The Phosphorus Cycle

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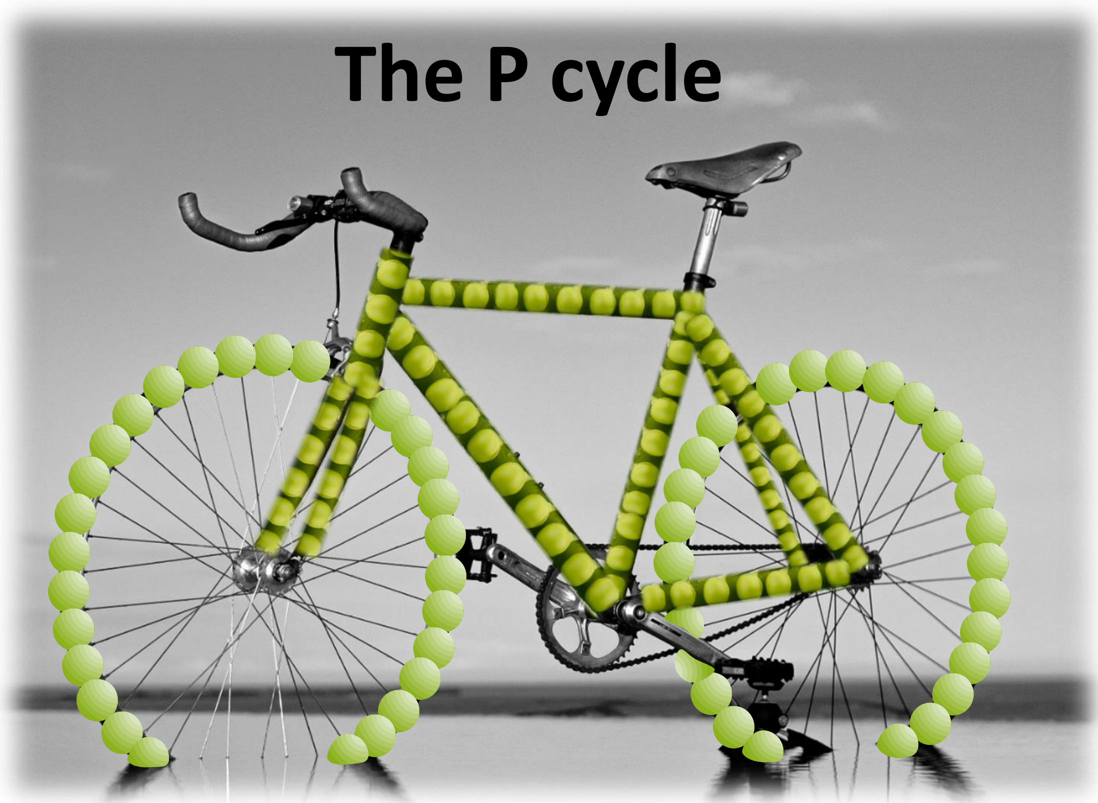

The pea cycle: image made from original pictures taken by Zoltan Tasi on Unsplash and Bill Ebbesen on Wikipedia commons via a Creative Commons Attribution-Share Alike 3.0 Unported license.

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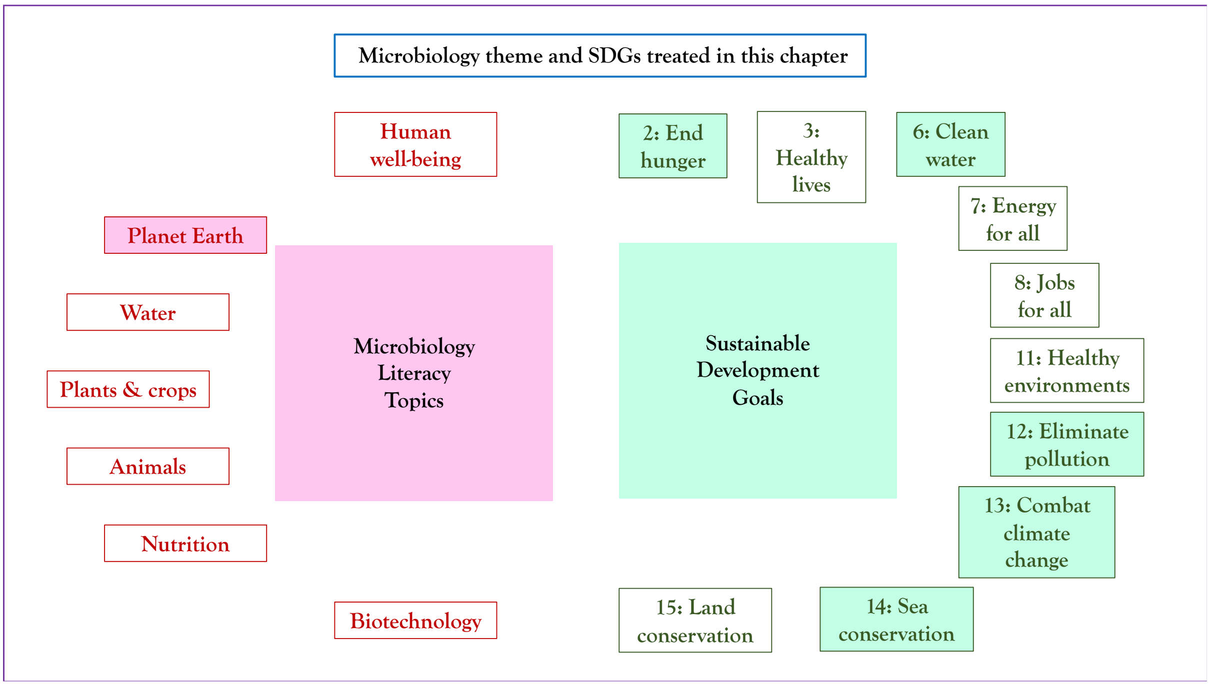
Phosphorus cycle

