The Looming Phosphate Crisis: the importance of the element P (phosphorus) in a nutshell and how microbes can contribute to a sustainable P future.

Mum, is my pee the fertilizer of the future?

Manneken Pis, Brussels landmark (image: Ivan Drazic, Pexels)

Nicole Maassen and Lars M. Blank

iAMB-Institute of Applied Microbiology, ABBt-Aachen Biology and Biotechnology, RWTH Aachen, Germany

The Looming Phosphate Crisis

Storyline

Phosphorus (P) is an essential component of all living organisms, making it an indispensable nutrient for the growth and maintenance of all life. Therefore, all crops farmers cultivate to nourish the global population also need P, or more precisely, soluble inorganic phosphate (PO_4^{3-}). Although P exists in low concentrations throughout the environment, accessible phosphate for plants can be so depleted in certain soils, particularly in areas of intensive agricultural activity, that plant growth is restricted. In such scenarios, the addition of phosphate fertilizers becomes necessary. These fertilizers are derived from phosphate rock, a finite resource, that is mined using costly and energy-intensive processes. Approximately 85-90% of mined phosphate is used to produce fertilizers for agriculture.

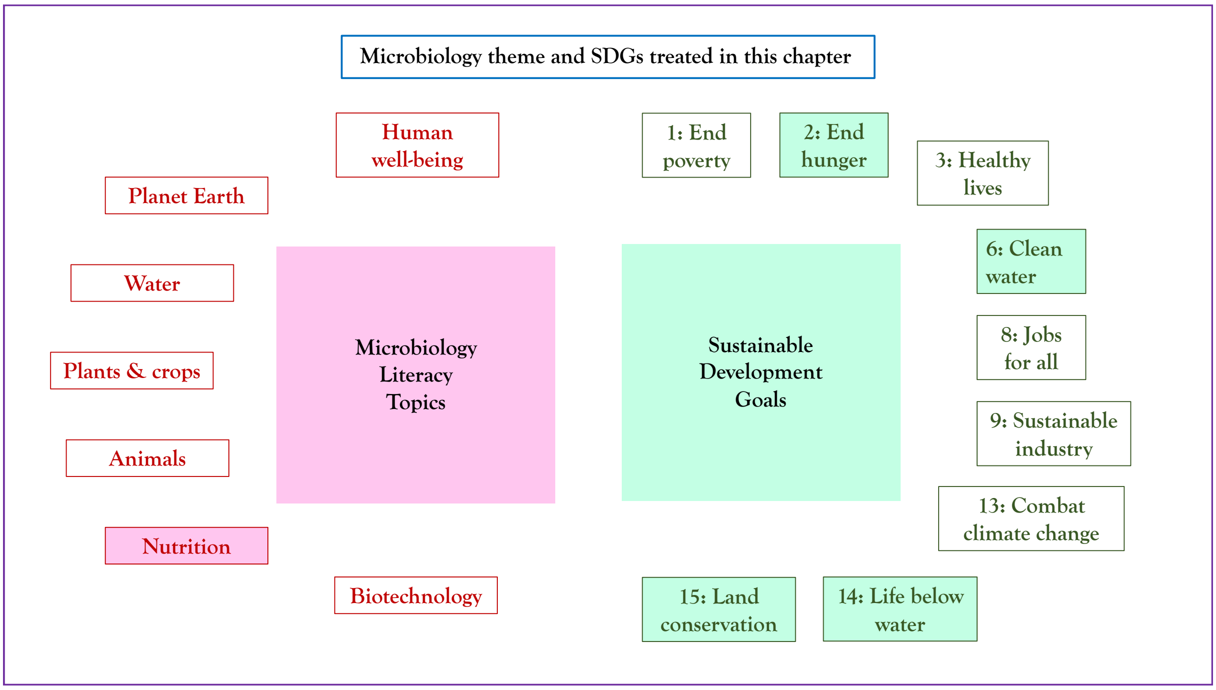
An alternative and renewable phosphate fertilizer source could be urine (including human urine), which contains a high concentration of P compared to sewage sludge or wastewater. This innovative approach not only offers a potential solution to the problem of depleting phosphate rock reserves, but also poses a challenge to the sustainable management of human waste. However, in addition to finding alternative, renewable sources of P to counteract a phosphate crisis, it is also important to establish a sustainable P future.

Fertilizing fields. Fields usually need to be fertilized to ensure optimal growth of agricultural plants (image: Mirko Farbian, Pixabay).

