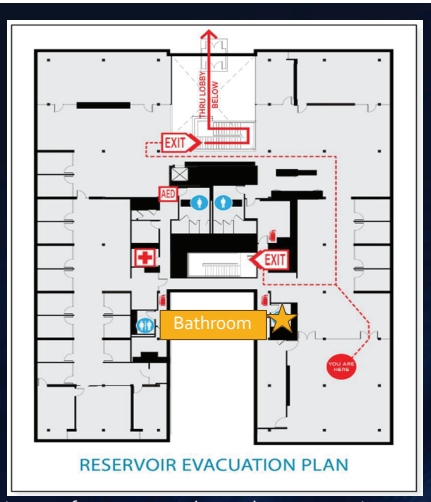


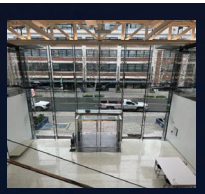
Welcome to Phosphorus Forum 2026!

Sustainable Phosphorus Alliance

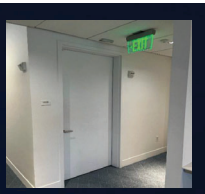


RESERVOIR EVACUATION PLAN

In case of an emergency locate the nearest stairs and proceed to the first floor and exit the building.



1st FLOOR NORTH



2ND FLOOR WEST



MEETING POINT: SOUTH SIDE OF BUILDING/ALONG ANACOSTIA RIVER

Made Possible by our Members

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OCP · NACWA · OSTARA · The Water Research Foundation · Nutrien · Mosaic · ARVA Intelligence · PHOSPHOLUTIONS · The Sustainability Consortium · STEPS · GreenEdge GreenTechnologies, LLC · KOCH Agronomic Services · HUMA · S&F AGRITECH · KASE Warbonnet, Inc.

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Yesterday's Social Event Brought to you by....

PHOSPHOLUTIONS

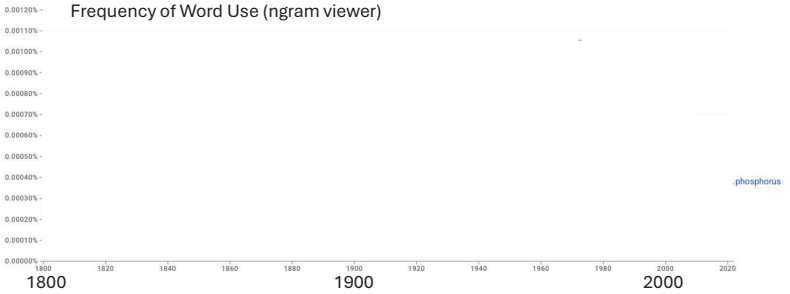
Nutrien

Today's Agenda

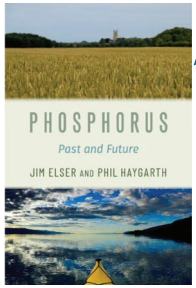
9:00 am - 9:15 am	**Welcome** Jim Elser, Speaker • General Presentation	
9:15 am - 9:45 am	**Energy, Waste, and Circularity** Rebecca Muenich, Speaker • General Presentation	
9:45 am - 11:00 am	**Circularity of Phosphorus in Manure Streams** Ke'Shan Lighty, Moderator • Steve Levitsky, Speaker • Steph Kulesza, Speaker • Holly Porter, Speaker • Josh McGrath, Speaker • Panel Discussion	
11:00 am - 11:15 am	**Coffee Break** Break	
11:15 am - 12:15 pm	**Breakout Session: Supply Chain Resilience** Breakout Room #1 Add to My Agenda	**Breakout Session: Use and Circularity** Breakout Room #2 Add to My Agenda
12:15 pm - 12:30 pm	**Closing Remarks and Lunch** Justin Baker, Speaker • Meal Break	
12:30 pm - 1:30 pm	**Optional Breakout Session** Breakout Room #1	

Access agenda online by taking a picture of this:

