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Achieving Sustainable Phosphorus Use in Food Systems through Circularisation

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Abstract: The notion of a phosphorus (P) circular economy provides the philosophy, framework, and opportunity to enable food production systems to become more efficient, sustainable, and resilient to a future P scarcity or sudden price shock. Whilst P recovery and recycling are central strategies for closing the P cycle, additional gains in environmental performance of food systems can be obtained by further minimising the amounts of P (a) introduced into the food system by lowering system P demand and (b) lost from the system by utilising legacy P stores in the landscape. This minimisation is an important cascading component of circularisation because it reduces the amounts of P circulating in the system, the amounts of P required to be recycled/recovered and the storage of unused P in the landscape, whilst maintaining agricultural output. The potential for circularisation and minimisation depends on regional differences in these P flow dynamics. We consider incremental and transformative management interventions towards P minimisation within circular economies, and how these might be tempered by the need to deliver a range of ecosystem services. These interventions move away from current production philosophies based on risk-averse, insurance-based farming, and current consumption patterns which have little regard for their environmental impact. We argue that a greater focus on P minimisation and circularisation should catalyse different actors and sectors in the food chain to embrace P sustainability and should empower future research needs to provide the confidence for them to do so without sacrificing future regional food security.

Keywords: phosphorus; food system; circular economy; circularisation; minimisation; efficiency; resilience; sustainability

1. Introduction

The long-term adverse impacts of societal functioning on air, soil and water quality and ecosystem integrity are becoming more and more evident and are a cause of increasing concern for planetary stability and human well-being [1,2]. A major driver of this environmental damage has been the intensification of agriculture to satisfy a growing demand for food and changing dietary patterns, and further degradation is forecast as the population continues to expand and urbanise [3,4]. Depletion of non-renewable resources required for food production, regional imbalance in accessibility to resources required for closing yield gaps, declines in global biodiversity due to land clearing for agriculture, and the confounding effects of climate change are additional pressing issues that society needs to address. Future global food security therefore critically depends on using our natural resources more efficiently and sustainably and simultaneously improving the productivity and environmental management of agricultural land. Doing so may require a radical redesign and fostering of new, more resilient agri-food economies involving all stakeholders (including consumers) and more innovative management of agricultural systems [5–7].

One of the critical resource inputs for securing sustainable food production is phosphorus (P). Alongside other essential inputs such as nitrogen (N) and water, a lack of P availability greatly restricts crop and animal production in many regions, whilst past overuse of P in agriculture in other regions has led to unnecessary soil P accumulation, and widespread P leakage causing endemic aquatic eutrophication and reduced biodiversity [8–10]. This system leakage is much greater than occurs naturally over geological timescales and has become exaggerated by the insurance-based approach to P management that advocates using too much fertiliser rather than too little. Further environmental damage can be anticipated in those regions which have yet to expand their use of reactive P for future food security. Although phosphate rock (PR) is now widely recognised as a finite and price volatile resource of variable quality (see Mew et al. [11] for a recent review), the reactive P produced from PR is still used very inefficiently in the food system [12,13]. Conserving PR resources is therefore of critical importance for future food security, especially for those more vulnerable regions with high P demand and little or no PR reserves of their own. The economic, environmental, and social justification for increasing the efficiency and sustainability of P use in the global food system is therefore very clear.

Circular and green economies offer a key philosophical and strategic paradigm to improve the efficiency and sustainability of P use in the food system, not least because of the large opportunities for recovery and recycling of nutrients embedded in the food chain [14,15]. Some vulnerable developed regions with widespread eutrophication (e.g., Europe) are now starting to embrace the circular economy [16], whilst developing regions with more limited access to resources (e.g., to reactive P) and less nutrient demand have been practising circularisation for many years [17,18]. Other regions will perceive the need to continue with the current linear model of food production (i.e., a take-make-waste approach) to maintain economic growth (e.g., Asia, South America) [19,20]. Maximising the environmental performance of a circular economy will also require all actors (producers, processers, retailers, consumers, and regulators) and sectors (e.g., commodities) to take responsibility for delivering the broader sustainability principles (e.g., minimum inputs and zero waste) on which a circular economy was founded [21,22] (for example, the recent adoption of green chemistry in fertiliser P manufacture [23]). This necessitates an interdisciplinary and multi-scale approach to tackling the drivers of unsustainability [24,25], which in the case of P are the policies and practices that generate too much reactive P in the food chain, and its unbalanced distribution across rural and urban landscapes (Figure 1).