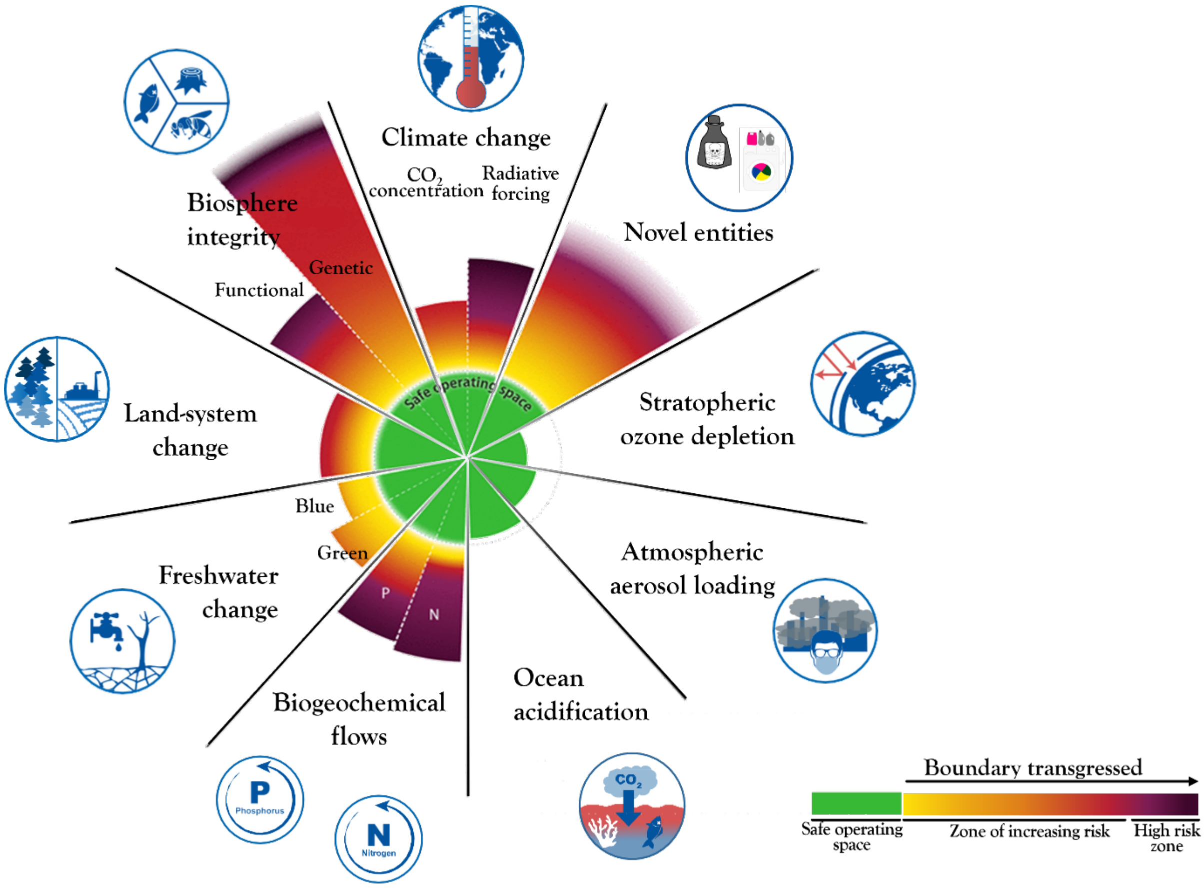
Phosphorus and Societal Context

All organisms need phosphorus as a nutrient – however, disturbing the biogeochemical flows by humankind causes dramatic changes in some ecosystems and a gloomy outlook for existing agricultural systems. P is essential for the growth and maintenance of all living organisms, but excess P in an ecosystem can lead to significant environmental problems. For example, high anthropogenic P-inputs to water bodies can lead to algal blooms and eutrophication. This eutrophication, in turn, can lead to anoxic (oxygen-free) zones in affected water bodies, resulting in the death of oxygen-requiring animals living in them, and creating so-called dead zones. Ecosystems already thus affected include the Gulf of Mexico and the Chesapeake Bay in the eastern United States.

Since excess P can lead to environmental problems, and at the same time, P is essential for the growth and maintenance of all life, including crops, this element becomes central to several Sustainable Development Goals (SDGs), and is a component of the concept of planetary boundaries (2015). For example, SDG2 "End hunger" cannot be achieved if there is not enough phosphate, mainly in the form of fertilizer, available for food production. At the same time, excessive P entry into water bodies can endanger water resources through eutrophication (SDG 6 "Clean water") and pose a threat to aquatic life (SDG 14) and terrestrial life (SDG 15).



In the concept of planetary boundaries, two thresholds for P-input to the environment have been defined. One of these thresholds is the global P-input from freshwater into the oceans, and the other is the regional P-input from fertilizers into erodible soils. Both thresholds have already been exceeded (Steffen *et al.*, 2015). Given the growing world population and the need for food supply, a rapid decrease of these two P-inputs is not to be expected.

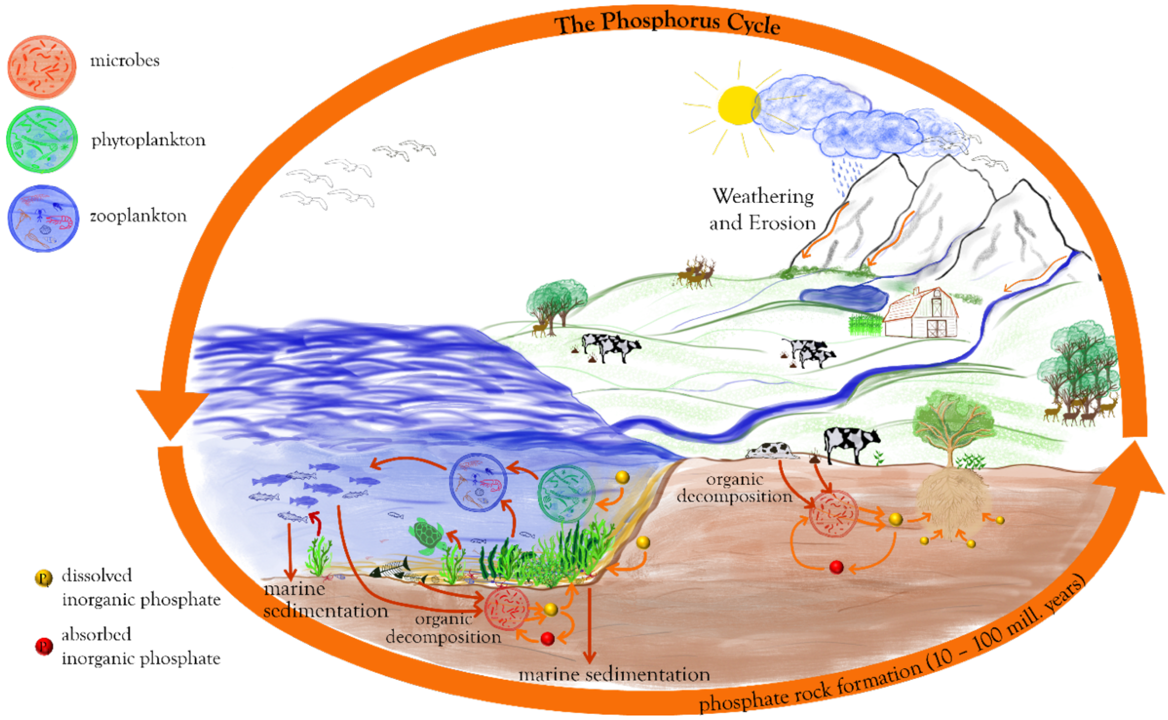


The current status of the control variables for all nine planetary boundaries. In 2023, six of the nine boundaries were considered to have been transgressed. In addition, ocean acidification is approaching its planetary boundary. The green zone is the safe operating space. Yellow to red represents the zone of increasing risk. Purple indicates the high-risk zone where interglacial Earth system conditions are transgressed with high confidence. Values for control variables are normalized so that the origin represents mean Holocene conditions, and the planetary boundary (lower end of zone of increasing risk, dotted circle) lies at the same radius for all boundaries (except for the wedges representing green and blue water). Wedge lengths are scaled logarithmically. The upper edges of the wedges for the novel entities and the genetic diversity component of the biosphere integrity boundaries are blurred, either because the upper end of the zone of increasing risk has not yet been quantitatively defined (novel entities), or because the current value is known only with great uncertainty (loss of genetic diversity). Both, however, are well outside the safe operating space. Transgression of these boundaries reflects unprecedented human disruption of the Earth system but is associated with significant scientific uncertainties. (From Richardson *et al.*, 2023, reprinted with permission from *Science*).

