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PERSPECTIVE

Integrating legacy soil phosphorus into sustainable nutrient management strategies for future food, bioenergy and water security

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Abstract Legacy phosphorus (P) that has accumulated in soils from past inputs of fertilizers and manures is a large secondary global source of P that could substitute manufactured fertilizers, help preserve critical reserves of finite phosphate rock to ensure future food and bioenergy supply, and gradually improve water quality. We explore the issues and management options to better utilize legacy soil P and conclude that it represents a valuable and largely accessible P resource. The future value and period over which legacy soil P can be accessed depends on the amount present and its distribution, its availability to crops and rates of drawdown determined by the cropping system. Full exploitation of legacy P requires a transition to a more holistic system approach to nutrient management based on technological advances in precision farming, plant breeding and microbial engineering together with a greater reliance on recovered and recycled P. We propose the term 'agro-engineering' to encompass this integrated

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approach. Smaller targeted applications of fertilizer P may still be needed to optimize crop yields where legacy soil P cannot fully meet crop demands. Farm profitability margins, the need to recycle animal manures and the extent of local eutrophication problems will dictate when, where and how quickly legacy P is best exploited. Based on our analysis, we outline the stages and drivers in a transition to the full utilization of legacy soil P as part of more sustainable regional and global nutrient management.

Keywords Legacy phosphorus · Sustainable nutrient management · Crop production · Phosphate rock · P use efficiency · P recycling · Eutrophication

Introduction

Phosphorus (P) is an essential element for food and bioenergy production and a critical resource for global and regional food security, but it is not being used sustainably. Poor utilization of P in the food chain, and over-application of fertilizer P in intensive crop and animal production systems, has increased pressure on finite global reserves of phosphate rock (PR), and led to widespread eutrophication of inland and coastal waters (Elser and Bennett 2011; Chowdhury et al. 2014). Imports of manufactured PR-based fertilizers are also an expensive input into modern farming systems and further price increases are likely (Elser et al. 2014). Improved stewardship of P based on five key R strategies (5R) has been proposed to address these issues: **R**ealign P inputs more precisely to maximise efficiency, **R**educe P losses to the oceans, **R**ecycle more P in bioresources, **R**ecover and reuse P from wastes and **R**edefine P requirements in the food chain (Withers et al. 2015). This transition towards greater P sustainability will require a paradigm shift in current philosophies of nutrient management and attitudes towards food and bioenergy production (Gomiero et al. 2011; Withers et al. 2014; Jarvie et al. 2015).

One option (‘Realign’) to reduce dependence on fertilizer P imports is to improve the utilization of the large reserve of residual P present in soils left behind by past excess applications of inorganic fertilizers, animal manures, and biosolids. This accumulation of past P surpluses in soil represents a substantial secondary P resource that could potentially substitute for primary inputs of inorganic P fertilizers, with a large cumulative global influence (Sattari et al. 2012). For example, Rubaek et al. (2013) estimated that Danish agricultural soils had accumulated an average of 2.3 Mg P ha^{-1} to 75 cm depth since 1900 amounting to ca. 6 Tg. Ringeval et al. (2014) estimated that over 80 % of the total P in French soils is associated with past P inputs (equivalent to ca. 65 Tg). Withers et al. (2001) estimated that UK soils had accumulated over 1 Mg ha^{-1} of surplus P since the 1930s amounting to a total legacy P resource of ca. 12 Tg of P. In China, an average of 242 kg P ha^{-1} has accumulated in intensively farmed arable soils between 1980 and 2007 amounting to over 31 Tg of P (Li et al. 2011). Maximising the re-use of these legacy soil P resources requires information on where and in what form they are distributed, when they should be used, and how they can be accessed efficiently. Not all legacy soil P may be readily available to crops due to the variable capacity of soils to immobilise P into plant-inaccessible forms, depending on soil mineralogy and pH (Shen et al. 2011; Barrow and Debnath 2014), or due to migration to lower soil depths (e.g. Rubaek et al. 2013).

A more immediate environmental concern is that legacy P in soils is a continuous source of soluble and particulate P to water every time rainfall generates land runoff (Carpenter 2005). Typical and relatively small annual catchment losses of P (e.g. <1 to 7 kg P ha^{-1}, Alvarez-Cobelas et al. 2009) collectively represent a global threat to water quality, biodiversity and human health (Smith and Schindler 2009; Rabalais et al. 2010). Bennett et al. (2001) argued that agricultural intensification and clean water supplies are incompatible unless the continued accumulation of P in the soil is abated. In some areas, such as the Chesapeake Bay on the US East Coast, legacy soil P has been recognised as a distinct and major source of eutrophication problems affecting drinking water quality, fisheries, and the incidence of harmful algal blooms (Staver and Brinsfield 2001). Sharpley et al. (2013) recently provided a number of other examples where legacy P in soils and river and lake sediments is delaying the restoration of eutrophied waters. Linkages between legacy P and the enrichment of ground water are a particular concern because ground waters continually contribute nutrients to river baseflows (McDowell et al. 2015).

Legacy soil P is therefore a valuable resource but is also a pollutant. Strategies to utilize legacy soil P consequently have dual long-term benefits and represent a key sustainability goal, but are also a challenge for land managers. In this paper we consider how legacy soil P could be better exploited for economic, resource and environmental gains. Our specific objectives are to: (1) review the nature and availability of legacy soil P for reuse by crops; (2) assess the primary management options to exploit legacy soil P, including soil P drawdown and developing more P-sustainable cropping systems; and (3) discuss the issues and levers for facilitating uptake of these management options.

Understanding legacy P in soils

A global resource

Legacy soil P is defined here as the cumulative P that has been added to soils in fertilizers and manures since they were first cultivated, minus P removed in harvested crops and in run-off through erosion and leaching. In concept it is similar to the residual P estimated through soil-crop modelling by Sattari et al. (2012), and can be measured as the increase in total P over time as agriculture has intensified in many regions (Fig. 1a). A recent meta-analysis of uncultivated sites with agricultural land-use histories showed persistent elevation of soil P across several regions and soil types compared to nearby areas that were never cultivated (MacDonald et al. 2012). For example, over 50 % of the P added since 1952 to a grazed pasture soil in New Zealand was retained as legacy P in the soil (McDowell and Condron 2012). Over 80 % of fertilizer P applied to continuous barley on sandy soils over 51 years in the UK was retained by the soil (Blake et al. 2003). In a tropical savannah soil in Brazil, 40 % of the P applied over 45 years of cultivation remained in the soil (Agbenin and Goladi 1998).

