PHOSPHORUS FUTURE
8:45 - 9:30 AM

JACOB JONES

Director

STEPS

#PWEEK22

PHOSPHORUS FUTURE

Jacob L. Jones

Kobe Steel Distinguished Professor of Materials Science and Engineering, NC State University

Director, Science and Technologies for Phosphorus Sustainability (STEPS) Center

Phosphorus Forum and P Week, Nov. 2, 2022

STEPS

Science and Technologies for Phosphorus Sustainability

This presentation is based in part upon work supported by the National Science Foundation under Grant No. CBET-2019435. Any opinions, findings and conclusions or recommendations expressed in this website are those of the author(s) and do not necessarily reflect the views of the National Science Foundation (NSF).

OUTLINE

PART ONE
Welcome from STEPS

PART TWO
The Wicked Problem of Phosphorus Sustainability

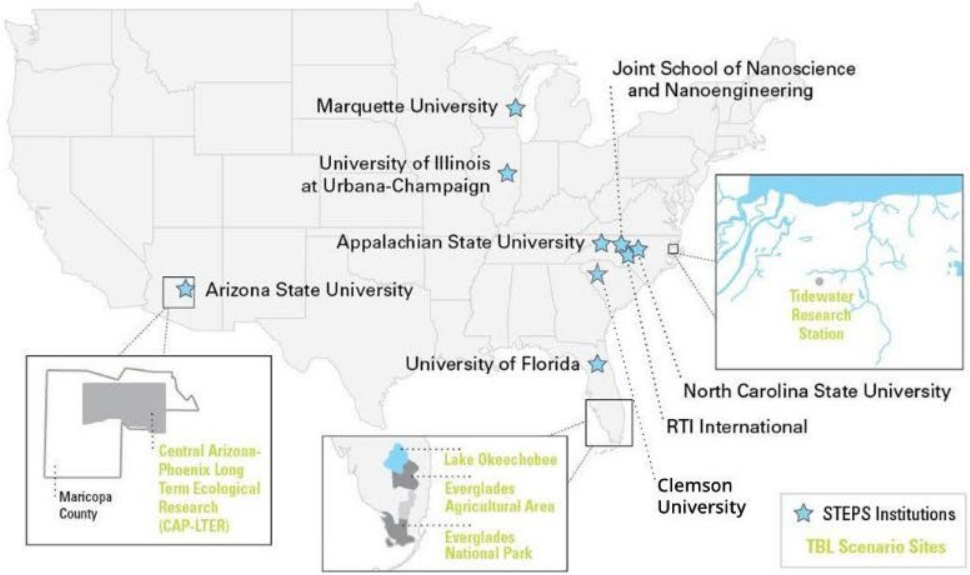
PART THREE
STEPS Convergence Research Center

PART FOUR
Roadmapping Process

01 Welcome from STEPS

WELCOME FROM STEPS!

SCIENCE AND TECHNOLOGIES FOR PHOSPHORUS SUSTAINABILITY (STEPS) CENTER



NORTH CAROLINA STATE UNIVERSITY

ARIZONA STATE UNIVERSITY

UNIVERSITY OF FLORIDA

RTI INTERNATIONAL

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

APPALACHIAN STATE UNIVERSITY

MARQUETTE UNIVERSITY

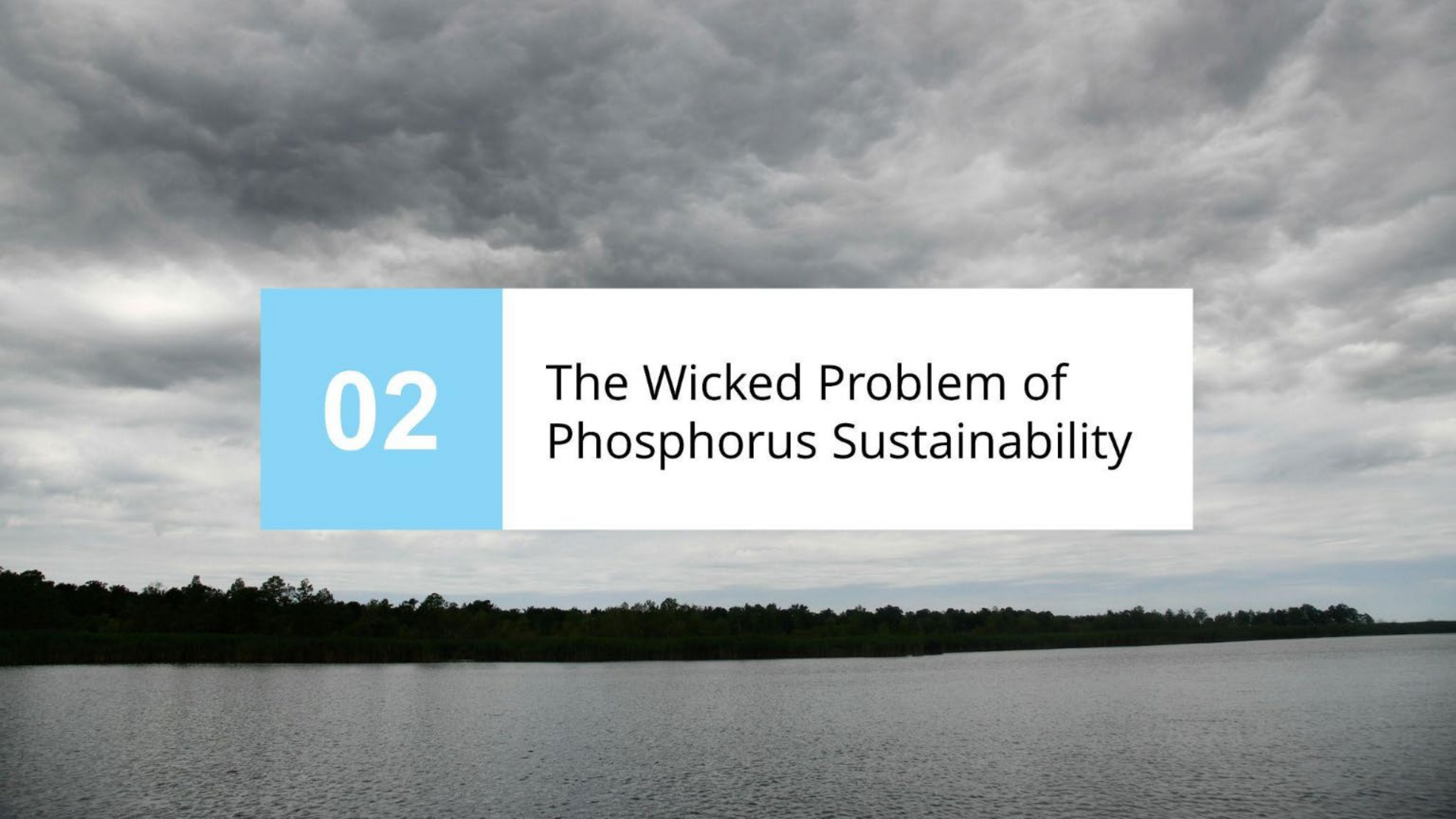
JOINT SCHOOL OF NANOSCIENCE AND NANOENGINEERING
A partnership between North Carolina A&T and the University of North Carolina at Greensboro

CLEMSON UNIVERSITY

STEPS

Science and Technologies for Phosphorus Sustainability

STEPS is a **Convergence Research Center** with **Phosphorus Sustainability** as the Vehicle



02 The Wicked Problem of Phosphorus Sustainability

All living things need phosphorus – it is an essential nutrient for animals, plants, and microbes.