Making such an all-embracing change requires rapid global acceptance of an essentially incontrovertible old philosophy: circularisation aimed at closing the P cycle. Here we revisit the foundations of circular economies using global P sustainability as our example. Since P cycles span timescales ranging from geological eras to minutes, we consider the typical annual P cycle of a food system. We argue that there should be a greater focus on minimisation within the P circular economy of a food system and that circularisation should actively reduce the amounts of this critical nutrient entering and circulating within the food chain, and in doing so reduce wastage and leakage. Since the circular economy philosophy is still very much in its infancy with respect to its implementation within agriculture, we highlight management opportunities for transformative innovations toward minimisation.

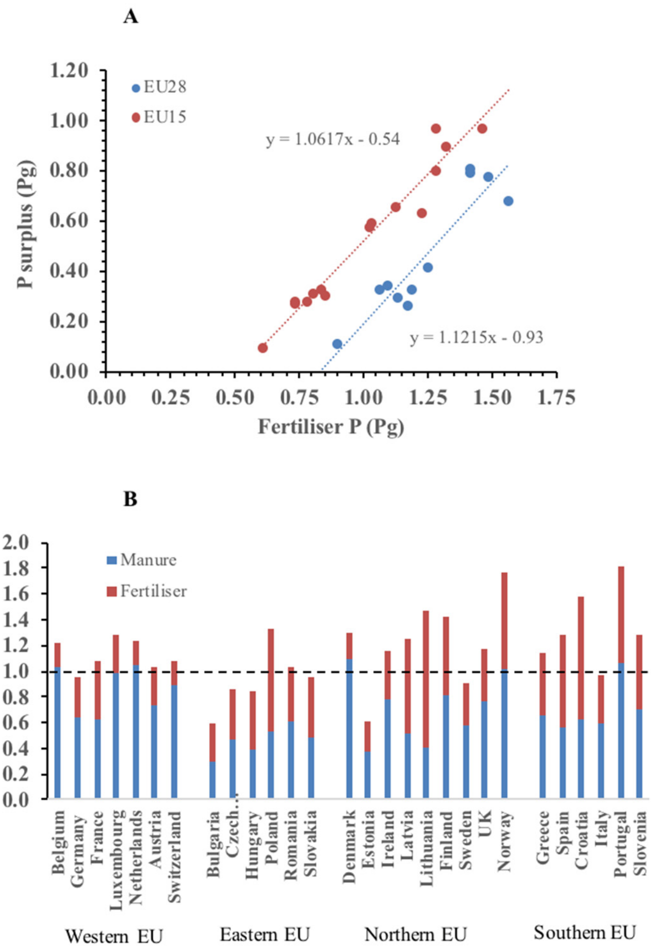

Figure 1. (**A**) Inputs of reactive P in fertilisers drive the annual surpluses of P that reflect P inefficiency and pollution risk across Europe during 2005–2014. Recent reductions in fertiliser P use in the EU have driven down surpluses to nearly zero, but there is variation in the distribution of the surplus between countries; (**B**) The relative contribution of fertiliser and manure P inputs to total crop P demand (ratio 1.0) in different EU countries averaged for the period 2005–2014. Inputs of fertiliser P could still be reduced in many countries and still meet crop P demand, if manure P could be recycled and substituted for fertiliser more effectively. Data are Eurostat statistics on nutrient balances (http://ec.europa.eu/eurostat/statistics).

2. Minimisation of P within the Circular Economy

Developing a circular economy for P provides a means to facilitate the transition to greater P sustainability within agriculture by closing the P cycle and adopting P stewardship across multiple scales. For example, Withers et al. [26] proposed a 5R stewardship strategy (1R:Realign P inputs, 2R:Reduce P losses, 3R:Recycle P in bio-resources, 4R:Recover P in wastes, and 5R:Redefine P in food systems) for managing P that would lead to a more resource-efficient, competitive, sustainable and healthy society. Circular economies were conceived from a cradle to cradle philosophy which considers the life cycle of any system, commodity or product in terms of its use of natural resources, environmental impact and social impact [16,21,23]. Circular economies are built on the green chemistry principles of developing environmentally benign production systems that are output driven (i.e., use the minimum inputs necessary), run-on renewable materials and embed diversity, and which design out waste and reduce losses. They therefore not only envision closed-loop systems through recycling and recovery, but implicitly work on the principle of minimisation which, in the context of sustainable

P use, requires proactive reductions in the amounts of nutrients introduced into, circulating within and lost from the food chain.