Data compiled by Sattari et al. (2012) suggest global accumulation of legacy P in soil between 1965 and 2007 averaged ca. 550 kg P ha^{-1}, amounting to 815 Tg of P. Compared to the amounts of P fertilizer currently used (ca. 20 Tg P year^{-1}), and projected global crop demand for P up to 2050 (ca. 18 Tg P year^{-1}), legacy soil P could theoretically substitute for a large fraction of P fertilizer use globally, meeting crop P demands for approximately 9–22 years depending on the scenarios for its availability (Table 1). However, regional estimates of legacy soil P varied from 160 kg P ha^{-1} in Africa, where access to affordable soluble inorganic P fertilizers and organic P sources has been very limited (Nziguheba et al. 2015), to 1115 kg P ha^{-1} in Western Europe where P fertilizers have been historically liberally applied (Table 1). Similarly, MacDonald and Bennett (2009) found vast differences in the cumulative net-P inputs to cropland soils across sub-catchments of the St Lawrence River basin of north-eastern North America (ranging from −1 to 1200 kg P ha^{-1}), reflecting changes in nutrient management and livestock densities over the last century. Stocks of legacy soil P are therefore substantial, but are spatially heterogeneous at the regional scale and require long-term datasets to accurately quantify.

Forms and availability

Although fertilizer P typically enters the soil in predominantly soluble inorganic forms (Pi), it may not all be readily available for subsequent uptake by crops due to its rapid immobilization by sorption onto soil mineral (clay, Fe, Al, Ca) surfaces, or by incorporation into soil organic matter (SOM) complexes (Frossard et al. 2000; Shen et al. 2011). Fertilizer and manure inputs are therefore retained in soils in a continuum of P availabilities (Fig. 1b): ranging from highly labile P forms (i.e. weakly sorbed and rapidly mineralized P) that readily diffuse into the soil solution, to more strongly sorbed and moderately labile P forms that help to maintain reserves of fully labile P as they become depleted through crop uptake, to non-labile stable P forms (e.g., occluded complexes with SOM and in primary minerals) that must be mobilized into solution by microbial and plant root exudates in the rhizosphere (Negassa and Leinweber 2009; Johnston et al. 2014).

A small proportion of legacy soil P (typically <15 %) is regularly quantified by a large range of different soil P tests (soil test P, STP) that have been calibrated to predict the likelihood of a crop response to applied P. Critical concentrations of STP have been identified for different soil-crop combinations to guide decisions on fertilizer use at the field scale and to ensure that crops do not run short of P during their short growing seasons (Dodd and Mallarino 2005; Bai et al. 2013; Johnston et al. 2014). STP is therefore considered to be part of the labile P in soils, and the amount extracted depends on the soil test used (Beegle

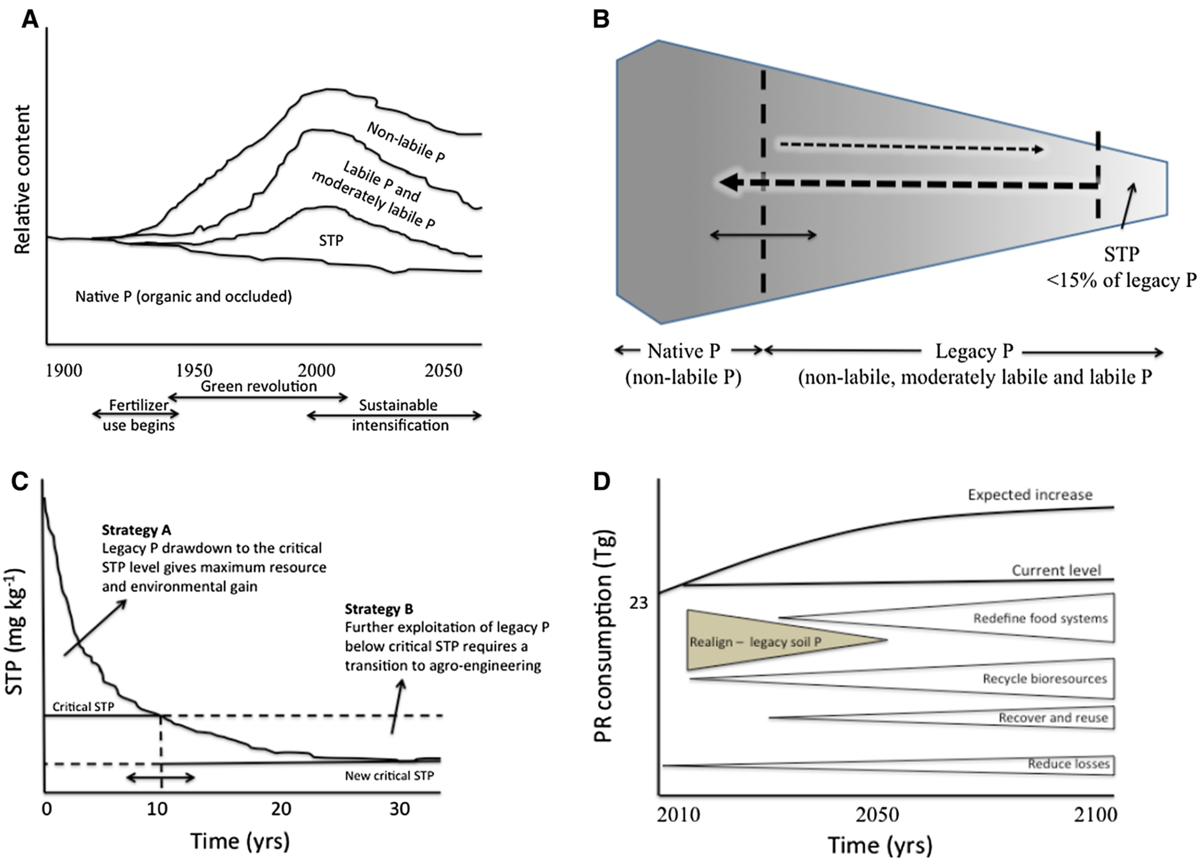

Fig. 1 Understanding legacy soil P concepts. **a** The evolution of legacy P and its distribution as soil test P (STP), labile and moderately-labile P and non-labile P over time in response to past and future policy drivers (adapted from Walker and Syers 1976); **b** relative content and distribution of native and legacy P in the soil: soil P exists in a continuum of availability ranging from highly labile (*light grey*) to non-labile (*dark grey*) whose dynamics are dominated by sorption diffusion pathways (*thick dotted arrow*). STP must decline to allow P to diffuse out of legacy P storage into solution (*thin dotted arrow*), (adapted from Withers et al. 2014); **c** withdrawal strategies to reduce legacy P in relation to the trajectory of STP decline and a critical STP concentration; **d** a wedge diagram showing the conceptualized relative contribution of legacy P utilization to reduced phosphate rock (PR) consumption to 2100 in relation to other 5R strategies (Withers et al. 2015). The legacy soil P wedge is a shorter-term option that would allow substitution of primary fertilizer P for a few decades before other 5R options become fully operational

2005; Jordan-Meille et al. 2012). However, critical STP concentrations have been greatly exceeded in many areas, either due to overuse of fertilizers, or due to high manure P loadings in areas with high livestock densities (MacDonald et al. 2011; Tóth et al. 2014). In these areas with excessive STP, the release of soil P to surface and sub-surface runoff, and therefore eutrophication risk, is greatly increased (Maguire et al. 2005). A key priority for eutrophication control is to reduce STP concentrations down to the agronomically critical level or below (Fig. 1c).