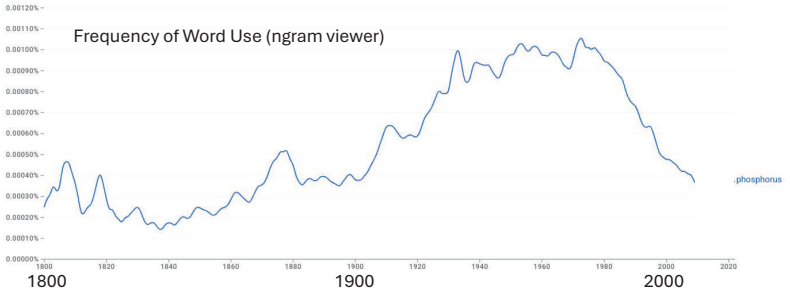
Sustainable Phosphorus Alliance



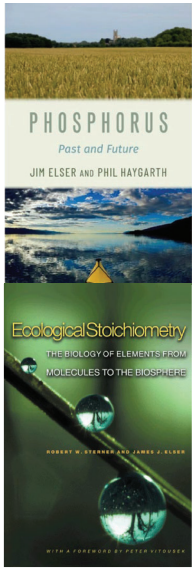
Sustainable Phosphorus Alliance

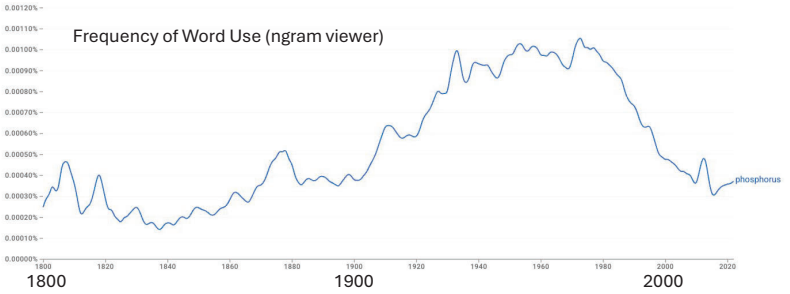


"phosphorus" used 1323 times!

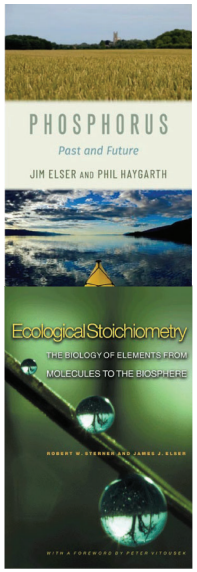


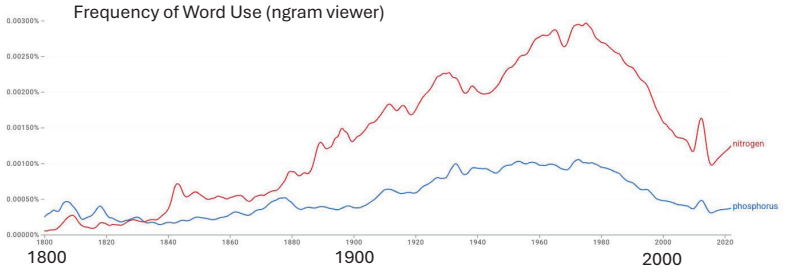
Sustainable Phosphorus Alliance



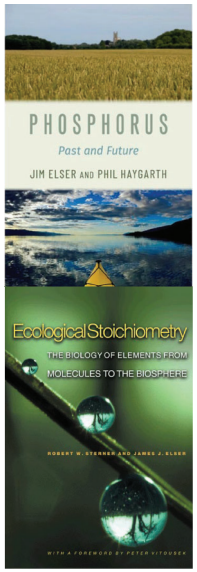


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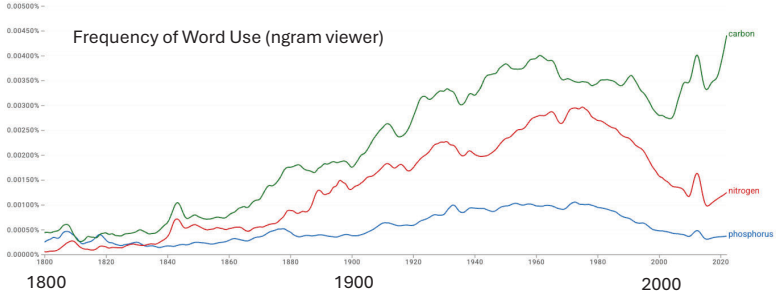




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Tie your wagon to CARBON!



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STEPS
Science and Technologies for Phosphorus Sustainability

ARTICLE

https://doi.org/10.1038/s41467-019-09100-5 OPEN

Eutrophication will increase methane emissions from lakes and impoundments during the 21st century

Jake J. Beaul

Our literature review indicates that global TP loading of inland waters will increase over the 21st century, stimulating aquatic productivity and CH_4 emissions. We find that these changes could result in total lake CH_4 emissions having an atmospheric impact equivalent to 18–33% of that from current fossil fuel CO_2 emissions (Table 2). In fact, the net increase in CH_4 emissions due to projected nutrient loading alone would have an atmospheric effect more than increased CO_2 emissions from land use change (i.e., conversion of forests to agriculture) or up to half of the global oceanic and land carbon sinks (Table 2 [3,34]).



