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Toitū te Whenua,
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Strategies to improve the efficiency and decrease the negative environmental impacts from phosphorous fertiliser use

Dr Charles N. Merfield MRSNZ

Merfield Agronomy Ltd and The BHU Future Farming Centre

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We may be able to substitute nuclear power for coal, and plastics for wood, and yeast for meat, and friendliness for isolation but for phosphorus there is neither substitute nor replacement.

Asimov, 1974

Life can multiply until all the phosphorus has gone and then there is an inexorable halt which nothing can prevent.

Asimov, 1974

1. Introduction and context

This report is part of an Our Land and Water, National Science Challenges funded project identifying strategies to improve phosphorus (P) use efficiency, decrease the negative environmental impacts from P fertiliser use and identify sources of P rock in Aotearoa New Zealand (A-NZ). This is the first report of two that provides a background to possible strategies. The second report The viability, feasibility, and environmental impact from using New Zealand sourced phosphate. The *Sustainable Phosphate Futures for New Zealand* Project was funded by the National Science Challenge – Our Land and Water through their Rural Professionals Fund.

This report is written for a general audience assuming some basic scientific understanding. As there is a very extensive global and local scientific literature on this topic, referencing is limited to key sources, e.g., review papers.

The introduction provides some context for P fertiliser use, in terms of the global planetary challenges facing humanity and how P fertiliser is intertwined with many of them. It then explains the fundamental knowledge of P, and P fertilisers to build a picture of the global challenge of P management. The concept of the circular economy and bioeconomy are explained as context for the need to close the P cycles. Then the flows of P in A-NZ are explained, and the key losses where P recycling could be improved are identified. The final section details methods for better managing P in agriculture including outlining the key agricultural mitigation techniques.

1.1. The global context of phosphorus fertiliser

Globally and in A-NZ, the problem of accessing, using, and loss to the environment of P is becoming ever more acute (Brownlie *et al.*, 2022c). Phosphorus is the next most important essential nutrient in biology after nitrogen (N) and is also an essential component of number of manufactured products and processes.

However, current P systems are highly linear: It is mined from fossil reserves of rock with a high P content, which is processed to concentrate the P and reduce unwanted contaminants, before mostly being used as fertiliser as well as in a range of manufactured products. Much of the P is eventually lost to the environment, mostly to waterbodies, through multiple pathways.

For example, there are direct losses of P from farm land, such as leaching of dissolved P into waterways, and the P in food ends up in sewerage systems, which discharge some of the P into waterways. The additional P in the environment creates multiple harms, particularly eutrophication of waterways. Much of the P thus ends up in the oceans where there are limited options to retrieve it economically and practically. The natural P cycles have thus been turned into linear streams at human time scales. For example, mined P is used as fertiliser, turned into food, which is consumed, the resulting sewerage is treated but the P is not captured, the discharge goes to rivers, so the P is then lost to the ocean. This occurs at time scales of years to decades, compared with the tens to hundreds of millions of years of the geological P cycle.

The costs of P lost to the environment are very difficult to estimate so there are few such studies. One example of the cost of fresh water eutrophication in the USA was US$2.2 billion annually covering losses to industry, real-estate, and management for conservation of endangered species and drinking water supply (Dodds *et al.*, 2009).

1.2. Planetary Boundaries

The Nine Planetary Boundaries are a framework of the main planetary systems that regulate life on earth (Anon., 2015; Steffen *et al.*, 2015). Humanities impacts on the nine earth systems are assessed if they have transgressed the limits — boundaries — of their self-regulation. These are regularly updated as scientific knowledge is expanded. Biogeochemical flows of P are the 4th most transgressed boundary after (in order) nitrogen, novel entities (synthetic chemicals such as pesticides and plastics) and biosphere integrity: extinctions per million species per Year (E/MSY) more generally called biodiversity loss (Figure 1).

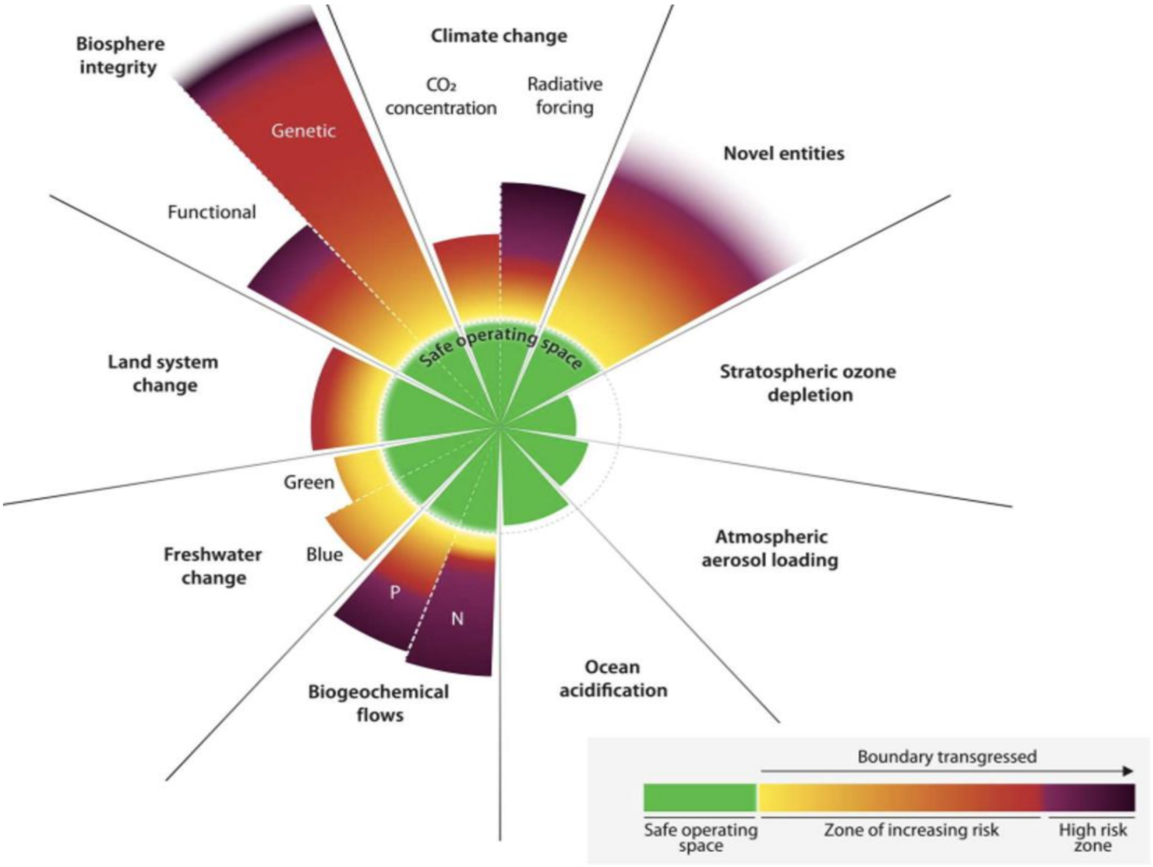

Figure 1. Richardson, K., Steffen, W., Lucht, W., et al. (2023). Earth beyond six of nine planetary boundaries. Science Advances, 9(37), eadh2458. doi:10.1126/sciadv.adh2458

Reducing biogeochemical flows of P to the environment is therefore a key aspect of reducing planetary boundary transgressions.

1.3. Ecosystem services

Ecosystem services are the direct and indirect contributions of ecosystems to human well-being (Costanza *et al.*, 2017) (Figure 2)

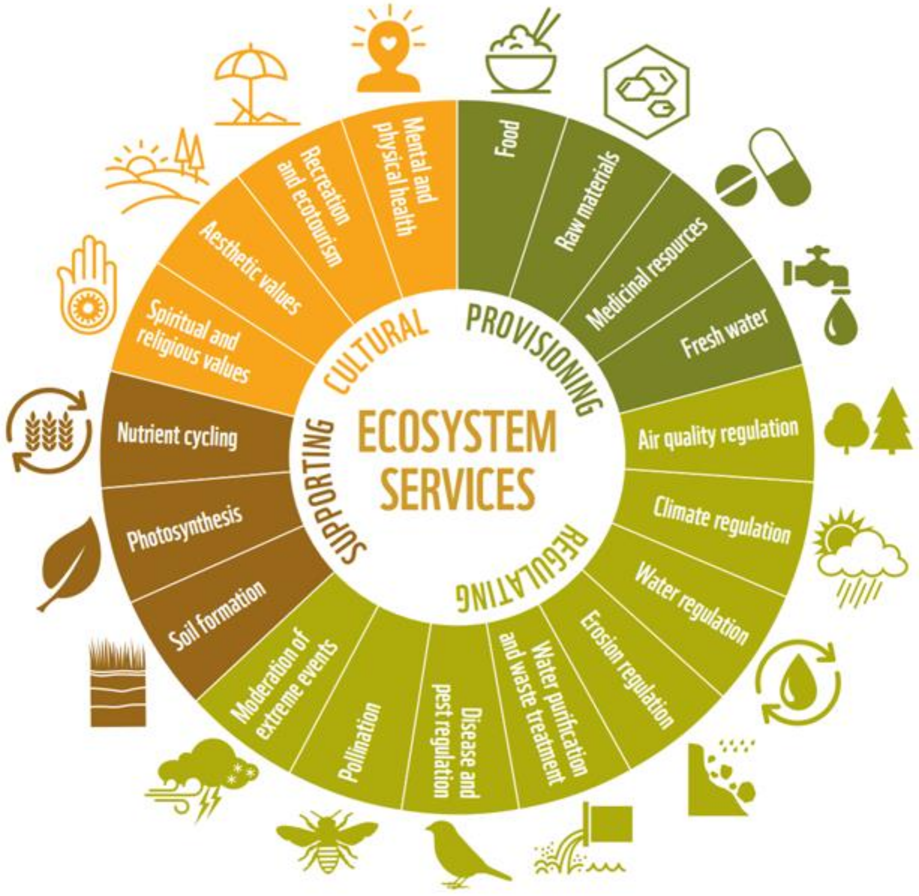

Figure 2. Ecosystem services (WWF, 2016).

Agriculture provides ecosystem services as it is an ecosystem. However, compared with natural ecosystems, agroecosystem service provision is often much reduced due to the simplification of the ecosystem and a focus on the single ecosystem service of food & fibre production. Phosphorus has a key role in supporting the provision of ecosystem services and avoiding disservices such as reduced biodiversity through excess P in waterbodies (Macintosh *et al.*, 2019).

Thus, there are multiple challenges around phosphorous to address. Re-establishing P cycles and minimising losses to ensure the long-term sustainability of P use, while also reducing the environmental and other negative impacts of P.

1.4. Phosphorus and other global challenges

At the same time, it is essential that P challenges are not addressed alone. Other issues, such as the global nitrogen deluge (Sutton *et al.*, 2011) unsustainable use of lithospheric nutrient (see section 2.5.1. Lithospheric nutrient cycles) other than P, climate change, biodiversity loss, and other planetary boundaries and ecosystem services are all interlinked. It is consequently imperative that the P challenge is addressed in unison with the other global challenges.

2. An introduction to Phosphorous

This section outlines the foundational physical, chemical and biological concepts of P. While these foundational concepts will be familiar to some, especially those working in science and agriculture, it is considered important that they are made explicit as they are not necessarily understood by everyone.

2.1. Phosphorous

Phosphorous is a nonmetal element with multiple allotropes (having different forms). All elemental forms of P are highly reactive so it is never found as a free element. The most common natural P compound is phosphate (PO_4^{3-}).

Being a chemical element P cannot be created or destroyed in the conditions (temperature, pressure, etc.,) on earth. It is only created and destroyed (transformed into other elements) by stellar nucleosynthesis, i.e., in stars. It is also completely stable, so does not undergo radioactive decay. This means it is impossible to manufacture P, it can only be extracted from the environment. It also means that P cannot be destroyed, e.g., where it is an environmental pollutant it cannot be broken down to get rid of it, it can only be removed / extracted. And unlike mineral and organic forms of reactive nitrogen, which can be denitrified back to gaseous dinitrogen (N_2, see section 2.8. A comparison of nitrogen and phosphorous global cycles and fertilisers) to remove it, P does not have a gas phase so it has to be physically removed. For example, removing sediment from ponds, or removing plant biomass that has taken up the P.

2.2. Essential nutrients

Phosphorous is an essential nutrient. An essential nutrient is a chemical element that is absolutely necessary for living organisms to survive, grow, and reproduce and which cannot be substituted by any other chemical element (Arnon & Stout, 1939; Brown *et al.*, 2022).

If the essential nutrient is not present in the right amount in an organism, both too much and too little, the organism will be unable to achieve its full genetic potential, e.g., it may be stunted or die (Figure 3).

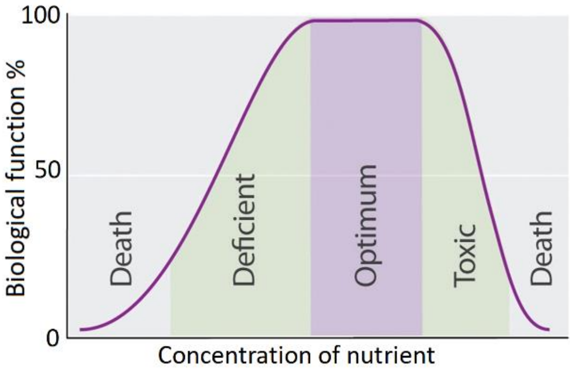

Figure 3. Generalised deficient, optimum, and toxic concentrations of essential nutrients. The shape of the curve varies for different nutrients. (Plunkett *et al.*, 2019)

Biological stoichiometry is the science that studies how the proportion / ratio of nutrients and energy influences an organism's or an ecosystem's functioning. All living things are composed of a similar proportion of nutrients, principally carbon, oxygen, and hydrogen accounting for ~96% of plants and ~93% of animals, with the proportion of nitrogen, phosphorus, potassium, and calcium in plants being ~3% and animals ~6%. All the other essential nutrients including boron, chromium, cobalt, chlorine, copper, fluorine, iodine, iron, magnesium, manganese, molybdenum, selenium, silicon, sodium, sulphur, tin, vanadium, and zinc, represent about 1%. That organisms have a relatively narrow range of nutrient proportions has significant implications and limitations. For example, if organic carbon is to be sequestered in soil, sufficient nitrogen, phosphorous, etc., must be added to the soil system to achieve a stoichiometric balance with the additional organic carbon.

2.3. The law of the minimum

Following on from biological stoichiometry is the law of the minimum. Developed by Carl Sprengel in 1840 it was popularised by Justus von Liebig and is also referred to as 'Liebig's law of the minimum', or simply 'Liebig's law'. It states that the growth of an organism is dictated by the scarcest nutrient — the limiting factor — not by total resources available. This is often visualised as Liebig's barrel (Figure 4).

The level of liquid in a barrel with unequal length staves is limited by the shortest stave, so is an organisms growth limited by the nutrient in shortest supply. Thus a deficient nutrient cannot be substituted by an excess of any other nutrient. For example, if soil is deficient in P that deficiency cannot be compensated by adding extra nitrogen fertiliser, it can only be resolved by adding sufficient P fertiliser to eliminate the deficiency.

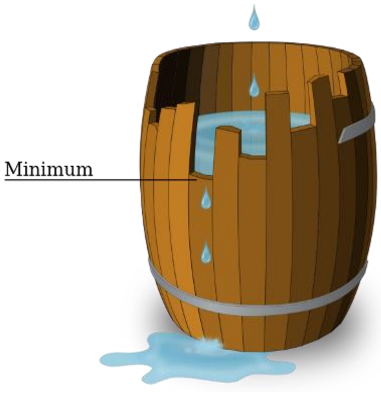

Figure 4. Liebig's barrel (Wikipedia).

2.4. The role of phosphorous in biology and manufactured products and processes

Phosphorus is the most important nutrient in biology after carbon, oxygen, hydrogen and nitrogen. It makes up ~1% of animals and ~0.2% of plants. It has many functions, for example, it is part of the 'backbone' of DNA (deoxyribonucleic acid) and RNA (ribonucleic acid), and at the core of ATP (adenosine triphosphate) the energy carrying molecule used by all forms of life, and in vertebrates it is a key component of bone. Insufficient P therefore causes breakdowns of multiple biochemical systems, making it bio-essential.

Phosphorous is also a key component of a wide range of manufactured products and processes. The dominant use is in fertilisers, both straight and compound fertilisers. It is also used in many other products such as fire retardants, food additives e.g., preservatives, plasticisers, pesticides e.g., glyphosate, electronics, pharmaceuticals, laundry detergents, toothpaste, specialised glasses, bone china, rust remover, etching agents, catalysts, lubricants, flotation agents, metal plating, battery electrolytes, antiscale agents, luminescent materials, military purposes e.g., tracer ammunition, safety matches and fireworks (de Boer *et al.*, 2019). Phosphorus can be substituted or just removed from some of these products, e.g., a number of jurisdiction have banned the use of phosphates in consumer detergents, however, for a number of products and processes this is impossible, for example the herbicide glyphosate.

Phosphorous is therefore indispensable and unsubstitutable in both biology and many manufactured products and processes.

2.5. Natural phosphorous cycles

There are two phosphorus cycles: the soil cycle and the geological cycle (Figure 5).

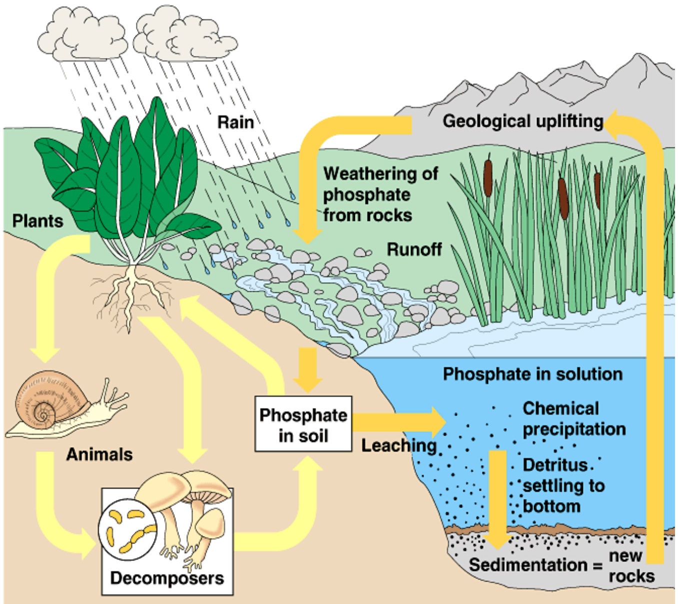

Figure 5. The two phosphorous cycles: soil and geological. Image from Pearson Education.