Intensive agriculture has evolved into an industry based on the linear economy model with exactly the opposite goals to those of circular economies—for example, in the case of P, agricultural systems are input driven and do not consider end-user P requirements. They are heavily dependent on a non-renewable resource at least in the Anthropocene (i.e., PR), have actively reduced plant diversity in favour of intensive rotations with few crop types, produce copious amounts of bulky waste that is difficult to handle, and cause considerable environmental degradation at significant cost to society [27]. These intensive systems have been driven by short-term economic gains that fuelled the green revolution, and in the case of P, a founding need to build-up soil fertility. Their slow evolution has precipitated traditional beliefs and attitudes centred on insurance-based, risk averse input management that will be hard to change [28]. The more intensive agriculture has become, the more it has moved toward this linear model, and the more P-inefficient it has become. Facilitating a return to a more sustainable circular P economy that focuses on minimisation within agriculture is therefore going to require a radical change in philosophies, attitudes and practices by all actors, and across all sectors, of the food chain from production to consumption [29,30]. Clearly, such minimisation must not jeopardise the economic viability of farming businesses by incurring unacceptable costs, or by reducing agricultural output in the longer term.

3. Managing a P Circular Economy to Promote Minimisation

The concept of a circular economy in respect of agriculture, and more specifically P use in agriculture, is in its infancy and is justifiably concentrating on turning waste into a secondary P resource, where the largest opportunity for business development resides [31]. For example, a number of nutrient platforms and action plans have recently emerged to help facilitate industry investment in recovery and recycling technologies and the future development of markets in secondary P resources [32]. Recovering and recycling P inherently helps to close the P cycle by reducing point-source P loss through wastage (e.g., as wastewater effluent), and lowering inputs of primary reactive P through substitution. However, these options increase the amounts of P circulating in the food system (i.e., the sum of all internal P flows), and they do not reduce the surplus P that accumulates in the soil, both of which increase the risk of diffuse-source P loss in land runoff. A circular economy which simply generates secondary resources through recovery and recycling therefore underestimates the potential for economic and environmental gain by further minimising the amounts of P introduced into, and lost from, the food chain. Further gains in the environmental performance of circular P economies are possible by lowering the P demands of the system, the amounts of unused P that need to be recovered and recycled, and those losses associated with P circulating or stored in the food system.

Conceptually, the P circular economy can be considered as a closed system, with the boundaries of the system defined by stakeholder needs and perceptions. The spatial scale at which the system operates (e.g., farm, catchment, national, food system and global) determines the quantity of P circulating around the system and the P stored within it (Figure 2). Here, we consider the system boundary to be an annual cycle of the food system, which Cordell and Neset [25] define as a combination of the production and consumption system, both of which include socio-economic (e.g., sectors) and biophysical (e.g., landscape) sub-systems that incorporate human and non-human actors. The food system is fed by P *inputs*, which are defined by its perceived P demand: at the farm scale this is the anticipated P requirement of crops (crop P offtake) and animals (dietary intake). The P outputs from the food system include P *exports* related to global trade and market conditions, and P wastage and *losses* to the environment. For example, losses occur not only as a result of incomplete P recapture at wastewater treatment centres, but also due to landscape release of the P which is circulating (e.g., in manures) and stored (e.g., in soil) at farm scale [33].

The amount of P circulating in the system is driven by the *momentum* of the system. Momentum is the mass of P in motion, or circulating, in the system dependent on the cropping area, the numbers of animals and the number of consumers relying on the food system. This motion is exemplified by the journey added P makes in the food system: fertiliser to soil, soil to crop, crop to animal, crop and animal to food processor, food processor to households, all food system manures returned back to soil. In addition to P, system momentum is controlled by other inputs (e.g., energy, water, other nutrients), and consequently, the amount of circulating P cannot be reduced below the minimum P requirement of the system to function, i.e., produce nutritious and sufficient food. The *stores* of P represent the amounts of unused or surplus P in the natural environment. Stores of unused anthropogenic P (legacy P) have built up over time, largely in soils [34], and in addition to accessible recycled/recovered P resources, confer resilience against future P shortages. However, legacy soil P stores are also an endemic source of P loss to water, and therefore need to be optimised [35]. The capacity of the landscape to store P without accelerated P leakage (termed catchment P buffering capacity [36]) is also an important sustainability metric to minimise eutrophication impacts.

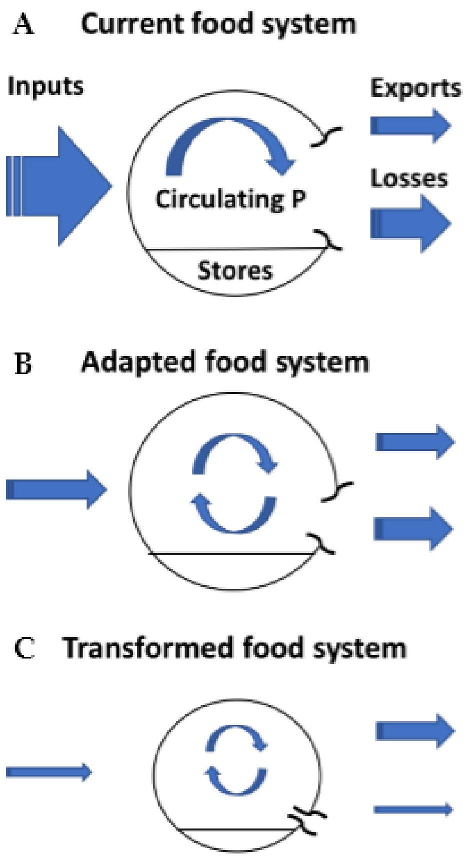

Figure 2. Conceptual representation of P flows in a circular economy based on inputs, outputs, circulating and stored P and the potential impact of management adaptations and transformations on these flows. The size of the arrows reflects the magnitude of the flow which will vary in different regions. A transformed circular economy which embraces full minimization potential has the greatest environmental benefit (lowest inputs and losses).

