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Legacy Phosphorus in Agricultural Soils: Management Methods to Address Drawdown, Environmental Protection, and Yield Concerns

This paper explores the issue of soils overloaded with "legacy phosphorus" and highlights and categorizes emerging management strategies for addressing this nutrient management concern in annual cropping systems.

Introduction

In undisturbed ecosystems, essential plant elements like nitrogen (N), carbon (C), and phosphorus (P) cycle interrelatedly. In these settings, a diversity of plants and other living things take up N, C, P, and other nutrients into their biomass and then senesce, die, and decompose allowing them to reincorporate into the pool of elements available for future organisms to access (Sharpley et al., 2013). But in annual cropping systems, large amounts of crop biomass are removed every year during harvest. To maintain high yields, compensatory nutrients are applied at rates that decouple natural elemental cycling, resulting in large nutrient system losses that can cause serious environmental degradation (Drinkwater & Snapp, 2007; Sharpley et al., 2013). At the same time, farm operations have become larger and more specialized, and nutrients that are present in large quantities in livestock waste are concentrated in specific regions while crops that might benefit from these nutrients are geographically isolated. Because manure transport to the crop production systems is often cost prohibitive under these circumstances (Paudel et al., 2009), a ready source of nutrients instead becomes a separate problem of disposal and pollution.

Managers of annual cropping systems have traditionally been encouraged to apply P, an important agronomic nutrient that can be difficult for crops to access, to their production fields at relatively high rates compared to crop uptake (Withers et al., 2014). These historic over-applications, often in the form of animal manures (Qin & Shober, 2018), have resulted in the buildup of P in agricultural soils, a phenomenon which has been termed "legacy P" (Sharpley, 2013). This paper aims to explore the issue of soils overloaded with legacy P and management strategies for addressing polluting losses of dissolved P.

While P is needed in relatively large quantities in annual cropping systems, even small amounts of P losses into sensitive waterways can result in notable aquatic ecosystem damage (Kleinman et al., 2017). An influx of P can lead to eutrophication of waterways in which excess nutrients stimulate excessive plant growth such as devastating algal blooms that suffocate the diversity of plants and animals living in creeks, rivers, bays, and oceans (Smith & Schindler, 2009). P is predominantly lost from the agroecosystem through the erosion of farm soil whose particles can be enriched in P (Sims & Kleinman 2005; Kleinman et al. 2019). However, P can also be lost from the agroecosystem as dissolved P that exits farm fields as water moves across or through the soil (Osmond et al., 2019).

In the Mid-Atlantic region of the US, an evolving coalition of states has been working together to try to reduce nutrient losses into the Chesapeake Bay, a highly diverse and productive estuary ecosystem, since 1983 (National Research Council, 2011). States have implemented Best Management Plans (BMPs) to attempt to reduce aquatic ecosystem eutrophication from the influx of excessive nutrients associated with agriculture and other human activities (Sharpley et al., 2011). Initially, when the first environmental BMPs were implemented, sediment P was thought to be the primary cause of eutrophication (Howarth & Marino, 2006). But in the 1990s, it became widely accepted that dissolved N also played an important role in driving eutrophication in coastal aquatic ecosystems (Howarth & Marino, 2006). In the Chesapeake Bay, the dominant driver of eutrophication changes seasonally over the course of the year between N and P (Malone et al., 1996). This is because of the differing nutrient needs of the lifecycle activities of phytoplankton in waterways, which impact eutrophication (Malone et al., 1996). For example, lower N:P ratios increase eutrophication in the spring while higher N:P ratios increase eutrophication in the summer (Malone et al., 1996). Over 20 billion dollars were spent nationally between 2005 and 2010 on conservation programs that target the reduction of polluting nutrients entering sensitive waterways such as the Chesapeake Bay (Sharpley et al., 2013).

Unfortunately, the BMPs implemented using this funding have failed to achieve the expected results. Nutrient levels remain unnaturally high in the Chesapeake Bay as well as other sensitive waterways (Jarvie et al., 2013). In part, this failure is the result of a misunderstanding of legacy P soil dynamics and nutrient loss pathways. Abundant evidence now demonstrates that dissolved P entering waterways from legacy P soils is one major cause of the lag in environmental improvement in watersheds where conservation measures have been put in place (Jarvie et al., 2013; Sharpley et al., 2013; Kleinman et al., 2019). And the BMPs that have been implemented to reduce particulate P losses often do not concurrently address dissolved P losses nor the intensifying role that hydrology plays (Buda et al., 2009; Kleinman et al., 2011; Kleinman 2017; Qin & Shober, 2018).