The Looming Phosphate Crisis

1. ***Why is phosphorus essential?*** Phosphorus (P) is a life-sustaining nutrient for all living organisms, as it plays a central role in a high number of biological processes. For example, P is a component of many proteins and lipids, which are essential components of cell membranes. P forms the backbone of the nucleic acids DNA and RNA, the genetic material of every cell. Likewise, P is a component of adenosine triphosphate (ATP), the universal energy currency of every cell, and ATP is therefore of fundamental importance for energy conversion processes in any organism.

2. ***P is a limited and non-renewable resource that is available in ecosystems through the P cycle.*** This cycle is one of the biogeochemical cycles that play a crucial role in maintaining the Earth´s ecological balance and the functioning of its ecosystems. These nutrient cycles are complex natural processes in which various chemical elements such as carbon (C), nitrogen (N), sulfur (S), hydrogen (H), and phosphorus (P) and molecules containing these elements circulate through biological, geological, and atmospheric interactions.



Natural cycling of phosphorus. Inorganic P in sediments and rocks is released by weathering and erosion and slowly enters water bodies and soil, where it can be taken up by photosynthetic organisms (plants, algae) to become organic P. Organic P is transmitted through the food chain and returned to the soil or water as excrement or dead organisms. Organic P is mineralized by microorganisms, making it available to, e.g., plants as inorganic soluble P. The bound inorganic P in the soil or sediments is also mobilized by microorganisms, making it available to plants. Sedimentation and other geological processes return P to the lithosphere.

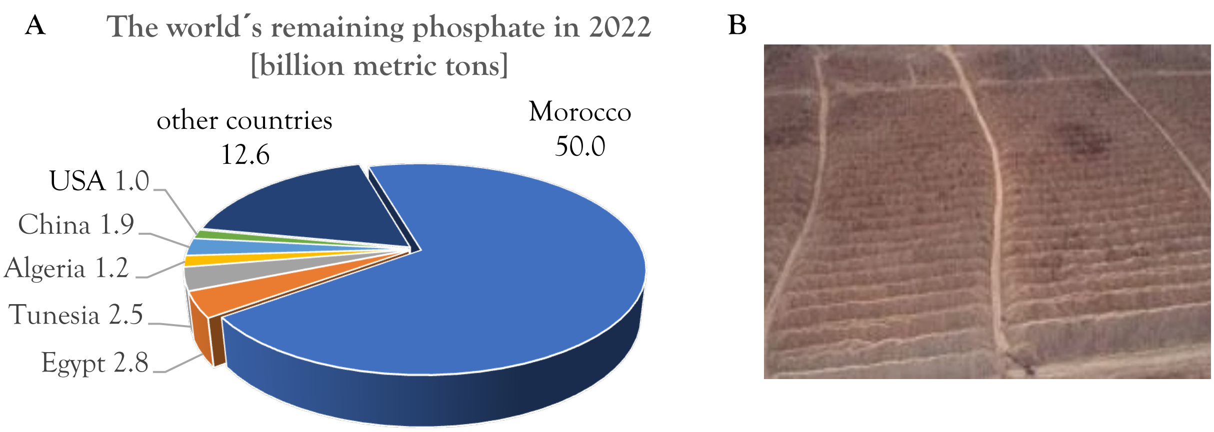
In its natural form, P occurs primarily as a phosphate mineral in sediments and rocks formed over millions of years. These phosphates are released from the P-containing rocks through weathering and erosion and slowly enter water bodies and soils, where plants and other organisms can take them up. Plants take up P from the soil, mainly in the form of orthophosphate

($[PO_4]^{3-}$), and use it for the growth of roots, leaves, seeds, and fruits. This P is transported further up the food chain by herbivores, which in turn are eaten by other animals. In this way, P also enters our bodies through food, and is needed to build bones and teeth, for example. The decomposition of dead animal and plant remains returns the phosphate to the soil and water. This natural cycle ensures the availability of nutrients that are essential for the ecological balance in the entire ecosystem.

The return of P to the lithosphere occurs through sedimentation and geological processes. This formation of P-containing rock is a prolonged process that takes millions of years. For this reason, P is considered a non-renewable resource that must be carefully managed.

3. ***Challenges and importance of phosphorus use for sustainable development.*** P plays an important role not only as an essential nutrient in food production but also in many other applications, including technology. For example, P is used to produce lithium-ion phosphate ($LiFePO_4$) batteries used in electric vehicles and to store renewable energy. These $LiFePO_4$ batteries are considered less susceptible to thermal instability, overheating, and fire, compared with other lithium-ion batteries. They also have a long lifespan, making them ideal for electric mobility. $LiFePO_4$ batteries currently have a large market share in China (90%), presumably also because production is currently cheaper due to the elimination of nickel and cobalt.

Because P is used in many different areas, its uneven global distribution and use is a challenge for sustainable development. The only economic source for extracting P is (currently) phosphate rock. According to the United States Geological Survey (USGS), about 70% of the World´s P reserves (72,000 mil. metric tons) are located in Morocco (50,000 million metric tons, 2022). Due to its economic importance and supply risk, P was included in the list of critical raw materials by the European Commission in 2014.