A sustainable food system based on a P circular economy must therefore be driven by the minimum P required for the continued momentum of the system; i.e., crop P, animal dietary P, and human dietary P demand. The momentum of the food system is governed by the co-optimisation of all required resources for the system to function (i.e., not just P) and will therefore usually exceed the minimum human dietary P demand that would otherwise drive system P momentum. The inputs required to satisfy this minimum demand will depend on the P supplied by P stores in the system, the synergies in system management which can augment the supply of stored P with recycled P, and the efficiency with which the different P inputs are utilised. This can be represented by a fundamental equation

$$P_I = P_D - (P_S + P_R)/P_E \quad (1)$$

where P_I is the requirement of the food system for reactive P inputs, P_D is the P demand of the food system driven by system momentum, P_S is the P supplied by the P stores in the food system, P_R is the P recycled in the system, and P_E is the efficiency with which P_D, P_S, and P_I are utilised.

In highly developed regions, the current food system receives more reactive P than is required, circulates and stores more P than it needs with the result that foods are very rich in P and P losses to water are relatively high (Figure 2A). In developing regions, total P demand and the amounts of P circulating in the food system are lower, reflecting restricted yield potential due to limited access to reactive nutrient inputs, and soil losses due to erosion [37]. Consideration of Equation (1) suggests that management interventions in the food system to facilitate the transition to a P circular economy should occur in three strategic ways: managing the P momentum of the system to lower P demand (P_D), maximising potential synergies in the system through P recycling and recovery opportunities (P_R) and managing the soil P store (P_S) to minimise P losses (Figure 3). Interventions may encompass both incremental change (i.e., adaptations to the system) and transformative change (system transformations) [38,39].

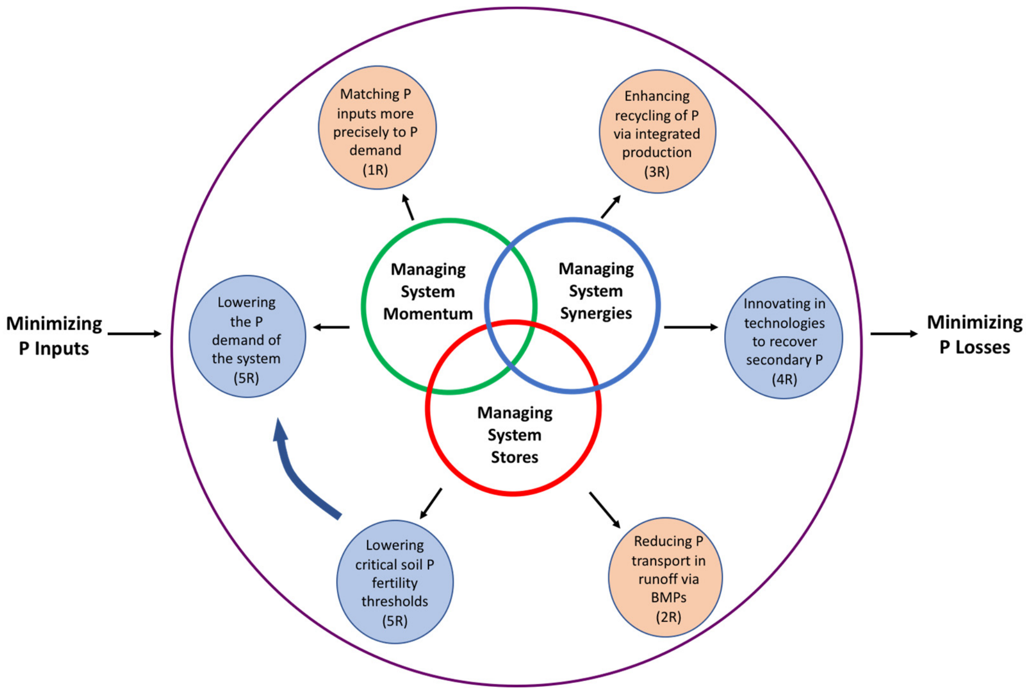

Figure 3. Three strategic approaches towards minimization in the P circular economy of the food system based on managing system momentum, managing system synergies and managing system stores. Examples of adaptive (coloured in brown) and transformative (coloured in blue) 5R P stewardship interventions that interface to these three approaches are also shown. The P stewardship 5Rs are 1R:Realign P inputs, 2R:Reduce P losses, 3R:Recycle P in bio-resources, 4R:Recover P in wastes, and 5R:Redefine P in food systems, [26]).

