STEPS

Science and Technologies for Phosphorus Sustainability

25-in-25: A Roadmap Toward U.S. Phosphorus Sustainability

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STEPS

Science and Technologies for Phosphorus Sustainability

About STEPS

In 2021, the National Science Foundation funded the Science and Technologies for Phosphorus Sustainability (STEPS) Center to address the complex problem of phosphorus sustainability. The 25-in-25 vision of STEPS aims to facilitate a 25% reduction in human dependence on mined phosphates and a 25% reduction in losses of point and nonpoint sources of phosphorus to soils and water resources within 25 years, leading to enhanced resilience of food systems and reduced environmental damage. STEPS is a convergence research community of diverse and leading scientists that addresses the complex challenges in phosphorus sustainability by integrating disciplinary contributions across the physical, life, social, and economic sciences. The STEPS Center assembles researchers from ten partner institutions: North Carolina State University, Appalachian State University, Arizona State University, Clemson University, Joint School of Nanoscience and Engineering (a collaboration between North Carolina A&T University and University of North Carolina at Greensboro), Marquette University, RTI International, University of Florida, and University of Illinois at Urbana-Champaign. For more information, visit www.steps-center.org.

About RTI

Development of this roadmap was driven by the RTI Innovation Advisors team, a business unit of RTI International that helps corporations, foundations, and federal agencies solve complex innovation challenges. RTI is an independent nonprofit research institute dedicated to improving the human condition. With a rich history spanning over six decades, RTI has emerged as a global leader in innovative research and evidence-based solutions. Our team of around 6,000 experts across more than 75 countries hold degrees in over 250 scientific, technical, and professional disciplines across the social and laboratory sciences, engineering, and international development fields. Combining scientific rigor and technical proficiency, we deliver reliable data, thorough analysis, innovative methods, novel technologies, and sustainable programs that help clients inform public policy and ground practice in evidence.
For more information, visit www.rti.org.

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Executive Summary

What Is This Roadmap?

This roadmap serves as a guide for the actions needed to improve sustainable management of phosphorus in the United States. It outlines our current phosphorus management problems and their impact on stakeholders and organizes sets of actions into Impact Opportunities. This roadmap is the culmination of research and collaboration between researchers from the Science and Technologies for Phosphorus Sustainability (STEPS) Center and external stakeholders, including industry representatives, policymakers, and others. Stakeholders should come away from this document understanding both the urgent need to address the phosphorus challenge and what actions they can take to make a positive change toward a sustainable future.

Why Does It Matter?

Phosphorus is a key element that plays a crucial role in many aspects of daily life, but most mined phosphorus is used as fertilizer to grow food. The production of fertilizer has undergone significant industrialization over the past century to meet rising food demands, resulting in a steady incline in the demand for phosphorus. However, phosphorus is a finite resource, and much of what is mined is not recovered. Legacy phosphorus is trapped in soils where it is not easily used by crops, whereas phosphorus pollution of water bodies leads to harmful algal blooms that damage aquatic ecosystems. Thus, the phosphorus problem—phosphorus is essential to modern life, but it has negative environmental effects when not well-managed.

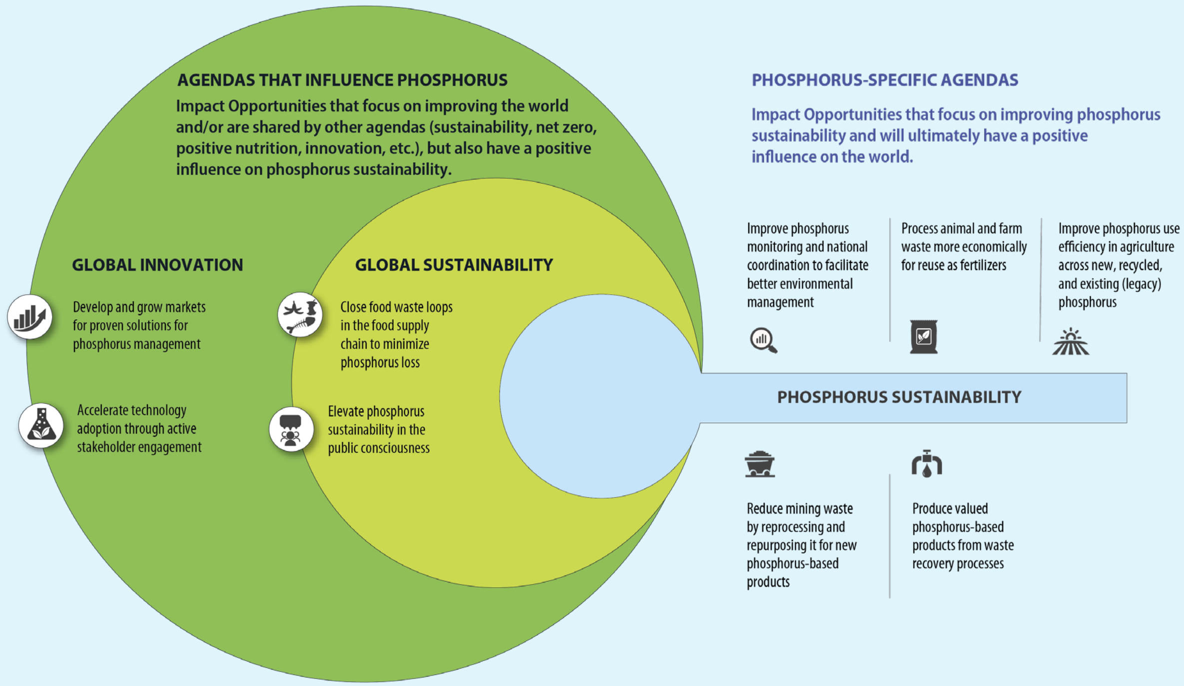
Who Is With Us?

To achieve more sustainable use and management of phosphorus, we must inspire all of you, as policymakers, researchers, farmers, producers, industry and municipal employees, and members of society, to align your actions and goals toward a more sustainable phosphorus future. We have built this roadmap to enable all readers to find their own path toward sustainable phosphorus management over the next 25 years. Where are you best suited to create a positive impact? This roadmap identifies nine key stakeholder groups we think are essential to advancing the vision:

- Advocacy
- Education, academia, and nonprofits
- Farmers and producers
- Finance
- Food, fertilizer, and agriculture industry
- Government, regulators, and standards
- Infrastructure and wastewater treatment industry
- Mining and other industries
- Public and media

What Can We Do?

STEPS advocates for a 25-in-25 vision of phosphorus sustainability for the United States: reducing human dependence on mined phosphates and losses of phosphorus to the environment by 25% each in the next 25 years. This roadmap identifies **nine Impact Opportunities (IOs)** that should be pursued to advance this vision.



Impact Opportunities mapped across spheres of influence: phosphorus sustainability, global sustainability, and global innovation

Preface

The STEPS Center will use this roadmap as one of the guidelines through which we prioritize our research activities.

We will consider this roadmap a living document and seek your feedback. This roadmap does the following:

Focuses on the United States. We acknowledge that the U.S. phosphorus supply chain is inextricably linked to a global context, and our roadmap will seek to include this context when it is most relevant. To be actionable, we must set boundaries of focus.

Presents a sector-wide and long-term view of phosphorus sustainability, considering the actions of many stakeholders across a 25-year time period.

Remains neutral about which technologies, policies, and management solutions will be the most effective. For example, our roadmap recognizes the need to improve measurement of legacy phosphorus in soils (both speciation and quantity) to improve phosphorus use efficiency in agriculture. We remain open to both existing and novel technical solutions for how this measurement is best accomplished.

Encourages a broad, frequent, and nuanced conversation about phosphorus sustainability, similar in importance to discussions on carbon and nitrogen sustainability, that is grounded in our advancing scientific understanding of chemistry, biology, and human behavior.

The power of any roadmap comes from its ability to catalyze collective action, which is based on buy-in from a diverse set of stakeholders. With collective action from diverse stakeholders as a north star, our roadmap creation process relied heavily on facilitated co-creation sessions with external stakeholders. Over 90 stakeholders across industry, government, academia, and nongovernmental organizations (NGOs) provided input that has been synthesized into key solutions, or Impact Opportunities (IOs), in this roadmap.[1] Smaller working groups including both external stakeholders and STEPS researchers refined each IO and articulated specific actions.

Stakeholder groups discussing actions to advance phosphorus sustainability

2022 August and September	2022 November	2023 March and April	FUTURE
Co-creation sessions with STEPS researchers to develop draft Impact Opportunities	Phosphorus Forum workshop to gather input and feedback on Impact Opportunities	Working group meetings to develop content for Impact Opportunity profiles and interviews with external experts to gain further perspectives and insights	Continuous updates and refinement of the dynamic roadmap based on stakeholder feedback

The roadmapping process, which began in the fall of 2022, is iterative and dynamic and we will continue to gather further stakeholder input and feedback

External Stakeholder Input

Input for this roadmap was collected during a half-day workshop in November 2022 and through individual working groups. STEPS plans to continue to broaden participation across all stakeholders in future updates of the roadmap.

Phosphorus Forum workshop participants (n=80)

59% were from an academic university (e.g., researchers, extension professionals)

16% were from industry

5% were from a government agency

8% were from a nonprofit, trade organization, or research institute

13% were N/A (unknown)

Impact Opportunity working group participants (n=48)

56% were from an academic university (e.g., researchers, extension professionals)

6% were from industry

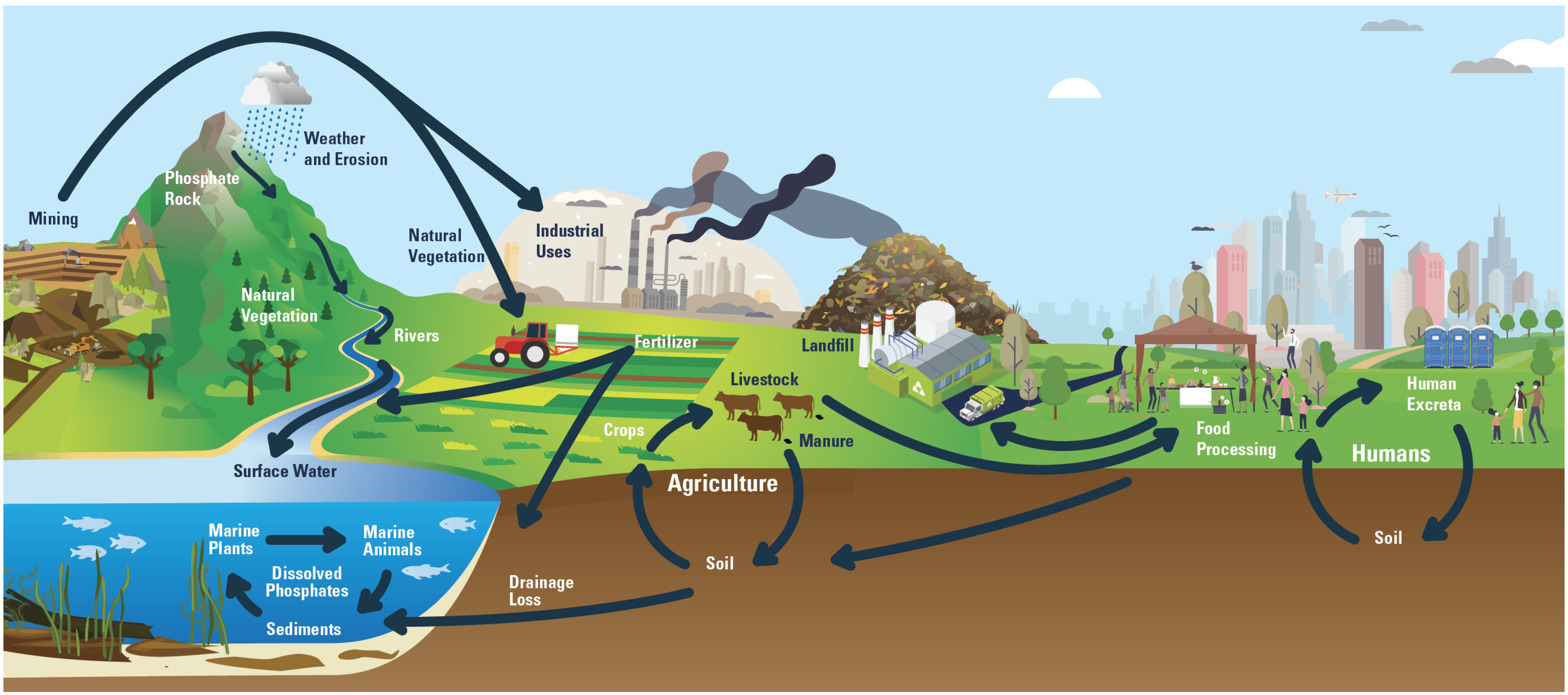
8% were from a government agency

29% were from a nonprofit, trade organization, or research institute

Our Phosphorus Problem

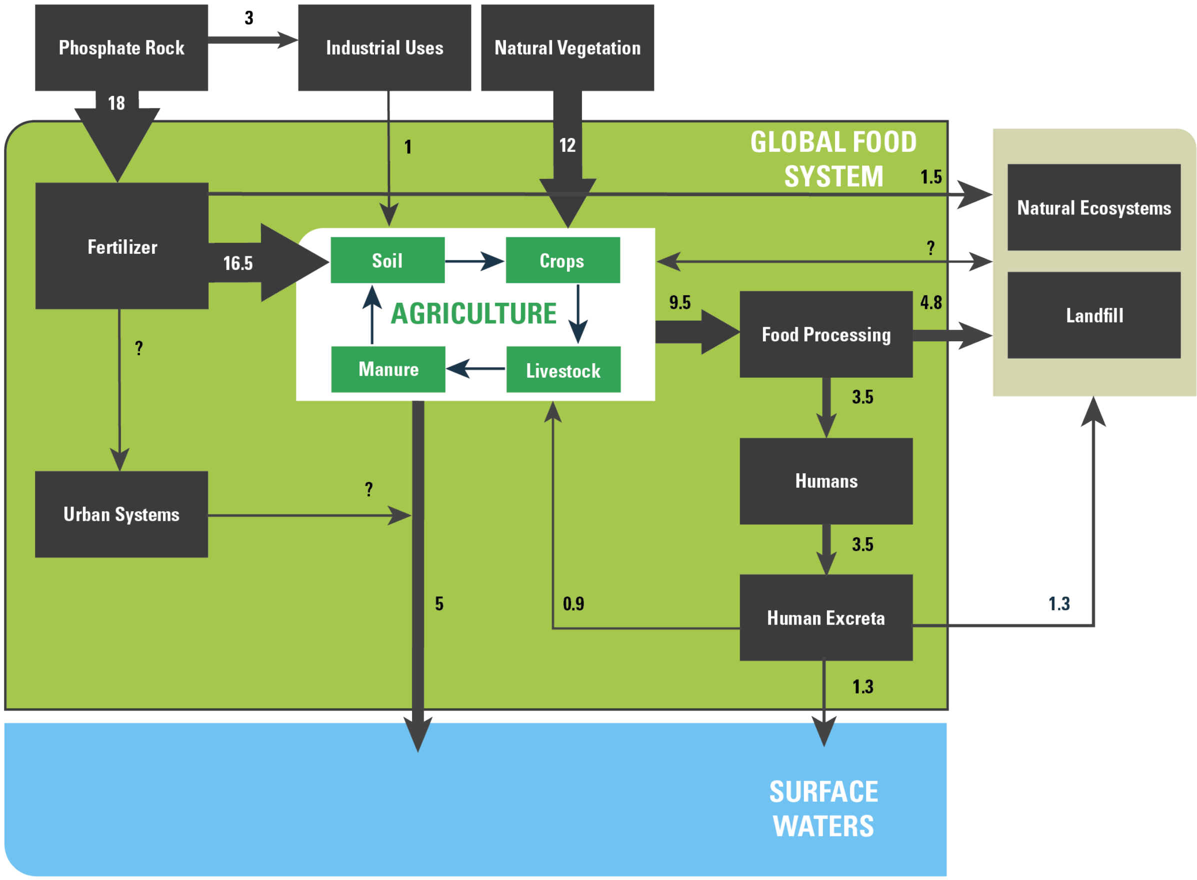
Do you know how much phosphorus you consumed in the lunch you ate today?