The soil cycle (see section 2.6. The human phosphorus stream below for detailed information) at a high level is quite simple, plants take up P from the soil, when they die, shed leaves and roots, the P returns to the soil, or they are eaten by animals which excrete P in manure and urine returning it to the soil, and also returning P to the soil when they die. The returned P is therefore in an organic form which must be mineralised (decomposed) back to inorganic forms, mainly phosphate, before it can be taken up by plants again, completing the cycle. The length of time for P to cycle in soil varies from as little as a few hours to many years. For example, P may be taken up by a plant but then rapidly returned to the soil as root exudates to feed microbes which then quickly mineralises the exudates back to inorganic P. Or, the organic form of P may be converted into mineral associated organic matter (MAOM) which may persist for centuries (Cotrufo *et al.*, 2022).

The geological cycle is also conceptually simple at a high level. Phosphorous is lost from the soil through soil and organic matter particles eroded from soil by wind and rain and by leaching into rivers and streams i.e., the hydrosphere. It is then transported to the seas and oceans where if it is soluble it precipitates out and if bound to particles it settles out, to the ocean floor along with other sediments. The sediments build up over time causing the lower levels to be compressed and potentially turned into rock. Plate tectonics causes geological uplift of the ocean floor turning it back into land. The uplifted rock and sediments are then eroded / weathered and may form new soil. The P is then returned to the soil cycle. The geological cycle is vastly slower than the soil cycle with cycle times of 10s to 100s of millions of years (de Boer *et al.*, 2019).

2.5.1. Lithospheric nutrient cycles

These cycles apply to all the other 'lithospheric nutrients' which are nutrients which do not cycle via the atmosphere i.e., 'atmospheric nutrients'. Carbon, hydrogen, oxygen and nitrogen are atmospheric nutrients. Thus phosphorus, potassium, calcium, and all the other essential nutrients are lithospheric nutrients. Many of the issues with humanities disruption of the natural P cycles therefore applies to all lithospheric nutrients.

2.6. The human phosphorus stream

The immensely different time scales of the soil and geological P cycles and the linkage between them are at the heart of the global P challenge. Phosphorus that moves from the soil cycle and enters the geological P cycle is effectively lost to humanity as retrieving P from the seas and oceans, in the same quantities that it is being lost, is currently economically unviable and practically exceptionally difficult (de Boer *et al.*, 2019). At human time scales (decades to centuries) the loss of P from the soil cycle to the geological cycle is effectively a stream, i.e., a linear process with a source and a sink. The source of P is mined fossil phosphate rock (see section 4.1. Sources of Aotearoa-New Zealand phosphorus) and the sink is the oceans. Phosphate rock is produced as part of the geological cycle and is akin to fossil fuels, e.g., coal, in that the rock was created tens to hundreds of millions of years ago and is being extracted at an immeasurably faster rate than new phosphate rock is being laid down. Globally, there are thus finite reserves of phosphate rock.

Estimating the amount of the reserves and how long they will last is difficult for multiple reasons but the latest estimates are that there are around 300 years left (Brownlie *et al.*, 2022b; Argus Media Group, 2023). As P is indispensable and unsubstitutable in biology, as phosphate rock reserves dwindle agricultural production (yield) will reduce to potentially very low levels. The same applies to manufactured products and processes which will be curtailed even halted as P supplies diminish. As the availability of P reduces the price of P will increase making currently uneconomic reserves financially viable and increase the viability of recycling. However, that does not address the fundamental issue that dependence on fossil reserves has to end at some point. Increased P prices also flows through to the products made from them, including food. Hence the vital need to turn the anthropogenic phosphorus stream back into a full cycle with minimal leakage.

2.7. Soil phosphorous

The detailed behaviour of the P cycle in soil is considerably more complex than the high-level soil P cycle (Figure 6). It is influenced by multiple factors including:

- The nature of the inorganic and organic solid phases,
- Type and extent of biological activity,
- Chemistry of the soil solution e.g., pH, ionic strength, redox (reduction—oxidation) potential, and
- Environmental factors such as soil moisture and temperature.

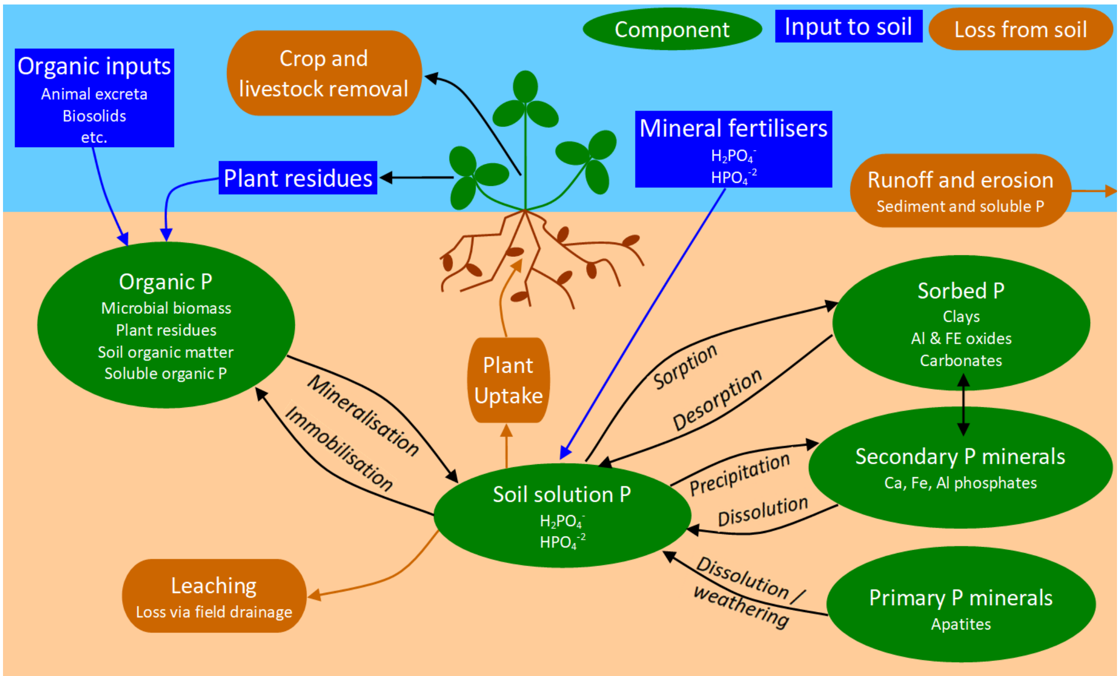

Figure 6. The soil phosphorus cycle and pools. Redrawn from (Prasad & Chakraborty, 2019).

2.7.1. The soil phosphorous pools

The soil solution P pool is P that is in soluble forms, called orthophosphate, that can be taken up by plants and leached (Figure 6). The concentration of the soil solution is generally very low, such that there is less than 1 kg of soluble P per ha, or 1% of total soil P. The soluble P pool exchanges P with three other soil P pools, the organic, sorbed and secondary mineral pools.

Sorbed P is bound to the surface of aluminium and iron oxides and carbonates. Sorption and desorption are generally quick processes. Soils with bigger concentrations of iron and aluminium oxides have greater ability to adsorb phosphorus than soils with relatively low iron and aluminium oxides. The same applies to clay content. The sorbed P pool is therefore particularly important for replenishing the soluble pool as it is depleted by plant update. Plants may have sufficient P or be deficient in P depending on how quickly the soluble pool is replenished from the sorbed P pool.

Precipitation and dissolution, between the soluble P pool and secondary P minerals such as calcium, iron and aluminium phosphates is a much slower process. Metal ions such as Al^{3+} and

Fe^{3+} are dominant in acidic soils and Ca^{2+} are dominant in calcareous soils. These react with phosphate ions in the soluble P pool to form minerals such as Al$^{-,}$ Fe^{-}, or Ca^{-} phosphates.

The soluble P pool is also very slowly replenished from the primary P minerals in the soil, principally apatites, through physical, chemical and biological weathering of the parent rock material. This is a one way process within soil.

2.7.2. Soil phosphorous cycles

As soluble P is removed, either by plant uptake or leaching losses, it is replenished primarily by desorption from the sorbed P pool and some mineralisation from organic P pools (Figure 6 above). This process also works in reverse; where soluble P is sorbed onto clays, aluminium and iron oxides and carbonates, and soluble P is immobilised into organic P, e.g., through being taken up by microbes. Due to the small size of the soluble P pool compared with the larger amount of P required by plants the soluble P pool needs to be replenished multiple times during the growing season.

When soluble mineral (inorganic) P fertilisers, such as superphosphate, are added to the soil, they enter the soluble P pool. If enough fertiliser is applied some of the soluble fertilizers P enters the sorbed and secondary P mineral pools, making them unavailable to plants. Some of the soluble P from fertiliser is also immobilised into the organic P pool. When P is added in organic forms (manure, compost etc.) it enters the organic P pool, so only becomes plant available after it has been mineralised (decomposed).

As noted above, the movement of P between these different pools is mediated by a wide range of both biotic and abiotic conditions, e.g., soil temperature and microbiology. pH is particularly important determining availability to plants (Figure 7).

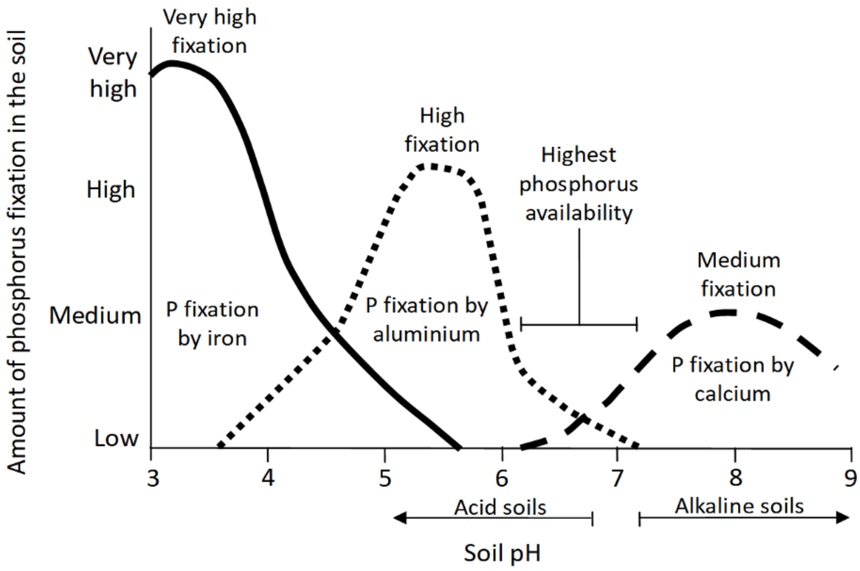

Figure 7. Influence of soil pH on P availability and fixation in the soil. (Plunkett et al., 2019).

In acid soils, P fixation is higher and it is fixed by iron and aluminium. In alkaline soils, P fixation is lower and is fixed by calcium. The least P fixation / highest P availability is between pH 6–7.

2.7.2.1. Key factors influencing soil phosphorus availability

The key factors that influence soil P availability are:

- Organic matter, increasing organic matter increases P availability,
- Clay content, the more clay the higher the soil P retention capacity,
- Soil mineralogy, the higher the level of Al^{3+} and Fe^{3+} the greater the phosphorus sorption capacity.

2.7.3. Soil phosphorous removal and losses

The main path for loss (removal) of P from soil is via the harvest and removal of produce, i.e., plants and livestock. Leaching loss is where soluble orthophosphates in the soluble pool are lost through water draining from soil. The rate of leaching is effected by multiple factors, particularly the amount of soluble P in the soil and soil water levels, particularly when above field capacity which is principally when drainage occurs. Runoff and erosion losses are where soil particles and/or pieces of organic matter, with P sorbed to them or containing mineral P, are eroded e.g., by wind and water, from the soil and carried away. While the losses via leaching, runoff and erosion are generally small in comparison to harvest removal, they are still often sufficient to deposit levels of P in the environment that are detrimental.

2.8. A comparison of nitrogen and phosphorous global cycles and fertilisers

In some commentaries on fertilisers, particularly regarding their environmental impacts and on-farm use Nitrogen (N) and Phosphorous (and the other lithospheric nutrients) are often grouped together and described as ‘chemical’, ‘mineral’ or ‘synthetic’ fertilisers. However they are fundamentally different in terms of their global cycles, and if they are essential or not as fertilisers (Merfield, 2022). This short comparison of N and P aims to reinforce that P (and other lithospheric nutrients) that are removed and/or lost from farming systems have to be replaced by importing nutrients, e.g., as mineral and/or organic fertilisers. In comparison N can be fixed on farm directly from atmospheric nitrogen gas (N_2), so that it is entirely possible to farm without N fertilisers, as organic agriculture does. It also shows the importance of understanding the biogeochemical cycles of nutrients to understand how to manage them from on-farm to the global scale.

In terms of their global cycles N is an atmospheric nutrient and P is a lithospheric nutrient (section 2.5.1. Lithospheric nutrient cycles). Nitrogen is further unique among the essential nutrients in that virtually all the N on the planet is in the atmosphere, due to the highly unreactive nature of molecular di-nitrogen gas (N_2). This is due to its triple chemical bonds which require considerable energy to break and therefore making it difficult to break apart. It therefore very rarely is part of the chemistry of rocks. The atmosphere is also 78% N[1]. This means that nearly all the N in biological systems originates in the atmosphere. In comparison all P in biological systems originates from rock.

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[1] https://en.wikipedia.org/wiki/Atmosphere_of_Earth

The nitrogen cycle starts when atmospheric di-nitrogen is fixed by diazotrophs: mainly bacteria and archaea that can turn dinitrogen (N_2) into ammonia (NH_3) (Figure 8). The ability to fix nitrogen is limited to a small number of microbe genera.

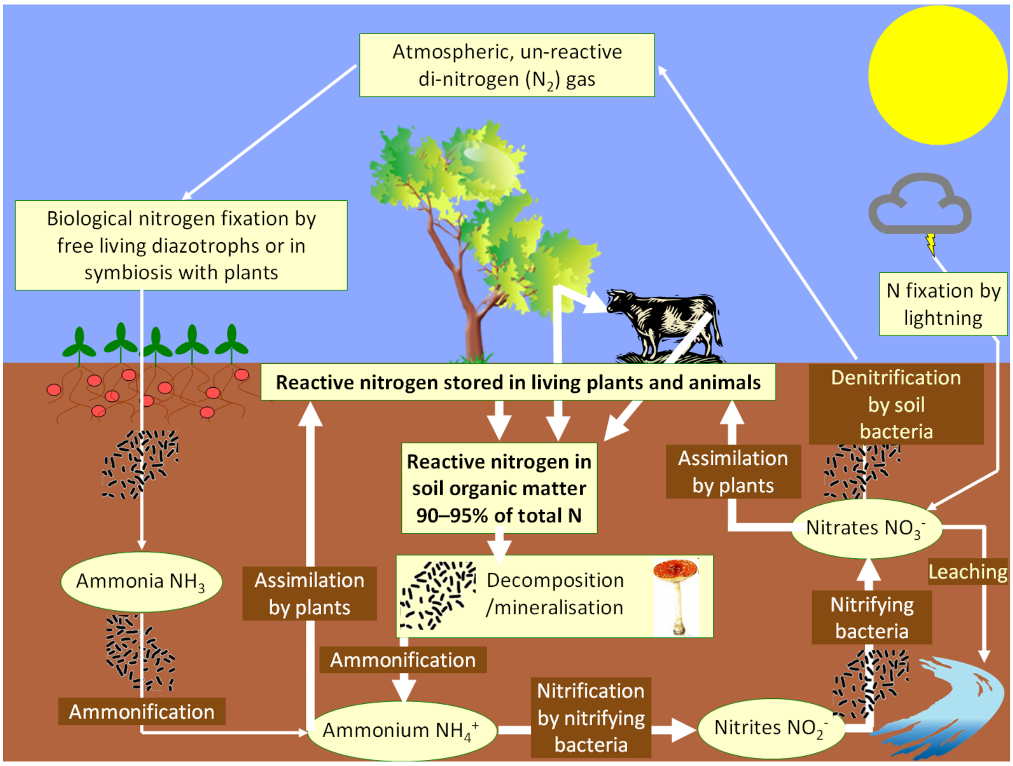

Figure 8. A simplified terrestrial nitrogen cycle. (After Johnson et al., 2005).

There are two linked N cycles in soil: the mineral and organic cycles. In the mineral cycle atmospheric N_2 is fixed by diazotrophs into ammonia (NH_3), which is then converted into ammonium NH_4^+, then nitrites NO_2^-, and nitrates (NO_3^-) before being denitrified back to dinitrogen. These chemical transformations are mostly performed by microbes, mostly bacteria and archaea. Ammonium and nitrate are the two forms that can be taken up by plants. When taken up by plants or any mineral form is taken up by microbes, the N is converted to an organic (biological) form, i.e., it becomes part of the organism's biochemistry. When the organism dies, or sheds material, e.g., plant leaves, they enter the soil organic matter pool. The N in organic matter is not plant available, and has to be decomposed / mineralised back to ammonium before it can be taken up again by plants (Figure 8). As there is very little N in the parent rock from which soil is formed this means around > 90% of N in soil is in the form of organic matter, the rest in the mineral forms described above. This contrasts with P where most of the P is in the mineral form and a small percentage is organic P (Figure 6).