Improving the efficiency and sustainability of P in the food system is currently based upon incremental adaptations to system management. An adapted food system can be considered as one where management has been altered to be more P efficient at the farm scale (e.g., targeted P inputs [40]), recycling is optimised as much as possible through integrated farming practices [41], and P losses are managed by implementation of best management practices [42]. Further benefits to ES delivery will arise by relocating production systems to more closely match land use capability, resource availability and environmental sensitivity [36,43], but essentially the P momentum and demand of an adapted system has not been greatly altered (Figure 2B). In contrast, a transformed system can be considered as one where the P momentum of the system is changed by minimising the P demand of the system for a required output and which would have a cascading effect on the P circulating in, and lost from, the system (Figure 2C). For example, fertiliser and feed P inputs would be lowered to meet the reduced P demand, foods and feeds will then have reduced P contents, and the manures and wastes recycled to land would have lower P content. If their P content is not low enough for return to the land, P would need to be recovered before they are recycled to land. Inherently lower surpluses of P in a transformed system would lead to lower soil P storage, which would both reduce P losses from the system and increase catchment P buffering capacity.

3.1. Changing the Momentum of the System

An effective circular economy requires that agricultural systems should be output driven (i.e., pull-system) rather than input driven (i.e., push-system). Fertiliser P and animal feed P supplements have been generously applied in the past to maximise food production potential but with little regard for actual end user P requirements or human dietary demand for P [44]. Fuelled by economic gain, such a push system generates food and feed commodities richer in P than they need to be. In addition to the P embedded in farm produce, P is typically added during processing to enhance the appearance, taste and shelf-life of foods and feeds [45,46]. Consequently, humans and animals in prospering nations have an excess of P in their diets which is surplus to metabolic needs, nutritionally redundant due to chelation of mineral elements (Ca, Mg, Fe, and Zn) by phytate, and may even be harmful to health in some vulnerable people [47,48]. Excess dietary P also leads to higher amounts of P excreted requiring treatment, disposal and/or recycling, which considerably increases the risk of wastage and eventual leakage of P to inland and coastal waters because manures are difficult and costly to manage precisely [19,49].

Given that this excess dietary P is not all useful, and that expensive reactive fertiliser and feed P inputs are generously coupled to crop and animal P demand, lowering the P content of foods seems a logical step towards minimisation of P in the circular economy since it has a positive cascading effect on the amounts of P circulating in the system. Modulating animal diets through precision feeding [50], withholding inorganic P supplements in ruminant diets [51], or substituting phytase for inorganic P in non-ruminant diets [52], regular soil analysis and adopting 4R (right source, rate, time and place [40]) nutrient management on the farm are examples of beneficial incremental adaptations to source P management within crop and animal farming systems. Further adaptations to the human diet by reducing the amount of P additives used during food processing might be anticipated if human health concerns over dietary P excess prove real. Such incremental management changes are based on the principle of avoiding overuse of P by more precisely matching P inputs to actual demand (a 1R P stewardship strategy [26]). However, whilst they will improve P use efficiency often to economic advantage, they do not change the momentum of the system and therefore its functional P demand.

An additional and more challenging transformative change to food system momentum is to reduce crop and animal P demand through selective breeding for improved P efficiency. Minimising the P demands of the food chain whilst maintaining yield is economically, environmentally, and socially attractive because it provides a framework for automatically driving lower P inputs, reduces the amounts of P excreted, and is nutritionally beneficial in reduced phytate levels—for example, by lowering the total P and phytate-P content of cereal grain [47,53]. These are essential ingredients for catalysing a circular P economy based on minimisation with benefits for overall P use efficiency, provided crop vigour, yield, and quality are not compromised in the longer term. Lowering P demand could also have a major impact in achieving sustainable intensification in developing countries where the financial resources to purchase P fertilisers are limited [54,55]. Crops and animals demonstrate significant variation in phenotypic traits for soil P acquisition and P utilization depending on their environment [56,57], and a number of molecular breeding techniques are available and developing to progress desirable trait enhancement, including the use of gene markers, mutagenesis (e.g., CRISPR technology) and epigenetic inheritance [58–61]. For example, a mutant genotype of barley (*Hordeum vulgare* L.) with a *lpa1−1* allele for low phytic acid generated seed with a 35% reduction in endosperm P and a 15% reduction in total seed P [62]. A transition toward P-efficient crop and animal breeding programmes is currently confounded by a lack of industry desire to define what minimum level of end user P demand is realistic and to accept that P efficiency is a trait worth selecting for.