Three categories of legacy soil P can therefore be distinguished from a management perspective: STP that currently guides fertilizer P inputs on farms, labile and moderately labile P that is potentially accessible to crops, and non-labile P, which is released into soil solution too slowly to reliably meet crop needs (Fig. 1a). The relative proportions of these forms will vary depending on soil type (parent material and degree of pedogenesis) and soil pH, the amount and nature of P inputs, and land use history (Negassa and Leinweber 2009; MacDonald et al. 2012). For example, highly weathered, acidic soils with high Fe and Al will bind inorganic P much more strongly than young base-rich temperate soils and therefore be less accessible to plants (Tiessen et al. 1984). Furthermore, the

Table 1 Global and regional estimates of legacy soil P in relation to current and future crop demand and fertilizer use up to 2050 and the potential years of crop P supply according to two scenarios of soil P availability

Region	Legacy soil P[a] 1965–2007 Tg (kg ha^{-1})	Crop demand[a] 2007 Tg (kg ha^{-1})	Crop demand[a] 2050 Tg (kg ha^{-1})	Fertilizer P use[b] 2012 Tg (kg ha^{-1})	Years of crop P supply (20 %)[c] 2008–2050 %	Years of crop P supply (50 %)[c] 2008–2050 %
Western Europe	105 (1115)	0.93 (9.9)	0.98 (10.4)	0.93 (9.9)	21	54
Eastern Europe	86 (430)	0.78 (3.9)	0.88 (4.4)	0.69 (3.4)	20	49
North America	105 (465)	1.98 (8.8)	2.86 (12.7)	2.06 (9.1)	7	18
Latin America	82 (480)	1.51 (8.9)	2.24 (13.2)	2.66 (15.7)	7	18
Asia	373 (690)	5.41 (10.0)	8.55 (15.8)	12.73 (23.5)	9	22
Africa	40 (160)	0.77 (3.1)	2.05 (8.3)	0.61 (2.5)	4	10
Oceania	26 (560)	0.12 (2.5)	0.30 (6.5)	0.58 (12.6)	17	43
World	815 (550)	11.5 (7.6)	17.9 (11.8)	20.3 (13.3)	9	22

[a] Sattari et al. (2012)

[b] FAOSTAT (2015)

[c] The number of years legacy soil P (1965–2007) would meet the annual crop demand (2008–2050) if 20 or 50 % of that legacy P was plant available. 20 % of legacy soil P amounts to 163 Tg of P and 50 % of legacy soil P amounts to 408 Tg of P

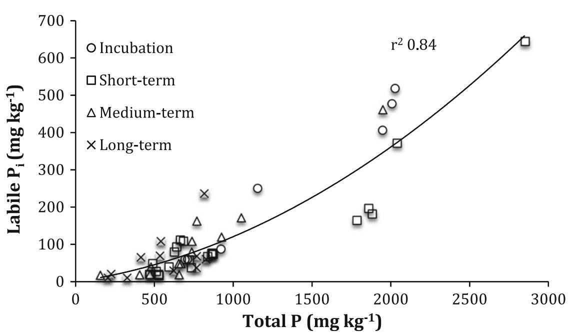

Fig. 2 Examples of the preferential accumulation of labile inorganic P (Pi) as total P increases in temperate soils due to inputs of fertilizers and manures over time. A meta-analysis of 20 short, medium and long-term experiments compiled by Negassa and Leinweber (2009), where labile Pi was measured as the sum of resin + bicarbonate Pi and represents P that is weakly adsorbed to clays and secondary Fe, Al, and Ca compound surfaces, and becomes plant-available because it readily exchanges with other anions (Shen et al. 2011)

addition of manures or lime, and adoption of no-till agriculture can lead to an increase in organic P forms, and/or a higher proportion of calcium-stabilized P as soil pH rises (Sharpley et al. 2004; Condron and Goh 1989; Rodrigues et al. 2015).

There is compelling evidence of preferential accumulation of fully labile Pi in temperate soils where legacy P stocks are greatest (Fig. 2), but this can differ in tropical soils. Studies using sequential soil P fractionation schemes and spectroscopic analysis to investigate P forms in soil have concluded that legacy soil P has accumulated as labile and moderately labile inorganic P (Pi) in temperate soils, and as moderately labile and non-labile Pi in tropical soils (Beauchemin et al. 2003; Blake et al. 2003; McDowell et al. 2005; Negassa and Leinweber 2009; Bai et al. 2013; Rodrigues et al. 2015). This preferential accumulation of Pi in temperate soils has led to large increases in STP and has recently been attributed to the blocking of P immobilization pathways when P sorption sites become more and more negatively charged as they saturate with phosphate (PO_4^{3-}) (Barrow and Debnath 2014).

It can be concluded that a significant but variable proportion of legacy soil P occurs in forms that are potentially available for crop uptake, especially in temperate soils. The accessibility and successful exploitation of labile legacy soil P will consequently depend on its distribution across agricultural landscapes and regions, the type of farming system and its P demand as well as the socio-economic conditions necessary to enable the necessary changes in management on the farm (Fig. 3).

Management options to exploit legacy P

Legacy P is a valuable resource only if it can be sustainably used without loss in crop productivity.

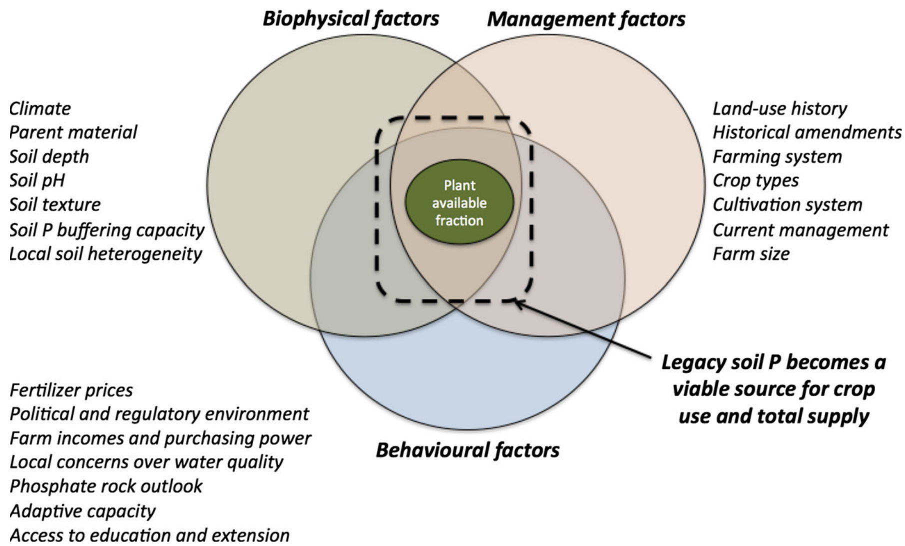

Fig. 3 Legacy soil P becomes a viable source for crops when biophysical, management and behavioural conditions become aligned. Driving factors that might influence this alignment are also shown

This in turn raises questions over how long it can be utilized and under what circumstances must legacy P be augmented by new P fertilizer use? Local eutrophication issues may, in particular, dictate the timeframe of legacy P utilization on farms. Our current understanding of P dynamics in soils suggests there are two main strategies for utilizing legacy P: by (A) simply withholding part or all P fertilizer until soil P fertility has been reduced to the agronomically critical STP level, and (B) developing more sustainable cropping systems that enable optimal production at further reduced (i.e. low) STP levels through efficiency gains in soil P acquisition and crop P utilization. These two strategies can be linked to the form of legacy soil P in that strategy A exploits the more labile forms of legacy soil P, while strategy B seeks to mobilize total legacy soil P stocks including more recalcitrant forms (Fig. 1c). Strategy B is also relevant to the acquisition of native non-labile P in soils. The potential stages, research requirements and practical innovations required for the progression from strategy A to strategy B are outlined in Fig. 4.

