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Transforming soil phosphorus fertility management strategies to support the delivery of multiple ecosystem services from agricultural systems

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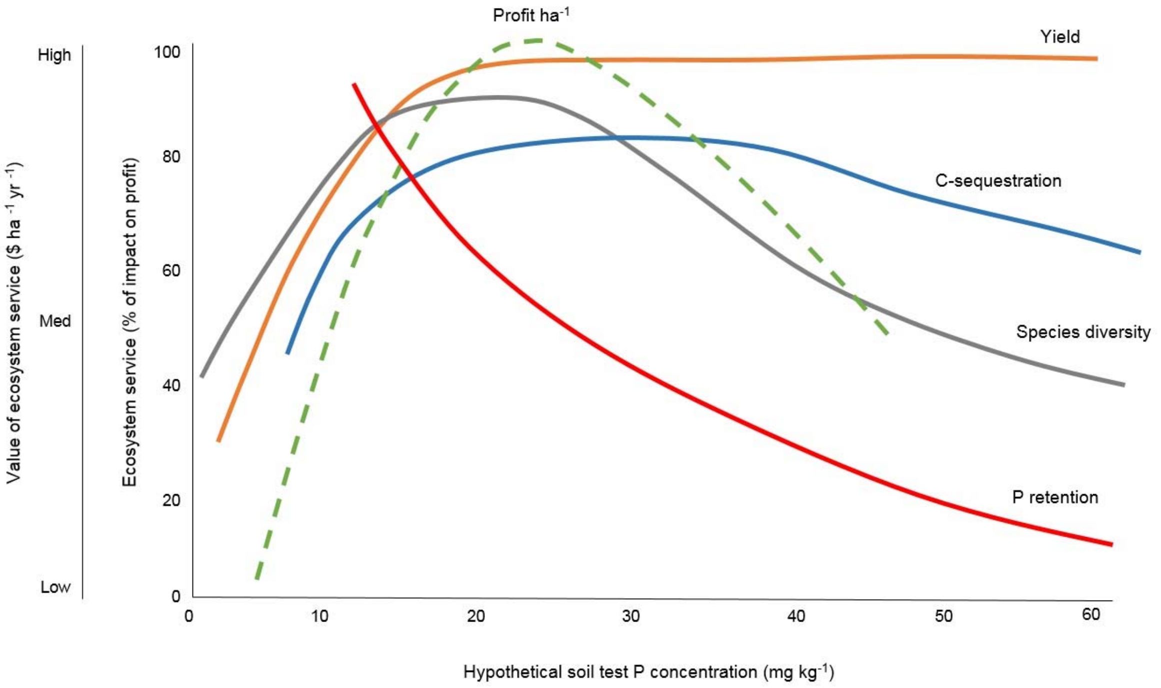
Graphical Abstract



Abstract

Despite greater emphasis on holistic phosphorus (P) management, current nutrient advice delivered at farm-scale still focuses almost exclusively on agricultural production. This limits our ability to address national and international strategies for the delivery of multiple ecosystem services (ES). Currently there is no operational framework in place to manage P fertility for multiple ES delivery and to identify the costs of potentially sacrificing crop yield and/or quality. As soil P fertility plays a central role in ES delivery, we argue that soil test phosphorus (STP) concentration provides a suitable common unit of measure by which delivering multiple ES can be economically valued relative to maximum potential yield, in \$ ha^{-1} yr^{-1} units. This value can then be traded, or payments made against one another, at spatio-temporal scales relevant for farmer and national policy objectives. Implementation of this framework into current P fertility management strategies would allow for the integration and interaction of different stakeholder interests in ES delivery on-farm and in the wider landscape. Further progress in biophysical modeling of soil P dynamics is needed to inform its adoption across diverse landscapes.

Keywords: Phosphorus; Sustainable Management; Soil Fertility; Soil Test Phosphorus; Ecosystems Services.

1. Introduction

Agricultural production is driven by economics and the demand to deliver maximum potential yield: this is often to the detriment of the environment and impacts negatively on other ecosystem services (ES) and natural capital (Tscharntke et al. 2005). Recent international and national strategies, such as the Millenium Ecosystem Services Assessment (Costanza et al. 2017; MEA, 2005), advocate the balanced delivery of a range of ES to stakeholders, and with the appropriate management of trade-offs between different ES (Costanza et al. 2017; Spake et al. 2017). However, in practice the implementation of more integrated ecologically-focused or environmentally-friendly farming strategies focused on supporting, regulating and cultural ES, at the farm scale, continues to be overlooked in favour of provisoning ES, most notably as food, fibre and biofuel production (Liebig et al. 2017). This is in part because many existing farm management practices are not currently designed to deliver multiple ES, and do not account for the large spatial and temporal heterogeneity in landscape characteristics underpining ES delivery (Bennett et al. 2009; 2015; Qui and Turner, 2013).

The importance of phosphorus (P) in the delivery of multiple ES has received increased attention (Doody et al. 2016; Jarvie et al. 2015; McDonald et al. 2016). Jarvie et al. (2015) highlighted the central role that sustainable P management plays in balancing different ES across the water-energy-food continuum. McDonald et al. (2016) proposed the P Ecosystem Services Cascade as a conceptual framework to integrate sustainable P management with key ES processes and functions from soil to large river basin scale. Holistic approaches to farm nutrient management have recently been adopted to provide a greater focus on multiple ES. For instance, the fertilizer industry has adopted the 4R Nutrient Stewardship Strategy (Right Rate, Right Time, Right Place and Right Form) to promote more efficient use of fertilizer and reduce field-scale nutrient export to water (Bruulsema et al. 2009). In Europe, a 5R approach to sustainable P management has also been promoted (Re-align P inputs; Reduce P loss to water; Recycle P; Recover P in wastes; and Redefine P in food systems) that embraces both field-scale and wider regional P stewardship to reduce dependency on finite reserves of P-rock, and negative impacts on the environment (Withers et al. 2015). These approaches are moving from a paradigm of simply managing nutrient inputs for crop production to one that considers the sustainable use of resources for other ES.