Defining a minimum system P demand is a key first step in redesigning the food system to be more efficient with minimum waste (a 5R P stewardship strategy [26]). In a true circular economy, the minimum dietary P demand by the human population within the food system boundary should drive the P momentum of the system. Although this is not feasible because of the need to co-optimise resources other than P required for the food system to function, dietary choice and in particular the ratio of meat, dairy, and eggs to plant in the human diet has a very large influence on the P momentum of the food system [63,64] and the overall efficiency with which P (and other nutrients) are utilised in the food chain and their environmental impact [65]. This is because animal production systems are inherently more P inefficient than crop production systems, and they require significantly more P inputs to provide the same amount of protein. Shifting to a more plant-based diet would therefore lower system P demand considerably, with positive cascading effects on the P circulating and lost from the food system. For example, Thaler et al. [66] estimated that food system P demand was reduced by 20–25%, and P loss to water was reduced by 5–6%, when the average Austrian diet contained 60% less meat.

However, policies to help implement such a transformative societal change as changing human diets are lacking because of the need to productively manage land not suitable for crops, maintain livelihoods of rural communities, and to maintain freedom of consumer choice. This puts the onus on consumers and the stakeholders who have a large influence on consumer behaviour. In reality, global diets are likely to shift toward more P-consuming meat-based diets as developing nations become wealthy and with increasing urbanisation of an expanding population [67]. Changing society's dietary habits toward more environmentally friendly food choices therefore remains an important challenge for sustainable P management and for optimising minimisation and the environmental performance of circular P economies.

3.2. Managing the Recycling/Recovery Synergies in the System

Reuse, recycle, and recovery are traditional R concepts in any circular economy and are key to minimising P inputs to the system [23]. In the context of P, reuse is a redundant R because reactive P immediately changes its state on entering the food system. However, opportunities for reducing P surpluses by recycling and recovery are large because P inputs in fertilisers and manures still exceed current crop P demand in many of the developed countries (Figure 1B). In reality, implementing these opportunities cost-effectively is very challenging due to scale disconnects in nutrient distribution: examples of the current difficulties are the general inaccessibility to manure P on intensive arable farms [68], the excessive amounts of P produced by factory farms with limited land area and associated increased pollution risk [69], and the limited recycling of P from urban areas back to agricultural land [13]. For example, in a small Pennsylvania catchment, Nord and Lanyon [70] found that 20% of the farms accounted for over 80% of N and P flows in the catchment; no crops grown in the catchment were fed to the animals in the catchment, and <50% of manure applied in the catchment came from the livestock farms in the catchment even though they were largely responsible for the nutrient surpluses. Sharing resources between neighbouring systems through recycling would have minimised the need for external inputs and increased nutrient use efficiency in this catchment.

Diversification of farm enterprises and the development of more integrated farming systems provides a potential pathway to minimising P inputs by enabling synergistic nutrient recycling within and between farms providing such systems can be profitable and not too onerous to manage [41,71,72].

Mixed crop-livestock farming, wider crop diversification and manure trading are examples of farm-scale adaptations which would stimulate P minimisation through P recycling. Such recycling of bioresources is a key 3R P stewardship strategy [26], that benefits overall soil quality [73], landscape biodiversity [74], and the resilience of farming systems, for example, to pest and disease attack [7] or to commodity price fluctuations [75]. However, land use capability, or regulatory restrictions, may limit the potential for functional integration of crops and livestock in some areas or the balanced recycling of nutrients [43,76]. For example, animal stocking densities may still be too high in some catchments to dissipate the nutrient loading uniformly, or urban wastes may not be of sufficient quality to be recycled cost-effectively. An economic or social need for farming systems to remain more specialised may drive more transformative change, such as developing alternative recovery technologies that enable secondary P products to be transported safely as fertiliser products over longer distances for recycling to land, especially in areas where the eutrophication risk or land contamination risk is perceived to be high [77,78].