Storyline

We often consume products without thinking where they come from or what natural resources are used in their production. A biogeochemical cycle might be difficult for a child or teenager to envisage or engage with but think about breaking this down into a constituent element that is vital to all life and that is liberally used to promote crop production, and you can instantly see a connection with sustainable development goals. What we eat and grow though can be modified and our consumption of natural resources made more sustainable if we can access elements potentially locked away in soils and sediments. The phosphorus (P) cycle is a prime example of this and which highlights the role that microbes might play in mobilising this locked away P element.

The microbiology and societal context

The microbiology: Elements like P are essential for cellular processes. Organisms consume this resource but also excrete variants of the element as waste or release it following death. Most P in soil is unavailable, but microbes can solubilise it and make it available for plants and themselves. Microbes mediate P cycling. *Sustainability issues*: Only a small fraction of soluble forms of P and N added as fertiliser to increase crop yields is used by target plants, and most is washed out of soils as run-off, which can cause pollution, eutrophication, algal blooms, etc. Over-use of an essential resource will cause long term sustainability issues linked to health, food production, economic output, environmental pollution. Unlike the two other major elements, carbon and nitrogen, there is no major gaseous form of P in the atmosphere that can be 'fixed' into biological cells. Therefore, there is no short-term regeneration of new 'useful' P into the earth ecosystem. The principal form of P fertiliser, rock phosphate, is a dwindling Earth resource required to maintain our food supply and that needs careful management.



Phosphorus cycle: the microbiology

1. ***Dad, there are so many people now on planet Earth I'm worried we will run out of something we really need. Should I be concerned?*** See **https://www.theguardian.com/environment/blog/2011/oct/31/six-natural-resources-population.** There are almost 8 billion people on planet Earth and probably the resource that is most often thought to be in short supply is water. Whilst it's predicted that by 2025 1.8 billion people will live in areas of water scarcity, in reality the element that will likely run out first is phosphorus – which is predicted to run out in 100-300 years unless new reserves are found. See **https://www.theguardian.com/environment/2019/sep/06/phosphate-fertiliser-crisis-threatens-world-food-supply**