Despite this change in emphasis, the majority of P management decisions remain largely focused on agricultural production because this drives profitability and livelihoods. For example, the build-up and maintenance of critical levels of soil P fertility remains the cornerstone of fertilizer recommendation systems to optimise crop yield and quality across the world (Syers et al. 2008). In addition, a range of different and largely historic soil P testing procedures (soil test P, STP), which were developed and calibrated to crop yield response, continue to be used to characterise soil P fertility and guide on-farm P use across widely differing landscapes (Jordan-Meille et al. 2012). However, soil P fertility also has a major impact upon ES other than food provision raising potential conflicts in ES delivery. For example, critical STP concentration thresholds in soils have been set at an elevated '*insurance*' level to overcome shortfalls in soil P supply caused by landscape heterogeneity, leading to accelerated P transport in land runoff causing eutrophication and loss of ES related to water function (e.g., Fischer et al. 2017; Withers et al. 2014). Additional drivers for '*insurance*' levels include maintaining soil P fertility to prevent the likelihood of crop limitation and to '*bank*' P in soil as a buffer against potential variability in global chemical P fertilizer prices. However, environmental concerns over water quality and biodiversity are drawing attention to the need for more precise management of soil P fertility. Managing STP for a wider range of ES will require a common metric to facilitate the prioritisation and trade-offs between them (Costanza et al. 2017).

Research work has already begun to attribute economic value to many ES (e.g. Dominati et al. 2014), thus allowing management objectives for single, multiple or bundled ES to be compared and traded (Spake et al. 2017). However, this has yet to be incorporated into current P fertility management advice delivered on-farm. Although a wide range of farm practices and biophysical variables are involved in delivering multiple ES in agricultural systems, a focus on soil P fertility is strategically essential because this important metric of natural capital changes only slowly in response to management, and therefore has potential long-term impacts on future delivery of multiple ES and well-being. Although previous research (e.g, Jarvie et al. 2015; McDonald et al. 2016) highlight the link between P and ES, there is currently no operational framework to consider the trade-offs between delivering ES and optimum STP levels across diverse cropping systems, including extensive farming enterprises. In this paper we:

1) Explore the relationship between STP and the delivery of four key metrics, namely crop yield as an ES, and P retention (water quality proxy), biodiversity and C-sequestration as indicators of ES.
2) Present a conceptual model for advancing soil P fertility management based on the delivery of the four key ES or indicators of ES by providing a method of attributing economic value to ES or indicators of ES influenced by STP concentration.
3) Examine the modifications required to current P fertility strategies for the delivery of our four key ES or indicators of ES impacted by soil P fertility.

For simplicity, throughout the paper we use the term ES in the context of crop yield, P retention, biodiversity and C-sequestration, but acknowledge that the last three are indicators of ES rather than being an ES in their own right (Keeler et al. 2012; MEA, 2005).

2. Site heterogeneity in the relationship between STP and the delivery of ES

2.1. Crop yield

The relationship between STP and crop yield is usually described by a rapid increase in yield with modest increases in STP concentration, followed by a plateau in yield as STP concentrations further increase (**Fig. 1** and **2**). Typical soil P fertility advice advocates for achieving a critical STP concentration that translates to 95-98% of relative maximum yield; an agronomic optimum. However, despite decades of research relating STP concentrations to crop yield, STP concentrations do not always accurately predict the adequacy of soil P supply for optimum yield if factors such as soil type, soil pH, soil buffering capacity, crop rooting depth and the supply of other nutrients are not accounted for. For example, Schulte and Herlihy (2007) found that STP concentrations and fertilizer P applications explained on average 34% of the variation in yield and 73% of the variation in herbage P in 32 grassland sites representing eight different soil series. Furthermore, **Fig. 3** illustrates that more than half of UK study sites, as reported by Johnston et al. (2014) and Morris et al. (2017), actually require less than the recommended agronomic STP concentration for optimum wheat and barley yield. Clearly, advice based on STP interpretation could vary significantly without taking site specific factors into account.

2.2. P retention (water quality proxy)

The potential for P loss from land to fresh water (via surface runoff or sub-surface flow) increases linearly, or exponentially, with increasing STP concentration (**Fig. 4**). The relationship between soil P and P loss in runoff is a function of a soils ability to retain P, as determimed by its geochemical, biological and hydrological characteristics (Kleinman, 2017). For example, significant variation in P retention occurs due to differences in soil Al- and Fe-oxide concentrations, organic matter, pH, texture and redox potential in soil (e.g., Cade-Menum et al. 2017; Hart and Cornish, 2012), and in management systems that concentrate P at the soil surface (e.g., no-tillage, permanent grassland (Haygarth et al. 1998; Jarvie et al. 2017)). In general, the assumption has been that the potential for enhanced P loss to water occurs only above the agronomic optimum STP concentration, whereafter increased P saturation of binding sites in the soil (i.e. via adsorption & precipitation) results in progressively lower P retention and increased loss in runoff (Kleinman, 2017). However, increasingly it is being recognised that site specific factors, that impact on P retention, result in significant P loss to water even below the agronomic optimum STP level. For example soils low in P-sorbing Al- and Fe-oxides can desorb significant quantities of P in runoff even at low STP concentrations, whilst microbially catalysed mobilisation of P can also contribute to soil P loss (Glæsner et al. 2013). Furthermore, P loss can also occur at low soil STP due to wetting and drying cycles that mobilise Fe-bound P due to changes in redox potential (e.g., Cassidy et al. 2016; Scalenghe et al. 2002). McDowell et al. (2003) demonstrated that Olsen P thresholds in soils, required to protect water quality, ranged from 5-51 mg kg^{-1} in a number of different soil types in New Zealand. Hence, economic optimum STP concentrations to deliver ES relating to water quality, could be significantly different to agronomic optimum concentrations required for crop yield, if variation in P retention is not taken into account (e.g., Duncan et al. 2017).

