The sixth R: Revitalizing the natural phosphorus pump

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Key Points:

- Animals increase availability of phosphorus globally, but this role had been minimized through extinctions and population reductions.
- Humans may be approaching peak phosphorus and need better ways to recycle phosphorus**.**
- We propose a phosphorus trading system to revitalize the natural animal-mediated phosphorus pump

Abstract – Humans and natural systems face three pressing concerns: the loss of large animal biodiversity, eutrophication of many aquatic systems, and the need to better recycle phosphorus. Here we propose a mechanism to help alleviate these problems. Some have hypothesized that we are approaching "peak phosphorus," where phosphorus may become more expensive as it becomes rarer, thus endangering the green agricultural revolution and the ability to feed ourselves. Animals play a key role in the recycling of phosphorus (P) from the ocean depths to the continental interiors, but this movement has declined by >90% over the past 10,000 years. Prior to this decline, animals played a critical role in the global P budget and the pre-Anthropocene P budget was in steady state only after accounting for animal P inputs. Recently a 5R strategy was developed by Withers et al (2015) to Realign P inputs, Reduce P losses, Recycle P in bio-resources, Recover P in wastes, and Redefine P in food systems. Here we suggest a sixth R, to Revitalize the natural phosphorus pump. Countries are starting to mandate P recycling, and here we propose a P-trading scheme based on REDD+, where a country could partially achieve its recycling goals through revitalizing the natural P pump. Accrued money from this scheme could be used to restore or conserve wild animal populations while increasing natural phosphorus recycling.

Key words – Biodiversity loss, Eutrophication, Peak P, phosphorus, REDD, RNPP, Rewilding

Introduction

Phosphorus (P) is an irreplaceable element vital to all life, and a steady supply is essential for human society. In the past, P was widely transported by animals, from the ocean depths to the continental interiors. However, species extinctions, diminished population abundances and constraints on animal movement have reduced this process by more than 90% since the late Pleistocene [*Doughty et al., 2016*]. Today, anthropogenic use of P in many parts of the world vastly exceeds planetary boundaries, causing eutrophication [*Diaz and Rosenberg,* 2008] [*Steffen et al.,* 2015], whilst there are also concerns about insufficient P supplies for future populations [*Edixhoven et al.,* 2014][*Neset and Cordell,* 2012] [*Geissler et al.,* 2018] [*Scholz and Hirth,* 2015a] [*Ulrich,* 2016a]. The inefficient use of P today in industrial and agriculture systems results in losses of up to 95% along the supply chain [*Scholz and Wellmer 2015*]. As a result, recent work has focused on developing a circular P economy of efficient recycling [*Steiner and Geissler,* 2018] forwarding a 5R strategy: 1. Realign P inputs, 2. Reduce P losses, 3. Recycle P in bioresources, 4. Recover P in wastes, and 5. Redefine P in food systems [*Withers et al.,* 2015] [*Withers et al.,* 2018]. Here we suggest a sixth R: Revitalize the natural phosphorus pump.

By restoring wild populations of whales, seabirds, anadromous fish, herbivores, scavengers, and filter feeders, we can enhance the retention of phosphorus across ecosystems. We emphasize that this is the sixth R, or just one component of a broader system to better mitigate P loss. Human mediated transport of P dwarfs the natural animal mediated movement of P today, but past global P budget was likely only in steady state with animal inputs. In addition, animals can greatly alter the connections, drivers and dynamics of P cycling in wild ecosystems. In this paper, we will first review the important roles animals play in the P cycle, show how these vital nutrient arteries have been severed, and put the former role of animals into a global P budget. Then, we review the current state of human P usage and show how our system to revitalize the natural phosphorus pump might work in practice.

I. Animals can greatly alter the connections, drivers and dynamics of P cycling in ecosystems

All animals are important for nutrient recycling because animal digestion accelerates cycling of nutrients from more recalcitrant forms in plants to more labile forms in excreta [*Hobbs*, 1996]. However, animals are also key in the transport of nutrients such as P across concentration gradients or between different systems (e.g., aquatic to terrestrial). Animals are not just key in increasing concentrations but they move P upstream against gravity, the redistribute it more evenly across the landscape, they filter it, and they increase retention. For example:

1. *Upstream movement*: Many empirical studies show animal movement of nutrients against gravity. Many wild animals, including whales, migratory fish, and seabirds, play an important role in the phosphorus cycle. Whales transport nutrients laterally, in moving between feeding and breeding areas, and vertically by transporting nutrients from nutrient-rich deep waters to surface waters via fecal plumes and urine, where it is available to phytoplankton [*Roman et al.*, 2014] [*Roman and McCarthy*, 2010][*Nicol et al.*, 2010] . Studies in the Gulf of Maine show that cetaceans and other marine mammals deliver large amounts of N and P to the photic zone by feeding at or below the thermocline and then excreting fecal N and P near the surface [*Roman and McCarthy*, 2010] [*Roman et al.*, 2016].

Seabirds act as nutrient vectors by transporting nutrients from marine foraging areas to terrestrial breeding colonies (*Otero et al. 2018*). Studies have shown that soil P concentrations on seabird islands were greater than on non-seabird islands [*Mulder et al.,* 2011]. In some sites, increased soil P more than doubled plant P concentrations [*Mulder et al.,* 2011].

Many fish species, such as salmonids and river herring, provide an important link between marine and freshwater systems (*Tiegs et al. 2011, West et al. 2010*). Sea turtles move marine P to beaches through their eggs during nesting season (*Bouchard and Bjorndal 2000)*. Other species, including pelagic or bottom feeders such as the redhorse (*Moxostoma* spp.), potentially provide important nutrient transport during migration to upstream breeding grounds in freshwater systems (e.g., *Reid 2006*). There is still uncertainty about how much of the P moved by whales, fish, and seabirds is retained at the surface and further studies will need to quantify this.

2. *Filtering.* In addition to moving and distributing nutrients, animals can absorb and filter phosphorus, typically through feeding or engineering ecosystems. Filter feeders, such as oysters, are especially effective at taking up and retaining phosphorus and other nutrients *(Dame et al. 1989*). In contrast to the upstream movement and distribution of P by anadromous fish and scavengers, bivalve suspension feeders transfer P from the water column to sediments in the bio-deposits, helping to reduce nutrient pollution (*Newell et al. 2005*). Such filtering can be especially important to counter eutrophication (*Diaz and Rosenberg, 2008*).

3. Retention. Some species, such as beavers, engineer ecosystems in ways that can reduce phosphorus runoff, although the effectiveness of beaver dams in reducing phosphate levels continues to be debated. Puttock et al. (2017) found reduced phosphate levels below beaver dams, and Muskopf (2007) found increased levels of P after the removal of dams near Lake Tahoe. Other studies have found higher levels of phosphate downstream or no detectable effect

(Rosell et al. 2005). The role of beavers in the phosphorus cycle is an important research topic in revitalizing efforts.

4. *Diffusion and directional transport*: Herbivores, scavengers, and carnivores can distribute phosphorus across the landscape. Animal digestion accelerates the cycling of nutrients from more recalcitrant forms in decomposing plant matter to more labile forms in excreta (*Hobbs 1996)*. Wide-ranging carnivores can further distribute phosphorus when they prey on ungulates and other herbivores. In terrestrial systems, moose (*Alces americanus*) move aquatic-derived nutrients to terrestrial systems, thus enhancing terrestrial fertility[*Bump et al.,* 2009] [*Bump,* 2018]. Isotopic evidence has verified that terrestrial predators (such as eagles, bears, and otters) that feed on anadromous fish, transport ocean-derived nutrients to terrestrial ecosystems [*Reimchen et al.,* 2003]. Predator effects also include nutrient excretion, translocation within and across ecosystem boundaries after prey consumption, and indirect effects of predator interactions with prey *(Schmitz et al. 2010*). Marine mammals were important in the diet of coastal scavengers, such as condors and polar bears, though dietary shifts occurred after the commercial harvest of cetaceans and pinnipeds (*Chamberlain et al. 2005, Laidre et al. 2018*). Such scavenging likely resulted in the distribution of P and other nutrients across the coastal landscape. Animals can act as dispersal agents moving significant quantities of nutrients from areas of high nutrient concentration to areas of lower nutrient concentrations even without mass flow of faeces out of the fertile area. In Amazonia, woolly monkeys (*Lagothrix lagothricha*) eating and defecating across a floodplain nutrient concentration gradient transported more P than arrives from dust inputs [*Stevenson and Guzmán-Caro,* 2010].

Table 1 (see bottom)

Loss of the planet's nutrient arteries

Most ecosystems lost their large animals at the Late Pleistocene and early Holocene, with around 150 mammal megafaunal species (here defined as ≥44 kg body mass) going extinct [*Sandom et al.,* 2014]. Large animals tend to be the most prone to extinctions and range declines and such declines continue into the present [*Dirzo et al.*, 2014], yet these same groups are the most important for nutrient dispersal [*Wolf et al 2013*][*Doughty et al 2013*].

Similarly, in marine systems, large bodied and upper trophic organisms have undergone steep declines [*McCauley et al 2015*]. Since the advent of commercial whaling, many species were reduced to near extinction. For instance, the blue whale (*Balaenoptera musculus*), the largest animal ever to have existed, remains at about 1% of its prehunting population size in the Southern Ocean [*Branch and Williams,* 2006] [*Christensen,* 2006]. Freshwater megafauna species such as sturgeons, river dolphins, and turtles have also experienced large declines and 58% of the 132 megafauna freshwater species are threatened [*Carrizo et al.,* 2017].

Seabirds and anadromous fish, which transport nutrients from sea to land, have also declined as a result of overharvesting, invasive species, and habitat modification. Global seabird abundance declined by 69.7% between 1950 and 2010 [*Paleczny et al., 2015*]. Populations of anadromous fish have declined by more than 90% of their historical numbers in the Pacific Northwest [*Gresh et al.,* 2000] and in the northeastern and northwestern Atlantic [*Groot,* 2002] [*Limburg and Waldman,* 2009]. Anadromous fish in freshwater systems are currently at about 6.7% of the biomass capacity [*Mattocks et al.,* 2017].

Many studies consider the importance of individual species on nutrient movement (see Table 1). However, what is most important is the nutrient movement by all animals over long periods of time in an ecosystem. Two studies recently quantified the impact on nutrient distribution of all animals in an ecosystem over long periods of time [*Wolf et al.*, 2013; *Doughty et al.*, 2013]. To address this, they compiled data for terrestrial mammals for various traits such as metabolic rate, day range, population density, and lifetime in order to relate nutrient distribution capacity to body mass. They found a size-dependent relationship, with larger animals having disproportionately greater importance to the distribution of nutrients across a concentration gradient. They first validated this framework using basaltic/granite concentration gradient in Kruger National park and showed mammal-driven nutrient transport is comparable in magnitude to other (abiotic) nutrient fluxes [*Wolf et al.*, 2013]. Then they estimated that following the extinction of megafauna in Amazonia, there was a decrease of >98% of the lateral nutrient flux, with large impacts on ecosystem P concentrations outside of the fertile floodplain regions [*Doughty et al.*, 2013].

