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Guiding phosphorus stewardship for multiple ecosystem services

Graham K. MacDonald,^{1,17} Helen P. Jarvie,² Paul J. A. Withers,³ Donnacha G. Doody,⁴ Bonnie L. Keeler,⁵ Philip M. Haygarth,⁶ Laura T. Johnson,⁷ Richard W. McDowell,^{8,9} Michael K. Miyittah,¹⁰ Stephen M. Powers,¹¹ Andrew N. Sharpley,¹² Jianbo Shen,¹³ Douglas R. Smith,¹⁴ Michael N. Weintraub,¹⁵ and Tiequan Zhang,¹⁶

¹Department of Geography, McGill University, 805 Sherbrooke Street West, Montreal, Quebec H3A 0B9 Canada

²Centre for Ecology and Hydrology, Wallingford OX10 8BB UK

³School of Environment, Natural Resources and Geography, Bangor University, Bangor LL57 2UW UK

⁴Agri-Food and Biosciences Institute, Belfast BT9 5PX UK

⁵Institute on the Environment, University of Minnesota, Saint Paul, Minnesota 55108 USA

⁶Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ UK

⁷National Center for Water Quality Research, Heidelberg University, 310 East Market Street, Tiffin, Ohio 44883 USA

⁸Invermay Agricultural Centre, AgResearch, Private Bag 50034, Mosgiel 9011 New Zealand

⁹Soil and Physical Sciences, Faculty of Agriculture and Life Sciences, Lincoln University, PO Box 84, Lincoln 7647 New Zealand

¹⁰Department of Environmental Sciences, University of Cape Coast, Cape Coast, Ghana

¹¹Center for Environmental Research, Education, and Outreach (CEREO), Washington State University, Pullman, Washington 99164 USA

¹²Division of Agriculture, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, Arkansas 72701 USA

¹³Key Laboratory of Plant-Soil Interactions, Department of Plant Nutrition, Ministry of Education, China Agricultural University, Beijing 100193 China

¹⁴Grassland, Soil and Water Research Laboratory, USDA-ARS, 808 East Blackland Road, Temple, Texas 76502 USA

¹⁵Department of Environmental Sciences, University of Toledo, Toledo, Ohio 43606 USA

¹⁶Harrow Research and Development Center, Agriculture and Agri-Food Canada, Harrow, Ontario N0R 1G0 Canada

Abstract. The essential role of phosphorus (P) for agriculture and its impact on water quality has received decades of research attention. However, the benefits of sustainable P use and management for society due to its downstream impacts on multiple ecosystem services are rarely acknowledged. We propose a conceptual framework—the “phosphorus-ecosystem services cascade” (PESC)—to integrate the key ecosystem processes and functions that moderate the relationship between P released to the environment from human actions and ecosystem services at distinct spatial and temporal scales. Indirect pathways in the cascade via soil and aquatic processes link anthropogenic P to biodiversity and multiple services, including recreation, drinking water provision, and fisheries. As anthropogenic P cascades through catchments, it often shifts from a subsidy to a stressor of ecosystem services. Phosphorus stewardship can have emergent ecosystem service co-benefits due to synergies with other societal or management goals (e.g., recycling of livestock manures and organic wastes could impact soil carbon storage). Applying the PESC framework, we identify key research priorities to align P stewardship with the management of multiple ecosystem services, such as incorporating additional services into agri-environmental P indices, assessing how widespread recycling of organic P sources could differentially impact agricultural yields and water quality, and accounting for shifting baselines in P stewardship due to climate change. Ultimately, P impacts depend on site-specific agricultural and biogeophysical contexts, so greater precision in targeting stewardship strategies to specific locations would help to optimize for ecosystem services and to more effectively internalize the downstream costs of farm nutrient management.

Key words: *agriculture; ecosystem services; phosphorus; sustainability; water quality.*

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Introduction

Judicious use of phosphorus (P) is crucial to agricultural production and maintaining or enhancing water quality (Jarvie et al. 2015). The benefits of P addition to plant

growth and crop yields have been recognized for about 200 years (Syers et al. 2008). However, losses of agricultural P can impair water quality, costing society via lost recreation opportunities, reduced waterfront property values, and increased need to treat drinking water (Dodds et al. 2008, Smith et al. 2015a). A key challenge of P management is how to maximize the benefits of P for agriculture while reducing the negative impacts of P for

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¹⁷ E-mail: graham.macdonald@mcgill.ca

society, which is particularly important given the finite nature of phosphate rock from which mineral P fertilizers are derived (Cordell and White 2014, Nesme and Withers 2016).

Considerable progress has been made in connecting anthropogenic nitrogen (N) loading to ecosystem services, including its cascading economic implications (e.g., Moomaw and Birch 2005, Compton et al. 2011, Sobota et al. 2015). However, similar frameworks do not exist for P, making it difficult to account for the diverse impacts P has on terrestrial, freshwater, and coastal ecosystems and associated socioeconomic consequences. Beyond agricultural production and water quality, linkages between P and other ecosystem services have not been fully explored.