Sustainable Phosphorus Alliance

STEPS
Science and Technologies for Phosphorus Sustainability

Correspondence

https://doi.org/10.1038/s41893-024-01507-3

A critical eutrophication–climate change link

Check for updates

Matthew J. Scholz[1]✉, Daniel R. Obenour[2], Elise S. Morrison[3] & James J. Elser[1]✉
[1]Global Futures Laboratory, Arizona State University, Tempe, AZ, USA. [2]Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC, USA. [3]Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL, USA.
✉e-mail: matthew.scholz@asu.edu

Published online: 17 January 2025

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2. Soucek, M. et al. Preprint at earth-syst. Sci. Data https://doi.org/10.5194/essd-2024-151 (2024).
3. Beaulieu, J. J., Tank, J. L., Hamilton, S. K., Wollheim, W. M., Hall, R. O., Mulholland, P. J., Peterson, B. J., Ashkenas, L. R., Cooper, L. A., Dahm, C. N., Dodds, W. K., Grimm, N. B., Johnson, S. L., McDowell, W. H., Poole, G. C., Valett, H. M., Arango, C. P., Bernot, M. J., Burgin, A. J., Bunn, C. L., Davis, C. B., Davis, T. D., Hamrick, P. J., Helton, A. M., Hlavinka, M. A., Hofmeister, K. L., Johnson, S. K., Lauck, L. T., Lehrter, J. C., Norberg, J. E., Raikow, D. F., Stanley, H., Stapp, J. R., Tobias, C. R., Treece, G. D., Wathen, J. B., Webb, B. M., White, S. A. & Zeglin, L. H. Proc. Natl. Acad. Sci. USA 119, e2121911119 (2022).
4. US Environmental Protection Agency. Data from the National Aquatic Resource Surveys (EPA, accessed 2024). https://www.epa.gov/national-aquatic-resource-surveys-data
5. Steffen, W. et al. Science 347, 1259855 (2015).



"...abatement of lake eutrophication, then, should be addressed as a key climate change mitigation target."



Rebecca Muenich
Associate Professor
University of Arkansas

Phosphorus Policy Forum: October 15, 2026

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When #2 is our #1

On the need and barriers to circular economies for manure







Setting up this talk, and recognizing the feelings of my team, and maybe you after this talk!

Credit: *The Office*

Team Acknowledgements

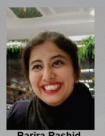


Dr. Milton Orlando Valencia Ortiz
Postdoctoral Researcher



Dr. Kanaan Hardaway
Postdoctoral Researcher

TBD
Postdoctoral Researcher



Barira Rashid
Ph.D. Candidate



Danna Villarreal
Ph.D. Candidate



Erin Grantz
Ph.D. Student

Undergraduate Researchers Not Pictured
- Nicole McKellar

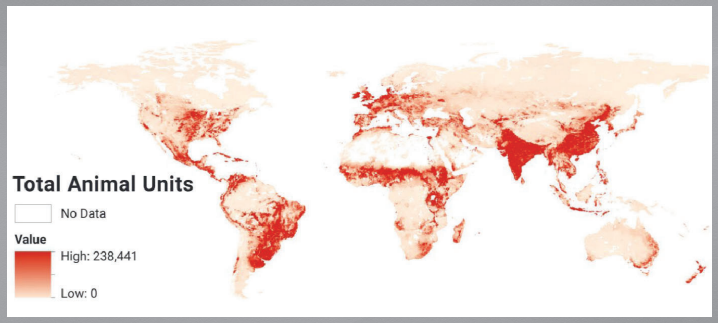
Past Graduate and Postdoctoral Scholars
- Dr. Noah Rudko (SFEI)
- Dr. Emma Bonham (Intera)
- Dr. Nusrat Khan (EPCOR)
- Dr. Ting Liu (Huadian Heavy Industries Co., Ltd, China Huadian Corporation)
- Dr. Arghajeet Saha (Asst. Prof., UKansas/KGS)
- Dr. Danica Schaffer-Smith (USFWS)
- Dr. Lorrayne Miralha (Asst. Prof., Ohio State)
- Dr. Ellie Rauh (NC DEQ)
- Dr. Maria Elena Menchu Maldonado (INFOM)
- Abigael Villeneuve (Maury Regional Health)
- Tannis (Breure) Abdoli (Carbonfuture)
- William Krukowski (Westland Resources Inc.)
- Suraya Sidique (Washington Dept. of Fish & Wildlife)
- Kelly Shea (KB Home)