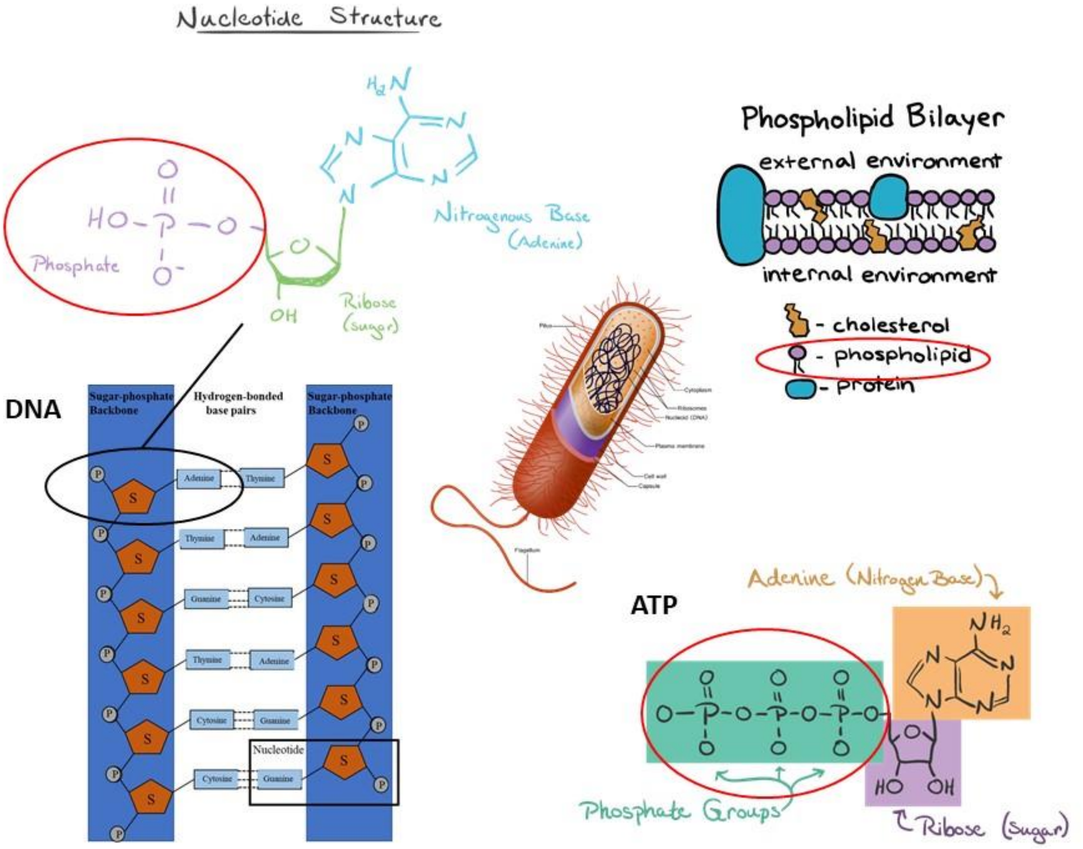
2. ***Dad: What's phosphorus and why do we need it?*** You've heard me say many times before son "it's tea time – so get stuck in and eat", since this will keep you healthy and get your energy levels up. All life forms have to 'eat' or they'll die. Most organisms on earth including microbes need about 100 times more carbon (usually carbohydrates e.g. in the form of sugars, such as glucose or fructose) than phosphorus and about 10-20 times more nitrogen. These three elements are known as macronutrients, meaning they are needed in relatively large amounts. We eat to obtain these essential nutrients that are required for basic cellular processes.

Phosphorus is one of those nutrients (elements) and is a particularly interesting one since the energy currency of a cell – ATP – contains a lot of phosphorus in the form of phosphate (PO_4^{3-} the ionic form of phosphoric acid) (Figure 1). Moreover, the genetic blueprint of all cells are genes – no, NOT jeans son, those are what you wear. GENES are short segments of DNA that store information for building proteins that perform cellular processes. Genes are often called the blueprint that comprise our make-up and indeed, the make-up of all life including bacteria – this is part of the central dogma of life on Earth – DNA makes RNA makes protein. DNA is a complex molecule and phosphorus (as phosphate) performs a crucial role in holding this molecule together, forming the 'backbone'.

Phosphorus is also an important part of the cell membrane, the bag that captures and contains all cellular contents. Finally, phosphorus in the form of a phosphate bond is often used to tag proteins (phosphorylate them) and this is used extensively in cell signalling – deciphering and responding to messages about our 'environment'. Just so you know – and this may sound gruesome son – but an average person contains about 0.7 kg of phosphorus – mostly in bones and teeth.

3. ***So where is all this phosphorus and why are we running out of it?*** The Earth's crust contains about one gram of phosphorus per kg of material. It is usually found as a phosphate mineral in rocks. Farmers use this phosphorus (rock phosphate) to help grow the crops and animals we eat. Rock phosphate takes a very long time to form, similar to the formation of oil. We are now using so much rock phosphate to grow our food that the reserves found in rocks are starting to run out. Mining rock phosphate is an expensive process and we cannot simply use phosphorus stored anywhere in the Earth's crust. China, the USA, India and Morocco are the countries with the largest rock phosphate reserves and mining activities.