The world´s phosphate reserves. About 70% of the World´s P reserves are in Morocco (A, data from USGS). Therefore, and due to the low-cost mining conditions, Morocco is the world´s leading exporter country of phosphoric acid and polyphosphoric acids (Statista Research Department 2023). B, phosphate mine in the Western Sahara (image: Spektrum).

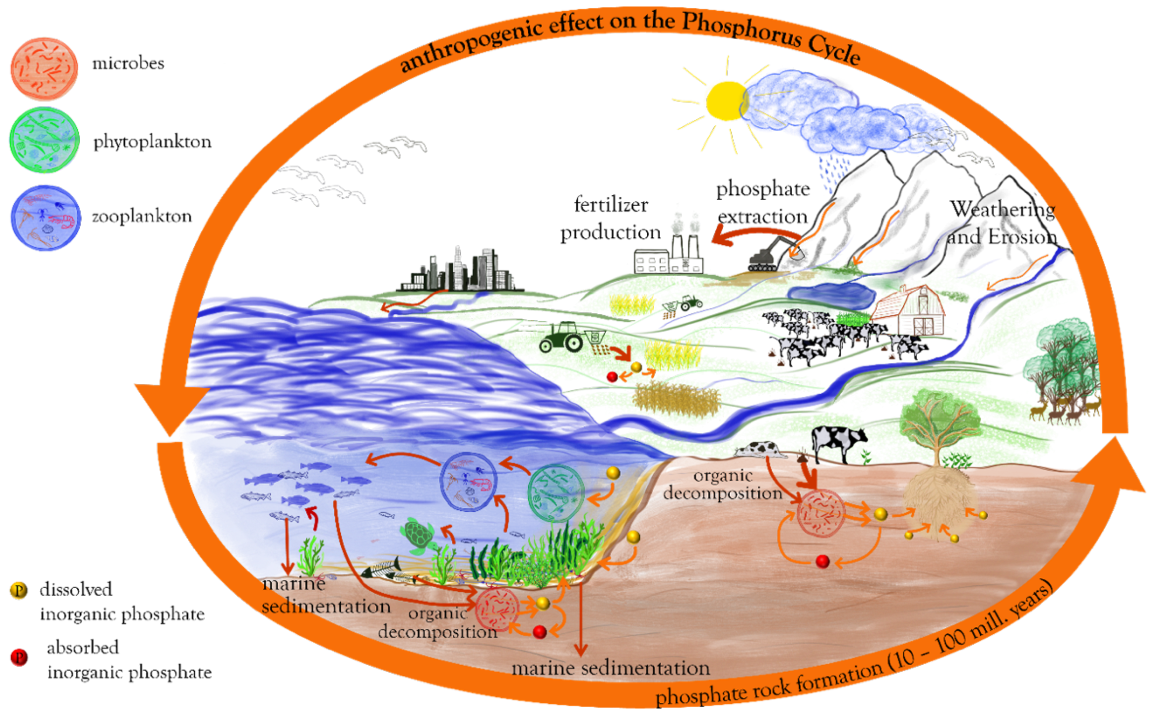
4. ***The anthropogenic effect on the natural phosphorus cycle.*** The P used in various applications is thus extracted from P-bearing rocks (about 200 million tons per year) and returned to the natural phosphate cycle via various routes. In this way, humans have a significant impact on the P cycle. For example, all plants cultivated by humans need PO_4^{3-} in addition to various other nutrients for good growth. However, even though P is generally present in most soils, the

phosphate plants can use is not available in sufficient quantities in many soils. Because this PO_4^{3-} is often the growth-limiting factor in plants, P is supplied as mineral fertilizers.

However, most agricultural technologies fertilize the soil, not the plant *per se*. As a result, the plants use only a fraction of the applied P-fertilizer (10-30%). The rest remains in the soil or is washed out by leaching and erosion, and ends in surface waters.

Why is that? The *problem* is that plants can only take up dissolved phosphate ions. Phosphate applied to the soil, however, readily complexes with existing metal ions such as iron, aluminum, and calcium to form insoluble salts that are not or only very slowly accessible for plants. As a result, in regions with a long history of P-fertilizer use, although the amount of P in the soil can is high and can last an estimated two centuries, P-fertilizer still has to be added to achieve good crop yields. Another challenge of P accumulation in the soil, besides the insoluble salts, is the very short diffusion length in the soil. It is estimated that P often does not diffuse even millimeters, making it difficult for plants to reach this essential element.

How then is P contributing to water pollution and is finally lost to the ocean? Soil erosion occurs in all fields through wind and water, and direct runoffs are also possible. However, the problem with P fertilization of fields is not only the P surplus in the water bodies, which, as mentioned above, can lead to algal blooms and ultimately to eutrophication. Importantly, the phosphate ultimately lost to the ocean cannot be recovered and re-used. And, although P can be mined, used as fertiliser, and be washed into the sea in a matter of months, P only cycles through sedimentation back into rock over a time frame of centuries. This is a key aspect of the anthropogenic perturbation of the P-cycle.



The phosphorus cycle. In 2020, 47 million tons of P_2O_5 were used worldwide, which was extracted from P-containing rocks and sediments. About 85% of the extracted P is used to produce fertilizers. Only a very small fraction of the phosphate applied to the fields is directly used by the plants. The majority remains bound or complexed in the soil and, over time, enters water bodies through erosion, etc. Excessive P input to the water bodies can lead to significant environmental problems, including eutrophication.