But society's use of phosphorus is **unsustainable and harmful** to humans and the environment.

P is mined from non-renewable resources

P is an essential nutrient in the food system, but also a pollutant

Only 20% of P enters the human diet

Freshwater eutrophication and associated algal blooms and kills fish

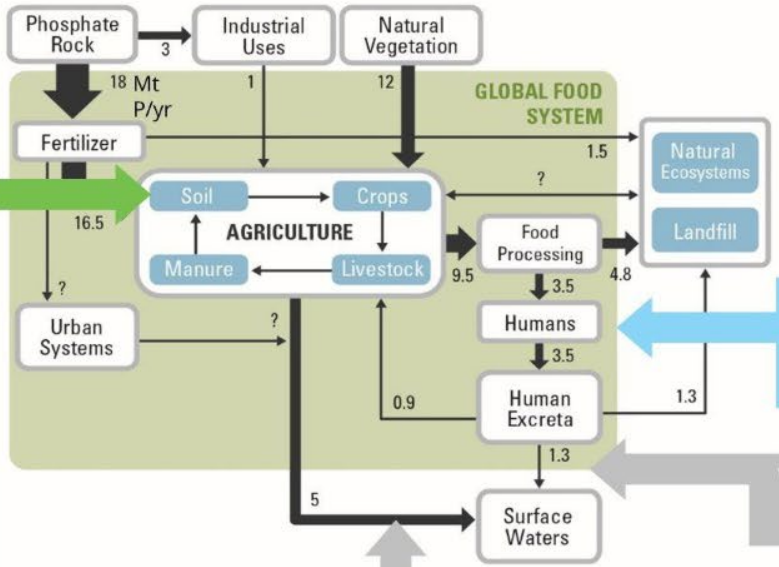
Since 1950, society has **increased global P mining dependence TENFOLD** from ~2 MT/yr to over 20 MT/yr and it continues to grow

N. Nelson, M. Cuchiara, C. Hendren, J. L. Jones, A.-M. Marshall, "Hazardous Spills at Retired Fertilizer Manufacturing Plants Will Continue to Occur in the Absence of Scientific Innovation and Regulatory Enforcement," Environmental Science & Technology, Vol. 55, pp. 16267-16269 (2021)
J. L. Jones, Phosphorus Sustainability Perspectives, https://phosphorusalliance.org/2022/04/phosphorus-sustainability-perspectives-from-phosphates-2022/

SINGLE-USE, EXTRACTIVE PROCESS

MINE, USE, LOSE

Mass balance of inputs and outputs demonstrate increasing legacy P in soils (bio-inaccessible)



Humans pass through small amounts of phosphorus, but food demands increase upstream losses

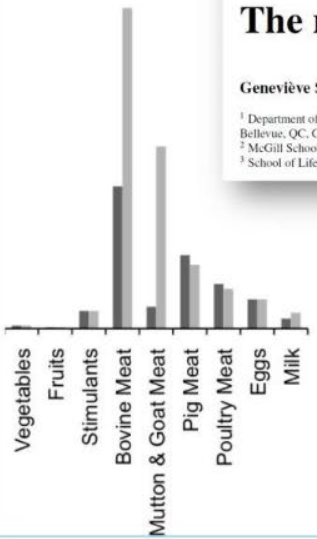
Wastewater treatment plants discharge phosphates into surface waters

Loss to surface waters is the main driver for freshwater eutrophication with associated algal blooms

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

PHOSPHORUS FOOTPRINTS

upstream P FOOTPRINT



OPEN ACCESS
IOP PUBLISHING — ENVIRONMENTAL RESEARCH LETTERS
Environ. Res. Lett. 7 (2012) 044043 (10pp) — doi:10.1088/1748-9326/7/4/044043

The role of diet in phosphorus demand

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

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

"About 72% of the global average dietary P footprint between 1961 and 2007 was due to consumption of animal-based food groups."

downstream P FOOTPRINT

IOP Publishing — Environ. Res. Lett. 15 (2020) 105022 — https://doi.org/10.1088/1748-9326/abc781

Environmental Research Letters

PAPER

The U.S. consumer phosphorus footprint: where do nitrogen and phosphorus diverge?

OPEN ACCESS

RECEIVED
26 April 2020

REVISED
3 July 2020

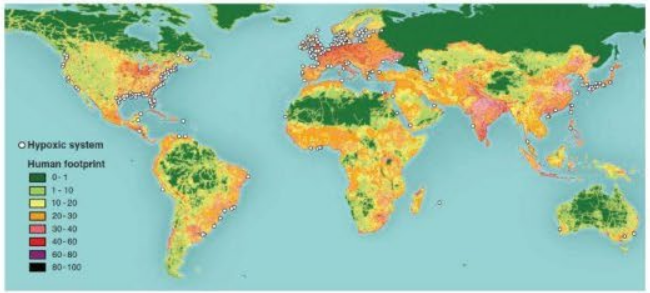
Genevieve S Metson[1,3,4], Graham K MacDonald[1], Allison M Leach[2], Jana E Compton[2], John A Harrison[1] and James N Galloway[2]

"Moving toward more **plant-based diets** would decrease demand for mineral P fertilizer; however such diets also **increase losses to waterways** from human excreta..."

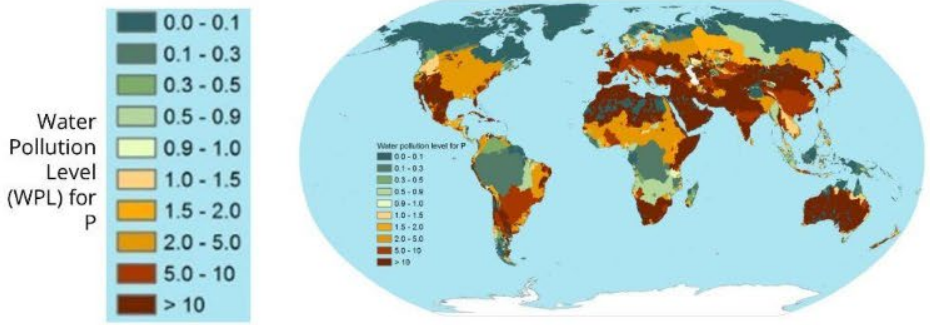
9

GLOBAL PROBLEM WITH GEOPOLITICAL AND PUBLIC POLICY FACTORS

Global distribution of >400 systems of **eutrophication-associated coastal dead zones**[2]



