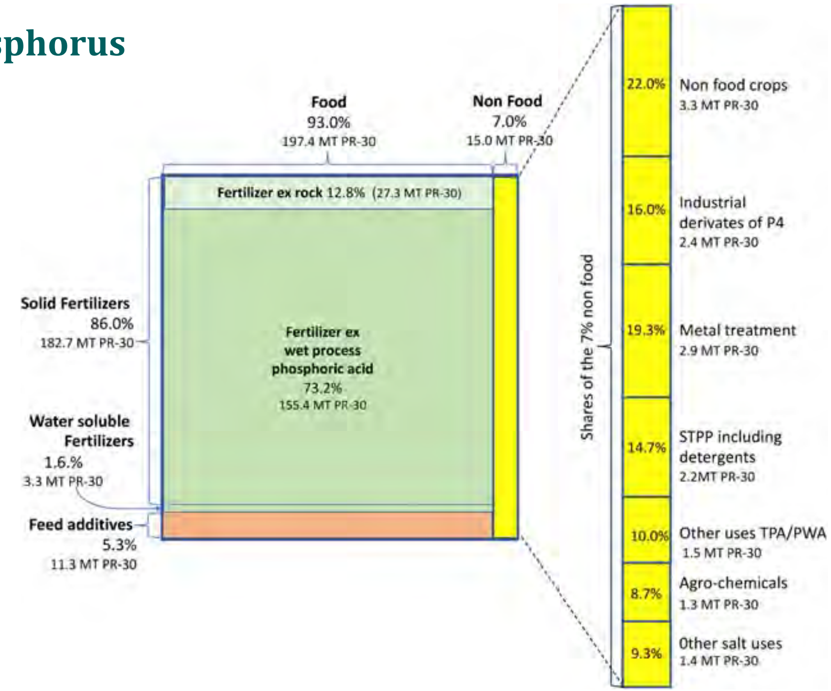
Herfindahl-Hirschman-Indices (HHI) of 53 commodities and country risks of phosphate supply



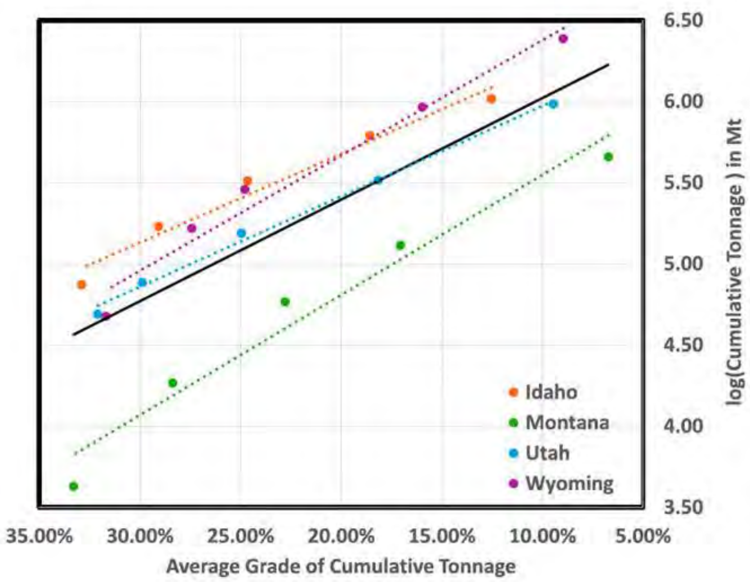
Major components of sustainable phosphorus management

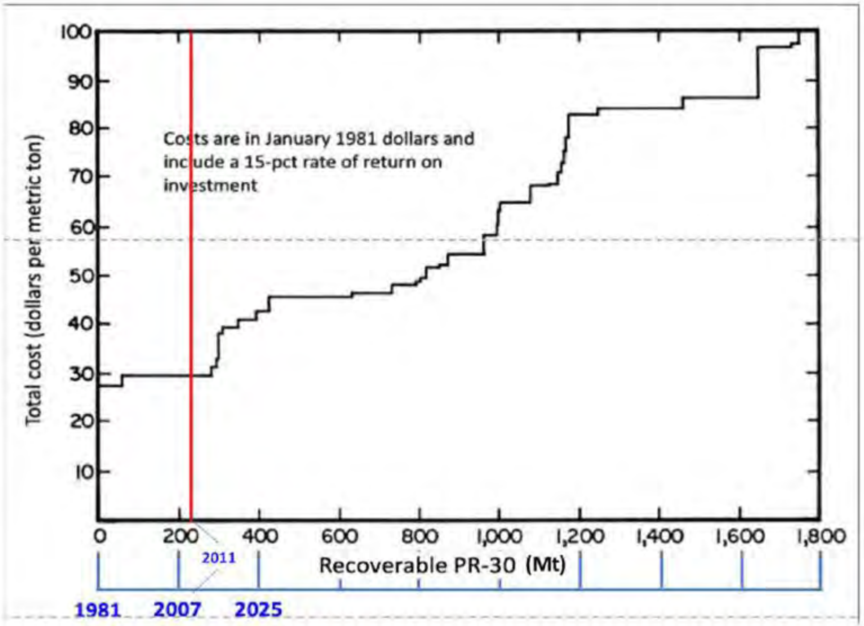
Demand dynamics and its social, technological, and environmental constraints

Consumption of mineral phosphorus



Exponential growths of cumulative tonnage increase with decreasing phosphate grades



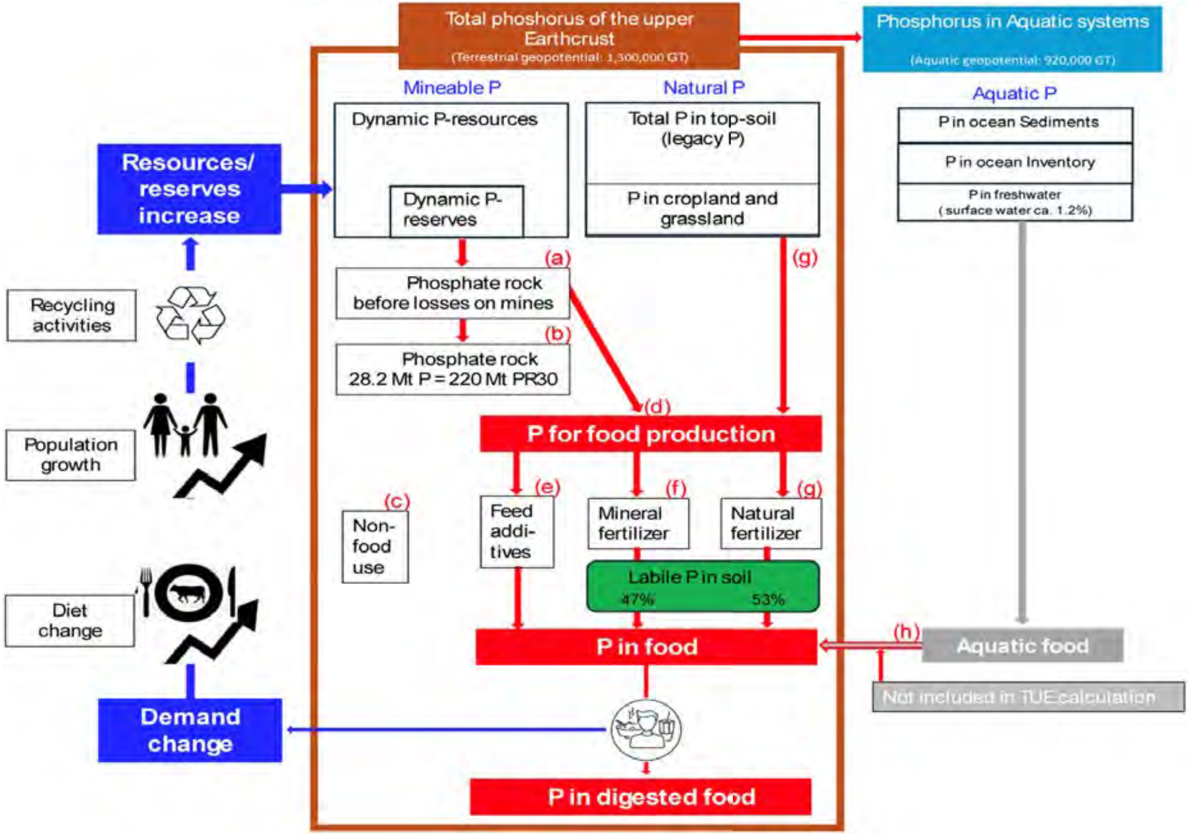


The cumulative CAC for phosphate rock of the WPF (Richard J. Fantel et al., 1983)

Important perspectives for extending P reserves lifespan:

- **P use efficiency is very low** (**10 %** excluding industrial products and considering weathered P as input) : there is a significant potential for improvement.
- **Recycling potential is huge**: There is a need for further innovation in sustainable technologies.
- **Innovation - new technologies** for low grade phosphate rock consumption and / or for improving recovery rates.

Rationale for assessing the Total Use Efficiency (TUE)



Mineral phosphorus for food (middle box) and drivers that change phosphorus demand and recycling (left side) and non-considered phosphorus in aquatic food

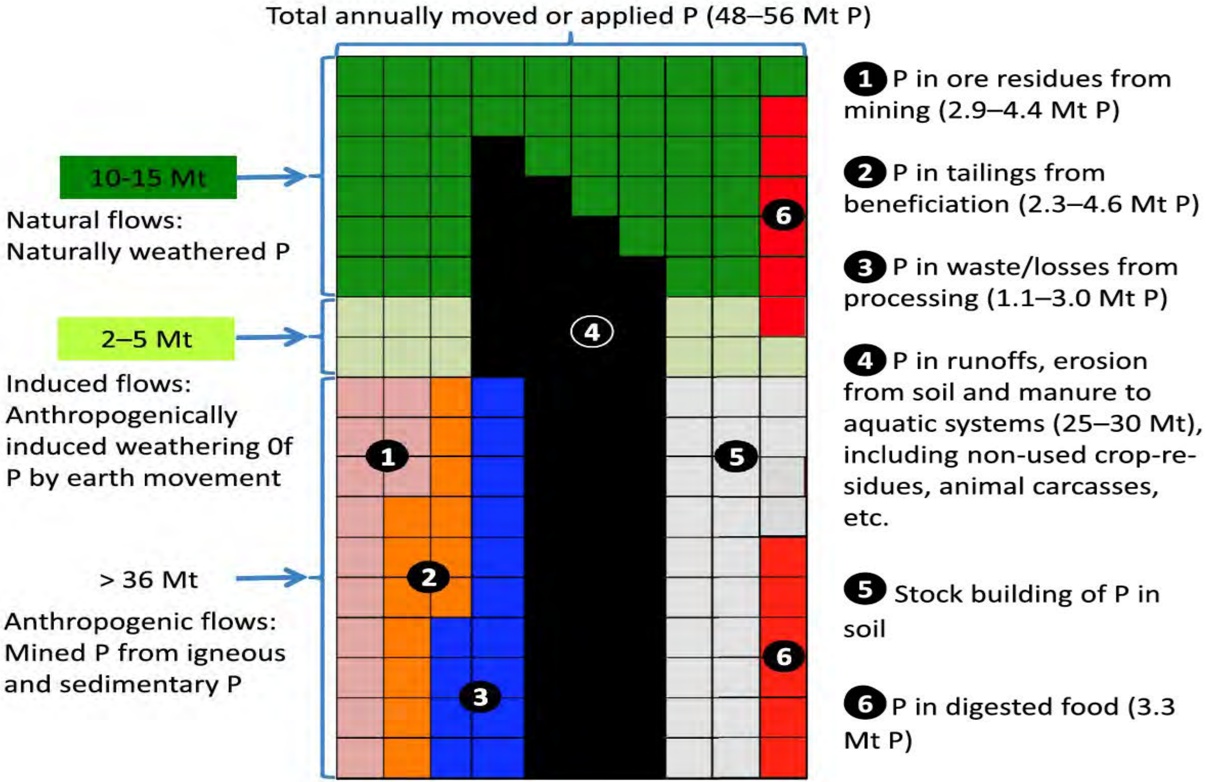
P-demand by food increases by 40% till 2060 by population growth and diet change