Phosphorus limits primary production in most freshwater ecosystems and often co-limits production with N in terrestrial and coastal ecosystems (Elser et al. 2007). As a result, P transfer and cycling along the land-water continuum affects soil ecosystem functions, water quality, hydrology, and biodiversity. Along with N and carbon (C), P is central to soil functions that moderate or support hydrologic services (e.g., soil water storage), nutrient cycling (e.g., soil fertility), C storage, and soil biodiversity, primarily via its impacts on soil organic matter content and quality (Brauman et al. 2007, Haygarth and Ritz 2009, Smith et al. 2015b, Orgiazzi et al. 2016). Soil functions, often referred to as “supporting services,” indirectly benefit society by underpinning provisioning, regulating, and cultural services (MA 2005, Smith et al. 2015b). Phosphorus is a primary contributor to eutrophication in freshwater and coastal systems, with impacts on multiple services including water quantity, recreation, aesthetic quality, fisheries, and aquatic biodiversity (Wilson and Carpenter 1999, Keeler et al. 2012). Biodiversity can be an intermediary that affects ecosystem processes and functions, a final ecosystem service (e.g., pollination), and an ecosystem good subject to valuation (e.g., harvest of wild species) (Mace et al. 2012). In the context of P use and management, we view biodiversity as a regulating service, in that changes in P availability can affect the supply of ecosystem goods and services (e.g., P use affects aquatic ecosystem structure, which could in turn affect a service such as fisheries).

Here, we develop a new conceptual framework for the “phosphorus-ecosystem services cascade” (PESC) to examine the effect of P stewardship on the delivery of multiple ecosystem services along the land-water continuum. Phosphorus stewardship encompasses diverse strategies for managing P inputs, losses, recycling, recovery, and demand at scales ranging from agricultural fields to the global food system (Withers et al. 2015, Shepherd et al. 2016). Our focus is on stewardship of the agricultural uses of P (e.g., fertilizer and manure management), but we also identify key gaps and uncertainties regarding how broader P stewardship strategies align with ecosystem service management.

The PESC framework complements the “ecosystem services cascade model” (Haines-Young and Potschin 2010, Braat and de Groot 2012), which describes a production chain where services form a link between ecosystems (including ecosystem processes, functions, and biodiversity) and benefits that society derives. The PESC also builds on the “nitrogen cascade” proposed by Galloway et al. (2003). A cascade approach acknowledges that impacts are often decoupled from P sources due to spatial discontinuities and time lags associated with P transport through catchments (Sharpley et al. 2013), and also captures the important role of P cycling for multiple ecosystem services. Although we do not discuss economic valuation of the PESC, P-related services can be valued using integrated biophysical and economic models (Brauman et al. 2007, Keeler et al. 2012).

The phosphorus-ecosystem services cascade

The “phosphorus cascade” is a sequential chain of P transfers through catchments via successive hydrologic and biogeochemical pathways, including intermediate landscape, fluvial, and biomass storage pools as P moves downstream (Sharpley et al. 2013). The PESC further describes impacts on ecosystem services related to the addition, storage, and flow of “anthropogenic” P in soils and aquatic ecosystems (Fig. 1). We consider anthropogenic P to be any P released to the environment from human actions or management, including application of mineral P fertilizers derived from phosphate rock, recycling of manure and organic P by-products, use of recalcitrant soil P pools, and erosion of P due to soil disturbance. The P cascade begins when water discharge is generated and P is mobilized either with eroded sediment or in solution, whereas the role of P in the ecosystem services cascade starts when anthropogenic P is mobilized or P is applied to crops as mineral fertilizer or organic P sources.

We identify 12 ecosystem services relevant to the PESC and hypothesize about the mechanisms underlying their relationship to anthropogenic P (Table 1). The delivery of most P-related provisioning and regulating services is moderated by ecological, biogeochemical, and hydrologic controls on P cycling and transport (Doody et al. 2016). The response of crops, other vegetation, and soil biota to changes in P use and management in turn affects downstream provisioning and cultural services. The same atom of P can therefore affect multiple ecosystem services as it moves through a catchment (*sensu* Galloway et al. 2003). For example, application of P to the land intended to support a provisioning service (agriculture) can in turn result in P losses to water that degrade water quality and reduce the supply of other services (e.g., safe drinking water); negative impacts on downstream ecosystem services can be partially offset by P retention and removal in catchments—a regulating service (Fig. 1). We therefore conceptualize three types of ecosystem service relationships in the PESC: (1) services *directly* impacted