Throughout the world, anthropogenic (human-induced) phosphorus loads in river basins is **too much for the basin's waste assimilation capacity to take up the pollutant load**[1]

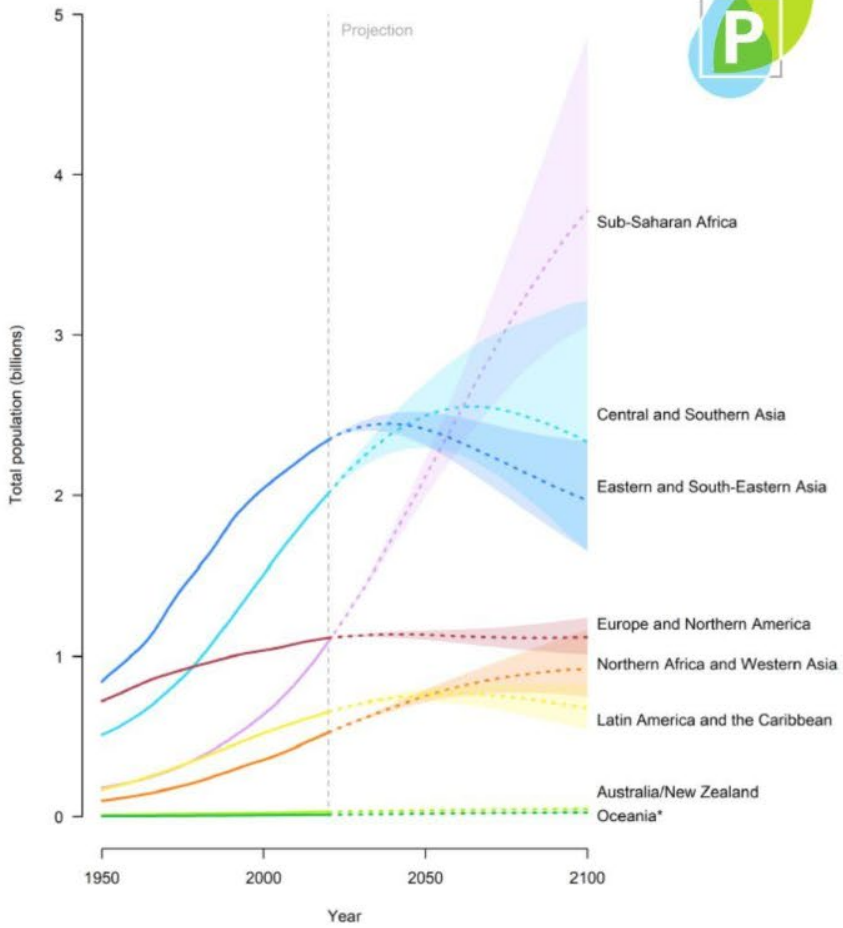


A WPL exceeding 1 indicates the violation of the water quality standards and that the basin's waste assimilation capacity is not big enough to take up the pollutant load (for time period 2002–2010).

[1]From M.M. Mekonnen, A.Y. Hoekstra, Water Resour. Res. 54, 345 (2018)
[2] Diaz and Rosenberg, Science, 321, 926 (2008).
[3] Beaulieu, DelSontro, and Downing, Nature Communications, 10, 1375 (2019).
Visualization of global methane in Jan. 26, 2018, from https://phys.org/news/2020-07-global-methane-emissions-soar-high.html

- Phosphorus demand is projected to increase due to a growing population – an additional two billion persons in the world by 2050 – the risk-averse nature of producers, and the rising affluence in certain parts of the world which generally leads to increased meat consumption.
- If we do nothing, our dependence on mined phosphate and the loss of phosphorus to the environment will worsen and the food system will become increasingly insecure.

POPULATION GROWTH IN AFRICA IS CRITICAL TO UNDERSTANDING LONG-TERM IMPACTS OF PHOSPHORUS SUSTAINABILITY



United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019: Highlights (ST/ESA/SER.A/423).

INNOVATION · DIVERSITY · CONVERGENCE

"Many scholars are exploring the relationship of diversity and excellence, innovation and productivity. **We are beginning to understand that our research and education cannot be excellent unless they are inclusive—that the lenses that diverse people bring to scientific research and discovery improve the inputs and the outcomes.**"

Shirley Malcom's most recent public address at the National Academies in October of 2022:

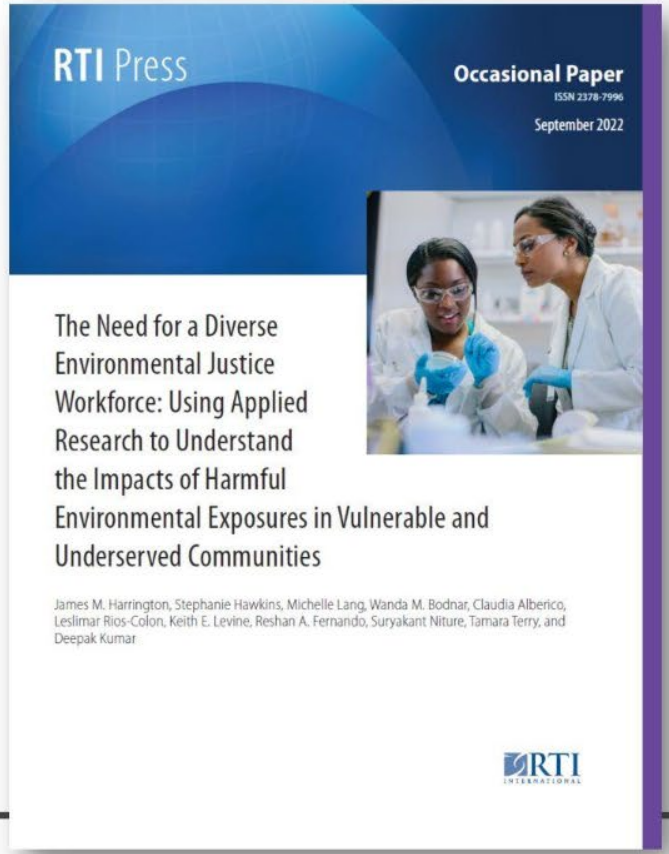
From testimony of Dr. Shirley Malcom, Senior Advisor and Director of SEA Change at AAAS to the Committee on Science, Space and Technology in the U.S. House of Representatives, May 9, 2019; Full Malcom testimony available at https://science.house.gov/download/dr-malcolm-testimony

INNOVATION · DIVERSITY · CONVERGENCE

> The success of environmental justice programs can only be achieved through the **active engagement of those who are most impacted by these harms and inequalities.** … it is incumbent upon scientific professionals to develop a **diverse workforce that reflects the experiences of the affected communities.**

"Some proposed aspects of university-industry partnerships that can produce greater diversity include:

- industry funded science programs aimed at students from underrepresented groups;
- formal mentorship programs;
- formalized industry training in diversity, equity, and inclusion and the
- elimination of unpaid or underpaid internships and entry-level positions."



https://doi.org/10.3768/rtipress.2022.op.0078.2209

Phosphorus sustainability is a "**WICKED PROBLEM**" that requires convergence across 17 orders of magnitude in length scale.