- Population growth (by 33%) is split to
  - Poor population from 1.49 to 3.91 (+169%)
  - Developed population
- Diet change
  - Poor population (no per capita change expected)
  - Developed: GDP-increase based increase by growths of meat consumptions by 24%

	OECD+10		Africa+		World	
Amount / Year	2020	2060	2020	2060	2020	2060
Population (billon people)	6.35	6.16 (6.66)*	1.49	3.91	7.84	10.07 (10,44)
Share of total population in %	81	61	19	39		
WheatEQ per capita	547	678	352	370		
GDP per capita (tsd US$ 2015 equivalent)	20.1	45.8	12.8	12.7	18.7	33.0
Share meat kcal in%	56	61				
Increases (in multiplicative factor each)	**Change factors of world regions and the world, 2020–2060**					
Population	0.97 (1.03)*		2.62		1.28 (1.33)*	
GDP per capita (US$ 2015 equivalent)	2.28		1.00		1.76	
WheatEQ demand per capita	1.24		1.05		1.09 (1.10)*	
World region's wheatEQ demand	1.20		2.76		1.37 (1.41)*	

Table 2: Population[35], share of population, and P-demand (per capita and per person) for the OECD+10,

Recycling potential : Use, losses, and stock building of phosphorus, based on 2011 data and assuming induced natural flows by earth movements, acid rain, etc.



Innovation options for the future: the case of phosphorus fertilizer production

Alternatives for traditional technologies

- Technologies serving circular economy: a systemic perspective
- How to extend existing technology portfolios?
- How to use very low grade phosphate rock?
- How to increase recovery rate during mining and fertilizers production
- How to overcome possible bottlenecks in production: 50 % of the sulfuric acid produced worldwide is used for fertilizers, and ~90-95 % of the world’s P fertilizers are based on sulfuric acid.
- Increasing the resilience of future production scenarios: from vulnerabilities to technology innovation niches

Innovation options for the future: the case of phosphorus fertilizer production

Examples of **achieved improvements**:

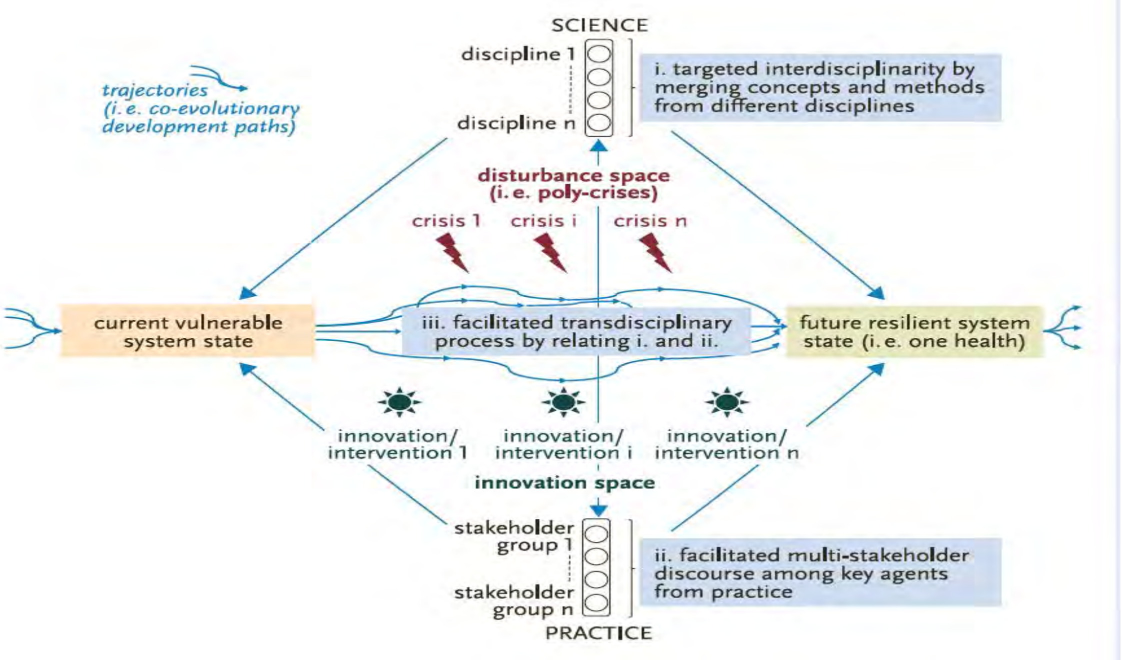
- adoption of innovative flotation processes allowed an increase in low grade phosphate rock use in several parts of the world,
- innovations in sulfuric and phosphoric acids production led to higher yield and lower energy consumption,
- hydraulic transport of phosphate rock led to lower losses between the mine and chemical plants and reduced significantly water and energy consumption

Examples of **ongoing developments/innovations**:

- IHP process for using lower grade phosphate rock (increasing reserves)
- IHP process for sulphur recovery from phosphogypsum
- Paraphos process, for phosphoric acid production and others under development primarily for recovery of phosphorus from sewage sludge ash.

Moving towards more resilient technology portfolios

- Reducing dependency on necessary raw materials
- Resilient in dealing with crises and disturbances
- Striving for climate neutrality, zero waste production, low CO2 footprint, water conservation, renewable energy use, and energy and resource efficiency



Take away messages

1. **No phosphate rock scarcity** expected for medium and long term. Reserves are **dynamic**, not static

1. **Important perspectives for extending P reserves lifespan**:
   - **P use efficiency is very low (10 %**excluding industrial products and considering weathered P as input**)** : There is a significant potential for improvement.
   - **Recycling potential is huge**: There is a need for further innovation in sustainable technologies.
   - **Innovations in mining and chemical processing of phosphate rock.**

1. **Geographical distribution of Phosphate Reserves and production :** no more concentration of mining and production than for other minerals.

New Developments & Initiatives

Dan Obenour
Associate Professor
NCSU

Identification of Priority Lakes and Watersheds for Nutrient Intervention

17 Sept 2025

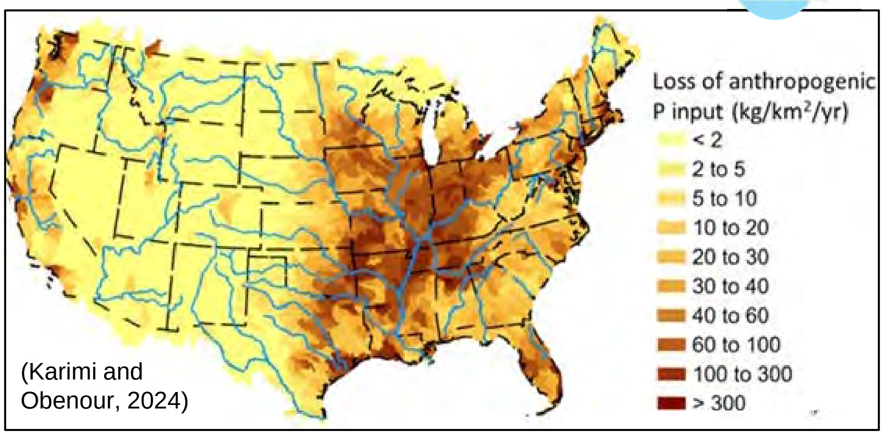
Daniel Obenour, Professor
Environmental Engineering, NC State University

Other STEPS contributors:
Matthew Scholz, Rebecca Muenich,
James Elser, Natalie Nelson,
Smitom Borah, Christopher Oates

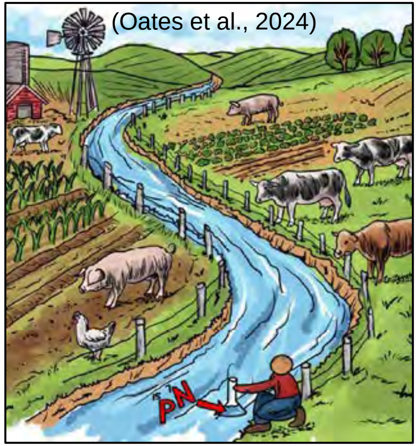
Institutional collaborators:
ACWA, NALMS, USACE, USDA,
USEPA, USFWS, USGS, SPA,
Univ. of Illinois

Motivation

- Each year, nearly 4 Tg of P enter agricultural and urban systems across the U.S. (Sabo et al., 2021)
- About 4% of gross agricultural P inputs and 13% of urban/household P inputs are lost to U.S. waterways (Karimi and Obenour, 2024).



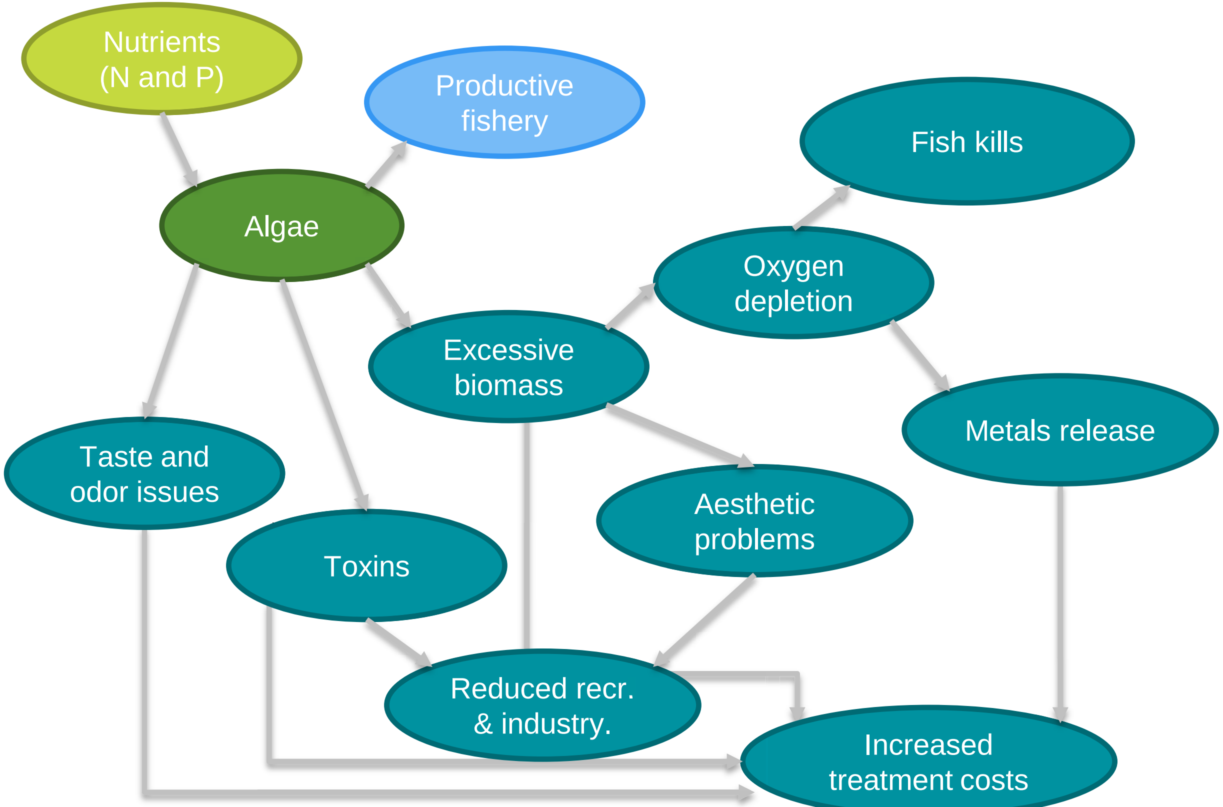
(Karimi and Obenour, 2024)