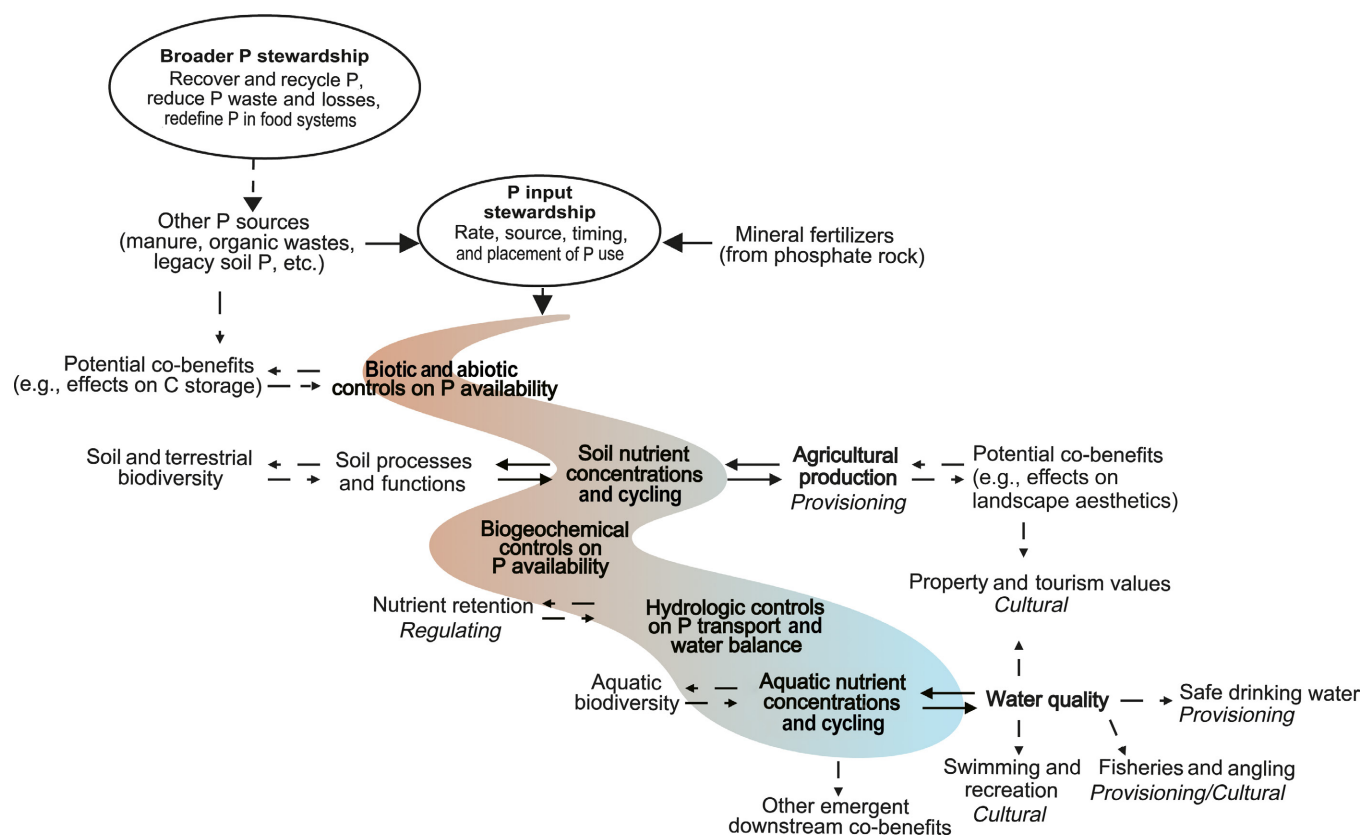


Fig. 1. Conceptual framework for the P-ecosystem services cascade (PESC). A gradient of soil and aquatic processes (shaded in brown and blue, respectively) links P input stewardship to biodiversity and different provisioning, regulating, and cultural services. Solid arrows indicate direct relationships between anthropogenic P and ecosystem services, while dotted arrows indicate indirect or intermediary linkages through the cascade. These services are influenced by biogeochemical controls on P availability (e.g., microbial activity) and hydrology (e.g., farm runoff). Some stewardship strategies operate outside of the cascade but are likely to influence P input stewardship and potential co-benefits related to the form of P inputs (e.g., recovery of P in urban wastes could influence the degree of P recycling from cities to agricultural land). Ideally, changes in the delivery of service benefits or co-benefits should feedback to influence P use and management, but this is often inhibited by systemic P disconnects.

by P (e.g., agricultural production); (2) services indirectly impacted through intermediary linkages between P, soil processes, water quality, biodiversity, or hydrology (e.g., recreation and water supply); and (3) services that are co-benefits of P stewardship interventions that encompass other societal or management goals (e.g., recycling of livestock manure and organic wastes in agriculture could promote soil C storage). Co-benefits in the PESC include any ecosystem services that are unintentionally enhanced by P stewardship actions.

The effects of phosphorus use on the ecosystem services cascade

Altered biogeochemical and hydrologic functioning due to agricultural P use and management has distinct outcomes on the PESC at each scale. Each focal scale in the PESC (plant–soil, landscape, and catchment/basin) shares common ecosystem services, but these vary in importance based on processes controlling P delivery and availability (Fig. 2).

Some ecosystem services are not fully realized at the plant–soil scale, but this scale underpins benefits delivered at larger scales. The effects of P on soil functions and linkages with soil N and C processing through mobilization and immobilization mediated by soil microorganisms are particularly important. Phosphorus availability affects crop root system development and influences N-use efficiency, which could subsequently affect crop transpiration and water storage in some soils (French and Schultz 1984, IPNI 1999, Grant et al. 2001). A substantial proportion of applied P can be immobilized by abiotic and biotic fixation within soils (Rowe et al. 2016). Where P-use efficiency is low due to fixation, P can only be remobilized by large changes in soil pH, plant root exudates (e.g., carboxylates), or microbial activity (Shen et al. 2013, Zhang et al. 2016), which in turn is influenced by C and N availability and soil fauna. For example, soil biota in a maize field enhanced plant P uptake and reduced P leaching losses relative to biota-limited treatments (Bender and van der Heijden 2015).

At the landscape scale, agricultural production also represents a cultural service with heritage value or

Table 1. Summary of key P-related ecosystem services in the cascade.