Phosphorus is one of the most essential elements in our lives, but most of us rarely consider its importance. The lack of consideration of the importance of phosphorus has resulted in a system without a means to account for or recover phosphorus. Simply put, our current system of phosphorus use is unsustainable. The mining of phosphate rock to produce agricultural fertilizer (and other industrial products) has increased both availability and affordability of food. However, the system is inefficient, and a large portion of the phosphorus we mine is lost before it reaches our plates.



The phosphorus cycle as it moves through rocks, soil, sediments, water, and organisms

Phosphorus management is a complex problem with competing solutions, making it an exceptionally difficult problem to solve. The beneficial and detrimental flows of phosphorus are interconnected (see diagram below).[2]



Phosphorus flow diagram with numbers that represent the globally averaged, annual weight of elemental phosphorus in units of million metric tons[8]

About Phosphorus

Phosphorus was first discovered and isolated in 1669 by Henning Brand, although humans were interacting with and impacting phosphorus well before we knew what it was. Cultures in Amazonia and China, for example, were creating and maintaining nutrient-rich islands through the application of waste (food waste, human waste, and animal waste are all rich in phosphorus) for thousands of years.[3,4] In the late 20th century, the adoption of mineral phosphorus fertilizers helped enable the Green Revolution, enhancing crop yields to meet the food production needs of the 20th and 21st centuries.[5] Beyond food production, phosphorus is a key component in electronics[6] such as computer chips, light-emitting diodes (LEDs), solar cells, and electric vehicle batteries.

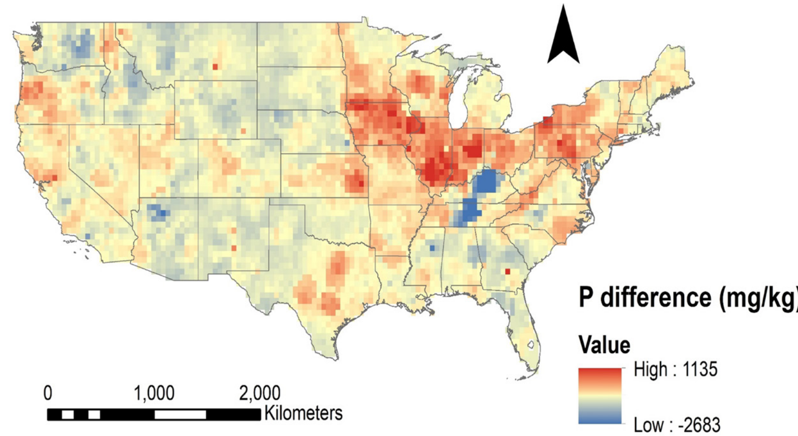
Phosphorus management may not seem like a pressing problem after the chaos and worry of the COVID-19 pandemic. However, there are many dimensions to phosphorus scarcity: physical scarcity, managerial scarcity (when phosphorus becomes lost through mismanagement), geopolitical scarcity (when phosphorus becomes less available due to trade disruption), and economic scarcity (when phosphorus becomes unaffordable for those who need it).[7]

Balancing the (sometimes competing) dimensions of phosphorus sustainability is challenging. How should we reconcile the variation in phosphorus content in soils with the current practice of consistent phosphorus application every year?[9-15] How should we balance the continued need to fertilize with the reality that 40% of the phosphorus applied is either trapped in the soil as **legacy phosphorus** or contributes to **water pollution** in fresh water rivers, ponds, and lakes?[16] How should we address the finite nature of mined phosphorus amid complicated **market dynamics** where sources of phosphorus (e.g., from food waste, livestock manure, urban wastewaters) are not aligned with demand? Before we can tackle any of these problems, we must understand the challenges that legacy phosphorus, water pollution, and market dynamics present.

Legacy Phosphorus

Most phosphorus used by crops comes from the application of fertilizers. Some of the phosphorus that is applied but not used by the crops remains in the soil in various mineralized forms. Phosphorus from past applications of fertilizer is called legacy phosphorus. Some crops can make use of some forms of legacy phosphorus, and this is an active area of crop and soil science, but much of the legacy phosphorus in farmland is effectively stuck and not well-utilized by crops.

In the United States, STEPS research quantifies the impact of fertilizer and manure application on legacy phosphorus. Farming areas in the Midwest are most affected, with some areas estimated to have phosphorus concentrations in surface soil that are over 500ppm higher than the concentration in the underlying geologic soil (represented as red zones in "Difference in phosphorus concentration"). Other areas have depleted phosphorus concentrations in surface soils (represented as blue zones in "Difference in phosphorus concentration"), where processes like erosion and crop harvesting have reduced phosphorus over time.



Difference in phosphorus concentration between surface soils and underlying geologic soils[16]

Water Pollution

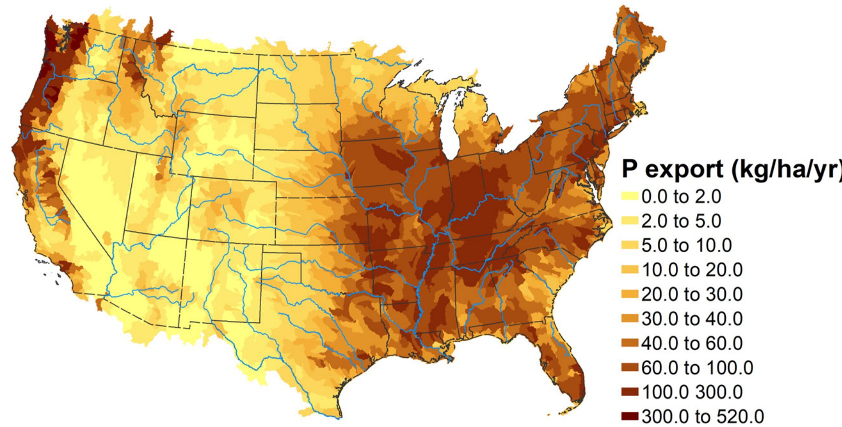
Over time, legacy phosphorus, fertilizer runoff, and phosphorus emissions from point and nonpoint sources enters fresh-water bodies. This runoff contributes to eutrophication and algal blooms, which can produce toxins and kill fish.[17-19] Furthermore, this nutrient pollution produces unsightly and noxious scum which decreases tourism and property values in waterfront areas and introduces taste and odor compounds into the water supply, increasing water treatment costs. STEPS research estimates that, in parts of the Mississippi River and Ohio River valleys, as well as in highly developed coastal areas, hundreds of kilograms of phosphorus per hectare is lost to water bodies every year (see "Estimates of phosphorus export" on the next page). One hundred kilograms of phosphorus is sufficient to supply around 2 hectares of corn production at typical application rates. In other words, areas losing more than 50 kg per hectare per year of phosphorus are losing enough phosphorus to support a second hectare of corn production.[20]

Symptoms from interacting with harmful algal blooms can range from stomach pain and headaches to vomiting, diarrhea, and even liver damage, according to the Centers for Disease Control and Prevention.[21-24] There is a statistically significant association between cyanobacterial blooms and nonalcoholic liver disease in the United States, suggesting that, for every 1% increase in algal bloom coverage, there is a 0.3% increased risk of disease.[25]

Water Pollution's Effect on Disadvantaged Populations

In 2014, unsafe levels of microcystin, a toxin that can be released from algal blooms, in Lake Erie contaminated the city drinking water for Toledo, Ohio. In response, city officials advised residents not to drink or cook with the water for 3 days. In a study conducted by an environmental working group, analysis found that Lake Erie's annual algae outbreak mostly threatens the health of people in disadvantaged communities that have a "higher percentage of people of color than the state's average and have household incomes that are less than 80 percent of average state income levels."[26]

Satellite image of Lake Erie with an algal bloom



Estimates of phosphorus export (hydrologic loss) across the United States under average climate conditions, from Bayesian modeling[27]

Market Dynamics

Although domestic resources are vast, domestic reserves—defined as known deposits that are economically extractable using current technology—are sufficient to meet demand for phosphorus for less than 40 more years in the United States. Approximately 70% of global phosphate reserves are within Morocco (according to current estimates). Will that leave U.S. farms and ranches dependent on an international phosphorus supply chain (and competing with all other nations) to access the phosphorus needed to grow crops and raise livestock that will feed our growing population? We have already seen how disruptions to supply chains from COVID-19, geopolitical events such as the Russia-Ukraine war, and regional trade restrictions have reduced the supply of phosphorus fertilizers to the global market, fueling a price surge.[28-31] Current estimates suggest that global fertilizer prices will return to normal,[32] but in our increasingly volatile world, are we willing to bet that continued geopolitical conflicts will not impact food security?

Our Vision for Phosphorus Sustainability

The vision we have, which we hope you join us in, is to reduce human dependence on mined phosphates and reduce phosphorus lost to the environment.

What if, 250 years ago, amid the start of the Industrial Revolution and the introduction of mechanization and steam power, scientists considered the human and environmental costs of greenhouse gas emissions and acted to mitigate them? With phosphorus, we still have an opportunity to better manage this resource before we cause further harm.

Our team refers to our vision for sustainable phosphorus management as 25-in-25; we aim to facilitate a **25% reduction** in human dependence on mined phosphates and a **25% reduction** in losses of point and nonpoint sources of phosphorus to soils and water resources within **25 years**, leading to enhanced resilience of food systems and reduced environmental damage in the United States as we approach the middle of this century. This vision complements the goals of other organizations. The Our Phosphorus Future roadmap, for example, sets a global goal of a 50% reduction in global phosphorus pollution and a 50% increase in the recycling of phosphorus lost in residues/wastes by 2050.[33]

25-in-25 represents a realistic, long-term view: we know we need phosphorus, and we need to be better stewards of it as a resource. Phosphorus mining will remain critical to sourcing the amounts of phosphorus required by the food system, and humans will remain dependent upon mined phosphorus moving forward. But, we need to use what we mine more efficiently, recovering it from soils and surface waters for reuse in agriculture.

Phosphorus is a "wicked problem," meaning it is a multi-variate problem, with many stakeholders and competing interests, no objectively true and complete solution, and it can't be solved with a single new technology or policy intervention.[34] Therefore, we advocate for a convergence approach in which researchers from all disciplines and stakeholders across all industries combine their expertise to advance our collective vision. This convergence approach translates diverse viewpoints into understandings about the **intersection** between technology, policy, education, engagement, and other interventions—a true systems perspective.

The STEPS Vision: 25-in-25

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

A Way Forward

One of the values of STEPS is *epistemic humility*,[35] which leads us to acknowledge that our understanding of science can never reach objective truth and must always be subject to revision based on new knowledge.

This value extends to our actions: *STEPS research and actions alone cannot solve the problems of phosphorus sustainability that our planet faces.* STEPS believes that convergence, sustainability, engagement, education, and diversity are key values that must underpin any solutions, or Impact Opportunities (IOs), necessary to advancing 25-in-25.[36] What does this mean in practice? It means having an intentional approach to accessing diverse stakeholders that is relevant to their needs and interests, that innovative new products are co-created and that equitable solutions are enacted.[37] It means that consensus is built as part of the process, rather than as an aspirational end goal.

We have approached identifying solutions, our Impact Opportunities, from a holistic, convergence perspective. We have sought and leveraged expertise across start-ups, industry, regulatory agencies, nonprofits, and academia. The 25-in-25 vision cannot advance without collective action from all of you reading this roadmap, and we invite you to shape this journey with us along the way. This document does not contain all the answers to such a complex, difficult, and global problem, but it does outline actions that enable all parties to contribute to solutions. On the next page is the list of Impact Opportunities we've identified to move toward 25-in-25 for the United States.

Nine Impact Opportunities to Reach Phosphorus Sustainability

Optimize Use

Improve phosphorus use efficiency in agriculture across new, recycled, and existing (legacy) phosphorus: Improving phosphorus use efficiency will reduce costs and demand for phosphate mining, increasing farmer income and decreasing phosphorus water pollution. To achieve this, microbial- and plant-based solutions must be enhanced, circularity must be improved, adoption of new solutions should be incentivized, and partnerships should be encouraged (see page 22).

Reclaim Waste

Process animal and farm waste more economically for reuse as fertilizers: Developing technology to reuse animal and farm waste as a source of phosphorus for fertilizer could meet as much as 50% of U.S. demand. But successful impact requires improved business models, rules to limit over-application, and economically viable processing technologies that make waste products both desirable and feasible (see page 25).

Recover Valued Products

Produce valued phosphorus-based products from waste recovery processes: Recovering phosphorus from wastewater streams can reduce phosphorus-driven water pollution and supplant demand for mineral phosphate. Focusing on high-value products, such as those that are based on co-recovery (e.g., struvite, biosolids), and including economic assessments in the technology development process can support development of compelling solutions (see page 28).

Reduce Mining Waste

Reduce mining waste by reprocessing and repurposing it for new phosphorus-based products: Mining companies have an important role in phosphorus sustainability, and this should be one component of their overall strategy. Maximizing phosphorus yield through alternative recovery, extraction, and processing methods is part of the solution, as is exploring ways to reuse mining waste (see page 31).

Reduce Food Waste

Close food waste loops in the food supply chain to minimize phosphorus loss: Actors in the food supply chain must engage in reducing and recovering food waste. Upcycling food waste at the site of generation to avoid separation issues, adopting technology advancements and laws that keep organic waste or compost out of landfills, and increasing consumer awareness will all be necessary (see page 34).

Enhance Monitoring

Improve phosphorus monitoring and national coordination to facilitate better environmental management: One key to better phosphorus management is real-time data networks that enable better monitoring, modeling, and enforceable regulations. Citizen science should be leveraged, and existing, private-party measurements that are not currently publicly reported (e.g., from drinking water providers) should be incorporated (see page 37).

Grow Markets

Develop and grow markets for proven solutions for phosphorus management: Developing and growing the markets for sustainable phosphorus products will increase the consumer demand and lower barriers to market entry for future solutions. Advancements in true cost are needed to support the business case, as are more availability of patient capital, innovative financing, and insurance mechanisms (see page 40).

Accelerate Solutions

Accelerate technology adoption through active stakeholder engagement: Stakeholder engagement can help overcome nonscientific or nontechnological hurdles, such as regulatory, social, or ethical concerns, and advance technology adoption. Researchers working on phosphorus management should place extra emphasis on stakeholder engagement early in technology development (see page 43).