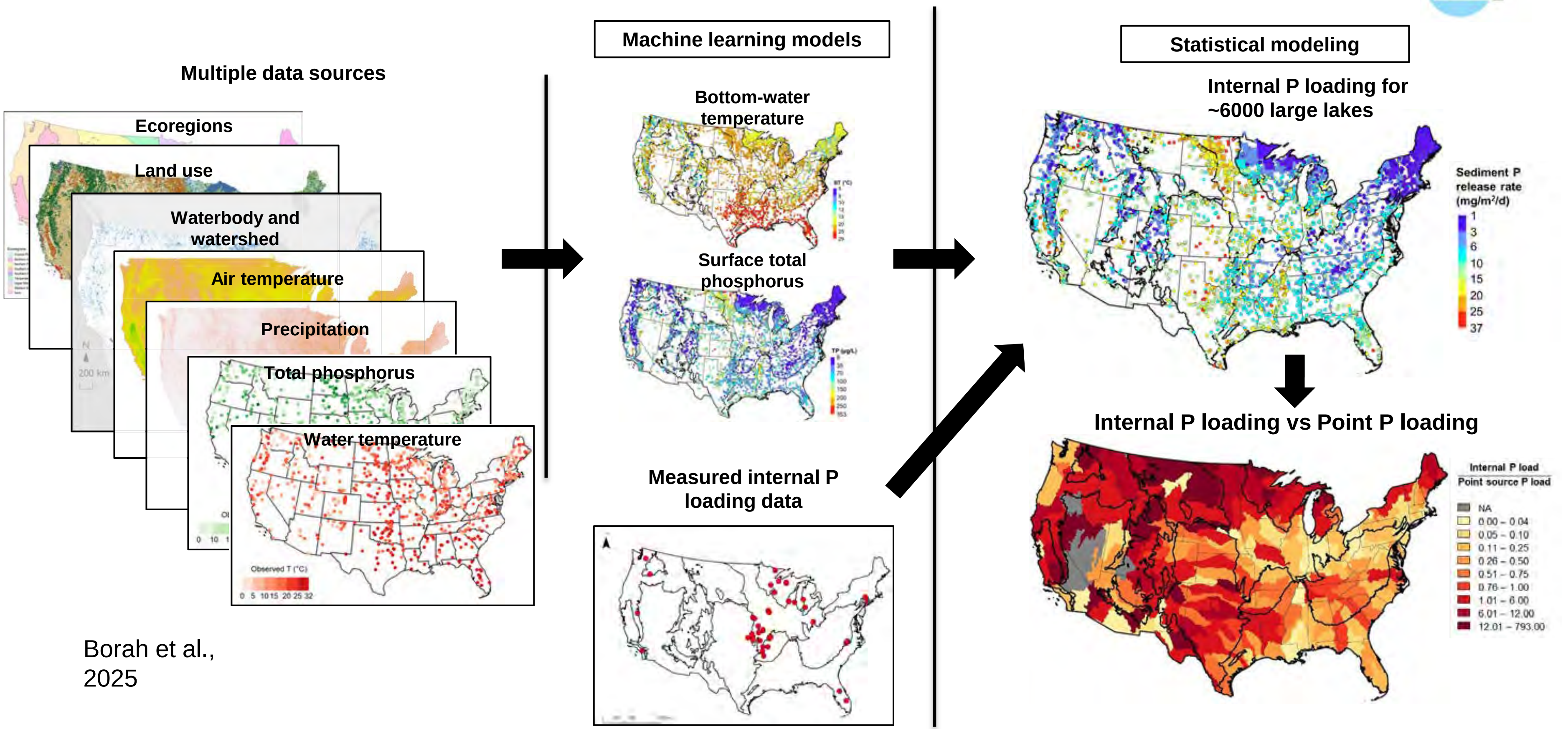
(Oates et al., 2024)

- Hydrologic P losses are a major driver of nuisance and harmful algal blooms and hypoxia (a.k.a. dead zones).
- 50% of US lakes in poor condition for P (and 47% for N) according to the US EPA National Lakes Assessment (2024).
- **How do we prioritize limited nutrient management resources to provide the greatest water quality, ecological, and societal benefits?**

Eutrophication issues



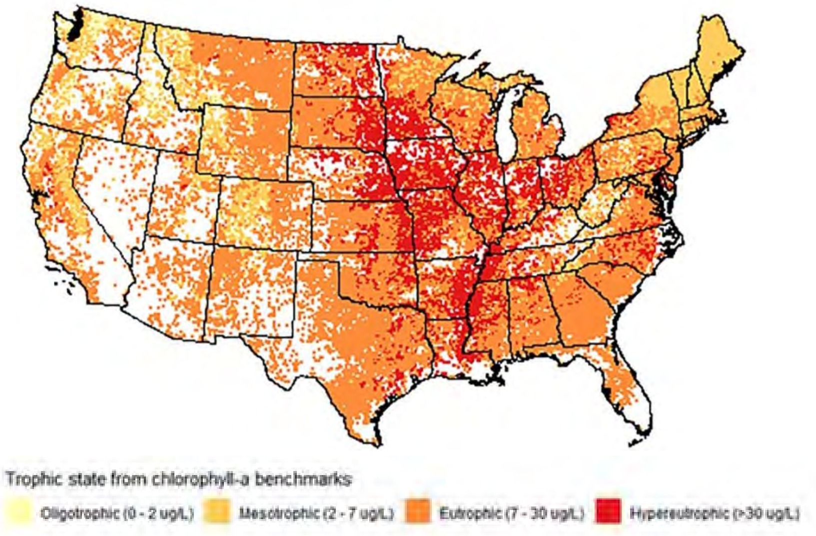
New data and methods → Opportunities



Borah et al., 2025

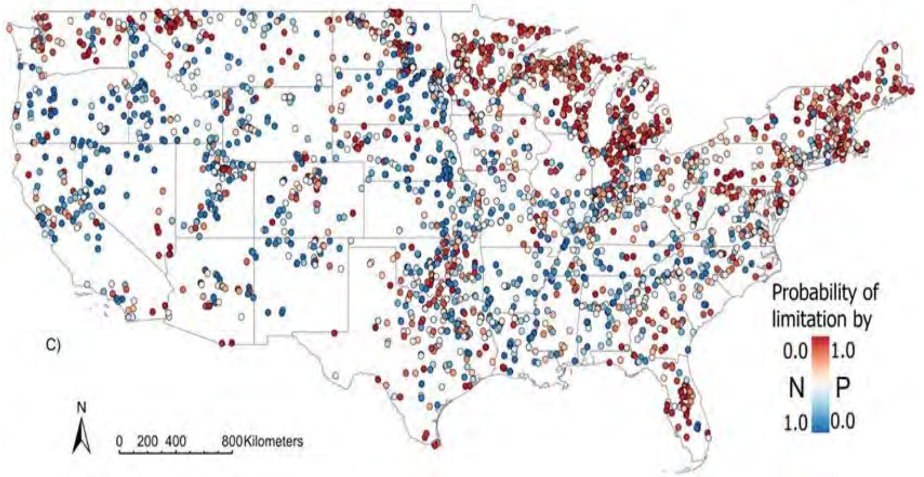
National scale algal modeling

Machine learning prediction of nutrients and chlorophyll at ~112,000 lakes



Brehob et al., 2024

Statistical estimation of the limiting nutrient across ~3000 lakes



Baird et al. *in review*

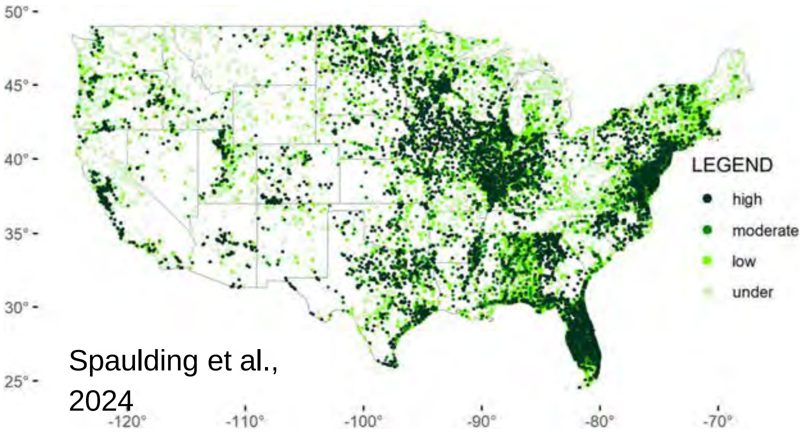
Priority Lakes: Guiding principles

1. Synthesize the latest national datasets for lake water quality, watershed inputs, and socioeconomic conditions.
2. Consider both natural and man-made lakes (reservoirs).
3. Consider both nitrogen and phosphorus in our evaluation of lake water quality. (Watershed opportunities may focus more on phosphorus.)
4. Consider not just lake water quality, but also where there is the most opportunity for improvement:
    - Where are there controllable nutrient sources?
    - Where are vulnerable populations or industries?
5. Develop a robust workflow, so that assessment can be updated and expanded in the future.

Priority Lakes: Key data sources

Lakes:

- Algal concentrations:
  - Monitoring compilations (Spaulding et al., 2024)
  - Remote-sensing (Meyer et al., 2024)
- Nutrients, dissolved oxygen, algal toxins
  - National Lakes Assessments (USEPA, 2024)
  - State & local monitoring (WQP, 2021)
- Lake morphology data such as lake depth, area, etc. (Cheruvelil et al., 2021; USGS, 2019a)



Spaulding et al., 2024

Watersheds:

- Watershed nutrient inputs (manure, fertilizer, etc.): National Nutrient Inventory (Sabo et al. 2021)
- Wastewater treatment plant inputs (USGS, 2019b)
- National land cover data (USGS, Dewitz, 2019)
- Precipitation and temperature data (PRISM climate group)
- Socio-economic data (U.S. Census Bureau), including population, income, education, etc.

Priority Lakes: Scope of work

	Year 1	Year 2
1. Develop comprehensive databases on lake and watershed characteristics.	✓	
2. Impute missing data needed for a comprehensive lakes assessment.	✓	
3. Assess the potential efficacy of nutrient management across lakes.	✓	✓
4. Assess the potential socio-economic and ecological benefits across lakes.		✓
5. Develop and apply prioritization framework.	✓	✓
6. Knowledge transfer through online and other resources.		✓

Feedback from institutional collaborators

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Meet the Team:

Project leads:

Dan Obenour

Natalie Nelson

Rebecca Muenich

Matt Scholz

Other collaborators:

Jim Elser

Roger von Haefen

Jay Rickabaugh

Students and post-docs :

Christopher Oates

Smitom Borah

Questions?