Background

- The desire for meat, dairy and other animal products has increased over time (worldwide)
  - Approximately 3x the livestock as humans
- Trend towards larger operations (economies of scale)
- Operations concentrated with respect to animals per farm **and** in space
- These large farms or clusters of large farms can produce the same amount of waste per year as cities

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The Scale of the Problem



Elser, J. J.; Baker, J. J.; Boyer, T. H.; Grieger, K. D.; Liu, T.; Muenich, R. L.; Rittmann, B. E.; Saha, A. Creating an Alternative Future for Earth's Phosphorus Cycle in the Anthropocene via Eco-Prospecting, Eco-Mining, and Eco-Refining. In Treatise on Geochemistry (Third edition); Anbar, A., Weis, D., Eds.; Elsevier: Oxford, 2025; pp 263–280. https://doi.org/10.1016/B978-0-323-99762-1.00023-1

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In the U.S.

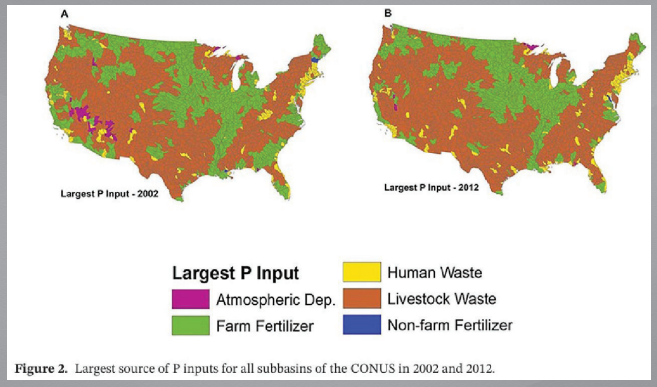


Figure 2. Largest source of P inputs for all subbasins of the CONUS in 2002 and 2012.

Sabo, R.; Clark, C.; Gibbs, D.; Metson, G.; Todd, J.; LeDuc, S.; Greiner, D.; Fry, M.; Polinsky, R.; Yang, Q. Phosphorus Inventory for the Conterminous United States (2002-2012). *Journal of Geophysical Research-Biogeosciences* 2021.

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If manure is everywhere, why don't we just recover it?



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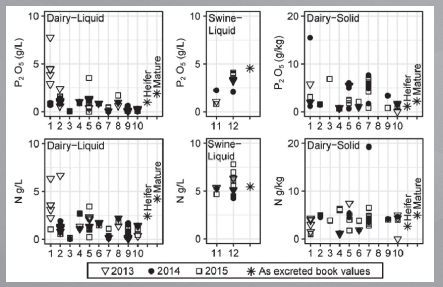
A lot of potential answers…

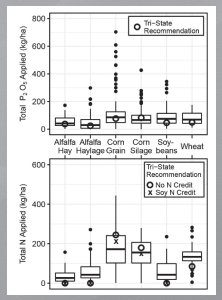
- Most of that manure is applied to the land
- There are some recovery projects driven by energy generation (e.g. AgSTAR program), but we have gaps in data, management, economics, & policy to move large scale project forward

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Most of that manure is applied to the land…BUT

- N:P ratios are off vs. crop needs



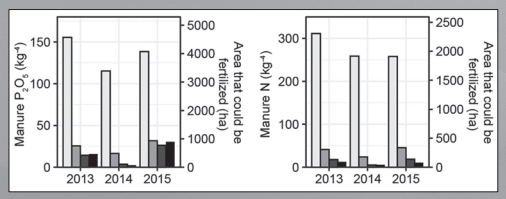


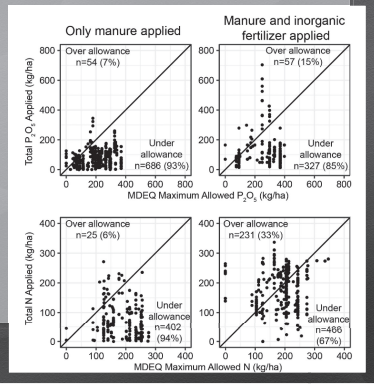
C. M. Long, R. L. Muenich, M. M. Kalcic, D. Scavia, (2018). Use of manure nutrients from concentrated animal feeding operations. *Journal of Great Lakes Research*, doi:10.1016/j.jglr.2018.01.006.