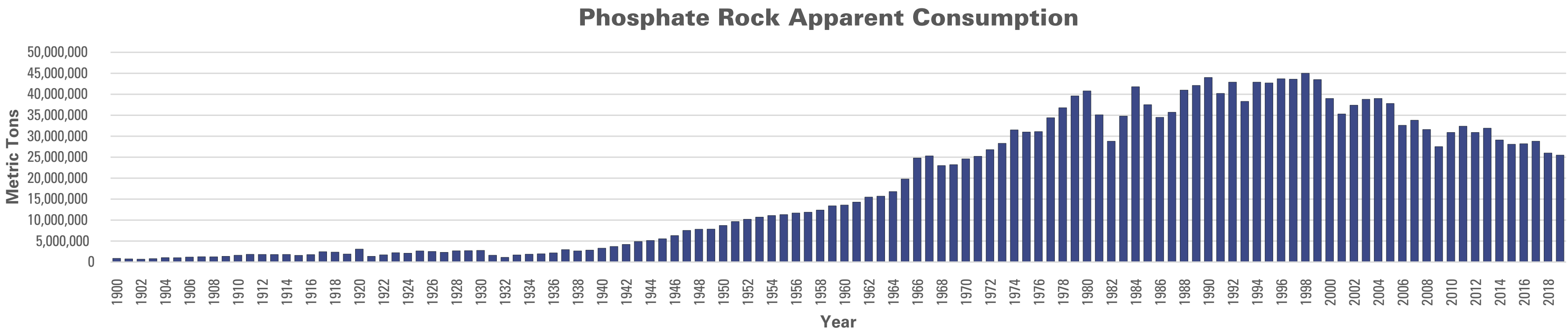
Increase Awareness

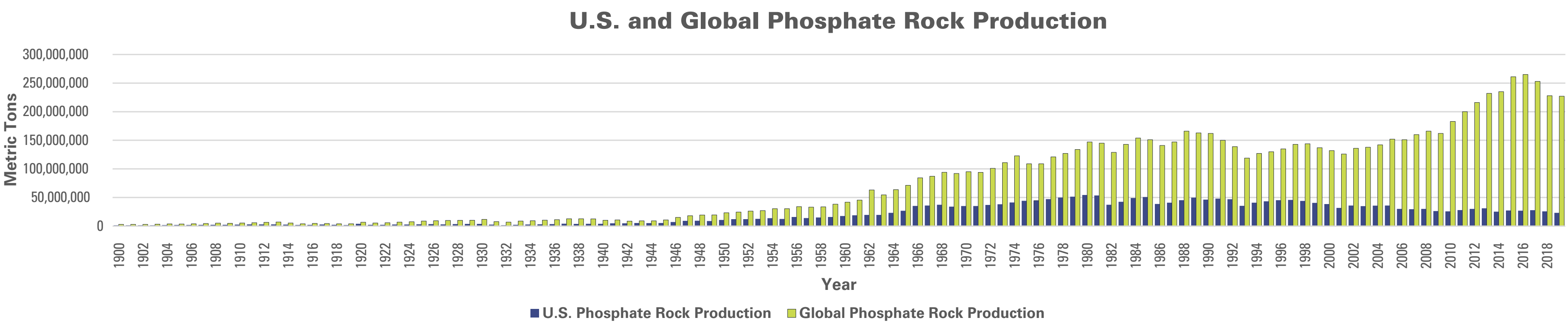
Elevate phosphorus sustainability in the public consciousness: Successfully raising awareness of phosphorus sustainability in the public is necessary to achieve behavior change and advocacy. Once consumers are aware of their individual phosphorus footprints, they need a way to advocate for, purchase, and consume products that support phosphorus sustainability (see page 46).

A Global Perspective

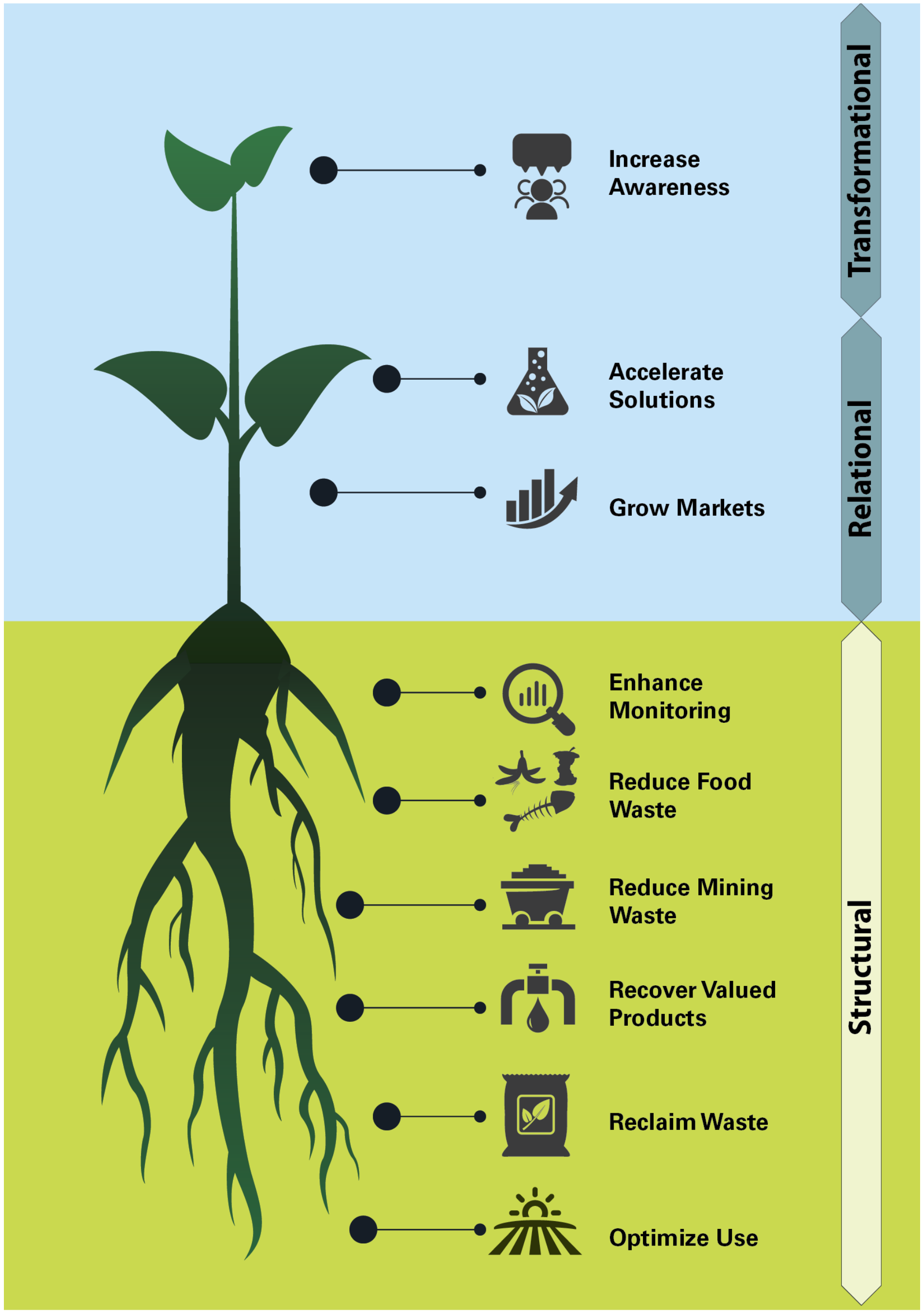
U.S. phosphorus demand has been decreasing from its peak in the 1990s.[38] Globally, however, demand for phosphorus has increased since ~2015. Although mineral phosphorus should meet demand for at least 300 years at current levels of demand, global inequities are already in play.[39] For example, much of the phosphorus in the world is mined in China but exported to support food production globally. Fertilizer consumption (in kilograms per hectare of arable land per country) is generally highest in nations in Central and South America and portions of Southeast Asia.[40]

Developing countries with large population growth will have a larger demand for food, often shifting to more meat-based diets that have a higher phosphorus footprint.[41] Although the demand for phosphorus in the United States may be much lower in 25 years, we recognize that it may be (and should be) much higher in other countries as they grow and prosper. Not all the IOs and actions are suited to every country. Global differences in available phosphorus in the soil (legacy phosphorus), preferred technological solutions, and levers that are most effective for large-scale change will create different opportunities for impact. Other groups, such as the Global Phosphorus Institute[42] in Morocco and RePhoKUs in the United Kingdom, are thinking through these questions for their countries or regions and are a good source for a more global perspective.[43]





Apparent consumption of phosphate rock from 1900 to 2019 refers to the sold or used phosphate rock plus imported phosphate rock and minus exported phosphate rock in the U.S. (top); U.S. and global phosphate rock production from 1900 to 2019 refers to the marketable or beneficiated phosphate rock product that generally ranges between 26–34% P_2O_5 (bottom)[44]



A Systems Approach

Combined, these Impact Opportunities become more than the sum of their parts. They interact and build on each other to address the different levels of systems change: structural, relational, and transformational. Phosphorus sustainability is not simply a technology, policy, financial, or advocacy problem. It is a problem requiring coordination across many stakeholders and many actions to be solved.

To tackle these actions and Impact Opportunities to advance 25-in-25, all stakeholders must do their part! Although the level of stakeholder involvement varies across specific actions (covered within the IO profiles), improving phosphorus management will require involvement from many different sectors:

- **Advocacy** (see Appendix, page 51)
- **Education, academia, and nonprofits** (see Appendix, page 52)
- **Farmers and producers** (see Appendix, page 53)
- **Finance** (see Appendix, page 54)
- **Food, fertilizer, and agriculture industry** (see Appendix, page 55)
- **Government, regulators, and standards** (see Appendix, page 56)
- **Infrastructure and wastewater treatment industry** (see Appendix, page 57)
- **Mining and other industries** (see Appendix, page 58)
- **Public and media** (see Appendix, page 59)

Impact Opportunities organized across structural, relational, and transformational levels of systems change

Waterfall on the Bronx River

Coming Together for Environmental Justice

At the receiving end of the Bronx River, communities in the Bronx are recognized as the victims of upstream pollution. The flow of sewage and trash down the river to an already overburdened and underresourced community has perpetuated existing issues of injustice. In response, the Bronx River Alliance, representing over 100 community groups, in collaboration with academics, took a systems approach to help protect, improve, and restore the health and environment of the Bronx River.[45] Together, they implemented a multiscale, environmental justice approach that considers the political ecology of systems-wide relationships. The work led to thousands of local students and community members monitoring the river and using the data as a call to action for clean water. This effort highlighted the environmental justice problems created when multiple municipalities share a single watershed. It also serves as a model for understanding the importance of community collaborations for making change.

Beware Unintended Consequences

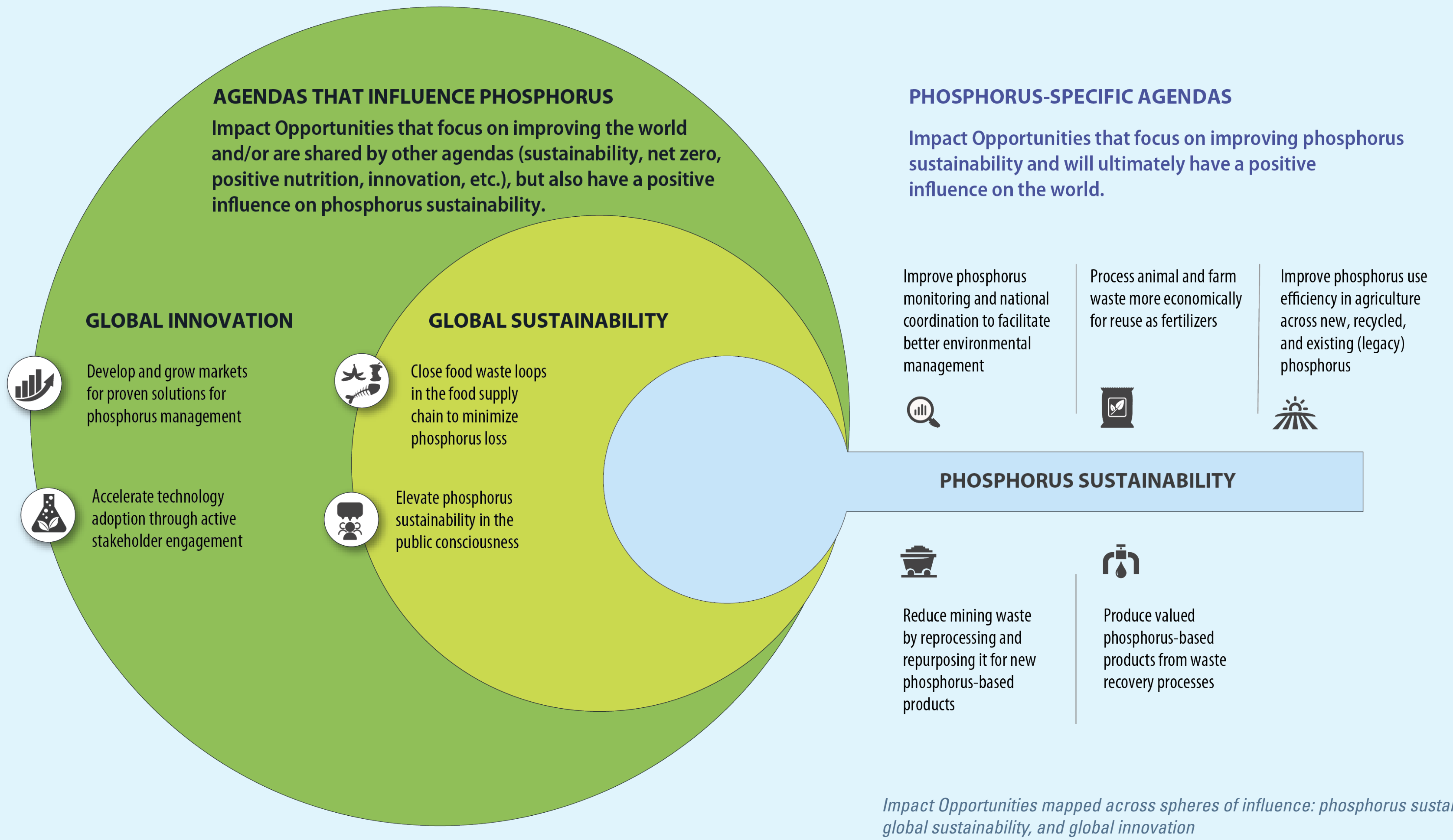
In 2021, the Sri Lanka government imposed a transition to organic farming by banning nationwide imports of synthetic fertilizers and pesticides. This mandate forced over 2 million farmers to go organic without available organic alternatives. The result was a 20% reduction in domestic rice production in 6 months, leading to a 50% increase in domestic prices and requiring the import of $450 million in rice.[46] The bans also devasted the tea crop, which was the nation's primary form of foreign exchange. The economic and societal impacts were far reaching, forcing many citizens into poverty and causing political unrest, protests, and violence.

Tea farms in Sri Lanka

Only together can we achieve phosphorus sustainability. Leveraging a diverse set of stakeholders to tackle a diverse set of problems though a diverse set of actions will help ensure that thoughtful, equitable systemic change occurs. Even with the best intentions, potential solutions can result in unintended consequences. Thoughtful research and study of phosphorus management solutions is needed to ensure they will benefit as many individuals as possible.

Across the Ecosystem

Phosphorus sustainability impacts all global ecosystems and is linked to many other environmental issues. Improving phosphorus management could help accelerate solutions to other challenges. Many of the Impact Opportunities highlighted here touch on broader sustainability discussions including those on the circular economy, food waste, greenhouse gas emissions and carbon footprints, environmental justice, critical minerals, and planetary boundaries. Phosphorus sustainability is part of all these topics, and focusing on phosphorus can accelerate the global sustainability flywheel.



Impact Opportunities mapped across spheres of influence: phosphorus sustainability, global sustainability, and global innovation

Impact Opportunities

We hope that this document sparks new thinking, catalyzes new conversations, encourages new actions, and reinforces commitments to current actions.

We at STEPS will use this document as one of the guidelines through which we prioritize our research activities. It will inform (but not be the only deciding factor) when considering which projects we support, what expertise we seek when recruiting new primary investigators, and how we approach partnerships with other organizations. We recognize that these Impact Opportunities represent a high-level, overarching perspective and do not list every possible action, stakeholder, and consideration. We hope this roadmap acts as a conversation starter and springboard for new ideas for years to come.

In the following pages, you will find information about each Impact Opportunity, including details about its challenges, its envisioned solutions, specific actions to take to achieve it, and identified stakeholders we are calling upon to take those action. Actions appear in conjunction with estimated timelines of when they may start and end across three time-frames: short-term (0 to 5 years), medium-term (5 to 15 years), and long-term (15 to 25 years). Actions' categorization within expanded tables is based on when they are expected to be completed. Also included are case studies of groups or organizations who are currently addressing or have addressed these Impact Opportunities.

Improve Phosphorus Use Efficiency in Agriculture Across New, Recycled, and Existing (Legacy) Phosphorus

Optimize Use

The Challenge

Pollution of water bodies from phosphorus runoff is, in part, a result of inefficient application of synthetic fertilizers containing phosphorus. Most crops cannot depend on legacy phosphorus in the soil to meet their nutrient needs. Because of the role of phosphorus in ensuring crop yield, fertilizers are often applied in excess. Waste fertilizer cannot be economically recovered and reused, creating an incentive to adopt technologies that improve phosphorus efficiency. But success is not guaranteed. Varied regulatory requirements across states, limitations on available capital, and crops that are increasingly reliant on legacy phosphorus are all barriers to technology adoption.