Suggestions?

drobenour@ncsu.edu

This study is supported by the Science and Technologies for Phosphorus Sustainability (STEPS) Center, a National Science Foundation Science and Technology Center (CBET-2019435)

New Developments & Initiatives

Anna-Maria Marshall
Associate Professor of Sociology and Law
University of Illinois, Urbana-Champaign

STEPS Policy Forum

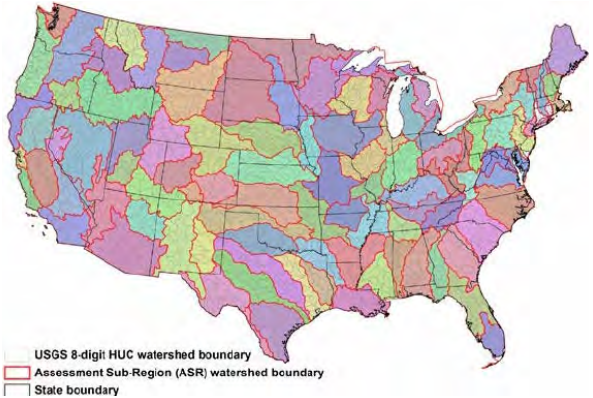
17 Sept 2025

Anna-Maria Marshall
Associate Professor of Sociology and Law
University of Illinois, Urbana-Champaign

Other STEPS contributors:
Graham Ambrose, Justin Baker, Jonathan Coppess, Shwetha Delanthamajalu,
Jay Rickabaugh, Matthew Scholz

Department of Phosphorus? If Only . . .

Lessons Learned from STEPS I



- Phosphorus Policy-Making is Hard
  - Wastewater Treatment Permitting Standards Can Be Static,
    - Discourages Innovation
  - Watersheds Do Not Care What County They're In
  - Who Says What a Best Management Practice Is?

Law Needs to Keep Up with Innovation

- Flexibility
- Evidence-Driven
  - Scientific Expertise
- Accountable Institutions
  - Collective Governance

STEPS Research on Policy and Governance

Policy Design

Evidence-Driven Policy-Making

- Public Data
- Computational Modeling and Visualization

UIUC Policy Design Lab


Jonathan Coppess
UIUC


Justin Baker
NC State

STEPS Research on Policy and Governance

Collective Governance

Soil and Water Conservation Districts

- Scientific Knowledge
  - Technical Assistance

- Social Networks
  - Outreach

- Variation in Resources, Activity

Graham Abrose
NC State

Jay Rickabaugh
NC State

STEPS Research on Regulation and Governance

P POLICY FORUM

Document the Regulatory Environment for Successful P Management

Input from Stakeholders

- Industry
- Advocacy
- Regulators

STEPS Research on Regulation and Governance

P POLICY FORUM

Workshops with Stakeholders
- Policy Pathways
- Institutional Obstacles, Drivers, and Alternatives

Actionable Research

Policy Recommendations

QUESTIONS?

COMMENTS?

POLICY AND GOVERNANCE TEAM

Jonathan Coppess
UIUC

Justin Baker
NC State

Graham Abrose
NC State

Jay Rickabaugh
NC State

Shwetha Delanthamajalu
UIUC

Anna-Maria Marshall
UIUC

This research is supported by the Science and Technologies for Phosphorus Sustainability (STEPS) Center, a National Science Foundation Science and Technology Center (CBET-2019435)

New Developments & Initiatives

Jango Bhadha
Associate Professor
University of Florida

Talk Removed at Presenter’s Request

New Developments & Initiatives

Stephanie Kulesza
Associate Professor, NCSU
SERA-17

Innovative Solutions to Minimize Phosphorus Loss from Agriculture

NC STATE UNIVERSITY Stephanie Kulesza, Incoming Chair

Sept 17-18, 2025

Mission – Promote actionable consensus around agricultural P in the environment

SERA - 17

1. **Advance the science** around P in the landscape, with an emphasis on agriculture.
2. **Develop standardized, robust protocols** for field, lab and modeling efforts for advancing the science around P bioavailability, fate, and transport in the landscape.
3. **Respond** to stakeholders on priority areas related to P management in agriculture.
4. **Communicate the science**


Journal of Environmental Quality

ASA | CSSA | SSSA

PERSPECTIVE | Open Access

The importance of consensus science to managing phosphorus in the environment: SERA-17 and the legacy of Andrew Sharpley

Merrin L. Macrae, Peter J. A. Kleinman, Deanna Osmond, Amy Shober, Nathan Nelson

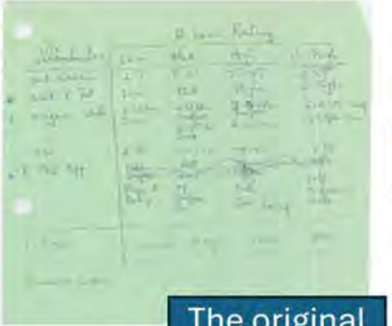
First published: 10 February 2024 | https://doi.org/10.1002/jeq2.20546 | Citations: 6

A long history of effective consensus-building

SERA - 17

1996. First Meeting - "Proper P Management"

2000-2006. US National Phosphorus Project



The original P Index concept

Coordinated research on P runoff

Publications

Standard Methods

Methods of Phosphorus Analysis
for Soils, Sediments, Residuals, and Waters

2000

Southern Cooperative Series Bulletin

Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters
Second Edition

Southern Cooperative Series Bulletin No. 408

June, 2009

Contact Information
Editors
John L. Kovar
USDA-ARS National Soil Tilth Laboratory

Gary M. Pierzynski
Department of Agronomy
Kansas State University

2009

Fact Sheets

Phosphorus Conservation Practices – Fact Sheets

Barnyard/Feedlot Runoff Management
Blind Inlets to Reduce Sediment Loading from Farmed Depressional Areas
Conservation Practices for Reducing Snowmelt Runoff Phosphorus
Constructed Wetlands
Cover Crops
Dietary Phosphorus Levels for Dairy Cows
Drainage Water Management (Controlled Drainage)
Erosion Control Systems
Filter Strips
Grassed Waterways
Lake and Pond Treatment for Phosphorus Inactivation
Management of Spray Fields
Manure Testing
Milkhouse Treatment Areas
No-Till and Reduced Tillage
Nutrient Management
Optimizing Grazing Management
Phosphorus Balance

Phosphorus Conservation Practices
Protecting Water Quality

SERA - 17

Sera17.wordpress.ncsu.ed

Position Papers

1. Phosphorus Indices to Predict Risk for Phosphorus Runoff
2. Predicting Phosphorus Losses
3. Soil Phosphorus Threshold Levels
4. Phosphorus Determination in Waters and Extracts of Soils and By-Products: ICP vs Color Methodology
5. The Importance of Sampling Depth when Testing Soils for their Potential to Supply Phosphorus to Surface Runoff
6. Phosphorus Management Within Multi-State Watersheds
7. Soil Sampling Methods for Phosphorus – Spatial Concerns
8. Threshold P Survey

Legacy P Perspectives

Andrew Margenot, Pete Kleinman (leads), Merrin Macrae, Amy Shober, Donna Neer, Zach Simpson, Joshua Mott, Grace Miner, Sheri Spiegal, et al.

Solicited submissions → **53 submissions from 67 authors across 6 continents** → **Analysis of responses**

Perspective (650 words)
and accompanying survey


Legacy P Perspectives: Author information

Please use this quick questionnaire to tell us a bit of your personal context as it relates to "legacy P"

* Required

1. What is your current occupation? *

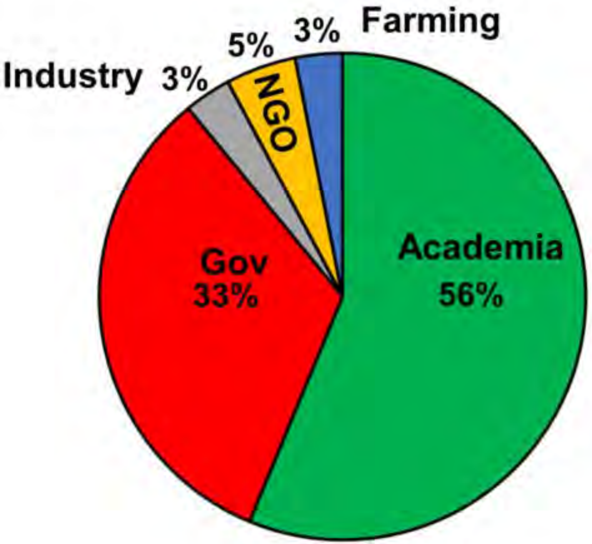
- Academia
- Government
- Industry
- Student
- Non-governmental organization
- Other

2. What best describes your field of science or discipline? *

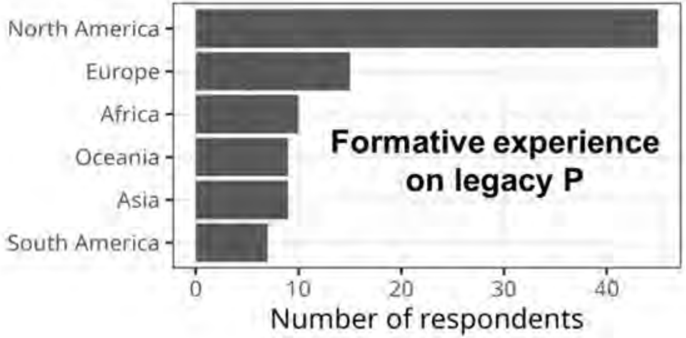
Enter your answer

3. Where is your current location for work? (Country, Region, City) *

Enter your answer



- Mixed support for the multidimensionality hypothesis
- Frequent focus on agronomic cause
- Clear need for improved models
- Less common perspectives of legacy P



P in Drainage Waters Working Group

Merrin Macrae (lead), Mark Williams, Kevin King, Doug Smith, Tony Buda, Chad Penn, Margaret Kalcic, Pete Kleinman

Advancing our Understanding of the Linkages Between Tile Drainage and Agricultural P Loss

SERA - 17

P in Drainage Waters Working Group Activities

- Reviewing state of the science around P in drainage water (tile and surface drainage)
- Exploring (1) existing knowledge, (2) recent advances, and (3) emerging developments and knowledge gaps around 4 thematic areas:
  - Processes
  - Management
  - Modeling
  - Measurement

Existing Knowledge	Recent Advances	Emerging Devs & Gaps
• Drainage critical in the P story • Preferential flow (PF) central to P mobilization in tile drainage	• Continued work on spatial and temporal variability in P loss in tile drainage • Efforts to quantify and predict PF and P loss in tile drainage	*Challenge*: the dynamic nature of pref flow and the delivery of both water and P into tile drains • Emerging work considers interplay between connectivity and biogeochemical processes (sorption affinity) • Framework emerging but next steps are quantification and subsequent modelling of these dynamics

"Process" example

SERA - 17

P in stream banks workgroup

Andrew Margenot, Zach Simpson (leads), Christy Dolph, Eric Young, John Kovar, Keith Schilling, Shengnan Zhou, Bruce Rhoads, Katharine Wiley