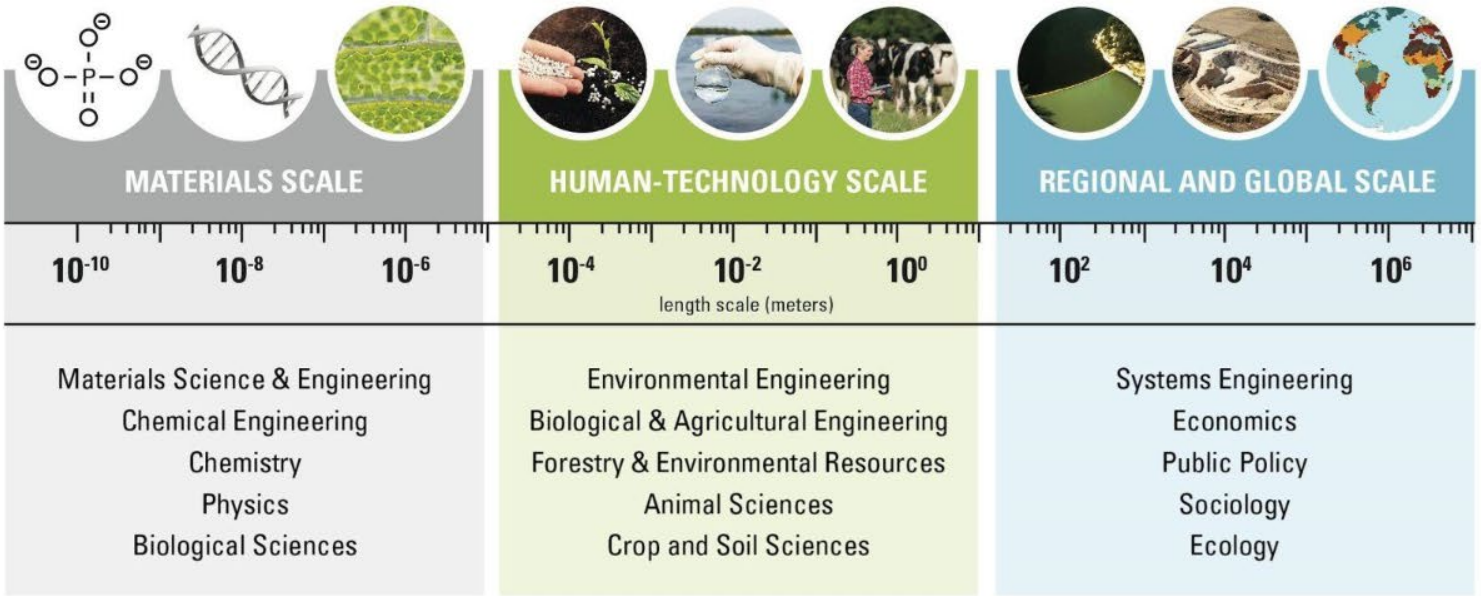


Image is derivative of Jones, Yingling, Reaney, and Westerhoff, MRS Bulletin (2020), https://doi.org/10.1557/mrs.2020.4

Papers Introducing "Wicked Problems":

Head, Wicked Problems in Public Policy, Public Policy 3, 2, 101-118 (2008).

Rittel and Webber, Dilemmas in a General Theory of Planning, Policy Sciences, 4, 155-169 (1973).

In 2018, Growing Convergence Research became an NSF "Big Idea"

NSF'S 10 BIG IDEAS

"The grand challenges of today—protecting human health; understanding the food, energy, water nexus; exploring the universe at all scales -- will not be solved by one discipline alone. They require convergence: the merging of ideas, approaches and technologies from widely diverse fields of knowledge to stimulate innovation and discovery."

From https://www.nsf.gov/news/special_reports/big_ideas/convergent.jsp

03 STEPS Convergence Research Center

NSF Science and Technology Center (STC) Competition

Most prestigious Centers awarded by the National Science Foundation, cutting across all areas of science & engineering that NSF supports

Large awards of $5M/yr up to **$50 million over 10 years**

Highest level of competition

- Over the past 10 years, 10 awards have been made, meaning that, on average, NSF supports about **one new Center per year**
- Each university can submit only 3 preliminary proposals
- NSF receives about 250 preliminary proposals in each cycle
- 6 or fewer are eventually awarded across all of NSF after a two year review process

STCs are driven by notion of "**CONVERGENCE RESEARCH**" – they support highly interdisciplinary work on very specific problems

STEPS was conceived in 2017 and awarded Oct. 1, 2021

STEPS

Science and Technologies for Phosphorus Sustainability

STEPS Center is headquartered in the new Plant Sciences Building at the lead institution, NC State

- NSF Science and Technology Centers (STCs) are highly competitive and prestigious; over the past 10 yrs, NSF has awarded 10 new STCs
- STEPS started 1 Oct. 2021
- $25M USD over 5 years with expectation for 5-year renewal
- ~40 senior investigators & ~40 graduate students/postdocs, ~12 undergraduates, and 15 summer REU students per year

NC STATE UNIVERSITY · ASU Arizona State University · UF University of Florida · RTI International · Illinois · Marquette University · JSNN Joint School of Nanoscience and Nanoengineering · Appalachian State University · Clemson University

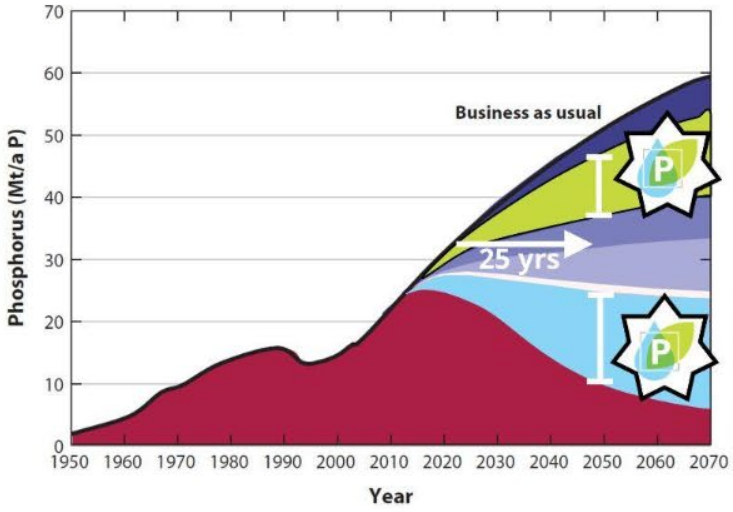
THE STEPS VISION

25-IN-25

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

The 25-in-25 vision is aligned with the 2020 USDA Innovation Initiative to reduce nutrient loss by 30% nationally by 2050 with supporting data from the EPA, e.g. https://www.epa.gov/national-aquatic-resource-surveys/nla