The Solution

Improving phosphorus use efficiency creates a triple bottom-line effect: it reduces cost and demand for mined phosphate, increases farmer income, and reduces phosphorus pollution in water. This effect can be achieved by improving phosphorus management, using microbial and plant technologies, improving circulation, incentivizing adoption, and increasing partnerships. Technologies that detect phosphorus abundance in the soil and improve phosphorus availability would enable greater reliance on legacy phosphorus. Realized efforts would result in environmental and financial returns, improving the holistic farm continuum and benefiting the livelihoods of those who currently carry the burden of phosphorus mismanagement and pollution.

The Actions

Short-Term (0-5 years) ● ○ ○ **Medium-Term (5-15 years)** ● ● ○ **Long-Term (15-25 years)** ● ● ●

1. Leverage partnerships with trusted and established companies to improve technology adoption
2. Reduce consumption of mined phosphorus per unit of crop by improving circularity of phosphorus flows in agricultural systems
3. Work across the agriculture ecosystem to engage, inform, and operationalize sustainable phosphorus management
4. Develop new sensing technology to quantify phosphorus availability in the soil to inform precision management
5. Develop technology for enhancing phosphorus availability in soil and organic material
6. Develop microbials (biostimulants) to improve the uptake of phosphorus
7. Invest in breeding and genetic research to develop new varieties of plants that use phosphorus more efficiently
8. Restructure current federal programs and policies to improve nutrient use efficiency dependence

Case Study: John Deere

The development and patenting of the Harvest Labs 3000 by John Deere, through partnership with Carl-Zeiss,[47] provides an example of technology being applied to improve phosphorus use efficiency. Originally used for silage chopping and silage feeding, Harvest Labs 3000 Manure Constituent Sensing is now used to inform manure management. NIR technology measures, in real-time, the moisture content and nutrient content of manure during its application and slows down or speeds up the tractor[48] accordingly to meet application goals, including mitigating the overapplication of phosphorus.

John Deere tractor applying liquid fertilizer to crops

Short-Term (0-5 years) ● ○ ○	Stakeholders
1. Leverage partnerships with trusted and established companies to improve technology adoption. Some technologies are being developed to help monitor phosphorus and stimulate phosphorus uptake in plants, yet they are not widely distributed. To increase adoption rates, encourage companies developing new technologies to partner with companies that producers and farmers consistently engage with to buy seeds, equipment, etc., for their farms. This partnership will raise awareness and accessibility among the farmers.	Startups, biotech, engineering, seed, or chemical companies marketing the new technology; companies that are actively engaging with producers and farmers on a regular basis
2. Reduce consumption of mined phosphorus per unit of crop by improving circularity of phosphorus flows in agricultural systems. Many people avoid using manure-based fertilizers due to their adverse perceptions and implications, which may continue to detract from their adoption in the future. Making efforts to change the mindset of nonmanure users and guiding manure-based fertilizer recommendations through articles, websites, trade journals, public events, and more will help create a market for the widespread adoption of manure-based fertilizers.	The farmers and producers receiving the information; others who may play a role in delimitating the information including government agencies; academics and extension agencies that provide information and recommendations
3. Work across the agriculture ecosystem to engage, inform, and operationalize sustainable phosphorus management. The North Carolina extension network can provide other states with a model to improve their educational services. By improving education on the implications of inorganic phosphorus use and how to mitigate dependence on it, this network can directly inform precision management efforts and indirectly help adopt new technologies.	Extension agencies that educate and inform; academics setting recommendations around phosphorus management; companies developing technologies to better manage, use, and recycle phosphorus

Medium-Term (5-15 years)	Stakeholders
4. Develop new sensing technology to quantify phosphorus availability in the soil to inform precision management. Changes in environmental conditions over time alter phosphorus availability. Sensing orthophosphorus content in real time will enable producers to optimize application rates in accordance with plant needs to mitigate excess consumption, as well as runoff and erosion management to mitigate phosphorus pollution in nearby waterbodies.	Biotech, engineering, startup companies or academic researchers developing the sensing technology; producers who will implement the technology
5. Develop technology for enhancing phosphorus availability in soil and organic material. Developing technology, such as enhanced efficiency fertilizers, that modify the soil based on its chemistry to increase the availability of phosphorus can enable greater dependence on legacy phosphorus and reduce the need for new phosphorus.	Fertilizer and chemical companies that develop new technology; producers who will use the new technology
6. Develop microbials (biostimulants) to improve the uptake of phosphorus. Applying microorganisms that enhance the rate at which plants uptake and consume phosphorus can reduce the need for fertilizer inputs to achieve optimal plant yield.	Research and development teams in industry that develop this technology; producer associations who will help to disseminate and use the technology; academics informing the development of technology

Long-Term (15-25 years)	Stakeholders
7. Invest in breeding and genetic research to develop new varieties of plants that use phosphorus more efficiently. Although years of research have been invested in the breeding of plants to improve nitrogen efficiency, very little effort has been put toward phosphorus efficiency. Plants with improved phosphorus uptake would reduce the inputs needed to grow the respective plant.	Seed and breeding companies, including breeders, producers who invest in and implement research; policymakers who set regulations around gene-edited plant varieties
8. Restructure current federal programs and policies to improve nutrient use efficiency dependence. This action may include developing a task force to first understand the incentives set up by policies such as the Farm Bill and programs such as commodity support programs or crop insurance. Next, advocate for change in programs and policies that align incentivizes with use efficiency and minimize waste.	Academic researchers and scientists who evaluate the implications of policies and programs; advocacy organizations, lobbyists, and nonprofits that advocate for change; regulatory agencies and legislators who restructure policies and programs; the fertilizer industry; and farmers who implement changes according to regulations

Process Animal and Farm Waste More Economically for Reuse as Fertilizers

Reclaim Waste

The Challenge

Farm waste, specifically manure, is a rich source of phosphorus. It is not commonly treated as a commodity (e.g., not distributed between farms) due to high transportation costs and unsuitable nitrogen-to-phosphorus ratios for certain crops. State regulations for fertilizer application rates can also contribute to overapplication of phosphorus when the rates are based on nitrogen requirements. Technologies to reduce water content and optimize nutrient content are currently too expensive to be widely adopted. When accounting for the full environmental and health costs of synthetic fertilizers, processed waste fertilizers can be economical, but adopting these products usually requires changes to current farming operations. As a result, many farmers rely on synthetic fertilizers.

The Solution

Forty to fifty percent of the U.S. demand for phosphorus could be met with recycling the outputs from farm and agriculture applications.[49] In so doing, nonpoint source water pollution would be reduced, thereby decreasing the presence of algal blooms, and American food security would be improved. Advancement toward increasing use of animal and farm waste might consider changing nutrient management plans to require manure application at agronomic rates. Incentivization of efforts toward nitrogen management, such as reducing nitrogen volatilization, would impact phosphorus sustainability by improving nutrient ratios and, consequently, would increase the appeal of manure as a commodity.

The Actions

Short-Term (0-5 years) ● ○ ○ | **Medium-Term (5-15 years)** ● ● ○ | **Long-Term (15-25 years)** ● ● ●

1. Improve the economics of phosphorus recovery technologies from farm waste (Short-Term to Medium-Term)
2. Require that the limiting nutrient, whether nitrogen or phosphorus (usually phosphorus), stands as the regulated nutrient for application of manure products on fields at the national level (Short-Term to Long-Term)
3. Include the cost of the negative externalities (e.g., economic, health, and water quality impacts) associated with the production of food products into the price that consumers pay (Medium-Term to Long-Term)

Case Study: Phinite

Phinite[50] has developed a breakthrough technology to transform farm waste into regenerative biofertilizer. Recognizing the value of phosphorus-rich manure, they developed a natural method to reduce its water content and lower the transportation cost associated with the movement of manure. The company shares the proceeds from the sale of the manure product with the farmers, providing them with a profitable return on their assets (the manure processing equipment). The solution provides a means to manage agriculture waste while also ensuring phosphorus from manure is recycled back into fertilizers.

Dairy farm waste

Short-Term (0-5 years)	Stakeholders
1. Improve the economics of phosphorus recovery technologies from farm waste. Reducing the cost of harvesting, treating, and processing manure to recover phosphorus will develop a consumer demand for recycled phosphorus fertilizers. Key technical areas for improvement involve recovering phosphorus in fertilizer forms that can serve as drop-in replacements for synthetic fertilizers. Stakeholders developing the technology need to be on the ground with end-users to understand and work with, rather than against, their business models.	Startups, universities, and research institutes that develop such technologies; state and federal funding agencies, investment firms, corporations and advocacy groups that fund the research and promote adoption and scaling of technologies; legislators and regulators who support innovation and remove hindrances to technology use through policy incentives, funding, and regulations; farmers and producers who would implement new technologies

Medium-Term (5-15 years) ● ● ○	Stakeholders
2. Require that the limiting nutrient, whether nitrogen or phosphorus (usually phosphorus), stands as the regulated nutrient for application of manure products on fields at the national level. This action includes the development of policies that discourage excessive use of phosphorus due to farmers applying fertilizer at nitrogen rates, which results in the overapplication of phosphorus. Implementation of new regulations must consider the time necessary for farmers or producers to change operations and the regions where legacy phosphorus is abundant in the soils. Additionally, efforts toward reducing nitrogen volatilization may further mitigate the overapplication of nitrogen and phosphorus. Regulators are not likely to change policies if academics continue suggesting the use of the phosphorus risk index. This index is currently not effective because of its broad interpretation. When academia provides solutions in the form of manure conversion to enable transport of phosphorus to the regions where it is needed—building further revenue streams for the producers—the land-grant universities system and the extension services and academics involved must communicate to regulators the need for changes in such policies.	State regulators and legislatures who restructure policies; academics who inform regulators of the need for new indices; environmental quality enforcement bodies that enforce regulations; affected industries and farmers
Long-Term (15-25 years) ● ● ●	**Stakeholders**
3. Include the cost of the negative externalities (e.g., economic, health, and water quality impacts) associated with production of food products into the price that consumers pay. Introduce a commodity checkoff program for food products (especially phosphorus-intensive animal products) to support research and cover the costs associated with phosphorus pollution and manure conversion.	Industry, advocacy, academic, nonprofit, and government researchers developing methodology to account for the cost of negative externalities; farmers and producers; producer organizations and the U.S. Department of Agriculture (USDA) to encourage and implement checkoff programs; manure conversion companies and programs receiving funds; food and beverage companies and consumers who adapt to new commodity cost

Produce Valued Phosphorus-Based Products from Waste Recovery Processes

Recover Valued Products

The Challenge

Phosphorus is essential for food growth, but it is often not economically viable to recover alone. Current phosphorus recovery is derived mainly from organic waste sources, but economic, social, and cultural factors limit their adoption. For phosphorus recovered from human waste, concern about micro-pollutants and hormones hinders adoption.[51] And costs are high, due to the expensive absorbents required and the need for wastewater streams with high phosphorus concentrations (point sources of pollution). No commercial technologies recover phosphorus from dilute, nonpoint sources, and any future technologies must prove to be economically viable. Furthermore, regulations and consumer preference require that final products must be in a usable form and free from natural (i.e., radiological) and emerging contaminants such as per- and polyfluoroalkyl substances.

The Solution

Producing high-value products from the phosphorus recovery process offers an opportunity to drive reductions in phosphorus losses to the environment and reduce consumption of finite phosphate rock reserves. Focusing on high value products, such as those that are based on co-recovery (e.g., struvite, biosolids), can increase the recognition and actualize the total value of phosphorus recovery. Technical development should be paired with Life Cycle Assessment (LCA) and technoeconomic analysis to inform design. Co-recovery systems should go beyond struvite and biosolids into higher-value products to increase demand and drive investments in recovery and production facilities.

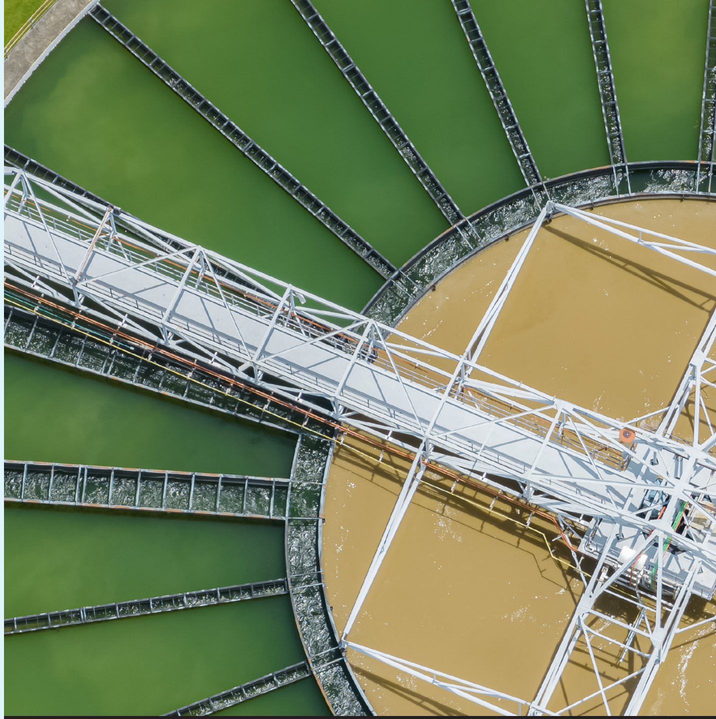
The Actions

Short-Term (0-5 years) ● ○ ○ **Medium-Term (5-15 years)** ● ● ○ **Long-Term (15-25 years)** ● ● ●

1. Increase awareness of the phosphate challenge among phosphorus users and the general public to drive demand for recovered phosphorus products
2. Evaluate barriers to adoption and tackle potential solutions, including standardization, certifications, and incorporation of the true value of products
3. Improve the performance of phosphorus and phosphorus+ recovery systems
4. Develop and scale next-generation waste recovery processes, including for other forms of phosphate used in non-agricultural applications
5. Promote a shift in mindsets such that wastewater facilities are thought of as resource recovery facilities
6. Incentivize developing more facilities that remove and recover phosphate from wastewater through regulation

Case Study: Ostara

Mindsets are shifting, from considering wastewater facilities as only waste treatment plants to looking at them as resource-recovery facilities. Resource recovery facilities are addressing the historical problem of phosphate precipitation, specifically struvite, at treatment plants that use anaerobic digesters for sludge treatment. In the study *Struvite precipitation within wastewater treatment: A problem or a circular economy opportunity?*, scholars show that controlled struvite recovery via an Ostara crystallization reactor is economically viable and environmentally beneficial as a soil amendment and fertilizer.[52] The study recommends that wastewater treatment plant operators across the globe consider fitting a crystallization reactor to appropriate plants.