- Address gaps in the science identified by Margenot et al., 2023


Journal of Environmental Quality

PERSPECTIVE

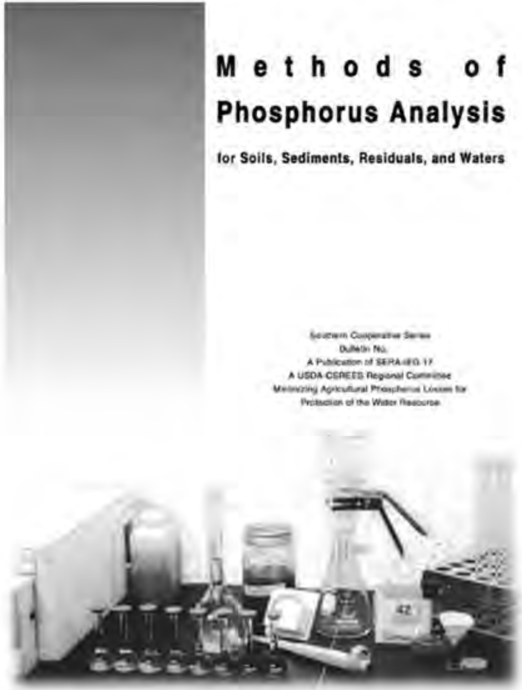
Streambank erosion and phosphorus loading to surface waters: Knowns, unknowns, and implications for nutrient loss reduction research and policy

Andrew J. Margenot[1,2] | Shengnan Zhou[2] | Richard McDowell[3] | Thomas Hebert[4] | Garey Fox[5] | Keith Schilling[6] | Shawn Richmond[7] | John L. Kovar[8] | Niranga Wickramarathne[2] | Dean Lemke[9] | Kathy Boomer[10] | Shani Golovay[11]

- Empirical inquiry
  - Combine *existing* datasets
  - Generate *additional* data from consolidated sample set of streambank soils across our work regions

- Communication products
  - Fact sheets – Introduction to P in streambanks ("101"), In-channel conservation practices
  - Research article – address data gaps (how much does P vary, best practices for estimating streambank erosion, forms of P, gross vs. net loading…

SERA-17 P Methods Manual – Third Edition



Current Process

- ✓ Assemble editorial board and establish publishing details (2024)
- ✓ Solicit contributions (2024-2025)
- ➢ Set up shared folder on Google Drive (July – September 2025)
- ➢ Authors submit first drafts (July – December 2025)
- ➢ Review of chapter drafts (December 2025 – 2026)
- ➢ Update on manual provided at next SERA-17 meeting (2026)
- ➢ Publish (2026 as completed)

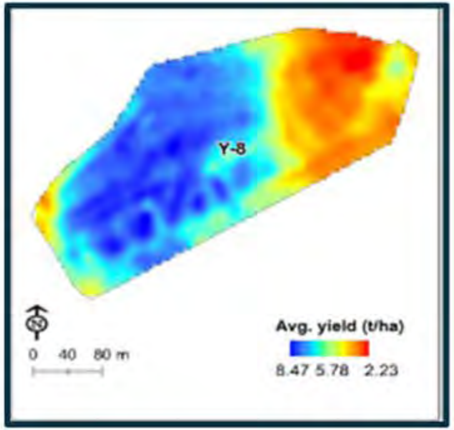
Contact Information

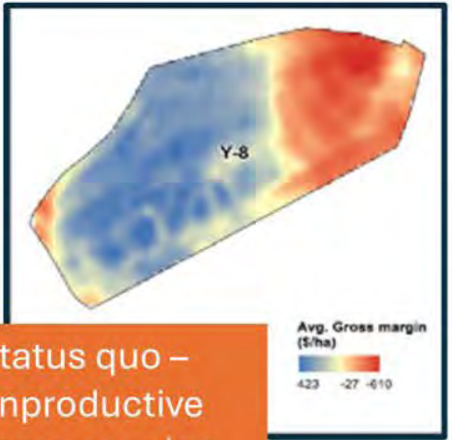
John Kovar: john.Kovar@usda.gov

Barbara Cade-Menun: Barbara.cade-menun@agr.gc.ca

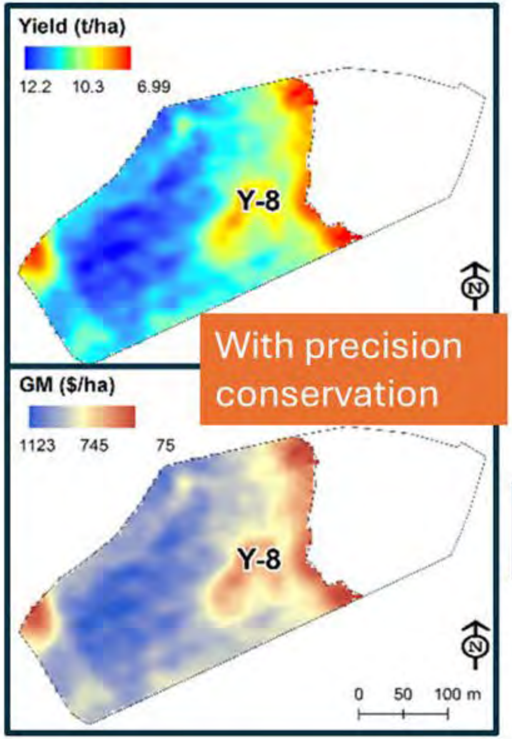
Precision conservation workgroup

lead - Doug Smith





Status quo – unproductive areas are also those prone to P loss



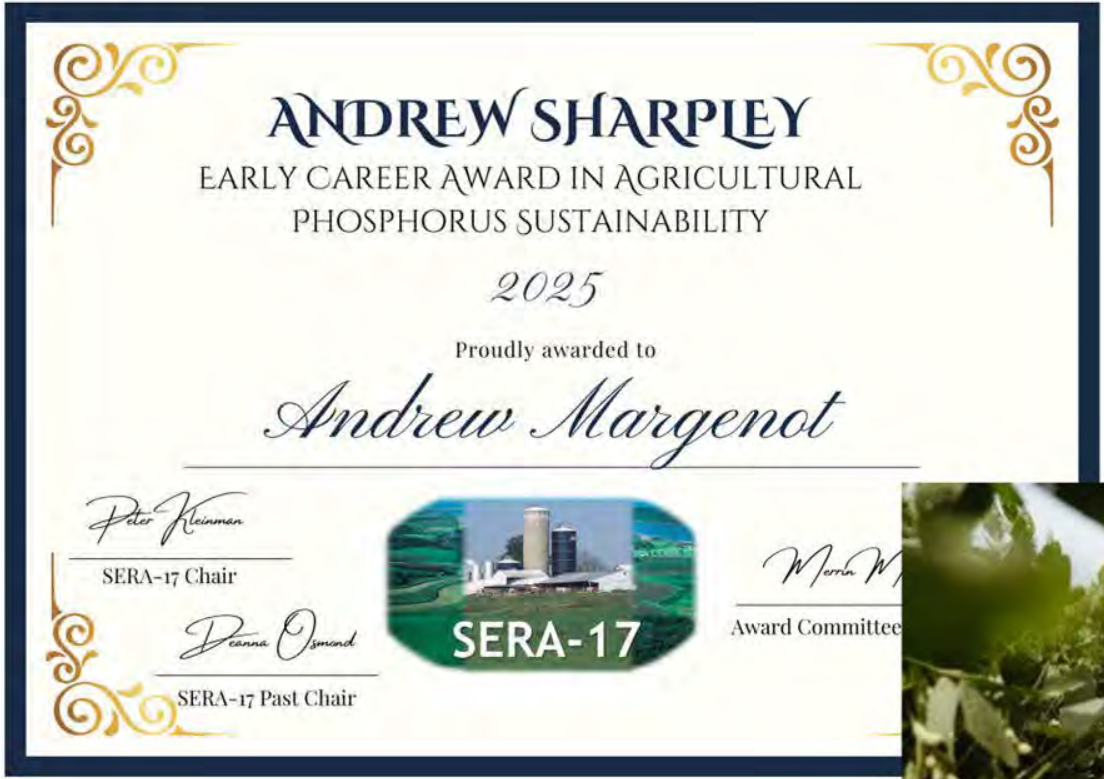
With precision conservation

OBJECTIVE: Develop defensible within-field management recommendations

- *Improved Commodity Yield*
- *More Profitable*
- *Decrease P Runoff by 75%*

Sharpley Award

First recipient - 2025



Future SERA-17 meetings

- Coordinated with American Society of Agronomy
- Portland, OR
- Nov. 1-4, 2026

New Developments & Initiatives

Jeff Costantino
Communications Director
ReFED

Food Waste and Phosphorus: Opportunities and Challenges

Presented by Jeff Costantino

September 17, 2025

WHO WE ARE

ReFED is a national nonprofit working to catalyze the food system toward evidence-based action to stop wasting food.

OUR VISION

A sustainable, resilient, and inclusive food system that optimizes environmental resources, minimizes climate impacts, and makes the best use of the food we grow.

DATA & INSIGHTS

Leveraging data and insights to highlight supply chain inefficiencies and economic opportunities

CAPITAL & INNOVATION

Catalyzing capital to spur innovation and scale high-impact initiatives

BUSINESS INITIATIVES

Enabling waste generator adoption of viable solutions through measurement, advisory, and internal capacity building

COLLECTIVE ACTION

Mobilizing and connecting stakeholders to learn, share, and collaborate on targeted action

WHAT'S NEEDED

$15.9B
INVESTMENT ANNUALLY

$3.6B PUBLIC

$10B PRIVATE

$2.2B PHILANTHROPIC

40+
SOLUTIONS

WASTE REDUCTION

18.8M
ANNUAL FOOD WASTE DIVERSION (TONS)

IMPACT PER YEAR

- $60.8B NET FINANCIAL BENEFIT
- 5T GALLONS IN WATER SAVINGS
- 79M MT CO_2e EMISSION REDUCTION POTENTIAL
- 4.6B MEALS FOR PEOPLE IN NEED
- 50K JOBS CREATED THROUGH FULL SOLUTION IMPLEMENTATION

Source: ReFED/2023 Data (Published Feb 2025)

ReFED

PROJECT DRAWDOWN

Food waste ranked #1 of 93 solutions for reversing climate change globally by Project Drawdown.[1]

Top 10 Solutions

Rank	Solution	Gigatons Reduced/ Sequestered (2020-2050)
1	**Reduced Food Waste**	**88.50**
2	Plant-Rich Diets	78.33
3	Family Planning and Education	68.90
4	Refrigerant Management	57.15
5	Tropical Forest Restoration	54.45
6	Onshore Wind Turbines	46.95
7	Alternative Refrigerants	42.73
8	Utility-Scale Solar Photovoltaics	40.83
9	Clean Cooking	31.38
10	Distributed Photovoltaics	26.65

[1] Scenario 1, *Drawdown Review*, 2022

Food Waste and Phosphorus

$$\frac{\text{195,170,127 kg — Total P in Surplus Food (2022)}}{\text{1,700,000,000 kg — Annual P Use in Agriculture (2022)}} = 11.48\%$$

195,170,127 kg
Total P in Surplus Food
(2022)

1,700,000,000 kg
Annual P Use in Agriculture
(2022)