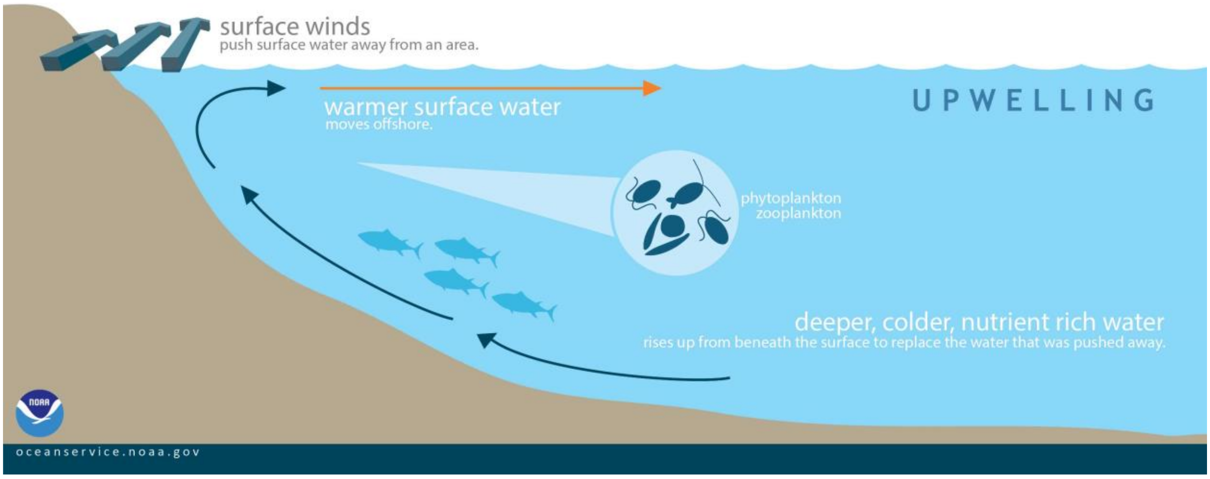
However, probably the vast majority of phosphorus on Earth is on the ocean floor. Weathering of rocks causes runoff from rivers into the oceans and some P is also deposited into the ocean via rainfall or dust or from glaciers. Microbes can process this particulate phosphorus into a dissolved form since, as I mentioned earlier, P is needed for all life including bacteria. Don't forget that the bones and teeth of fish also contain phosphorus and these can also be deposited and buried on the ocean floor.



Phosphorus is a key component of all cells – being a component of DNA and cell membranes, as well as part of the major energy currency of a cell, ATP. Images courtesy of Ali Zifan (Bacterial cell) via Wikimedia commons licence CC BY-SA 4.0 licence see https://creativecommons.org/licenses/by-sa/4.0; The DNA image is from Wikimedia Commons under the Creative Commons Attribution-Share Alike 4.0 International license. The ATP, nucleotide structure and phospholipid bilayer images are from https://www.khanacademy.org/science/ap-biology/cell-structure-and-function/membrane-permeability/a/fluid-mosaic-model-cell-membranes-article using a CC-BY-NC-SA 4.0 license https://creativecommons.org/licenses/by-nc-sa/4.0/

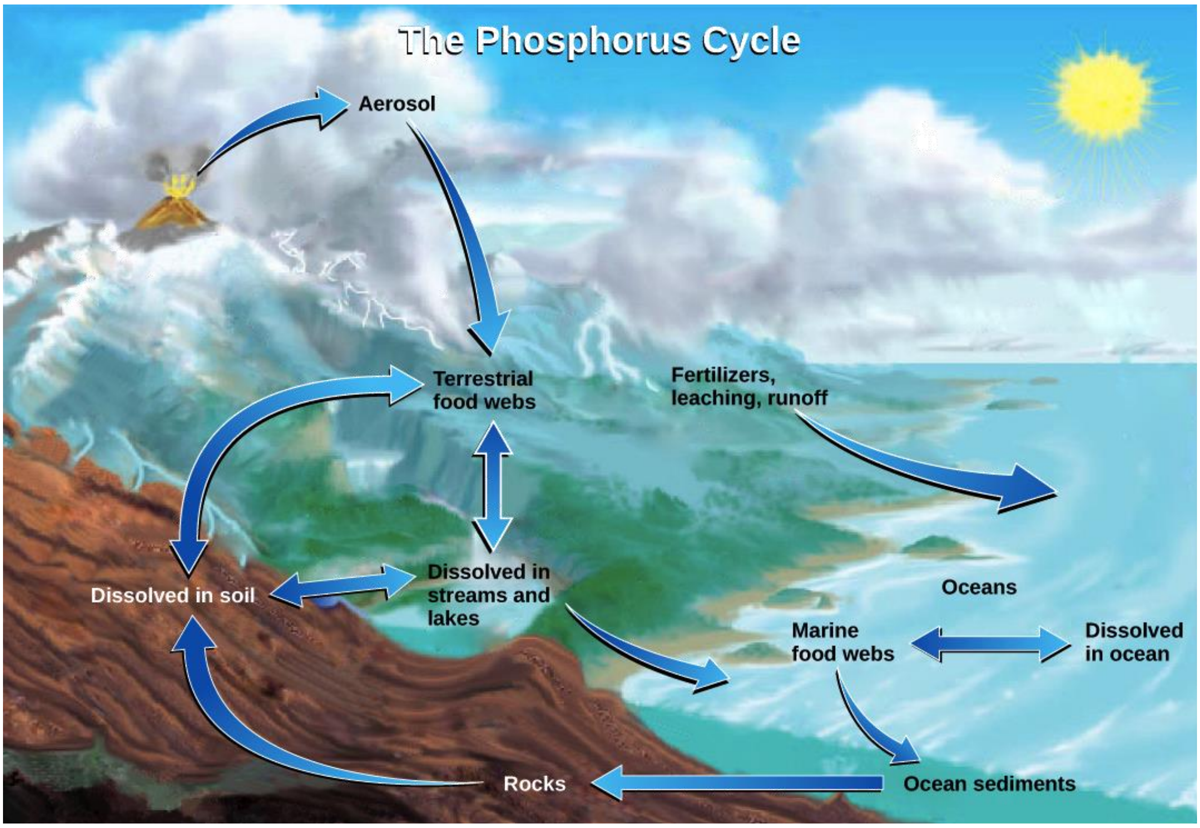
4. ***So, what happens to all this P on the ocean floor?*** Well, this reservoir of P is slowly processed by bacteria and released as soluble phosphate from the seafloor into the seawater. However, most of the ocean is really deep. The next part of the story is really cool: winds blowing over the ocean surface causes seawater to be pushed along horizontally. Water then rises up from beneath the surface to replace the water that has been pushed away. This process is called upwelling. This upwelling water containing lots of phosphate and provides nutrients for microorganisms living in the surface ocean.