Strategy A: Drawdown of STP

The preferential accumulation of STP and other labile forms of legacy P in fertilized soils appears to be largely reversible suggesting it is an accessible resource. This is borne out by many studies investigating crop P uptake rates on P-rich soils in the absence of fresh fertilizer (e.g. Delgado and Torrent 1997; Gallet et al. 2003a, b), and changes in P forms in soils from long-term experiments where P has been added for long periods and then withheld for long periods (e.g. McCollum 1991; Blake et al. 2003); some example data are shown in Table 2. These studies show that: (1) legacy P can generally support adequate crop yields on many soils for periods of up to 10 years or more; (2) 60–70 % of the decrease in labile Pi in unfertilized soils can be accounted for by crop uptake; (3) conversion of P from moderately labile forms (e.g. NaOH-extractable P) to labile Pi occurs actively and is pH dependent; and (4) migration of P from non-labile stable P forms can still supply small amounts of P when labile Pi is exhausted. The depletion of organic P occurs more in soils with limited labile Pi (Agbenin and Goladi 1998; Blake et al. 2003; Gallet et al. 2003a; Negassa and Leinweber 2009). How quickly labile Pi falls depends primarily on rates of crop P removal (Schulte et al. 2010), which will vary seasonally, according to the rate of N applied and whether the whole crop, or just the seed, is harvested. Values of P offtake for different crop types can differ by an order of magnitude from <10 to >100 kg ha^{-1} (Delorme et al. 2000; Sharma et al. 2009). For example Gallet et al. (2003b) found that the P demand of white clover was 30–90 % greater than that of ryegrass across three different soils and depleted legacy P more quickly. Modern high-yielding transgenic crop varieties and those for bioenergy production may have particularly high rates of P removal (e.g. Bender et al. 2013).

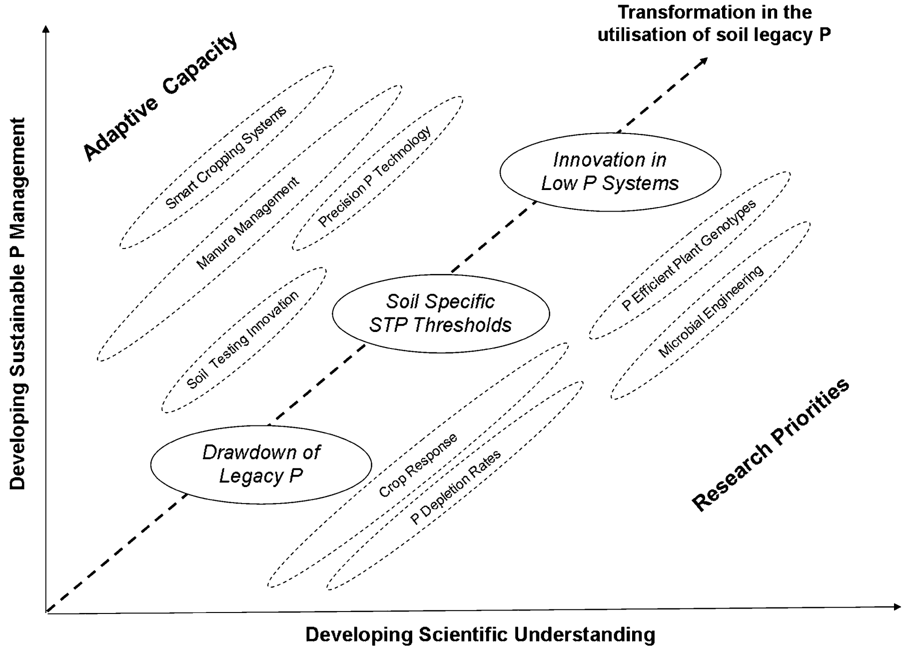

Fig. 4 The three stages of transformation and associated research and practical innovations required to progress from current P management practices into a more sustainable system that fully utilises legacy soil P for agricultural productivity (Adapted from Reynolds 2006)

On farms, the utilization of legacy P is monitored as a gradual fall in STP concentrations. Soils with high STP will meet crop P demands over a longer time period than soils with lower STP (Table 2). Declines in STP are initially rapid on very P-rich soils, and then decline more slowly as the labile P not extracted by STP replenishes P in the soil solution (McCollum 1991; Schulte et al. 2010; Coad et al. 2014; Johnston et al. 2014; Fig. 1c). In many cases, crops will not show a yield decline when P fertilizer is withheld until STP falls below critical agronomic levels (Johnston et al. 2001; Dodd and Mallarino 2005). However, STP is not always a reliable guide to the adequacy of soil P supply because it does not take account of soil P buffering capacity: the ability of a soil to maintain Pi in the soil solution as Pi is removed by crops (Holford 1980; Ehlert et al. 2003). Current STP methods also extract vastly different amounts and forms of soil P depending on the method used, and the role of rhizosphere processes in soil P acquisition is not adequately captured. Hence there are soils that can supply adequate Pi in solution even when STP is low (Herlihy et al. 2004; Paris et al. 2004), and Pi in the soil solution can decline faster than STP when P fertilizer is withheld (van der Salm et al. 2009; Dodd et al. 2012; Coad et al. 2014). Thus, yield reductions from drawing down legacy P have been observed on some soils after relatively short periods, even though STP appears adequate, or even high (Table 2). These uncertainties in soil P availability during STP decline need to be resolved if legacy soil P is to be relied upon for crop P supply. Recent innovation in soil testing to more closely mimic soil P acquisition processes (e.g. Deluca et al. 2015), and accounting for differences in P buffering capacity between soils (Sánchez-Alcalá et al. 2014) may help overcome these uncertainties.

These uncertainties in predicting when crops will run short of P when fertilizer is withheld suggests partial withdrawal of P inputs rather than complete withdrawal may be a more pragmatic approach to the utilization of legacy P. Small, targeted applications of inorganic P (e.g. seed P dressings, placed P [fertilizer or manure], or foliar–applied P) will help to overcome any temporary shortage in soil P supply as legacy soil P declines (Simpson et al. 2011; McLaughlin et al. 2012; Withers et al. 2014). For example, in temperate agroecosystems, low soil temperatures (<15° C) can limit microbial mineralization (i.e., phosphatase enzyme production and enzyme kinetics) and diffusion of P across the soil-root interface during early plant growth stages (Frossard et al. 2000; Grant et al. 2001). Provided targeted fertilizer P inputs are less than crop P offtake, then legacy soil P (and STP) will continue to be utilized, albeit more slowly, with less risk of yield reduction.