2.3. Biodiversity

Severely impoverished ecosystems are characterised as having low biodiversity, which increases rapidly toward a plateau as soil P accumulates, beyond which biodiversity declines as more dominant species prevail (**Fig. 1**). For example, higher clover content in grass swards increases biodiversity and provides a crop quality response through improved protein concentration in the forage (**Fig. 2**). The precise relationship between STP level and species biodiversity is likely to vary depending on the particular plant species required. Ceulemans et al. (2014) examined the impact of soil P fertility on grassland biodiversity at 501 sites across Europe, and found that plant species richness was negatively correlated with STP (Olsen P) concentration. They observed a similar relationship between STP concentration, measured as Olsen P, and species richness in three categories of grassland: lowland hay meadows, calcareous grasslands and *Nardus* grasslands. However, the STP concentration (Olsen P) at which there was no further decline in species richness varied, with species richness stabilising at 12.5 species quatrat^{-1} at a STP concentration of 105 mg kg^{-1} in the Nardus grassland; 17.2 species quatrat^{-1} at a STP concentration of 128 mg kg^{-1} in the calcareous grassland; and 9.8 species quatrat^{-1} at a STP concentraton of 124 mg kg^{-1} in the lowland hay meadows (Ceulemans et al. 2014).

Dorrough et al. (2006) explored the interaction between extractable soil P, tree cover and livestock grazing on native and exotic plant species richness in central Victoria, Australia. The study highlighted that low levels of native plant species biodiversity were associated with high intensity grazing and fertilizer additions, whereas exotic species richness remained largely unchanged. Moreover, at low levels of STP, total species richness declined with increased grazing frequency (Dorrough et al. 2006). This highlights the importance of sustainable grazing practices, particularly at low STP levels, to deliver on native plant species biodiversity management. Therefore for robust soil fertility advice to account for biodiversity, regional if not local scale variation in plant species response may have to be considered.

Increased plant diversity, as part of intercropping in agriculture, has also been shown to increase yield productivity through organic-P mobilization. Organic-P stores in soil represent a substantial, untapped pool of P and crop species (such as legumes) that are capable of mobilizing such stores offer benefits to both themselves and to their interplanted species not capable of soil P-mobilization (Li et al. 2014). This highlights the exciting potential offered by exploiting plant functional traits for the dual benefits of soil fertility, P availability and improved use efficiency, as well as for ES delivery (Darch et al. 2018; Faucon et al. 2017). Soil microbial communities are also important drivers of soil ES linked to terrestrial biodiversity and crop productivity (van der Heijden et al. 2008) and control soil P cycling. STP concentrations can influence microbial biodiversity by altering the ratio of fungal to bacterial organisms in soils, and consequently mechanisms of nutrient capture and resilience to environmental stress (Cruz et al. 2009; de Fries and Shade, 2013). However, the heterogeneity in the relationships between STP and soil microbial diversity are poorly defined.

2.4. Soil C-sequestration

The P retention capacity of the soil, as discussed in section 2.2, can be considered a limiting factor for C-sequestration, where continued application of C-rich biosolids or manures is prohibited because of the increase in STP and greater risk of P loss to water. However, the relationship between STP and C-sequestration is more complex that just an environmental STP threshold limiting the application of C-sources. In general, the addition of P and nitrogen fertilizer to low P soils increases C-sequestration through enhanced crop production and return of P-rich biomass to the soil (Jones and Donnelly, 2004). The increase in C-sequestration is accelerated when transitioning from a cropping system that removes most plant biomass to one that removes a smaller portion and/or boosts yield. For example, declines in C-stocks as a result of the use of a continuous arable rotation (10% per 10 years) are ameliorated by the use of a regularly fertilized grassland ley (Bowman et al. 1990) or permanent pasture. However, increases in C-sequestration under any constantly-managed system (e.g. permanent pasture) plateaus as new limiting factors arise. Some authors even argue that in the long-term, subtly changing a constant system that does not focus on the limiting factor (or further limits it) can deplete C-stocks, particularly if P or nitrogen levels are limiting (Schipper et al. 2007). In a long-term study of manure addition to grassland, Fornara et al. (2016) demonstrated that the type and rate of organic fertilizer applied to grassland soil impacted upon C-sequestration, with cattle slurry containing higher concentrations of organic matter such as lignocelluloses, resulting in greater C-sequestration compared to other forms of livestock manure. Therefore, in contrast to the other ES discussed, STP concentrations may play a less significant role in C-sequestration compared to other limiting factors in productive agricultural systems. Nevertheless, Peñuelas et al. (2013) highlights that if projected future shortages of phosphate rock eventuates, crop growth and C-sequestration will be impaired, and in-turn atmospheric CO_2 concentrations and climate change.