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Most of that manure is applied to the land…BUT

- It's expensive to haul so it may not get to where it is most needed



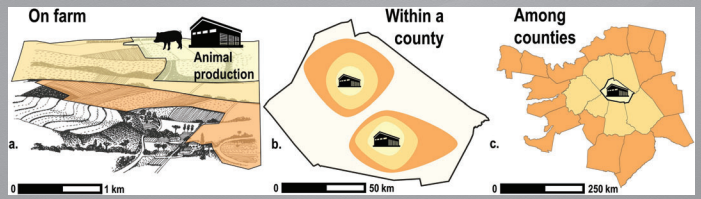


C. M. Long, R. L. Muenich, M. M. Kalcic, D. Scavia, (2018). Use of manure nutrients from concentrated animal feeding operations. *Journal of Great Lakes Research*, doi:10.1016/j.jglr.2018.01.006.

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Spiegal, S., Kleinman, P.J.A., Endale, D.M., Bryant, R.B., Dell, C., Goslee, S., Meinen, R.J., Flynn, K.C., Baker, J.M., Browning, D.M., McCarty, G., Bittman, S., Carter, J., Cavigelli, M., Duncan, E., Gowda, P., Li, X., Ponce-Campos, G.E., Cibin, R., Silveira, M.L., Smith, D.R., Arthur, D.K., Yang, Q., 2020. Manuresheds: Advancing nutrient recycling in US agriculture. Agricultural Systems 182, 102813. https://doi.org/10.1016/j.agsy.2020.102813

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Most of that manure is applied to the land…BUT

- Applying fertilizer and applying manure is typically done with different equipment
- Variable rates as you apply, especially for liquid manure slurries
- …and more

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Ok, if reusing in place not viable everywhere, we have plenty of technologies, so why aren't we recovering it?

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Background

- Large animal operations >> What is a CAFO?
  - Concentrated Animal Feeding Operation (CAFO)

AFO
  - Animals confined for 45 days or more in a 12-month period
  - Crops, vegetation not sustained in normal growing season over any portion of lot facility

C
  - Meets animal size numbers or actively discharges via pipe, ditch, etc.

Why do we care about CAFOs?

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Background

- Example CAFO numbers



Animal Sector	Size Thresholds (number of animals)		
	Large CAFOs	Medium CAFOs[1]	Small CAFOs[2]
cattle or cow/calf pairs	1,000 or more	300 - 999	less than 300
mature dairy cattle	700 or more	200 - 699	less than 200
veal calves	1,000 or more	300 - 999	less than 300
swine (weighing over 55 pounds)	2,500 or more	750 - 2,499	less than 750
swine (weighing less than 55 pounds)	10,000 or more	3,000 - 9,999	less than 3,000
horses	500 or more	150 - 499	less than 150
sheep or lambs	10,000 or more	3,000 - 9,999	less than 3,000
turkeys	55,000 or more	16,500 - 54,999	less than 16,500
laying hens or broilers (liquid manure handling systems)	30,000 or more	9,000 - 29,999	less than 9,000
chickens other than laying hens (other than a liquid manure handling systems)	125,000 or more	37,500 - 124,999	less than 37,500
laying hens (other than a liquid manure handling systems)	82,000 or more	25,000 - 81,999	less than 25,000
ducks (other than a liquid manure handling systems)	30,000 or more	10,000 - 29,999	less than 10,000
ducks (liquid manure handling systems)	5,000 or more	1,500 - 4,999	less than 1,500

[1] Must also meet one of two "method of discharge" criteria to be defined as a CAFO or may be designated.
[2] Never a CAFO by regulatory definition, but may be designated as a CAFO on a case-by-case basis.

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Background

State CAFO numbers*

NPDES CAFO Permitting Status Report:
National Summary, Endyear 2024, completed July 18, 2025
(as reported by EPA Regions)

State	EPA Region	Total CAFOs[1]
Alabama	4	558
Alaska	10	0
Arizona	9	115
Arkansas	6	776
California	9	1,063
Colorado	8	217
Connecticut	1	6
Delaware	3	511
Florida	4	100
Georgia	4	828
Hawaii	9	1
Idaho	10	274
Illinois	5	522
Indian Country (R7)	7	9
Indian Country (R8)	8	5
Indiana	5	846
Iowa	7	3,938
Kansas	7	429
Kentucky	4	150
Louisiana	6	250
Maine	1	6

** Per federal definition*

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Regulatory Complexities

- CAFOs are regulated by National Pollutant Discharge Elimination System (NPDES) under the Clean Water Act
  - In 40 CFR Part 122 and 40 CFR Part 412
- Recent rule changes and interpretations of federal CAFO regulations has led to more focus and emphasis at the state and local level
  - Not all CAFOs are required to get NPDES permits