Table 2 Some examples of the period over which legacy soil P can be utilized without a reduction in crop yield

System, location	Soil type, pH	STP[a] (mg kg^{-1} or mg L^{-1})	Experimental period (years)	P added[b] (kg ha^{-1} year^{-1})	Years before crop response[c]	References
Continuous cereals, Tetbury, UK	Shallow clay loam pH 8.0	49, 30 (O)	1980–1988 (8)	0 or 22	5	Withers et al. (1994)
Continuous wheat, Canada	Chernozem, pH 6.5	14, 9 (O)	1994–2005 (12)	10	>12	Selles et al. (2011)
Alfalfa, potato, rye, sugar beet, barley, Germany	Luvic Phaeozem pH 5.8	100, 50 (DL) (+ subsoil P)	1949–1999 (50)	0–45	25	Gransee and Merbach (2000)
Wheat, maize, lucerne, Italy	30–46 % clay, pH 6.7–7.6	23, 7 (O)	1987–2001 (15)	0– 52	>15	Paris et al. (2004)
Corn, soybean, Carolina, USA	Clay loam	11, 4 (M1)	1975–1989 (14)	0–40	13	Kamprath (1999)
	Loamy sand	54, 20 (M1)			14	
	Sandy loam	97, 60 (M1)			>14	
Corn, soybean, Boone, Iowa, USA	Fine loamy soils	21, 10 (B1)	1975–2002 (27)	0–33	8–9	Dodd and Mallarino (2005)
		59, 15 (B1)			10–11	
		96, 20 (B1)			14–19	
Corn, soybean, Kanawha, Iowa, USA	Fine loamy soils	17, 10 (B1)	1976–2002 (26)	0–33	4	Dodd and Mallarino (2005)
		43, 12 (B1)			10–11	
		85, 14 (B1)			17	
Corn,soybean Nashua, Iowa, USA	Fine loamy soils	28, 10 (B1)	1979–2002 (22)	0–44	12–17	Dodd and Mallarino (2005)
Wheat, flax, Canada	Chernozem, loam–clay loam pH 6.7–7.6	7–149, 10 (O)	1966–1974 (19)	0–400	6–19	Read et al. (1977)
Grazed grass, Northern Ireland	Sandy clay loam pH 6.2	22, 22 (O)	2000–2005 (5)	0–80	>5	Watson et al. (2007)
Cut grass, Ireland	8 different soil series, 31 trials	4, 2 (M)	1997–2000 (4)	0–60	3–4 (2 of 11 trials)	Herlihy (2004)
		13, 4 (M)			4 (2 of 20 trials)	
Grazed ryegrass-white clover, Te Kuite, New Zealand	Loam, pH 5.7	14, 7 (O)	1983–1997 (15)	0 or 22	4	Dodd and Ledgard (1999)
Grazed ryegrass-white clover, Whatawhata, New Zealand	Silt loam pH 5.1–5.3	15, 10 (O)	1984–1999 (15)	0–100	15 (pasture quality decline after 5)	Dodd and Ledgard (1999)
Grazed ryegrass-white clover, Lismore, New Zealand	Silt loam pH 6.0–6.1	21, 13 (O)	1958–1962 (4)	0–34	2	McBride et al. (1990)

Table 2 continued

System, location	Soil type, pH	STP[a] (mg kg^{-1} or mg L^{-1})	Experimental period (years)	P added[b] (kg ha^{-1} $year^{-1}$)	Years before crop response[c]	References
		36, 24(O)	1977–1983 (6)	0–34	1	McDowell and Condron (2012)
Cereals or grass, Finland	Loam, 12 % clay, pH 7.0	31, 20 (AAA) 14, 6 (W)	1978–1995 (18)	0–79	>18 (but yields very variable)	Jaakola et al. (1997)
6 sites in arable, 1 site in grass, Switzerland	9–54 % clay, pH 6.3–7.9	5–33, 5 (E_{1min})	1990–1998 (9) 1971–1998 (27)	0–46 (if crop offtake is 20)	5 to >9	Gallet et al. (2003a)

[a] Soil test P (STP) methods: *O* Olsen, *B1* Bray 1, *DL* double lactate, *M1* Mehlich 1, E_{1min} isotopically exchangeable P within 1 min, *M* Morgans reagent, *AAA* acid ammonium acetate, *W* water. The two values given separated by a comma are the STP concentrations at the start of the experiment and the concentration at which a consistent yield response was obtained or at the end of the experiment if there was no yield response

[b] The range of P treatments used in the study to assess effects on soil STP and yield response

[c] The year of the soil P rundown period when there was a statistically significant yield response to added P

As Pi in the soil solution falls, small targeted inputs of fertilizers will also be used more efficiently (Gallet et al. 2003b; Withers et al. 2014). If these targeted P inputs can be sourced from recovered and recycled P rather than primary products derived directly from PR, this will further improve overall food chain P efficiency and help close the P cycle (Hanserud et al. 2015; Metson et al. 2015; Withers et al. 2015). Much research will be required to clarify the fertilizer value of recovered P products as they are commercialized. For example, struvite recovered from wastewater has proven to be an effective slow-release fertilizer (Massey et al. 2009). Gradual reductions in fertilizer P applications, and increased substitution with manures and bioresources, will also have the added benefit of stimulating more diverse and active soil biological communities enhancing biological P cycling, and aiding a transition to more sustainable systems of farming (Strategy B). This in turn will enhance the provision of soil ecosystem services and increasing resilience of crop production systems to climate change (de Vries et al. 2013).

Strategy B: Developing P-sustainable cropping systems

Drawing down STP to agronomically critical levels by withholding P inputs will not fully utilize the total stores of legacy P. For example, assuming it takes 10 years to draw down STP to critical levels (Fig. 1c), ten annual crops might remove ca. 200–300 kg P ha^{-1}, which equates to 60–90 mg kg^{-1} of total P to a depth of 25 cm. Total legacy P to this depth is at least 200–400 mg kg^{-1} on the majority of intensively managed soils (Withers et al. 2001; Rubaek et al. 2013; Delmas et al. 2015). A variable proportion of this unused legacy soil P may still be potentially available to crops. Full utilization of legacy soil P reserves therefore requires further lowering of critical STP to allow diffusion and greater mobilization of legacy P not extracted by STP (Manschadi et al. 2014; Withers et al. 2014 and Fig. 1b). The challenge is to enhance the mobilization of P in the rhizosphere in low STP soils to compensate for lower diffusion rates of orthophosphate from labile Pi into the soil solution as critical STP falls.

This enhanced mobilization of legacy soil P can be achieved by taking a long-term, whole system, multi-dimensional and technological approach to managing soil nutrients, including the re-incorporation of agroecological options and optimal use of recovered and recycled P. We propose the term 'agro-engineering' to encompass this approach and define it here as 'the integrated adoption of precision soil, crop and nutrient management in different farming systems together with advances in plant breeding and microbial engineering'. Agro-engineering represents a significant departure from the current practice of 'insurance-based' nutrient management that simply uses more fertilizer and/or a higher critical STP level to compensate for uncertainties and variability in soil P supply (Shen et al. 2013; Withers et al. 2014).