Ecosystem service (ES) impacted	Main linkage	Hypothesized mechanism linking service to P use and management	ES relationship to P use and management
Agricultural production <i>Provisioning</i>	Soil processes	Enhanced soil P fertility and modified rhizosphere processes improve crop growth (+)	Strong, direct link to soil processes
Safe drinking water <i>Provisioning</i>	Water quality	Algae/phytoplankton blooms and cyanobacteria toxins (e.g., microcystin) increase water treatment costs (–)	Strong, direct link to water quality
Swimming and recreation <i>Cultural</i>	Water quality	Reduced water clarity decreases recreational demand; toxic cyanobacteria can make water unsafe for contact (–)	Strong, indirect; social context dependent
Waterfront property <i>Cultural</i>	Water quality	Reduced water clarity lowers waterfront property values (–)	Strong, indirect; social context dependent
Inland fisheries and angling <i>Provisioning Cultural</i>	Water quality	Small increases in P concentrations may stimulate production of some species, but eutrophication results in fish kills due to loss of dissolved oxygen (+/–)	Strong, indirect; response is species dependent
Aquatic biodiversity <i>Regulating</i>	Ecosystem processes	Dominance of nutrient tolerant species and reduced aquatic biodiversity (–)	Strong, indirect; thresholds could vary
Belowground C storage <i>Regulating</i>	Soil processes	Organic amendments (e.g., manure) to promote C and P/N retention maintain soil C (+)	Strong, indirect; depends on management
Soil biodiversity <i>Regulating</i>	Soil processes	Promoting soil biodiversity (e.g., with organic amendments) enhances crop-soil diversity and P availability (+/–)	Strong, indirect; depends on management
Terrestrial biodiversity <i>Regulating</i>	Ecosystem processes	Soil weathering during pedogenesis determines patterns of P availability, plant diversity, and plant growth (–/+)	Strong, indirect; determines baseline fertility
Water supply and flow attenuation <i>Regulating</i>	Hydrology	Nature of P use affects crop transpiration and soil water balance via root systems (+/–); may also reduce peak runoff (+)	Mixed, indirect; depends on biomass response to added P
Aboveground C storage <i>Regulating</i>	Ecosystem processes	Nature of P use can directly or indirectly (e.g., via N-use efficiency) affect net primary production (+/–)	Mixed, co-benefit; pathways are ambiguous
Landscape heritage <i>Cultural</i>	Cultural context	P use affects agricultural mosaic; nutrient management forms part of agricultural tradition (+)	Theoretical, co-benefit; social context dependent

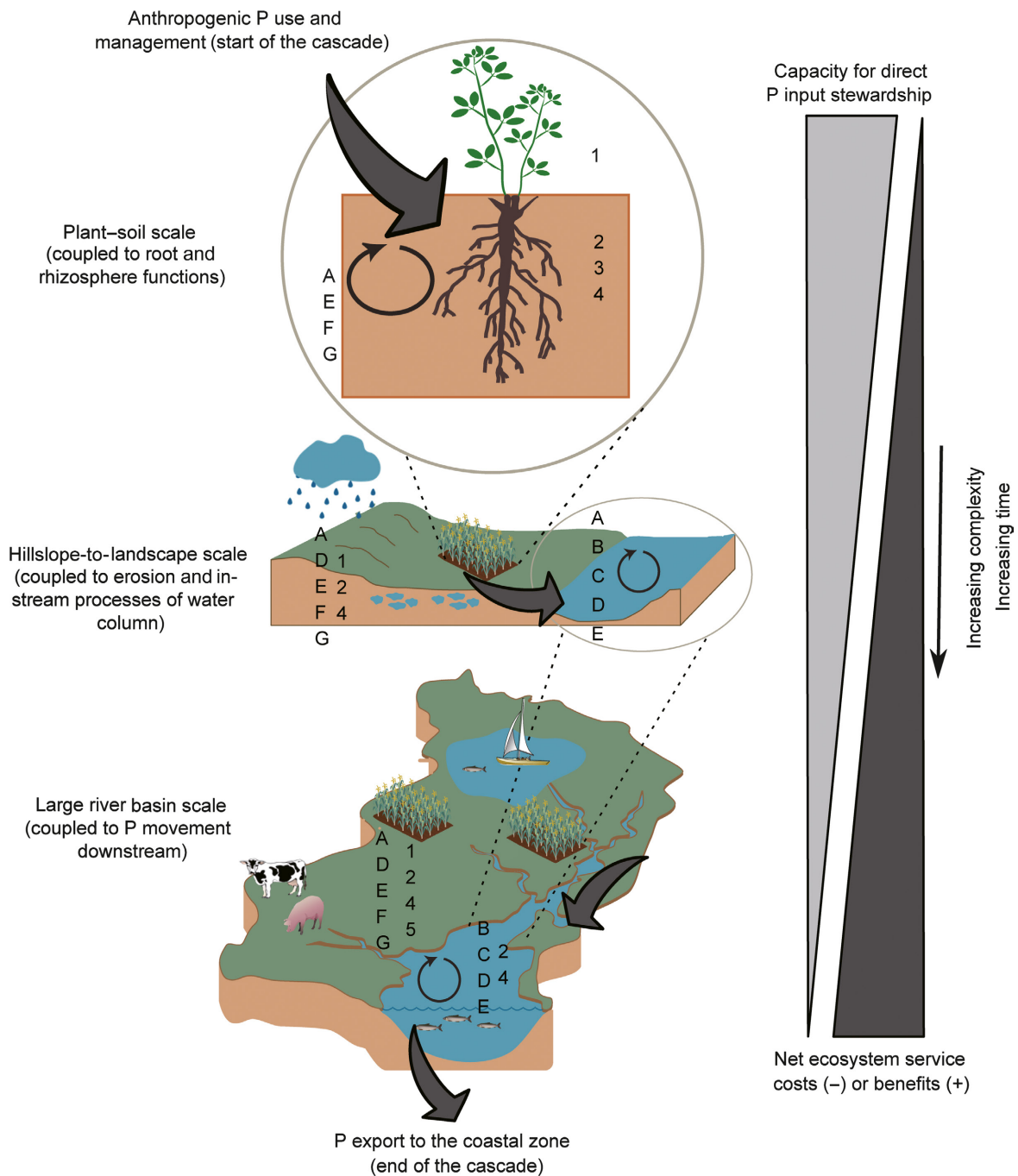
Notes: For hypothesized effects, (+) indicates where “good” P stewardship can enhance the service, while (–) indicates where “poor” P stewardship can degrade the service. Services are ordered from the strongest and most *direct* linkage to P (at the top) to those with more *indirect* linkages through intermediaries or co-benefits of management (at the bottom).