=

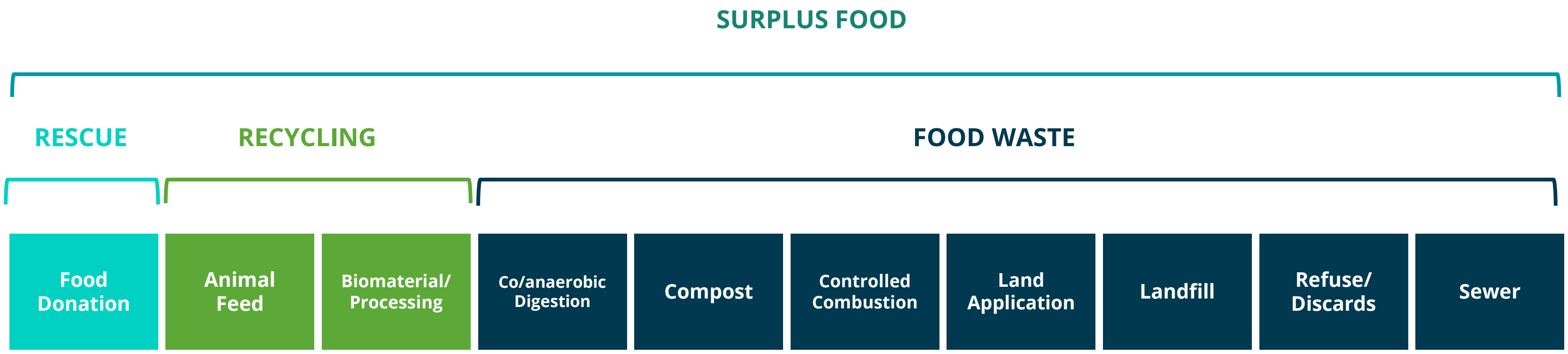
11.48%

Of P Used for Agriculture

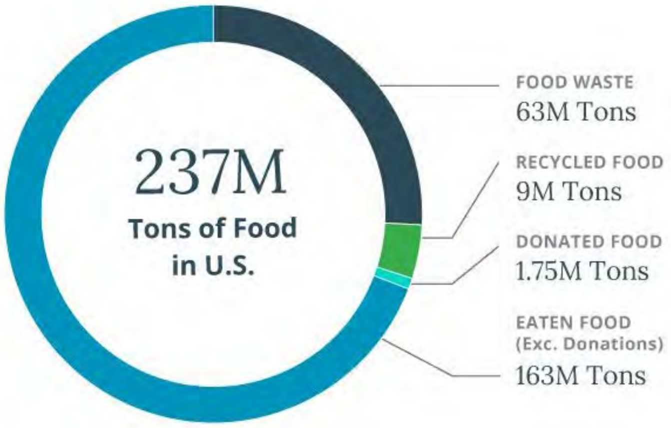
ReFED

What is “Surplus Food?”

All food that goes *unsold* or *unused* by a business or that goes *uneaten* at home—including food and inedible parts (e.g., peels, pits, bones) that are fed to animals, repurposed to produce other products, composted, or anaerobically digested. It also includes food that is *donated*.



ReFED



Source: ReFED/2023 Data (Published Feb 2025)

31% of all food went unsold or uneaten in 2023.

ReFED

$782

Annual amount spent per person on food that is never eaten

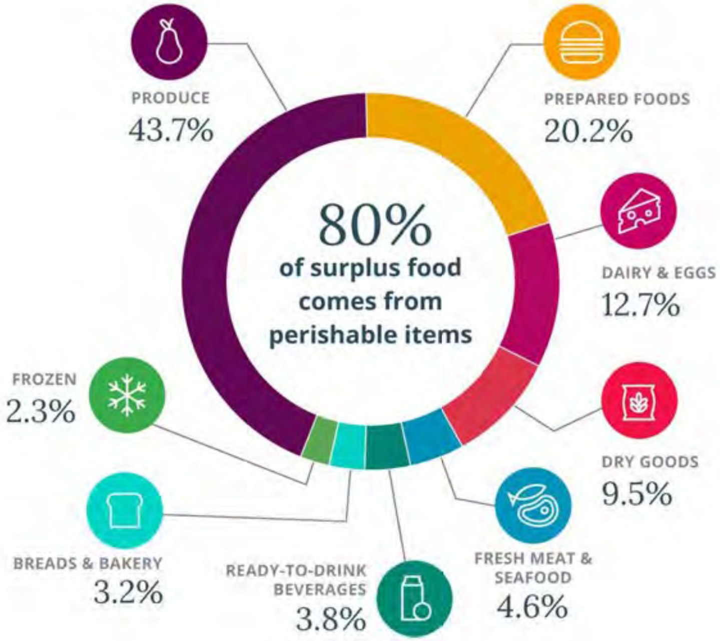
WHERE DOES SURPLUS OCCUR:

Majority of Surplus Food Comes from Homes

ReFED

WHERE DOES SURPLUS OCCUR:

Fruit and Vegetables Constitute Nearly Half of Surplus



Source: ReFED/2023 Data (Published Feb 2025)

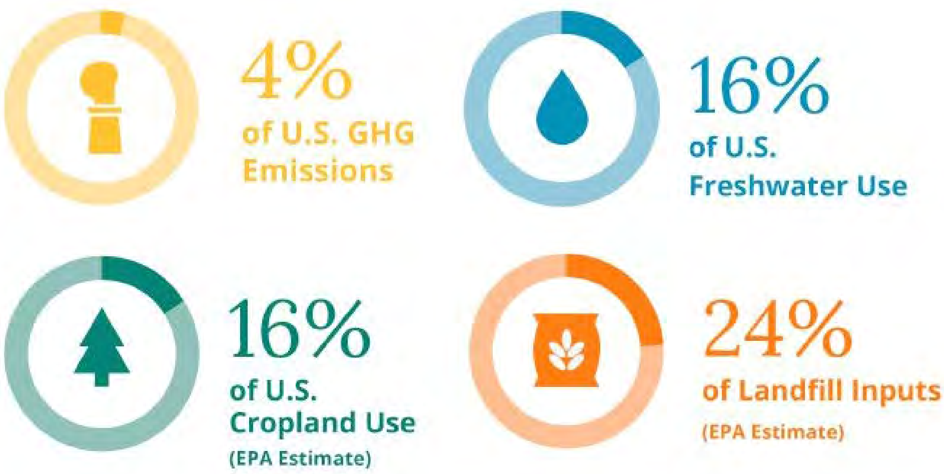
ReFED

IMPACTS OF UNEATEN FOOD:

Environmental

Equivalent to driving **54 million cars** over the year

An area the size of **California and New York** combined



As much water as **7 showers** each day for everyone in the U.S

#1 input to landfills

Source: ReFED/2023 Data (Publiched Feb 2025)

ReFED

Global Scale

⅓ of all food produced[1]

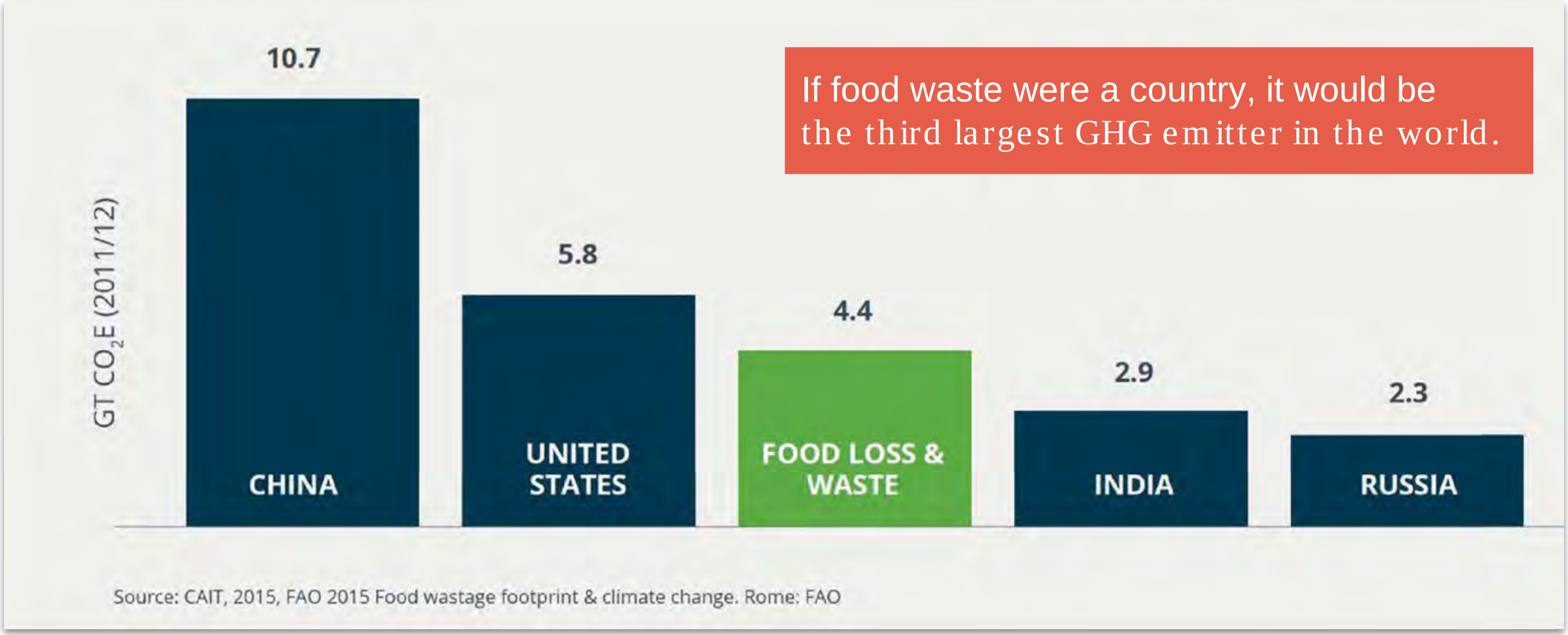
$1T in value[2]

8% of global GHG emissions[3]

[1] FAO, *Food Wastage Footprint & Climate Change*, 2011
[2] FAO, 2014
[1] Mbow et al., 2019

ReFED

GHG Emissions by Country



If food waste were a country, it would be the third largest GHG emitter in the world.

ReFED

Feeding More People with Fewer Resources

50%

The United Nations predicts we'll need to increase global food supply by this amount to feed the population in 2050...

Yet a new study shows that agricultural productivity has decreased by this amount due to the impacts of climate change...

21%

Other SDGs Related to Food Waste:

ReFED

Barriers to Addressing Food Waste

- Misalignment of costs and benefits
- Low cost of food and disposal
- Disaggregated supply and demand information and data gaps
- Competing cultural priorities and expectations
- Organizational silos
- Low priority and capacity within food industry to monitor and make change

ReFED

ReFED

Roadmap to 2030: Reducing U.S. Food Waste | Find Details on Each Solution in the ReFED Insights Engine | insights.refed.org

Action Areas

OPTIMIZE THE HARVEST
Avoid over-production, then harvest as much as possible. For wild caught products, source only what is needed.

ENHANCE PRODUCT DISTRIBUTION
Leverage technology to create smart systems that help efficiently move products to maximize freshness and selling time.

REFINE PRODUCT MANAGEMENT
Align purchases with sales as closely as possible and find secondary outlets for surplus. Build out systems and processes for optimal on-site handling.

MAXIMIZE PRODUCT UTILIZATION
Design facilities, operations, and menus to use as much of each product as possible. Upcycle surplus and byproducts into food products.

RESHAPE CONSUMER ENVIRONMENTS
Drive consumers towards better food management and less waste by creating shopping, cooking, and eating environments that promote those behaviors. Shift culture to place more value on food and reduce waste.

STRENGTHEN FOOD RESCUE
Further the rescue of high-quality, nutritious food by increasing capacity, addressing bottlenecks, and improving communication flow.

RECYCLE ANYTHING REMAINING
Find the highest and best use for any remaining food or food scraps in order to capture nutrients, energy, or other residual value.