MODELS INFORM PRIORITIES
- market demands

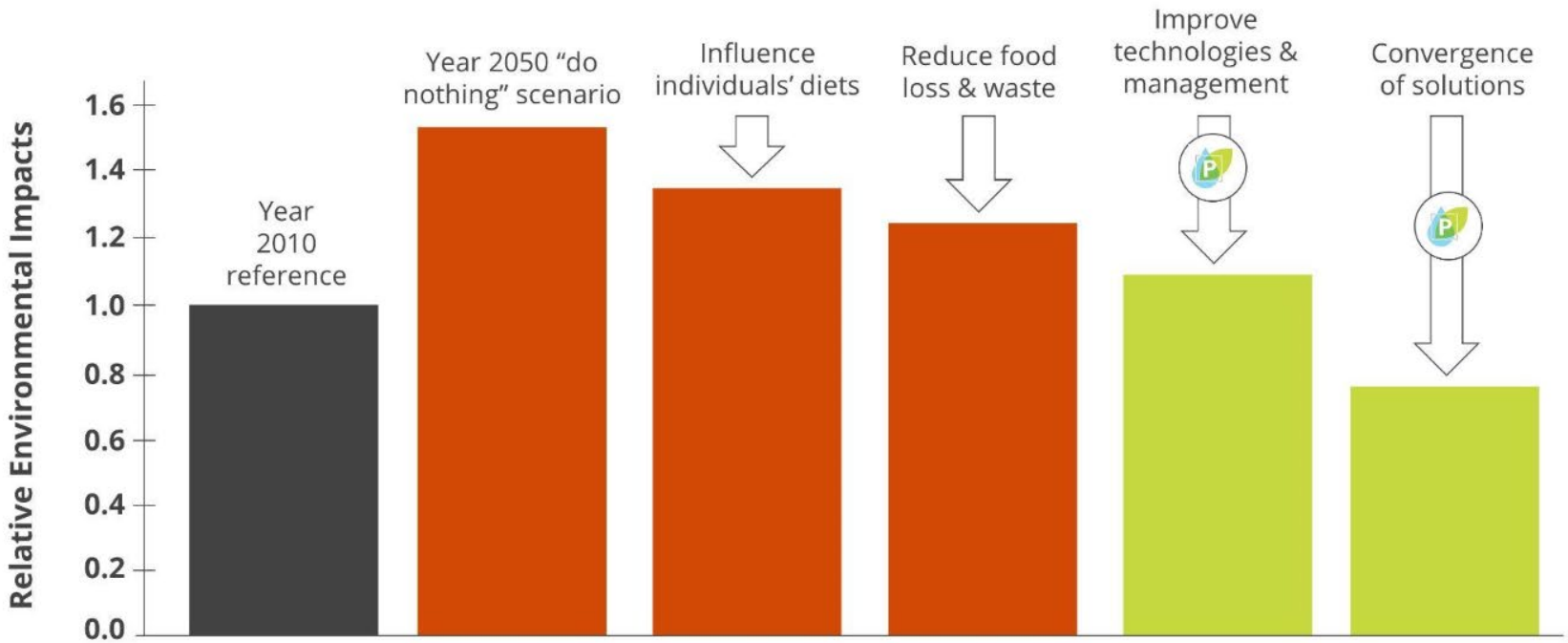


- Phosphorus demand is projected to increase due to a **growing population** – an additional two billion persons in the world by 2050 – the **risk-averse nature of producers**, and the **rising affluence in certain parts of the world** which generally leads to increased meat consumption.
- **If we do nothing, our dependence on mined phosphate and the loss of phosphorus to the environment will worsen and the food system will become increasingly insecure.**
- It is not enough to act. We need to act now, **before we inevitably reach crisis mode**.

Graph from Cordell and White, Annu. Rev. Environ. Resour. 2014. 39:161–88

MODELS INFORM PRIORITIES

-environmental pressures



Replotted using data from Springmann et al., Nature, 562, 519 (2018).

PRIORITY AMBITIONS

SOIL-BOUND-PHOSPHORUS

Materials, crops, and processes to make soil-bound phosphorus bioavailable to crops

Soybean plants at Tidewater Research Station, NC

SURFACE WATER

Crops and materials to trap dilute phosphorus to prevent eutrophication

Algal bloom in FL Everglades

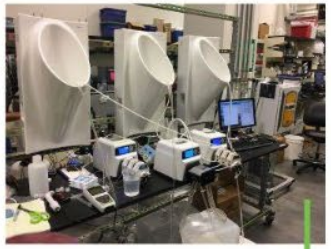
ANIMAL MANURE

Phosphorus capture from animal manure for reuse as fertilizers

Swine-waste lagoon at Tidewater Research Station, NC

HUMAN URINE

Materials and processes to capture phosphorus from concentrated solutions

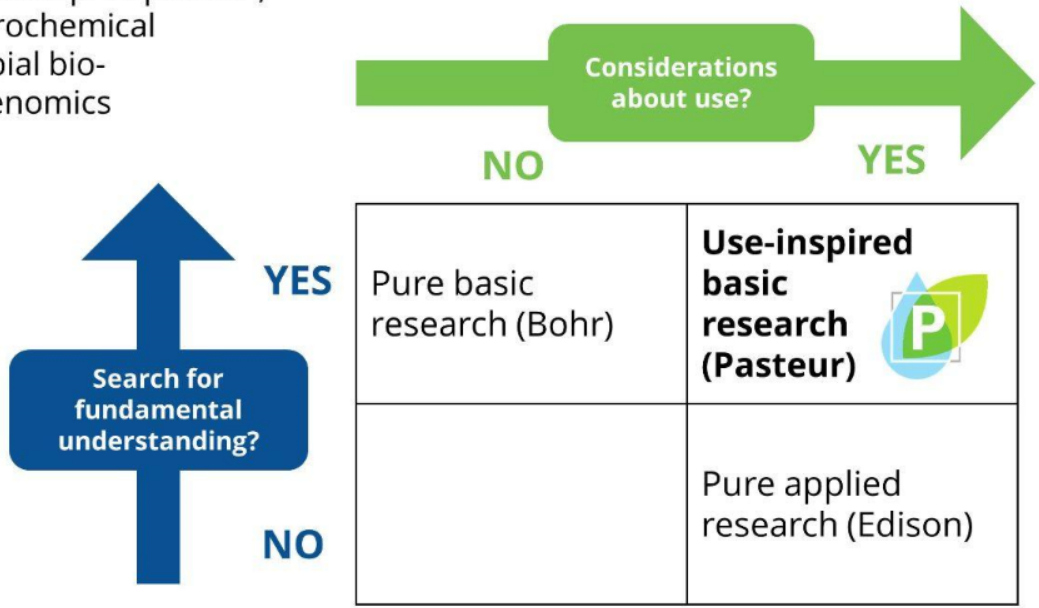


Waterless urinal experiments at ASU

STEPS SUPPORTS USE-INSPIRED BASIC RESEARCH

FUNDAMENTAL SCIENCE PHENOMENA
e.g. sorption, chemical precipitation, physical and electrochemical separation, microbial bio-transformation, genomics