Wastewater treatment plant

Short-Term (0-5 years)	Stakeholders
1. Increase awareness of the phosphate challenge among phosphorus users and the general public to drive demand for recovered phosphorus products. Raising awareness among the general public can help drive market demand for recovered phosphorus products and accelerate technology deployment (see IO: Increase Awareness).	Academics and researchers who inform the phosphorus challenge; advocacy groups and industries that are impacted by phosphorus; NGOs that directly educate citizens
2. Evaluate barriers to adoption and tackle potential solutions including standardization, certifications, and incorporation of the true value of products. There are many non-technical barriers to wide scale adoption of recovered phosphorus products from waste streams. Developing standardization and certifications and lobbying for Organic Materials Review Institute registration based on agronomic trials and other data may play a role. Using a more holistic perspective in LCA and technoeconomic analysis studies that include both internalities and externalities will alter the cost-benefit equation of phosphate recovery. Lastly, researching how to increase the marketability and acceptance of recovered products to establish larger market demand, continuing to address concerns about emerging contaminants (e.g., per- and polyfluoroalkyl substances) and demonstrate product safety, and mapping and matching of phosphorus from waste streams to localized reuse options may help mitigate these barriers. This action might also include identifying high-value, albeit niche, beachhead markets as first points of entry.	Academics or industry groups that conduct analyses on product cost; standard-setting bodies or organizations and regulatory groups that create standards or certification programs for products; wastewater treatment facilities, agricultural groups, and civil society that inform barriers to adoption; industry groups that identify market entry points

Medium-Term (5-15 years) ●●○	Stakeholders
3. Improve the performance of phosphorus and phosphorus+ recovery systems. Improving the performance of phosphorus will ultimately drive down the costs of recovery, increasing overall adoption. Cost improvement can also be achieved through co-product recovery (e.g., water, nitrogen, carbon), increased equipment efficiency, energy use efficiency, and improvements in the chemistry, biology, and catalysts used in the phosphorus recovery process. It may also include improvements in the ability to recover from dilute waste streams.	Academic researchers, industry researchers, and startups developing new technologies; government agencies and investors funding development; engineering firms, wastewater treatment plants, and fertilizer companies providing and implementing recovery technology
4. Develop and scale next-generation waste recovery processes, including for other forms of phosphate used in non-agricultural applications. Scaling technologies may also include evaluating the financial viability of recovering phosphorus from streams other than municipal wastewater treatment plants. Phosphorus recovery from mining operations, industrial wastewater (especially slaughterhouses), livestock operations, and meat and bonemeal processing should all be explored.	Academic and industry researchers who identify the means to recover and convert phosphorus into usable forms; economists who inform scaling pathways and financial viability of technologies; industries (e.g., mining, livestock, slaughterhouses, wastewater) that provide waste and implement recovery technologies
Long-Term (15-25 years) ●●●	**Stakeholders**
5. Promote a shift in mindsets such that wastewater facilities are thought of as resource recovery facilities. In the past, wastewater facilities were predominately thought of as treatment (mitigation) facilities. Mindsets are increasingly shifting to a focus on resource recovery, which is key to wide-scale phosphorus recovery and is likely driven, in part, by the availability and scale of new technologies.	Wastewater treatment facilities that work to rebrand their work; local and national governments and media that informs civil society of recovery operations; citizens who develop a shift in mindset
6. Incentivize developing more facilities that remove and recover phosphate from wastewater through regulation. Regulatory levers are key to wide-scale market adoption. These levers can include changes to the amount of phosphorus legally allowed to be discharged as waste, which can alter the cost-benefit equation of removing phosphate, and the implementation of financial credits (e.g., tax breaks) that incentivize removal and recovery.	Local, state, and national regulatory agencies that incentivize the recovery of phosphorus through regulation; wastewater treatment plants that implement recovery practices; environmental advocacy groups

Reduce Mining Waste by Reprocessing and Repurposing It for New Phosphorus-Based Products

Reduce Mining Waste

The Challenge

Repurposing mining waste may enhance mining yields and reduce dependence on newly mined phosphorus. Waste materials from phosphate mining are stored as stacks (essentially piles of material), which can contaminate surrounding environments via leaching, spills, weather-related events, sinkholes, and other problems when they are not well-managed. This is a pressing problem *today*. The waste materials, primarily phosphogypsum, contain small amounts of naturally occurring uranium nuclides and other toxic components, making safe reprocessing a necessity. Regulatory concerns about waste reuse, opposition from environmental advocates, and the lack of evidence-based studies demonstrating the safety of reuse are all barriers that will need to be overcome.

The Solution

Successful and safe reprocessing and reuse of mining waste can reduce risks posed to the environment from runoff pollution to populations living near waste stacks. It can also provide economic value to mining operations by requiring less management of toxic waste and generating additional revenue from the waste product. Mining companies have a necessary and important role in phosphorus sustainability. As key stakeholders, their potential to drive impact by adopting sustainable phosphorus management strategies is far-reaching. Success of this IO hinges on thoroughly demonstrating the safety of reprocessed waste, which would engender support from environmental advocacy groups and policymakers.

The Actions

Short-Term (0-5 years)	Medium-Term (5-15 years)	Long-Term (15-25 years)
1. Assess reuse avenues of phosphate mining wastes by evaluating safety risks and potential product value across relevant sectors		
2. Educate and collaborate with environmental interest groups and regulators around the benefits of reusing phosphate mining waste materials	2. (continued)	
3. Leverage pilots to develop and scale alternative phosphorus recovery, extraction, and processing methods for mining wastes	3. (continued)	
		4. Increase regulatory requirements for phosphate mining and clean-up of produced waste

Case Study: Phosphate Mine Waste Rocks

The Moroccan guide for road earthworks currently classifies phosphate mine waste rocks as waste products, which has limited their use. However, in a study investigating the valorization of phosphate mine waste rocks (PMWR) as alternative raw materials in road construction, the PMWR samples taken from the phosphate mine site of Gantour, Morocco exhibited satisfying physical, geotechnical, chemical, mineralogical, and environmental properties, making them suitable for use in road construction.[53] The PMWR possess the required geotechnical properties to be used as materials for embankments, and none of the samples released any contaminants in leaching tests.

Phosphate mine in Gantour, Morocco

Short-Term (0-5 years) ●○○	Stakeholders
1. Assess reuse avenues of phosphate mining wastes by evaluating safety risks and potential product value across relevant sectors. Evaluating the potential health risks is crucial for adoption, and there is a lack of understanding about radiological, physical, and chemical risks. Understanding tradeoffs also requires assessing the risks of not acting. Furthermore, analyzing costs through economic and LCAs can provide insights into market requirements for applications such as construction materials or batteries.	Regulators evaluating the safety of mined phosphate waste; technology transfer offices and economists informing new potential applications of mined phosphate waste; industries (such as construction or batteries) willing to assess the application of recovered phosphorus for their products
Medium-Term (5-15 years) ●●○	**Stakeholders**
2. Educate and collaborate with environmental interest groups and regulators around the benefits of reusing phosphate mining waste materials. Leveraging objective data around the health risk for different potential reuse cases may assist environmental interest groups in better understanding the potential value of reuse. That buy-in has the potential to permeate to other civil society groups.	Academics and regulators that generate safety data; advocacy and special interest groups, environmental interest groups, government, and regulators that are informed of the safe reuse of mined phosphate waste

3. Leverage pilots to develop and scale alternative phosphorus recovery, extraction, and processing methods for mining wastes. Alternative phosphorus recovery methods might include improved wet acid processes to generate phosphoric acid from recovered phosphorus products, processes to reduce low-grade phosphorus into elemental phosphorus, and purifying or recovering phosphorus from phosphogypsum. The project must include financial feasibility studies informed by pilot scale demonstrations and would rely on government funding support to mobilize.	Academic or industry researchers trialing processes to recover, convert, and create usable products from phosphogypsum; industries (e.g., construction, concrete, batteries, fertilizer) willing to test new recovered phosphorus within their products; government agencies funding pilot studies
Long-Term (15-25 years)	**Stakeholders**
4. Increase regulatory requirements for phosphate mining and clean-up of produced waste. Efforts toward this action include local or state bans on phosphate mining and contributions to clean-up funds, which may be enacted as a result of pressure placed by environmental interest groups.	State agencies and regulators that enforce new phosphogypsum regulations; advocacy and environmental interest groups that support regulatory change; the mining industry that implements regulations

Close Food Waste Loops in the Food Supply Chain to Minimize Phosphorus Loss

Reduce Food Waste

The Challenge

In the United States, one-third of food produced, which required phosphorus fertilizers to grow and contains phosphorus itself, is wasted and becomes the most common material in landfills.[54] Food waste occurs across the supply chain, requiring a variety of unique solutions for prevention and recovery. Despite financial incentives for producers, distributors, manufacturers, and retailers, food waste persists due to unsightly food, spoilage, and excess production. Half of food waste is generated by the last stage of the supply chain, which includes households and restaurants.[55] Once in landfills, separating food waste from municipal waste is difficult, creating challenges in recovering phosphorus.

The Solution

Efforts to reduce and recover food waste must involve all individuals—from producers to consumers—across the food supply chain. Donating or upcycling food waste at the site of generation to avoid separation issues offers a sound approach. However, it requires technical capacity and market acceptability for individual foods or food product that may become waste. Advances in technologies such as co-digestion with anaerobic digesters present a path forward for processing mixed food waste. Momentum from states and municipalities implementing laws to treat organic waste or compost and efforts to motivate consumer change and awareness by aligning with parallel issues, such as climate change, circular economy, malnutrition, will drive systems-level transformation.

The Actions

Short-Term (0-5 years) | **Medium-Term (5-15 years)** | **Long-Term (15-25 years)**

1. Align with efforts already established by others with agendas to mitigate food waste
2. Modify grading standards and buying specifications for food products to minimize waste
3. Clarify expiration dates to prevent consumer confusion and unnecessary waste
4. Collaborate with large institutions to identify ways to mitigate or recover food waste
5. Improve consumer perception of food waste recovery
6. Grow the market for upcycled ingredients in business-to-business (B2B) sales
7. Develop technologies to improve the feasibility of upcycling food waste
8. Optimize and improve the use of co-digestion for mixed food waste
9. Develop policies encouraging both consumer and industrial food composting and discouraging food in landfills

Case Study: University of Massachusetts Amherst

In 2014, Massachusetts implemented a ban on food waste disposal for institutions or businesses that generate more than one-half ton of food waste per week. In response to the policy, University of Massachusetts Amherst has made significant strides toward reducing food waste, becoming the largest independent foodservice program in the nation.[56] The program uses the LeanPath system, which photographs each food item wasted. It identified that roughly 50% of food waste results from portions of produce generally considered inedible or undesirable: peels, pulp, cores, rings, stems, etc. The remainder comes from over-production. These learnings informed changes in purchasing habits to reduce overproduction and inspired the idea to independently sort different types of waste for specific upcycling applications. The implementation of trayless dining led to a 30% reduction in post-consumer waste, and the remaining food that is wasted is now sent either to a donation bank or to a commercial composting facility.

Accumulated food waste

Short-Term (0-5 years) ● ○ ○	Stakeholders
1. Align with efforts already established by others with agendas to mitigate food waste. Reducing food waste not only reduces our demand for phosphorus but also decreases greenhouse gas emissions, water consumption, food security, malnutrition, and more. Specifically, leveraging efforts that will most effectively diminish food waste based on the data that detail where most food waste occurs in the supply chain and prioritizing more impactful solutions will make large strides toward mitigation. Providing support for efforts that are already underway by partnering with other organizations working to reduce food waste may be one of the most effective means of furthering progress toward closing food-waste loops.	Associations, consortiums, companies, and advocacy groups that are actively addressing food waste; all actors across the food supply chain that may be involved in carrying out various activities

Medium-Term (5-15 years) ● ● ○	Stakeholders
2. Modify grading standards and buying specifications for food products to minimize waste. Food waste and loss at the primary production stage is not well accounted for because of a lack of data. But waste due to produce grading standards or buying specifications is preventable. Working with buyers and retailers to continue to grow the market for "unfit" food consumption may cut down on food wasted at the agricultural level.	Start-ups, retailers, or buyers that create markets for food that do not meet traditional standards; consumers willing to buy and consume "unfit" foods

3. Clarify expiration dates to prevent consumer confusion and unnecessary waste. Food manufacturers determine use by, best by, and sell by dates, often based on a metric of product quality rather than safety. This lends to food being wasted without reason. Working with regulators and brand owners to change expiration dates, most importantly for commodities high in phosphorus, may bring clarity to consumers and result in less household food waste that is sent to landfills.	Brand owners and regulators responsible for setting the standards around expiration dates; consumers who decide whether to eat or throw away food based on the expiration dates
4. Collaborate with large institutions to identify ways to mitigate or recover food waste. Large institutions are primary contributors to food waste because they often produce excess food, and consumers don't consume all the food they receive. Finding suitable solutions that motivate institutions and final consumers within the institutions to be part of the solution for food waste recovery could significantly reduce the food waste generated at the consumption level.	Institutions such as schools, universities, hospitals, military bases, and prisons that encourage food waste reduction
5. Improve consumer perception of food waste recovery. Historical attempts at food waste recovery have resulted in scrutiny from consumers (e.g., lean, finely textured beef is added to ground beef to minimize waste, but has been termed "pink slime" and received push-back from consumers).[57] Raising consumer awareness and industry transparency around the processing and safety of upcycled foods will improve adoption and acceptability (see IO: Increase Awareness).	Advocacy groups or other organizations that educate consumers on industries purposes and practices; food manufacturers willing to be transparent about their processing and who ensure the safety of upcycled food
6. Grow the market for upcycled ingredients in business-to-business (B2B) sales. Improve the market for B2B upcycled ingredients and reduce the liability such that the manufacturer upcycling food is not liable for the end product delivered to the consumer.	General counsel and insurance companies that can provide the means to reduce liability; manufacturers that sell by-product or food scraps
7. Develop technologies to improve the feasibility of upcycling food waste. In many cases, upcycling food is cost prohibitive. Technologies customized to the waste product are needed to stabilize the waste so that it can be stored or transported for reuse.	Start-ups or food manufacturers that provide custom solutions for stabilizing and recovering food scraps; buyers, other manufacturers, or retailers of recovered or upcycled foods
8. Optimize and improve the use of co-digestion for mixed food waste. Often food waste is mixed with municipal waste, making upcycling difficult. Anaerobic digestion provides an approach to recovering phosphorus when food waste is mixed with other waste. Advancing ongoing research will optimize the recovery—and speed of recovery—of phosphorus during anaerobic digestion.	Researchers or companies working to optimize anaerobic digestion efficiency for phosphorus recovery; municipalities, institutions, or others that use the technology
Long-Term (15-25 years)	**Stakeholders**
9. Develop policies encouraging both consumer and industrial food composting and discouraging food in landfills. Some cities, such as Seattle, and states, such as California, have already made progress in implementing composting laws to discourage food waste in landfills. Continued policy changes around food waste will reduce phosphorus lost to landfills.	Organizations such as National Resources Defense Council (NRDC) that work with cities to implement such laws; consumers and companies that abide by the laws implemented; composting facilities that provide the infrastructure

Improve Phosphorus Monitoring and National Coordination to Facilitate Better Environmental Management

Enhance Monitoring

The Challenge

Improving water quality delivers health and economic benefits.[58-60] But continued research is required to understand and set acceptable water quality limits.[61,62] Improvements in water quality monitoring are also necessary to identify effective management practices for reducing phosphorus losses. However, monitoring is expensive and time consuming and can produce data with varying levels of precision and quality. In addition, monitoring of riparian or floodplain phosphorus storage (i.e., legacy phosphorus) is minimal. The lack of available data, combined with uncoordinated access and data sharing, complicates the ability to leverage monitoring data to evaluate best practices, enforce existing regulations, and develop new, data-informed regulations.

The Solution

Additional real-time data networks would contribute to improved monitoring, modeling, regulations, and enforce-ability. Monitoring the effectiveness of conservation actions, administering regulations, and developing best practices requires the coordination of several stakeholders including farmers, water quality groups, and government regulatory agencies. Measurement data should be catalogued and stored in an accessible database, where all stakeholders can benefit from its collection. Citizen scientists should be leveraged, and existing, routine measurements that are not publicly reported (e.g., from drinking water providers) should be incorporated.

The Actions

Short-Term (0-5 years) ● ○ ○ | **Medium-Term (5-15 years)** ● ● ○ | **Long-Term (15-25 years)** ● ● ●

1. Promote awareness, consensus, and buy-in for an accessible repository for data that enables phosphorus monitoring
2. Develop and coordinate citizen science initiatives across the United States to extend current phosphorus-monitoring infrastructure
3. Include monitoring of input data from point and nonpoint sources in data repository
4. Develop, test, commercialize, and scale new sensors and models that better fit the varied monitoring needs
5. Develop robust, nationwide, and transparent sensor networks and coordinated programs to monitor discharges of phosphorus in water
6. Develop data-informed best practices, increase enforcement of existing regulations, and develop new, right-sized regulations

Case Study: Dublin, Ireland

In a study examining water quality in the River Liffey in Dublin, Ireland, citizen scientists (such as recreational river users) used field chemistry kits to measure nitrate and phosphate at 19 locations on a monthly basis over 9 months.[63] Results showed that 10% of nitrate samples and 35.6% of phosphate samples indicated low-quality water. Observational notes and photographs from citizen scientists were essential in identifying pollution sources. Land use seemed to be a factor in elevated water pollution, especially in areas of recent housing development, indicating the possibility that urban wastewater discharge was improperly connected to stormwater sewers rather than sanitary sewers.