Modeled Solutions

Unmodeled Solutions

Best Practices

OPTIMIZE THE HARVEST	ENHANCE PRODUCT DISTRIBUTION	REFINE PRODUCT MANAGEMENT	MAXIMIZE PRODUCT UTILIZATION	RESHAPE CONSUMER ENVIRONMENTS	STRENGTHEN FOOD RESCUE	RECYCLE ANYTHING REMAINING
Buyer Spec Expansion	Decreased Transit Time	Assisted Distressed Sales	Active & Intelligent Packaging	Meal Kits	Donation Coordination & Matching	Centralized Anaerobic Digestion
Gleaning	First Expired First Out	Decreased Minimum Order Quantity	Manufacturing Byproduct Utilization (Upcycling)	Buffet Signage	Donation Education	Community Composting
Imperfect & Surplus Produce Channels	Intelligent Routing	Dynamic Pricing	Manufacturing Line Optimization	Consumer Education Campaigns	Donation Storage Handling & Capacity	Centralized Composting
Partial Order Acceptance	Temperature Monitoring (Pallet Transport)	Enhanced Demand Planning	Edible Coatings	K-12 Lunch Improvements	Donation Transportation	Co-digestion at Wastewater Treatment Plants
Field Cooling Units	Reduced Warehouse Handling	Increased Delivery Frequency	Improved Recipe Planning	Package Design	Donation Value-Added Processing	Home Composting
In-Field Sanitation Monitoring	Advanced Shipment Notifications	Markdown Alert Applications	In-House Repurposing	Portion Sizes	Blast Chilling to Enable Donations	Livestock Feed
Innovative Grower Contracts	Early Spoilage Detection (Hyperspectral Imaging)	Minimized On-Hand Inventory	Precision Food Safety	Small Plates	Donation Reverse Logistics	Waste-Derived Agricultural Inputs
Labor Matching	Inventory Traceability	Temperature Monitoring (Foodservice)	Discount Meal Plates	Standardized Date Labels	High-Frequency Reliable Pickups	Insect Farming
Smaller Harvest Lots	Modified Atmosphere Packaging System	Waste Tracking (Foodservice)	Employee Meals	K-12 Education Campaigns	Established Relationships with Businesses	Rendering
Improved Communication for Planting Schedules	Vibration & Drops Tracking	Low Waste Event Contracts	Larger Quantities for Take Home	Trayless	Culling SOPs	Waste-Derived Processed Animal Feed
Sanitation Practices & Monitoring	Optimized Truck Packing, Loading & Unloading (e.g., Cross-Docking)	Direct to Consumer Channels	Small and Versatile Menus	Home Shelf-life Extension Technologies		Waste-Derived Bioplastics
Optimized Harvesting Schedules	Enforcing Cold Chain SOPs	Online Marketplace Platform	Sous-Vide Cooking	Smart Home Devices		Waste-Derived Biomaterials
On-Farm / Near-Farm Processing	Regular Maintenance on Refrigerated Trucks	Online, Advanced Grocery Sales		Waste Conscious Promotions		Enabling Technologies (e.g. depackaging and pre-treatment)
Local Food Systems	Cross-Docking	Precision Event Attendance		Frozen Value-Added Processing of Fresh Produce		Separation & Measurement
Clear Product Ownership		Repackaging Partially Damaged Products		Customizable Menus/ Options		Relationships with Waste Haulers
		Retail Automated Order Fulfillment		To-Go Offerings		Waste Audits by Waste Haulers
		SKU Rationalization		Free Items Offered Upon Request (e.g., bread, chips)		
		Markdowns		Storytelling (e.g. product impact, source, upcycled ingredient components)		
		Optimal Storage				
		Reduced Displays				
		Optimized Walk-In Layouts				

PREVENTION

Optimize The Harvest

IMPERFECT & SURPLUS CHANNELS
Imperfect Foods, Seal the Seasons, Full Harvest, Misfits Market, Hungry Harvest

GLEANING
AGO Association of Gleaning Organizations, Boston Area Gleaners, Society of St. Andrew, Center for Agriculture & Food Systems, National Gleaning Project

IMPROVED PLANNING & LABOR MATCHING
GigSmart, Ganaz, agtools

Enhance Product Distribution

INTELLIGENT ROUTING & INVENTORY TRACEABILITY
RipeLocker, Zest Labs, ripe.io, IBM Food Trust, HwyHaul

TEMPERATURE MONITORING & COLD CHAIN
VeriSolutions, Evigence Sensors, Lineage, IoTLogistics, Procuro, Cold Chain Technologies

EARLY SPOILAGE PREVENTION & DETECTION
Clean Crop Technologies, AgShift, impact vision, FreshSurety, condi food, Strella Biotechnology

Refine Product Management

ENHANCED DEMAND PLANNING & SECONDARY RESALE
Afresh, crisp., Shelf Engine, Date Check Pro, Spoiler Alert, FoodMaven

DYNAMIC PRICING & MARKDOWN ALERTS
Too Good To Go, Karma, Flashfood, wasteless

WASTE TRACKING
Kitro, Leanpath, winnow, phood

Maximize Product Utilization

UPCYCLING
barnana, Upcycled Food Association, Renewal Mill, Regrained, Griffith, matriark foods

SHELF-LIFE EXTENSION
Apeel, mori, AgroFresh, Startchy, Hazel Technologies, Ryp Labs

ACTIVE & INTELLIGENT PACKAGING
Avery Dennison, Blakbear, Infratab, mimica

Reshape Consumer Environments

MEAL KITS
Sunbasket, Blue Apron, Hello Fresh, freshly, Kroger, Home Chef, Easy For You!

HOME SHELF-LIFE EXTENSION
Producemate, bluapple, The Fresh Glow Co, Food Huggers, Tupperware

CONSUMER & K-12 EDUCATION
Make Food Not Waste, Hellmann's, Make Taste, Not Waste, OLIO, Save the Food.com

RESCUE

Strengthen Food Rescue

DONATION COORDINATION, MATCHING & TRANSPORTATION
Food Recovery Network, Plentiful, D.C. Central Kitchen, Goodr, Food Runners, brighterbites, Copia, farmlink, forager, Move for Hunger, SeaShare, Food Forward, Dreaming Out Loud, Food Donation Connection, lovin' spoonfuls, Daily Table, Food Rescue US, Table to Table, Feeding America, replate, Partnership for a Healthier America, DoorDash

RECYCLING

Recycle Anything Remaining

COMPOSTING & AD
Recology, Blue Earth Compost, HomeBiogas, Generate, Impact, WM Waste Management, Atlas

ANIMAL & PET FEED
KDC, Protix, shameless pets, Enviroflight, Grubbly Farms

WASTE-DERIVED AG INPUTS
WISErg, Biochar Now, BCD Bioscience, CSS, Re-Nuble

RESEARCH, MEASUREMENT, CONVENING, POLICY & ADVOCACY
ReFED, World Resources Institute, WWF, Food Waste Reduction Alliance, BioCycle, FFAR, wrap, Pacific Coast Collaborative, Drexel University Food Lab, NRDC, UC Davis Food Science and Technology, FLPC Food Law and Policy Clinic Harvard Law School, Champions 12.3, Google

REFED INSIGHTS ENGINE:
The System Tool Driving Change

Understand the Problem
Visit the Food Waste Monitor ▶

Explore the Solutions
Visit the Solutions Database ▶

Find Solution Providers
Visit the Solution Provider Directory ▶

Calculate Impact
Visit the Impact Calculator ▶

Track Capital
Visit the Capital Tracker ▶

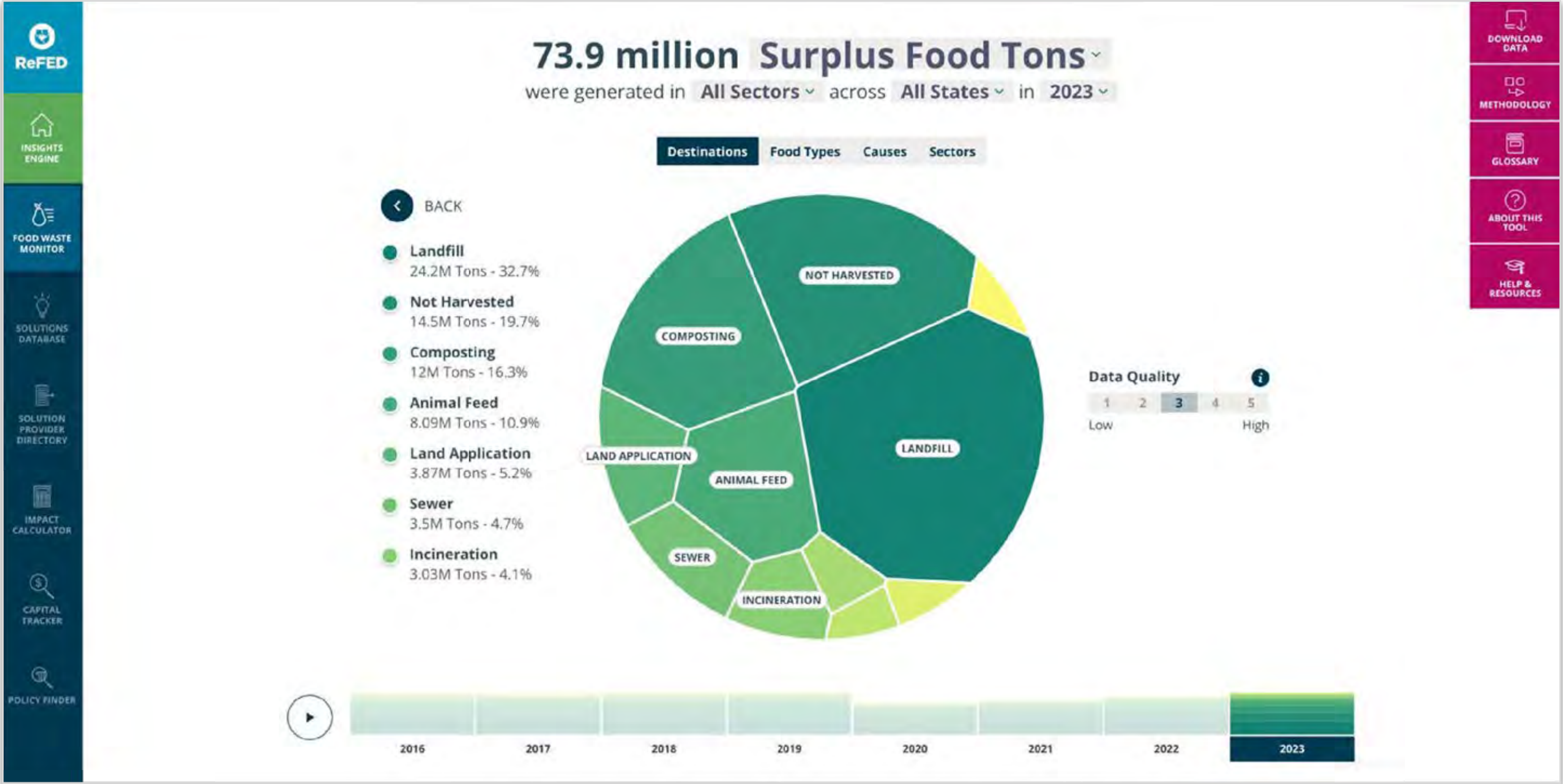
Review Policies
Visit the Policy Finder ▶