One important group of microorganisms is the phytoplankton, which are tiny single-celled organisms, almost like miniature plants. They capture energy in sunlight, in a process called photosynthesis, and use these nutrients including phosphorus to grow and make more living cells. These organisms are called primary producers since they support all life up the food chain, by harnessing energy directly from the sun.



The process of ocean upwelling. Image from What is upwelling? National Ocean Service website, https://oceanservice.noaa.gov/facts/upwelling.html, 04/09/20 via Wikimedia commons. This work is in the public domain.

5. ***So Dad, is this all part of a nutrient cycle?*** Yes, that's right. So elements cycle between organisms and their environment. The P entering the oceans from rivers at the surface ultimately sinks and is locked away for thousands of years on the ocean floor, before eventually microbes recycle this P and upwelling systems return it to the surface. It is this cycle which is one of the major biogeochemical cycles on Earth that moves elements like P in different forms around our planet.



The Phosphorus cycle. Image from *Biogeochemical cycles: Figure 5* by OpenStax College, Concepts of Biology, using creative commons licence CC BY 4.0; modification of work by John M. Evans and Howard Perlman, USGS see https://openstax.org/books/concepts-biology/pages/1-introduction

Biology is just as important as chemistry and physics in this process and microbes are the major drivers of the biological part of this cycle. This is the engine of our planet – and like a car engine it needs fuel to work. Hence, as major consumers of these natural P resources, humans need to be able to manage these really carefully or we will be without a major element required for our food supply and ultimately our existence.

Doesn't this make you see son that protecting our planet and its resources is crucial to maintain all life on planet Earth and we need to be really careful to be sustainable in this respect so that these resources last far into the future?

6. ***Dad, you mentioned an engine here – what do you mean by that?*** Well, if you think of the oceans as an engine, then all the elements that are cycling in the ocean ultimately are used to make biomass and fuel the whole system. In the oceans, the phytoplankton fuel the rest of the food chain. These tiny phytoplankton provide food for tiny animals (zooplankton) which in turn are eaten by larger zooplankton, and so on until they are eaten by fish. Ultimately humans are the top ocean predators removing millions of tonnes of fish each year for consumption (see http://www.fao.org/state-of-fisheries-aquaculture).

You might think that on Earth it is plants that are key to photosynthesis. However, it is the oceans that are the 'beating heart' of the Earth's carbon cycle: 'with ~1 billion tonnes of phytoplankton alive in the ocean at any one time but with 45 billion tonnes of new phytoplankton produced each year, phytoplankton have to reproduce themselves entirely, on average, 45 times a year, or roughly once a week.

In contrast, the world's land plants have a total biomass of 500 billion tonnes, most of it wood, but with much slower growth compared to phytoplankton plants, and reproduce themselves entirely only once every ten years'. So whilst soils (three billion tonnes carbon per year) currently soak up more CO_2 than the oceans (two billion tonnes carbon per year) (https://www.nature.com/scitable/knowledge/library/soil-carbon-storage-84223790/), the microbes in the oceans have a greater potential to adapt and evolve to the drastic environmental changes caused by human activities. The functioning of the oceanic and terrestrial carbon pumps can be limited by the availability of resources like phosphorus – like your car engine needing a supply of petrol. In this way, these biogeochemical cycles then become inextricably linked.