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Regulatory Complexities

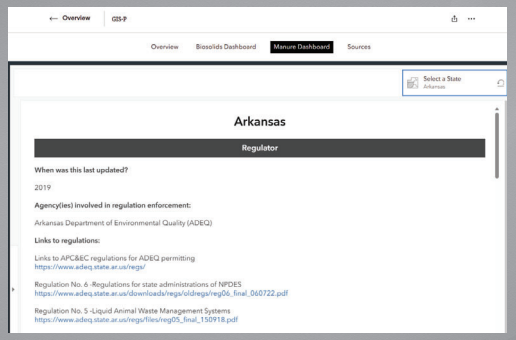
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Sustainable Phosphorus Alliance

Regulatory Complexities



https://phosphorusalliance.org/research/gis-p/

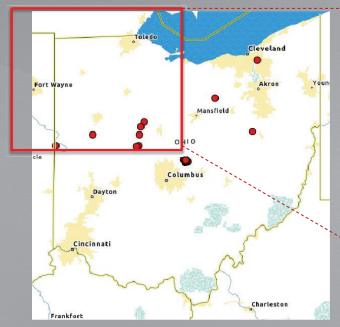
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Regulatory Complexities

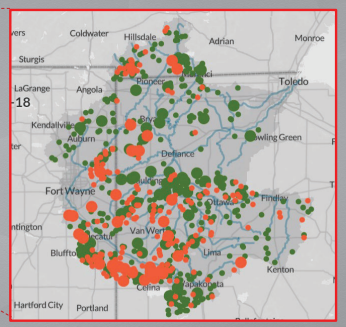


How does this impact recovery?

Where are CAFOs?



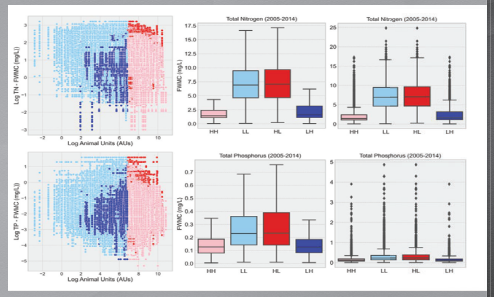
Credit: *Ohio EPA*



Credit: *EWG*

[BY THE WAY]

- Even if we had NPDES permits for ALL CAFOS…we'd still be missing out of a lot of manure and Phosphorus!



If a cow poops in a small AFO, can it be recovered?

Miralha, L., Sidique, S., Logsdon Muenich, R., 2022. The spatial organization of CAFOs and its relationship to water quality in the United States. *Journal of Hydrology* 613, 128301. https://doi.org/10.1016/j.jhydrol.2022.128301

Harder to recover P when we don't know where, when, how much, or what kind it is…

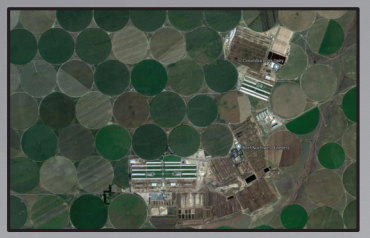
1. Where are livestock facilities? Their storage structures?
2. How many and what type of animals are in the facilities? At a given time?
3. Where and when is manure getting applied?
4. What is the composition of those manures applied?



Let's start at the source



Later ask me about a funny story for this manure pond



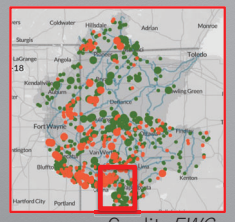






How can we find these barns?

- Where are the CAFOs?
  - NAIP Image
  - LiDAR



Credit: *EWG*

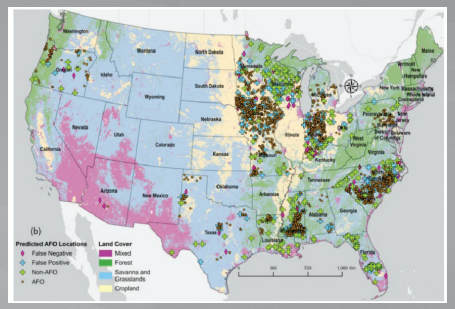


Existing Methods to Find CAFOs

- EWG/ELPC: manual mapping
  - Human TIME intensive
  - Difficult to do over large spaces, multiple time periods, or update over time
- Daniel Ho group from Stanford – ML/AI on aerial imagery
  A lot of training data and time required
  - May not work well outside of development area
- Muenich Lab past work – ML using LiDAR and NDVI
  - Data intensive, LiDAR not available everywhere or over time
  - Both above computationally intensive

Recently…

- Mapping existing AFOs data for validation
- Model on non-aerial image data accuracy of 87% for entire U.S.