Though the issue of dissolved P loss from our agroecosystems is clear, a roadmap that annual cropping system managers can use to control these losses is absent from the literature. Current scientific papers outlining techniques to deal with dissolved P losses from legacy P soils vary in scope and scale and have not generated a comprehensive approach for managers to implement. After summarizing the factors that influence the loss of dissolved P from legacy P soils, this paper highlights and categorizes management strategies from the literature that could be implemented in annual cropping systems to avoid or reduce further P applications to legacy P soils and to remobilize or cycle the P already present.

Phosphorus Dynamics

Phosphorus: An Agronomic Macronutrient

P is needed by all living things, including plants. Plants use P for the creation of ATP, DNA/RNA, and phospholipids, which are necessary for energy storage, genetic encoding, and cell membranes, respectively. It is typically present in agronomic crops in quantities ranging from 0.1% and 0.5% of the dry weight of plant tissues (Havlin et al., 2016). P is also key for developmental stages like flowering, fruiting, seed production, and N-fixation. After N, P is often the nutrient required in highest concentrations by agronomic crops though its concentration in the soil in plant-available forms is relatively low (Brady & Weil, 2008).

The fraction of P in the soil that is plant-available includes the dissolved P in the soil solution as well as the organic and inorganic P that may be released into the soil solution over time via chemical and biological processes to resupply the P that has been taken up by plants or another living organism (Ebelhar, 2008). Plants absorb P from the soil solution through their roots. Because P is not very mobile in the soil, many crops develop symbioses with Arbuscular Mycorrhizal Fungi (AMF) to increase their access to soil P (Smith & Reed, 2008), which is discussed in greater detail in the management section of this document.

The Phosphorus Cycle

The global phosphorus cycle operates on a very slow geologic time scale. The earth's crust is high in P. Its slow migration from rock form into waterways is primarily driven by physical weathering with some associated chemical and biological interactions. P sediment that makes its way into streams, rivers, and eventually oceans will settle to the bottom, get covered by other sediments, and later uplift during tectonic plate shifting. Once exposed to weathering and erosion, P erodes back into waterways and the cycle continues. For this reason, there is less P in more weathered soils (Brady & Weil, 2008).

On a much smaller scale and in shorter time periods, P also cycles within an agroecosystem's soil between various forms that may be inaccessible to crops or accessible to crops. Crops access P in two molecular forms: dihydrogen phosphate ($H_2PO_4^-$) and hydrogen phosphate (HPO_4^{2-}) (Havlin et al., 2016). Soil pH determines which is most available. $H_2PO_4^-$ is the predominant P anion in soils whose pH is below 7.2. HPO_4^{2-} is the predominant anion in soils whose pH is above 7.2 but its uptake by plants is slower (Havlin et al., 2016). However, these two phosphate molecules are not the dominant pools of P in the soil. The major pools of inorganic P in the soil are Calcium (Ca)-P, Aluminum (Al)-P, Iron (Fe)-P, and organic P (Stevenson & Cole, 1999).

Soil P exists on a continuum of availability to crops (Frossard et al., 2000; Johnston et al., 2014). P that has been adsorbed tightly or bonded tightly with soil minerals, which tends to happen as more time passes, may have very low accessibility to crops. P that is held less tightly by minerals via surface-adsorption is more likely to be made accessible to a crop (Johnston et al., 2014). Various soil processes described in subsequent sections can unlock this pool of P. The ability of a soil to resupply the soil solution with additional P is known as the buffering capacity (Kleinman et al., 2011). This concept is defined by the ratio of P intensity, the amount of soil solution P, to P quantity, the amount of P in other pools that may resupply the soil solution P if it is taken up or lost (Holford, 1997). A higher P sorption capacity generally represents a greater ability, or buffering capacity, to replenish the soil solution (Breeuwsma & Silva, 1992) and consequently a greater ability to pollute via dissolved P losses via runoff and leaching (Kleinman et al., 2011; Kleinman, 2017).