Soil, crop and nutrient management

Wide soil type, crop type and seasonal variation in critical STP concentrations for optimum yield (Simpson et al. 2011; Johnston et al. 2014) suggests there is scope to further reduce STP by taking more account of site conditions and adopting more precise farming practices (in essence, precision farming). Part of this variation reflects the inadequacies of soil P tests, their adoption and interpretation (e.g. Jordan-Meille et al. 2012), part is due to the often large spatial variability in STP across and within fields (Rehm et al. 1995; McCormick et al. 2009), and part is due to the often neglected effects of soil and crop management on crop rooting patterns (Unger and Kaspar 1993; Shen et al. 2013). Most current STP methods do not quantify soil P buffering effects, which limits their usefulness for optimising orthophosphate P concentrations in the soil solution on different soil types. Further refinement of critical STP thresholds according to soil type would therefore help to lower STP (Fig. 4). For example, lowering of critical STP values will be possible on soils with lower capacities to strongly adsorb P (Holford 1980; Sánchez-Alcalá et al. 2014). Furthermore, crops with extensive rooting systems on well-structured soils typically need less STP in the soil for optimum crop yields than soils on thin, compacted, or poorly structured soils. Restricting STP analysis to topsoil depth currently confounds this agro-engineering approach, and subsoils enriched with P can be an effective resource if crop rooting systems are extensive (Gransee and Merbach 2000; Kautz et al. 2013). Reduced cultivations, subsoiling and removing soil compaction will all help ensure well distributed root systems, promote stable mycorrhizal networks in soil and enhance the acquisition of legacy P (Lynch 2007; Miras-Avalos et al. 2011; Shen et al. 2013). Spatial variability in soil P within fields can be beneficially managed by more precise variable rate application techniques based on intensive soil sampling and sensor technology (Juang et al. 2002; Scott Grandt et al. 2010).

Cropping sequences on different soils can also help mine legacy P. When plant species with different P acquisition efficiencies are grown together, or are combined in rotation, improved soil P acquisition for the whole system occurs by facilitation, or complementarity between plant species (Zhang et al. 2010; Hinsinger et al. 2011; Shen et al. 2013). For example, faba beans (Vicia faba L.) can release a large amount of protons and carboxylates (citrate and malate) into the rhizosphere to mobilize sparingly soluble soil P for intercropped maize, or cereal crops (Li et al. 2007; Zhang et al. 2015). In one study, citrate exudation was controlled predominantly by shoot P concentration, and occurred in plants at a critical level of 2–3 mg P g^{-1} dry weight or less, indicating systemic signaling regulated by internal P supply (Li et al. 2008). Legumes often have stronger P mobilization ability than cereals, which could contribute to enhanced P acquisition by neighbouring cereals (Shen et al. 2013; Zhang et al. 2015).

Interactions with fertilizer inputs can also be advantageous. For example, in China, maize plants receiving localized (albeit large) application of ammonium N and soluble P fertilizer 10 cm from the seed at sowing exhibited 20–50 % greater leaf expansion rate, 23–30 % greater total root length, and 18–77 % greater plant growth rate as compared to plants provided with broadcast nutrients on a low STP soil (Jing et al. 2012). Applying ammonium with the P decreased patch soil pH by 2–3 units and helped to mobilize P from calcium phosphates, leading to enhanced N and P uptake at an early critical growth stage. Similar results were recorded by Gahoonia et al. (1992) for ryegrass grown in a calcareous soil with ammonium N fertilizer which caused a pH drop of 1.6 units. However, in a Fe-rich soil, the same authors found that soil P mobilization was enhanced more by nitrate which caused a pH increase of 0.6 units leading to ligand exchange of P. Knowledge of P dynamics in different soil types therefore has potential to inform more precise management.

Plant breeding

Crops differ widely in their response to low P environments; they can extend their root systems and develop root hairs to explore more soil volume (Gahoonia and Nielsen 2004; Lynch 2007), release exudates to stimulate microbial activity, or directly mobilise stable soil P fractions (Jones 1998), alter their physiological state (e.g. aerenchyma) to lower photosynthate requirements (Postma and Lynch 2010), and/or mobilise internal stores of P (Veneklaas et al. 2012). This phenotypic variation in crops' ability to mobilize soil P and utilize P once in the plant can be exploited through crop breeding (Gaxiola et al. 2011; Veneklaas et al. 2012; Manschadi et al. 2014). Breeding more P-efficient plants will lower P demand and allow legacy soil P resources to be utilized over a longer period and is therefore an important component of agro-engineering and sustainable farming systems. Various metrics and definitions of crop P use efficiency have been used (White and Hammond 2008), but crop breeding programmes have been separated into those that seek to improve crop P uptake (i.e. P acquisition efficiency PAE), and those that seek to improve internal utilization efficiency (PUE) (Wang et al. 2010). An important aspect of this research is the need to further develop crop breeding programmes in low P soils so that traits for positive synergistic soil-microbial-crop interactions can be fully expressed.

Progress is being made in isolating genes that enhance P utilization in different crop varieties (Liang et al. 2014; Wu et al. 2013). Recent studies have observed high PUE in Proteaceae growing on severely P deficient soil in south-western Australia (Lambers et al. 2011). These Proteaceae species have significantly reduced their phospholipid levels during leaf development, while their galactolipids and sulfolipids increased (Lambers et al. 2012). These species also show very low levels of rRNA (usually 40–60 % of leaf organic P) and slow development of the photosynthetic apparatus in immature leaves compared to mature leaves (Sulpice et al. 2014; Veneklaas et al. 2012). Lowering grain P content in cereals by breeding crops with reduced capacity to translocate P to the developing grains is another approach based on the hypothesis that not all of the P that is stored in plants is metabolically necessary for yield (Raboy 2009; Withers et al. 2014). Possible reductions in seed P requirements of up to 25 % have been suggested, but concerns over seedling vigour and human health remain to be resolved before this approach will gain wider acceptance (Rose et al. 2013).

In other studies, Pi transporter genes have been isolated from tomato *Lycopersicon esculentum* (Daram et al. 1998), legume *Medicago truncatula* (Liu et al. 1998) and wheat *Triticum aestivum* (Guo et al. 2014) for potential gene transfer. Transgenic tobacco cell cultures with *Arabidopsis thaliana* Pi transporter genes over-expressed showed an increase in Pi uptake under P limited conditions (Mitsukawa et al. 1997). The citrate synthase gene from *Pseudomonas aeruginosa* has been overexpressed in tomato and the transgenic line produced more yield than a control under Pi-limiting conditions. Another gene, AVP1 from *A. thaliana,* when over-expressed in *Arabidopsis*, tomato, and rice resulted in enhanced root growth and more efficient scavenging of P in P-poor soil (Yang et al. 2007, 2014). Gamuyao et al. (2012) found that a trait locus for a phosphate-starvation gene (PSTOL1) in traditional varieties of rice enhanced early root growth for improved P uptake in P-deficient soil. The introduction of the locus into modern rice varieties could considerably enhance crop productivity in low P systems.