7. ***Dad, so you haven't answered yet why we are running out of it?*** Well son, we eat plants for our food and we also use plants to feed other animals we eat for food – crops sustain all human life. Plants also need P to grow, the same as the phytoplankton and as we all do. One of the great advances in agriculture came in Britain when farmers starting rotating different crops in their fields. Farmers learned that by using clover in between grass crops, such as wheat and barley, plant and livestock productivity was massively increased. This is because clover has certain microorganisms living in their roots which help convert nitrogen in the atmosphere into forms available for plants to grow. This process acts to 'fertilise' soils with N.

Unfortunately, there is no similar process for P, so farmers soon had to apply chemical P fertilisers to maintain this increased crop growth. Humans are now trapped in this unnatural cycle where we need to apply excessive amounts of chemical P fertilisers (and extra chemical N fertilisers) to help sustain our interminable need for food as our global population rises. It is these P fertilisers that are running out.

Moreover, because soil is so chemically, biologically and physically complex, only ~20% of the chemical P fertiliser farmers apply ends up as plant biomass. The remaining majority is either chemically-fixed into soils in forms that plants can no longer access or flushed away quickly into our rivers, causing problems of groundwater contamination and eutrophication of lake and coastal systems. Given rock phosphate is a limiting resource this is clearly not sustainable and will lead to future political tensions between countries, as well as driving the price of all our food higher.

Don't forget that currently there are also large problems of food waste, and dietary requirements for milk and meat mean a large proportion of crops are fed to animals. The latter is very inefficient with 36% of calories from crop production used in animal feed but only 12% of these feed calories ultimately ending up in the human diet. However, crops generally have a lower water footprint than animal foods. A plant-based diet is known to dramatically decrease the amount of nitrogen lost to the environment during the food production and consumption stages. Likewise, the amount of mined phosphate required to produce the food consumed in a conventional meat-heavy diet is much greater than that of a plant-based diet.

One estimate suggests that if consumers in the USA shifted to a plant-based diet, the country's phosphorus fertilizer demand could decrease by 44%. Moreover, the addition of phytate-degrading enzymes (phytases) into plant-based animal feeds also helps to improve the efficiency of P cycling from crops to animals. Not only do phytases help break down phytate to biologically available phosphate so animals can grow, they also reduce the amount of P being released to the environment in animal excreta. Thus, using microbial enzymes massively helps to reduce the impact agriculture can have on the global P cycle, which, as discussed above, is tightly linked to both the N and C cycles.

8. ***Dad, I have heard of eutrophication, why is it so bad for humans though?*** This huge input of fertilisers stimulates phytoplankton growth, just the same as the upwelling of nutrient-rich deep sea water does. Some of these algal blooms are massive and release toxic substances which can cause harm to humans.

The large input of nutrients from farmland into rivers and lakes causes algal blooms, seen here as a green mat over the top of the pond, to occur. This is the first sign of eutrophication that often leads to the death of natural wildlife in the affected area. Image from Wikimedia commons and accessed via https://commons.wikimedia.org/wiki/File:EutrophicationEutrophisationEutrophierung.jpg crediting use of a Creative Commons Attribution-Share Alike 2.5 Generic license

When these huge algal blooms die, bacteria rapidly feed on the dead algal biomass and in doing so they use up the oxygen in the water. When this happens, fish and other aquatic life can no longer breathe and they die. Many humans rely heavily on lake, river and coastal ecosystems for food and tourism. Thus, eutrophication can have very serious consequences for local economies and human health due to the loss of fish and shellfish and the closure of beaches and lakes.

9. ***Dad, so if we are running out of P, what can we do?*** There is now an urgent need to make plants give a higher yield whilst using more sustainable agricultural management practices. Perhaps one of the biggest changes will need to be how we use chemical P fertilisers, i.e. using much less without sacrificing the growth of crops. One big area of interest is to look at how microorganisms can help release all the various forms of phosphorus that are 'locked-up' in soils and are otherwise unavailable to plants.

One major fraction of soil phosphorus is called organic phosphorus (organophosphorus), compounds, such as membrane lipids, nucleic acids (e.g. DNA), sugar phosphates and glycoproteins that have been made through biological processes. In soils, a major organophosphorus compound is the plant P storage molecule phytate (sugar-phosphate). Microbes possess special enzymes which they release from their cells to break down various organophosphorus compounds, including phytate. This microbial activity can help fertilise the soil with labile phosphate that plants can take up for growth.