aesthetic significance (MA 2005). Crop and soil management associated with P use has a direct role in water quality (e.g., via cover crops and other measures to limit erosion, P mobilization and transport), which can cascade to other secondary hydrologic services related to water quantity (e.g., via increased soil water-holding capacity and infiltration). By influencing water storage, routing, and timing of flows, there is a subsequent influence on downstream P uptake and retention (e.g., in riparian areas) (Naiman and Decamps 1997, Jarvie et al. 2013a).

At the river basin scale, surface waters provide a range of cultural and economic values for society (Wilson and Carpenter 1999). On entering surface waters, further opportunity for P recycling and retention depends on a variety of factors, including water and sediment residence times (Withers and Jarvie 2008). The degree of P enrichment will govern the direction, magnitude, and types of ecosystem services that are affected. For example, a small increase in P concentrations can increase fish

catches (Stockner et al. 2000), yet further P enrichment is likely to have negative impacts, such as loss of dissolved oxygen and fish kills, or toxic algal blooms that are harmful to human health (Smith and Schindler 2009). In many cases, the impacts of P vary according to the supply of P relative to N (Elser et al. 2007). For example, reductions in P loading due to regulatory efforts have contributed to an increase in the N:P ratio of river water draining to European seas, which exacerbates coastal eutrophication problems (Grizzetti et al. 2012, Burson et al. 2016).

There is general consensus that either too little P or too much P exerts negative pressure on biodiversity globally (MA 2005, Vörösmarty et al. 2010, Teste et al. 2016). Society’s reliance on a relatively limited range of agricultural crops and regular inputs of agrochemicals negatively influences terrestrial biodiversity (Aktar et al. 2009). This could represent a tradeoff between more P-fertile soils for agricultural productivity and lower P fertility that may support higher species richness in near-by ecosystems. For example, agricultural P enrichment



Ecosystem functions or services

- 1: Food, fiber and bioenergy
- 2: Nutrient cycling and retention
- 3: C sequestration
- 4: Water filtration and retention
- 5: Agricultural landscape and heritage

Effects on supply of ecosystem services

- A: Δ nutrient and sediment retention
- B: Δ water quality
- C: Δ fish catches
- D: Δ recreation and property value
- E: Δ biodiversity
- F: Δ soil and above-ground C storage
- G: Δ water supply and attenuation

Fig. 2. Key relationships between anthropogenic P inputs, biodiversity, and ecosystem services at three distinct spatial scales of the PESC. As scale increases, the capacity for direct P input stewardship decreases, while the complexity of P stewardship interventions increases due to, for example, spatial discontinuities, time lags, and unfavorable economies of scale (*sensu* Haygarth et al. 2005). With increasing scale, the number of stakeholders and the need to coordinate multiple processes required for any given P stewardship strategy will also increase. Vector graphics were derived from the Integration and Application Network, University of Maryland Center for Environmental Science (see *Acknowledgments*).

of semi-natural grasslands in Europe appears to drive a gradient of reduced species richness (Ceulemans et al. 2014). Excessive fertilizer application also reduces soil biodiversity and potentially the resilience of agricultural systems to future stresses, such as climate change (Chagnon and Bradley 2013).

Phosphorus disconnects alter the supply of ecosystem services

The episodic nature of P cascades (e.g., the timing of fertilizer use and major runoff events) gives rise to spatially and temporally disjointed impacts at locations geographically distant from the original P source (Sharpley et al. 2013). As scale increases, the relationship between P stewardship and ecosystem services is increasingly complex due to dependencies on other ecosystem processes (C and N cycling, hydrology, and biodiversity) (Fig. 2; Haygarth et al. 2005). With increasing distance from the anthropogenic P source, ease of implementation (e.g., cost-effectiveness) of stewardship strategies decreases due to the number of stakeholders involved and increased diversity of farming systems, soils, and hydrology over the landscape mosaic (McDowell et al. 2016). Addressing P stewardship at the plant–soil scale with input management (timing, source, rate, and placement of P fertilizers) before P is lost from targeted cropping systems is therefore more efficient and cost-effective than mitigating P impacts downstream or restoring systems after they have been degraded (McDowell and Nash 2012, Jarvie et al. 2013b).