These studies have been expanded to consider movement of P at a global scale by all animal groups. Following extinctions and animal population losses, there has been a gradual loss of animal mediated P recycling over the past 12,000 years (Fig 1). Animals moved phosphorus from the ocean depths to the continental interiors through the bodies and feces of marine mammals, anadromous fish, seabirds, and terrestrial animals [*Doughty et al.*, 2016]. For example, whales and other marine mammals formerly moved about 340 million kg P yr^{-1} from the deep sea to surface waters and anadromous fish moved 150 million kg P yr^{-1} globally from the ocean to land. A recent study used an inventory of global seabird populations and a bioenergetics model to estimate that total phosphorus (P) excreted by seabirds was 99 million kg P y^{-1} [*Otero et al.*, 2018]. If global seabird abundance declined by 69.7% [*Paleczny et al., 2015*] then prior flux of P could have been as high as 330 million kg P y^{-1}. Large terrestrial animals moved nutrients away from these coastal and riverine nutrient hotspots into the continental interior [*Doughty et al.,* 2016]. We had previously calculated that the extinctions and population reductions has reduced nutrient movement by about 92% on land and 95% in the ocean. Empirical results comparing a world with no tetrapod herbivores (the Carboniferous) to a world with the largest terrestrial herbivores to have ever existed (in the Cretaceous) demonstrated the importance of nutrient movement by animals over long periods of time and at continental scales [*Doughty,* 2017]. This work suggests that tetrapod herbivores increase P concentrations by 350% (from a median of 81.6 ± 8 to 392 ± 43 ppm in coal deposits). This study also demonstrated animals role in redistributing nutrients more evenly across the landscape with nutrients such a P being 55% more evenly distributed (s.d./median across the landscape) when tetrapod herbivores were present.

Animals in the context of the global P cycle

Animals have traditionally not been considered an important part of the global P cycle, but we contend this is partially because their role has been reduced by >90% (Doughty et al 2016). Schlesinger's classic biogeochemistry textbook shows the paradigm of the global phosphorus cycle, but did not include estimates of animal P movement (Schleshinger 1997). Here, we put the pre-Anthropocene estimates of animal P movement into the global context. In the Schleshinger work (Table 12.6), dust transports 1 (all units are 10^12 gP/yr) from the land to the sea, rivers transport 21 (only 2 available to biota) from the land to sea, mining extracts 12 from rock, and 2 is buried at the ocean bottoms. Our numbers suggest that prior to widespread hunting and extinctions, marine mammals moved 0.34 vertically in the ocean, seabirds moved 0.33 from the ocean to the land and migratory fish moved 0.14 from the ocean to the land. The role of all terrestrial animals diffusing P onto land is more complicated, but potentially very significant, with animals increasing terrestrial plant P concentrations by ~2 (Doughty et al 2013) to ~3 fold (Doughty 2017).

One would assume that the global P budget was in steady state prior to the Anthropocene. However, this is difficult to ascertain because humans have so thoroughly modified the global P budget (mining 12) (Schleshinger 1997). However, we hypothesize that the pre-Anthropocene atmospheric dust transport of P from land to oceans was balanced by animal input of P from ocean to land. For instance, global P deposition has increased 1.4 times compared to preindustrial rates [*Brahney et al.*, 2015]. Therefore, if current P transport from land to ocean is one, then preindustrial loss to the oceans is ~0.7. Here we estimate that the sum of seabirds and migratory fish moving P from oceans to land is 0.47. Since the vertical movement of P by marine mammals would have increased surface water P, 0.47 is likely an underestimate and animal transport may have offset dust transport of P into the oceans. Would terrestrial diffusion of nutrients by animals offset pre-Anthropocene river transport (river transport 21- mining 12 = 9)? Pre-Anthropocene terrestrial P cycle could have been in steady state if we take into account animal diffusion which increase leaf P approximately two (Doughty et al 2013) to three fold (Doughty 2017) (3000 cycled yearly globally between leaves and soil) (Schleshinger 1997). However, further research is needed before these numbers could be added to a global P budget with confidence.

II. Human usage of P

Pre-Anthropocene human role in the P cycle - Currently, P efficiently moves from mined deposits to the bottom of the oceans with few large-scale methods of keeping it within our natural or agricultural systems (Fig 2a). However, this was not always the case. Early civilisations living in low P environments recycled P for thousands of years. For instance, aboriginal communities in Australia converted P to bioavailable forms using ‘firestick’ burning ~40,000 years ago, in rural Asia the application of ‘night-soil’ (faeces and excreta) to fields has been common for at least 5000 years and in Medieval England peasants could graze their sheep on the land of nobility, but faced severe punishment if caught removing their droppings [*Cordell et al., 2009; Ashley et al., 2011*]. More recently, (mid-19th century), people began to mine guano mainly from Peruvian and South Pacific islands (Smil 2000). However, guano deposits were almost completely exploited by the end of the 19th century (Stewart et al., 2005), when humans mainly shifted to non-renewable phosphate rock.

Modern human P usage – Currently, phosphate is mined in sedimentary (87%) or igneous (13%) deposits, and guano no longer plays a major role in global markets. More than 80% of P mined each year is used for human consumption, through the development of chemical fertilizers for farms for food for human or for animals [*Mew et al.,* 2018].

There are serious concerns that we face a scarcity of phosphorus today. Humans have quadrupled P use since the middle of the twentieth century as human population size and meat consumption has increased [*Cordell et al.,* 2009], although phosphorus supply has historically kept pace with population trends over time [*Mew et al.,* 2018]. Recently a debate has emerged about whether we are approaching peak P where future price and availability of P might be like the Hubbert curve that popularized the idea of peak oil [*Hubbert,* 1956]. The combined impact of increasing demand, dwindling reserves, and geopolitical constraints could decrease the supply of P and increase its price. In the last 50 years, however, there have been two periods when P prices have increased by more than a factor of 5, during 1974-75 and 2007-08, indicating supply concerns. However, the US Geological Survey (USGS) reported an increase in global P reserves from 16,000 Mt P in 2010 to 67,000 Mt P in 2014 [*Van Kauwenbergh*, 2010] *[USGS, 2014]*. Based on these results, some have concluded that peak P is not a concern and that P supplies are secure. Others have suggested that such changes to P reserves may have presented an inflated picture of global reserves [*Edixhoven et al.,* 2014]. Several recent special issues have delved into this issue more deeply than we can here, and we recommend the following recent special issues for the interested reader [*Steiner and Geissler*, 2018][*Ulrich,* 2016b] [*Scholz and Hirth,* 2015].

Whether P supplies dwindle or become more expensive in coming years, there is widespread agreement that future recycling of P or reducing use is necessary [*Steiner and Geissler*, 2018]. Agricultural practices could move from a push system – where P is applied liberally in concentrations higher than necessary, with possible detrimental human health effects [*Calvo et al.*, 2014] – to systems of precision agriculture where animals receive the precise amount of P necessary and soil is analysed to add only the correct amount of P. Even those that argue that there is no physical scarcity of phosphorus agree that there are legitimate reasons to ensure future generations' long-term supply [*Brundtland 1987*] [*Steiner and Geissler*, 2018].

Recent efforts have focused on developing a formal circular P economy, or complete regional recycling of all P inputs [*Steiner and Geissler*, 2018] and this can lead to surprising results such as Denmark imports three-fold more P from animal feed than mineral fertilizers [*Klinglmair et al.*, 2015]. Many countries are starting to develop laws to mandate P recycling [*European Commission.,* 2018] [*Mehr et al.,* 2018]. The Ordinance on Avoidance and Disposal of Waste in Switzerland requires the recovery of P from wastewater, sewage sludge, and sewage sludge ashes and the material utilization of P in meat and bone meal by 2026. Germany obliges wastewater treatment plants in populations of more than 50,000 to implement P recovery within the next 12 to 15 years. More countries may follow suit with similar laws in the future [*European Commission.,* 2018]. Recent studies have shown possible complications in achieving the goal of complete P recycling [*Mehr et al.*, 2018]. Today, less P is currently recycled in Switzerland than 10-15 years ago despite the above-mentioned laws [*Mehr et al.*, 2018]. P stopped being recycled in bones in Switzerland because of concerns about the spread of *Bovine Spongiform Encephalitis* (mad cow disease). Health concerns have also led to a ban on sewage sludge import for agriculture. Political decisions made for health reasons are typically enforced more quickly than decisions for environmental reasons, such as the ban of phosphates from laundry detergent [*Mehr et al.,* 2018]. Why is current recycling of P not more widespread? Many water boards indicate that the main barrier to constructing new wastewater treatment plants is the high investment cost with an uncertain return on investment for recovery processes [*de Boer et al.,* 2018]. Future uncertainty in the value of P may also play a role in reducing investment.

Given these complications, below we suggest a P trading system may be more efficient, effective, and have long-term ecological benefits.

III. Revitalize the Phosphorus Pump (RPP) trading scheme

If it is cheaper and easier to invest in a biodiversity project that recycles a known quantity of P, should countries invest in such projects (Fig 2b)? Switzerland now recycles much less P (Box 1) than previously [*Mehr et al.*, 2018] despite laws and enthusiasm to increase P recycling. Switzerland could outsource P recycling to a biodiversity project to help them meet national goals when policy decisions made it difficult (i.e. no bone recycling due to concerns about *Bovine spongiform encephalitis*). We note that laws mandating phosphorus recycling have similarities to laws mandating reducing carbon emissions and will explore this further below.

Box 1 – P trading

Switzerland has reduced P recycling from ~6e6kg yr^{-1} in 1989 to ~2e6kg yr^{-1} in 2015 despite goals to increase P recycling over time. If Switzerland decided it wanted to maintain a constant P recycling rate (i.e. make up the 4e6kg yr^{-1} shortfall), could it do so through biodiversity projects? We had previously calculated that in the past marine mammals likely recycled 340e6 kg yr^{-1} P and migratory fish recycled 140e6 kg yr^{-1} P and therefore to make up this 4e6 kg yr^{-1} shortfall, Switzerland would need to increase whale P recycling (from the historic baseline) by (combined) 0.33%, fish by 1%, and seabirds by 0.33%[*Doughty et al 2016*][*Otero et al.,* 2018] (Fig 3).

One way of addressing phosphorus scarcity and pollution is by restoring wild terrestrial and aquatic animal populations. We have described several broad ways including increasing upstream movement, distribution, filtering and retention of P (Table 1).

Restoration and conservation projects are expensive and here we propose a REDD+ type (Reducing Emissions from Deforestation and Degradation) type trading scenario to provide funds for such projects [*Miles and Kapos*, 2008]. REDD+ is a mechanism to encourage carbon removal from the atmosphere either by reducing CO_2 pollution from factories or by keeping forests intact and their carbon sequestered. If it is too expensive for a factory to upgrade its pollution control, then it can essentially pay a country to keep its forests intact. In a parallel system, if expense or bureaucratic issues make industrial P recycling difficult, the locality would have the option to invest in the natural system of animal-mediated phosphorus recycling. Here we propose a trading system that could reduce nutrient pollution and redistribute phosphorus by natural means (RNPP – Revitalize the Natural Phosphorus Pump).

Money to restore sustainable recycled phosphorus could come from a global phosphate tax on mined phosphorus (for instance, a phased in 10% tax on phosphate revenues could raise $4.5 billion annually – assuming a 2017 revenue of $45 billion) or individual projects funded through voluntary P credits (bought like carbon credits). We estimate the pre-hunting value of the phosphorus moved by marine mammals to surface waters at $0.85 to 3.5 billion per year, based on the variations in P price over the past 15 years. Likewise, we calculate the peak estimated transport of phosphorus from sea to land by anadromous fish at between $0.37 and $1.5 billion per year. On land, P movement by terrestrial herbivores in the Amazon basin alone could be valued at $900 million [*Doughty et al.*, 2013]. From this perspective, land-sharing with animals begins to look more attractive than land sparing, which relies on intensive, industrialized replacements of animal mediated fertilization.