The River Liffey in Dublin, Ireland

Short-Term (0-5 years) ● ○ ○	Stakeholders
1. Promote awareness, consensus, and buy-in for an accessible repository for data that enables phosphorus monitoring. These data can include both source (e.g., fertilizer application rates and legacy phosphorus) and monitoring data (e.g., phosphorus measured in waterways). Incorporating the current efforts and needs articulated by regulators and NGOs into the design and implementation and leveraging existing repositories such as the Water Quality Portal will lead to successful outcomes.	Government agencies that deploy monitoring activities and manage data; NGOs, companies, or other groups with existing datasets or monitoring efforts underway; municipalities, districts, state environmental and health departments, and crop and animal farm groups that participate in and use monitoring data
2. Develop and coordinate citizen science initiatives across the United States to extend current phosphorus-monitoring infrastructure. Leveraging citizen science can enable the production of more data more frequently and with greater accuracy to inform water quality models, decrease the impact of monitoring on municipal and state budgets, improve monitoring of noncompliance and help alert water and health authorities to the potential development of harmful algal blooms.	Citizen scientists, lay citizens, famers, and waterkeepers collecting or analyzing data; NGOs or other organizations that coordinate citizen science initiatives; government agencies informed by data analysis

Medium-Term (5-15 years) ● ● ○	Stakeholders
3. Include monitoring of input data (including agricultural fertilizers and manures, residential fertilizer inputs, and wastewater) from point and nonpoint sources in data repository. This may include data about phosphorus inputs into the landscape, soil monitoring (soil phosphorus testing) and assessment of legacy phosphorus, data from water quality monitoring, and citizen science data. It may also require the establishment of crop, soil, and landscape monitoring protocols. Furthermore, federal funding requirements may play a key role in incentivizing the continual addition of new data to the repository.	Academics, researchers, state departments, and extension agencies that establish new monitoring protocols; farm groups, fertilizer industry groups, landowners, and others who inform monitoring data; federal agencies that own and operate the data repository and incentivize its continual use
4. Develop, test, commercialize, and scale new sensors and models that better fit the varied monitoring needs. New sensors may be less expensive or have enhanced sensitivities to use directly for point and nonpoint source monitoring and for remote sensing applications.	University, federal research labs, and university intellectual property programs informing new sensor development; technology incubators, existing sensor companies, satellite companies, and drone and aircraft companies that provide and scale new sensors; state and federal discharge regulators that regulate the use of sensors; stormwater and wastewater utilities; crop and animal farm groups that use sensors

Long-Term (15-25 years) ● ● ●	Stakeholders
5. Develop robust, nationwide, and transparent sensor networks and coordinated programs to monitor discharges of phosphorus in water. Sensors could be both ground-based and remote and cover both point and nonpoint sources. Coordination between multiple actors and stakeholder groups is key to the success of creating and operationalizing sensor networks. This coordination might include development of broader modeling and monitoring networks across the United States, not focused solely on areas in which we are aware of issues.	Government agencies that manage the modeling and coordinated monitoring; companies that provide sensors, NGOs, universities, and federal and state regulatory authorities engaging in operationalizing sensor networks
6. Develop data-informed best practices, increase enforcement of existing regulations, and develop new, right-sized regulations. Sensor development, improvements in data collection and modeling, and the development of a robust, open-source repository are important as they inform interventions to phosphorus application practices. This can include developing and disseminating locally tailored best practices guidance that should be widely adopted, using data to both improve enforcement of existing regulations and guide development of more informed, numeric based regulations and best practices, including for nonpoint sources.	State environmental agencies, who are responsible for creating the total maximum daily loads that would determine new regulations; extension offices, NGOs, and government agencies that inform and enforce regulations

Develop and Grow Markets for Proven Solutions for Phosphorus Management

Grow Markets

The Challenge

To reduce our dependence on mined phosphorus, appropriate solutions (e.g., technologies, products, services, regulations) and consumers who are ready to adopt new ways of working are required. Even with these requirements, the return on investment (ROI) for phosphorus management solutions may not be favorable. The lack of financial incentives is compounded by the lack of knowledge and demand for phosphorus sustainability. Today, corporations are striving to incorporate metrics for carbon footprints and water consumption into their labels, but phosphorus—another component of sustainable agriculture—is not yet on their radar. These factors combine to create market barriers that reduce the adoption of phosphorus management solutions.

The Solution

Demand for new solutions that reduce the human dependence of mined phosphorus must be robust and include phosphorus recovery technologies, agricultural management practices, and dietary shifts. Advancements in true cost accounting methods, which calculate the financial, environmental, and health costs associated with a solution's production, delivery, and use, may help build the business case for adoption. An influx of capital tailored to longer ROI timescales, through innovative financing and insurance mechanisms, will help new solutions scale and aid in their adoption.

The Actions

Action	Short-Term (0-5 years)	Medium-Term (5-15 years)	Long-Term (15-25 years)
1. Develop innovative business models that address the unique needs of both phosphorus management solutions and sectors	X		
2. Develop phosphorus-informed methodologies for true cost accounting that encourage shifts in behavior	X		
3. Develop and scale innovative finance tools to deliver patient capital to scale new solutions	X	X	
4. De-risk new technology investments through insurance and financial mechanisms to enable end-user adoption	X	X	
5. Increase the breadth and number of venture capital firms and impact investors supporting agriculture and dietary shifts		X	
6. Incorporate phosphorus metrics into corporate performance and risk reporting		X	
7. Leverage consumer, special interest, and advocacy groups and corporate demand to incentivize reduction, reuse, and reprocessing of phosphorus	X	X	X

Case Study: RePlant Capital

RePlant Capital, an impact investment firm focused on regenerative agriculture and food system solutions, embodies the opportunity for impact that growing markets can have on sustainability in agriculture. The company's mission is to improve farmer profitability and environmental outcomes through financing the transition of farmland to regenerative and organic agriculture.[64] To achieve this mission, RePlant Capital partners with regional and multinational food companies to access U.S. farmers in their supply chain and subsequently develops financing options for the farmers to transition to regenerative and organic agriculture. In so doing, RePlant Capital de-risks investments from multinational food companies to be more sustainable and better for people and the planet.

Birds-eye-view of expansive farmland

Short-Term (0-5 years) ● ○ ○	Stakeholders
1. Develop innovative business models that address the unique needs of both phosphorus management solutions and sectors. Identifying the right business model for a business is both complicated and critical. What's trendy (e.g., technology startups deploying software-as-a-service) may not be the best fit for all situations. Teams trying to scale new solutions to the phosphorus management problem might need to create and test new business models, identify niche beachhead markets, understand how and when to use key partnerships, and identify and leverage co-benefits such as recovery of water, reduction in total fertilizer production, reduction in CO_2 emissions, or similar.	Venture capital firms, industry finance groups, banks, or other entities that provide capital; agricultural and phosphorus recovery startups and companies that are incentivized to adopt technology due to new business models
2. Develop phosphorus-informed methodologies for true cost accounting that encourage shifts in behavior. Efforts toward this action include accounting for the negative externalities associated with environmental and health costs of poor phosphorus management. Identifying and quantifying all the added costs is an important step in making the business case for phosphorus use reduction and pollution mitigation. Incorporating true cost accounting in labeling provides consumers with transparency and should encourage shifts away from phosphorus-intensive products (e.g., dietary shifts away from animal-based products), when coupled with increased public awareness of phosphorus sustainability (see IO: Increase Awareness).	Nonprofits, standard setting organizations, or advocacy groups that provide the data and methods for true cost accounting; food and beverage companies, farmers and producers, livestock operations, consumers, etc., that shift practices and behaviors to mitigate environmental and health implications of phosphorus use

Medium-Term (5-15 years)	Stakeholders
3. Develop and scale innovative finance tools to deliver patient capital to scale new solutions. Long ROIs are a major hurdle to adoption of sustainable solutions, including those that decrease human dependence on phosphorus. Development of innovative finance that incentivizes adoption through first-of-a-kind demonstrations targeted at solving specific frictions within the system will help accelerate impact. Some examples might include catalytic funding from venture capital firms, family foundations, and/or government loans for large capital investments, similar to the Loan Programs Office at the Department of Energy.	Nonprofits, family foundations, venture capital firms, government funding agencies, insurance agencies, bonds, etc., that provide patient capital to encourage adoption of technology with a long ROI
4. De-risk new technology investments through insurance and financial mechanisms to enable end-user adoption. New technology solutions do not necessarily fit into the traditional financial structures and mechanisms used. However, financial support and insurance guarantees are key to protecting the end-user (e.g., farmer). Increasing availability of this support should increase the willingness for adoption, when paired with good stakeholder engagement (see IO: Accelerate Solutions).	Financial and insurance companies to de-risk investments; federal agencies that provide mechanisms to reduce risk
5. Increase the breadth and number of venture capital firms and impact investors supporting agriculture and dietary shifts. Investment in cellular agriculture, fermentation technologies, regenerative agriculture, precision agriculture, and others often aim to improve environmental sustainability at large. These transitions also encourage a shift away from phosphorus dependence. Often, early-stage and hard-tech (non-software) technologies lack the capital required to scale to market, so increasing the number of financing sources can support advancement of more technologies.	USDA/Natural Resources Conservation Service (NRCS) and crop technology retailers, venture capital firms, and impact investors that support shifts in agriculture and dietary habits; agriculture and sustainable food startups that provide solutions for decreasing phosphorus dependence; consumers who create demand for the respective solutions
6. Incorporate phosphorus metrics into corporate performance and risk reporting. Though depletion of phosphorus poses significant environmental risk, it is not currently tracked or reported on within corporate metrics. Corporate reporting (e.g., environmental, social, and governance [ESG]) would raise awareness and motivate shifts in production and product portfolios that reflect mitigating phosphorus use.	Private equity firms focused on green returns, government regulators (especially the U.S. Securities and Exchange Commission), and other organizations tracking ESG performance that encourage corporate reporting; corporations within the food, fertilizer, agricultural, or other industries that provide ESG reporting; consumers and advocacy groups create continued demand for transparency

Long-Term (15-25 years)	Stakeholders
7. Leverage consumer, special interest, and advocacy groups and corporate demand to incentivize reduction, reuse, and reprocessing of phosphorus. Incentives may take the form of consumer demand, subsidies, tax credits, points systems, laws, or otherwise to encourage the use of fertilizer recovered from farm waste. These incentives support the kinds of products and solutions suggested by IOs Reclaim Waste, Recover Valued Products, and Reduce Mining Waste, and must be preceded by greater public awareness of phosphorus management (see IO: Increase Awareness).	Government agencies and tax offices that provide incentive structures encouraging reduction and reuse; consumers advocacy groups that create a demand for products reducing or reusing phosphorus; fertilizer companies, food and beverage companies, and companies providing solutions to reduce and reuse phosphorus

Accelerate Technology Adoption Through Active Stakeholder Engagement

Accelerate Solutions

The Challenge

Although including stakeholders in the development process promotes adoption of new technologies,[65,66] stakeholders are currently not adequately engaged. Realizing and implementing stakeholder engagement in development of technologies for phosphorus management is highly complex. Phosphorus sustainability technologies require specific stakeholders; strategies vary across research stages; U.S. agricultural production is decentralized; farming types require diverse processes; technology adoption in agriculture demands trust; and infrastructure upgrades require broad stakeholder buy-in. These all require changes in mindsets and methods from traditional to use-inspired or participatory research practices.

The Solution

To advance 25-in-25, swifter adoption of technological solutions for phosphorus management is necessary. Stakeholder engagement can help address and overcome non-scientific or non-technological hurdles, such as regulatory issues, social and/or ethical concerns and market barriers. Engaging with food producers, water resource recovery facilities, and mining companies moves the needle toward achieving a truly circular economy. To effectively engage stakeholders, trusted relationships must be built using known strategies such as surveys, ethnographic interviews, field observation, and demonstrations and pilot projects. Bringing stakeholders upstream in the innovation process maximizes inclusivity, which increases buy-in of sustainable management practices, and offers opportunities for early detection of barriers to adoption.

The Actions

Action	Short-Term (0-5 years) ●○○	Medium-Term (5-15 years) ●●○	Long-Term (15-25 years) ●●●
1. Incentivize and prioritize stakeholder engagement as a core component of all phosphorus management research	✓	✓	✓
2. Promote matchmaking across stakeholders to support technology transfer	✓	✓	✓
3. Develop stakeholder-led collaborations and establish pilot projects to drive emerging technologies toward adoption	✓	✓	✓
4. Build and leverage regional innovation ecosystems to understand demand and develop new technologies across diverse industries and stakeholders		✓	✓
5. Enact requirements for stakeholder engagement and environmental justice within all state and federal grants		✓	✓

Case Study: Scottish and Southern Electricity

Another benefit to using stakeholder engagement to accelerate technology adoption is the opportunity to improve equity. As an example of corporate strategy that touches on equity and the value of co-creation, in November 2020, Scottish and Southern Electricity (SSE) became the first company to publish a Just Transition Strategy.[67] The strategy consists of 20 principles to steer SSE's decision-making process and promote more equitable outcomes for those affected by the decrease in high-carbon economic practices, as well as increase the potential for climate action opportunities. SSE's framework is coupled with action; from 2021 to 2022, SSE engaged extensively with stakeholders to develop its Just Transition Strategy. This involved consulting with a diverse range of groups such as policymakers, trade unions, suppliers, oil and gas companies, investors, academics, and industry and skills organizations. Additionally, SSE also actively sought input from its own employees.

Solar farm in Scotland

Long-Term (15-25 years)	Stakeholders
1. Incentivize and prioritize stakeholder engagement as a core component of all phosphorus management research. As a first step, consider policy and funding changes that incentivize prioritizing stakeholder engagement throughout research. In turn, researchers can commit to understanding and implementing stakeholder engagement practices, whereas universities and research organizations can expand access to training and resources.	Government funding agencies and investment firms that require stakeholder engagement; researchers and startups engaging stakeholders; universities and other organizations providing resources and training; end-users (farmers, producers, wastewater treatment plants, food manufactures, government monitoring groups) who inform development and adoption of new technology
2. Promote matchmaking across stakeholders to support technology transfer. Building networks to lay the foundation for future successful partnerships is of equal importance to conducting research. Avenues to do so include engagement with technology transfer or partnership functions within universities, federal labs, or companies. In turn, industry might reach out to researchers and look for opportunities to trial earlier stage technologies, as well as be willing to shape and support their development.	University licensing and patent offices and open innovation groups that inform technology transfer; academics, industry researchers, government laboratories, and end-users who trial new technology solutions; trade associations, organizations, etc., that provide networking opportunities

3. Develop stakeholder-led collaborations and establish pilot projects to drive emerging technologies toward adoption. Pilot projects are necessary to demonstrate the viability of technologies and encourage adoption. Successful technology pilots with farmers and producers require the engagement of trusted stakeholders. More importantly, farmers and producers should not merely be included; they should be given decision-making power as a central participant in the development process.[68] Funding pilot studies can be a challenge; researchers might consider opportunities for cost-sharing or similar agreements with stakeholder partners.	Federal and government laboratories, academic researchers, industry researchers, and startups that develop and collaborate on emerging technology; government funding agencies that fund pilot studies; end-users, including farmers and producers, food manufactures, government monitoring groups, etc., who engage in the development process
4. Build and leverage regional innovation ecosystems to understand demand for and develop new technologies across diverse industries and stakeholders. Through active engagement with diverse stakeholders all along the phosphorus flow diagram, researchers can better understand technology needs, gaps, and barriers to adoption. These discussions can help industry stakeholders and other practitioners learn more about the prospects for developing new technologies tailored to their needs and pain points. Engaging with a wide variety of stakeholders "upstream" in the innovation pipeline will help researchers anticipate and respond to potential issues with adoption and implementation.[69] Attention should be paid to stakeholders who may not have been engaged through other means, to ensure engagement processes are inclusive.	National and government laboratories, government extension programs (e.g., National Institutes of Standards and Technology's Manufacturing Extension Partnership), extension agencies, start-up incubators, etc., that mobilize innovations; fertilizer industry, mining industry, wastewater treatment facilities, food processors, farmers and producers, and other potential end-users who inform the needs, gaps, and barriers to adoption
5. Enact requirements for stakeholder engagement and environmental justice within all state and federal grants. Requiring research grants to dedicate a portion of the research to working with the individuals intended to own and use the technology under development would target mitigating unintended environmental justice concerns and consequences resulting from newly developed technologies.	Government funding agencies that set new research requirements; academic researchers, start-ups, and other entities receiving government grants such as industry research and development groups across fertilizer, mining, food manufacturing, wastewater treatment facilities, etc. that are required to engage end-users; end-users who guide the development of new technology

Elevate Phosphorus Sustainability in the Public Consciousness

Increase Awareness

The Challenge

Sustained change to the status-quo is often a result of public demand and outcry, which motivates companies and institutions to act and legislators to pass new laws and regulations. This approach to reach phosphorus sustainability calls for a prior step—the public must first be aware that it is an issue worth paying attention. Awareness and understanding cannot be achieved overnight. Rather, it requires a longer time horizon to truly effect transformation in public mindsets and behaviors. Individuals, groups, and communities across the full system must be actively and intentionally engaged—to not only ensure inclusion of diverse perspectives, but to also build, one-by-one, a collective movement toward change.