Microbial engineering

Emerging research is shifting our understanding of the role of microorganisms in manipulating the ostensibly abiotic components of P cycling in addition to their well-known role in decomposing organic P by producing phosphatase and phytase extracellular enzymes (Araújo et al. 2008; Hayes et al. 2000). Microbial release of protons, organic acids, high-affinity iron chelating siderophores and hormones within the rhizosphere also help to stimulate rooting and solubilize strongly-bound soil inorganic P through acidification and ligand exchange at P sorption sites (Khan et al. 2007; Richardson et al. 2009; Rashid et al. 2012). Many fungal and bacterial isolates have been identified that appear to have exceptional abilities to mobilize P under laboratory conditions (Banik and Dey 1983; Malboobi et al. 2009). Several commercial bio-innoculant products containing single species, or mixtures of species, are now available that purport to be effective at mobilizing soil P (Owen et al. 2015). A recent review by Khan et al. (2009) suggests P solubilizing microorganisms can increase biological N fixation, give up to 30–40 % increase in crop yield and/or reduce inputs of inorganic P fertilizer by 50 % without affecting crop yield. However, their efficacy in field studies remains poor, not least due to the difficulty of mimicking the complexity of soil microbial communities and their competitive interactions in the rhizosphere (Jones and Oburger 2011).

Fostering agricultural practices that support arbuscular mycorrhizal (AM) fungi is increasingly viewed as an important component of creating a more resilient and sustainable agriculture, including P supply (Roy-Bolduc and Hijri 2011; Smith et al. 2011). AM fungi have a well known role in facilitating plant P uptake through hyphal associations in return for photosynthate, but they also mediate bacterial populations and functioning through their exudates and signalling (Johansson, et al. 2004; Toljander et al. 2007; Herman et al. 2012). Although quite ubiquitous in soil, AM activity and their ecosystem benefits are modulated by high legacy P (Zhu et al. 2001; Hao et al. 2008). Plants and AM fungi exist along a "mutualism – parasitic" continuum, whereby plants in low nutrient soils with AM fungi tend to have higher biomass than plants in the same soils without AM fungi; but in high nutrient environments, plants tend to have less growth when grown in soils with AM fungi compared to soils without AM fungi (Johnson et al. 1997; Rowe et al. 2007). If N is also high in legacy P fields, these conditions have been shown to support microbial communities that are less beneficial to plant growth, suggesting we select for less beneficial microbial communities with some of our current cultural practices that favour domination of fewer or inferior species in the rhizosphere (Johnson 1993).

Adopting alternative management practices such as no-till, diverse cover crop mixes and reduced agrochemical inputs will all promote AM fungi and more diverse microbial communities, while also building soil structure and organic matter and reducing erosion, which is key for reducing total P losses to water. Further understanding of the role of competing microorganisms in nutrient supply through molecular biology is needed to advance microbial engineering as a strategy for enhancing legacy P utilization (Rodriguez et al. 2006).

Environmental benefits and trade-offs

In addition to resource (PR) savings, the utilization of legacy soil P will also have an environmental benefit in gradually reducing P losses to aquatic systems (Jarvie et al. 2013; Sharpley et al. 2013). This raises the question over whether there are any conflicts between managing legacy P for agricultural productivity versus environmental goals such as improving water quality. Most environmental gain from utilising legacy P can be expected where STP concentrations are well above the agronomic optimum, and are already leading to high concentrations of dissolved P in land runoff. Policies that advocate negative farm P balances to reduce STP from excessive levels to the agronomic optimum are now operational in some countries and states as part of P-based eutrophication control strategies (Schulte et al. 2010; Kleinman et al. 2015).

However it may take decades to achieve the environmental gains required. For example, Dodd et al. (2012) estimated it would take between 23 and 44 years to lower STP sufficiently to reach a soluble-reactive P (SRP) concentration of 0.02 mg L^{-1} in runoff from grazed grassland required for eutrophication control. Even longer timescales can be expected to reduce the P content of eroding soil particles due to their insensitivity to changes in STP in agricultural settings (Withers et al. 2009). Lowering of STP and SRP release to runoff may also be more difficult to achieve in agricultural systems that rely on no-till, crop residue and cover crop management techniques that concentrate available soil P at the surface (Smith et al. 2014). This suggests that in areas with severe eutrophication problems, additional strategies to enable more rapid utilization of legacy P, and more rapid reduction in STP concentrations, may be required.

Agricultural crops do not appear to be P hyperaccumulators and so phyto-extraction as a strategy to reduce legacy P more quickly for environmental gain appears limited without investment in transgenic biology (Novak and Chan 2002; Sharma et al. 2009). However, Dodd et al. (2014) found that strategic N additions could increase the drawdown of legacy P in pasture soils by increasing P uptake with highly significant reductions (up to 70 %) in dissolved P losses in surface runoff. Combining N application with reductions in P inputs further reduced P losses in runoff due to P immobilization by an N-stimulated microbial biomass. Another strategy is to reduce the surface accumulation of STP through ploughing to invert the soil layers. Sharpley (2003) demonstrated that deep tillage reduced average STP by 65–90 % in the surface soil, leading to a reduced total P concentration in surface runoff from 3.4 to 1.79 mg L^{-1} and in dissolved P from 2.9 to 0.3 mg L^{-1}. McDowell et al. (2014) similarly showed that ploughing around the near stream area decreased STP by 60 % in grazed dairy catchments with enriched STP. Planting the near stream area in a ryegrass monoculture tolerant of low STP, while sowing a monoculture of white clover elsewhere, decreased catchment P losses by 40 %, and due to better pasture performance of the monocultures, increased profitability by at least 10 %. The potential long-term benefits of lowering surface runoff P by inverting soils with highly stratified P result from the combined effects of dilution by mixing surface soils of high STP and low P sorption with subsoil of low STP and high P sorption. This provides landowners the option of keeping those soils in production under P-based nutrient management strategies imposed in areas with eutrophication targets.

The addition of soil amendments that immobilize solution Pi (e.g. by precipitation, adsorption or altering soil pH) can also help to address water quality concerns from excessive STP levels (Buda et al. 2012; Penn et al. 2014). For example, by-products from the coal combustion industry, such as fluidized bed combustion fly ash and flue gas desulfurization gypsum, can greatly reduce the SRP release to surface runoff without appreciably reducing the plant-available P and plant growth (Stout et al. 2000). However, both soil amendments and soil profile inversion only redistribute legacy soil P forms rather than utilize them, and these options should therefore not be viewed as solutions to the greater problem of excessive P application to soils. Furthermore, in the case of deep tillage, the tradeoff between reduced STP levels and increased susceptibility to soil erosion and loss of soil carbon must be considered. Further catchment-based research is required to resolve these conflicts and in the context of wider ecosystem service delivery.