Funds might be allotted by calculating the quantity of phosphorus that will be transported from ocean to land in the fish biomass at historical populations and multiplying this by an estimated price of phosphorus over a period of time (for instance, a period of 30 years). Countries could be assigned gradually increasing phosphorus mandates that could be achieved through conservation projects and the construction of wastewater recycling plants. To oversee such a process, an international framework similar to REDD with the expressed goal of recycling phosphorus and restoring ecosystems could be setup. Any REDD policy must ensure that emissions reductions are real, measurable, and verifiable and market-based mechanisms must validate the integrity of both emissions reduction and carbon markets. Likewise, our system must also ensure that P recycled through biodiversity conservation is real, measurable, and verifiable. Initially, we can rely on modelled outputs, but later such efforts must be tracked.

These funds could be used, for example, to restore migratory fish populations. The restoration of the Elwha River in Washington State, USA, is the largest dam removal project in history, costing ~350 million USD. Following removal, Pacific salmon and trout (*Oncorhynchus* spp.) quickly recolonized the area, restoring ancient phosphorus pathways [*Shaffer et al.*, 2017].

Isotopic data suggest that species such as the Elwha River bull trout, almost entirely landlocked for a century, are rapidly resuming anadromy [*Quinn et al.*, 2017], restoring the flux of marine P to the area. A recent study of the Selune River in Normandy, France, showed that dam removal would reconnect 827 km^2 of catchment area to the sea [*Forget et al.*, 2018]. Models estimate that migratory fish, such as salmon, would increase suitable habitat three-fold for juveniles and greatly increase the mean number of returning salmon. Such models could potentially predict the value of P moved following dam removal. Often restoring one system will increase productivity in others. For instance, one study found total bird and insectivore densities in the summer were strongly predicted by salmon biomass in the autumn [*Field and Reynolds (2011)*].

Terrestrial restoration projects could include restoring natural movement of P away from aquatic environments, such as bears feeding on migratory fish [*Reimchen et al.*, 2003] or moose consuming aquatic plants [*Bump*, 2018]. They could include sustainable human consumption of native mussels in waters with too many nutrients. They could include rethinking pasture systems to encourage movement of P across concentration gradients or into natural ecosystems. For instance, fenceless, biodiverse native animals in pasture systems could redistribute phosphorus into surrounding ecosystems. Natural pastures could restore a balance in the ratio between domestic and wild mammals. Recently, the dry mass of all domesticated animals was an estimated 0.1 Gt of C compared to just 0.007 Gt of C for all wild mammals [*Bar-on et al 2018*]. Even landlocked areas could benefit from a revitalized phosphorus pump [Box 2]. In Vermont, excess P runoff threatens to cost the state approximately $25 million per year to reduce P runoff into Lake Champlain. Restoring native mussels, salmon, beavers, bears, and deer could help redistribute phosphorus throughout the Lake Champlain basin, moving some phosphorus upstream and filtering and retaining much of the rest. Such place-based conservation plans are not a quick fix, but slow conservation can provide more lasting solutions [*Draheim et al.*, 2015] [*Roman*, 2016]. The revitalization of the P cycle would have other benefits including carbon sequestration, through the feeding, growth, and death of fish and whales [*Roman et al., 2014*, http://bluecsolutions.org/fish-carbon]; seed dispersal (large herbivores); and biodiversity protection and enhancement.

Box 2 - Revitalizing the Phosphorus Cycle

Case Study: New England

In the eastern US, phosphorus runoff from urban and agriculture lands has resulted in high loads in lakes and other waterbodies. Among the effects are eutrophication in rivers and lakes and repeated cyanobacteria blooms, such as in the shallow bays of Lake Champlain, located between Vermont and New York *(Carpenter et al. 1998)(Ghebremichael et al. 2010)*. To date, efforts have largely focused on monitoring and reducing phosphorus loads, which will be essential in increasing water quality.

Little attention has been paid to the role that wild animals could play in this system. Worthy of consideration is a holistic approach that would include the upstream movement of P by spawning fish, potential ecological engineering by beavers and their dams, the role of bivalves in filtering phosphorus, and distribution of nutrients by terrestrial herbivores, scavengers, and carnivores.

In Connecticut, alewives, *Alosa pseudoharengus* transport phosphorus from oceans to lake systems. Before widespread habitat alterations—especially in the form of dams, some of which date back more than 300 years—these anadromous fish supplied up to 95% of the phosphorus to coastal lakes in the form of carcasses, gametes, and excretion (*Twining et al. 2013, West et al. 2010*). Other diadromous fish, such as Atlantic salmon, American shad, and sea lampreys, also played important roles in phosphorus and other nutrient cycles before commercial harvest and river alterations in New England *(Saunders et al. 2006*).

Recent research shows that wild and aquaculture filter feeders could be employed to reduce phosphorus pollution. Oyster reefs can uptake 98 g P m^{-2} yr^{-1} (*Dame et al. 1989*). The production of activated oyster shells through pyrolysis shows promise in wastewater treatment, efficiently removing phosphates form wastewater (Kwon et al. 2004). The recent growth of oyster aquaculture in New England could be employed to help further revitalize phosphorus in the region.

Case Study: Amazon Basin

Phosphorus is a key nutrient in tropical forests, and has long been known to significantly limit the productivity of these globally-important ecosystems (*Vituosek, 1984*). Rapid decomposition, a nutrient-poor substrate and intense leaching as a result of high precipitation rates, make these regions particularly prone to P deficiency (*Jordan and Herrera, 1981*). In the Amazon, P is primarily derived from the weathering of rocks in the Andes mountain range to the west and transported to the Amazonia lowlands through an arterial network of rivers and streams. The seasonal flood of these nutrient-rich, or whitewater, rivers deposits large quantities of P onto fertile floodplains (*Queseda et al., 2010*). However, for much of the basin, which is either classified as *terra firme* and lies above the maximum height of the seasonal floods or is fed by nutrient-poor black or clearwater rivers, the ecosystems here remain P deficient.

Animals provide mobile linkages between these P-rich and P-poor landscapes. Fish migrating from nutrient-rich whitewater to black or clearwater rivers can transport P to oligotrophic waters, whilst on land terrestrial animals feeding in riparian areas act as key fluxes of lateral P movement. In Columbia, a group of woolly monkeys (*Lagothrix lagothricha lugens*) was found to transport 13.2 g P ha^{-1} yr^{-1} to *terra firme* in the seeds of fruits eaten from flooded forests, a quantity of the same order of magnitude as abiotic inputs from atmospheric deposition and weathering processes (Stevenson and Guzman-Caro, 2010). Theoretical modelling studies suggest that lateral P transport by all animals scaled across the whole Amazon basin may have historically provided an ecosystem service worth up to \$900 million yr^{-1} (Doughty et al., 2013, Doughty et al., 2016).

Like other tropical forest regions, the Amazon is suffering from defaunation (Dirzo et al., 2014; Abrahams et al., 2017). Where P inputs are low, the removal of animals from tropical forest ecosystems can extract a significant source of P in their bodies (*Brodie and McIntyre, 2018*), as well as considerably reducing lateral P redistribution by wild animals (*Doughty et al., 2013*). Investing in projects that promote wild animal biomass, or that allows these animals to maintain their mobile linkages between environments of high and low P in the Amazon will revitalise phosphorus in this region.

Each of these possibilities could have positive benefits of restoring P flow to terrestrial ecosystems, but they would have to be done carefully to avoid potential hazards. Restoration of bears and moose require significant space and could not be done everywhere. Many filter feeders, such as the zebra mussel (*Dreissena polymorpha*), are invasive, casing large problems, and should not be viewed as a substitute for native, sustainably harvested filter feeders. Essential in any restoration effort is a focus on returning native species to their historic roles in their ecosystems. In no sense should our proposal be used to justify the protection or spread of alien and invasive species. Such efforts could come at a large cost to ecological function and regional biodiversity. Rethinking pastures would involve major logistical difficulties and fenceless systems have a range of problems.

Some animal groups, such as seabirds, concentrate P, while other animals, such as terrestrial herbivores, disperse P across landscapes. Concentrated P deposits, like cave guano, are more accessible to humans for use in agriculture, whereas the dispersal of P can be more useful to natural ecosystems. We suggest that both systems, indeed any natural vector that keeps P away from the ocean bottom and from causing harmful algal blooms, should be considered for P trading. Diffusive processes of P into natural systems, will not improve crop fertility, but they will restore P flows to natural ecosystems that may have lost native animal vectors. Likewise, the concentration of P, such as in guano deposits, can form a point source that can be sustainably harvested and added to agricultural fields. Other benefits include subsidies by birds and other animals that can help coastal systems buffer climate change impacts *[Graham et al. 2018]*. More generally, more P in P limited natural systems could increase growth rates, thus increasing carbon uptake and reducing atmospheric carbon.

Natural atmospheric P deposition has changed over time, increasing in some regions while decreasing in others (Fig 4). Biodiversity restoration could be more or less valuable in different places depending on historic changes in P deposition or movement. For example, in tropical regions, unsustainable bushmeat hunting in terrestrial regions is common, which can greatly reduce mammal populations [*Lopez et al.,* 2017]. A recent study compared atmospheric P deposition rates to P loss via hunting on 36 sites on 3 continents and found that in most sites P input exceeded P output, but at 4 sites, P removal exceeded inputs by factors of 1.7 – 10.4 (Kenya) and 11.0 – 25.0 (Indonesia) [*Brodie and McIntyre 2019*]. Those ecosystems facing a P deficit could be specifically targeted by RNPP.

How would such efforts function in a working landscape? In many cases, humans and wildlife populations are segregated, and the transport of phosphorus would be considered a process most applicable to uninhabited islands or nature reserves. Yet in recent years, we have seen the restoration of urban and peri-urban wildlife, with attempts to reinvent natural processes (Janis et al. 2016). There are many species that could help pump or retain phosphorus in human-dominated, or working, landscapes. Protecting threatened natural areas where P is currently being transported are as important as revitalizing new ones and potentially more cost effective. The loss of such existing systems would have a clear and measurable cost in terms of lost P over time. Here we propose that private landowners could sell the P moving capacity on their intact systems to the national government or to voluntary markets. Our work would be complementary to ecological engineering efforts that have been proposed to reduce P loss. Roy (2016) reviewed several ecological engineering techniques for phosphorus recovery and recycling, including assimilation of P by macrophytes, algae, and trees; and aquaculture and aquaponics design that could combine innovations in the P recycling sector with our proposed wildlife restoration efforts.

Accounting for P movement in human and natural systems at the country and regional level is necessary prior to any widespread adaptation of P trading. The circular-economy literature for phosphorus has several detailed examples that can serve as a starting point for human systems, such as Switzerland [*Mehr et al.,* 2018]. Likewise, the natural science literature has many empirical case studies (Table 1) and is starting to develop global frameworks to better understand P recycling in natural systems [*Doughty et al 2016*]. However, key future steps will be to link these studies at the regional level and increase our understanding of the movement and retention of P by wildlife following the examples set by Coupled Natural and Human Systems (CNHs) [*Liu et al 2007*], which over the last decade, have begun to overcome the traditional separation of ecological and social sciences.

Conclusion

Phosphorus is an indispensable element for both human and natural systems, yet we suffer from the effects of excess in some areas, such as aquatic systems, and from scarcity in others. A defining attribute of animals is their ability to move. By restoring historic pathways, and facilitating movement across land and seas, we can take steps toward solving some of the intractable and urgent problems associated with this irreplaceable element. Let us add a 6^{th} R to our future phosphorus recycling strategies and revitalize the natural phosphorus pump.