Technological innovations to fully or partially recover P from food system wastes and by-products will generate a range of locally or regionally produced secondary P materials of variable composition (from inorganic salts to biosolids) that can act as fertiliser substitutes or as recycled ingredients in animal feed. Although a strategic 4R P stewardship strategy [26], many P recovery technologies are in their infancy and still require a sound economic base and markets to facilitate the widespread use of accredited products [14,79]. They must also be as environmentally benign as possible [80]. Recovery technologies have most potential at wastewater treatment centres or on factory farms, where a sufficient critical mass of P has accumulated to allow cost-effective treatment. Recovery of P from multiple sources widely dispersed in the environment is operationally and economically more difficult to justify. Accessibility, acceptability, consistency, safety, fertiliser substitution value, and added value benefits (e.g., C and other nutrient elements) are all aspects of these secondary materials that will vary and have yet to determined rigorously and standardised in many cases [81]. However, the potential business opportunities for the fertiliser industry in the marketing of secondary P is large and encouraged by proposed amendments to the fertiliser regulations in Europe to accommodate recovered materials. Technologies that can increase the cost-effectiveness of their use by maximising the plant available P in marketable products are likely to be most acceptable to the farming industry. However, full P minimisation value will only be obtained when the total P content of secondary materials is accounted for in nutrient management planning [82,83]. A transition to integrated production systems and the regular use of these secondary P materials on the farm therefore still requires a supporting policy framework and a business case [14], but the potential societal benefits for soil quality, resource protection and the environment are large [31,84].

3.3. Managing the Legacy Soil P Store

The considerable amounts of surplus P that have accumulated in the soil from past inputs of reactive P represent the main store of P in the food system. Whilst some storage of plant-available P in soil (typically measured as soil test P, STP) is necessary to optimise agricultural productivity and encourage biodiversity and carbon sequestration [5,35], legacy soil P is an endemic source of bioavailable and particulate P losses from land to water that poses a major threat to water quality [85,86]. These legacy P stores are undoubtedly much greater than they need to be in intensively farmed regions (most recently in China [87]), yet they are also the largest source of secondary P that can be potentially recycled in-situ and which does not incur the costs of P recycling (e.g., transport costs) or P recovery (e.g., P removal). They therefore can provide a strategic P bank to buffer against future P scarcity or future PR price shocks, provided local eutrophication is not a major concern.

This trade-off between optimising soil P fertility for food production (and other ecosystem services) and minimising the transfer of P in land runoff to water will vary according to land use capability and inherent catchment P buffering capacity [36,88]. Site-specific soil and landscape management to minimise runoff and prevent erosion (to reduce particulate P loss) and regular soil analysis to ensure STP concentrations are maintained no higher than the agronomic optimum (to reduce bioavailable P loss) are incremental 2R P stewardship adaptations [26] that will help to balance this trade-off (Figure 3). However, hydrological and biogeochemical time lags in detecting positive effects of these P stewardship options on ecosystem recovery can be expected, and more transformative management may be required in the future to achieve desired environmental improvements [89,90].

A more radical transition toward minimisation of P losses would be to maintain a lower agronomic optimum STP level than is currently recommended [28,86,91]. Current guidelines on STP concentration thresholds for maximising crop yields are set at a relatively high insurance level to compensate for poor growing conditions and imprecise management. Actual STP concentrations required for optimum yield are often lower than the recommended critical STP thresholds, especially in adequately fertilised crops growing in well-structured soils [92]. This suggests there is scope to lower critical STP thresholds without yield loss through more accurate prediction of soil P supply and more precise soil and crop management that maintains healthy well rooted crops. Lowering STP will also slowly reduce reserves of legacy soil P not extracted by soil tests through diffusion and therfore confers environmental gain by reducing the mobilisation of both soluble and particulate P. Transition to a lower agronomic optimum soil P fertility level (a 5R P stewardship option [26]) therefore provides a dual benefit in lowering both the economic and environmental costs of establishing and maintaining a higher STP than is actually necessary, and minimises the quantity of new P inputs (whether recycled or inorganic fertilisers) required to maintain this threshold [28].

In making this transformative change, a clear distinction must be made between farming systems on impoverished soils (e.g., developing countries) which have little legacy soil P reserves and limited financial resources to purchase P [93], and those on P-fertile soils where substantial amounts of legacy soil P (e.g., in more developed nations) have accumulated to maintain soil supply of crop available P for many years in the absence of fresh P fertiliser [35,94]. In the former case, reliance on low STP requires innovation in developing P-efficient cropping systems that need less P, and that can operate profitably using the innate soil P-mobilization mechanisms that plants, and their associations with the soil microbial community, possess to acquire soil P [55,95]. In the latter case, management needs to take account of the crop availability of legacy P and STP rundown rates. For example, in tropical soils with high sesquioxide contents, legacy soil P reserves accumulated over many years still largely remain in forms which diffuse only slowly into solution [96,97].

Reliance on lower STP in soils rich in legacy soil P might be achieved by refining interpretation of STP concentrations according to soil P buffering capacity and increasing P use efficiency through more precise management that targets P inputs more closely to plant demand [28,36,98]. Lowering STP will not always be feasible in areas with high livestock densities due to the nutrient loading pressure from excreted manures and will not always lead to lower eutrophication risk due to other overriding hydrological and/or soil chemical processes in soils that influence P loads delivered in land runoff [99,100]. In this context further research is required to explore how to maximise the availability of legacy soil P to plants, while not simultaneously increasing the risk of P export to water causing eutrophication.