TECHNOLOGIES
e.g., packed-bed adsorbent filters, non- woven fabric- based filters, functionalized coatings or gels, mineral-organic and metal-organic-framework particles and bulk materials

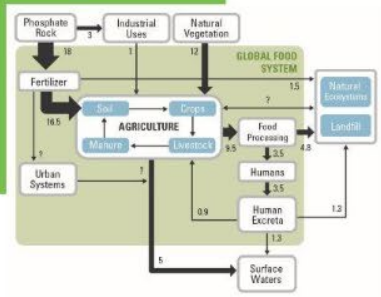


ADOPTION
e.g., by farmers, growers, municipal wastewater treatment facilities, mines, fertilizer companies.

APPLICATIONS
e.g., wastewater treatment plants, in situ sorbent in urine collection systems or agricultural drainage systems, phosphorus sensors, next-generation plant-responsive fertilizers

Use-inspired basic research is the Pasteur quadrant of the Stokes research classification.

STEPS IS A CONVERGENCE RESEARCH CENTER



- STEPS draws from fields of **Science of Team Science** as well as **Integration and Implementation Science**
- Dedicated **STEPS Integration Director**, Christine Hendren
- STEPS develops what we call **Convergence Informatics**, or integrating data across highly disparate disciplines and using informatics to guide research directions
- STEPS **Stakeholder Groups** guide research and allow for rapid and broad dissemination and adoption of products
- STEPS utilizes **Convergence Boundary Objects** as tangible or conceptual connection points, e.g. P-flow diagrams, Triple-Bottom-Line (TBL) scenario sites

TRIPLE-BOTTOM-LINE (TBL) SCENARIO SITES

- Specific locations with well-defined geographical footprints
- Well-defined inputs and outputs, system constraints, existing data, and stakeholder narratives to study triple-bottom-line factors to sustainability (economic, environmental, and social)
- Contain real field test sites for new materials, processes, practices, and technologies
- TBL Sites are locations of student immersion activities, e.g. for research and annual meetings

RURAL FARMLAND

Tidewater Research Station
Plymouth, NC

URBAN ECOSYSTEM

Central Arizona-Phoenix Long-Term Ecological Research

AQUATIC ECOSYSTEM

Lake Okeechobee, Everglades Agricultural Area, and Everglades National Park

STEPS Research Integrates Students, Investigators, and Stakeholders across **17 Orders of Magnitude in Length Scale**

RESEARCH THEME 1

discovers and develops **new inorganic, organic, and bio-inspired materials** to selectively, effectively, and efficiently **liberate, capture, and recover phosphorus and phosphorus-containing species** from liquids and solids

RESEARCH THEME 2

evaluates the **viability of technologies for recovering phosphorus** from complex waste streams, optimization of **soil properties**, and processes to **improve bio-accessibility of recovered phosphate** and reuse of **recovered phosphorus as a crop nutrient**

RESEARCH THEME 3

uses a systems-level approach to evaluate how **human intervention**, **policy intervention**, and **technology adoption** could affect phosphorus sustainability at different scales under various alternative socio-economic, policy, and environmental change scenarios

Cross-cutting areas include, e.g., Convergence Informatics, Education Research, Pre-college Outreach, Research on convergence research, and STEPS REU/REF

STEPS RESEARCH

Integrates Students, Investigators, and Stakeholders across **17 Orders of Magnitude in Length Scale**

Paul Westerhoff and Ross Sozani
Co-Deputy Directors

Yara Yingling
Theme 1 Co-Lead

Jan Genzer
Theme 1 Co-Lead

Owen Duckworth
Theme 2 Co-Lead

Treavor Boyer
Theme 2 Co-Lead

Becca Muenich
Theme 3 Co-Lead

Justin Baker
Theme 3 Co-Lead

Cross-cutting areas include, e.g., Convergence Informatics, Education Research, Pre-college Outreach, Research on convergence research, and STEPS REU/REF

Yara Yingling
Conv. Informatics

Rada Chirkova
Conv. Informatics

Cranos Williams
Conv. Informatics

Gail Jones
Education Research

YEAR 1 RESEARCH PORTFOLIO

Each project led by a Research Theme PI and required to be collaborative across Research Themes and institutions

#	Project PI	Project Name
1.1	Brooke Mayer	Chemical and biological transformations of non-reactive phosphorus
1.2	Paul Westerhoff	Standardizing & advancing phosphorus analytics
1.3	Brooke Mayer	Bio-inspired phosphorus removal and recovery
1.4	Jan Genzer	High-throughput screening of phosphate adsorption in polymer brushes
1.5	Chris Muhich	Metal cations for phosphorus recovery
1.6	Wei Gao	Biomimetic phosphate sorbents via chemical modification of 2D materials
2.1	Treavor Boyer	Human urine as boundary object for advancing phosphorus recovery
2.2	Bruce Rittmann	Characterizing phosphorus after anaerobic treatment of high-strength organic waste streams
2.3	Owen Duckworth	Developing phosphite as a sustainable, next-generation fertilizer
2.4	Rubén Rellán-Álvarez	Understanding of the genetic mechanisms involved in the regulation of plant phosphorus use efficiency
2.5	Luke Gatiboni	Controlling and utilizing legacy phosphorus in soils
2.6	Eric McLamore	Exploring stimulus-response nanobrush materials for phosphorus sensing
3.1	Daniel Obenour	National phosphorus budget and mapping - Phase I
3.2	Natalie Nelson	Establishing baseline data and tools for simulating phosphorus flows at the TBLs
3.3	Khara Grieger	Evaluating stakeholder perceptions, needs, and networks in STEPS research
3.4	Anna-Maria Marshall	Adoption and diffusion of innovation: case studies of STEPS technologies
3.5	Justin Baker	Systems modeling, decision support, and roadmapping to achieve 25-in-25
4.1	Yaroslava Yingling	Convergence informatics I: gathering and fusing data
4.2	Gail Jones	Convergence science education research
4.3	John Classen	Developing technical and convergence educational resources
4.4	Gail Jones	Precollege STEPS education
4.5	Maude Cuchiara	Research experience for undergraduates
4.6	Christine Hendren	Appalachian State collaborative research: P flow mass balance in a rural mountain agricultural system
4.7	Christine Hendren	Convergence research: developing, applying and studying transdisciplinary team interventions for enabling convergence