Facilitating a system change

Reducing excessive STP levels in soils to the agronomic optimum is already an integral part of many fertilizer recommendation systems in the developed world (e.g., DEFRA 2010), but has had limited adoption in some areas due to engrained attitudes towards P fertilizer need, or is difficult to achieve in areas with high animal stocking densities. Successful and full exploitation of legacy P will clearly require a step-change in P management strategies that move away from insurance-based approaches that do not take account of environmental impacts, and rely too heavily on primary sourced inorganic P fertilizers (Withers et al. 2014). Here we discuss the main drivers for such change, the importance of local innovation and the rationale for policy intervention. Full utilization of legacy P could considerably reduce pressure on global PR resources and the dependence of some regions on PR imports; model outputs suggest at least 50 % saving in EU fertilizer imports (Sattari et al. 2012) and a 20 % saving in P use in China up to 2050 (Sattari et al. 2014). However compared to other 5R strategies, the utilization of legacy P is relatively short term (Fig. 1d); for example if 50 % of legacy soil P reserves are exploitable they will last only 20 years (Table 1), although this can be extended if only partial drawdown of STP is implemented. In principle, the utilization of legacy P should be more easily achieved compared to the large economic and technological constraints that are likely to limit the adoption of recovery and recycling routes for secondary P recovery (Lederer et al. 2014). Legacy P utilization therefore provides a more tangible option for reducing current high dependency on imported PR-based fertilizers, whilst other longer-term 5R strategies such as redefining consumer attitudes and improving P recovery and recycling options are progressed (Fig. 1d). A major concern to producers is that an over-reliance on legacy P may lead to crop P shortages and would require additional agronomic interventions, but again research has not yet led to firm recommendations on the situations where this is required.

Achieving change will therefore critically depend on the scientific evidence to support more sustainable P use, the availability of decision tools to inform best management options, and whether farmers are motivated and can adapt to a practice change cost-effectively with the resources at their disposal (Brown et al. 2010). As the environmental and resource benefits of exploiting legacy P are long-term, the immediate motivation for utilizing legacy soil P is the economic saving in P fertilizer. Many farmers have already reacted to the large increase in the price of P fertilizers in 2008 by limiting their use and relying on legacy soil P. Future fluctuations in the price of P fertilizers are therefore a key short-term driver that is likely to affect farmer attitudes to utilizing legacy P (Elser et al. 2014). Adaptive capacity constraints such as lack of trust, limited understanding, and the need for investment in other technologies such as precision fertilizer application and more intensive P soil testing and crop monitoring may also be important factors. Farmers must juggle multiple inputs of information that are local and contextual but interact with wide-scale biophysical and socioeconomic factors (Jacobs and Brown 2014). Hence, they will require practical advice and tools tailored to local conditions to make informed decisions. Capacity building through local innovation and on-farm experimentation by groups of farmers would help to encourage them to overcome these uncertainties (e.g. Ashby 1987).

Government policy may be required to achieve adoption of more sustainable nutrient management on a scale required to deliver the desired longer-term environmental and resource benefits (Atwell et al. 2009; Pretty et al. 2001). Justification for policy intervention rests on the causes of market failure. Using Pannell's (2011) framework, these market failures for P might occur (1) where use of P fertilizers causes side effects for others that are not taken into consideration by farm managers (market externalities), (2) where the public would derive more benefit than farmers from legacy P reduction (i.e. reduction in water pollution), and (3) where government knows substantially more than farmers about the long-term benefits of legacy P drawdown (e.g. resource protection). The selection of a policy mechanism depends on the relative levels of public versus private net benefit that accrue from improvements to legacy-P management (Fig. 5). Where private net benefits are high (i.e., savings in fertilizer costs), farmers could be expected to adopt the new practice primarily through extension efforts. Where private net benefits are negative (e.g., yield reductions), but public net benefits are high (e.g., improved water quality), positive incentives would be needed to compensate farmers. Alternatively, mandatory soil testing may help in facilitating legacy P management; for example compliance with P-based nutrient management programmes in some areas of the US and with certain farming systems has reduced inputs of P fertilizer and manure (Kleinman et al. 2015).

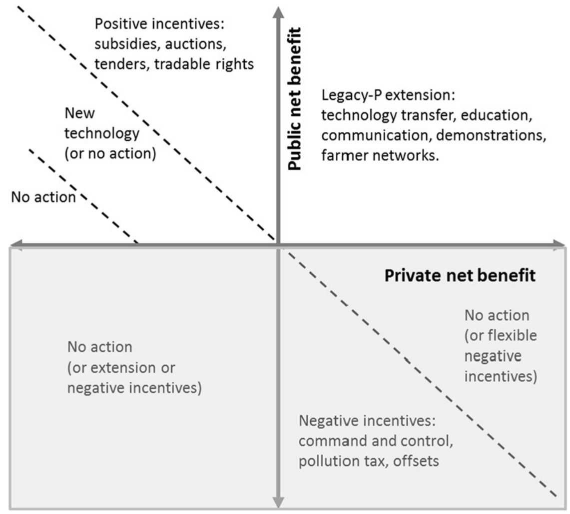

Fig. 5 Suggested main policy mechanisms depending on public and private net benefits. For legacy-P, a policy response would be required where the public net benefits are positive (*upper unshaded quadrants*). The selection of mechanism would rely on the expected level of private net benefits to the farmer (Adapted from Pannell 2011, with permission)

Conclusion

The paradigm of continually accumulating crop available P in the soil emerged during the green revolution when fertilizers were relatively cheap, and before the environmental consequences of high STP and total P in soils and concerns over global PR reserves became apparent. Whilst it might be argued that farmers should leave legacy P in the soil until some future time when the price or scarcity of inorganic fertilizers becomes more critical, this viewpoint ignores the continuing widespread environmental damage caused by soil P loss in runoff, and the possibility that legacy soil P might become increasingly difficult to exploit over time. The value and accessibility of legacy soil P will be site specific and governed by: (1) the local distribution of legacy P depending on past management and P inputs; (2) its availability depending on soil biogeochemistry; and (3) socio-economic drivers including fertilizer prices, local eutrophication problems and associated regulations, and the adaptive capacity of farmers and landowners to make the change (Fig. 3). However, the most tangible justification to use legacy P in soils is the economic driver for reducing or omitting fertilizer inputs.

We outline a progressive strategy for introducing change to utilize legacy P more effectively as part of sustainable agricultural development. This strategy should include transition studies that:

- assess the distribution of legacy P in different catchments and farming systems
- develop innovative soil tests for characterizing P buffering capacity and P mobilization in soils as STP declines
- maximise the potential of transgenics and crop breeding programmes to improve soil P acquisition and crop P utilization efficiency
- manage and offset yield dips through 'agro-engineering', i.e., innovative and integrated soil, crop and nutrient management, including more efficient use of manures and recovered P
- restore microbial diversity and lost soil function
- assess potential market and policy levers and tools for assisting with market and infrastructure development
- introduce improved knowledge transfer and decision support tools that help empower farmers to adapt to more sustainable farming.

Multi-disciplinary research and the development of robust soil-crop models are clearly required to support this transition in management in different farming systems. Our analysis concludes that reducing primary P fertilizer inputs and relying on legacy soil P as a secondary P source for crops is a highly promising strategy for improving both the efficiency, sustainability and profitability of agricultural systems, as well as for reducing eutrophication risk and contributing to improved food, bioenergy and water security.

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