3. Attributing economic value to ES influenced by STP concentration

Estimating the total economic value (TEV) of ES at farm-scale requires an assessment of the direct costs of their delivery, as well as to any value attributed to their environmental or cultural benefits (i.e sum of the direct, indirect and non-use values) (de Groot et al. 2010). However, obtaining this information on a farm-by-farm basis is not realistic, and a more pragmatic metric to assess the economic trade-off of ES related to soil fertility management is required. One such metric is the opportunity cost (i.e the benefits a farmer misses out on when choosing one option over another) of delivering a specific ES when compared to the potential profit (\$ ha^{-1}) for food production from the same area of land. In relation to nutrient management, a key and well established concept and tool for guiding fertilizer input costs for maximum crop yield is the *economic optimum (* i.e the yield at which further inputs to the system does not increase the \$ ha^{-1} profit a farmer will achieve) (e.g., Sylvester-Bradley and Kindred, 2009; Williams et al. 2007). In principle, this approach can also be applied to the impact of soil P fertility on a wide range of ES provided there is an ES response relative to changes in STP concentration.

The application of an economic optimum approach to the management of multiple ES is illustrated conceptually in **Fig. 1**: a hypothetic yield response curve, with profit (\$ ha^{-1}) as a function of STP (mg kg^{-1}): applicable to all STP tests. Braat & ten Brink (2008) presented the relationship between land-use intensity and multiple ES delivered by biodiversity, and similarly **Fig. 1** illustrates the theoretical relationship between STP and agronomic yield, P retention (water quality proxy), biodiversity and C-sequestration, with each ES functionality peaking at a hypothetical optimum or threshold STP concentration. In addition, **Fig. 1** presents a theoretical profit curve i.e \$ ha^{-1} profit per unit increase in STP that a farmer can achieve. This is calculated based on the additional profit a farmer can achieve when taking into account the cost of inputs (e.g fertilizer, lime, transport etc) and resulting commodity prices a farmer will receive post-harvest (note: while the curve types presented in **Fig. 1** are based on current understanding of the relationship between STP and each ES, the characteristics of these curves i.e. slope, magnitude, maximum etc, and position relative to the profit curve is hypothetical and will vary based on the factors outlined in section 2). For example in a livestock grazing system, restriction on manure application above a certain STP threshold, will result in a reduction in profits due to the requirement to transport manure off-farm to another location. This profit curve will be farm specific and vary depending on *inter alia* crop, soil, farm type and intensity. By locating the optimum STP, for the delivery of a specific ES, on the profit curve, the opportunity cost to the farmer can be estimated. While this does not provide the TEV of delivering a specific ES, it does provide a suitable common unit of measure to faciliate comparison and trade-offs between ES delivery across spatial (\$ ha^{-1}) and temporal (\$ ha^{-1} yr^{-1}) scales in the context of P fertility advice being provided to farmers, and the wider industry goals of sustainable P use. The hypothetical curves for all four ES metrics, depicted in **Fig. 1**, will vary spatially and temporally depending on *inter alia* soil type, soil health, farming intensity, farm inputs, landscape characteristics, legacy soil P and seasonal influences on the interactions between soil, crop and environment; there is a research need to model such interactions across spatio-temporal scales.

An example, depicted in **Fig. 2** shows long-term fertilizer field trial data under irrigation for pasture production at Winchmore, mid-Canterbury, New Zealand. A grassland case-study was selected as it incorporates data for the delivery of our four key ES impacted by soil P fertility. The trial was located on a Lismore stony silt loam soil; mean annual rainfall of 745 mm (Smith et al. 2012). After normalising the indicators a farmer may set an objective in STP concentration to achieve 98% of relative yield (often seen as an agronomic optimum), which equates to an STP concentration of 20 mg kg^{-1} or greater (**Fig. 2**). Whereas a STP concentration of approximately 15 mg kg^{-1} or less may be considered the STP target for meeting water quality objectives. No profit curve is available for the study in **Fig. 2**, so instead, by away of example, if the values of 20 mg kg^{-1} and 15 mg kg^{-1} are extrapolated from the x-axis to hypothetical profit curve in **Fig. 1**, the 5 mg kg^{-1} reduction in STP would result in an approximately a 28% reduction in \$ ha^{-1} the farmer can achieve. In this example, similar trade-offs can be made for % carbon and % clover (as proxy for biodiversity in this particular pasture based system) and the resulting opportunity costs traded between stakeholders or payments made to farmers to incentivise or compensate for reductions in profit margins. Note that, in this example, clover (comprising white, Montgomery red and subterranean species - Mt. Barker and Tallarook) was selected as a surrogate for desired species, which supports nitrogen-fixation, and increased ryegrass production. The conceptual model proposed in this paper is applicable to all cropping systems and is also inclusive of extensive enterprises. Of note is that differing crop species will have different STP requirements, and the STP concentration appropriate for multiple ES delivery will be depend on the species being cultivated or the management regime being implemented.

4. Barriers and actions for change

Implementing an economic optimum approach to STP mamagement, that optimises the delivery of multiple ES, will require significant changes to current soil sampling and testing procedures, interpretation guidance, and management of inorganic and organic P inputs. Many of the barriers and actions required to meet a desired outcome are listed in **Table 1**. A central tenet to change is the calibration and integration of existing soil test procedures for multiple ES delivery, thus moving current P fertility advice beyond maximum yield and/or quality, and '*insurance*' level applications. Adaptations to deliver increased soil data resolution, by incorporating subsoil sampling at depth in the soil profile, coupled with expanded sampling efforts in critical source areas and improved temporal resolution, would help to reduce uncertaincy and improve predictions in actual and modeled systems. Sampling the subsoil at depth will enhance understanding of soil P cycling, storage and loss potential beyond the rooting zone. Incorporation of soil P buffering capacity metrics to better define soil P release offers dual benefits in terms of improved precision on fertilizer inputs for crop uptake and yield (for example, Fischer et al. 2017; van Rotterdam et al. 2013). A study by Burkitt et al. (2002), emphasises the value of adopting a simple soil buffering capacity index as a standard soil test parameter to determine plant P bioavailability in Australian soils; benefits included increased accuracy in P fertilizer recommendations and use efficiency, thus maintaining yield and mitigating against P losses.