This is why it is possible to farm without any N fertilisers but impossible to farm without P fertilisers. Nitrogen can always be fixed on farm from the atmosphere, typically by growing legumes, while any P exported in harvest or lost from the farm via leaching and erosion, cannot be replaced at the same rate by weathering of the primary P minerals (Figure 6). Thus, P must be imported back onto the farm, in the mineral or organic forms to replace that removed. This is not however, to say that relying on biological N fixation is easy; it requires greater farmer expertise and often redesign of the farm system, e.g., increasing the crop rotation diversity to include more leguminous crops that can fix nitrogen.

2.9. The form and processes of phosphorous loss from farmland to the environment

2.9.1. Point and non-point losses and urban and agricultural losses

There are many sources of P loss to the environment, not just from agriculture but all of society, plus the natural environment. Sources of P are split into point and non-point (also called diffuse) sources. Point sources are typically end of pipe discharges, e.g., water exiting a sewage work, or an urban drainage system. These are almost entirely human made sources. Non-point sources release P from a wide area, e.g., farmland and natural landscapes. As P loss from natural landscapes is part of the natural P cycles, both soil and geological, it will not be covered any further here. Most point sources of P loss are from urban areas, with a few exceptions such as field drains. As the focus of this report is on P loss from agriculture, urban sources of P loss are also outside of this report's scope.

2.9.2. Forms of phosphorous lost from farmland

Phosphorous is lost in a range of forms from farmland and other sources. The two main divisions are soluble and particulate (Figure 9).

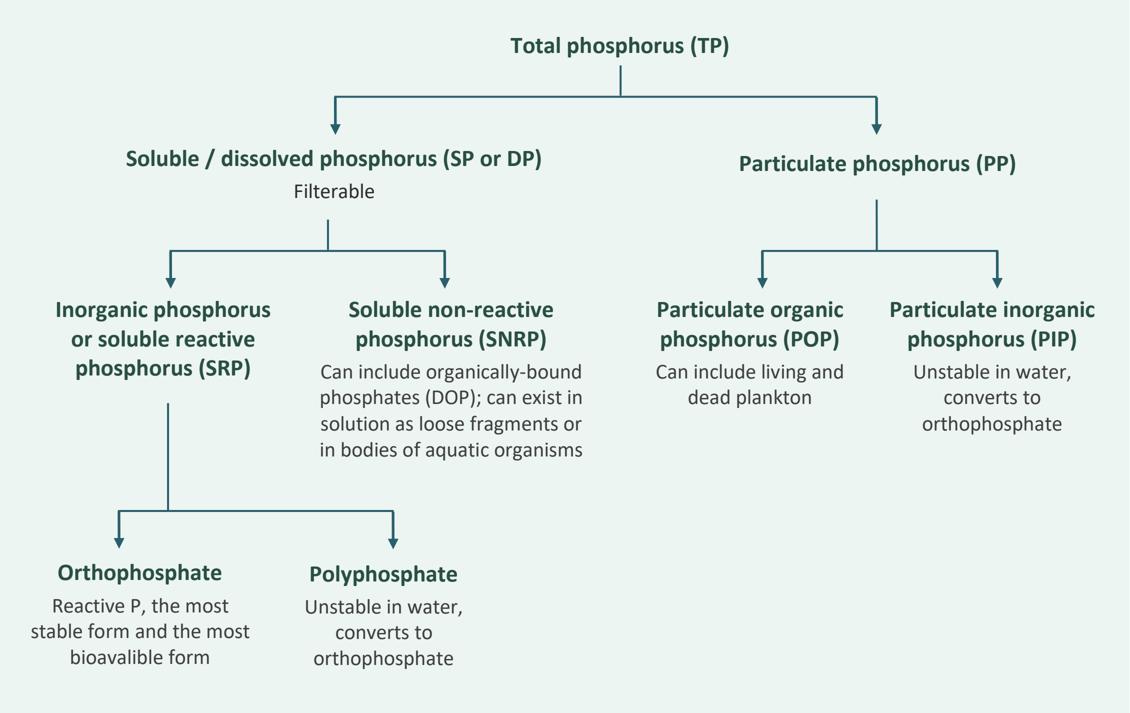

Figure 9. Phosphorous forms and their characteristics. From (Macintosh et al., 2018).

Dissolved / soluble P is defined as passing through a 0.45 µm filter while particulate P is that which is trapped by the same filter (McKergow *et al.*, 2007). Phosphorus lost by leaching is almost entirely dissolved P, while P lost overland, e.g., by surface flow, is both particulate and dissolved P. Particulate P can be in either an organic or mineral (inorganic) form. Dissolved P can be in reactive forms, i.e., available for uptake by plants and other organisms, and non-reactive forms which cannot be easily taken up by organisms. Then there are two sub-forms of dissolved reactive forms: orthophosphate and polyphosphate, but the latter quickly converts to orthophosphate in water, so orthophosphate is the soluble reactive form of P found in waterways. The different forms of P have different implication and outcomes for their impact on the environment.

2.9.3. The role of the hydrological cycle, soil type and contour in P loss from farmland

Within agriculture, P losses from farmland are driven by the hydrological cycle, soil type and contour. Water moving from farmland to the environment carries both dissolved and particulate P. The more water that moves from farmland to the environment, particularly in high rainfall events, the larger the potential losses of P. As discussed in section 2.7, soil type including the proportion of sand, silt, and clay (soil texture), organic matter, iron and aluminium oxides, carbonates and secondary P minerals determine if P is retained by a soil (higher P retention capacity) or is more easily lost (lower P retention capacity). Soil texture, organic matter and soil structure (e.g., well aggregated) also determine how resistant to erosion the soil is. Contour, i.e., the slope of the land determines the speed which water flows over the soil surface, especially in high rainfall events, which influences the ability of the water to carry soil particles and cause erosion.

2.9.4. Phosphate retention capacity

Phosphate retention capacity is an empirical measure of the speed at which a soil removes phosphorus from solution. It is considered to be a precursor to the much slower process of phosphorus fixation, which renders phosphorus unavailable to plants. A key test to determine a soils retention capacity involves mixing a quantity of soil in solution with a known amount of soluble P for a set period of time. The amount of P remaining in solution measures the soil's ability to 'fix' phosphorus and therefore its retention capacity (see www.soilquality.org.au/factsheets/phosphorus).

Phosphate retention capacity is related to the anion storage capacity of a soil because the soluble orthophosphate forms of P ($H_2PO_4^-$ and HPO_4^{-2}) are anions (a negatively charged ion (an atom or molecule with a net electrical charge)). Soils with high P retention capacity are less likely to leach P at the same soil test P level as a low P retention capacity soil. However, high P retention capacity soils 'tie up' or 'fix' P fertiliser making it unavailable to plants. Therefore more P fertiliser is required to achieve the same level of plant available P (i.e., soluble orthophosphates) as a low P retention capacity soil. Phosphate fertiliser recommendations based on soil P tests results therefore need to take into account P retention capacity so that excess P fertilisers are not applied to soils with lower P retention capacities. Soils with an initial high P retention capacity that have received long term P fertiliser applications can become P saturated, i.e., the sorption sites are filled up and soil stores of aluminium and iron oxides are depleted as they are transformed into phosphates. Thus P retention capacity can reduce over time with regular P fertiliser applications.

2.9.5. How phosphorous is lost from farmland

As described in Figure 9, there are two main forms of P, dissolved (soluble) and particulate. These determine the two main routes by which P is lost from farmland (Figure 10).

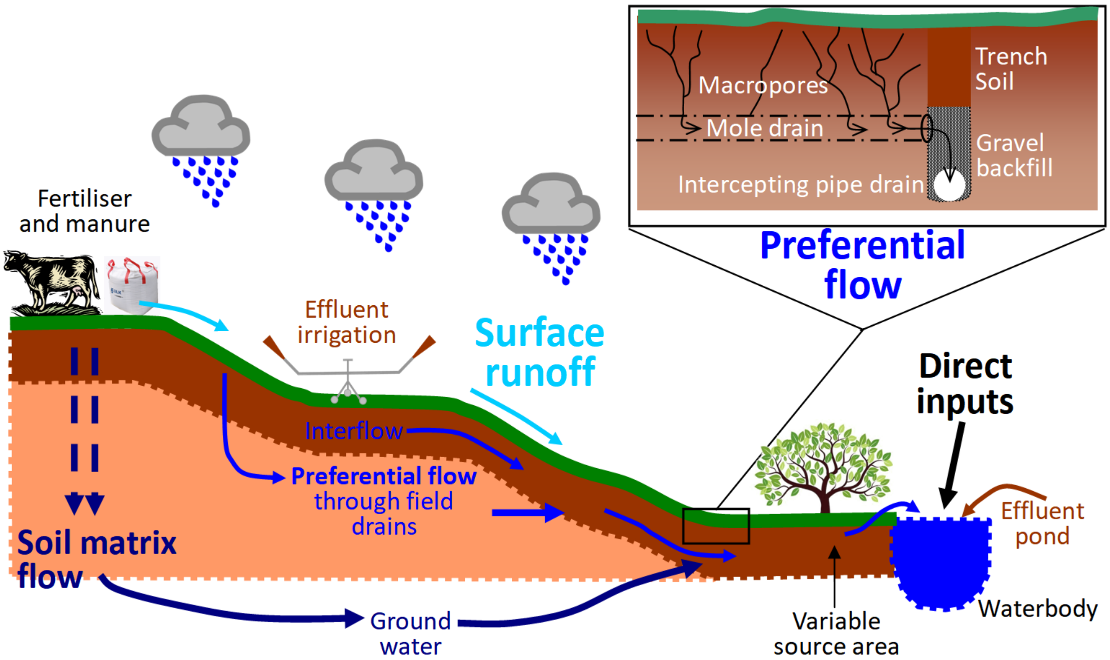

Figure 10. Conceptual diagram of potential sources and processes that transport phosphorus from farmland to surface water. Adapted from (McDowell & Nash, 2012).

Dissolved P is mostly lost via leaching through soil water drainage. Drainage takes multiple routes:

- Interflow through the top soil (A horizon),
- Preferential flow through artificial field drainage systems,
- Soil matrix flow via groundwater (Figure 10). Some dissolved P is also lost with surface runoff (Figure 10).

Particulate P is almost entirely lost via surface runoff, as particles of soil and organic matter e.g., manure. Where mineral fertilisers have been recently spread before rain, then, these can also be washed off by surface runoff. A small amount of particulate P is also lost via artificial drainage systems as sediment and organic matter, being washed down drainage pipes (Figure 10).

There is also direct loss to waterbodies, e.g. material from effluent ponds being emptied into streams and rivers and direct deposition from livestock, esp. cattle, standing in water bodies. There is also loss of the soil from the edge and bottom of the water body, e.g. the soil on the edge of a stream collapses into the stream, or, in a flood, the soil at the bottom of a river is scoured out (Figure 10).

2.10. The impact of excess phosphorous on the environment

While this report focuses on P it is imperative that phosphorous' impact on the environment and mitigation options must not be viewed in isolation from other environmental challenges particularly nitrogen (N), but also climate change, biodiversity loss, soil health and novel entities (Anon., 2015; Steffen *et al.*, 2015). In many cases mitigation for one environmental challenge will help address other challenges, even synergistically, but, some can be antagonistic (Cherry *et al.*, 2008; Macintosh *et al.*, 2019).

Specifically in terms of nutrient losses, N and P often interact in terms of environmental impacts. For example, water bodies are often nutrient limited for both N and P. If just one nutrient increases in level, plant growth is then still limited by the other nutrient — Liebig's Law of the Minimum applies to water just as much as soil (see section 2.3. The law of the minimum). When both N and P are added to a waterbody, they can act in a synergistic way supporting excessive growth of plants and other organisms.

Excess P in the environment has multiple and cascading effects (Johnes *et al.*, 2022). The primary impact is on waterbodies, both on land (e.g., rivers, streams, lakes) and in coastal waters (i.e., both fresh and salt waters). This process of nutrient enrichment of water is called eutrophication. Excess P increases the growth of water plants, particularly phytoplankton such as a green algae and cyanobacteria (which are also called blue-green algae, which is incorrect as they are true bacteria even though they photosynthesise[2]) producing algal blooms. The term 'eutrophication' is also sometimes used to describe this increase in phytoplankton biomass, but, technically eutrophication just means nutrient enrichment. The increased growth of phytoplankton directly cause multiple negative effects. They reduce water clarity (turbidity) stopping other water plants getting enough sunlight and animals (such as fish) being able to see and therefore navigate and find food and escape predators. They can also cover the surface of plants and animals stopping them functioning properly or killing them. Some phytoplankton, particularly cyanobacteria, produce a range of toxins, that can kill other organisms including humans and domesticated animals, through contact and particularly ingestion.

There are also indirect effects of increased phytoplankton biomass. When the phytoplankton dies its decomposition, mainly by bacteria, consumes dissolved oxygen in the water. These low oxygen conditions are called hypoxic. This negatively impacts many other organisms in the water, particularly animals that depend on oxygen, through reducing their oxygen supply. This process also produces toxins which can kill other organisms. If oxygen levels are reduced too much, then most oxygen dependent organisms will die, creating 'dead zones' at coastal sites and in large lakes.

Eutrophication also reduces the robustness and resilience of aquatic ecosystems making them more susceptible to environmental shocks, such as floods and droughts. It also makes them more sensitive to increasing water temperatures due to climate change which further exacerbates the growth of phytoplankton (Johnes *et al.*, 2022).

Eutrophic waters also add to the cost and complexity of treating drinking water, in terms of physically removing the excess phytoplankton, and well as the elevated nutrients and toxins release by the phytoplankton and bacteria decomposing them. Where drinking water is taken

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[2] https://en.wikipedia.org/wiki/Cyanobacteria

directly from waterbodies eutrophication makes it unsafe to drink. It can also stop water being used for other uses such as irrigation.

2.11. Brief history of phosphorous fertiliser sources and use in agriculture

This sections outlines humanities changing relationship with P and brings the foundational information discussed above into a human context. The history of P and all lithospheric nutrients (see section 2.5.1. Lithospheric nutrient cycles) is one of moving from cycles to streams and now trying to return to cycles once again (Ashley *et al.*, 2011). The history of P is also strongly intertwined with humanities management of wastes, particularly human manure.

A number of pre industrial and pre-historical agrarian civilisations understood the importance of biological 'wastes' such as returning human manure back to farmland. The most famous exploration of this is Prof. Franklin King's "Farmers of forty centuries, or permanent agriculture in China, Korea, and Japan" (King, 1911). The farmers King studied ensured that all biological materials, once they had reached the end of their life, were returned back to the fields, without exception. They thus maintained tightly closed nutrient cycles, such that they could farm the same land for 4,000 years — forty centuries.

The industrial revolution is the point that closed nutrient cycles first started to be significantly disrupted. It stared around 1760, first in the UK and then spreading to Europe and then globally. This entailed large parts of the rural population migrating from the countryside to the growing industrial cities. Food was then sent to the cities to feed the urban populations but their 'waste' was often not returned. Initially in towns and smaller centres night soil men collected the human manure from privies, but as the towns grew into cities and then conurbations this became impractical. The many 'wastes' produced in cities, not just human manure, but all types of organic materials were deposited into cesspits, other repositories or just dumped in gardens or the streets. Nutrient cycles were thus broken. Soil fertility consequently declined. New sources of fertility including P were thus required. It was found that crushed bones helped remedy degraded soils. For example, the value of bone imports to Britain increased from £14,400 in 1823 to £254,600 in 1837 (Foster & Magdoff, 1998). So desperate were European farmers in this period that they raided the Napoleonic battlefields (Waterloo, Austerlitz) for bones to spread over their fields (Boulaine, 1994).

The large amounts of decaying materials in cities and limited medical understanding during the 1800s resulted in large disease outbreaks, such as the London cholera epidemic of 1849 which killed 14,137 people (Ashley *et al.*, 2011). This lead to the development of the flush toilet and sewerage systems heralding the sanitation revolution in the mid 1800s. At the same time Justis von Liebig had discovered that plants did not grow from dead plants and animals, rather they took up nutrients in mineral / inorganic forms, thus founding the 'chemical' (mineral) fertiliser industry (Foster & Magdoff, 1998). Mineral P was becoming more widely available and used. Thus the broken nutrient cycles were turned completely into streams. Mineral P was taken from finite historic sources, then applied to farm land as fertiliser to produce food, the P in food and other farm products was transported to cities, which after 'use' was then deposited into sewerage and other refuse systems that transferred the P to rivers and then the oceans or into landfill. This situation prompted Karl Marx to create his concept of the "Metabolic Rift" i.e., his conception of ecological crisis.

> *Capitalist production ... disturbs the metabolic interaction between man and the earth, i.e. it prevents the return to the soil of its constituent elements consumed by man in the form of food and clothing; hence it hinders the operation of the eternal natural condition for the fertility of the soil …*
> *(Marx, 1976, p 637-638, First published in German in 1867).*

The linear P stream therefore needed new sources of P. It was discovered that guano was a concentrated mineral source of phosphorus as well as other essential elements. Large amounts, for the time, were found off the coast of Peru, and on islands in the South Pacific, such as Nauru and Christmas Island. This launched the era of 'guano imperialism' with the US Congress passing the 'Guano Islands Act' in 1856 to facilitate access to islands in the Pacific and Atlantic that held significant guano reserves (Boulaine, 1994; Ashley *et al.*, 2011). However, the guano deposits were tiny compared with the demands so they were quickly exhausted (Figure 11). Further novel sources of P were therefore needed. The discovery of rock phosphate solved the problem at the time (Smil, 2000).

The mid 1800s also saw the discovery of superphosphate - calcium phosphate - $Ca(H_2PO_4)_2$ (now known as ordinary superphosphate) by treating P-containing material, including P rock, bones and even coprolites (fossilised faeces), with sulphuric acid (Smil, 2000). Calcium phosphate is more soluble than phosphate rock making more of the P plant available and available faster. This was followed in the 1870s with the invention of triple superphosphate ($Ca\ (H_2PO_4)_2$) where the P rock is treated with phosphoric acid (Smil, 2000). Triple superphosphate (often just called 'super') is more soluble still and contains 19–20% P compared with 8–9% P for ordinary superphosphate, meaning that more of the P in the super is directly available to plants.