There can be extensive lag times between P stewardship and its outcomes on downstream ecosystem services (Meals et al. 2010). This disconnect occurs due to abiotic and biotic immobilization and gradual accumulation of P applied to the soil over many years (legacy soil P), and cascading effects may not be realized for days to decades after the initial P applications as hydrologic processes transport legacy soil P offsite (McDowell et al. 2001, Sharpley et al. 2013, Barrow and Debnath 2014). These processes may slow P movement across the landscape, effectively enhancing P buffering capacity in catchments if soil biota and biogeochemical function are intact (Fraterrigo and Downing 2008, Doody et al. 2016).

Urbanization, agricultural intensification, globalization, and dietary change pose further challenges to P stewardship for ecosystem services. Under- or over-application of P at the field scale is a manifestation of broader societal facets of the built environment, economy, and policies that results in regional P imbalances (MacDonald et al. 2011). At the landscape scale, segregation of crop and livestock production can concentrate manure P use on nearby croplands, often leading to excess P application when manure is applied to match crop N requirements due to its typically low N:P ratio

(Heathwaite et al. 2000, Li et al. 2011b, Nesme et al. 2015). Urban areas are major sinks for P consumed in imported foods and industrial products, with potentially large magnitudes of P land-filled or discharged via municipal waste streams to surface waters (Metson et al. 2015). Large quantities of P also move internationally in traded livestock feed grains linked to growing demand for animal products, contributing to manure P imbalances in feed-importing nations and compounding the challenge of P recycling on domestic farmlands (Schipanski and Bennett 2012). In contrast, economic and sociopolitical factors limit access to P fertilizers in many lower income countries (Nziguheba et al. 2016).

As a result of these systemic disconnects, there can be immense distances (from tens of kilometers for local food to many thousands of kilometers for imported foods) between on-farm P use and ecosystem service outcomes (e.g., food consumption or degraded water quality). Legacy P retention and remobilization, combined with the temporal dynamics of P in soils and surface waters, could also “lock-in” future ecosystem service outcomes. Ideally, net downstream ecosystem service impacts should feedback to encourage P input stewardship upstream, but this is obfuscated by systemic disconnects (Fig. 1). A key obstacle is that disconnects and stewardship strategies do not scale linearly and are compounded at larger scales. For example, N and P inputs from agriculture and cities hundreds of kilometers upstream in the Mississippi River Basin drive seasonal hypoxia in the Gulf of Mexico (Jacobson et al. 2011).

Overcoming disconnects to promote a more beneficial and direct cascade of ecosystem services warrants a broader stewardship approach that tackles P inputs, losses, recycling, recovery, and consumer demand. To illustrate this, we matched the diverse P stewardship strategies proposed by Withers et al. (2015) to different social–ecological system components that could affect the PESC—primarily by altering the magnitude, source, and nature of P use in the agricultural system (Fig. 3). Achieving more efficient P use through careful application, combined with measures to enhance retention and recycling at every opportunity, entails changes to agricultural management, technology, and policy (Withers et al. 2015). Such changes could indirectly result in broader co-benefits for ecosystem services in the cascade (Fig. 1). However, P stewardship is challenged by global change pressures, particularly climate change, which can increase rates of P cycling in soil, risk of P transfer to surface waters, and alter the response of aquatic ecosystems to eutrophication (Ockenden et al. 2016).

Research priorities for the PESC

Quantifying how P use and management functionally enhance or degrade specific services, including via indirect pathways, is a key research priority. Although