Enhanced understanding regarding the impacts of STP on all ES in terms of spatio-temporal scales (Bennett et al. 2005; Qui and Turner, 2013), and knowledge exchange between key agri-food stakeholders to this effect, are imperative to improving soil test interpretation for the delivery of precision P fertility advice. The management and governance of ES tends to occur at multiple scales ranging from the field and farm scale, to sub-watershed and watershed based initiatives, to regional and global strategies such as the United Nations Sustainable Development Goals (Qiu et al. 2018; U.N. 2015). The conceptual model proposed in **Fig. 1** is predominantly a farm-scale tool designed to inform field scale management decisions, but is also applicable at the regional scale in relation to informing trade-offs between food production and environmental objectives. It could be used to guide where sustainable intensification should occur, or to identify farming enterprises that ought to be economically supported to deliver on supporting, regulating and cultural ES, as dictated by landscape characteristics (Qiu et al. 2018). However, as noted by Melland et al. (2018), policy makers must recognise that long-term investment is required in strategies, such as soil P fertility management for ES delivery, were it can take up to 20 years or more to detect improvement in water quality due to lag and legacy effects. The robustness of hypothetical curves presented in **Fig. 1** should also be modelled to account for additional factors such as climatic extremes.

Inorganic fertilizers are currently used for yield response and most are highly water soluble, and vulnerable to loss (Hart et al. 2004). Exploring the bioavailability and nutrient retention capacities of alternative inorganic and organic fertilizer sources remains a priority area in relation to ES delivery. Furthermore, precision farming techniques, such as variable rate application technologies, novel fertilizers, P placement and foliar P applications offer targeted P applications that link more precisely to variation in soil P supply and crop requirement, therefore also reducing the risk of P loss to water (McLaughlin et al. 2012; Withers et al. 2014). Crop type, rotations and intercropping also offer scope for ES delivery through the identification of varieties or cultivars that are P efficient or capable of mobilizing organic-P legacy stores (Li et al. 2014; Rowe et al. 2015; Simpson et al. 2014; Vance et al. 2003). Adaptations to current soil P fertility management protocols to account for all ES requirements can be simple, such as modifying sampling depths to better estimate P loss or C-sequestration, or complex such as refining fertilizer advice based on profit and linking to other ES functions. Existing soil P tests require reform to take account of biological functioning for biodiversity, or to simultaneously predict crop yield and the risk of P loss in runoff (Fischer et al. 2017; Rubæk, 2015). Furthermore, new innovative technologies such as diffusive gradients in thin films (DGT) may offer improved data resolution and bioavailability assessment of soil chemical fluxes in some circumstances (Blackburn et al. 2016; Zhang and Davison. 2015).

Measurements of both ES and STP vary spatio-temporally (Bennett et al. 2005). Such variation will always challenge the interpretation of ES indicators and STP concentrations. For example, Jordan-Meille et al. (2012) noted that current European fertilizer recommendation systems do not generally take account of soil type differences in P supply, nor localised environmental pressures that might constrain P use. Through the concept of Functional Land Management, Schulte et al. (2014) highlighted the importance of understanding and managing for specific soil function, if society is to achieve the objective of deliverying multiple ES from agricultural landscapes. Soil fertility and function are intricately linked and consequently many on-farm practices need to be modified to take account of the spatial and temporal variability in soil and landscape characteristics that define which suite of ES are best delivered in different land parcels.

More research on the measurement of ES indicators and soil testing protocols for STP measurement will improve their accuracy and precision. However, due to spatial and temporal variation, advice on current tests and indicators needs to be calibrated at a local (e.g. on a field-by-field basis) or regional scale (e.g. on a watershed level) and over a long-enough time period so that relationships between ES and STP measurements become statistically robust (Costanza et al. 1997; de Groot et al. 2012). Not only will accounting for spatio-temporal variation ensure that robust soil P fertility advice is given to inform stakeholder decisions, estimates of P application rates could be tallied against national strategies for ES delivery. Nevertheless, the costs associated with such advances to increase data resolution and precision, reduce uncertainty, and account for landscape heterogeneity in terms of ES delivery (Mitchell et al. 2015; Spake et al. 2017), will be challenging in practical terms and the potential for modelled systems must be assessed to deliver on cost-effectiveness (Costanza et al. 2017).

A large number of agronomic trials have been carried out across a range of soil type and geoclimatic zones, and form the basis of current P fertility advice in many countries (Bai et al. 2013; Syers et al. 2008; Valkama et al. 2011). Some studies have also examined the relationship between STP and water quality (McDowell et al. 2003; Vadas et al. 2005; Withers et al. 2017), and to a lesser extent C-sequestration and biodiversity (Ceulemans et al. 2014). Individual studies with good data resolution enable the determination of the economic optimum STP for the delivery of each ES, but only over a limited range of conditions. In order to implement this approach to P fertility management, the relationships between ES, STP and \$ ha^{-1}, need to be transferred over a wide geographical area, and on to farms where data availability, resources and logistics constrain the direct valuation of ES on a site-specific basis. However, biophysical models describing the physical, chemical and biological P dynamics and interactions in soils, the numerous factors affecting these dynamics, and their relationship to ES delivery are generally poorly developed and disjointed (Vereecken et al. 2016). Detailed mechanistic mathematical models are being developed to help refine fertilizer P inputs (e.g., Heppell et al. 2016), and more simplified one/two soil P compartment models have been used to predict residual soil P supply (e.g., Sattari et al. 2012), but these models currently lack the capability to include synergistic P capture afforded by innate plant P mechanisms for mobilising soil P or sequestering C (Mollier et al. 2008). If an STP economic optimum approach to the management of ES is to be implemented, further progress in biophysical modelling of soil P dynamics is urgently needed to inform this implementation across diverse landscapes.