Data Availability statement – This is a review paper with all relevant data available in the cited papers.

Tables

Theme	Mechanism	Example		
		Biodiversity Group	Location	Reference(s)
Upstream movement	Increase marine mammal populations to return P to surface waters.	Baleen whales	USA	Roman and McCarthy (2010)
		Right whales	Canada	Roman et al. (2016)
		Baleen whales	Southern Ocean	Ratnarajah et al. (2014)
		Sea lions	Australia	Lavery et al. (2012)
	Increase number of seabirds that bring P to land in guano	Seabirds	Global	Otero et al. (2018)
		Seabirds	Indian Ocean	Graham et al. (2018)
		Seabirds	USA	Ellis et al. (2006)
	Increase number of animals that bring P ashore at haul-out sites	Sea lions	Galapagos	Fariña et al. (2003)
		Seals	New Zealand	Wing et al. (2017)
		Turtles	South Africa	Le Gouvello et al. (2017)
		Otters	USA	Ben-David et al. (2005)
	Remove dams and increase anadromous fish P transport (*)	Herring	USA	Walters et al. (2009)
		Fish	North America	Twinning et al. (2017)
		Salmon	Canada	Field and Reynolds (2011)
		Salmon	USA	Moore and Schindler (2004)
Distribution	Increase terrestrial animals feeding in P-rich riparian environments	Moose	USA	Bump (2018)
		Bears	N America	Hilderbrand et al. (1999)
		Monkeys	Amazon	Stevenson and Guzmán-Caro, (2010)
		Insects	Iceland	Dreyer et al. (2015)
		Alligators	USA	Subalusky et al. (2009)
	Increase number of wild animals moving P through terrestrial environments	Mammalian herbivores	South Africa	Wolf et al. (2013)
		Mammalian herbivores	Amazon	Doughty et al. (2013)
		Mammalian herbivores	Africa	Hempson et al. (2017)
		Tetrapod herbivores	USA	Doughty et al. (2017)
		Insects	Global	Landry and Parrott (2016)
		Deer	Nepal	Moe and Wegge (2008)

	Increase connectivity of land to known P hotspots (floodplains, volcanic soils, etc).	Remove bomas Remove fences Deer	Kenya Serengeti Europe	Augustine (2003) McNaughton (1988) Abbas et al. (2012)
Retention	Reduce P removal in wild animal biomass from ecosystems	Terrestrial mammals	Tropics	Brodie and McIntyre (2018)
	Reduce P consumption in domestic animals	Domestic animals Domestic animals	China UK	Lui et al. (2016) Withers et al. (2001)
	Recycle P in animal faeces and urine	Humans (faeces) Humans (urine) Domestic animals	Global Uganda Global	Ashley et al. (2011) Anderson et al. (2015) Cordell et al. (2009)
	Application of arbuscular mycorrhizae P symbioses	Mycorrhizae Mycorrhizae	Global Serengeti	Roy-Bolduc and Hijri (2011) Stevens et al. (2018)
	Reduce P removed in deforestation/timber production	Trees Trees Trees	Global Borneo Finland	Achat et al. (2015) Imai et al. (2012) Kaila et al. (2015)
	Restore P retention in natural dams (**)	Beavers Beavers	USA USA	Wegener et al. (2017) Correll et al. (2000)
	Allow rivers to flood and deposit P-rich floodplains	Rivers Rivers	USA Neotropics	Noe and Hupp (2005) Small et al. (2015)
Filtering	Capture P in salt marsh and mangrove ecosystems	Mangroves Mangroves Salt marsh Salt marsh	India Australia China USA	Hussain and Badola (2008) Boto and Wellington (1984) Shao et al. (2013) Alexander et al. (2008)
	Capture of P by zooextraction	Mussels Oysters	Sweden Australia	Spångberg et al. (2012) Gifford et al. (2005)
	Capture P by macrophytes and algae	Kelp Duckweed Water hyacinth	China USA Sri Lanka	Xu et al. (2011) Adhikari et al. (2015) Jayaweera and Kasturiarachchi (2004)

Table 1: Examples of animal P subsidies.

* Removal of dams may lose potential source of P-rich sediments held behind dams. See Maavara et al. (2015) for more details.

** Research is inconclusive and could even increase source of nutrients to rivers. See Ecke et al. (2017) for more details.

Figures

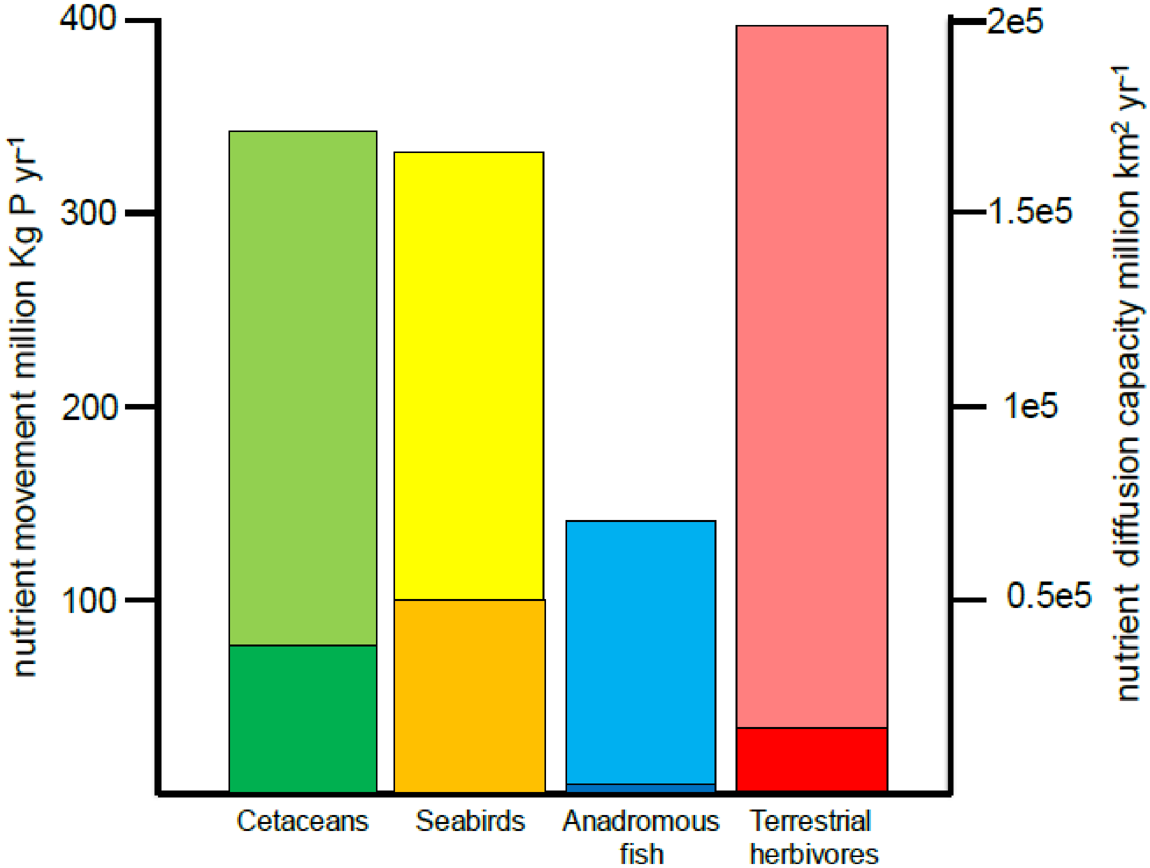

Figure 1 - Bar chart showing prior P distribution compared to current values. Cetaceans, seabirds, and anadromous fish move P directionally (kg P yr-1) against gravity and terrestrial herbivores are calculated as a diffusion capacity (km^2 yr^{-1}), from Doughty et al 2016.

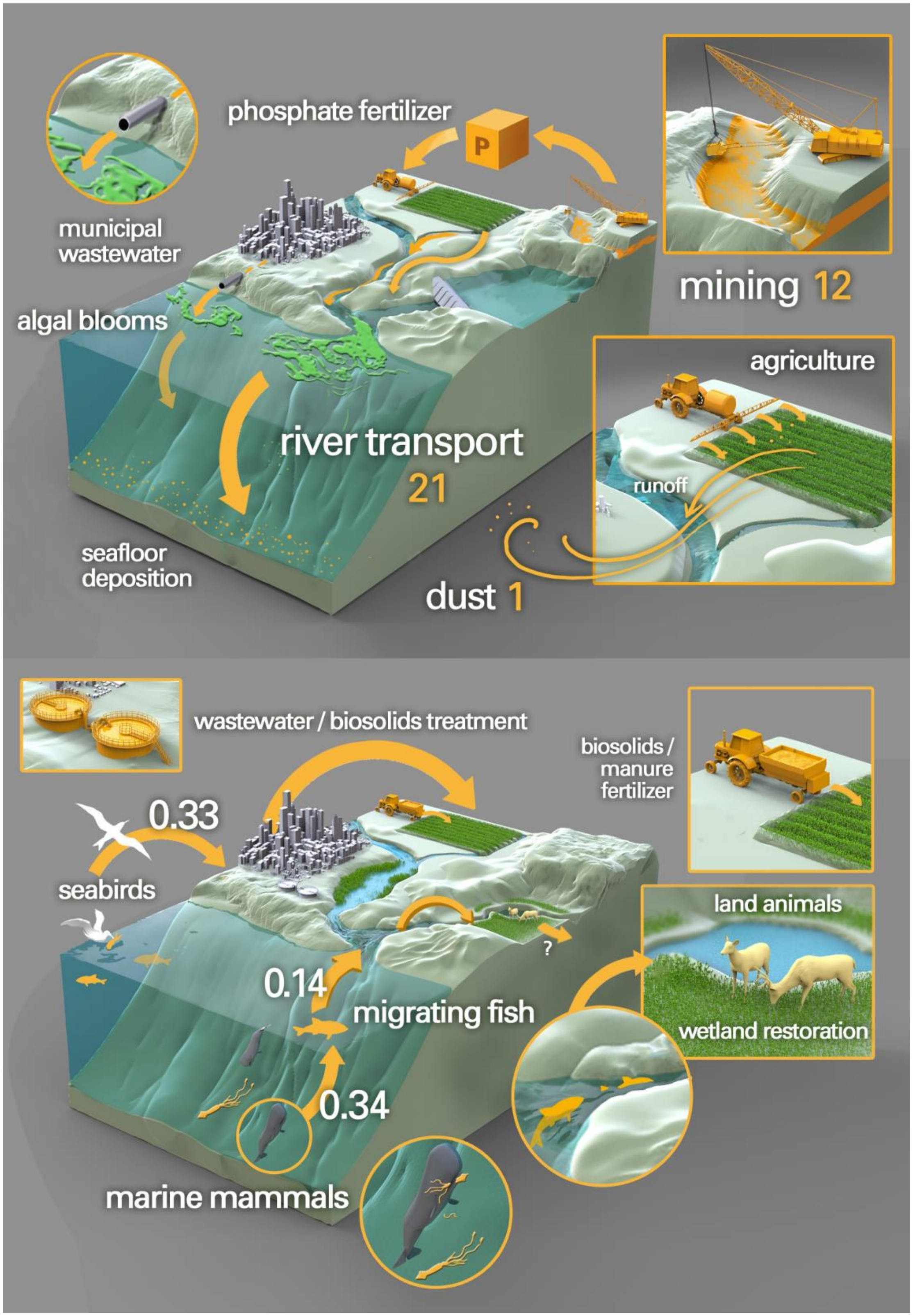

Figure 2. Current (top) versus idealized (bottom) P cycle. All units are 10^12 gP/yr