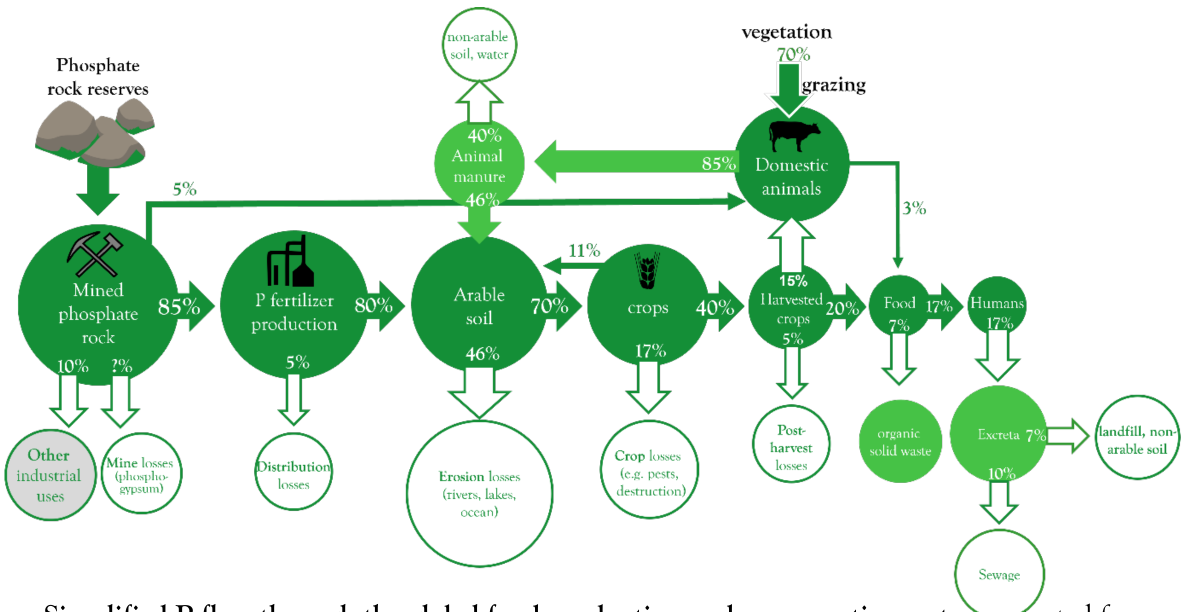
5. ***Phosphate is an element that might see peak production soon.*** As phosphate is a finite resource, the production of P-containing products will peak at a certain point in time, namely when economic depletion is nearing completion. Predictions about the timing of this peak vary depending on the underlying data and modelling of future scenarios. However, several authors assume that the peak will be reached before the end of this century, possibly before 2040.

Estimates of the range of phosphate rock reserves also vary between 30 and 300 years. These differences are mainly due to different assumptions regarding demand rates, P concentrations in phosphate rock, and the economic feasibility of unusual sites, like deep ocean mining. However, the consensus is that high-quality phosphate rock reserves will become scarcer, and mining conditions will become more complex, subsequently increasing mining costs.

Just recently, in July 2023, a Norwegian company (Norge Mining) reported a new P resource that is said to be almost as large as the world reserve proclaimed by the USGS. The deposit was discovered in 2018, but surveys have now been completed (Norge Mining, 70,000 million tons). However, as far as can be seen from the reports, the phosphate content in this rock is far below the P_2O_5 content of currently operating mines. Based on the information available so far, the German Phosphorus Platform concludes that the valuable material content of the deposit is to be classified as low concerning mineability.

But whether in a few decades or a few hundred years, at some point, the fertility elixir phosphorus will run out, with all the negative consequences, such as rising prices for fertilizer and thus food. *And: unlike oil, phosphorus would not be replaceable.*

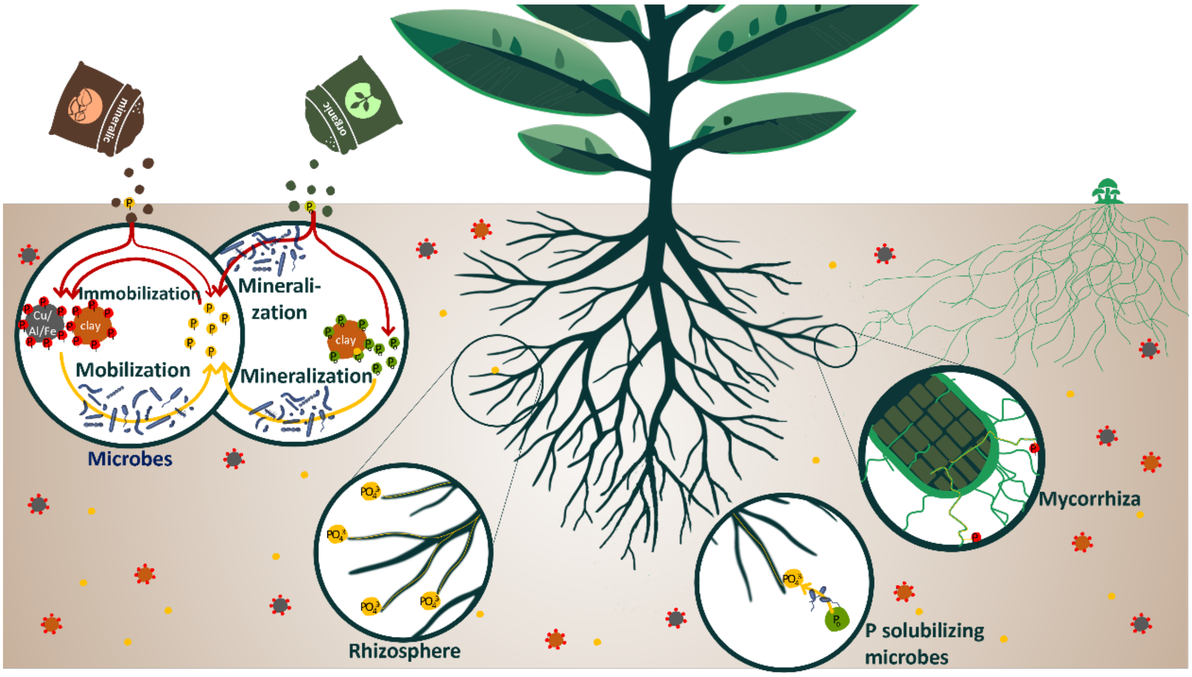
Notably, in human timelines, there is no P-cycle, as the natural one is estimated to last 10 to 100 million years. The general P-use network was sketched early by Elser (Figure see below), highlighting the unsustainable loss of P that exceeds actual P-fertilizer amounts, as grazing animals take up additional P from non-fertilized pastures. The author concluded 10 years ago: "Given the scale and scope of the changes required in the coming decades, concerted efforts in research, technology transfer, and regulatory and institutional innovation should already be underway. I conclude this post by expressing my concern that this is not the case."