5. Conclusions

National and international strategies have established ambitious objectives for the delivery of multiple ES within the context of agriculture against a backdrop of sustainable intensification. However, the practicality of balancing the trade-offs between these ES at the farm-scale has not yet been adequately addressed. While this paper has focused on P fertility management, we acknowledge that a wide range of farm practices and biophysical variables are involved in the delivery of multiple ES in agricultural systems. Changes to many other farm practices, that influence the delivery of ES, also warrant attention. Although soil P fertility is only one contributing factor in ES delivery, effective nutrient management is integral to the success of such strategies and sustainable farming. However, there is currently no operational framework in place to manage P fertility for multiple ES and to identify the costs of potentially sacrificing crop yield and/or quality. We propose the use of an economic optimum approach to P fertility management by which different ES can be assessed and traded against one another. This approach facilitates the monetisation of ES strategy at the farm-scale through evaluation of their impact on farm profits. The approach accounts for both local level variation in biophysical varaibles, and farm performance, to ensure temporal robustness. This can then be benchmarked against regional or national strategy to facilitate stakeholder engagement and negotiations. A key step in the adoption of our conceptual framework into policy is to produce and collate datasets, and case-study examples that demonstrate the curves depicted in **Fig. 1** over a wide range of conditions and farming enterprises. How such an approach can be incorporated into existing frameworks of Payment for ES is an area warranting further consideration.

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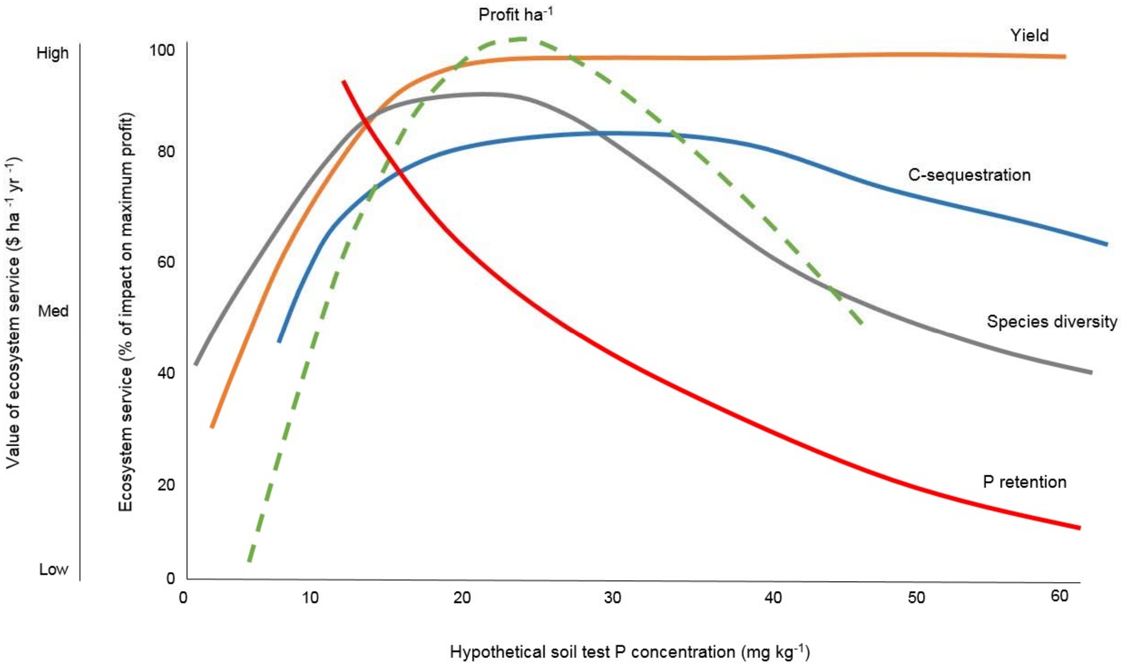

Fig. 1. Hypothetical relationship between different ES (yield [orange line], species diversity [grey line], C-sequestration [blue line] and P retention (a proxy for water quality) [red line]), and profit ha^{-1} [green dashed line], presented as a relative impact on potential profit and STP concentration.