Recent Output Highlights

Environmental Science & Technology
pubs.acs.org/est
Viewpoint

Hazardous Spills at Retired Fertilizer Manufacturing Plants Will Continue to Occur in the Absence of Scientific Innovation and Regulatory Enforcement

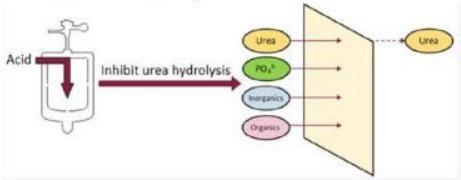
Natalie G. Nelson,* Maude L. Cuchiara, Christine Ogilvie Hendren, Jacob L. Jones, and Anna-Maria Marshall

>1600 views since publication in Nov. 2021

ACS ES&T Water
pubs.acs.org/estwater
Article

Recovery of Urea from Human Urine Using Nanofiltration and Reverse Osmosis

Lucas Crane,* Hannah Ray, François Perreault, and Treavor H. Boyer*



PNAS
RESEARCH ARTICLE | PLANT BIOLOGY

An adaptive teosinte *mexicana* introgression modulates phosphatidylcholine levels and is associated with maize flowering time

Allison C. Barnes[a,1], Fausto Rodríguez-Zapata[a,b,1], Karla A. Juárez-Núñez[b,1], Daniel J. Gates[c], Garrett M. Janzen[d,e], Andi Kur[a], Li Wang[a], Sarah E. Jensen[f], Juan M. Estévez-Palmas[b], Taylor M. Crow[a], Heli S. Kavi[a], Hannah D. Pil[a], Ruthie L. Stokes[a], Kevan T. Knizner[a], Maria R. Aguilar-Rangel[b], Edgar Demesa-Arévalo[c], Tara Skopelitis[c], Sergio Pérez-Limón[b], Whitney L. Stutts[a], Peter Thompson[a], Yu-Chun Chiu[a], David Jackson[a], David C. Muddiman[e], Oliver Fiehn[a], Daniel Runcie[e], Edward S. Buckler[f], Jeffrey Ross-Ibarra[c], Matthew B. Hufford[d], Ruairidh J. H. Sawers[b], and Rubén Rellán-Álvarez[a,b,2]

The Challenge of Non-Reactive Phosphorus: Mechanisms of Treatment and Improved Recoverability Using Electrooxidation

30 Pages • Posted: 4 Oct 2022

Synthia Mallick
Marquette University

Mohammad Shakhawat Hossain
University of South Florida

Arash Takshi
University of South Florida

Douglas F. Call
North Carolina State University - Department of Civil, Construction, and Environmental Engineering

Brooke K. Mayer
Marquette University

SSRN
Tomorrow's Research Today

STEPS HEADQUARTERS

ESTABLISHED IN NEW INTERDISCIPLINARY PLANT SCIENCES BUILDING (PSB)

- STEPS HQ occupies **>5000 ft.^{2} of dedicated space** in the PSB for offices and interdisciplinary laboratories, with access to the **many other resources** of the building and institute
- Facilitates **intersectional collisions** and **synergistic interactions** with other PSI visitors and stakeholders
- Leverages administrative infrastructure within PSI, including admin & communications
- About 20 STEPS participants now in STEPS Headquarters

NC PLANT SCIENCES INITIATIVE

- Agribusiness in NC is an $85 billion industry (2017 data)
- NC Plant Sciences Initiative (PSI) forms and enables interdisciplinary teams and collaborations with NC stakeholders
- Plant Sciences Building (PSB), a 185,000 ft.^{2} world-class facility with Makerspaces, ThinkTanks, core labs, greenhouses, etc.
- Bayer, BASF, SAS, and Novozymes were the first industries to take up residence in the building

Opportunities for Industry to Engage with STEPS

Participate in a Technical Working Group through STEPS Knowledge Transfer component

Provide input to STEPS faculty leading projects and proposing new projects

Support new research project(s) to amplify or leverage the STEPS research portfolio and STEPS expertise

Provide a gift to help STEPS advance its mission and vision in ways that complement the NSF support (e.g., for graduate student fellowships, event sponsorship)