In essence, this is similar to the microbes in clover converting atmospheric nitrogen into forms the plant can take up. We are still learning lots about these special enzymes and how they work, but we do know that because there are so many different microbes in the soil, the diversity of these enzymes is enormous. This gives us an opportunity to develop ways to transform these different forms of phosphorus into plant-available phosphate.

One exciting area of future research will be understanding how different mixtures of microbes can work together in 'teams' to release the most phosphate for plants by transforming all the various forms found in soil. In addition to soil bacteria, a special group of fungi (mycorrhizal fungi) can help plants take up phosphate. The fungi grow from inside the plants roots outwards into the soil extending the surface area of plant roots in the soil in long filaments, called hyphae.

Recent research has now shown that bacteria living alongside these fungal hyphae help break down organophosphorus and immobilised inorganic P complexes into plant-available phosphate, which the fungi then take up and transfer to the plant!! Scientists are now looking at how these microbes can be used to grow plants outside normal soil systems, in particular growing plants in recycled plastics and water systems (hydroponics). Scientists are even investigating if we can use waste products (pooh!) from fish grown in aquaculture to supply the nutrients for these hydroponic systems!!

10. ***Dad: if we are wasting so much P, is there any way we can recover it?*** Well, as I just mentioned, microbes can help to remove P from entering waterways which helps to reduce the number of free nutrients in the water which the algal feed off. This idea is already being put to good use in swimming pools. Many companies are developing microbial water filters which combine microbial communities being housed in special water tanks. As the pool water moves through the filter the microbes use the nutrients, including phosphorus, recreating the pristine water conditions, like those found in glacial lakes. In turn this reduces our use of hazardous chlorinated chemicals. Similar approaches are already being used to try and recover P from wastewater treatment plants.

Anaerobic digesters are used to help reduce the amount of organic compounds in water, acting like a giant filter. Whilst research has traditionally identified phosphate accumulating bacteria, a special group of microorganisms related to Archaea that are abundant inside these anaerobic digesters are being studied to see how they can take up P and store it inside their cells, which can later be harvested.

Relevance for Sustainable Development Goals and Grand Challenges
(https://sdgs.un.org/2030agenda)

- **Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture** (*end hunger and malnutrition, increase agricultural productivity)*. Higher crop productivity relies on a constant source of phosphorus in soils so plants can grow large. Humans have an insatiable demand for meat and dairy products, necessitating increased food production and the land area crops and livestock are grown or grazed upon. Remember son that the human population is rapidly increasing. Currently there are ~7.8 billion people on the planet and this number is predicted to rise to 9.6 billion by 2050. This is having a massive impact on our natural world with the clearing of forests, and this in turn contributes to increased greenhouse gas emissions, biodiversity loss and soil degradation, particularly erosion (due to increased tillage and grazing). Increased flooding due to climate change in turn increases the soil erosion problem.
- **Goal 6. Ensure availability and sustainable management of water and sanitation for all** (*assure safe drinking water, improve water quality, reduce pollution, protect water-related ecosystems, improve water and sanitation management)*. Agricultural run-off of P into groundwater causing contamination, and into lakes causing eutrophication, is a clear problem. The latter causes algal blooms that not only deoxygenate the water column but may also produce toxins harmful to humans and animals.
- **Goal 12. Ensure sustainable consumption and production patterns** *(achieve sustainable production and use/consumption practices, reduce waste production/pollutant release into the environment, attain zero waste lifecycles, inform people about sustainable development practices)*. The use of microbes to unlock the large deposits of organic phosphates in soil (described above) – will require knowledge of new microbial P acquisition systems which is just being worked out in soil systems.
- **Goal 13. Take urgent action to combat climate change and its impacts** *(reduce greenhouse gas emissions, mitigate consequences of global warming, develop early warning systems for global warming consequences, improve education about greenhouse gas production and global warming)*. Food production is clearly linked to deforestation and increased greenhouse gas emissions. The absence of rock phosphate will exacerbate this further.
- **Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development** *(reduce pollution of marine systems by toxic chemicals/agricultural nutrients/wastes like plastics, develop mitigation measures for acidification, enhance sustainable use of oceans and their resources)*. A major source of P to the oceans is via riverine input from P fertilisers applied to soil systems. A natural component of the P cycle is the return of nutrient (P)-rich water to the surface via upwelling events. This sustains primary production which supports the whole marine food web, provides oxygen that we all breathe and consumes the greenhouse gas carbon dioxide. Any perturbations to this natural cycle may have unforeseen consequences for the workings of the whole ocean engine.