The size of the P stream then accelerated dramatically in the mid 1900s with the advent of intensive agriculture and the Green Revolution (Figure 11).

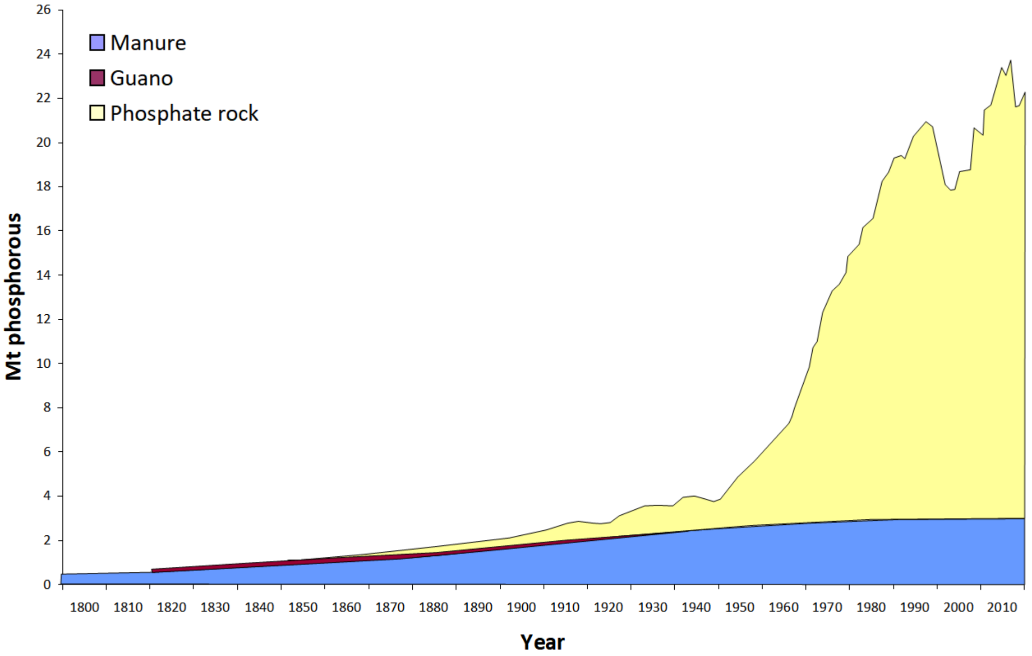

Figure 11. Historical sources of phosphorus fertilizers used in agriculture globally (1800–2010). After (Ashley *et al.*, 2011).

While the pollution caused by the original sewerage systems (1800s) was increasingly resolved, the impact of the massive increase in the use of P fertilisers and other products such as detergents, after the second world war started to be felt in the form of eutrophication by the 1960s. Writing in 1974 Vallentyne predicted that by the year 2000 we would be living in an environmental disaster he called the Algal Bowl (after the dust bowl) (Vallentyne, 1974). A prediction that has come to pass (Ashley *et al.*, 2011).

Globally humanities relationship with P is viewed with ever increasing concern: the unsustainability of supply, our utter dependence on it for food and fibre production, and environmental pollution. The need to return the linear P stream to a fully closed cycle is becoming ever more urgent. Civilisation is coming full circle in regard to P and biological waste management. As Franklin King recorded, some early agricultural civilisations were fanatical about recycling all biological products and by doing so sustained farming for over four millennia (King, 1911). As Figure 12 shows, we are now starting to return towards a circular P system again.

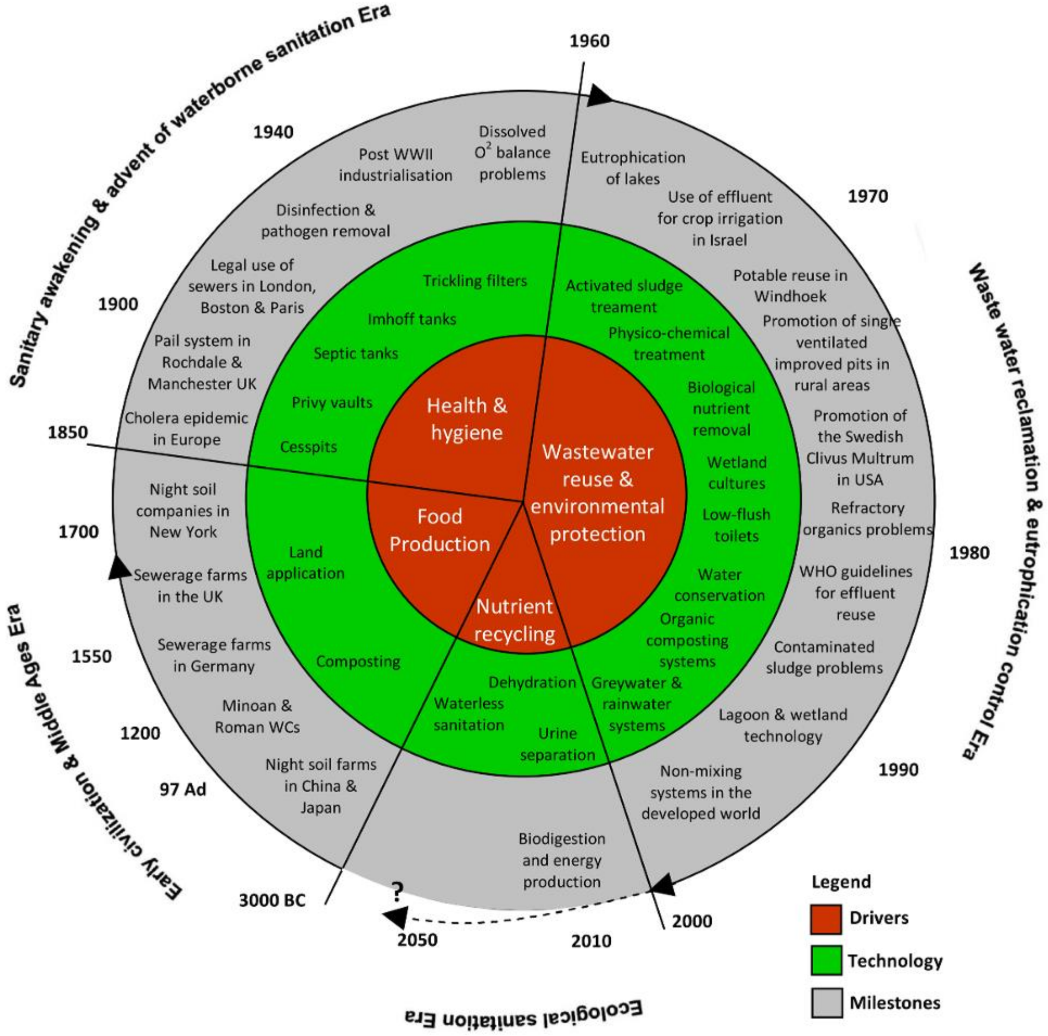

Figure 12. Evolution of anthropogenic nutrient cycles into streams and future cycles. Redrawn from (Gumbo, 2005).

2.11.1. History of phosphorous in Aotearoa New Zealand

The history of P in Aotearoa New Zealand (A-NZ) mirrors international history. The first European settlers arriving in the mid 1800s may have been aware of the advances in agricultural chemistry occurring in Europe. Initially there was little use of fertiliser due to the stored fertility left in the soil when native vegetation, particularly forest was cleared. However, as that stored fertility was depleted the need for fertilisers, particularly P, increased (McCaskill, 1929).

Canterbury Agricultural College (CAC) founded in 1878 (now Lincoln University) was a pioneer of fertiliser research in A-NZ particularly superphosphate (McCaskill, 1929; Hogan & Williamson, 2000). There was initially considerable scepticism from farmers and government alike regarding the value of fertilisers but the work at Canterbury Agricultural College changed that (McCaskill, 1929).

When A-NZ was mostly exporting wool, the export of P from farms and the country was limited as wool only contains between 0.0003% to 0.0008% P it being mostly carbon, oxygen, hydrogen, nitrogen and sulphur (Zheljazkov, 2005; Sharma *et al.*, 2019). However, when frozen meat exports started in the 1880s, particularly with whole carcasses being shipped, the amount of P exported from farms and the whole country increased significantly as bone is mostly made of hydroxyapatite ($Ca_5(PO_4)_3(OH)$) which is 8% to 11 % P (Cordell & White, 2013) and around 80% of the P in ruminants is in bones and teeth with about 1% of the total mass of livestock being P (Sims & Sharpley, 2005).

The first import of P fertiliser to A-NZ is 459 tons (imperial ton) of guano in 1867 ((McCaskill, 1929). The same as global consumption of P fertilisers (Figure 11) A-NZ also saw a P fertiliser consumption increase rapidly from the start of the 1900s with interruptions to supply caused by the First World War (McCaskill, 1929) (Figure 13) with demand peaking in the 1970s and early 2000s (Figure 14).

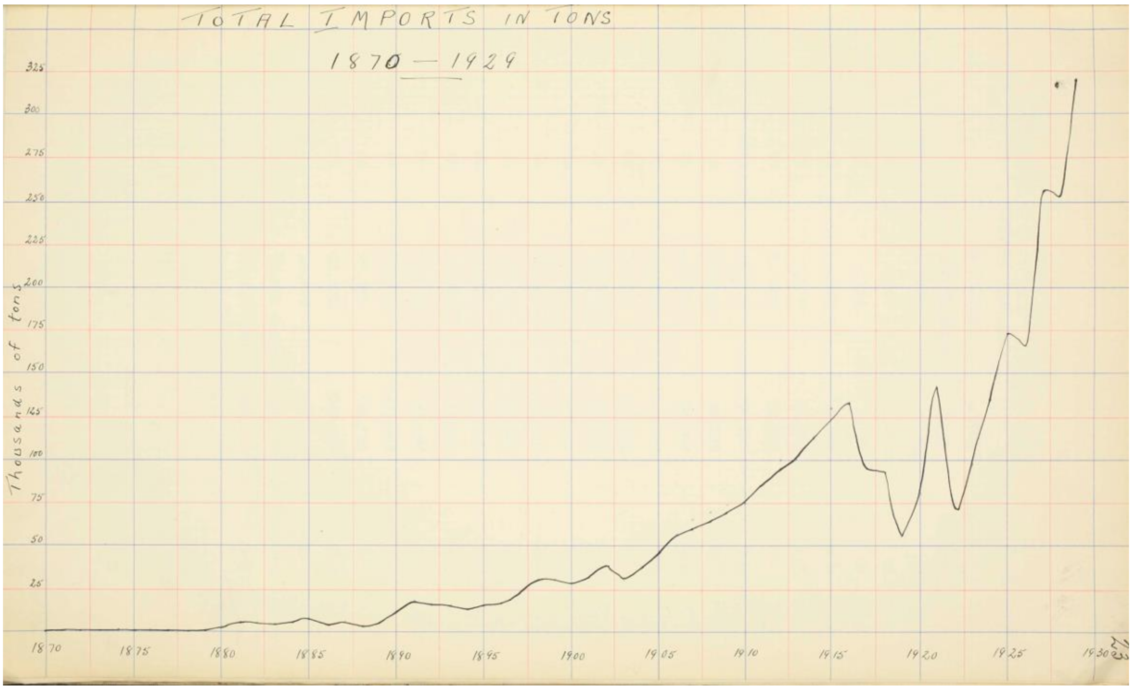

Figure 13. Imports to Aotearoa New Zealand of phosphorus fertiliser in imperial tons from 1870 to 1930. From (McCaskill, 1929).

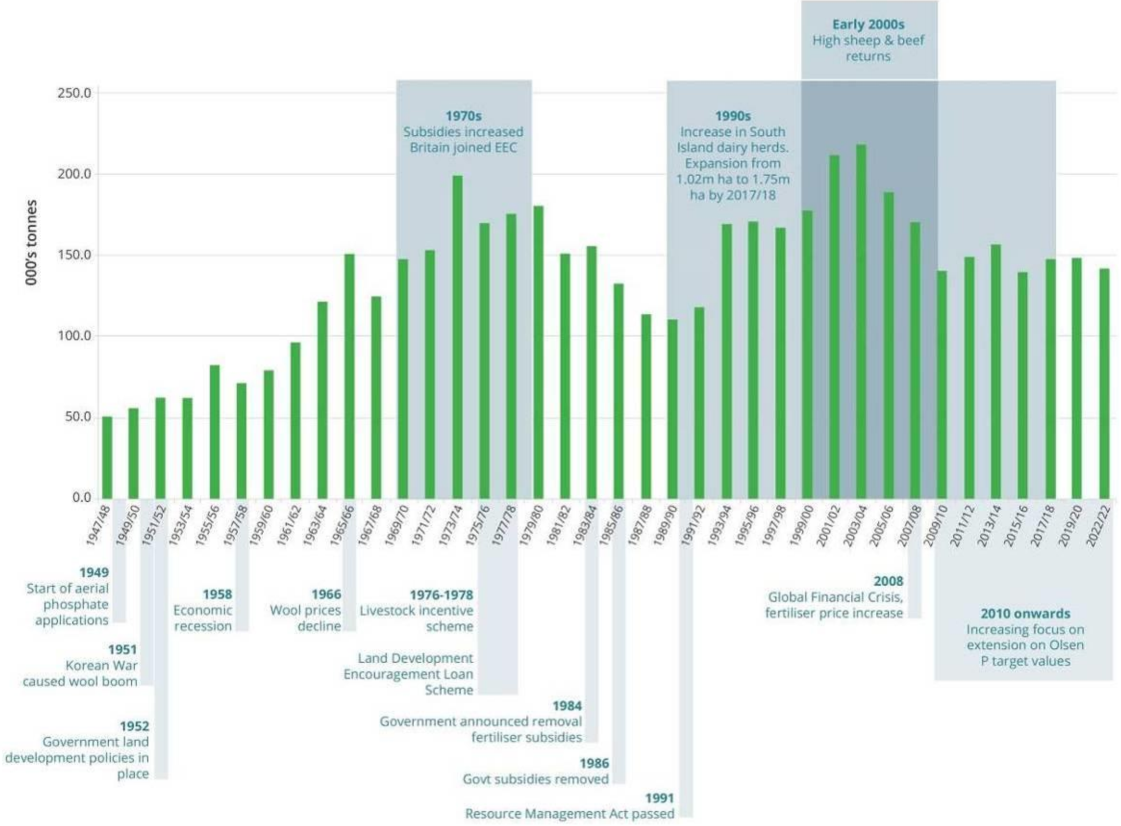

Figure 14. Fertiliser phosphorus consumption in Aotearoa New Zealand 1947-2022. From www.fertiliser.org.nz/Site/news/articles/75th-anniversary.aspx

To encourage domestic production of P fertiliser the government offered financial rewards for its production. The first factory producing P fertiliser was in Dunedin in 1882. In the 1890s it was accidentally discovered that Nauru had high quality phosphate ore. This was then mined on Nauru as well as the neighbouring Banaba and Christmas Island.

The British Phosphate Commission was established in 1920 by the British, Australian and New Zealand governments to manage the Nauru and Banaba Christmas Island phosphate resources. Most of the phosphate was shipped to Australian and New Zealand for use on farms. The commission was finally wound up in 1981 after the indigenous peoples of the islands regained their sovereignty starting in 1968 (McCaskill, 1929; Hogan & Williamson, 2000). The Agricultural and Marketing Research and Development Trust (AGMARDT) was established in 1987 by the New Zealand Government with funds from the winding up of the British Phosphate Commission.

The first fertiliser cooperatives were established post the Second World War. The Fertiliser Association was established in 1947, originally being called The New Zealand Fertiliser Manufacturers' Research Association, with its initial focus being on research. The political changes in the 1980s, which included the removal of fertiliser subsidies, caused significant changes to the industry with amalgamations of the fertiliser co-ops and companies along with the Fertiliser Association closing its research centre and focusing more on advocacy, commissioning research and promoting good management practices (www.fertiliser.org.nz/Site/news/articles/75th-anniversary.aspx).

2.12. Conclusions of an introduction to phosphorous

This section has explained why P is vital to humans and the biosphere and is unsubstitutable and irreplaceable. That the natural soil and geological P cycles have been hugely disrupted and the soil cycle turned into a stream. The P stream has a finite life of a few hundred years before it is exhausted. At the same time too much of the P in the stream is lost to the environment where it can cause extensive harm, principally eutrophication of waterways, resulting in significantly reduced ecosystem services and breaching biogeochemical planetary boundaries. The modern history of P is closely tied to the use of P fertilisers to boost agricultural production and the management of biological ‘wastes’ particularly sewerage systems. There is consequently an increasingly urgent need to turn the P stream back into a tightly closed cycle, again.

3. The circular (bio)economy

This section provides a brief explanation of the concepts of the circular economy and bioeconomy, to provide context for the following section on addressing the P challenges in A-NZ.

A circular economy is the opposite of the current linear economy. In a linear economy natural resources are extracted from the environment (take), turned into products (make), consumed (use), and then disposed of which causes pollution (Figure 15). In contrast the circular economy aims to eliminate extraction from the environment: once products reach the end of their life, they are reused, remade and/or recycled back into their constituent parts to be used as the inputs for manufacturing future products while also aiming to eliminate pollution (Figure 15).