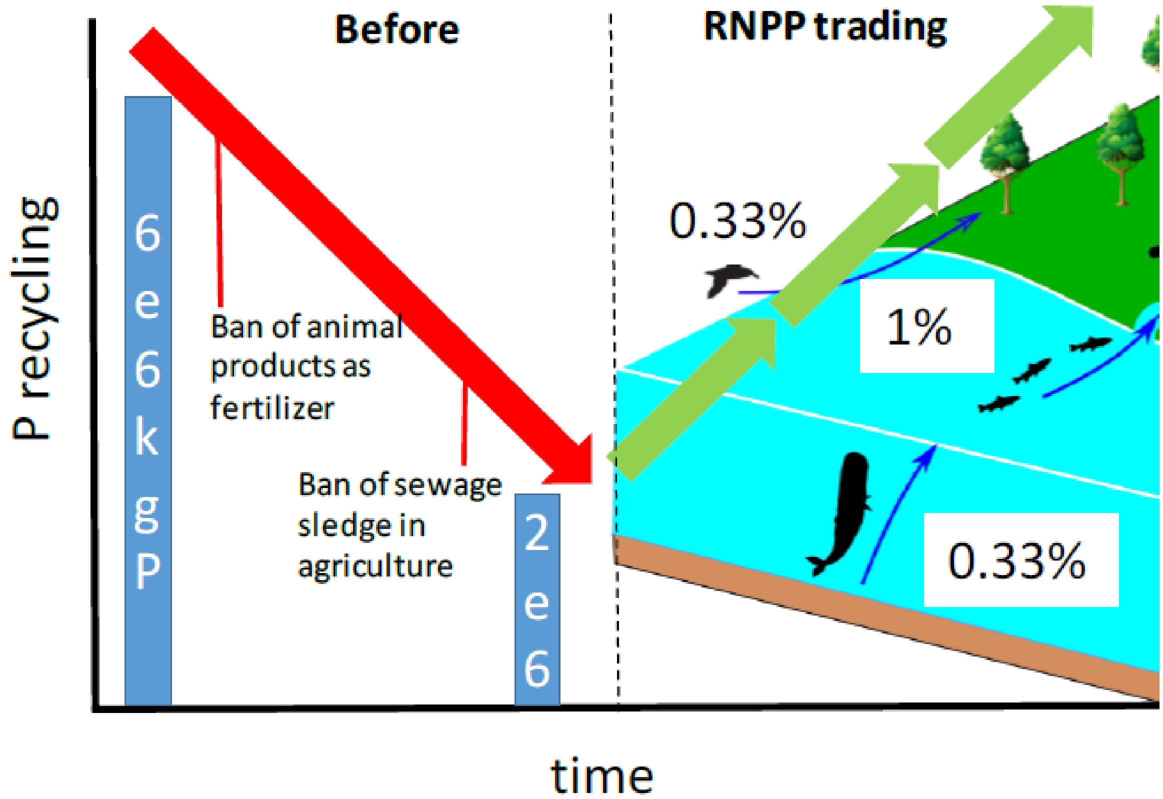

Figure 3 – Cartoon representing possible P tradeoffs between Switzerland, whose P recycling has declined from 6e6B kg yr^{-1} to 2e6 kg yr^{-1} since 1989, and possible biodiversity restoration projects. To make up the 4e6 kg yr^{-1} P shortfall, Switzerland could sponsor projects to restore 0.33% of marine mammal uplift, 1% of anadromous fish, or 0.33% of seabirds.

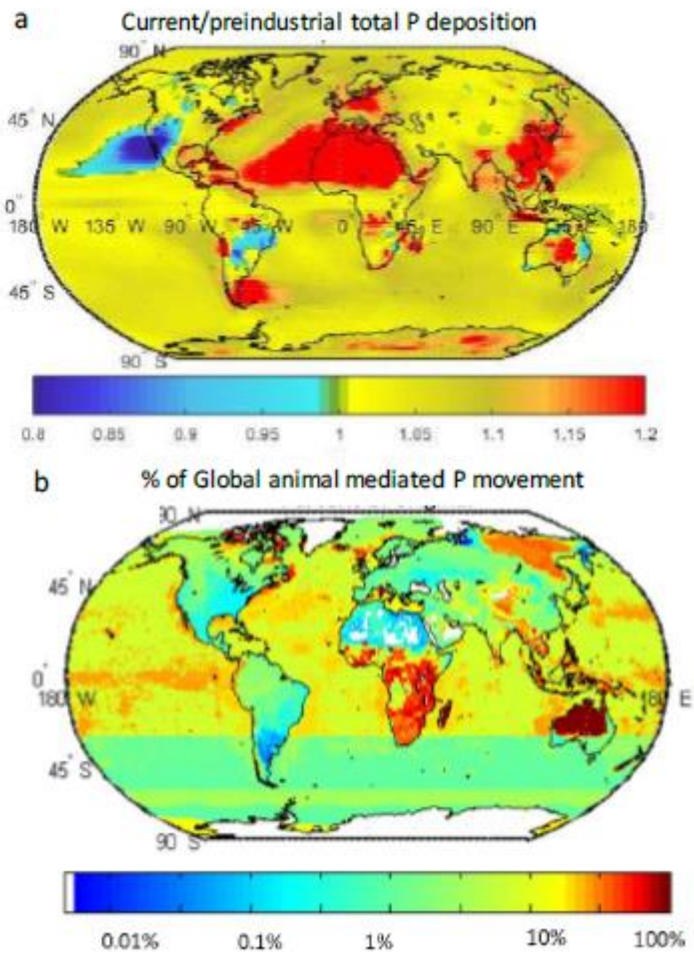

Figure 4 – **Modifications to the global P cycle.** (A) The ratio of current to preindustrial P deposition modified from [*Brahney et al.*, 2015] (B) Percent of animal mediated P movement in the nutrient diffusion capacity between the late Pleistocene and today for terrestrial mammals and marine great whales modified from [*Doughty et al.*, 2016].

REFERENCES

Abbas, F., Merlet, J., Morellet, N., Verheyden, H., Hewison, A. J. M., Cargnelutti, B., … Daufresne, T. (2012). Roe deer may markedly alter forest nitrogen and phosphorus budgets across Europe. *Oikos*, *121*(8), 1271–1278.

Abrahams, M. I., Peres, C. A., & Costa, H. C. M. (2017). Measuring local depletion of terrestrial game vertebrates by central-place hunters in rural Amazonia. *PLoS ONE*, *12*(10), 1–25.

Achat, D. L., Deleuze, C., Landmann, G., Pousse, N., Ranger, J., & Augusto, L. (2015). Quantifying consequences of removing harvesting residues on forest soils and tree growth - A meta-analysis. *Forest Ecology and Management*, *348*, 124–141.

Adhikari, U., Harrigan, T., & Reinhold, D. M. (2015). Use of duckweed-based constructed wetlands for nutrient recovery and pollutant reduction from dairy wastewater. *Ecological Engineering*, *78*, 6–14.

Alexander, R. B., Smith, R. A., Schwarz, G. E., Boyer, E. W., Nolan, J. V., & Brakebill, J. W. (2008). Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River Basin. *Environmental Science and Technology*, *42*(3), 822–830.

Altieri, A. H., & Gedan, K. B. (2015). Climate change and dead zones. *Global Change Biology*, *21*(4), 1395–1406.

Altieri, A. H., Harrison, S. B., Seemann, J., Collin, R., Diaz, R. J., & Knowlton, N. (2017). Tropical dead zones and mass mortalities on coral reefs. *Proceedings of the National Academy of Sciences*, *114*(14), 3660–3665.

Anderson, N. J., Bennion, H., & Lotter, A. F. (2014). Lake eutrophication and its implications for organic carbon sequestration in Europe. *Global Change Biology*, *20*(9), 2741–2751.

Andersen, J. H., Carstensen, J., Conley, D. J., Dromph, K., Fleming-Lehtinen, V., Gustafsson, B. G., … Murray, C. (2017). Long-term temporal and spatial trends in eutrophication status of the Baltic Sea. *Biological Reviews*, *92*(1), 135–149.

Andersson, E. (2016). Turning waste into value: using human urine to enrich soils for sustainable food production in Uganda. *Journal of Cleaner Production*, *20*(1), 290–298.

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.

Augustine, D. J. (2003). Long-term , livestock-mediated redistribution of nitrogen and phosphorus in an East African savanna. *Journal of Animal Ecology*, *40*, 137–149.

Bar-On, Y.M., Phillips, R., and Milo, R (2018), The biomass distribution on Earth PNAS 115 (25) 6506-6511

Ben-David, M., Blundell, G. M., Kern, J. W., Maier, J. A. K., Brown, E. D., & Jewett, S. C. (2005). Communication in river otters: Creation of variable resource sheds for terrestrial communities. *Ecology*, *86* (5), 1331–1345.

Bongaerts, J. (2018), A Model for the Optimal Recovery of Multiple Substances from Waste Water with a Focus on Phosphate, *Sustainability*, *10*(8), 2867, doi: 10.3390/su10082867.

Boto, K. G., & Wellington, J. T. (1984). Soil characteristics and nutrient status in a Northern Australian mangrove forest. *Estuaries*, *7*(1), 61–69.

Bouchard SS, Bjorndal KA. 2000. Sea turtles as biological transporters of nutrients and energy from marine to terrestrial ecosystems. Ecology 81:2305-2313.

Brahney, J., N. Mahowald, D. S. Ward, A. P. Ballantyne, and J. C. Neff (2015), Is atmospheric phosphorus pollution altering global alpine Lake stoichiometry?, *Global Biogeochem. Cycles*, *29*(9), 1369-1383, doi: 10.1002/2015GB005137.

BRANCH T, A. and TERRIE M. WILLIAMS (2006), Legacy of industrial whaling, in *Whales, Whaling, and Ocean Ecosystems*, 1st edn.Anonymous , pp. 262, University of California Press.

Brodie, J. F. and P. B. McIntyre (2019), Bushmeat biogeochemistry: the role of tropical mammals in ecosystem phosphorus budgets.

Brundtland, G.H. Report of the World Commission on Environment and Development: Our Common Future; World Commission on Environment and Development: Oslo, Norway, 1987.

Bump, Keren B. Tischler, Amy J. Schrank, Rolf O. Peterson, and John A. Vucetich (2009), Large Herbivores and Aquatic-Terrestrial Links in Southern Boreal Forests, *Journal of Animal Ecology*, *78*(2), 338-345, doi: 10.1111/j.1365-2656.2008.01498.x.

Bump, J. (2018), Fertilizing riparian forests: nutrient repletion across ecotones with trophic rewilding, *Philosophical Transactions B*.

Calvo, M. S., A. J. Moshfegh, and K. L. Tucker (2014), Assessing the Health Impact of Phosphorus in the Food Supply: Issues and Considerations, *Advances in Nutrition*, *5*(1), 104-113, doi: 10.3945/an.113.004861.

Carstensen, J., Conley, D. J., Bonsdorff, E., Gustafsson, B. G., Hietanen, S., Janas, U., … Voss, M. (2014). Hypoxia in the Baltic Sea: Biogeochemical cycles, benthic fauna, and management. *Ambio*, *43*(1), 26–36.

Carrizo, S. F., S. C. Jähnig, V. Bremerich, J. Freyhof, I. Harrison, F. He, S. D. Langhans, K. Tockner, C. Zarfl, and W. Darwall (2017), Freshwater Megafauna: Flagships for Freshwater Biodiversity under Threat, *Bioscience*, *67*(10), 919-927.