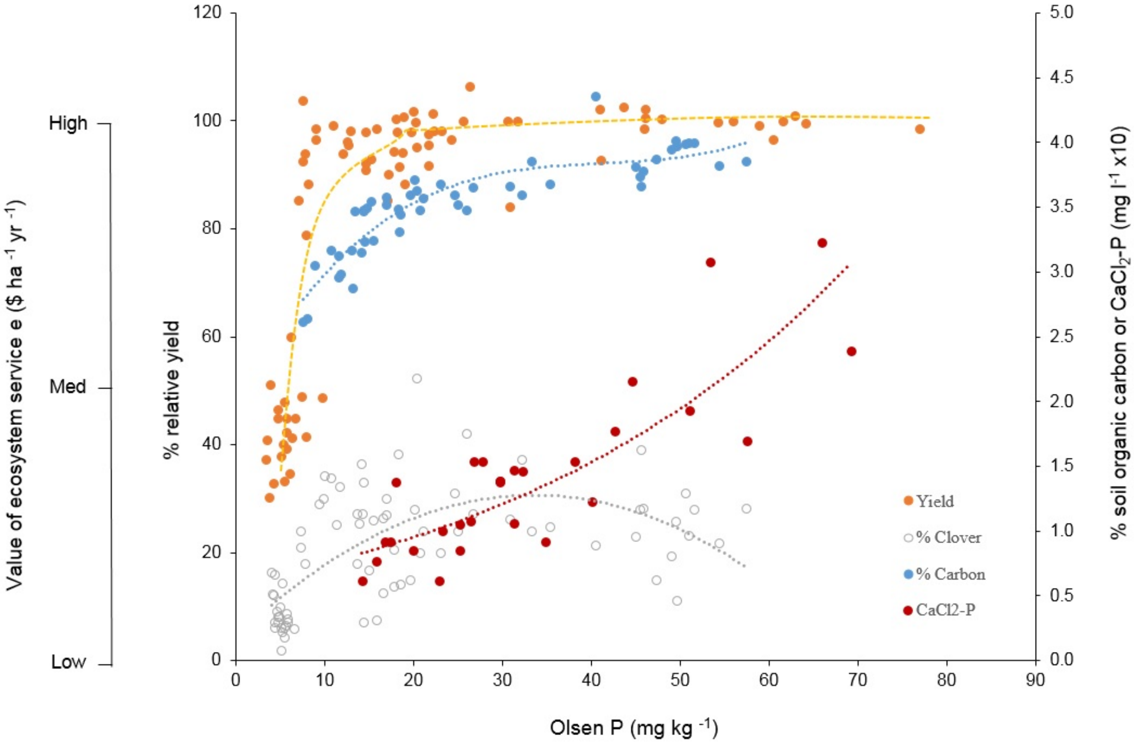

Fig. 2. Long-term fertilizer field trial data under irrigation at Winchmore, mid-Canterbury, New Zealand (from Condron et al. 2012; McDowell and Condron, 2012; Rickard and McBride, 1986) shows pasture yield production, the potential for P loss in subsurface drainage (as estimated by 0.01M $CaCl_2$-P), plant species richness (as % clover comprising white, Montgomery red and subterranean species (Mt. Barker and Tallarook)), C-sequestration rates (as % org C) and STP measured as Olsen P concentration.

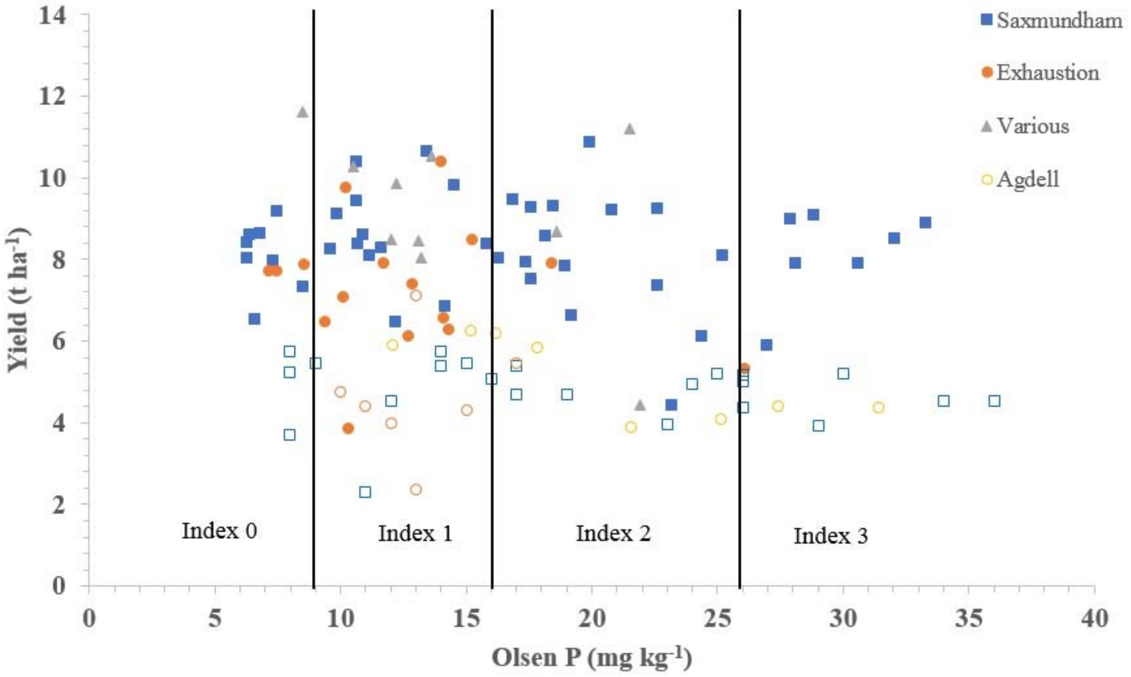

Fig. 3. Critical STP (Olsen P) concentrations for 98% of maximum yield vary widely across different sites, different seasons and when insufficient nitrogen is applied. Data are from UK sites reported by Johnston et al. 2014 and Morris et al. 2017. (Closed symbols represent wheat and open symbols barley). Over 50% of sites require less than the recommended STP for optimum yield, reflecting the current insurance-based approach to soil P fertility management. (Index 0 to 3 represents soil classification indices based on Olsen P as follows: Index 0: 0-9 mg l^{-1}; Index 1: 10-15 mg l^{-1}; Index 2 (2- and 2+): 16-25 mg l^{-1}; Index 3: 26-45 mg l^{-1}). The currently recommended range in the UK is Index 2.