The Solution

Successfully raising awareness of phosphorus sustainability in the public can promote behavior change and advocacy. Behavioral changes, such as practicing a more plant-focused diet or composting, would directly decrease demand for phosphorus and losses of phosphorus to landfills or locked in soils. Consumers may also develop a recognition of the value of, or even interest in, purchasing products that are more sustainable and reuse or reprocess phosphorus. Shifts in behavior and mindsets will likely extend to advocacy for new policies, regulations, and company action, pushing organizations and institutions and the government to act more swiftly and urgently.

The Actions

Short-Term (0-5 years) ● ○ ○ **Medium-Term (5-15 years)** ● ● ○ **Long-Term (15-25 years)** ● ● ●

1. Develop and implement a communication strategy for phosphorus sustainability
2. Develop *phosphorus footprint* tools and metrics that identify actions the general public can take
3. Educate teachers on phosphorus sustainability
4. Leverage existing sustainability campaigns to align phosphorus sustainability with larger narratives
5. Incorporate phosphorus education in K–12 curriculums
6. Incorporate *phosphorus footprint* into existing standards and labels
7. Educate underrecognized, affected industries on the importance of phosphorus to enable lobbying and policy change
8. Establish national and corporate goals that focus on phosphorus reuse and reduction

Case Study: Florida's Phosphate Management Program

Thirty years ago, phosphorus was identified by water management districts, local farmers, researchers, and citizens in Florida as one of the nutrients causing eutrophication in water. As a response, the diverse stakeholders across the ecosystem came together with the State of Florida to conduct research into a Phosphate Management Program. For over three decades, the program has worked to make industrial wastewater permitting, compliance, and enforcement activities for the phosphate industry publicly available. The program regulates the design, construction, operation, and maintenance of phosphogypsum stack systems, the wastewater systems associated with the chemical plants that process phosphate ore into fertilizer products.[70]

Water treatment ponds in Florida

Short-Term (0-5 years) ● ○ ○	Stakeholders
1. Develop and implement a communication strategy for phosphorus sustainability. Plans within the strategy may include outreach through channels such as podcasts, production of visual media, and creation of a day dedicated to phosphorus sustainability, among others.	Marketing and communication experts who develop a strategy; organizations, associations, podcast, or other media that serve as communication channels; industries impacted and included in communication such as the food, fertilizer, and mining industries
2. Develop *phosphorus footprint* tools and metrics that identify actions the general public can take. A *phosphorus footprint* calculator may allow the public to more concretely see the phosphorus impact of their actions and choices in their day-to-day living, making behavioral change more actionable and personalized.	Academic and industry researchers who develop metrics for evaluating *phosphorus footprints*; nonprofits, advocacy groups, and consumer product goods companies that socialize and use *phosphorus footprint* tools; citizens whose purchasing and habits are influenced
3. Educate teachers on phosphorus sustainability. Informal methods to reach educators include developing teacher workshops with phosphorus sustainability in mind, adding phosphorus sustainability information in publications for teachers, holding sustainability competitions geared toward primary, secondary, higher, and vocational education, and building programs that provide phosphorus-specific research to educators.	Educational researchers involved in educating on phosphorus sustainability; trade organizations, conferences, etc., creating a channel for communication; teachers informed on phosphorus sustainability

Medium-Term (5-15 years)	Stakeholders
4. Leverage existing sustainability campaigns to align phosphorus sustainability to larger narratives. This action first requires an investigation of existing sustainability movements that might include phosphorus and where phosphorus is not currently being discussed. Some campaigns include environmental sustainability at large, climate change, nutrient management, food and nutrition security, food waste, circular economy, etc. Subsequently, it would call for collaboration across many organizations to develop unified and consistent messaging around impacts, actions, and solutions.	Advocacy groups, trade organizations, associations, industry groups, media outlets, and corporations raising awareness and acting on topics that phosphorus is inherently a part of
5. Incorporate phosphorus education in K-12 school curriculums. Efforts toward this action may include working with education association groups to recognize the importance and prioritize the inclusion of phosphorus education and to develop and formalize K–12 education modules on environmental science.	State curriculum boards, departments of education, and association groups creating the curriculums; principals, administrators, and teachers implementing the curriculum
6. Incorporate *phosphorus footprint* into existing standards and labels. Similar to *carbon footprint*, labels used by companies, such as those in the food, beverage, and restaurant industry, could include information regarding *phosphorus footprint* to inform consumers.	Food and beverage companies or other consumer product goods companies that market the products with a *phosphorus footprint* label; regulatory agencies and certification organizations that regulate product labels
7. Educate underrecognized, affected industries on the importance of phosphorus to enable lobbying and policy change. Informing industries through the use of modeling and data on the health and financial implications of phosphorus management may galvanize action to call local and state legislation to respond and increase awareness of opportunities to lessen negative externalities, such as pollution.	Advocacy groups, nonprofits, lobbyists, and academic researchers who educate on the implications of poor phosphorus management; nontraditional industries (real estate, golfing, tourism, outdoor recreation, fishing) impacted by a lack of phosphorus management; local and national government regulators who enact policy change
Long-Term (15-25 years)	**Stakeholders**
8. Establish national and corporate goals that focus on phosphorus reuse and reduction. A national agenda would affirm the importance of phosphorus sustainability and motivate corporations and individuals to act. Examples of goals for institutions include prioritizing research and development and engineering solutions. Campaigns to encourage behavior change offer opportunities to reach the larger public.	Government legislators and funding agencies incentivizing phosphorus reuse and reduction; academic and industry researchers developing technologies to reduce and reuse phosphorus; food and beverage companies, farmers, producers, and members of the general public who might change their practices and behaviors

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Appendix

Key Action Recommendations Organized by Stakeholders

Holistic evaluation of actions across each Impact Opportunity identified key actions that each stakeholder group should consider, as they determine their role in improving phosphorus sustainability. The actions listed for each stakeholder group are not exhaustive of all the activities the respective group should carry out, but rather, outline the necessary actions for advancing the 25-in-25 vision. Within the table, each action highlighted is identified by the action's number associated with its respective Impact Opportunity.

Advocacy

Impact Opportunity	Action
Reduce Mining Waste by Reprocessing and Repurposing It for New Phosphorus-Based Products	**2. Educate and collaborate with environmental interest groups and regulators around the benefits of reusing phosphate mining waste materials.** Leveraging objective data around the health risk for different potential reuse cases may assist environmental interest groups in better understanding the potential value of reuse. That buy-in has the potential to permeate to other civil society groups.
Improve Phosphorus Monitoring and National Coordination to Facilitate Better Environmental Management	**1. Promote awareness, consensus, and buy-in for an accessible repository for data that enables phosphorus monitoring.** These data can include both source (e.g., fertilizer application rates and legacy phosphorus) and monitoring data (e.g., phosphorus measured in waterways). Incorporating the current efforts and needs articulated by regulators and NGOs into the design and implementation and leveraging existing repositories such as the Water Quality Portal will lead to successful outcomes.
Elevate Phosphorus Sustainability in the Public Consciousness	**7. Educate underrecognized, affected industries on the importance of phosphorus to enable lobbying and policy change.** Informing industries through the use of modeling and data on the health and financial implications of phosphorus management may galvanize action to call local and state legislation to respond and increase awareness of opportunities to lessen negative externalities, such as pollution.

Education, academia, and nonprofits

Impact Opportunity	Action
Improve Phosphorus Use Efficiency in Agriculture Across New, Recycled, and Existing (Legacy) Phosphorus	**8. Restructure current federal programs and policies to improve nutrient use efficiency dependence.** This action may include developing a task force to first understand the incentives set up by policies such as the Farm Bill and programs such as commodity support programs or crop insurance. Next, advocate for change in programs and policies that align incentivizes with use efficiency and minimize waste.
Process Animal and Farm Waste More Economically for Reuse as Fertilizers	**2. Require that the limiting nutrient, whether nitrogen or phosphorus (usually phosphorus), stands as the regulated nutrient for application of manure products on fields at the national level.** This action includes the development of policies that discourage excessive use of phosphorus due to farmers applying fertilizer at nitrogen rates, which results in the overapplication of phosphorus. Implementation of new regulations must consider the time necessary for farmers or producers to change operations and the regions where legacy phosphorus is abundant in the soils. Additionally, efforts toward reducing nitrogen volatilization may further mitigate the overapplication of nitrogen and phosphorus. Regulators are not likely to change policies if academics continue suggesting the use of the phosphorus risk index. This index is currently not effective because of its broad interpretation. When academia provides solutions in the form of manure conversion to enable transport of phosphorus to the regions where it is needed, building further revenue streams for the producers, the land-grant universities system and the extension services and academics involved must communicate to regulators the need for changes in such policies.
Produce Valued Phosphorus-Based Products from Waste Recovery Processes	**3. Improve the performance of phosphorus and phosphorus+ recovery systems.** Improving the performance of phosphorus will ultimately drive down the costs of recovery, increasing overall adoption. Cost improvement can also be achieved through co-product recovery (e.g., water, nitrogen, carbon), increased equipment efficiency, energy use efficiency, and improvements in the chemistry, biology, and catalysts used in the phosphorus recovery process. It may also include improvements in the ability to recover from dilute waste streams.
Improve Phosphorus Monitoring and National Coordination to Facilitate Better Environmental Management	**2. Develop and coordinate citizen science initiatives across the United States to extend current phosphorus-monitoring infrastructure.** Leveraging citizen science can enable the production of more data, more frequently and with greater accuracy to inform water quality models, decrease the impact of monitoring on municipal and state budgets, improve monitoring of noncompliance and help alert water and health authorities to the potential development of harmful algal blooms.

Farmers and producers

Impact Opportunity	Action
Improve Phosphorus Use Efficiency in Agriculture Across New, Recycled, and Existing (Legacy) Phosphorus	**1. Leverage partnerships with trusted and established companies to improve technology adoption.** Some technologies are being developed to help monitor phosphorus and stimulate phosphorus uptake in plants, yet they are not widely distributed. To increase adoption rates, encourage companies developing new technologies to partner with companies that producers and farmers consistently engage with to buy seeds, equipment, etc., for their farms. This partnership will raise awareness and accessibility among the farmers.
	2. Reduce consumption of mined phosphorus per unit of crop by improving circularity of phosphorus flows in agricultural systems. Many people avoid using manure-based fertilizers due to their adverse perceptions and implications, which may continue to detract from their adoption in the future. Making efforts to change the mindset of non manure users and guiding manure-based fertilizer recommendations through articles, websites, trade journals, public events, and more will help create a market for the widespread adoption of manure-based fertilizers.
	4. Develop new sensing technology to quantify phosphorus availability in the soil to inform precision management. Changes in environmental conditions over time alter phosphorus availability. Sensing orthophosphorus content in real time will enable producers to optimize application rates in accordance with plant needs to mitigate excess consumption, as well as runoff and erosion management to mitigate phosphorus pollution in nearby waterbodies.

Finance

Impact Opportunity	Action
Develop and Grow Markets for Proven Solutions for Phosphorus Management	**3. Develop and scale innovative finance tools to deliver patient capital to scale new solutions.** Long ROIs are a major hurdle to adoption of sustainable solutions, including those that decrease human dependence on phosphorus. Development of innovative finance that incentivizes adoption through first-of-a-kind demonstrations targeted at solving specific frictions within the system will help accelerate impact. Some examples might include catalytic funding from venture capital firms, family foundations, and government loans for large capital investments, similar to the Loan Programs Office at the Department of Energy.
	4. De-risk new technology investments through insurance and financial mechanisms to enable end-user adoption. New technology solutions do not necessarily fit into the traditional financial structures and mechanisms used. However, financial support and insurance guarantees are key to protecting the end-user (e.g., farmer). Increasing availability of this support should increase the willingness for adoption, when paired with good stakeholder engagement (see IO: Accelerate Solutions).
	5. Increase the breadth and number of venture capital firms and impact investors supporting agriculture and dietary shifts. Investment in cellular agriculture, fermentation technologies, regenerative agriculture, precision agriculture, and others often aim to improve environmental sustainability at large. These transitions also encourage a shift away from phosphorus dependence. Often, early-stage and hard-tech (non-software) technologies lack the capital required to scale to market, so increasing the number of financing sources can support advancement of more technologies.
	6. Incorporate phosphorus metrics into corporate performance and risk reporting. Though depletion of phosphorus poses significant environmental risk, it is not currently tracked or reported on within corporate metrics. Corporate reporting (e.g., environmental, social, and governance [ESG]) would raise awareness and motivate shifts in production and product portfolios that reflect mitigating phosphorus use.

Food, fertilizer, and agriculture industry

Impact Opportunity	Action
Improve Phosphorus Use Efficiency in Agriculture Across New, Recycled, and Existing (Legacy) Phosphorus	**5. Develop technology for enhancing phosphorus availability in soil and organic material.** Developing technology, such as enhanced efficiency fertilizers, that modify the soil based on its chemistry to increase the availability of phosphorus can enable greater dependence on legacy phosphorus and reduce the need for new phosphorus.
Process Animal and Farm Waste More Economically for Reuse as Fertilizers	**1. Improve the economics of phosphorus recovery technologies from farm waste.** Reducing the cost of harvesting, treating, and processing manure to recover phosphorus will develop a consumer demand for recycled phosphorus fertilizers. Key technical areas for improvement involve recovering phosphorus in fertilizer forms that can serve as drop-in replacements for synthetic fertilizers. Stakeholders developing the technology need to be on the ground with end-users to understand and work with, rather than against, their business models.
Close Food Waste Loops in the Food Supply Chain to Minimize Phosphorus Loss	**3. Clarify expiration dates to prevent consumer confusion and unnecessary waste.** Food manufacturers determine use by, best by, and sell by dates, often based on a metric of product quality rather than safety. This lends to food being wasted without reason. Working with regulators and brand owners to change expiration dates, most importantly for commodities high in phosphorus, may bring clarity to consumers and result in less household food waste that is sent to landfills.
	7. Develop technologies to improve the feasibility of upcycling food waste. In many cases, upcycling food is cost prohibitive. Technologies customized to the waste product are needed to stabilize the waste so that it can be stored or transported for reuse.