Simplified P flow through the global food production and consumption system (adapted from Cordell *et al.*, 2009, with permission from *Elsevier*). Usage, losses and recovery are indicated. The percentages refer to the amount of phosphorus extracted from the phosphate rocks (17.5 million tons in 2006). The highest losses are associated with crop and livestock production.

6. ***Can microbes help us to reduce the anthropogenic impact on the biogeochemical P cycle? Indeed, they can.*** P is on the list of critical elements, not only for the EU but also for many other countries and communities. This declaration as a critical element is mainly due to two strong arguments: 1. no plants for food production without P, and 2. the discussed limited availability and regionally extremely unbalanced distribution of P. In addition, the human impact on the P cycle and the increased input of P into the environment entail risks for the Sustainable Development Goals and need to be taken into account within the concept of planetary boundaries. The solutions to these challenges lie in minimizing P consumption through more efficient use, and in recovering and recycling P to first slow down the demand for phosphate rock and later establish a circular economy. Innovative approaches to support these goals are therefore of great importance. There are already many developments and strategies to reduce and reuse P.

As 85% of human P consumption is for fertilizer production, more sustainable methods in the sector of food production are of particular interest. These methods should not only reduce the environmental impact but also meet the needs of the population. A closer look at the global P-system in the context of global food production and consumption clearly shows that especially P losses during the different processes should be minimized to reduce P use and promote or establish a circular economy (Figure above). In particular, agricultural fields lose a significant amount of P through erosion and leaching. This loss could be reduced by improving the uptake and use of P by plants, or by mobilizing insoluble phosphate compounds in the soil, both of which would reduce the need for mineral P fertilizer. For example, researchers are working on plants that secrete organic acids that solubilize P stored in insoluble P-salts, thereby mobilizing the P and making it available for the plant itself. Similarly, an N-fixing microbe, *Paenibacillus sonchi*, has been reported that could utilize a highly insoluble P-salt as sole P source. Such microbes also open new possibilities for soils containing significant amounts of insoluble P.



P in the soil. Plants can only take up dissolved phosphate ions (PO_4^{3-}). However, P added to the soil by fertilization is quickly bound or complexed and therefore unavailable to plants. On average, only 2% of the total P in soil is present as dissolved phosphate ions. The bound P can be mineralized or mobilized by microbes, resulting in soluble phosphate ions. Such P-solubilizing microbes are attracted to plant roots, producing soluble phosphate ions in the immediate vicinity. In addition, some plant roots form symbioses with mycorrhizal fungi to obtain phosphate from them.

The application of such P-providing microbes is often via seed encapsulation, another area showing many innovative developments. In addition to phosphate-solubilizing bacteria, such as *P. sonchi*, arbuscular mycorrhizal fungi are found in the rhizosphere of crop plants. They are known to provide nutrients such as P to plants, thus enhancing plant growth. For this, they often use the help of bacteria. Mycorrhizal fungi have been used for some time in organic farming to support phosphate uptake and, thus, plant growth.

7. ***Recovering phosphate***. Apart from efforts to avoid P loss and to improve P uptake in crops, phosphate recovery is an exciting option. For example, P recovery from wastewater treatment plants is envisioned, and indeed recently (2021) a commercial plant recovering 7,000 tons of high-purity phosphoric acid annually from 20,000 tons of sewage sludge ash opened (Remondis & Phosphor-Recycling Hamburg, 2021).

Another approach is based on the fact that much P is bound in agricultural side streams, like canola press cakes. These press cakes are used as animal feed, although monogastric animals like pigs cannot utilize the contained P, which is stored as phytate in plants, a sugar decorated with P. To recycle this P, it was suggested to release the P bound to the sugar (inositol) using enzymes, so-called phytases. Indeed, exploiting a recently demonstrated technology, researchers could mobilize significant amounts of P from a range of press cakes that would easily cover the polyphosphate (PolyP) market.

Polymers of P are used in the food and industrial sectors at the low million-ton scale, but notably, in high purity and high price. Hence, novel recycling technologies for P might be first installed in the PolyP market, as it is less price sensitive. One such idea is using baker's yeast as a polyP-producing microbe. After P starvation, baker's yeast hyper-accumulates P rapidly to PolyP, with a cell content of up to 30%. The yeast biomass can be used to manufacture polyP-rich yeast extract or isolate the polyP. The polyP-rich yeast extract can be used in the food industry and was showcased for the manufacturing of sausages.

Potential Implications for Decision

1. ***Individual***
    a. Inform yourself, raise your own awareness!
    b. Make friends and family aware of the importance of responsibly using phosphorus and related products, including P-containing detergents.
    c. Support recycling programs, including battery recycling
    d. Should we use more sustainable practices in our gardens, e.g., using fertilizers responsibly and as recommended? Avoid excessive fertilization of lawns and subsequent water application, as excess phosphorus is then released into water bodies.
    e. Should we change our diet preferences? Production of animal products requires a lot of phosphorus, so reducing meat consumption would save P.
    f. Which of the three R's - reduce, reuse, or recycle - should we focus on? Why?
    g. Do we need to overcome our aversion to using fertilizers produced by recycling human waste, including human excrement?
    h. Should we compost organic waste to bring valuable nutrients, including phosphorus, back into the soil?
    i. Should we support organic agriculture by purchasing appropriate products?

2. ***Community policies***
    a. Implement education and awareness programs

b. Political decisions to support new innovative P recycling technologies
c. Promote waste separation and recycling
d. Promote sewage sludge recycling - sewage sludge as fertilizer or other recycling
e. Promote sustainable agricultural practices

3. National policies

a. National certification to offer the consumer a reasonable basis for their decisions
b. Legislation and support to improve agricultural efficiency and sustainability
c. Legislation and support to manage plant nutrient cycles more efficiently
d. Revisit regulations and standards, e.g., on the use of phosphate in detergents and as a food additive
e. Political decisions to support recycling in general
f. Promote urban design to facilitate P recycling in the food chain
g. Regulatory frameworks – legal obstacles that slow the evaluation of, and potential adoption of, genetically modified crops, animals, and microbes
h. Regulatory frameworks to support (or not to inhibit) the assessment of genetically modified crops, animals, and microbes

Pupil Participation

1. Class Discussion of the issues associated with phosphorus

a. What products in our daily lives contain phosphorus? Is it added during production, or is it naturally present? Based on what kind of properties will it be used? Discuss your findings.
b. What are the advantages and disadvantages of using phosphorus in these products?
c. Is there a debate in society about the use of phosphorus? Why?