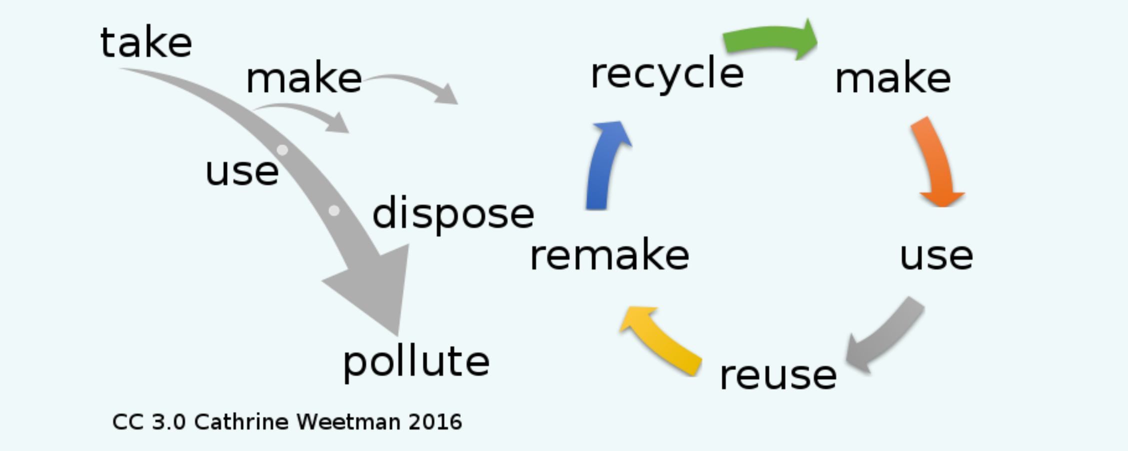

Figure 15. Conceptual diagram of the linear economy vs. the circular economy. CC 3.0 Cathrine Weetman 2016.

There is no waste in a circular economy, everything (all matter) constantly cycles around the economy, and all power (energy) is from renewable (i.e., non-fossil) sources. This mimics how the biosphere works, the flow of energy from the sun powers the cycling of matter though the biosphere.

The way that humanity has turned the natural P cycles (section 2.5. Natural phosphorous cycles) into a linear stream (section 2.6. The human phosphorus stream) is a specific example of the linear vs. the circular economy. The same as the current linear P stream is unsustainable, the current linear economy is also unsustainable and has to be transformed into a circular economy.

The bioeconomy is the part of the whole economy that uses biological resources from land and sea, such as crops, forests, fish, animals and micro-organisms, to produce food, materials (e.g., wool, wood) and energy. Primary production (agriculture, forestry, fisheries and aquaculture) comprises the majority of the bioeconomy. As illustrated by phosphorous, the bioeconomy can be linear or cyclical. Much of the current bioeconomy is linear. For example, the same as for P, most of the lithospheric nutrients (matter) (see section 2.5.1. Lithospheric nutrient cycles) are not cycled, rather they are mined, used as fertilisers, some of which is taken up by crops, some is lost to the environment as pollutants, and then most of the mined nutrients ends up in the oceans or landfill, only a small proportion is cycled, e.g., as compost. Primary production, also uses a significant amount of fossil energy, for example to power machinery and to manufacture nitrogen and process phosphorous fertilisers. Therefore, the bioeconomy also needs to become circular. All nutrients much be fully cycled, losses to the environment need to be minimised, and all energy needs to come from renewable sources.

4. Agricultural phosphorous challenges in Aotearoa-New Zealand

Aotearoa New Zealand (A-NZ), the same as the rest of the world, faces a number of challenges around phosphorus (P). These are:

- There are limited currently utilised domestic sources of P, though this project is identifying sizable local sources,
- A-NZ is currently reliant on imported P,
- Most of the imported P is used for fertiliser,
- More P fertiliser has historically been applied than has been removed in food, fibre and other production,
- There has been a build-up of soil P levels,
- Agricultural and urban P sources have and continue to cause environmental pollution, mainly eutrophication of waterbodies, i.e., streams, rivers and lakes,
- There is limited P recycling e.g., from sewerage systems.

It is recommended to improve phosphorus security and reduce environmental harms A-NZ needs to:

- Identify domestic P sources and determine their suitability for extraction and use,
- Make P security and use a higher policy and political issue,
- Improve implementation of the many existing P use and mitigation measures,
- Improve P recycling. (Brownlie *et al.*, 2022a, Hermann *et al.*, 2022).

4.1. Sources of Aotearoa-New Zealand phosphorus

There are several potential sources of P rock within A-NZ. These are mostly on the east coast of the South Island and are associated with other sedimentary rocks such as limestone. A main piece of the work and output of the project this report was written for is focused on the feasibility and viability of using NZ local phosphate resources. This issue will therefore be covered in the outputs of that part of the project.

4.1.1. Global phosphorus rock sources

Sources of phosphorus rock are described using multiple terms. The United States Geological Survey uses the following definitions:

Resource is defined as “a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth’s crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible”.

Reserve-base is defined as "that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices".

Reserve is defined as "that part of the reserve base which could be economically extracted or produced at the time of determination".

Globally five countries: China, Morocco, Western Sahara, the USA and Russia) hold around 85% of known phosphate reserves, with 70% found in Morocco and Western Sahara alone (Table 1) (Brownlie *et al.*, 2022b).

Region	M tonnes
Africa	54,450
Eastern Europe and Central Asia	3,450
West Asia	1,950
East Asia	1,150
North America	600
Oceania	500
Latin America	350
West & Central Europe	100
South Asia	25
World Total	**62,575**

Table 1. Regional breakdown of economic reserves of phosphate in concentrate terms. Adapted from (Argus Media Group, 2023) table 4-7, page 32.

The legality and legitimacy of production is Western Sahara is unresolved — additionally the political stability in other countries, e.g., Syria, can impact access to and the production of P rock (Brownlie *et al.*, 2022b).

4.1.2. Aotearoa-New Zealand phosphorus

In 2022 A-NZ used approx. 145,000 tonnes of P fertiliser, down from a peak of 220,000 tonnes in 2003/04 (Figure 14). Most of the P fertiliser is superphosphate with the majority of it being used on sheep & beef farms and then dairy farms (Figure 16).

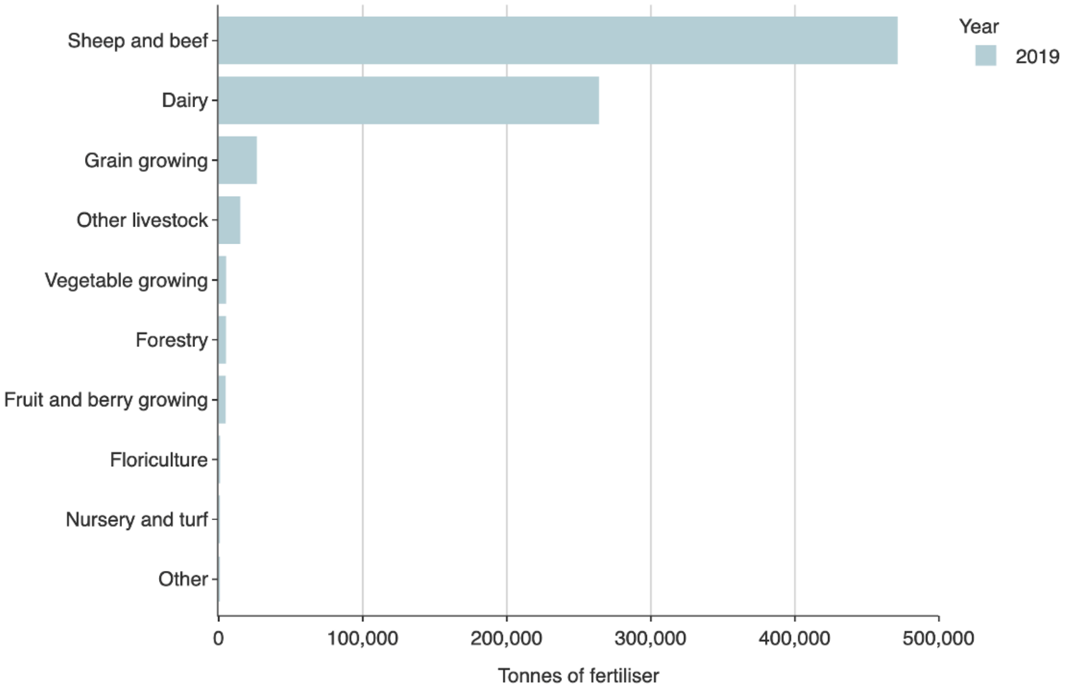

Figure 16. Superphosphate fertiliser applied to different farms types between 2002 and 2019. Source: Stats NZ.

4.2. Aotearoa-New Zealand phosphorous imports, exports and flows

Understanding the flows of P into and out of A-NZ as well as internal movements, is vital if P management is to be improved. Li *et al.*, (2015) undertook a detailed substance flow analysis of phosphorous within A-NZ. This is the only known analysis of the P imports, exports and internal cycling within A-NZ. While this paper is eight years old, P imports since 2010 have remained relatively constant, with 2015 and 2022 being very similar. It is also considered unlikely that there have been large changes to internal flows, so, the overall picture of P flows is still considered relevant.

Aotearoa-New Zealand is a net accumulator of P with 63% of total imports accumulated, representing 155,100 tonnes of P (Figure 17, Li *et al.*, 2015). Imports were 88% P rock and fertiliser comprising 214,000 tonnes out of a total import of 243,700 tonnes (Figure 17). Exports of P were nearly evenly split between food and non-food (Figure 17).

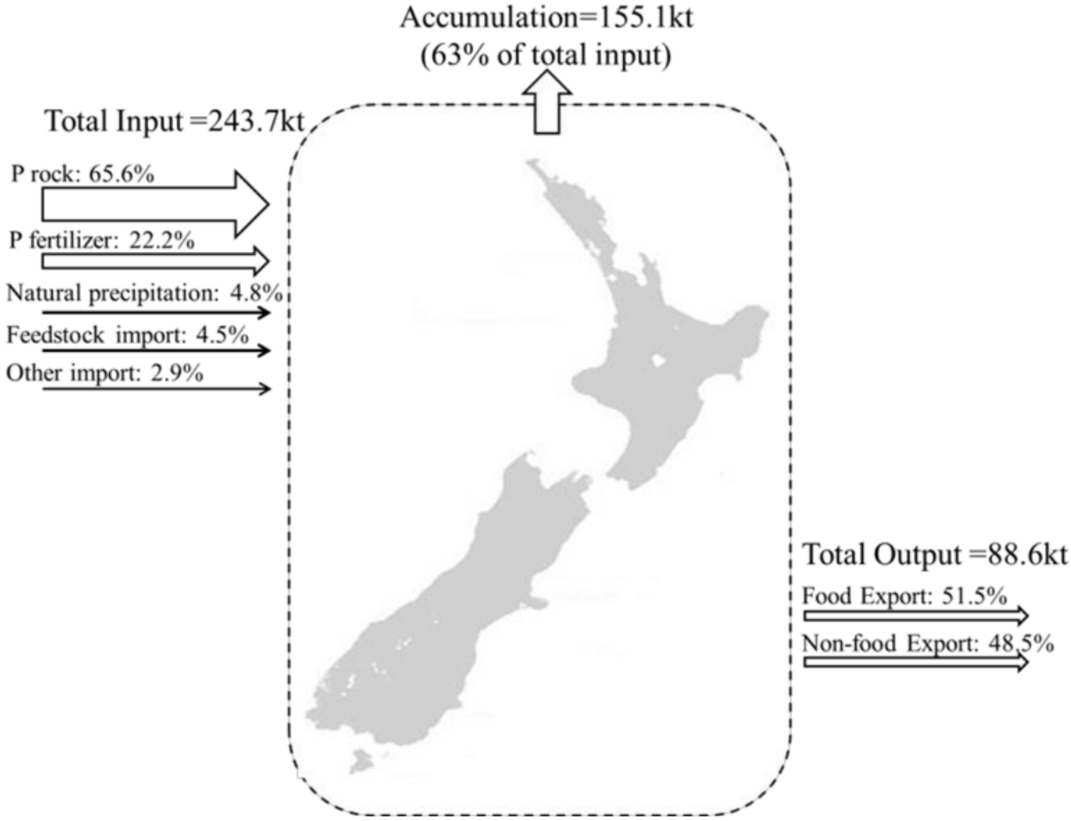

Figure 17. P input and output in Aotearoa-New Zealand in kt of elemental P. (Li *et al.*, 2015).

The internal flows of P in A-NZ are dominated by agriculture (Figure 18, Li *et al.*, 2015). Inputs into agriculture are exclusively as a nutrient source, either processed fertiliser (e.g., superphosphate) and a small amount of unprocessed rock phosphate (Figure 18). Outputs are approximately half being food outputs, with the other half being non-food products, which is mostly wood (Figure 18). There is also a large internal cycling of P in grazed pasture and other animal feeds (e.g. cereal grain) but with most of the P then returned to the soil via manure and urine, i.e., directly cycled on paddock (Figure 18). Of the 213,900 tonnes of P imported into farming systems (including imported plant material such as palm kernel expeller (PKE)), 65,600 tonnes (29%) was exported as food, 23,400 tonnes (10%) as non-food products, 46,100 tonnes (20%) was lost to waterbodies, and 89,900 tonnes (40%) was retained in the farming systems (Figure 18, Li *et al.*, 2015) (see section 5.7. Farm system mitigations regarding P retention).

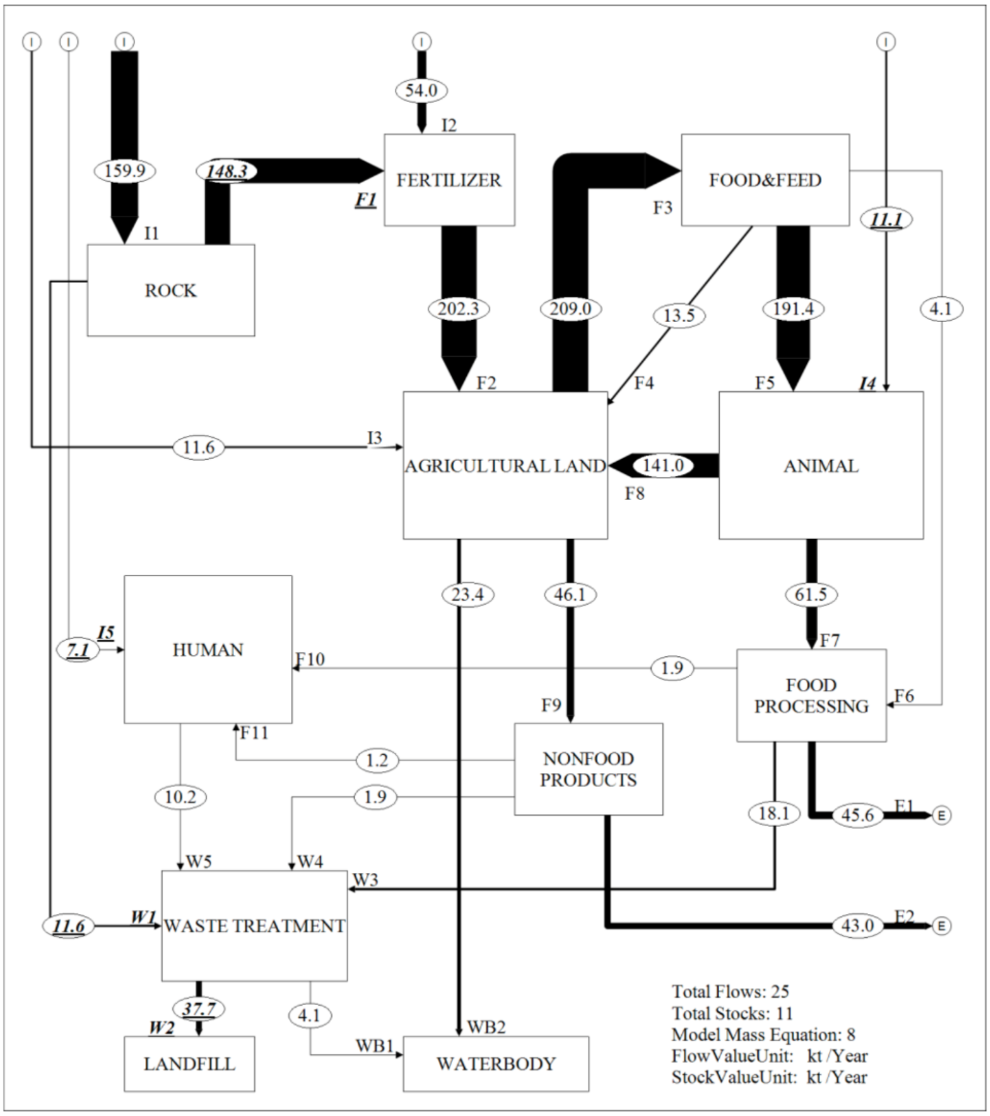

Figure 18. Substance flow analysis of P in New Zealand based on mean values of each flow in tonnes of elemental phosphorous. Unknown values are in bold print and underlined). WWTP = wastewater treatment plants. (Li *et al.*, 2015)

Flow	Amount kt	Flow	Amount kt
I1: Rock import	159.9	**F9: Other products**	46.1
I2: Fertilizer import	54.0	**F10: Domestic other**	1.9
I3: Natural precipitation	11.6	**W4: Non-food loss**	1.9
F2: P application	202.3	**W5: Human waste**	10.2
F3: Plant uptake	209.0	**WB1: WWTP effluent**	4.1
F4: Plant residual	13.5	**WB2: Crop land lost**	23.4
F6: Crop production	4.1	**E1: Food export**	45.6
F7: Livestock product	61.5	**E2: Non-food export**	43.0
F8: Livestock manure	141.0		

Table 2. Key for Figure 18.

In terms of losses of P to water bodies, 23,400 tonnes (85%) came from farms and 4,100 tonnes (15%) from waste processing, meaning that farming dominates P losses to waterbodies (Figure 18, Li *et al.*, 2015). Of the total P losses of 65,200 tonnes, landfill received 37,700 tonnes which is 58% of total losses (Figure 18). The P lost to landfill includes 2.53 million tonnes of municipal waste which at around 0.2% P equals 5,100 tonnes of P (Li *et al.*, 2015). The slaughter industry produces more than 15,200 tonnes of P in waste with a large proportion going to landfill (Li *et al.*, 2015). This compares with the third smaller losses from waste water treatment plants (sewerage plants) of 4,100 tonnes P (Li *et al.*, 2015).