4. Achieving Transformative Change

Circular economies provide the framework and opportunity to redesign food systems to deliver the increased agricultural input efficiency, P input/loss minimization and environmental performance required for sustainable intensification. A range of management adaptations and transformations can be implemented by actors and sectors in the food system to enable this redesign (Table 1). However, at present, the magnitude of food system redesign required to achieve environmental goals, and the full range of potential conflicts that need to be resolved to fully close the P cycle remain unclear. For example, a sole focus on P recovery and recycling may not provide the degree of P minimisation required to deliver environmental goals, and continued recycling of bioresources with elevated P contents will lead to accelerated storage of P, and a long-term eutrophication risk.

Some additional and more radical solutions to lowering the P demand of the food system by altering the P momentum of the food system (e.g., through crop/animal breeding or dietary change), or advanced P recovery options will almost certainly be required. Recent seminal analysis of various 5R P stewardship options in Austria clearly shows the large potential P input reductions that are possible when integrating all options (from 2.2 to 0.23 kg P $cap^{-1} \cdot yr^{-1}$), although P losses to water were reduced by only 28% [101]. This may not be sufficient to meet eutrophication control targets in some regions [33], but the saving in P resource use is much more sustainable than current practice. Research must continue to advance more dynamic modelling capability beyond material flow analysis to clarify the benefits of different adaptation and transformative changes to the food system, and then optimise the degree of minimisation required to achieve the right balance between ES delivery and environmental gain. For example, Clark and Tilman [65] found that the difference in environmental impact between types of foods was much greater than the difference in environmental impact between agricultural production systems producing the food, highlighting the greater transformative potential of shifting dietary choice. This suggests a need to shift dietary habits by producing and marketing food according to its environmental impact and benefits to biodiversity.

Table 1. Selected potential sector changes in P management toward a P circular economy and more sustainable P use in the food chain.

Sector	Incremental Change	Transformative Change
Producers	Adopt best management practices to minimise P losses to water	Lower critical P levels in soil to reduce eutrophication risk
	Adopt precision farming to manage P inputs more efficiently	Grow more efficient crop and livestock to lower system P demand
	Adopt integrated farming practices and optimise use of secondary P resources	Implement P recovery options on factory farms
Processors	Reduce P additives in food with non-P alternatives	Identify end user requirements for P
	Increase accessibility to secondary P resources	Develop innovative technologies to enhance P recovery and reduce P losses
Retailers	Source locally grown food	Brand foods according to their environmental impact
Consumers	Consume more locally produced food	Lower dietary P intake through food choice
Regulators	Increase awareness of P sustainability issues within the food chain	Enable adequate governance of P across catchments
	Mandate soil P testing to facilitate more precise nutrient management	Introduce taxation on reactive P imports

Such redesign also requires acceptance of greater social and environmental responsibility for sustainable P use by all the actors and sectors in the food chain, but this is a daunting task. The large number of different social groups within society have different definitions of well-being and different perceptions of sustainability [102]. A greater understanding of the knowledge flows in the food chain, and how these can be improved to increase awareness of food system inefficiencies and downstream environmental impacts could help to engender a culture of greater sustainability amongst all stakeholders. The complexity of modern food supply chains with heavy reliance on conserved and manufactured goods [103], and the overwhelming economic driver to simply obtain what resources we need via the cheapest route [24], are clearly confounding infrastructural and social factors that will require some system redesign; for example, through a return to locally sourced food, or food produced according to traceable sustainability practices [104]. A policy of minimisation may lead to conflicts between actors as each sector will have different thresholds of P below which they are unwilling or unable to go—for example, in lowering the P content of foods without affecting crop and animal health, vigour, and productivity. There is also a lack of governance of P beyond the farm gate to drive the infrastructure efficiency gains required for minimisation of P in the food system—for example, to overcome geographical disconnects in recycling P more uniformly. Solutions to the wider governance of P therefore still remain unresolved [70,105].

5. Conclusions

The philosophy of a circular economy provides the stimulus to move away from current food production systems that rely on risk averse P management strategies that do not consider resource requirements, efficiencies of use or the upstream or downstream environmental impacts. The minimisation principle inherent in a circular P economy has potential to deliver more efficient and sustainable food production systems with minimal demand and minimal losses that are more resilient to a future P scarcity. This may require both incremental and transformative management interventions to the momentum of the system and the stores of P in the system in addition to technological advances in P recovery and recycling. Successful circularisation will require integrated synergistic actions by all actors and sectors involved in the food chain and supported by improved flows of knowledge based on innovative research. Implementing change will require both bottom-up and top-down initiatives and a better understanding of the adaptive capacity of different stakeholders in the food chain to make the necessary management changes.

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