2. Pupil stakeholder awareness

a. What is the impact of my diet preferences on the phosphorus cycle?
b. What is the impact of my decisions on the phosphorus cycle?
c. How could it be rewarded if products (e.g., food) are produced sustainably?
d. Does knowledge of phosphorus use influence my behavior and my purchasing decisions?
e. Does my behavior as an individual have an impact on the phosphorus cycle?

The Evidence Base, Further Reading, and Teaching Aids

The Planetary Boundaries and what they mean for the Future of Humanity

Bindraban, P.S., Dimkpa, C.O., Pandey, R. Exploring phosphorus fertilizers and fertilization strategies for improved human and environmental health. *Biol Fertil Soils* **2020**, 56**,** 299–317. doi.org/10.1007/s00374-019-01430-2

Brito, L.F., López, M.G., Straube, L., Passaglia, L.M.P., Wendisch, V.F. Inorganic phosphate solubilization by rhizosphere bacterium *Paenibacillus sonchi*: Gene expression and physiological functions. *Front Microbiol* **2020**, 11, 3122. DOI=10.3389/fmicb.2020.588605

Christ, J.J. & Blank, L.M. Analytical polyphosphate extraction from *Saccharomyces cerevisiae*. Analytical Biochemistry **2018**, 563, 71-78, https://doi.org/10.1016/j.ab.2018.09.021

Christ, J.J. & Blank, L.M. *Saccharomyces cerevisiae* containing 28% polyphosphate and production of a polyphosphate-rich yeast extract thereof. *FEMS Yeast Res* **2019**, 19 (3), foz011. doi.org/10.1093/femsyr/foz011

Christ, J.J., Smith, S.A., Willbold, S., Morrissey, J.H., Blank, L.M. Biotechnological synthesis of water-soluble food-grade polyphosphate with *Saccharomyces cerevisiae*. *Biotechnol Bioeng* **2020a**, 95, 555–2099. doi.org/10.1002/bit.27337

Cordell, D., Drangert, J.-O., White, S. The story of phosphorus: Global food security and food for thought. *Glob Environ Change* **2009**, 19 (2), 292-305. doi.org/10.1016/j.gloenvcha.2008.10.009.

Cordell, D., Rosemarin, A., Schröder, J.J., Smit, A.L. Towards global phosphorus security: a systems framework for phosphorus recovery and reuse options. *Chemosphere* **2011**, 84 (6) 747-58. doi: 10.1016/j.chemosphere.2011.02.032.

Cordell, D. & White, S. Peak Phosphorus: Clarifying the key issues of a vigorous debate about long-term phosphorus security. *Sustainability* **2011**, 3, 2027-2049. doi.org/10.3390/su3102027

Cordell, D. & White, S. Sustainable phosphorus measures: Strategies and technologies for achieving phosphorus security. *Agronomy* **2013**, 3, 86-116. doi:10.3390/agronomy3010086

Diaz, R.J. & Rosenberg, R. Spreading dead zones and consequences for marine ecosystems. *Science* **2008**, 321, 926-929.

Elser JJ. Phosphorus: a limiting nutrient for humanity? *Curr Opin Biotechnol* **2012**, 23 (6), 833-8. doi: 10.1016/j.copbio.2012.03.001.

European Commission press release. 20 critical raw materials – major challenge for EU industry. 26th May 2014

European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, *Study on the review of the list of critical raw materials – Final report*, Publications Office, 2017, https://data.europa.eu/doi/10.2873/876644

Golroudbary, S.R., Wali, M.E., Kraslawski, A. Rationality of using phosphorus primary and secondary sources in circular economy: Game-theory-based analysis. *Environ Sci Pol* 2020, 106, 166-176. doi: 10.1016/j.envsci.2020.02.004

Herrmann, K.R., Ruff, A.J., Infanzón, B., Schwaneberg, U. Engineered phytases for emerging biotechnological applications beyond animal feeding. *Appl Microbiol Biotechnol* **2019**, 103 (16), 6435-6448. doi: 10.1007/s00253-019-09962-1.

Herrmann, K.R., Ruff, A.J., Schwaneberg, U. Phytase-Based Phosphorus Recovery Process for 20 Distinct Press Cakes. *ACS Sustain Chem Eng* **2020**, 8 (9), 3913-3921. DOI: 10.1021/acssuschemeng.9b07433

Herrmann, K.R., Fees, J., Christ, J.J., Hofmann, I., Block, C., Herzberg, D., Bröring, S., Reckels, B., Visscher, C., Blank, L.M., Schwaneberg, U., Ruff, A.J. Biotechnological production of food-grade polyphosphate from deoiled seeds and bran. *EFB Bioeconomy Journal* **2023**, 3, 100048. DOI: 10.1016/j.bioeco.2023.100048

Keyzer, M. Towards a Closed Phosphorus Cycle. *De Economist* **2010**, 158**,** 411–425. doi.org/10.1007/s10645-010-9150-5

Malhotra, H., Vandana, Sharma, S., and Pandey, R. Phosphorus nutrition: plant growth in response to deficiency and excess. *Plant Stress 2018*, 171–190.

Mo, X., Liu, G., Zhang, Z., Lu, X., Liang, C., Tian, J. Mechanisms underlying soybean response to phosphorus deficiency through integration of omics analysis. *Int J Mol Sci* **2022**, 23 (9), 4592. doi: 10.3390/ijms23094592

Mogollón, J.M., Beusen, A.H.W., van Grinsven, H.J.M, Westhoek, H., Bouwman, A.F. Future agricultural phosphorus demand according to the shared socioeconomic pathways. *Global Environmental Change* **2018**, 50, 149-163. doi.org/10.1016/j.gloenvcha.2018.03.007.