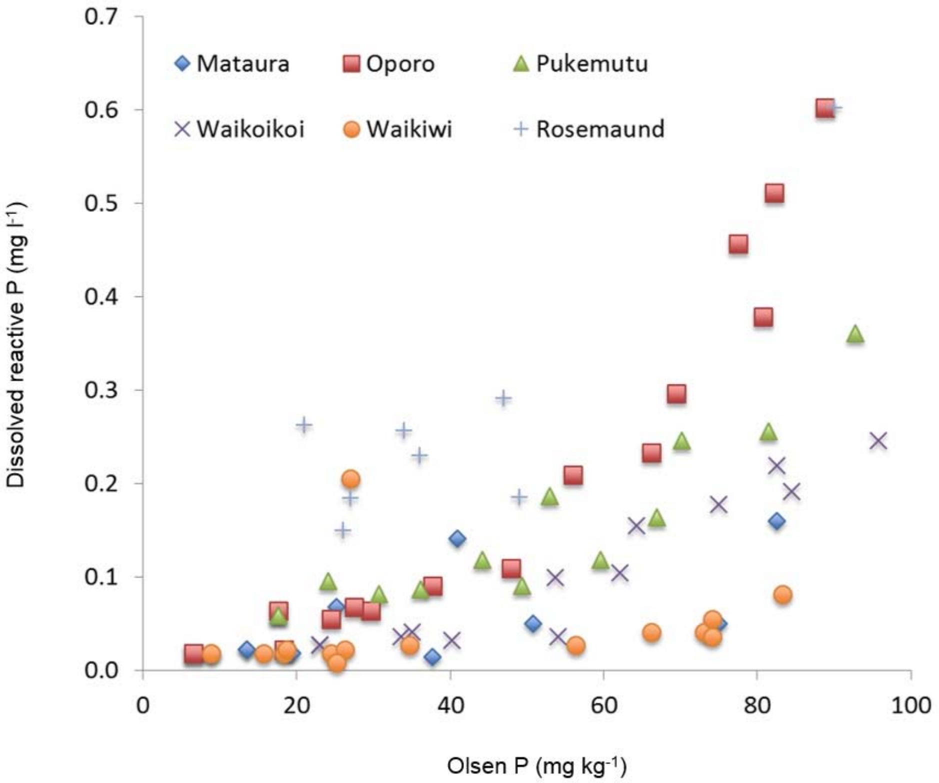

Fig. 4. Variation in the concentrations of dissolved reactive P (DRP) with increasing STP (Olsen P) across six sites, in New Zealand, of varying soil P soprtion capacity from very low (Rosemaund) to high (Waikiwi). Data are from McDowell et al. 2003.

Table 1. Barriers and actions required to achieve outcomes for P fertility management for multiple ES delivery.

Factor	Barriers	Action	Outcome
Soil Test	• Current soil tests only calibrated for crop yield response • Large number of different soil tests used in different regions • Lack of precision leads to large variability in results and uncertainty	• Improve exisiting soil tests or develop new tests that are calibrated for other ES (e.g. include P buffering capacity, capacity for biological turnover)	Specific soil tests identified for different ES delivery calibrated back to STP for yield for trade-off analysis
Soil Sampling	• Only partially linked to system management (e.g. single sampling depth) • No separate sampling of field runoff zones (e.g. for assessing critical source areas for eutrophication control management) • Timing linked to crop cycles only (e.g. infrequent rotational sampling)	• Upgrade sampling precision to fit system management (e.g. stratified or gridded sampling) • Adjust sampling regime according to site conditions and ES delivery (e.g. timing of sampling may differ for different ES)	Specific guidelines on sampling resolution, timing and depth to match different management systems and ES delivery
Interpretation of Soil Test Results	• Interpretation varies across regions and confounded by lack of site specific information • Lack of understanding about the impacts of STP on other ES (e.g. for soil biodiversity or C-sequestration)	• Change from agronomic optimum to economic optimum approach (e.g lower critical STP levels) • Generate data to support nutrient decisions for delivery of ES other than crop productivity • Precision based fertilizer recommendations moving beyond current '*insurance-based*' approaches	On-farm decision support tools deliver improved precision in optimizing nutrient inputs for ES delivery
Fertilizer Source	• Historic preference for using inorganic fertilisers for yield response • Lack of confidence in nutrient value of different bioresources • Lack of data on effect of fertilizer source on ES delivery	• Identify appropriate fertilizer sources to match ES delivery (e.g. bioresources for C-sequestration) • Develop improved database on bioresource bioavailability (e.g. struvite) • Develop tools to assess temporal variability in bioresource nutrient bioavailability • Optimize fertilizer advice based on profit ha^{-1}	Use of recycled and recovered P optimized and improved prediction of source bioavailability for different ES functions
Fertilizer Placement/Timing	• Timing of P inputs not geared to critical source areas (e.g. single application timing) • Lack of data on effect of source timing on other ES • Farming infrastructure not geared to precision targeting of P (e.g. placement)	• Advance precision farming technologies (e.g. to support variable rate application as routine) • Develop decision support technologies to provide farmers with real time information on soil and crop nutrient supply • Improve nutrient use efficiencies and profit ha^{-1}	Targeted P application to optimize P use efficiency to improve yield and reduce risk of P loss to water

Crop type	• Crop type used only for P inputs to match crop P offtake • Varietal variation in soil P acquisition and utilization efficiency largely unexplored • Lack of data on crop rotation sequences to optimize ES delivery	• Explore impact of soil-crop-fertilizer interactions on ES delivery (e.g. optimizing rhizosphere processes) • Identify P efficient varieties as part of agro-engineering	Guidelines on crop type and crop rotation design for optimizing delivery of different ES