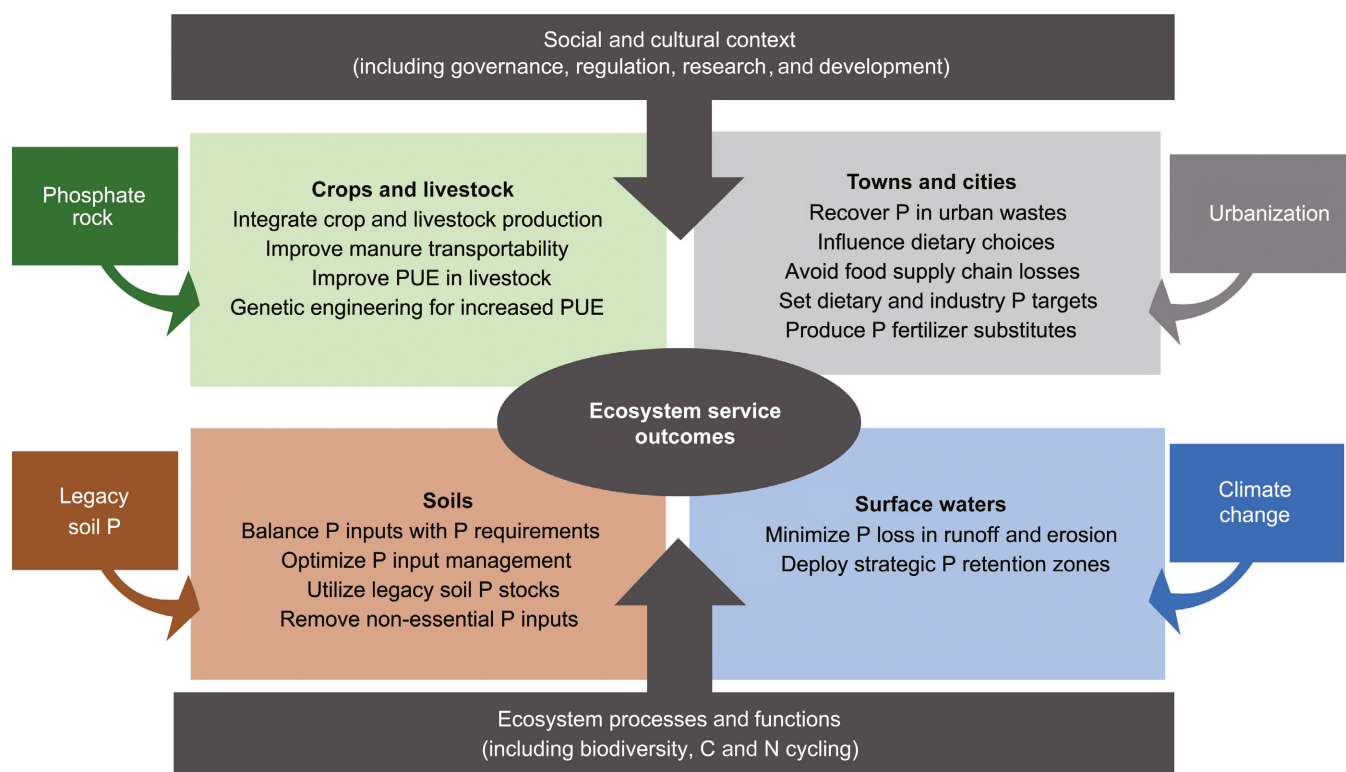


Fig. 3. Socioeconomic setting, ecosystem processes, phosphate rock availability and prices, climate change, and legacy soil P are “macro” controls on the PESC that underpin ecosystem service outcomes across scales. We classify the 15 P stewardship strategies proposed by Withers et al. (2015) into four spatial management components relevant to the PESC (light green, brown, blue, and gray boxes): soil systems, surface waters, agricultural production, and cities. Cities and towns are key to broader P stewardship as centers of food consumption, waste generation, and research and development. Important challenges related to each system component are shown (i.e., phosphate rock availability and prices, legacy soil P, urbanization, and climate change). PUE refers to phosphorus-use efficiency.

indirect or co-beneficiary links between P and ecosystems services in the cascade (e.g., hydrologic services and carbon storage) are unlikely to become primary drivers of policy and practice related to P, understanding synergies between P stewardship and other management goals could help to reduce tradeoffs among competing ecosystem services (Bennett et al. 2009). Applying the PESC framework, we outline six research priorities to help move toward this goal, grouped according to the management of P in soils (Box 1) and aquatic ecosystems (Box 2). These research priorities include the need for consideration of legacy soil P and climate change impacts (Fig. 3).

The outcomes of the PESC are scale dependent and ultimately depend on regional biophysical and socio-economic context that determine fertilizer use, waste flows and management, hydrologic fluxes, and recycling (Garnier et al. 2015). Managing P for ecosystem services requires an understanding of the historical factors that affect how much P has accumulated in catchments as a result of past anthropogenic activities (Powers et al. 2016) and what social-ecological factors drive P fluxes and the demand for ecosystem services in different places (Metson et al. 2015). Examining and synthesizing case studies from different locations worldwide would help

to guide local P stewardship strategies that account for socioeconomic, agricultural, and biogeophysical factors (e.g., Magliocca et al. 2015).

Summary and conclusions

Societal changes to the P cycle, driven largely by use of mineral fertilizers for ever increasing crop demand, impact multiple ecosystem services through linkages between agriculture, water quality, soil functions, hydrology, and biodiversity. Guiding P stewardship for multiple ecosystem services should help to balance tradeoffs among different landscape management priorities (Jarvie et al. 2015). Internalizing downstream costs of P use into management practices could incentivize cross-scale solutions, such as prioritizing effective use of existing P sources including organic by-products and legacy soil P resources in agriculture rather than “new” anthropogenic P derived from phosphate rock.

The PESC interacts with C and N cycling that links it to broader co-benefits (e.g., carbon storage and hydrology). Co-benefits associated with ecosystem services are considered, but seldom emphasized in management or policy. The collective impact of co-benefits, such as those linked to P stewardship strategies, could ultimately

Box 1.

Research priorities in the phosphorus-ecosystem services cascade related to soils and agricultural uses of P

Assess the cumulative, downstream impacts of plant–soil system P stewardship. Biological and abiotic soil processes have a vital role in nutrient cycling and water storage, but the long-term and broader implications for downstream ecosystem services are rarely considered. Phosphorus stewardship at the plant–soil interface could help to optimize soil nutrient cycling and water management to balance competing demands between food production and water quality (Doody et al. 2016). Soil and fertilizer P availability can be highly dependent on soil water status, so a tighter coupling of P with improved soil water management could promote improved crop yields with more efficient P use and less P loss (Liu et al. 2011, Shen et al. 2013). Managing soil biodiversity and root/rhizosphere interactions can also help to improve P-use efficiency in agriculture (Zhang et al. 2016).