Chamberlain CP, Waldbauer JR, Fox-Dobbs K, Newsome SD, Koch PL, Smith DR, Church ME, Chamberlain SD, Sorenson KL, Risebrough R. 2005. Pleistocene to recent dietary shifts in California condors. Proc. Natl. Acad. Sci. U.S.A. 102:16707-16711.

Christensen, L. B. (2006), Marine mammal populations: Reconstructing historical abundances at the global scale.

CONROY, J. D., W. J. EDWARDS, R. A. PONTIUS, D. D. KANE, H. ZHANG, J. F. SHEA, J. N. RICHEY, and D. A. CULVER (2005), Soluble nitrogen and phosphorus excretion of exotic freshwater mussels (Dreissena spp.): potential impacts for nutrient remineralisation in western Lake Erie, *Freshwat. Biol.*, *50*(7), 1146-1162, doi: 10.1111/j.1365-2427.2005.01392.x.

Conley, D. J., Björck, S., Bonsdorff, E., Carstensen, J., Destouni, G., Gustafsson, B. G., … Zillén, L. (2009). Hypoxia-Related Processes in the Baltic Sea. *Environmental Science & Technology*, *43*(10), 3412–3420.

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

Correll, D. L., Jordan, T. E., & Weller, D. E. (2000). Beaver pond biogeochemical effects in the Maryland Coastal Plain. *Biogeochemistry, 49*(3), 217–239.

Costanza, R. et al. (1997), The value of the world's ecosystem services and natural capital, *Nature, 387,* 253.

Dame R, Spurrier J, Wolaver T. 1989. Carbon, nitrogen and phosphorus processing by an oyster reef. Marine Ecology Progress Series 54:249-256.

de Boer, M., A. Romeo-Hall, T. Rooimans, and J. Slootweg (2018), An Assessment of the Drivers and Barriers for the Deployment of Urban Phosphorus Recovery Technologies: A Case Study of The Netherlands, *Sustainability, 10*(6), doi: 10.3390/su10061790.

Desmidt, E., K. Ghyselbrecht, Y. Zhang, L. Pinoy, B. Van der Bruggen, W. Verstraete, K. Rabaey, and B. Meesschaert (2015), Global Phosphorus Scarcity and Full-Scale P-Recovery Techniques: A Review, *Critical Reviews in Environmental Science and Technology, 45*(4), 336, doi: 10.1080/10643389.2013.866531.

Diaz, R. J. and R. Rosenberg (2008), Spreading Dead Zones and Consequences for Marine Ecosystems, *Science, 321*(5891), 926.

Dirzo, R., Hillary S. Young, Mauro Galetti, Gerardo Ceballos, Nick J. B. Isaac, and Ben Collen (2014), Defaunation in the Anthropocene, *Science, 345*(6195), 401-406, doi: 10.1126/science.1251817.

Doughty, C. E. (2017), Herbivores increase the global availability of nutrients over millions of years, *Nature Ecology & Evolution, 1*(12), 1820-1827, doi: 10.1038/s41559-017-0341-1.

Doughty, C. E., J. Roman, S. Faurby, A. Wolf, A. Haque, E. S. Bakker, Y. Malhi, J. B. Dunning, and J. Svenning (2016), Global nutrient transport in a world of giants, *Proc. Natl. Acad. Sci. USA*, *113*(4), 868-873, doi: 10.1073/pnas.1502549112.

Doughty, C. E., A. Wolf, and Y. Malhi (2013), The legacy of the Pleistocene megafauna extinctions on nutrient availability in Amazonia, *Nature Geoscience*, *6*(9), 761-764, doi: 10.1038/ngeo1895.

Draheim, M., F. Madden, J. McCarthy, and C. Parsons (2015), *Human-Wildlife Conflict*, Oxford University Press, Oxford.

Dreyer, J., Townsend, P. A., Hook, J. C., Hoekman, D., Vander Zanden, M. J., & Gratton, C. (2015). Quantifying aquatic insect deposition from lake to land. *Ecology*, *96*(2), 499–509.

Ecke, F., Levanoni, O., Audet, J., Carlson, P., Eklöf, K., Hartman, G., … Futter, M. (2017). Meta-analysis of environmental effects of beaver in relation to artificial dams. *Environmental Research Letters*, *12*(11).

Ellis, J. C., Fariña, J. M., & Witman, J. D. (2006). Nutrient transfer from sea to land: The case of gulls and cormorants in the Gulf of Maine. *Journal of Animal Ecology*, *75*(2), 565–574.

Edixhoven, J. D., J. Gupta, and H. H. G. Savenije (2014), Recent revisions of phosphate rock reserves and resources: a critique, *Earth Syst. Dynam*(5), 491-507.

EUROPEAN COMMISSION (2012), COMMISSION STAFF WORKING PAPER Analysis of options beyond 20% GHG emission reductions: Member State results .

European Commission. (2018), Closing the Loop—An EU Action Plan for the Circular Economy. Communication from the Commission to the Council and the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. , *2018*.

Fariña, J. M., Salazar, S., Wallem, K. P., Witman, J. D., & Ellis, J. C. (2003). Nutrient exchanges between marine and terrestrial ecosystems: The case of the Galapagos sea lion Zalophus wollebaecki. *Journal of Animal Ecology*, *72*(5), 873–887.

Field, R. D., & Reynolds, J. D. (2011). Sea to sky: Impacts of residual salmon-derived nutrients on estuarine breeding bird communities. *Proceedings of the Royal Society B: Biological Sciences*, *278*(1721), 3081–3088.

Forget, G., J. Baglinière, F. Marchand, A. Richard, M. Nevoux, and C. D. Handling editor: (2018), A new method to estimate habitat potential for Atlantic salmon (Salmo salar): predicting the influence of dam removal on the Sélune River (France) as a case study, *ICES J. Mar. Sci.*, fsy089.

Fowdar, H. S., B. E. Hatt, T. Cresswell, J. J. Harrison, P. L. M. Cook, and A. Deletic (2017), Phosphorus Fate and Dynamics in Greywater Biofiltration Systems, *Environ. Sci. Technol.*, *51*(4), 2280-2287, doi: 10.1021/acs.est.6b04181.

Geissler, B., G. Steiner, and M. C. Mew (2018), Clearing the fog on phosphate rock data – Uncertainties, fuzziness, and misunderstandings, *Sci. Total Environ.*, *642*, 250-263, doi: //doi.org/10.1016/j.scitotenv.2018.05.381.

Ghebremichael LT, Veith TL, Watzin MC. 2010. Determination of critical source areas for phosphorus loss: Lake Champlain Basin, Vermont. Transactions of the ASABE 53:1595-1604.

Gifford, S., Dunstan, H., O’Connor, W., & Macfarlane, G. R. (2005). Quantification of in situ nutrient and heavy metal remediation by a small pearl oyster (Pinctada imbricata) farm at Port Stephens, Australia. *Marine Pollution Bulletin*, *50*(4), 417–422.

Graham N. et al Seabirds enhance coral reef productivity and functioning in the absence of invasive rats. Nature **volume** 559, **pages**250–253 (2018)

Gresh, T., J. Lichatowich, and P. Schoonmaker (2000), An Estimation of Historic and Current Levels of Salmon Production in the Northeast Pacific Ecosystem: Evidence of a Nutrient Deficit in the Freshwater Systems of the Pacific Northwest, *Fisheries*, *25*(1), 15-21, doi: AEOHAC>2.0.CO;2.

Groot, d., S.J (2002), A review of the past and present status of anadromous fish species in the Netherlands: is restocking the Rhine feasible?, *Hydrobiologia*, *478*(1), 205-218, doi: 1021038916271.

Grubb, M. (2009), Reinforcing carbon markets under uncertainty:; the role of reserve price auctions and other options.

Guedes, P., N. Couto, E. Mateus, and A. Ribeiro (2017), Phosphorus Recovery in Sewage Sludge by Electrokinetic Based Technologies: A Multivariate and Circular Economy View, *Waste Biomass Valor*, *8*(5), 1587-1596, doi: 10.1007/s12649-017-9985-y.

Hamrick, K., A. Goldstein T, A. Thiel, M. Peters Stanley, G. Gonzalez, and E. Bodnar (2015), Ahead of the curve. State of the voluntary carbon markets 2015. Ecoystem marktplace (Forest Trends).

Hempson, G. P., Archibald, S., & Bond, W. J. (2017). The consequences of replacing wildlife with livestock in Africa. *Scientific Reports*, 7(1), 1–10.

Hilderbrand et al. (1999) Role of brown bears (Ursus arctos) in the flow of marine nitrogen into a terrestrial ecosystem. *Oecologia*, 121, 546–550

Hobbs NT. 1996. Modification of ecosystems by ungulates. Journal of Wildlife Management 60:695-710.

Hoellein, T. J., C. B. Zarnoch, D. A. Bruesewitz, and J. DeMartini (2017), Contributions of freshwater mussels (Unionidae) to nutrient cycling in an urban river: filtration, recycling, storage, and removal, *Biogeochemistry*, *135*(3), 307-324, doi: 10.1007/s10533-017-0376-z.

Hoagland, P., Jin, D., Beet, A., Kirkpatrick, B., Reich, A., Ullmann, S., … Kirkpatrick, G. (2014). The human health effects of Florida Red Tide (FRT) blooms: An expanded analysis. *Environment International*, *68*, 144–153.

Hubbert, M. K. (1956), Fossil Fuels and Nuclear Energy (1956).

Huisman, J., G. A. Codd, H. W. Paerl, B. W. Ibelings, J. M. H. Verspagen, and P. M. Visser (2018), Cyanobacterial blooms, *Nature Reviews Microbiology*, *16*(8), 471-483, doi: 10.1038/s41579-018-0040-1.

Hussain, S. A., & Badola, R. (2008). Valuing mangrove ecosystem services: Linking nutrient retention function of mangrove forests to enhanced agroecosystem production. *Wetlands*

Ecology and Management, *16*(6), 441–450.

Imai, N., Kitayama, K., & Titin, J. (2012). EFFECTS OF LOGGING ON PHOSPHORUS POOLS IN A TROPICAL RAINFOREST OF BORNEO. *Journal of Tropical Forest Science, 24*(1), 5-17.

Jayaweera, M., & Kasturiarachchi, J. (2004). Removal of nitrogen and phosphorus from wastewaters by phytoremediation using water hyacinth ieichhornia crassipiesy, *50 (6)*, 217–226.

Janis S, Birney L, Newton R. 2016. Billion Oyster Project: Linking public school teaching and learning to the ecological restoration of New York Harbor using innovative applications of environmental and digital technologies. International Journal of Digital Content Technology and Its Application. 10.

Jordon, C.F. and Herrera, R. (1981) Tropical Rain Forests: Are nutrients really critical? *The American Naturalist*, 117 (2), 167-180.

Kaila, A., Laurén, A., Sarkkola, S., Koivusalo, H., Ukonmaanaho, L., O'Driscoll, C., … Nieminen, M. (2015). Effect of clear-felling and harvest residue removal on nitrogen and phosphorus export from drained norway spruce mires in southern finland. *Boreal Environment Research*, *20*(6), 693–706.

Kang, Y. et al. (2019), Performance of constructed wetlands and associated mechanisms of PAHs removal with mussels, *Chem. Eng. J.*, *357*, 280-287, doi: //doi.org/10.1016/j.cej.2018.09.152.

Karin E. Limburg and John R. Waldman (2009), Dramatic Declines in North Atlantic Diadromous Fishes, *BioScience*, *59*(11), 955-965, doi: 10.1525/bio.2009.59.11.7.