Launch Insights Engine

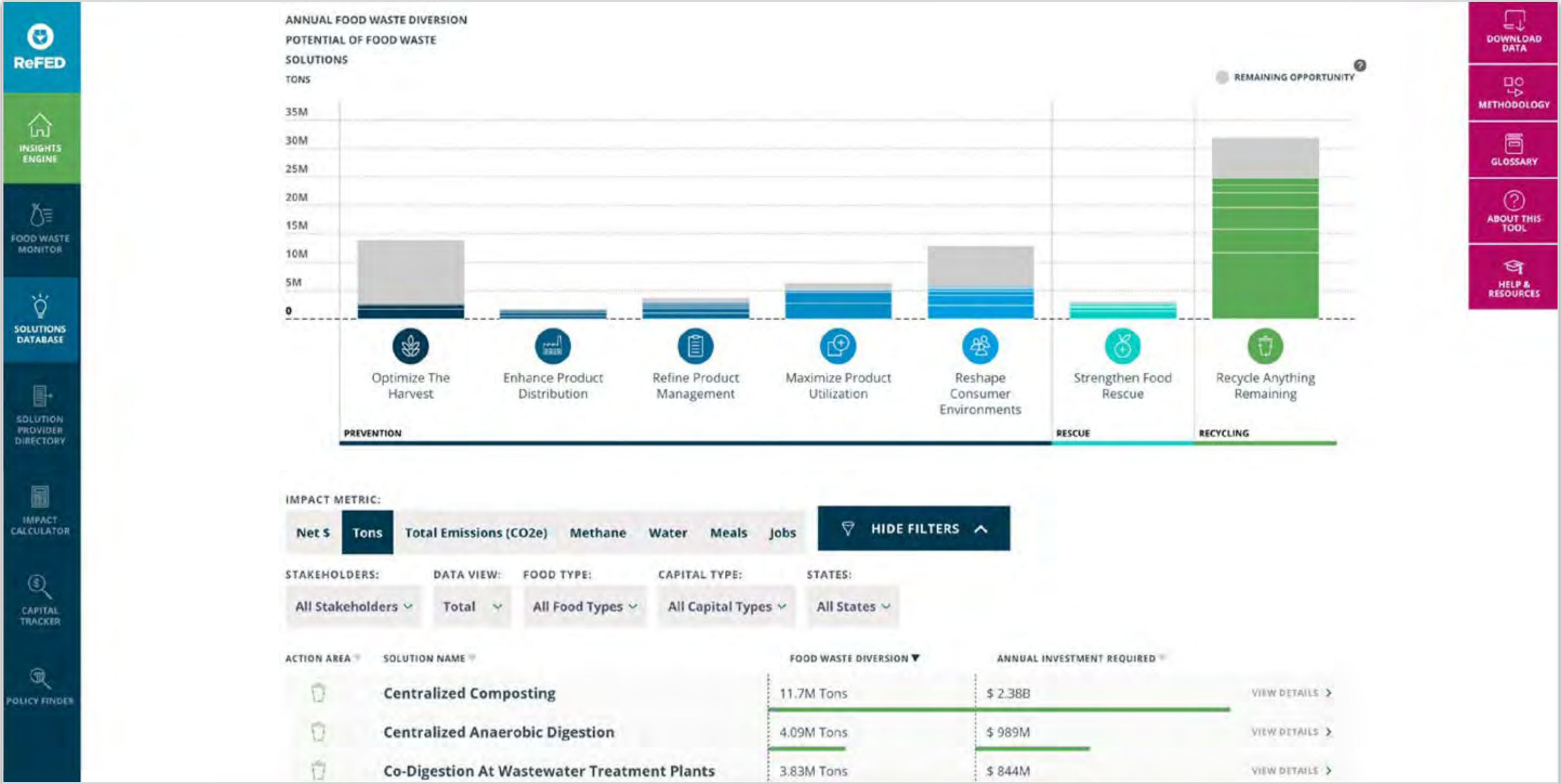
190,000
users

6 countries
requested
international IE

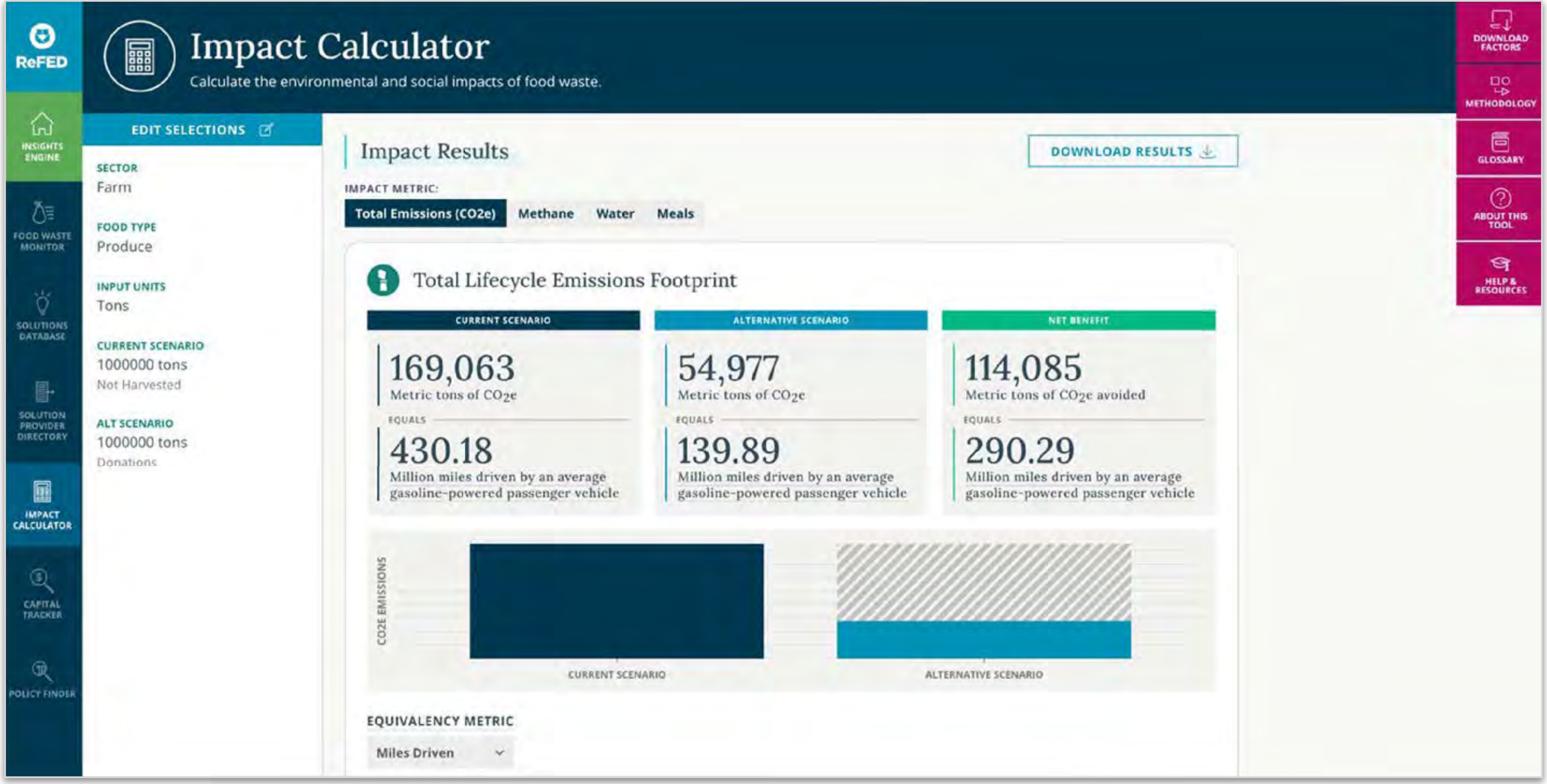
ReFED



ReFED
INSIGHTS ENGINE
FOOD WASTE MONITOR
SOLUTIONS DATABASE
SOLUTION PROVIDER DIRECTORY
IMPACT CALCULATOR
CAPITAL TRACKER
POLICY FINDER
73.9 million Surplus Food Tons
were generated in All Sectors across All States in 2023
Destinations
Food Types
Causes
Sectors
BACK
Landfill
24.2M Tons - 32.7%
Not Harvested
14.5M Tons - 19.7%
Composting
12M Tons - 16.3%
Animal Feed
8.09M Tons - 10.9%
Land Application
3.87M Tons - 5.2%
Sewer
3.5M Tons - 4.7%
Incineration
3.03M Tons - 4.1%
NOT HARVESTED
COMPOSTING
LANDFILL
LAND APPLICATION
ANIMAL FEED
SEWER
INCINERATION
Data Quality
1 2 3 4 5
Low
High
DOWNLOAD DATA
METHODOLOGY
GLOSSARY
ABOUT THIS TOOL
HELP & RESOURCES
2016
2017
2018
2019
2020
2021
2022
2023



ReFED
INSIGHTS ENGINE
FOOD WASTE MONITOR
SOLUTIONS DATABASE
SOLUTION PROVIDER DIRECTORY
IMPACT CALCULATOR
CAPITAL TRACKER
POLICY FINDER
ANNUAL FOOD WASTE DIVERSION POTENTIAL OF FOOD WASTE SOLUTIONS
TONS
REMAINING OPPORTUNITY
35M
30M
25M
20M
15M
10M
5M
0
Optimize The Harvest
Enhance Product Distribution
Refine Product Management
Maximize Product Utilization
Reshape Consumer Environments
Strengthen Food Rescue
Recycle Anything Remaining
PREVENTION
RESCUE
RECYCLING
DOWNLOAD DATA
METHODOLOGY
GLOSSARY
ABOUT THIS TOOL
HELP & RESOURCES
IMPACT METRIC:
Net $
Tons
Total Emissions (CO2e)
Methane
Water
Meals
Jobs
HIDE FILTERS
STAKEHOLDERS:
All Stakeholders
DATA VIEW:
Total
FOOD TYPE:
All Food Types
CAPITAL TYPE:
All Capital Types
STATES:
All States
ACTION AREA
SOLUTION NAME
FOOD WASTE DIVERSION
ANNUAL INVESTMENT REQUIRED
Centralized Composting
11.7M Tons
$ 2.38B
VIEW DETAILS
Centralized Anaerobic Digestion
4.09M Tons
$ 989M
VIEW DETAILS
Co-Digestion At Wastewater Treatment Plants
3.83M Tons
$ 844M
VIEW DETAILS


ReFED
Impact Calculator
Calculate the environmental and social impacts of food waste.
INSIGHTS ENGINE
FOOD WASTE MONITOR
SOLUTIONS DATABASE
SOLUTION PROVIDER DIRECTORY
IMPACT CALCULATOR
CAPITAL TRACKER
POLICY FINDER
EDIT SELECTIONS
SECTOR
Farm
FOOD TYPE
Produce
INPUT UNITS
Tons
CURRENT SCENARIO
1000000 tons
Not Harvested
ALT SCENARIO
1000000 tons
Donations
Impact Results
DOWNLOAD RESULTS
IMPACT METRIC:
Total Emissions (CO2e)
Methane
Water
Meals
Total Lifecycle Emissions Footprint
CURRENT SCENARIO
169,063
Metric tons of CO2e
EQUALS
430.18
Million miles driven by an average gasoline-powered passenger vehicle
ALTERNATIVE SCENARIO
54,977
Metric tons of CO2e
EQUALS
139.89
Million miles driven by an average gasoline-powered passenger vehicle
NET BENEFIT
114,085
Metric tons of CO2e avoided
EQUALS
290.29
Million miles driven by an average gasoline-powered passenger vehicle
CO2E EMISSIONS
CURRENT SCENARIO
ALTERNATIVE SCENARIO
EQUIVALENCY METRIC
Miles Driven
DOWNLOAD FACTORS
METHODOLOGY
GLOSSARY
ABOUT THIS TOOL
HELP & RESOURCES

The 2026 ReFED Food Waste Solutions Summit

May 19-21, 2026 • Charlotte, NC

#FoodWasteSummit26

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