4.3. Increasing phosphorous recycling in Aotearoa-New Zealand

As discussed in the first section of the report, a key tool in improving P management is improving recycling of P. A-NZ is unusual in that agriculture dominates P flows, as imported P for fertiliser and exports as food and biological non-food products. Losses from agriculture are mostly diffuse and as discussed above they are therefore difficult to capture and recycle and are best reduced at the source. The internal non-farm cycles are small in comparison (Figure 18). However, as discussed above there are sizeable losses to landfill and a smaller amount from wastewater treatment plants. No data on losses of other biological materials (e.g., food processing and preparation 'waste' and garden 'waste' such as lawn clippings) to landfill have been found. Losses to landfill and from waste water treatment plants appear to be the best options for increasing P recycling within A-NZ.

4.3.1. Recovering phosphorus from wastewater

There are a range of methods for recovering P from wastewater, including:

- Struvite precipitation,
- Ion exchange,
- Physico-chemical recovery from sewage sludge, sewage sludge ash and pyrolysis (Macintosh *et al.*, 2014).

There is now considerable expertise, experience and commercial products and processes overseas which could be implemented on waste water treatment plants in A-NZ. The amount of research on P recovery from wastewater is also rapidly increasing. Recovery of P from waste water treatment plants is also low in A-NZ (Li *et al.*, 2015) so there is considerable opportunity to increase recovery.

The main challenge to implementation in A-NZ is considered to be primarily economic, as the cost of removal is often significantly more than the value of the recovered P. In addition, many removal technologies are better suited, and more economic when used on larger waste water treatment plants. A-NZ's small and defuse population results in many small waste water treatment plants, which also works against economic viability (Macintosh *et al.*, 2014).

4.3.2. Recovering phosphorus from materials going to landfill

Landfilling of ‘waste’ is the epitome of a linear economy (see section 3. The circular (bio)economy). Reducing and then elimination of landfill is therefore a key aim of circular economies. Recovering P from materials that would of otherwise go to landfill is therefore part of the larger aim of eliminating landfill as part of A-NZ’s Waste Minimisation Strategy (environment.govt.nz/what-government-is-doing/areas-of-work/waste/aotearoa-new-zealand-waste-strategy).

While municipal waste represents a loss of 5,100 tonnes of P a year, at the low P concentration (0.2%) and the diverse range of materials in municipal waste make recovering the P currently unviable (Hermann *et al.*, 2022). The focus on recovering P from landfill should therefore focus on biological materials. Recovering P from biological materials going to landfill, not only reduces losses of P, but, has multiple other benefits. For example, biological materials in landfill represents a loss of other essential nutrients, so recycling them is also valuable. They are also the main source of methane in landfill, which is a key greenhouse gas, which must be prevented from entering the atmosphere.

There are a diverse range of methods to recover P from biological materials:

- **Aerobic composting:** biological degradation by microorganisms,
- **Vermicomposting:** biological degradation by earthworms,
- **Anaerobic digestion:** biological degradation by microbes in a digester,
- **Pyrolysis:** physical degradation by heating to temperatures > 150°C under oxygen-limited conditions,
- **Incineration:** physical degradation by heating in the presence of oxygen, i.e., burning,
- **No treatment/direct use:** e.g., direct application of manures and slurry to land,
- **Enhanced biological phosphorus removal:** heterotrophic bacteria that accumulate P are cultured within activated sewage sludge under anaerobic conditions,
- **Aquatic plants and algae:** taking up P in water and then harvested and processed,
- **Aquaponics:** Integrated animal husbandry-fish farming systems and sewage treatment fish farming systems. (Brownlie *et al.*, 2022a)

The different recovery systems are suited to different materials. For example, composting needs materials with higher carbon:nitrogen (C:N) ratios such as woody plants. Anaerobic digestion needs lower C:N ratios, e.g., green plant leaves and animal slurry.

The different systems also produce different forms of P. For example compost is partly decomposed biological material with the P in organic form and mixed with the full range of plant nutrients. In other systems materials such as struvite (magnesium ammonium phosphate, $NH_4MgPO_4 \cdot 6H_2O$) can be produced which can be directly used as P fertiliser (Hermann *et al.*, 2022).

As for wastewater treatment there is a wealth of expertise, research and commercial products and systems for recovering P from biological materials. However, as for wastewater, the economics of treatment are often a barrier to their uptake. As National and Local Government are already working on reducing landfilling with the Waste Minimisation Strategy, there are additional incentives to recycle P containing 'wastes' thus providing additional impetus to recycle P and potentially reducing the cost.\

4.3.3. The key areas where phosphorous recycling can be improved

Therefore there are three key areas where P and associated nutrients recycling could be improved:

The 15,200 tonnes of P in slaughter industry 'waste' going to landfill (Li *et al.*, 2015) comes from known point sources, and there are multiple well proven technologies to process it, e.g. composting and anaerobic biodigestion.

Many local councils already have separate green waste collection and processing systems, mainly composting, so scaling this up to all collection systems would further recover a considerable amount of P and other nutrients and divert that from landfill.

Waste water treatment plants could be upgraded to capture more P as well as other nutrients and organic materials, which would also have the benefit of reducing the eutrophication of the water bodies receiving the treated waste water.

4.3.4. Contamination of phosphorous recycling source materials

There are however increasing issues with contaminants in source materials for P recycling. For example, there are medical and recreational drugs in waste water which are resistant to destruction and pass through the P recycling system which can negatively impact organisms such as fish and amphibians (Brownlie *et al.*, 2022c). Micro and nano plastics are an increasing concern, for example contaminating sewerage sludge which then contaminates the soil on which it is spread (Qi *et al.*, 2020). Processing and recovery systems vary in their ability to remove and/or destroy such contaminants. Biological systems such as composting and biodigestion are less effective than physical systems such as pyrolysis (Brownlie *et al.*, 2022c). Increasing attention needs to be given to such contaminants to avoid creating new pollution problems through P recycling.

4.4. Barriers to using alternative phosphorous sources

There are several barriers to using alternative phosphorous sources, both recycled and new mined rock.

A primary issue is the amount of P in the source material. For both rocks and recycled the P content is too low to make it currently economically viable to recover the P. For example, as noted in section 4.2. Aotearoa-New Zealand phosphorous imports, exports and flows, municipal waste is about 0.2% P. However, as the price of P increases over the longer term due to supply and demand, currently uneconomic sources will become more economically viable.

As P is not found in its elemental form, it has to form chemical compounds which means there are always other elements and compounds in P containing material. Some are unwanted, for example cadmium in rock and microplastics in biological materials. However, some are beneficial, e.g., the calcium in rock phosphate is an essential nutrient and also used to raise the pH of farmland so its presence in P fertilisers is often beneficial. The key issues with co-occurring materials are:

- How easy are they to separate,
- The cost of separation,
- If they are useful co-products or have no use, i.e., 'waste',
- If they are 'wastes' if they are harmful or not, and
- If there is a satisfactory means of disposal.

Any co-products that are 'waste' are part of a linear economy and methods to recycle them are required.

The most well know contaminant in rock phosphate is Cadmium (Ca), which is a toxic non-food element. While only present in small amounts e.g., 20 mg Ca/kg in P rock, with repeated applications to farm land, the Ca builds up in soil, and can reach harmful levels over time. However, removing Ca, and many other contaminants is physically and/or chemically difficult and thus often also expensive (Smil, 2000). In the case of Ca in P fertiliser in A-NZ there is the "Cadmium Management Group" (CMG) a multi-stakeholder group convened by the Ministry for Primary Industries (MPI) to manage cadmium in the primary sector. For example, this sets limits on the concentration of Ca allowed in fertiliser, and a monitors Ca levels in pasture.

A key co-product of processing rock P into superphosphates is phosphogypsum. While it has uses, it is often contaminated by Uranium making it sufficiently radioactive that it cannot be used (Smil, 2000). For example, in Florida in the United States there are open air stacks of phosphogypsum containing tens of millions of tonnes that have no end use due to their radioactivity and no economically viable way of managing them apart from stockpiling (Smil, 2000).

For organic materials, e.g., compost, biodigestate, the P typically comes with a full range of other plant nutrients, such as nitrogen, potassium etc. Often this is beneficial, but, in some situations it can result in soil nutrients levels increasing above optimum (e.g., Asrade *et al.*, 2023), which can cause multiple problems, e.g. inhibiting other nutrient uptake or health issues for livestock. This puts limits on how much processed biological materials can be put onto land and the need for soil testing and nutrient budgets to ensure that excess nutrients are not applied.

After the source material (both P rock and recycled materials) has been processed that when it is applied to soil, the P has to be in a form, or be able to be converted into a form, that will become plant available. The invention of superphosphate by treating materials such as bones and phosphate rock with sulphuric acid is the primary example of this. The P in phosphate rock is often apatite (calcium phosphate) and it is insoluble so has to be weathered by soil processes to make it plant available, which occurs over three to five years. Treating it, e.g., into superphosphate, increases its solubility, such that can enter the soluble P pool in the soil (section 2.7.1. The soil phosphorous pools) and is plant available. However, not all forms of P in the source material, both mined rock and from 'waste' streams can currently be practically and/or economically be processed into forms that are or become plant available when applied to soil.

Transportation of P fertilisers and their source materials can also be a barrier to their use. For P fertilisers, the higher the P content the more economically viable it is to transport them longer distances as the cost of transport is only a small proportion of the fertilisers final price, and vice versa, the lower the P content, the shorter the distance as the cost of transportation dominates the fertiliser's price. The classic example of this is aerobic compost, which is about 0.4% P (Prasad, 2009). Compost mostly consists of carbon, oxygen and hydrogen as well as containing water, and has a bulk density of about 0.6 tonne / m^3. It is therefore not viable to transport compost long distances as the transport cost can exceed the value of the compost. Likewise, sources of P, such as waste water, with low P content, are not easy or economic to transport long distance requiring that they be processed close to the point of production, rather than being moved to a large central processing site.

These barriers all illustrate the multiple challenges to refining and recycling P containing materials into suitable forms for use as fertiliser.

5. Optimising phosphorus use efficiency and minimising on farm losses

There is a very substantial body of research and farmer level information (e.g., good/best management practices), both globally and within Aotearoa-New Zealand (A-NZ) on optimising phosphorus (P) use efficiency and minimising on farm losses. This includes primary research, review papers and books as well as extension information aimed at farmers and growers. Examples include: (McDowell *et al.*, 2004; McDowell & Catto, 2005; Sims & Sharpley, 2005; McKergow *et al.*, 2007; Monaghan *et al.*, 2007; Cherry *et al.*, 2008; McDowell & Nash, 2012; McDowell *et al.*, 2013; Johnston & Bruulsema, 2014; McDowell, 2014; Macintosh *et al.*, 2018; McDowell *et al.*, 2018; Macintosh *et al.*, 2019; Brownlie *et al.*, 2022c; Fertiliser Association of New Zealand, 2023) and also the 'Further sources of information' section 9 including fertiliser and primary industry guides. This section will therefore provide an overview of the main P use efficiency and loss minimisation strategies. It also mainly focuses on strategies within livestock farming / pasture-based production systems, as this represents the majority of land use in A-NZ. For example, in 2019 pastoral systems (sheep, beef and dairy) occupied 9,389,605 ha of land, while cropping (arable and horticulture) occupied just 620,480 ha of land. Forestry covered 1,597,957 ha but generally P losses from forestry are low (Stats NZ).

It also lists the strategies in Table 2 with an assessment of their effectiveness, cost and how rapidly they reduce P loss to the environment.

5.1. Prioritising phosphorous loss mitigation strategies

There is a clear priority in P loss mitigation strategies. It is far better from all perspectives (e.g., economic, environmental, animal welfare, etc.) to prevent P loss into the environment from the farm than trying to mitigate its impact once it has left the farm, e.g., has entered a waterway.

Figure 19. The 4Rs: right place, at the right time, at the right rate, and in the right form. (Fertiliser Association of New Zealand, 2023).

The starting point for preventing P loss is not applying more P than is agronomically necessary. This is encapsulated in the 4Rs' as promoted by the fertiliser industry, and primary industry bodies (Fertiliser Association of New Zealand, 2023). The 4Rs are:

- Right place,
- At the right time,
- At the right rate,
- In the right form.

Next is the concept of critical source areas (CSAs). These are areas on farm with a heightened risk of P loss, risk of larger P losses, and/or risk of higher transport of P to areas it can be lost from. Then comes overall farm management, with multiple techniques to minimise losses, e.g., grazing management and riparian plantings. Once P has left the farm and entered waterbodies mitigating the impact of P is generally much harder and more expensive. Some of these mitigations are on-farm, e.g., sediment traps and retention ponds. Then there are also a range of mitigations that are applied once the P leaves the farm, e.g., dredging of public rivers and lakes. It is noted that only on-farm mitigations will be covered in this report.

To decide which strategies to use it is important to take into account the:

- Cost or cost saving of the strategy, both direct cost of implementation and indirect cost of reduced or increased income,
- How practical / easy / simple it is to implement,
- How effective it is in reducing P loss to the environment, and
- The impact the strategy will have on the receiving environment, i.e., achieving the desired water quality objectives (McDowell & Nash, 2012, McDowell *et al.*, 2018).

This ensures that the largest improvement to water quality can be achieved for the lowest cost and in the most effective way.

5.2. The 4Rs: right place, right time, right rate, and right form

The 4Rs were developed internationally in 2014 and apply to all fertilisers not just P (Johnston & Bruulsema, 2014).

Right place includes avoiding critical source areas, soil with poor P sorption capacity i.e., anion storage capacity <10%, use of GPS mapping and proof of placement, and banding in cropping systems.

At the right time, means not applying highly water-soluble P fertilisers such as superphosphate if rainfall is scheduled within seven days that will likely to induce runoff. In cropping systems fertiliser should be applied to match crop demand.

At the right rate, the quantity of P loss increases with the rate of P applied so avoid applying more P than is necessary. Only apply enough capital fertiliser to raise P to the agronomic optimum, and only apply enough maintenance fertiliser to stay at the agronomic optimum. For soils unable to retain much P, i.e., with a low anion storage capacity, reduce the rate of P applied and consider lower P requirement crops.

In the right form, water solubility influences the availability of fertiliser-P for loss in surface runoff and leaching. Superphosphate is highly water soluble, while other forms such as serpentine super or reactive phosphate rock (RPR) are less water soluble resulting in a slower availability over time. Therefore use less water-soluble P fertiliser on soils with low anion storage capacity e.g., <15%, shallow and stony soils, pipe drained soils and where runoff risk is high.

The 4Rs are supported by information such as soil P tests, nutrient budgets, models such as Overseer FM, whole farm plans, and computer tools such as MitAgator which gives a spatial view of where contaminant losses are occurring and identifies critical source areas (ballance.co.nz/MitAgator), Ravensdown's LUCI-Ag which is a decision support tool that investigates current on-farm P and N losses (www.ravensdown.co.nz/expertise/luci-ag-a-pathway-for-catchment-scale-modelling) and the Southland physiographic model (www.es.govt.nz/community/farming/physiographics/introduction-to-physiographics).

5.3. Critical source areas

Critical source areas are typically overland flow paths that can accumulate and convey water to waterways. For example, small, low-lying parts of farms such as gullies and swales, areas next to waterbodies and stock laneways. Phosphorous often accumulates in high concentrations in these areas, often due to normal water movement, which is then lost in higher rainfall events. Critical source areas also occur where livestock congregate or move en-mass, e.g., stock camps under trees and laneways. Although these areas represent a small proportion of the total hectarage of a farm they can be responsible for the majority of P losses. Research has shown that when these small but critical areas are targeted, mitigation measures are six to seven time more cost effective than non-targeted interventions.

5.4. Specific mitigation techniques

There are a large range of on-farm mitigation techniques. Only those most applicable to A-NZ farming in terms of cost, practicality, and impact are included in this report. They are grouped by in-paddock, edge of paddock, farm infrastructure and in-water mitigations.

As noted in section 1.4. Phosphorus and other global challenges, P loss mitigations need to be considered and implemented in the context of addressing other farm environmental impacts such as nitrogen loss, biodiversity etc.

5.5. In-paddock mitigations

5.5.1. Fertiliser

As discussed in section 5.1. Prioritising phosphorous loss mitigation strategies, the most important way to reduce P loss from farms is correct fertiliser management. This includes:

- Follow fertiliser industry and primary sector body good/best fertiliser use guidelines i.e., the 4Rs,
- Using soil tests, nutrient budgets and computer models to determine if P fertiliser is required,
- Only applying P fertiliser up to agronomic requirements, or even slightly below,
- Identifying critical control areas and not applying P fertilisers to them,
- Don't apply P fertiliser if rain is forecast within a week / aim to apply when runoff is unlikely,
- In cropping, time P fertiliser application to crop needs and band it, including sub-surface application, next to crop rows,
- Using less soluble forms of P fertiliser (e.g., RPR) on low P retention soils and where rainfall is greater than 800 mm per year.

5.5.2. Critical source areas

Identify the critical source areas on farm, e.g., by using the MitAgator software tool. Management of critical source areas need to be tailored to farm type, e.g. livestock vs. cropping. Generic options for management of critical source areas include:

- Not applying P (or other fertilisers),
- Using grass only swards,
- Not grazing / mowing, i.e., leaving pasture long to create a filter strip,
- Use of chemical amendments such as alum and bauxite (red mud),
- Not cultivating / cropping, i.e., leave in permanent pasture,
- Do not site drinking troughs or stock movement routes (gates, lanes etc.) in or close to critical source areas,
- For stock laneways, ensure there are barriers, e.g., riparian strips to intercept manure and urine washed off the track.