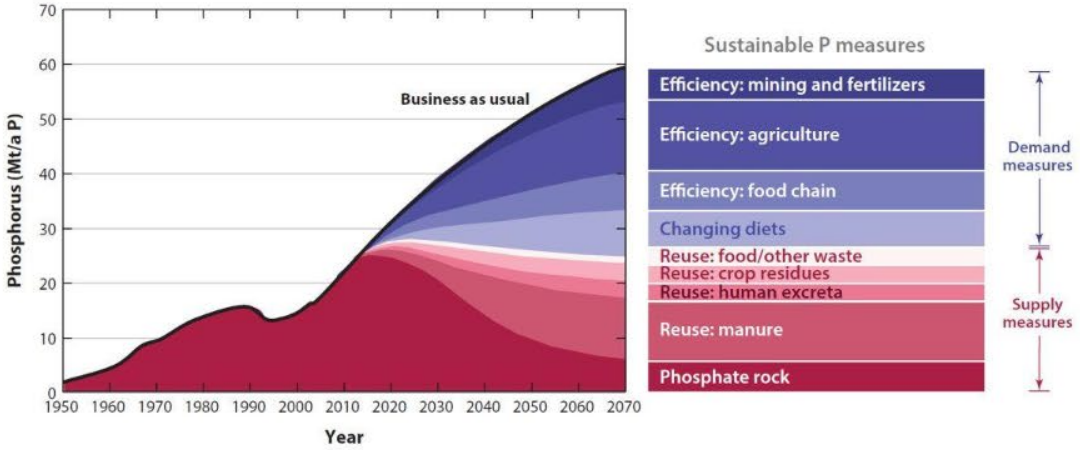

04
Roadmapping
Process

THE STEPS VISION

25-IN-25

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

Business as usual



Graph from Cordell and White, Annu. Rev. Environ. Resour. 2014. 39:161–88

THE STEPS VISION

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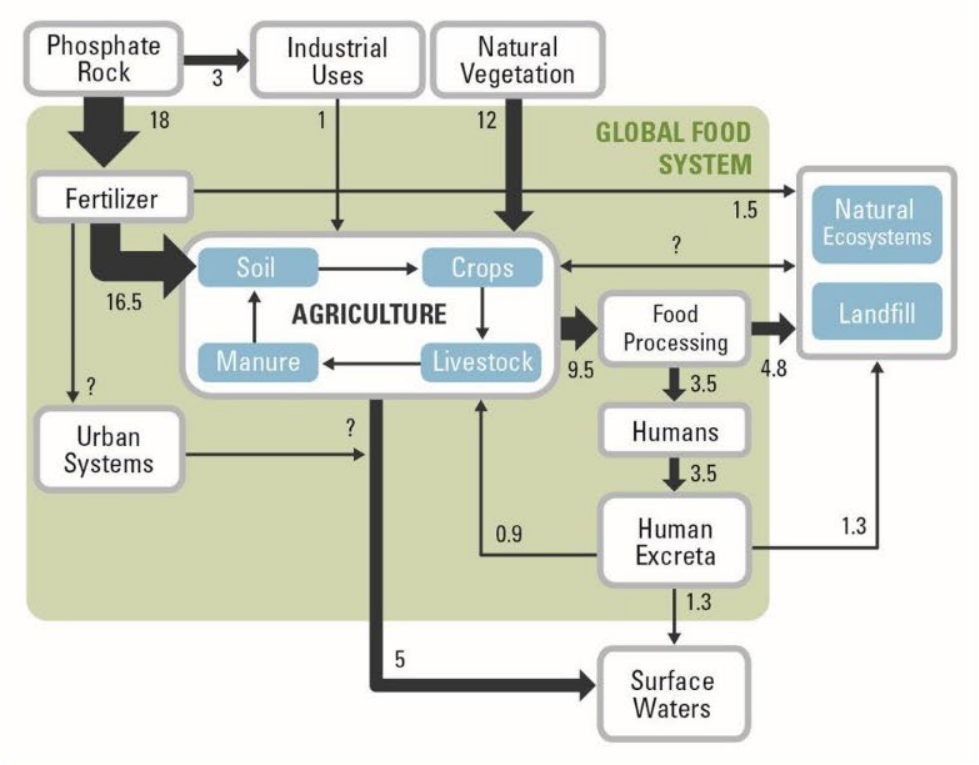
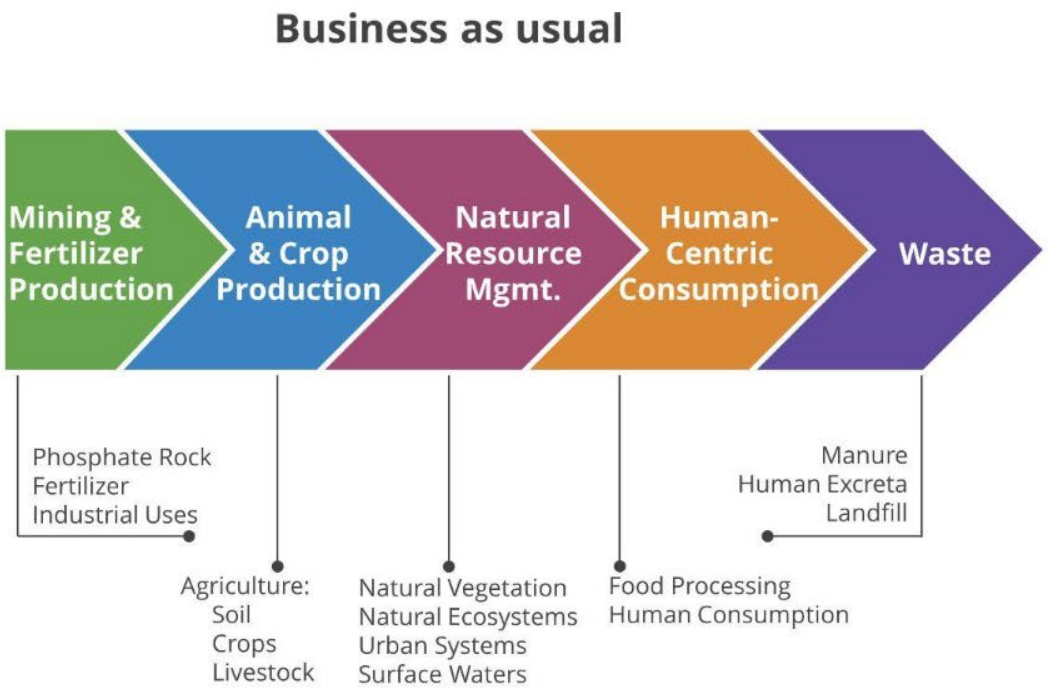


Some data from Rittmann, Mayer, Westerhoff, and Edwards, "Capturing the Lost Phosphorus," Chemosphere, 84, 846-853 (2011).
Flow diagram inspired by Cordell and White, Annu. Rev. Environ. Resour. 2014. 39:161–88.
Numbers alongside arrows represent million metric tons of phosphorus per year.

THE STEPS VISION

25-IN-25

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



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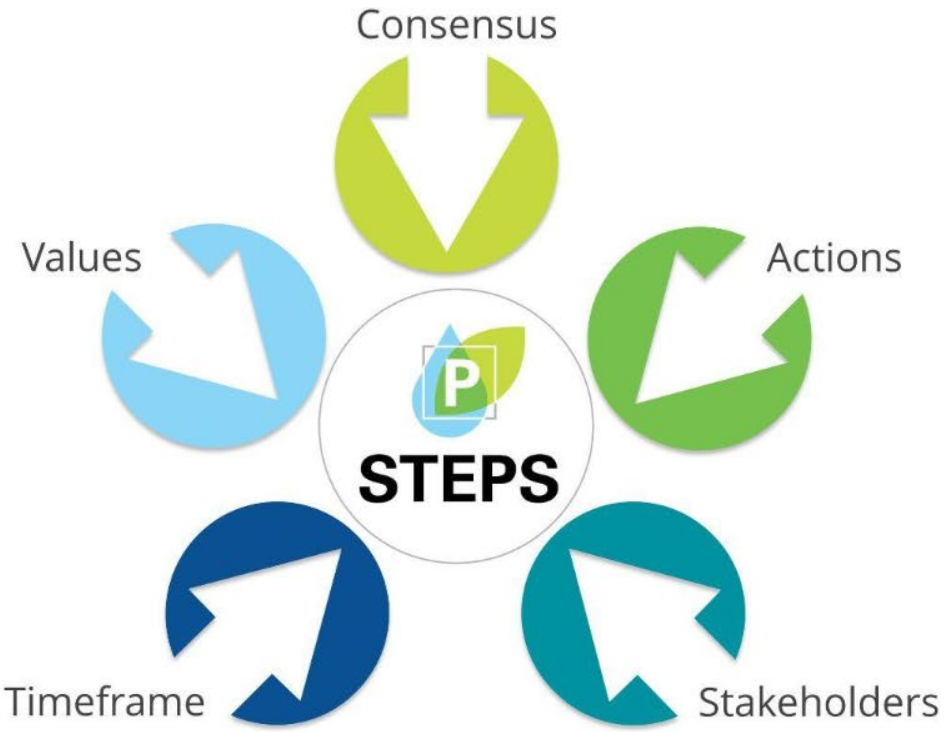

05 One more thing...

We choose to do convergence research for phosphorus sustainability, **not because it is easy, but because it is hard**. Because the 25-in-25 mission will **serve to organize and measure the best of our energies and skills**, because the challenges are those that we are willing to accept, ones we are unwilling to postpone, and **ones which we intend to win**.

Inspired by quotation from John F. Kennedy

STEPS

Science and Technologies for Phosphorus Sustainability

Not pictured: Ashley Tan, Sergei Rigin, Anne Fanatico