Klinglmair, M., C. Lemming, L. S. Jensen, H. Rechberger, T. F. Astrup, and C. Scheutz (2015), Phosphorus in Denmark: National and regional anthropogenic flows, *Resour. Conserv. Recycling*, *105*, 311-324, doi: //doi.org/10.1016/j.resconrec.2015.09.019.

Kormann (2018), How Carbon Trading Became a Way of Life for California's Yurok Tribe. https://www.newyorker.com/news/dispatch/how-carbon-trading-became-a-way-of-life-for-californias-yurok-tribe

Kwon H-B, Lee C-W, Jun B-S, Yun J, Weon S-Y, Koopman B. 2004. Recycling waste oyster shells for eutrophication control. Resour. Conserv. Recycl. 41:75-82.

Landry, J. S., & Parrott, L. (2016). Could the lateral transfer of nutrients by outbreaking insects lead to consequential landscape-scale effects? *Ecosphere*, *7*(3), 1–16.

Laidre KL, Stirling I, Estes JA, Kochnev A, Roberts J. 2018. Historical and potential future importance of large whales as food for polar bears. Frontiers in Ecology and the Environment 16:515-524

Lavery TJ, Roudnew B, Seymour J, Mitchell JG, Jeffries T (2012) High Nutrient Transport and Cycling Potential Revealed in the Microbial Metagenome of Australian Sea Lion (Neophoca cinerea) Faeces. PLoS ONE 7(5): e36478. doi:10.1371/journal.pone.0036478

Le Gouvello DZM, Nel R, Harris LR, Bezuidenhout K, Woodborne S (2017) Identifying potential pathways for turtle-derived nutrients cycling through beach ecosystems. *Marine Ecology Progress Series, 583:49-62.*

Lenders et al. (2016) Historical rise of waterpower initiated the collapse of salmon stocks. *Nature*.

Liu, J et al. (2007) Complexity of Coupled Human and Natural Systems:Vol. 317, Issue 5844, pp. 1513-1516DOI: 10.1126/science.1144004

Liu, Hu Sheng, Songyan Jiang, Zengwei Yuan, Chaosheng Zhang, and James J. Elser (2016), Intensification of phosphorus cycling in China since the 1600s, *Proceedings of the National Academy of Sciences, 113*(10), 2609-2614, doi: 10.1073/pnas.1519554113.

Lopez, A., R. Alkemade, D. J. Ingram, P. A. Verweij, J. A. J. Eikelboom, and M. A. J. Huijbregts (2017), The impact of hunting on tropical mammal and bird populations, *Science, 356*(6334), 180-183, doi: 10.1126/science.aaj1891.

Maseyk, F. J. F., A. D. Mackay, H. P. Possingham, E. J. Dominati, and Y. M. Buckley (2017), Managing Natural Capital Stocks for the Provision of Ecosystem Services, *CONSERVATION LETTERS*, *10*(2), 211-220, doi: 10.1111/conl.12242.

Mattocks, S., C. J. Hall, and A. Jordaan (2017), Damming, Lost Connectivity, and the Historical Role of Anadromous Fish in Freshwater Ecosystem Dynamics, *Bioscience*, *67*(8), 713-728.

Mehr, J., M. Jedelhauser, and C. Binder (2018), Transition of the Swiss Phosphorus System towards a Circular Economy—Part 1: Current State and Historical Developments, *Sustainability*, *10*(5), doi: 10.3390/su10051479.

Mew, C. M., G. Steiner, and B. Geissler (2018), Phosphorus Supply Chain—Scientific, Technical, and Economic Foundations: A Transdisciplinary Orientation, *Sustainability*, *10*(4), doi: 10.3390/su10041087.

Maavara, T., Parsons, C. T., Ridenour, C., Stojanovic, S., Dürr, H. H., Powley, H. R., & Van Cappellen, P. (2015). Global phosphorus retention by river damming. *Proceedings of the National Academy of Sciences*, 201511797.

McCauley, DJ., Pinsky, ML, Palumbi, SR, Estes, JA, Joyce, FH, Warner, RR (2015). Marine defaunation: Animal loss in the global ocean. *Science* Vol. 347, Issue 6219, 1255641 DOI: 10.1126/science.1255641

McNaughton, S. J. (1988). Mineral nutrition and spatial concentrations of African ungulates. *Nature*, *334*, 343.

Moe, S. R., & Wegge, Æ. P. (2008). Effects of deposition of deer dung on nutrient redistribution and on soil and plant nutrients on intensively grazed grasslands in lowland Nepal, 227–234.

Moore, J. W., & Schindler, D. E. (2004). Nutrient export from freshwater ecosystems by anadromous sockeye salmon (*Oncorhynchus nerka*). *Canadian Journal of Fisheries and Aquatic Sciences*, *61*(9), 1582–1589.

Miles, L. and V. Kapos (2008), Reducing Greenhouse Gas Emissions from Deforestation and Forest Degradation: Global Land-Use Implications, *Science*, *320*(5882), 1454.

Mulder, C. et al. (2011), Impacts of seabirds on plant and soil properties, in *Seabird Islands : Ecology, Invasion and Restoration*.

Muskopf S. 2007. The effect of beaver (Castor canadensis) dam removal on total phosphorus concentration in Taylor Creek and Wetland, South Lake Tahoe, California. Humboldt State University.

Neset, T. S. and D. Cordell (2012), Global phosphorus scarcity: identifying synergies for a sustainable future, *Journal of the Science of Food and Agriculture*, *92*(1), 2-6, doi: 10.1002/jsfa.4650.

Neset, T. S. and D. Cordell (2012), Global phosphorus scarcity: identifying synergies for a sustainable future, *J. Sci. Food Agric.*, *92*(1), 2-6, doi: 10.1002/jsfa.4650.

Newell R, Fisher T, Holyoke R, Cornwell J. 2005. Influence of eastern oysters on nitrogen and phosphorus regeneration in Chesapeake Bay, USA. Pages 93-120 in Dame R, Olenin S, eds. The Comparative Roles of Suspension-Feeders in Ecosystems. Netherlands: Springer

Nicol, S., A. Bowie, S. Jarman, D. Lannuzel, K. M. Meiners, and P. Van der Merwe (2010), Southern Ocean iron fertilization by baleen whales and Antarctic krill, *Fish and Fisheries, 11*(2), 203, doi: 10.1111/j.1467-2979.2010.00356.x.

Noe, G. B., & Hupp, C. R. (2005). Carbon, nitrogen, and phosphorus accumulation in floodplains of Atlantic Coastal Plain rivers, USA. *Ecological Applications*, *15*(4), 1178–1190.

Otero, X. L., D. L. Pe, A. Pérez-Alberti, T. O. Ferreira, and M. Huerta-Diaz (2018), Seabird colonies as important global drivers in the nitrogen and phosphorus cycles, *Nature Communications, 9*(1), 246, doi: 10.1038/s41467-017-02446-8.

O'Neil, J. M., Davis, T. W., Burford, M. A., & Gobler, C. J. (2012). The rise of harmful cyanobacteria blooms: The potential roles of eutrophication and climate change. *Harmful Algae*, *14*, 313–334.

Paerl, H. W., T. G. Otten, and R. Kudela (2018), Mitigating the Expansion of Harmful Algal Blooms Across the Freshwater-to-Marine Continuum, *Environ. Sci. Technol.*, *52*(10), 5519-5529, doi: 10.1021/acs.est.7b05950.

Paleczny, Edd Hammill, Vasiliki Karpouzi, and Daniel Pauly , (2015) Population Trend of the World's Monitored Seabirds, 1950-2010, *PLoS ONE*, *10*(6), e0129342, doi: 10.1371/journal.pone.0129342.

Puttock A, Graham H, Cunliffe A, Elliott M, Brazier R. 2017. Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands. Science of the Total Environment 576:430-443.

Quinn, T. P., M. H. Bond, S. J. Brenkman, R. Paradis, and R. J. Peters (2017), Re-awakening dormant life history variation: stable isotopes indicate anadromy in bull trout following dam removal on the Elwha River, Washington, *Environ. Biol. Fishes, 100*(12), 1659-1671, doi: 10.1007/s10641-017-0676-0.

Quesada, C.A., Lloyd, J., Schwarz, M., Patino, S., Baker, T.R., Czimczik, C., Fyllas, N.M., Martinelli, L., Nardoto, G.B., Schmerler, J., Santos, A.J.B., Hodnett, M.G., Herrera, R., Luizao, F.J., Arneth, A., Lloyd, G., Dezzeo, N., Hilke, I., Kuhlmann, I., Raessler, M., Brand, W.A., Geilmann, H., Moraes Filjo, J.O., Carvalho, F.P., Arauji Filho, R.N., Chabes, J.E., Cruz Junior, O.F. Pimentel, T.P. and Paiva, R. (2010) Variations in chemical and physical properties of Amazon forest soils in relation to their genesis. *Biogeosciences*, 7, 1515-1541.

Ratnarajah L, Bowie AR, Lannuzel D, Meiners KM, Nicol S (2014) The Biogeochemical Role of Baleen Whales and Krill in Southern Ocean Nutrient Cycling. PLoS ONE 9(12): e114067. doi:10.1371/journal.pone.0114067

Reimchen, T. E., D. D. Mathewson, M. D. Hocking, J. Moran, and D. Harris (2003), Isotopic evidence for enrichment of salmon-derived nutrients in vegetation, soil, and insects in Riparian zones in coastal British Columbia., *Am Fish S S*(34), 59-69.

Reid SM. 2006. Timing and demographic characteristics of redhorse spawning runs in three Great Lakes Basin rivers. Journal of Freshwater Ecology 21:249-258.

Reyes, O. and T. Gilbertson (2010), Carbon trading: how it works and why it fails, *Soundings, 45*(45), 89-100, doi: 10.3898/136266210792307050.

Richardson, A. J., Bakun, A., Hays, G. C., & Gibbons, M. J. (2009). The jellyfish joyride: causes, consequences and management responses to a more gelatinous future. *Trends in Ecology & Evolution*, *24*(6), 312–322.

Roman and James J McCarthy (2010), The Whale Pump: Marine Mammals Enhance Primary Productivity in a Coastal Basin, *PLoS One, 5*(10), e13255, doi: 10.1371/journal.pone.0013255.

Roman, John Nevins, Mark Altabet, Heather Koopman, and James McCarthy (2016), Endangered Right Whales Enhance Primary Productivity in the Bay of Fundy, *PLoS One, 11*(6), e0156553, doi: 10.1371/journal.pone.0156553.

Roman, J. (2016), Slow conservation, *Trends in Ecology & Evolution*(31), 491-493.

Roman, J., J. A. Estes, L. Morissette, C. Smith, D. Costa, J. McCarthy, J. Nation, S. Nicol, A. Pershing, and V. Smetacek (2014), Whales as marine ecosystem engineers, *Frontiers in Ecology and the Environment, 12*(7), 377-385, doi: 10.1890/130220.

Romar-Gasalla, A., J. C. Nóvoa-Muñoz, M. Arias-Estévez, M. J. Fernández-Sanjurjo, E. Álvarez-Rodríguez, and A. Núñez-Delgado (2018), Controlling risks of P water pollution by sorption on soils, pyritic material, granitic material, and different by-products: effects of pH and incubation time, *Environmental science and pollution research international*, 1-7, doi: 10.1007/s11356-018-2267-9.

Römer, W. and B. Steingrobe (2018), Fertilizer Effect of Phosphorus Recycling Products, *Sustainability, 10*(4), doi: 10.3390/su10041166.