5.5.3. Pasture and forage crop grazing management

When stock graze on pasture they deposit manure and urine which both contain P, as well as reducing soil protecting pasture cover and disturb (pug) the soil surface which can all increase P losses. In fodder crops soil disturbance is considerably increased due to most fodder crops being established with cultivation which significantly reduces soil structure and most fodder crop root systems do not bind soil aggregates together nearly as effectively as pasture. When surface flow occurs during and after grazing the amount of P lost can increase considerably. Grazing planning and management should therefore aim to avoid grazing paddocks with higher P loss risk, e.g., those next to water courses when there is risk of overland flow due to higher rainfall events. This particularly applies to fodder crops where alternative feeding options, such as standoff pads, need to be available when conditions are wet (see below).

5.5.4. Cropping systems — cultivation and cover crops

Cultivation / tillage harms soil structure, aggregation, topsoil (A horizon) organic matter levels, as well as other aspects of soil quality / health. These all increase the risk of P loss, particularly sediment P, as well as having a range other negative impacts, both on-farm, e.g., crop yield, and in the wider environment. The minimum amount of cultivation should be used to establish annual crops, i.e., avoid ploughing, use minimum till and ideally no-till.

Bare soil, is at the highest risk of erosion both by water and wind. Minimising the amount of bare soil by using no-till systems with residue retention and using cover crops whenever there are no cash crops covering it, even for a few weeks. Research by the Foundation for Arable Research has shown that cover crops grown for just a few weeks in late summer between cereal harvest and planting the next crop, showed improvements to soil quality measures such as aggregation compared with bare soil.

5.5.5. Irrigation management

The use of best irrigation management practices, particularly measuring soil moisture and only apply enough water to reach 80% of field capacity reduce the risk of P loss. If there is rain forecast, irrigation should be stopped.

Border dyke irrigation is a particular P loss risk due to the outwash carrying both dissolved and particulate P into the watercourses the irrigation water drains into. To mitigate P losses; avoid irrigating for several weeks and ideally after a grazing round, after P fertiliser, particularly superphosphate has been applied. Stop the inflow of water earlier to minimise and ideally eliminate outwash. Where outwash occurs collect it and reuse it on farm rather than discharge to water bodies.

Longer term measures include widening and levelling bays and changing to more precise irrigation systems, e.g., center pivots and sub-surface drip irrigation.

5.5.6. Effluent application

The risk of P loss from effluent application is highest on soils with preferential flow, artificial drainage, course soil textures (e.g. sandy soils) and sloping land with low infiltration. Industry have produce best management guidelines to follow. Key points are: do not applying effluent when soils are at more than 80% field capacity or when rain is forecast. Reduce application volumes, e.g., less than 10 mm an hour. Avoid applying to paddocks with artificial drainage, and avoid applying to sloping paddocks where there is a risk of runoff. Do not apply with 20 m of a waterbody with a land slope of less than 3°, 30 m for a slope of 3–5° and 90 m for slopes of >6° (Macintosh & McDowell, 2020).

5.5.7. Minimising erosion and slips

A significant proportion of soil lost from pasture land is caused by significant weather events where heavy rain causes landslips, slumps and other mass soil movement (Ministry for the Environment & Stats NZ, 2019). This not only causes considerable P loss to waterways it is also a loss of productive land as it can take decades for the eroded land to achieve the previous levels of productivity. Measures, such as implementing agroforestry (see section 5.7.4. Agroforestry) to minimise slips and mass soil movement are important to reduce P loss.

5.5.8. Pipe drain management.

Artificial drainage systems, e.g., mole drains, tile drains, perforated plastic pipe drains, etc. have been clearly shown to be significant sources of P loss direct to water bodies. Many mitigation measures have been researched, including:

- Blocking drains,
- Adding P-sorptive materials such as: zeolites, aluminium sulphate, water treatment residuals, and fluidized bed bottom-ash and fly ash from coal fired power plants,
- Avoid applying P fertiliser, especially soluble forms such as superphosphate to drained paddocks if rainfall is forecast,

- Don’t irrigate drained paddocks for at least one and ideally three weeks after applying P fertiliser.

There are several challenges with drain management. Blocking drains defeats their purpose of draining fields. P-sorptive materials have costs and may have other undesired impacts. Expert advise is essential if undertaking any drainage system mitigations.

5.5.9. Soil amendments

Materials such as alum (aluminium sulphate) and bauxite (red mud) are P-sorptive materials that when applied to soil reduce the size of the soluble P pool in the soil. Depending on the material they can be moderately to highly effective at reducing P loss and are generally fast acting. However, there are a range of issues around their use, such as environmental and livestock welfare and cost. Regular use on pasture is therefore questionable. They may have a role in situations where there is a high risk of P loss, for example, critical source areas and fodder crops. Expert advice must be taken before using such materials.

5.6. Edge of paddock mitigations

While edge of paddock mitigations to capture P before it enters water bodies can be effective, they should be viewed as the ‘ambulance at the bottom of the cliff’ and should always be secondary to the ‘ambulance at the top of the cliff’ i.e., in-paddock measures to avoid P loss in the first place. Economically it is far better keeping P in the paddock where it can grow crops and pasture, than trapping P at paddock margins where it can no longer add to profit.

5.6.1. Fencing off waterways

One of the most effective, low cost and rapid paddock margin mitigations is fencing off waterways. This prevents the direct deposition of manure and urine into the water by stock and damage to banks and stream / riverbeds which directly deposits soil and therefore particulate P into the water. Primary industry organisations such as DairyNZ and Beef + Lamb New Zealand offer considerable assistance to farmers to fence waterways.

5.6.2. Pasture / grass strips

A pasture strip alongside waterways is a reasonably effective and inexpensive P mitigation measure. Pure grass is preferable to grass and legumes due to grasses better ability to take up P. The strips decrease P loss in surface runoff by a combination of filtration, deposition and improving water infiltration. However, there are some key limitations to their use. They need the correct management via grazing / mowing to maintain their effectiveness. They can become clogged with silt, requiring removal or re-sowing. When the soil is saturated, they are less effective, and as they are situated on the edge of waterways they are more likely to be saturated than higher parts of the paddock. They function best under sheet flow, i.e., runoff water depth is even across the paddock, but in most situations runoff funnels into narrow channels with faster flow which overcome the strips ability to mitigate P loss (McKergow *et al.*, 2007).

5.6.3. Riparian strips

Riparian strips are a step up, often a significant step up from grass strips, in terms of P mitigation effectiveness, co-benefits and cost with up to 50% reduction in P losses (McDowell & Nash, 2012). They typically contain a mixture of perennial plants both woody (trees and shrubs) and herbaceous (e.g., pasture species and flaxes – *Phormium spp*.). They must be fenced off from stock. They also have several other benefits depending on how and what is planted, e.g., mitigation nitrogen losses, improving stream health and supporting native biodiversity. Due to the size and physical nature of the vegetation they can be more effective at interrupting overland flow than grass strips. The width of the strip is important in determining how effective they are. A well-designed strip should require minimal management once it is well established. Longer term they can however become reservoirs of P so vegetation may need to be harvested (removed) to remove P from the strip.

Getting good advice is essential to design an effective riparian strip for example the DairyNZ Riparian Planner https://www.dairynz.co.nz/environment/on-farm-actions/waterways/riparian-planner/, from local government, and consultants.

5.7. Farm system mitigations

Farm system mitigations are those that impact the whole farm system and/or are not directly related to in-paddock and paddock margin mitigations.

5.7.1. Stock bridges

Bridging river and stream stock crossings has the same benefits as, and is an extension of fencing off waterways. It prevents direct deposition of manure and urine into the water and stops bank and bed damage. This also applies to where farm machinery crosses waterways as they also stir up the bed and can cause soil loss from the banks. Bridges need to be designed so manure and urine deposited on the bridge structure does not drain into the water but is washed into an area, such as riparian planting that can attenuate it.

5.7.2. Manure management

Increasing the capacity of slurry and effluent ponds supports optimum effluent application (section 5.5.6. Effluent application), i.e., reducing the rate of application and not applying when soil and weather conditions are not suitable (Macintosh & McDowell, 2020).

Solid manure, such as farm yard manure (FYM), must be stored so the pile is protected from rain, and any leachate is captured and returned to the pile, or applied to soil as per effluent application. It should not be stockpiled on soil or other porous surfaces due to nutrient leaching causing the soil underneath to have excess nutrient levels (Bradley, 2019).

5.7.3. Standoff pads and permanent feedpads

Standoff pads are purpose built, drained loafing areas where stock can be held for short to long periods. Woodchip is commonly used to cover the areas which absorbs nutrients, and which can then be spread on land when conditions are suitable. Permanent feedpads are used for regular supplementary feeding and loafing of cattle. They have a either a solid foundation or concreted so that nutrients are captured. Both feed and standoff pads are used to keep livestock off pasture, and particularly fodder crops, when weather and soil conditions are unsuitable, i.e., when there is an elevated risk of P (and other contaminants) loss.

5.7.4. Agroforestry

Agroforestry is a form of intercropping where woody vegetation, typically trees, are planted at low density in pasture and cropping systems. Pasture agroforestry is also called silvopasture and cropping agroforestry silvoarable. Tree density can be as low as 20 trees / ha, e.g., rows 50 m apart with trees 10 m apart down the row, up to 400 trees / ha e.g., 5 × 5 m tree spacing. Agroforestry is uncommon in A-NZ but in many other countries, e.g., China, Canada, continental Europe, it is common, even the default farming system in some areas. There are multiple diverse benefits of agroforestry, for example: Increased biodiversity, climate change mitigation and adaptation, increased and more stable economic returns, reduced tree diseases, erosion control, shelter for crops, shade and shelter for livestock resulting in higher welfare and improved growth / productivity and conservation biocontrol. Agroforestry can also mitigate P loss, through reducing overall soil loss (e.g., acting in a similar fashion to a riparian planting within a paddock), reducing the chance of landslips, and taking up soluble P, especially from deeper soil layers (Udawatta *et al.*, 2002; Pavlidis & Tsihrintzis, 2018). With multiple benefits agroforestry offers considerable value to A-NZ farming systems. However, the system has to be designed and managed correctly as negative outcomes can occur (Mackay-Smith *et al.*, 2022; Mackay-Smith et al., 2024).

5.8. In-water mitigations

In-water mitigations are mitigations where P has entered waterbodies. There are many in-water P mitigation measures, many of which are more suitable for larger water bodies, e.g., rivers and lakes that are under public rather than smaller water bodies under private management.

5.8.1. Management of ditches, drains and small / temporary streams

There are a range of ditches, surface drains and small streams on farms that may only flow periodically or only have low water levels. They therefore experience a series of wetting and drying phases which have complex effects on how P behaves in the soil in and around them.

They are also often mechanically cleared and/or receive herbicide treatments which can increase P losses. Mechanical clearance at some point is unavoidable as ditches and drains collect soil / sediment so fill up and plant growth and ecological succession (e.g., trees establishing) will reach a point where they block the drain stopping it functioning. However, much of the herbicide use is nonessential, and some could be viewed as cosmetic. The application of herbicides around such water bodies is the direct opposite of grass / pasture strips and riparian plantings discussed above. Stopping herbicides application and allowing / establishing grass / pasture around and in ditches, drains and small water bodies, is both an effective mitigation strategy that also eliminates the cost of applying herbicides.

Ditches and drains can be viewed as long linear wetlands (McKergow *et al.*, 2007). Establishing suitable vegetation, e.g., grass, in them would increase water residence time and reduce sediment movement. This could be further enhanced by addition of series of low weirs. Contrarily, management of these ditches, drains and temporary streams, to minimise P loss (and loss of soil, nutrients and provision of ecosystem services) is nearly the complete opposite of their original purpose and management, i.e., the rapid removal of excess soil water and to prevent flooding. The design (size, shape) of ditches and drains may well have to be modified to ensure that they can still allow excess water to be removed while still minimising P loss and other environmental harms.

5.8.2. Sediment traps — dams, ponds and wetlands

A sediment traps is a long, deep pool that is dug within a waterway where the water flow slows significantly, allowing particles of fine sand and silt to drop out of suspension and sink to the bottom of the trap. They should be at least 1.5 times the width of the incoming channel, 10 times as long and dug out to 1.5 m below the original channel (McKergow *et al.*, 2007). They need to be cleaned out (i.e., accumulated sediment dug out) once to twice a year based on how fast the sediment builds up. Cleaning does create a short spike in P losses due to disturbance of the sediments, which are then carried downstream. They are highly effective at trapping sand, but, need a residence time of one day to trap silt. There is not enough research in A-NZ to confirm their how effective they are in mitigating P losses, and there is one example where P losses increased due to algae taking up P and then being washed out of the trap (Maxted *et al.*, 2005).

Dams and ponds are effectively large sediment traps. They can be both natural and artificial. Their bigger size means water flow rates are lower and retention time longer than traps so silts and even clays can settle out. This is particularly true where flows are temporary or sufficiently low that all the water infiltrates into the ground. However, the behaviour of P moving between dissolved and particulate forms means that in some instances P losses are reduced and in others increased.

Where the water in the dam or pond can be extracted and reused on farm, e.g., for irrigation, or treated as effluent this can reduce overall P losses.

Wetlands are areas of soil that are flooded or saturated by water either permanently (for years or decades) or seasonally (for weeks or months). This results in oxygen-free (anoxic) processes prevailing. Examples include swamps, marshes and peat bogs. They also can be both natural and artificial. They can reduce P losses by trapping sediment and plants growing in them taking up P. However, they are often poor at retaining soluble P, they can become saturated by P and turn from a sink to a source. Artificial wetlands can be designed to remove P for example, by increasing sedimentation, promote soluble P uptake by plants and other organisms and addition of P-sorptive materials, e.g., slag. However wetland experiments in A-NZ have found mixed results with P levels in outflow water being both higher and lower than inflow water so they cannot be generally recommended as a P mitigation measure.

5.8.3. Summary table of measures

Table 3 lists the mitigation strategies discussed above and rates their effectiveness, cost and how rapidly they reduce P losses.

P-loss mitigation strategy	Effectiveness	Cost	Response rate
In-paddock mitigations			
Only fertilising to P soil test results	Low	Low	Slow to fast
Low solubility P fertiliser	Mod	Low	Mod
Restricted grazing of winter fodder crops	High	Mod	Fast
Cover crops	High	Low	–
Minimum tillage	Low	Low	
Irrigation management	Mod	Low	–
Low rate effluent application	Mod	Low	Fast
Artificial drain amendments	High	Low	Fast
Soil amendments (alum, bauxite)	Mod to high	Mod	Fast
Edge of paddock mitigations			
Fencing off waterways	High	Low	Fast
Pasture / grass strips	Mod	High	Fast
Riparian strips	Mod	High	Fast
Farm system mitigations			
Stock bridges	Low	Mod	Fast
Increased effluent pond size and deferred application	Mod	Low	Fast
Standoff pads and permanent feedpads	Mod	High	Mod
Agroforestry	Mod	High	Slow
In-water mitigations			
Management of ditches, drains and small / temporary streams	Mod	High	-
Sediment traps — dams, ponds and wetlands	Low	High	-

Table 3. On-farm strategies to mitigate P loss to the environment, with ratings for effectiveness, cost and speed of response. Categorised into low, medium and high (equating to 0–33, 34–66, and 67–100%, respectively). From ed into low, medium and high (equating to 0–33, 34–66, and 67–100%, respectively). From (McDowell *et al.*, 2013; Macintosh & McDowell, 2020).

6. Conclusions

Due to phosphorous being essential and unsubstitutable to biology and many manufactured products it is vital that society manages P sustainably. This requires the current P stream, flowing from mined geological reserves through farmland, food, and manufactured products into the hydrosphere, is returned to a cycle at human time scales. With most human managed P being used for agricultural fertilisers, agriculture is at the center of the sustainable management of P. There is a substantial amount of research and farmer level information on multiple methods to minimise P loss to the environment and mitigate losses from farms. Wider society has a role in ensuring that P removed from agricultural systems in food and non-food products, is suitably processed so that it can be cycled back to farmland. In the short to medium term, while the phosphorous stream is returned to a cycle, additional sources of geological P with A-NZ need to be identified to ensure A-NZ's future phosphorous security.

7. Further sources of information

These are some key sources of information on phosphorous in general, best practice P fertiliser management, P in agriculture, P loss mitigation strategies, and the impact of P on the environment.