Government, regulators, and standards

Impact Opportunity	Action
Process Animal and Farm Waste More Economically for Reuse as Fertilizers	**3. Include the cost of the negative externalities (e.g., economic, health, and water quality impacts) associated with production of food products into the price that consumers pay.** Introduce a commodity checkoff program for food products (especially phosphorus-intensive animal products) to support research and cover the costs associated with phosphorus pollution and manure conversion.
Improve Phosphorus Monitoring and National Coordination to Facilitate Better Environmental Management	**3. Include monitoring of input data (including agricultural fertilizers and manures, residential fertilizer inputs and wastewater) from point and nonpoint sources in data repository.** This may include data about phosphorus inputs into the landscape, soil monitoring (soil phosphorus testing) and assessment of legacy phosphorus, data from water quality monitoring, and citizen science data. It may also require the establishment of crop, soil, and landscape monitoring protocols. Furthermore, federal funding requirements may play a key role in incentivizing the continual addition of new data to the repository.
Accelerate Technology Adoption Through Active Stakeholder Engagement	**1. Incentivize and prioritize stakeholder engagement as a core component of all phosphorus management research.** As a first step, consider policy and funding changes that incentivize prioritizing stakeholder engagement throughout research. In turn, researchers can commit to understanding and implementing stakeholder engagement practices, whereas universities and research organizations can expand access to training and resources.
	3. Develop stakeholder-led collaborations and establish pilot projects to drive emerging technologies toward adoption. Pilot projects are necessary to demonstrate the viability of technologies and encourage adoption. Successful technology pilots with farmers and producers require the engagement of trusted stakeholders. More importantly, farmers and producers should not merely be included; they should be given decision-making power as a central participant in the development process.[71] Funding pilot studies can be a challenge; researchers might consider opportunities for cost-sharing or similar agreements with stakeholder partners.

Infrastructure and wastewater treatment industry

Impact Opportunity	Action
Produce Valued Phosphorus-Based Products from Waste Recovery Processes	**4. Develop and scale next-generation waste recovery processes, including for other forms of phosphate used in non-agricultural applications.** Scaling technologies may also include evaluating the financial viability of recovering phosphorus from streams other than municipal wastewater treatment plants. Phosphorus recovery from mining operations, industrial wastewater (especially slaughterhouses), livestock operations, and meat and bonemeal processing should all be explored.
	6. Incentivize developing more facilities that remove and recover phosphate from wastewater through regulation. Regulatory levers are key to wide-scale market adoption. These levers can include changes to the amount of phosphorus legally allowed to be discharged as waste, which can alter the cost-benefit equation of removing phosphate, and the implementation of financial credits (e.g., tax breaks) that incentivize removal and recovery.
Close Food Waste Loops in the Food Supply Chain to Minimize Phosphorus Loss	**9. Develop policies encouraging both consumer and industrial food composting and discouraging food in landfills.** Municipalities, such as Seattle, and states, such as California, have already made progress in implementing composting laws to discourage food waste in landfills. Continued policy changes around food waste will reduce phosphorus loss in landfills.
Improve Phosphorus Monitoring and National Coordination to Facilitate Better Environmental Management	**5. Develop robust, nationwide, and transparent sensor networks and coordinated programs to monitor discharges of phosphorus in water.** Sensors could be both ground-based and remote and cover both point and nonpoint sources. Coordination between multiple actors and stakeholder groups is key to the success of creating and operationalizing sensor networks. This coordination might include development of broader modeling and monitoring networks across the United States, not focused solely on areas in which we are aware of issues.

Mining and other industries

Impact Opportunity	Action
Reduce Mining Waste by Reprocessing and Repurposing It for New Phosphorus-Based Products	**1. Assess reuse avenues of phosphate mining wastes by evaluating safety risks and potential product value across relevant sectors.** Evaluating the potential health risks is crucial for adoption, and there is a lack of understanding about radiological, physical, and chemical risks. Understanding tradeoffs also requires assessing the risks of not acting. Furthermore, analyzing costs through economic and LCAs can provide insights into market requirements for applications such as construction materials or batteries.
	3. Leverage pilots to develop and scale alternative phosphorus recovery, extraction, and processing methods for mining wastes. Alternative phosphorus recovery methods might include improved wet acid processes to generate phosphoric acid from recovered phosphorus products, processes to reduce low-grade phosphorus into elemental phosphorus, and purifying or recovering phosphorus from phosphogypsum. The project must include financial feasibility studies informed by pilot scale demonstrations and would rely on government funding support to mobilize
Close Food Waste Loops in the Food Supply Chain to Minimize Phosphorus Loss	**4. Collaborate with large institutions to identify ways to mitigate or recover food waste.** Large institutions are primary contributors to food waste because they often produce excess food, and consumers don't consume all the food they receive. Finding suitable solutions that motivate institutions and final consumers within the institutions to be part of the solution for food waste recovery could significantly reduce the food waste generated at the consumption level.

Public and media

Impact Opportunity	Action
Produce Valued Phosphorus-Based Products from Waste Recovery Processes	**1. Increase awareness of the phosphate challenge among phosphorus users and the general public to drive demand for recovered phosphorus products.** Raising awareness among the general public can help drive market demand for recovered phosphorus products and accelerate technology deployment (see IO: Increase Awareness).
	5. Promote a shift in mindsets such that wastewater facilities are thought of as resource recovery facilities. In the past, wastewater facilities were predominately thought of as treatment (mitigation) facilities. Mindsets are increasingly shifting to a focus on resource recovery, which is key to wide-scale phosphorus recovery and is likely driven, in part, by the availability and scale of new technologies.
Close Food Waste Loops in the Food Supply Chain to Minimize Phosphorus Loss	**5. Improve consumer perception of food waste recovery.** Historical attempts at food waste recovery have resulted in scrutiny from consumers (e.g., lean, finely textured beef is added to ground beef to minimize waste, but has been termed "pink slime" and received push-back from consumers).[72] Raising consumer awareness and industry transparency around the processing and safety of upcycled foods will improve adoption and acceptability (see IO: Increase Awareness).
Elevate Phosphorus Sustainability in the Public Consciousness	**4. Leverage existing sustainability campaigns to align phosphorus sustainability to larger narratives.** This action first requires an investigation of existing sustainability movements that might include phosphorus and where phosphorus is not currently being discussed. Some campaigns include environmental sustainability at large, climate change, nutrient management, food and nutrition security, food waste, circular economy, etc. Subsequently, it would call for collaboration across many organizations to develop unified and consistent messaging around impacts, actions, and solutions.

Appendix

Aggregated Impact Opportunities From Other Sources

Outside of the key Impact Opportunities listed within this roadmap, there exists a wealth of unique and valuable opportunities for achieving phosphorus sustainability. The Impact Opportunities listed below represent an aggregated, but not exhaustive, list drawn from other relevant roadmaps and publications.

Phosphorus Sustainability

Roadmap Name (Year)	Impact Opportunity
Our Phosphorus Future (2022)[73]	Implement integrated approaches for freshwater and coastal ecosystem restoration and protection at catchment, national, and transboundary scales
	Reduce the amount of phosphorus lost as food waste in food processing, retail, and domestic consumption
	Optimize animal diets and the use of supplements to reduce phosphorus excretion
	Improve global reporting and assessment of phosphorus emissions and their impact on freshwater and coastal ecosystems
	Optimize phosphorus inputs for agricultural soils and maximize crop uptake to minimize losses
	Ensure sufficient access to affordable phosphorus fertilizers (mineral, organic, and recycled) for all farmers
	Increase the appropriate application of manures, other phosphorus-rich residues, and recycled fertilizers to soils to complement appropriate mineral fertilizer use
	Increase the use of recycled phosphorus in fertilizer and other chemical industries as alternatives or supplements to phosphate rock
	Implement national to global strategies to increase recovery and recycling of phosphorus from solid and liquid residue streams
	Promote a global shift to healthy and nutritious diets with low phosphorus footprints

Phosphorus Sustainability

Roadmap Name (Year)	Impact Opportunity
RePhoKUS (2022)[74]	Provide incentives to encourage investment in technology, lower barriers to entry, and develop markets for a viable organic phosphorus sector that integrates other aspects of the circular economy (nitrogen, carbon) to reduce the burden of action on farmers
	Recognize phosphorus as a scarce resource and map existing policies to ensure coherence with promotion of a UK circular economy, consistently planning across regions/scales and alignment with public visioning of the benefits of phosphorus reuse
	Establish a UK nutrient platform and catchments-as-living-labs concepts linked to information dashboards to drive data sharing among stakeholders, public engagement, and cross-scale accountability of phosphorus management (imports, exports, recycling)
	Engage a broader range of stakeholders in setting direction and progress on achievement of catchment phosphorus targets that allow for local diversity in circular economy development pathways and demonstrate outcomes for public health and wellbeing (environment, society, and economy)
	Augment tailored nutrient management advice to the agricultural sector on effective use of recycled phosphorus sources (animal manures, food waste, biosolids) and soil legacy phosphorus in UK farming systems
	Develop, promote, and apply innovative, scalable, and cost-effective technologies for recovery of phosphorus streams, redistribution (especially animal manures) and reuse as viable renewable fertilizers
Global Actions for a Sustainable Phosphorus Future (2021)[75]	Intergovernmental coordination efforts that support governments, existing conventions, and intergovernmental frameworks
	Development of disaster response plans in regions where phosphorus pollution and management are contentious
	Develop mechanisms to ensure regulations exist and are adopted across the world to regulate and monitor food waste and set limits for harmful chemicals in food waste
	Governmental support of phosphorus-sustainable food systems through setting targets for organic waste recycling and maintenance of food waste
	Optimization of phosphorus consumption in animal growth stage

Phosphorus Sustainability

Roadmap Name (Year)	Impact Opportunity
Global Actions for a Sustainable Phosphorus Future (2021)	Optimization of phosphorus uptake by supplementing livestock diet with phytase enzymes
	Reduce consumption of phosphorus intensive agricultural products with large phosphorus footprints
	Increase public awareness by food labels and public education
	Legacy phosphorus management, testing, and optimization
	Recover phosphorus via effective recycling methods
	Equitable trade of rock phosphate and mineral phosphorus fertilizers toward phosphorus independence (reuse rather than purchased and imported phosphorus)
	Region-sensitive equitable access to affordable phosphorus to stabilize phosphorus stores
	Source-to-sea management of phosphorus loss
	Regulatory support toward a circular phosphorus economy
UNEP Nature Action (2021)[76]	Develop economic and regulatory policies that lower animal product consumption and waste production
	Minimize food waste to reduce phosphorus fertilizer demand and save money
	Raise awareness, transparency, and political equipment to monitor and assess and act on phosphorus security issues
	Optimize livestock and crop yields without additional phosphorus input through better agricultural practices
	Reduce consumption of phosphorus-rich agricultural products (meat, dairy) and promote wider adoption of healthy diets to reduce demand for mineral phosphorus fertilizers

Phosphorus Sustainability

Roadmap Name (Year)	Impact Opportunity
Towards Phosphorus Sustainability in North America: A Model for Transformational Change (2017)[77]	Research leading to management of soil as an ecosystem and effective manipulation of soil microorganisms and their role in nutrient efficient agriculture
	Evidence-based policy making that enables effective governance of phosphorus, eases its movement through the economy, and provides policy coherence in food, water, and energy sectors
	A pipeline approach to innovation that incubates research and development efforts in phosphorus recycling and efficiency with demand for appropriate and proven technology
	Development of economic instruments that integrate metrics, incentives, and market-based approaches to encourage sustainable phosphorus use that internalizes impacts along the supply chain
	Creation of networking opportunities among phosphorus sustainability actors that encourage communication, trust, and shared understanding toward development and implementation of mutually beneficial solutions
	Adoption of research approaches that investigate closed-loop phosphorus systems by integrating phosphorus stocks and flows across sectors, geographical scales, and social systems and that are sensitive to local control
	Better understanding of the motivations of farmers and other key actors in phosphorus systems and the capacity for generational change of societal attitudes for phosphorus use through co-learning techniques to inform behavior change

Corporate Sustainability Report

Roadmap Name (Year)	Impact Opportunity
OCP Sustainability Integrated Report (2021)[78]	Encourage innovation across OCP by increasing research and development internal budget to support development of new formulations, partnerships, education, and start-up initiatives
	Improve soil fertility to reduce waste in farming
	Preserve phosphate reserves by developing new recovery methods, recycling, and conducting feasibility studies

Nutrient Management

Roadmap Name (Year)	Impact Opportunity
WRF Holistic Approach to Improved Nutrient Management (2022)[79]	Knowledge sharing and goal-oriented reduction strategies
	Sustained funding opportunities for community-wide efforts
	Green infrastructure development, along with a methodological collaboration involving regulatory, environment and community stakeholders
	Integrated watershed restoration approaches
	Adoption of forestry nutrient management best practices
	Leadership among diverse watershed stakeholders
	Watershed-scale water quality trading standards across states, tribes, and stakeholders
	Nonpoint source regulatory frameworks
	Incentivize nutrient management
	Implement widespread adoption of agricultural best practices and treatment technologies to manage effluent and water reuse
	Attainable processes that support compliance with nutrient management
	Phosphorus removal treatment innovations
	Prioritize funding for nutrient management and develop guidance to equitably address and support watershed nutrient management
	Polices around optimized watershed management efforts
	Research toxins associated with algal blooms and explore methods for modeling outcomes by employing big data

Nutrient Management

Roadmap Name (Year)	Impact Opportunity
State of the Blue Print – Chesapeake Bay (2022)[80]	Financial support for long-term progress that supports farmers, municipalities, and communities
	Targeted investments that support community involvement, increased accountability, and innovative approaches that can address the challenges imposed by climate change
	Comprehensive pollution reduction targets and streamlined practices that are specific to a state or region
	Upgrades of municipality wastewater treatment equipment plants
	Restoration on the Chesapeake Bay to address agricultural pollution and storm water pollution from urban and suburban areas
	Equitable distribution and implementation of pollution reduction strategies
Hypoxia Task Force (2020)[81]	Continue to develop easy-to-use, field-scale conservation assessment tools that incorporate estimates of nutrient reduction benefits
	Develop a fertilizer efficiency metric that quantifies nutrient reduction to the environment in terms of water quality related to the 4Rs (reduce, reuse, recycle, and recover)
	Impact of legacy nutrients (internal loading) on water quality
	Improve understanding of underlying processes causing a lag between Best Management Practices (BMP) implementation and change in water quality in streams; incorporate lag response into regional and basin-scale models
	Enhance estimates of levels of conservation intensity required to see quantifiable change in water quality
	Edge-of-field to stream nutrient transport and relationship to overall water quality trends (at local and regional scales)

Nutrient Management

Roadmap Name (Year)	Impact Opportunity
Lake Erie Binational Nutrient Management Strategy: Protecting Lake Erie by Managing Phosphorus (2011)[82]	Promote awareness and understanding about the linkages between individual and communal actions and nutrient issues in Lake Erie to develop a strong sense of responsibility and motivation from everyone to participate in the reduction of phosphorus loadings
	Monitor the status of total phosphorus and soluble reactive phosphorus in open waters, near shore, and tributaries to identify trends and measure progress toward meeting nutrient targets
	Measure the progress of implementation efforts to ensure we are headed in a sustainable direction
	Monitor how the ecosystem responds to natural lake cycles, invasive species, and the implementation of management programs and beneficial (best) management practices
	Develop new and improve existing models to better predict the effects of stressors and alternative nutrient mitigation actions
	Continue to research and develop new technologies and best management practices for reducing phosphorus losses from land, reservoirs, rivers, and lakes
	Identify and focus efforts in priority watersheds where targets are being exceeded and on dominant sources of phosphorus in these watersheds
	Implement specific actions to reduce phosphorus loading in priority watersheds and from existing dominant sources
	Put in place appropriate policies, controls, and practices to mitigate the form and timing of dominant phosphorus sources across the Lake Erie Basin
	Conduct research to improve our understanding of how human activities change over time and how they impact nutrient conditions in Lake Erie to develop effective phosphorus management options
	Conduct research to improve our understanding of how nutrients affect Lake Erie's water quality and ecosystem processes

Net-Zero and Food Sustainability

Roadmap Name (Year)	Impact Opportunity
Roadmap for Achieving Net-Zero Emissions in Global Food Systems by 2050 (2022)[83]	Global coordination and engagement of food systems to align climate commitments (governance, capacity, finance, research, planned emission reductions, technical assistance)
	Improve production practices with existing technologies with a focus on livestock and rice value chain
	Reducing land use for livestock and rice, wheat, etc., farming and combat deforestation
	Develop institutional assessment and monitoring frameworks to enable growth of climate partnership funds
	Reduce consumption of livestock-based protein
	Develop renewable energy and energy-efficient funding vehicles that provide traditional access to loans and capital directly related to positive climate outcomes
	Agroforestry technologies to improve carbon sequestration
	Develop new technologies that are affordable and produce negative emissions

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