Saha, A., Rashid, B., Liu, T., Miralha, L., Muenich, R.L., 2025. Machine learning-based identification of animal feeding operations in the United States on a parcel-scale. Science of The Total Environment 960, 178312. https://doi.org/10.1016/j.scitotenv.2024.178312

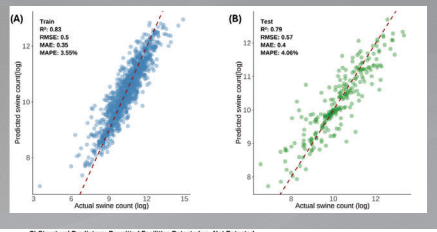
STEPS
Science and Technologies for Phosphorus Sustainability

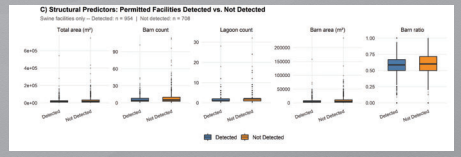
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https://steps-center.org/

Currently…

- Using structural data to improve and verify barns
- Using structural data to estimate livestock at the barns, both type and number





STEPS
Science and Technologies for Phosphorus Sustainability

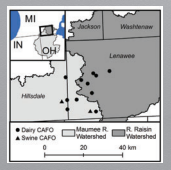
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https://steps-center.org/

When and where is manure going?

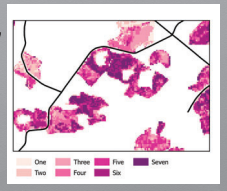
Hard Way

- In SE Michigan (where all federally-defined CAFOs are regulated) download hundreds of PDFs (1000s of pages) for 13 facilities in one watershed
- Digitize spray fields
- Digitize manure composition and application data



Less Hard Way

- Using Sentinel-1 radar data + covariates to identify manure spray fields
- Focused on Duplin County, North Carolina (have training data)
- Look at time periods with "dry" days and radar observations to try to identify manure sprayfields



C. M. Long, R. L. Muenich, M. M. Kalcic, D. Scavia, (2018). Use of manure nutrients from concentrated animal feeding operations. *Journal of Great Lakes Research*, doi:10.1016/j.jglr.2018.01.006.

Shea, K., Schaffer-Smith, D., Muenich, R.L., 2022. Using remote sensing to identify liquid manure applications in eastern North Carolina. *Journal of Environmental Management* 317, 115334. https://doi.org/10.1016/j.jenvman.2022.115334

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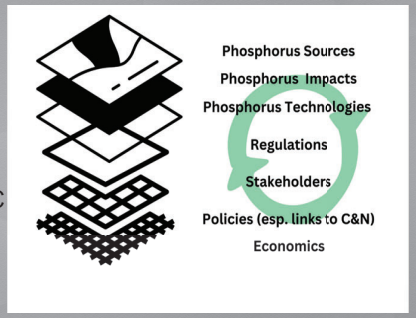
And still more data gaps…

- Composition of the manure (can get some data from NPDES permits and associated NMPs)
- Storage method and associated treatments
- Soil test phosphorus values to assess under vs. over application
- …and more!

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STEPS & P Opportunity Zones

- It's more than manure, or biosolids, or food waste…there is not a 'silver bullet' for P
- STEPS developing a dynamic framework to inform opportunities by space and sector



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Moving Forward

- We need a multi-faceted front to develop circular economies for manure
- This requires advances in technology, economic innovation, and policy follow-through (up next!)



https://muenichlab.uark.edu/

rlogsdo@uark.edu

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Circularity of Phosphorus in Manure Streams



Stephanie Kulesza: Associate Professor of Nutrient Management & Animal Waste, NCSU