- Our Land and Water ourlandandwater.nz
- Fertiliser Association of NZ www.fertiliser.org.nz
- DairyNZ www.dairynz.co.nz
- Beef +Lamb beeflambnz.com
- Foundation for Arable Research www.far.org.nz
- Ministry for the Environment environment.govt.nz
- European Sustainable Phosphorus Platform (ESPP) www.phosphorusplatform.eu
- Global Phosphorus Institute www.tgpi.org
- Our Phosphorus Future — Towards global phosphorus sustainability (Brownlie *et al.*, 2022c)
- Phosphorus: agriculture and the environment (Sims & Sharpley, 2005)
- Assessment of strategies to mitigate the impact or loss of contaminants from agricultural land to fresh waters (McDowell *et al.*, 2013)

8. References

Anon. (2015). *The Planetary Boundaries framework*, https://www.stockholmresilience.org/research/planetary-boundaries.html

Argus Media Group. (2023). Phosphate rock resources & reserves (pp. 48). Paris, France: International Fertilizer Association https://www.fertilizer.org/wp-content/uploads/2023/04/2023_Argus_IFA_Phosphate_Rock_Resources_and_Reserves_Final.pdf

Arnon, D. I. & Stout, P. R. (1939). The essentiality of certain elements in minute quantity for plants with special reference to copper. *Plant Physiology, 14*(2), 371-375. doi:10.1104/pp.14.2.371 https://academic.oup.com/plphys/article/14/2/371/6092851

Ashley, K., Cordell, D. & Mavinic, D. (2011). A brief history of phosphorus: From the philosopher's stone to nutrient recovery and reuse. *Chemosphere, 84*(6), 737-746. doi:10.1016/j.chemosphere.2011.03.001 https://www.sciencedirect.com/science/article/pii/S0045653511002499

Asimov, I. (1974). *Asimov on chemistry*. New York, USA: Doubleday

Asrade, D. A., Kulhánek, M., Balík, J., Černý, J. & Sedlář, O. (2023). Side effect of organic fertilizing on the phosphorus transformation and balance over 27 years of maize monoculture. *Field Crops Research, 295*, 108902. doi:10.1016/j.fcr.2023.108902 https://www.sciencedirect.com/science/article/pii/S0378429023000953

Boulaine, J. (1994). Early soil science and trends in the early literature. In P. McDonald (Ed.), *The literature of soil science* (pp. 24). Ithaca, USA: Cornell University Press

Bradley, A. L. (2019). *Manure management for small and hobby farms*. Brattleboro, Vermont, USA: Northeast Recycling Council, Inc. https://nerc.org/documents/manure_management/manure_management_handbook.pdf

Brown, P. H., Zhao, F.-J. & Dobermann, A. (2022). What is a plant nutrient? Changing definitions to advance science and innovation in plant nutrition. *Plant and Soil, 476*(1), 11-23. doi:10.1007/s11104-021-05171-w https://link.springer.com/article/10.1007/s11104-021-05171-w

Brownlie, W. J., Sakrabani, R., Metson, G. S., Blackwell, M. S. A. & Spears, B. M. (2022a). Opportunities to recycle phosphorus-rich organic materials. In W. J. Brownlie, M. A. Sutton, K. V. Heal, D. S. Reay & B. M. Spears (Eds.), *Our Phosphorus Future - Towards global phosphorus sustainability* (pp. 219-270). Edinburgh: UK Centre for Ecology & Hydrology doi:10.13140/RG.2.2.17834.08645 https://www.researchgate.net/publication/360477048_The_Our_Phosphorus_Future_Report

Brownlie, W. J., Sutton, M. A., de Boer, M. A., Camprubí, L., Hamilton, H. A., Heal, K. V., Morgandi, T., Neset, T.-S. & Spears, B. M. (2022b). Phosphorus reserves, resources and uses. In W. J. Brownlie, M. A. Sutton, K. V. Heal, D. S. Reay & B. M. Spears (Eds.), *Our Phosphorus Future - Towards global phosphorus sustainability* (pp. 20-71). Edinburgh: UK Centre for Ecology & Hydrology doi:10.13140/RG.2.2.17834.08645 https://www.researchgate.net/publication/360477048_The_Our_Phosphorus_Future_Report

Brownlie, W. J., Sutton, M. A., Heal, K. V., Reay, D. S. & Spears, B. M. (Eds.). (2022c). *Our Phosphorus Future - Towards global phosphorus sustainability*. Edinburgh: UK Centre for Ecology & Hydrology doi:10.13140/RG.2.2.17834.08645 https://www.researchgate.net/publication/360477048_The_Our_Phosphorus_Future_Report

Cherry, K. A., Shepherd, M., Withers, P. J. A. & Mooney, S. J. (2008). Assessing the effectiveness of actions to mitigate nutrient loss from agriculture: A review of methods. *Science of The Total Environment, 406*(1), 1-23. doi:j.scitotenv.2008.07.015 https://www.sciencedirect.com/science/article/pii/S0048969708007559

Cordell, D. & White, S. (2013). Sustainable phosphorus measures: Strategies and technologies for achieving phosphorus security. *Agronomy, 3*(1), 86-116. http://www.mdpi.com/2073-4395/3/1/86

Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S. & Grasso, M. (2017). Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosystem Services, 28*(Part A), 1-16. http://www.sciencedirect.com/science/article/pii/S2212041617304060

Cotrufo, M. F., Lavallee, J. M. & Sparks, D. L. (2022). Soil organic matter formation, persistence, and functioning: A synthesis of current understanding to inform its conservation and regeneration. In *Advances in Agronomy* (Vol. 172, pp. 1-66): Academic Press doi:10.1016/bs.agron.2021.11.002 https://www.sciencedirect.com/science/article/pii/S0065211321001048

de Boer, M. A., Wolzak, L. & Slootweg, J. C. (2019). Phosphorus: Reserves, production, and applications. In H. Ohtake & S. Tsuneda (Eds.), *Phosphorus Recovery and Recycling* (pp. 75-100). Singapore: Springer Singapore doi:10.1007/978-981-10-8031-9_5 https://link.springer.com/chapter/10.1007/978-981-10-8031-9_5

Dodds, W. K., Bouska, W. W., Eitzmann, J. L., Pilger, T. J., Pitts, K. L., Riley, A. J., Schloesser, J. T. & Thornbrugh, D. J. (2009). Eutrophication of U.S. freshwaters: Analysis of potential economic damages. *Environmental Science & Technology, 43*(1), 12-19. doi:10.1021/es801217q https://doi.org/10.1021/es801217q

Fertiliser Association of New Zealand. (2023). *Code of practice for fertiliser nutrient management*. Wellington, New Zealand: Fertiliser Association of New Zealand https://www.fertiliser.org.nz/Site/code-of-practice/

Foster, J. B. & Magdoff, F. (1998). Liebig, Marx, and the depletion of soil fertility: relevance for today's agriculture. *Monthly Review, 50*(3), 32. doi:10.14452/MR-050-03-1998-07_3 https://monthlyreviewarchives.org/index.php/mr/article/view/MR-050-03-1998-07_3

Gumbo, B. (2005). *Short-cutting the phosphorus cycle in urban ecosystems.* Delft University of Technology and UNESCO-IHE Institute for Water Education, Delft, Delft, Germany https://research.tudelft.nl/en/publications/short-cutting-the-phosphorus-cycle-in-urban-ecosystems

Hermann, L., McGrath, J. W., Kabbe, C., Macintosh, K. A., Dijk, K. v. & Brownlie, W. J. (2022). Opportunities for recovering phosphorus from residue streams. In W. J. Brownlie, M. A. Sutton, K. V. Heal, D. S. Reay & B. M. Spears (Eds.), *Our Phosphorus Future - Towards global phosphorus sustainability* (pp. 272-306). Edinburgh: UK Centre for Ecology & Hydrology doi:10.13140/RG.2.2.17834.08645 https://www.researchgate.net/publication/360477048_The_Our_Phosphorus_Future_Report

Hogan, D. J. & Williamson, B. E. (2000). *New Zealand is different: Chemical milestones in New Zealand History. Revised edition*. Christchurch, New Zealand: Clerestory Press for New Zealand Institute of Chemistry https://www.cambridge.org/core/article/denis-hogan-and-bryce-williamson-eds-new-zealand-is-different-chemical-milestones-in-new-zealand-history-revised-edition-christchurch-clerestory-press-for-new-zealand-institute-of-chemistry-2000-pp-xii308-isbn-095837

Johnes, P. J., Heathwaite, A. L., Spears, B. M., Brownlie, W. J., Elser, J. J., Haygarth, P. M., Macintosh, K. A. & Withers, P. J. A. (2022). Phosphorus and water quality. In W. J. Brownlie, M. A. Sutton, K. V. Heal, D. S. Reay & B. M. Spears (Eds.), *Our Phosphorus Future - Towards global phosphorus sustainability* (pp. 158-217). Edinburgh: UK Centre for Ecology & Hydrology doi:10.13140/RG.2.2.17834.08645 https://www.researchgate.net/publication/360477048_The_Our_Phosphorus_Future_Report

Johnson, C., Albrecht, G., Ketterings, Q., Beckman, J. & Stockin, K. (2005). *Nitrogen basics – The nitrogen cycle* East Syracuse, New York, USA: Cornell University Cooperative Extension http://cceonondaga.org/resources/nitrogen-basics-the-nitrogen-cycle

Johnston, A. M. & Bruulsema, T. W. (2014). 4R Nutrient Stewardship for Improved Nutrient Use Efficiency. *Procedia Engineering, 83*, 365-370. doi:10.1016/j.proeng.2014.09.029 https://www.sciencedirect.com/science/article/pii/S1877705814011229

King, F. H. (1911). *Farmers of forty centuries, or permanent agriculture in China, Korea, and Japan*: Mrs. F.H. King

Li, B., Boiarkina, I., Young, B. & Yu, W. (2015). Substance flow analysis of phosphorus within New Zealand and comparison with other countries. *Science of The Total Environment, 527-528*, 483-492. doi:10.1016/j.scitotenv.2015.04.060 https://www.sciencedirect.com/science/article/pii/S0048969715005112

Macintosh, K. A., Chin, J., McHugh, D., Connolly, J., Archilla, J. C., Pícon, J. A., McAleenan, P., Quinn, J. P., Manesiotis, P., O'Flaherty, V. & McGrath, J. W. (2014). *Phosphorus from wastewater: Novel technologies for advanced rreatment and re-use. Report No. 289*. Wexford, Ireland: Environmental Protection Agency

Macintosh, K. A., Doody, D. G., Withers, P. J. A., McDowell, R. W., Smith, D. R., Johnson, L. T., Bruulsema, T. W., O'Flaherty, V. & McGrath, J. W. (2019). Transforming soil phosphorus fertility management strategies to support the delivery of multiple ecosystem services from agricultural systems. *Science of The Total Environment, 649*, 90-98. doi:10.1016/j.scitotenv.2018.08.272 https://www.sciencedirect.com/science/article/pii/S0048969718332443

Macintosh, K. A., Mayer, B. K., McDowell, R. W., Powers, S. M., Baker, L. A., Boyer, T. H. & Rittmann, B. E. (2018). Managing diffuse phosphorus at the source versus at the sink. *Environmental Science & Technology, 52*(21), 11995-12009. doi:10.1021/acs.est.8b01143 https://pubs.acs.org/doi/10.1021/acs.est.8b01143

Macintosh, K. A. & McDowell, R. W. (2020). *DairyNZ body of knowledge: Phosphorus and sediment*: DairyNZ Limited

Mackay-Smith, T. H., Burkitt, L. L., López, I. F. & Reid, J. I. (2022). The impact of a kānuka silvopastoral system on surface runoff and sediment and nutrient losses in New Zealand hill country. *CATENA, 213*, 106215. doi:10.1016/j.catena.2022.106215 https://www.sciencedirect.com/science/article/pii/S0341816222002016

Mackay-Smith, TH, Spiekermann, RI, Richards, DR, Harcourt, N, and Burkitt, LL (2024). An integrative approach to silvopastoral system design: perspectives, potentials and principles. New Zealand Journal of Agricultural Research: 1-41. doi:10.1080/00288233.2023.2298922 https://www.tandfonline.com/doi/full/10.1080/00288233.2023.2298922

Marx, K. (1976). *Capital, Vol. I*. New York: Vintage

Maxted, J. R., McCready, C. H. & Scarsbrook, M. R. (2005). Effects of small ponds on stream water quality and macroinvertebrate communities. *New Zealand Journal of Marine and Freshwater Research, 39*(5), 1069-1084. doi:10.1080/00288330.2005.9517376 https://www.tandfonline.com/doi/abs/10.1080/00288330.2005.9517376

McCaskill, L. W. (1929). *Fertilizers in New Zealand, 1867-1929.* Canterbury Agricultural College, University of New Zealand, Lincoln https://hdl.handle.net/10182/8795

McDowell, R. W. (2014). *Solutions for the dairy industry to control phosphorus.* Proceedings of the Enduring Agricultural Solutions for improving water quality, Lincoln University, Canterbury, New Zealand

McDowell, R. W., Biggs, B. J. F., Sharpley, A. N. & Nguyen, L. (2004). Connecting phosphorus loss from agricultural landscapes to surface water quality. *Chemistry and Ecology, 20*(1), 1-40. doi:10.1080/02757540310001626092 https://www.tandfonline.com/doi/abs/10.1080/02757540310001626092

McDowell, R. W. & Catto, W. (2005). Alternative fertilisers and management to decrease incidental phosphorus loss. *Environmental Chemistry Letters, 2*(4), 169-174. doi:10.1007/s10311-005-0099-6 https://link.springer.com/article/10.1007/s10311-005-0099-6

McDowell, R. W. & Nash, D. (2012). A review of the cost-effectiveness and suitability of mitigation strategies to prevent phosphorus loss from dairy farms in New Zealand and Australia. *Journal of Environmental Quality, 41*(3), 680-693. doi:10.2134/jeq2011.0041 https://acsess.onlinelibrary.wiley.com/doi/abs/10.2134/jeq2011.0041

McDowell, R. W., Schallenberg, M. & Larned, S. (2018). A strategy for optimizing catchment management actions to stressor–response relationships in freshwaters. *Ecosphere, 9*(10), e02482. doi:10.1002/ecs2.2482 https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1002/ecs2.2482

McDowell, R. W., Wilcock, B. & Hamilton, D. P. (2013). *Assessment of strategies to mitigate the impact or loss of contaminants from agricultural land to fresh waters*. Lincoln, New Zealand: AgResearch https://environment.govt.nz/assets/Publications/Files/assessment-strategies-mitigate-impact-loss-contaminants-agricultural-land-freshwater_0.pdf

McKergow, L. A., Tanner, C. C., Monaghan, R. M. & Anderson, G. (2007). *Stocktake of diffuse pollution attenuation tools for New Zealand pastoral farming systems*. Hamilton, New Zealand: National Institute of Water & Atmospheric Research Ltd.. https://niwa.co.nz/freshwater/management-tools/water-quality-tools/stocktake-of-diffuse-pollution-attenuation-tools-for-new-zealand-pastoral

Merfield, C. (2022). Farmers don't need nitrogen fertilisers at all. *Newsroom*. https://www.newsroom.co.nz/farmers-dont-need-nitrogen-fertilisers-at-all

Ministry for the Environment & Stats NZ. (2019). *New Zealand's Environmental Reporting Series: Environment Aotearoa 2019*. Wellington, New Zealand: Ministry for the Environment & Stats NZ https://www.mfe.govt.nz/sites/default/files/media/Environmental%20reporting/environment%20-aotearoa-2019.pdf

Monaghan, R. M., Hedley, M. J., Di, H. J., McDowell, R. W., Cameron, K. C. & Ledgard, S. F. (2007). Nutrient management in New Zealand pastures - recent developments and future issue 2007 *New Zealand Journal of Agricultural Research, 50*, 181–201. doi:10.1080/00288230709510290 https://www.tandfonline.com/doi/abs/10.1080/00288230709510290

Pavlidis, G. & Tsihrintzis, V. A. (2018). Environmental benefits and control of pollution to surface water and groundwater by agroforestry systems: A review. *Water Resources Management, 32*(1), 1-29. doi:10.1007/s11269-017-1805-4 https://link.springer.com/article/10.1007/s11269-017-1805-4

Plunkett, M., Wall, D. & Sheil, T. (2019). *The efficient use of phosphorus in agricultural soils. Technical Bulletin Series – No. 4*. Cork, Ireland: The Fertilizer Association of Ireland and Teagasc https://fertilizer-assoc.ie/wp-content/uploads/2019/02/The-Efficient-Use-of-Phosphorus-In-Agricultural-Soils-Tech-Bulletin-No.-4.pdf

Prasad, M. (2009). *A literature review on the availability of phosphorus from compost in relation to the Nitrate Regulations SI 378 of 2006* Wexford, Ireland: Environmental Protection Agency http://www.cre.ie/docs/Phosphorus%20Review.pdf

Prasad, R. & Chakraborty, D. (2019). *Phosphorus basics: Understanding phosphorus forms and their cycling in the soil*. Auburn, Alabama, USA: Alabama Cooperative Extension System https://www.aces.edu/blog/topics/crop-production/understanding-phosphorus-forms-and-their-cycling-in-the-soil/

Qi, R., Jones, D. L., Li, Z., Liu, Q. & Yan, C. (2020). Behavior of microplastics and plastic film residues in the soil environment: A critical review. *Science of The Total Environment, 703*, 134722. doi:10.1016/j.scitotenv.2019.134722 https://www.sciencedirect.com/science/article/pii/S0048969719347138

Sharma, S. C., Sahoo, A. & Chand, R. (2019). Potential use of waste wool in agriculture: An overview. *Indian Journal of Small Ruminants (The), 25*(1), 1-12. doi:10.5958/0973-9718.2019.00019.9 https://www.indianjournals.com/ijor.aspx?target=ijor:ijsr&volume=25&issue=1&article=001

Sims, J. T. & Sharpley, A. N. (2005). *Phosphorus: agriculture and the environment* (Vol. 46). Madison, Wisconsin, USA: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. https://acsess.onlinelibrary.wiley.com/doi/book/10.2134/agronmonogr46

Smil, V. (2000). Phosphorus in the environment: Natural flows and human interferences. *Annual Review of Energy and the Environment, 25*(1), 53-88. doi:10.1146/annurev.energy.25.1.53 https://www.annualreviews.org/doi/abs/10.1146/annurev.energy.25.1.53

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B. & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science, 347*(6223), 736-747. doi:10.1126/science.1259855 https://www.science.org/doi/10.1126/science.1259855

Sutton, M. A., Howard, C. M., Erisman, J. W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H. & Grizzetti, B. (Eds.). (2011). *The European nitrogen assessment: Sources, effects and policy perspectives*. Cambridge: Cambridge University Press https://www.cambridge.org/core/books/european-nitrogen-assessment/7156D2A2F03CD36FFA0B6EC60BF9A497

Udawatta, R. P., Krstansky, J. J., Henderson, G. S. & Garrett, H. E. (2002). Agroforestry practices, runoff, and nutrient loss. *Journal of Environmental Quality, 31*(4), 1214-1225. doi:10.2134/jeq2002.1214 https://doi.org/10.2134/jeq2002.1214

Vallentyne, J. R. (1974). *The algal bowl: Lakes and man*. Ottawa, Canada: Dept of the Environment Fisheries and Marine Service

WWF. (2016). *Living Planet Report 2016: Risk and resilience in a new era*. Gland, Switzerland: WWF https://www.worldwildlife.org/pages/living-planet-report-2016

Zheljazkov, V. D. (2005). Assessment of wool waste and hair waste as soil amendment and nutrient source. *Journal of Environmental Quality, 34*(6), 2310-2317. doi:10.2134/jeq2004.0332 https://acsess.onlinelibrary.wiley.com/doi/abs/10.2134/jeq2004.0332