Rosell, F., Bozsér, O., Collen, P., & Parker, H. (2005). Ecological impact of beavers castor fiber and castor canadensis and their ability to modify ecosystems. *Mammal Review*, *35*(3–4), 248–276.

Roy, E. D. (2017). Phosphorus recovery and recycling with ecological engineering: A review. *Ecological Engineering*, *98*, 213–227.

Roy-Bolduc A, Hijri M (2011) The Use of Mycorrhizae to Enhance Phosphorus Uptake: A Way Out the Phosphorus Crisis. Journal of Biofertilizers & Biopesticides, 2 (104): doi:10.4172/2155-6202.1000104.

Rushforth, Richard R., Elizabeth A. Adams, and Benjamin L. Ruddell. "Generalizing ecological, water and carbon footprint methods and their worldview assumptions using Embedded Resource Accounting." *Water Resources and Industry* 1 (2013): 77-90.

Sandom, C., S. Faurby, B. Sandel, and J. C. Svenning (2014), Global late Quaternary megafauna extinctions linked to humans, not climate change, *Proc. Biol. Sci., 281*, 10.1098/rspb.2013.3254.

Saunders R, Hachey MA, Fay CW. 2006. Maine's diadromous fish community. Fisheries 31:537-547.

Schmitz OJ, Hawlena D, Trussell GC. 2010. Predator control of ecosystem nutrient dynamics. Ecology Letters 13:1199-1209.

Schlesinger, W.H. (1997) Biogeochemistry: An anlaysis of global change. Acdemic Press San Diego, Ca. 588pgs

Shao, X., Wu, M., Gu, B., Chen, Y., & Liang, X. (2013). Nutrient retention in plant biomass and sediments from the salt marsh in Hangzhou Bay estuary, China. *Environmental Science and Pollution Research*, *20*(9), 6382–6391.

Small, G. E., Ardón, M., Duff, J. H., Jackman, A. P., Ramírez, A., Triska, F. J., & Pringle, C. M. (2016). Phosphorus retention in a lowland Neotropical stream following an eight-year enrichment experiment. *Freshwater Science*, *35*(1), 1–11.

Smil, V. (2000) **Phosphorus in the environment: natural flows and human interferences.** Annual Review of Energy and the Environment, 25 (2000), pp. 53-88

Smith, V. H., Tilman, G. D., & Nekola, J. C. (1999). Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution*, *100*(1), 179–196.

Snickars, M., Weigel, B., & Bonsdorff, E. (2015). Impact of eutrophication and climate change on fish and zoobenthos in coastal waters of the Baltic Sea. *Marine Biology*, *162*(1), 141–151.

Spångberg, J., Jönsson, H., & Tidåker, P. (2013). Bringing nutrients from sea to land - Mussels as fertiliser from a life cycle perspective. *Journal of Cleaner Production*, *51*, 234–244.

Stewart, W., Hammond, L., Kauwenbergh, S.J.V., 2005. Phosphorus as a Natural Resource. Phosphorus: Agriculture and the Environment, Agronomy Monograph No. 46. Madison, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America

Stevens, B. M., Propster, J., Wilson, G. W. T., Abraham, A., Ridenour, C., Doughty, C., & Johnson, N. C. (2018). Mycorrhizal symbioses influence the trophic structure of the Serengeti. *Journal of Ecology*, *106*(2), 536–546.

Scholz, R. W. and T. Hirth (2015a), Losses and efficiencies – From myths to data: Lessons learned from sustainable phosphorus management, *Resour. Conserv. Recycling, 105*, 211-215, doi: //doi.org/10.1016/j.resconrec.2015.10.005.

Scholz, R. W. and F. Wellmer (2015), Losses and use efficiencies along the phosphorus cycle – Part 2: Understanding the concept of efficiency, *Resour. Conserv. Recycling, 105*, 259-274, doi: //doi.org/10.1016/j.resconrec.2015.10.003.

Scholz, R. W. and T. Hirth (2015b), Losses and efficiencies – From myths to data: Lessons learned from sustainable phosphorus management, *Resources, Conservation & Recycling, 105*, 211-215, doi: 10.1016/j.resconrec.2015.10.005.

Shaffer, J. A., F. Juanes, T. P. Quinn, D. Parks, T. McBride, J. Michel, C. Naumann, M. Hocking, and C. Byrnes (2017), Nearshore fish community responses to large scale dam removal: implications for watershed restoration and fish management, *Aquat. Sci., 79*(3), 643-660, doi: 10.1007/s00027-017-0526-3.

Shatova, O., S. R. Wing, L. Wing, M. Gault-Ringold, and L. J. Hoffmann (2016), Seabird guano enhances phytoplankton production in the Southern Ocean, *Journal of Experimental Marine Biology and Ecology, 483*, 74-87, doi: 10.1016/j.jembe.2016.07.004.

Smil, V (2012), *Harvesting the Biosphere*, Mit Press, Cambridge.

Someus, E. and M. Pugliese (2018), Concentrated Phosphorus Recovery from Food Grade Animal Bones, *Sustainability*, *10*(7), doi: 10.3390/su10072349.

Steffen, W. et al. (2015), Planetary boundaries: Guiding human development on a changing planet, *Science, 347*(6223).

Steiner, G. and B. Geissler (2018), Sustainable Mineral Resource Management—Insights into the Case of Phosphorus, *Sustainability*, *10*(8), doi: 10.3390/su10082732.

Stevenson, P. R. and D. C. Guzmán-Caro (2010), Nutrient transport within and between habitats through seed dispersal processes by woolly monkeys in north-western Amazonia, *American journal of primatology*, *72*(11), 992-1003, doi: 10.1002/ajp.20852.

Strauch, S., L. Wenzel, A. Bischoff, O. Dellwig, J. Klein, A. Schüch, B. Wasenitz, and H. Palm (2018), Commercial African Catfish (Clarias gariepinus) Recirculating Aquaculture Systems: Assessment of Element and Energy Pathways with Special Focus on the Phosphorus Cycle, *Sustainability*, *10*(6), doi: 10.3390/su10061805.

Subalusky, A. L., Fitzgerald, L. A., & Smith, L. L. (2009). Ontogenetic niche shifts in the American Alligator establish functional connectivity between aquatic systems. *Biological Conservation*, *142*(7), 1507–1514.

Tiegs SD, Rüegg J, Chaloner DT, Tank JL, Lamberti GA. 2011. Ecological Effects of Live Salmon Exceed Those of Carcasses During an Annual Spawning Migration. Ecosystems 14:598-614.

Twining, C. W., Palkovacs, E. P., Friedman, M. A., Hasselman, D. J., & Post, D. M. (2016). Nutrient loading by anadromous fishes: species-specific contributions and the effects of diversity. *Canadian Journal of Fisheries and Aquatic Sciences*, *74*(4), 609–619.

Thompson Hobbs (1996), Modification of Ecosystems by Ungulates, *The Journal of Wildlife Management*, *60*(4), 695-713, doi: 10.2307/3802368.

Twining CW, West DC, Post DM. 2013. Historical changes in nutrient inputs from humans and anadromous fishes in New England's coastal watersheds. Limnology and Oceanography 58:1286–1300.

Ulrich, A. (2016a), Taking Stock: Phosphorus Supply from Natural and Anthropogenic Pools in the 21st Century, *Sci. Total Environ.*, *542*, 1005-1007, doi: //doi.org/10.1016/j.scitotenv.2015.10.036.

Ulrich, A. (2016b), Taking Stock: Phosphorus Supply from Natural and Anthropogenic Pools in the 21st Century, *Science of the Total Environment*, *542*(Pt B), 1005-1007, doi: 10.1016/j.scitotenv.2015.10.036.

UNFCCC. (2016), CDM methodologies; small scale and large scale afforestation and reforestation.

USGS: Mineral Commodity Summaries, Phosphate Rock, US Geological Survey, Washington DC, 2014

van der Gaast, W. (2015), International climate negotiation conditions: past and future , Groningen: University of Groningen,.

Van Kauwenbergh, S. J. (2010), * World Phosphate Rock Reserves and Resources*, Muscle Shoals, Alabama.

Van, d. G., R. Sikkema, and M. Vohrer (2018), The contribution of forest carbon credit projects to addressing the climate change challenge, *Climate Policy*, *18*(1), 42-48, doi: 10.1080/14693062.2016.1242056.

Vituosek, P.M. (1984) Litterfall, Nutrient Cycling, and Nutrient Limitation in Tropical Forests. *Ecology*, 65 (1), 285-298.

Walters, A. W., Barnes, R. T., & Post, D. M. (2009). Anadromous alewives (Alosa pseudoharengus) contribute marine-derived nutrients to coastal stream food webs. *Canadian Journal of Fisheries and Aquatic Sciences*, *66*(3), 439–448.

Wellmer, F. and W. R. Scholz (2018), What Is the Optimal and Sustainable Lifetime of a Mine?, *Sustainability*, *10*(2), doi: 10.3390/su10020480.

Wegener, P., T. Covino, and E. Wohl (2017), Beaver-mediated lateral hydrologic connectivity, fluvial carbon and nutrient flux, and aquatic ecosystem metabolism, *Water Resources Research*, 53, 4606–4623.

West DC, Walters AW, Gephard S, Post DM. 2010. Nutrient loading by anadromous alewife

(*Alosa pseudoharengus*): contemporary patterns and predictions for restoration efforts. Canadian Journal of Fisheries and Aquatic Sciences 67:1211–1220.

White S., and Cordell, D., (2017) Ch 4: Phosphorus security: future pathways to reduce food systme vulnerability to a new global challenge. In Global Resource Scarcity: Catalyst for Conflict or Cooperation? edited by Marcelle C. Dawson, Christopher Rosin, Nave Wald

Wing, S. R., Wing, L. C., Shatova, O. A., & Van Hale, R. (2017). Marine micronutrient vectors: Seabirds, marine mammals and fishes egest high concentrations of bioactive metals in the subantarctic island ecosystem. *Marine Ecology Progress Series*, *563*, 13–23.

Withers, P. J. A., Withers, P. J. A., Edwards, A. C., & Foy, R. H. (2001). Phosphorus cycling in UK agriculture and implications for phosphorus loss from soil. *Soil Use and Management*, *17*(3), 139–149.

Withers, P., D. Doody, and R. Sylvester-Bradley (2018), Achieving Sustainable Phosphorus Use in Food Systems through Circularisation, *Sustainability*, *10*(6), doi: 10.3390/su10061804.

Withers, P. J. A., K. van Dijk C., T. S. Neset, T. Nesme, O. Oenema, G. Rubæk H., O. F. Schoumans, B. Smit, and S. Pellerin (2015), Stewardship to tackle global phosphorus inefficiency: The case of Europe, *Ambio*, *44*, 193-206, doi: 10.1007/s13280-014-0614-8.

Wolf, A., C. E. Doughty, and Y. Malhi (2013), Lateral Diffusion of Nutrients by Mammalian Herbivores in Terrestrial Ecosystems, *PLOS ONE*, *8*(8), e71352.

Xu, D., Gao, Z., Zhang, X., Qi, Z., Meng, C., Zhuang, Z., & Ye, N. (2011). Evaluation of the potential role of the macroalga Laminaria japonica for alleviating coastal eutrophication. *Bioresource Technology*, *102*(21), 9912–9918.

Zhu, J., M. Li, and M. Whelan (2018), Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: A review, *Sci. Total Environ.*, *612*, 522-537, doi: //doi.org/10.1016/j.scitotenv.2017.08.095.