Stephan Levitsky: Chief Administrative & Sustainability Officer, Phospholutions

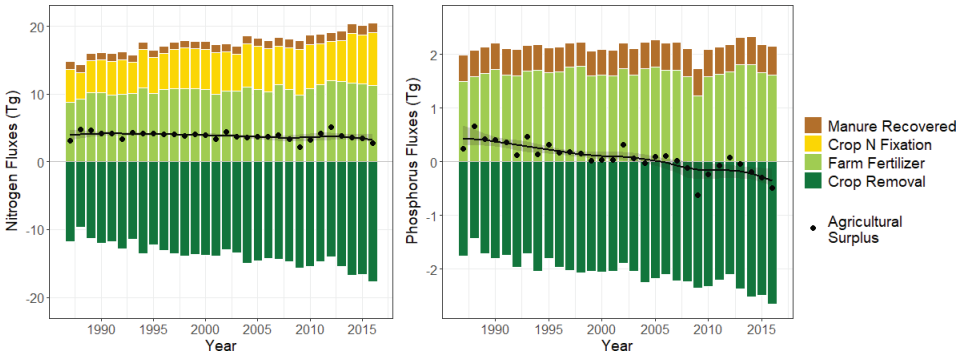


Josh McGrath: National Program Leader, USDA Agricultural Research Service



Holly Porter: Executive Director, Delmarva Chicken Association

Agricultural N and P surplus declined nationally, while crop production increased >50%



Agricultural N surplus declined from ~4.0 Tg N in the mid-1980s to ~3.5 Tg N post-2010.

Agricultural P surplus declined throughout the period of record, becoming negative after 2006.

Figure from Sabo et al. (in review)

Agricultural P surplus declined in most states, and is largely negative or near zero in 2016—drawdown becoming the norm?

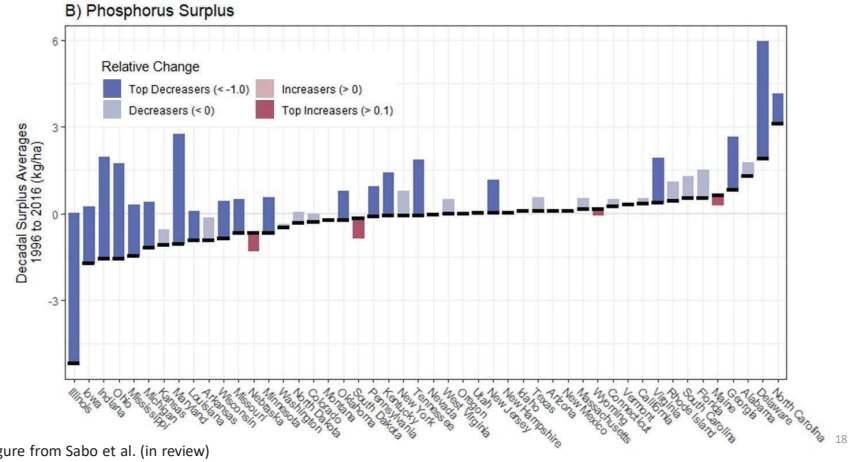


Figure from Sabo et al. (in review)

Farmers are largely improving NUE for P—how long will drawdown be maintained?

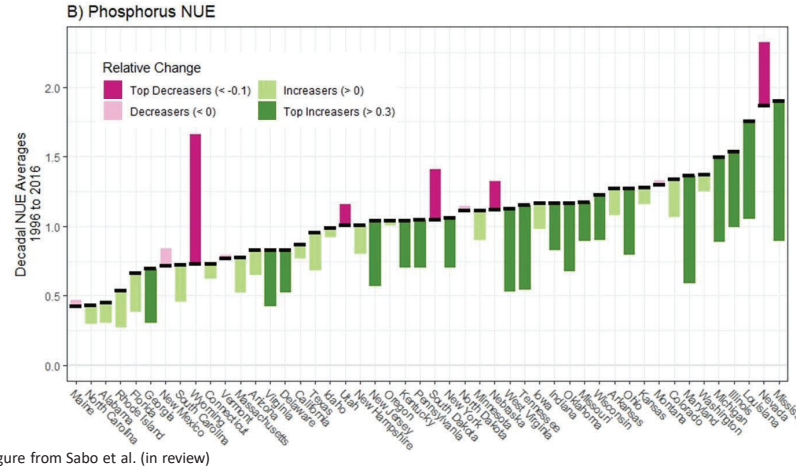


Figure from Sabo et al. (in review)

The last stops today:

- **Now:** Coffee Break: 11-11:15am
- **Next:** Breakout Session: *Who, What How* - 11:15am-12:15pm
  - Pick a room based on your interest or expertise

Multipurpose Room
(where you are now):
P Use & Circularity (Farm Bill)
Facilitators: Shwetha & Clayr

Conference Room 3
(by the coffee):
P Supply & Critical Minerals
Facilitator: Justin

- **Then:** Closing Remarks at 12:15pm
- (Optional) **Working Lunch**: 12:30-1:30pm
  - Network, socialize, or refine next steps for policy outputs