Incorporate multiple ecosystem services into agri-environmental P indices. In the past two decades, there has been extensive development and refinement of regional agri-environmental P indices (Osmond et al. 2012, Sharpley et al. 2012, Bai et al. 2013). Agronomically optimum P input rates for different soils and regions are typically calibrated to crop response or in some cases risk of P loss to aquatic systems. There is currently little research on which to base P management guidelines for managing a broader set of services, such as maintenance of drinking water quality, fisheries, and access to swimming. Despite targeting agronomically optimum soil P, water quality targets may not be achieved due to persistent losses of legacy P (Cassidy et al. 2016). Many interacting factors contribute to water quality. For example, river quality in New Zealand is commonly judged as “poor” when periphyton covers more than 30% of the stream bed, which is linked to land use practices and in turn P, but is also impacted by flow, shade, N inputs, and the innate response of the river (McDowell et al. 2016). Socioeconomic factors further moderate demand for water quality improvements depending on individual preferences, expected fisheries benefits, population density, and demand for recreation (Keeler et al. 2015).

Assess the implications of increased organic P recycling and use for multiple ecosystem services. Effective recycling of livestock manure and municipal waste is consistently identified as a priority to balance tradeoffs between agriculture and water quality (Metson et al. 2016). Yet, the effects of widespread substitutions of mineral P fertilizers for recycled organic P resources on agricultural provisioning and water quality services are uncertain. At the plant–soil scale, recycling of manure to croplands can improve nutrient availability, water-holding capacity, and soil structure (Chambers et al. 2003, Li et al. 2011a, b), potentially altering farmland water discharge pathways and volumes. Use of organic amendments, along with method of application and other management practices, can increase soil C storage in agricultural lands (Fornara et al. 2016), representing a co-benefit of P stewardship that favors manure amendments over mineral fertilizers. Enhanced soil organic matter is also expected to improve soil biodiversity (Pimentel et al. 2005). However, P availability to crops can vary depending on the organic source and time horizon after application (Hao et al. 2015), and there could be incidental losses of P in farmland water discharge due to increased amendments (Zhang et al. 2015). The low N:P of manure can also lead to excess P inputs when manure is applied to match crop N demands (Heathwaite et al. 2000).

outweigh the benefits of nutrient management approaches focused individually on P, N, or C. Integrating P, N, and C stewardship could therefore help to improve the resilience and functional integrity of multiple ecosystem services.

The PESC provides a new framework for recognizing, understanding, and accounting for a fuller range of co-benefits arising from sustainable P use and management. Further exploration of the PESC with empirical data is a next step to test cascade pathways, inform management priorities, and assess costs and benefits of P stewardship for society. Such studies could aid in developing new policy mechanisms for P sustainability that internalize the downstream costs of excess P in fertilizer prices,

optimize agronomic recommendations, or inform government nutrient management protocols.

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Box 2.**Research priorities in the phosphorus-ecosystem services cascade related to hydrology and aquatic ecosystems**

Determine water quality targets according to catchment-specific P “buffering capacity.” Phosphorus use follows a classic subsidy-stress gradient (Odum et al. 1979), wherein some additional P is beneficial until a threshold is passed that reduces the supply of ecosystem services, such as a change in trophic status of downstream waters. In this sense, when a threshold is passed, anthropogenic P becomes an ecosystem “disservice” that can negatively impact human well-being (Shackleton et al. 2016). However, determining the threshold where P changes from a “subsidy” to a “stressor” for downstream aquatic or nearby terrestrial ecosystems is challenging, being tempered by local conditions and historic practices (Withers and Jarvie 2008). At the catchment scale, biogeochemical, hydrologic, and ecological factors control P storage and recycling, resulting in a gradient of buffering capacities that determine how sensitive a catchment is to agricultural land use (Doody et al. 2016). Catchment buffering further depends on climate and legacy soil and sediment P, which are difficult to quantify (Powers et al. 2016).

Determine the salience of P stewardship impacts on hydrology. We suggest potential indirect links between P use and hydrologic services, such as water supply, by increasing crop biomass (Monteith 1986). However, the overall magnitude of these effects is uncertain. Where soil P fertility is optimum and yield responses to applied P are unlikely, there will be minimal effect of P inputs on hydrologic services. However, under low soil P fertility, biomass growth following P application should increase plant water uptake. Efforts to close crop yield gaps with added N and P are crucial to improving crop production (e.g., in sub-Saharan Africa; Mueller et al. 2012) but could also influence catchment water storage. Such interactions could compound eutrophication in areas facing water scarcity and reduced stream baseflow discharge.

Evaluate shifting baselines for P use and management due to climate change. There is a growing need to understand how extreme weather events will exacerbate current water quality problems, including incidence of algal blooms (Michalak 2016). Increasing mean temperatures have compounded the effects of nutrient loading in the growing dominance of cyanobacteria across northern temperate lakes (Taranu et al. 2015). The likelihood of warmer, wetter winters and hotter, drier summers with more extreme precipitation will elevate P transfers unless agricultural management is altered (Ockenden et al. 2016). Climate change may therefore shift the baseline in terms of effective P stewardship strategies needed in certain areas to enhance multiple ecosystem services, particularly in locations where large quantities of legacy soil and aquatic sediment P have accumulated (Carpenter 2005, Rowe et al. 2016).

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