Potential Implications for Decisions

1. ***Individual***

   a. Weighing up the various microbial and non-microbial factors and aligning them with personal convictions (We all need to eat to stay alive but what about the size of our families i.e. how many kids should we have? Since the human population is exponentially increasing and thus consuming more and more natural resources we have a responsibility here & to include environmental considerations).

   b. Do you think about how much food you buy, consume, but also potentially throw away?

   c. Do you consider organically farmed foods versus food produced via intensive farming practices? Would you pay more for food that was farmed 'friendlier' i.e. without excessive use of P fertilisers? Sustainability issues (crash of fish stocks in the 70s and 80s?) Do we seek out eating farmed fish versus wild varieties; biodiversity implications (e.g. palm oil monocultures widespread now in south-east Asia which have removed high diversity natural rain-forest habitats)

   d. *Non-microbial parameters:* Wider political issues on government subsidies for farming practices, environmental sustainability policies, fishing quotas, biodiversity implications (viz-a-viz 'robustness' of the natural environment).

2. ***Community policies***

   a. Local environmental consequences (pollution of public spaces and local water bodies with faeces, nitrogen, phosphorus), provision of clean drinking water

   b. Health costs associated with over-eating and conversely poor-nutrition

   c. *Non-microbial parameters:* support of rural businesses/economy; new technologies for sustainable food production; policy regarding agricultural run-off of nutrients into water-courses.

3. ***National policies relating to food supply***

   a. Environmental pollution

   b. Ensuring safe drinking water supplies

   c. Eutrophication/algal blooms/toxic algal blooms preventing use of surface water bodies, fisheries, tourism, etc.

   d. Greenhouse gas production and global warming

   e. Optimal use of agricultural land for food and renewable production; can potentially free up land for better flood protection.

   f. *Non-microbial parameters:* policies relating to sustainable agriculture; subsidies for wildlife friendly farming

Pupil Participation

1. Class discussion of the issues associated with supplying food to an ever-growing human population

2. Pupil stakeholder awareness

   a. An increasing human population generally has negative consequences for the SDGs. Which of these are most important to you personally/as a class?

b. Can you think of anything that might be done to reduce the negative consequences, especially in terms of new technologies that might allow us to unlock essential nutrients and produce more food with less environmental impacts?

c. Can you think of anything you might personally do to reduce your environmental footprint?

3. ***Exercises*** *(could be made at any level, but these are probably secondary education level)*

a. Most countries are not self-sufficient in terms of their food supply. What can your country do to change this?

b. Crops are mostly produced in large commercial facilities that involve intensive farming, often with little environmental consideration. Using your new knowledge of the P cycle how might you formulate more sustainable agricultural management practices with less environmental hazard consequences?

c. Looking at the SDGs, how can we change our approach to farming to bring it into sustainable living? What are the challenges and opportunities? Create a sustainable plan that takes account of future increases in the human population and their associated environmental impacts.

The Evidence Base, Further Reading and Teaching Aids

General reference

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Glossary

Algal bloom: a rapid increase in the growth of algae or cyanobacteria in freshwater or marine aquatic systems usually caused by nutrient input and often linked to an obvious discoloration of the water due to the pigments these organisms possess.

Archaea: a domain of microorganisms that have distinct molecular and physiological attributes separating them from bacteria and eukaryotes.

ATP: or adenosine 5'-triphosphate is the chemical used by all cells for storing and transferring energy, the so-called energy currency of a cell.

Biogeochemical cycle: the natural pathways by which elements cycle including how elements flow between living organisms and the environment and comprising biological, chemical and geological aspects.

Crop production: the process of producing a crop (plant or animal product) that can be extensively harvested for profit or subsistence use.

DNA: or deoxyribonucleic acid is the molecule that contains the genetic code of virtually all living organisms and thus carries the instructions for their growth and replication

Element: the primary chemical constituents of all matter none of which can be broken down into a smaller component

Eutrophication: the enrichment of a water body with nutrients and minerals

Groundwater contamination: chemical or waste pollutants that are released into the environment and leach into water bodies (groundwater) beneath the Earth's surface; such groundwater is important because it is a major source of public water supplies.

Natural resources: a material or substance that occurs naturally and that is often exploited for economic gain.

Photosynthesis: the process by which plants, algae and cyanobacteria use sunlight, carbon dioxide and water to produce organic nutrients (and oxygen) thereby converting light energy into chemical energy

Phytoplankton: all photosynthetic plankton, including e.g. algae and cyanobacteria, with plankton derived from Greek and meaning to wander and thus comprising organisms incapable of swimming against a current.

Primary production: the increase in phytoplankton biomass as a result of photosynthesis.