Ojeda-Rivera, J. O., Alejo-Jacuinde, G., Nájera-González, H. R., López-Arredondo, D. Prospects of genetics and breeding for low-phosphate tolerance: an integrated approach from soil to cell. *Theor Appl Genet* **2022**, 135 (11), 4125–4150. doi: 10.1007/s00122-022-04095-y
Remondis & Phosphor-Recycling Hamburg **2021**, Water from Hamburg – phosphorus for the world [Press release], www.remondis-aktuell.com
Richardson, A. E., and Simpson, R. J. Soil microorganisms mediating phosphorus availability update on microbial phosphorus. *Plant Physiol* **2011**, 156, 989–996. doi: 10.1104/pp.111.175448
Rockström, J., Steffen, W., Noone, K. *et al.* A safe operating space for humanity. *Nature* **2009**, 461, 472–475. doi.org/10.1038/461472a
Steffen, W., Richardson, K., Röckstrom, J., Cornell, S. E. *et al.* Planetary boundaries: Guiding human development on a changing planet. *Sci* **2015**, 347 (6223), 1259855. doi.org/10.1126/science.1259855
Tian, J., Wang, X., Tong, Y., Chen, X., Liao, H. Bioengineering and management for efficient phosphorus utilization in crops and pastures. *Curr Opin Biotech* **2012**, 23, 866-71
United Nations. Transforming our World: The 2030 Agenda for Sustainable Development. **2015**
United States Geological Survey (USGS), Reserves of phosphate rock worldwide in 2022, by country (in million metric tons). Statista **2023**
Vance, C. P., Uhde-Stone, C., and Allan, D. L. Phosphorus acquisition and use: critical adaptations by plants for securing a nonrenewable resource. New Phytol **2003**, 157, 423–447. doi: 10.1046/j.1469-8137.2003.00695.x

Glossary

Algal bloom: Increased nutrient input to water bodies stimulates algal growth. This results in rapid growth of microscopic algae, often resulting in a colored scum on the surface of the water. This phenomenon is known as an algal bloom. When these masses of algae die and decompose, the oxygen dissolved in the water is consumed. This consumption can lead to eutrophication or even the formation of dead zones.
Anthropogenic: is caused or influenced by humans or their activities
Anoxic: Anoxic designates an oxygen-free space.
ATP: Adenosine triphosphate is composed of the base adenine, the sugar ribose and three phosphate groups. It provides energy to drive and support many processes in living cells.
Lipids: e.g., phospholipids. Phospholipids are lipids with a hydrophilic head containing a phosphate group and two hydrophobic tails derived from fatty acids, joined by an alcohol residue.
Biogeochemical cycle: The term is derived from a combination of biosphere, geological components, and chemical elements. It refers to the complex interaction between biological, geological, and chemical processes contributing to nutrient cycling.
Decomposition: In biology, decomposition refers to the decomposition of dead organic matter.
DNA: Deoxyribonucleic acid is the molecule that carries genetic information for the development and functioning of an organism. It is a polymer composed of two polynucleotide chains that coil around each other to form a double helix.
Lithosphere: The Lithosphere is the solid outer part of Earth, including the brittle upper portion of the mantle and the crust.
Eutrophication: Extreme nutrient accumulation leads to extensive algal and/or plant growth, potentially damaging the ecosystem.
Mineralization: In biology and geology, mineralization refers to transforming organic substances into inorganic substances. In this context, the conversion of organic phosphate to inorganic phosphate by microbes is meant.

Monogastric animals: Monogastric animals are animals that have only one stomach or whose stomach is in one piece. Examples include humans, poultry, pigs, horses, rabbits, dogs, and cats. Most monogastric animals are generally unable to digest many cellulosic foods, such as grasses.
Mineral phosphate fertilizer (inorganic phosphate fertilizer): contains phosphates or other fertilizing substances mainly in the form of salts; these can generally be naturally occurring or synthetically obtained salts.
Mycorrhiza: Mycorrhiza is a symbiosis between plants and fungi in which the fungus is in contact with the plant's fine root system. The fungi involved in the symbiosis are called mycorrhizal fungi.
Orthophosphate: Orthophosphate (PO_4^{3-}) is the anion of phosphoric acid. As a component of amino acids, it plays a central role in the metabolism of organisms and is an essential plant nutrient.
Phosphorus: Phosphorus is a non-metal element that always occurs as the phosphate ion. Phosphate-containing minerals are apatite, phosphorite, and guano.
Phosphate: Phosphate occurs in ecosystems as both organic and inorganic phosphate. It is called organic phosphate when phosphate is bound in organic compounds, such as dead plant remains or excrement. Microbes can convert this organic phosphate to inorganic forms. Inorganic phosphate can occur in different ionic states in the soil. Plants can take it up directly if it is available as soluble inorganic phosphate. However, it tends to precipitate quickly with calcium, magnesium, or iron ions and is then present as complexed inorganic phosphate that can only be converted back to the soluble form by microbes.
Planetary boundaries: With planetary boundaries, experts have specified a corridor within which humans can act without irreversibly damaging the environment (Rockström *et al.* 2009; Steffen *et al.* 2015). Crossing planetary boundaries increases uncertainty and the risk of damage, and after crossing further parameters, the risk of irreversible damage increases. As one of the planetary boundaries, the phosphorus flux into the environment has two control values: the phosphorus flux from freshwater into the oceans and that from fertilizer into erodible soil. The first limit has been set at 11 Tg P per year and is already far exceeded at a current rate of 22 Tg P per year (1 Tg = 10^{12} g). The second limit value was set at 6.2 Tg per year and has also been exceeded at 14 Tg per year.
Polyphosphate: A polyphosphate is a highly anionic inorganic polymer composed of two or many repeating units of orthophosphate linked by high-energy phosphoanhydride bonds. It is a ubiquitous metabolite in all organisms, including humans and microorganisms.
Phytate: Phytate, or phytic acid, is used by plants to store phosphate, which they need for photosynthesis, among other things. The only mammals that can break down phytate and use the resulting phosphate are ruminants. In their stomachs, bacteria produce the necessary enzyme, phytase. In humans, however, consuming phytate-rich foods means that many of the minerals in the food cannot be absorbed because the phytate binds them.
Rhizosphere: The rhizosphere is the narrow region of soil or substrate around plant roots that is directly affected by root secretions and associated soil microbes.