Under the right chemical conditions, which are described in the following section, Ca-P, Al-P, and Fe-P can dissolve into the soil solution. Conversely, P may precipitate out of the soil solution when Ca-P, Fe-P, and Al-P minerals are formed (Brady & Weil, 2017). Chemical processes drive whether and when P can dissolve into the soil solution from the mineral form or be desorbed from soil minerals into the soil solution.

Up to this point of the P cycle, chemistry has been the main driver of P fluxes in the agroecosystem. However, biology is also responsible for cycling P between plant-available or unavailable forms (Schneider et al., 2019). Organic P, the last major pool of P in the soil, can be mineralized into plant-available P via microbes' metabolic processes (Simpson et al., 2011). Microbes can also immobilize $H_2PO_4^-$ and HPO_4^{2-} back into organic P as they synthesize the nutrient into their biomass since microbes also require P to survive (Richardson, 2001).

There are four main ways that P can be lost completely from the agroecosystem. The first and most concerning loss from an environmental standpoint is erosion (Sharpley et al. 2013), which can be water- or wind-driven (Brady & Weil, 2008). Since a large fraction of P is held in the mineral soil, this loss represents the greatest pollution potential from a production field (Sharpley et al., 2013). The second is via runoff in which dissolved P is carried away in water as it moves over a farm field (Brady & Weil, 2008). This loss pathway is concerning because dissolved P is immediately available for uptake by eutrophying organisms (Penn et al., 2014). The third is via harvest and the removal of crop biomass, which has taken up P from the soil. The final is via leaching, which is of greatest concern in coarse textured soils (Sims et al., 1998).

P Cycle Pools & Flux Factors

An overview of the pools and fluxes of P in the agroecosystem is detailed above. The factors influencing these pools and fluxes of P in agricultural soils are detailed below with the exception of the impacts managers can have on the P cycle through crop selection and fertilizer application, which are discussed in the management section.

Al/Fe-P Fixation or Dissolution

Soil P fixation removes P from the soil solution making the nutrient inaccessible to crops. It is driven by two chemical processes: precipitation and adsorption, which may occur concurrently. Precipitation, the process by which a molecule takes an insoluble form, is largely controlled by chemical factors. A main determinant of precipitation is the solubility product constant (Ksp) of molecules that are present in the soil solution in varying concentrations (Havlin et al., 2016). When a molecule has a relatively low Ksp and the molecule is present in proportions higher than the constant, it tends to resist dissolution and precipitate out of the soil solution and vice versa (Havlin et al., 2016). Soil pH also influences the precipitation of Al-P and Fe-P. When pH is low, P is more likely to react with Fe and Al hydrous oxides and precipitate out of solution (Brady & Weil, 2017). As described in the next section, P tends to precipitate with Ca at higher pH levels. The overall effect of pH, considering both Fe and Al precipitation and Ca precipitation, is that P is most often available in highest quantities at a pH range of around 6 to 6.5 (Havlin et al., 2016).

P may also adsorb to the soil's mineral surfaces. This takes place on the outer sphere of the mineral surface where P anions bind with positively charged hydroxides on the clay edge (Brady & Weil, 2017). This P may become more tightly adsorbed over time and be brought into the inner sphere of the Al or Fe oxide surfaces. Hysteresis, a common phenomenon in cropping systems (Havlin et al., 2016), occurs when more P is adsorbed onto the soil particles than is desorbed (Arthur et al., 2015).

There are many factors that control P fixation. Overall, soil mineralogy, soil pH, competition for sorption sites, soil organic matter (SOM) concentration, temperature, time, oxygen availability, and soil weathering all influence the occurrence of P fixation in the soil. These factors are outlined in Table 1 and discussed below.

First, soil mineralogy plays a large part in P fixation. In general, higher clay content in a soil correlates with higher P fixation (Havlin et al., 2016). Less crystalline minerals like those found in 1:1 clay soils generally lead to more soil P fixation than those of a 2:1 clay (Brady & Weil, 2017). Further, the concentration of Al and Fe, which are often plentiful in acidic soils as particles and coatings on soil surfaces, increases P sorption (Havlin et al., 2016). In calcareous soils, a higher concentration of Ca correlates with a higher P adsorption although the effect is less dramatic than in acidic soils high in Al and Fe (Havlin et al., 2016).

Other chemical factors like soil pH and the concentration of other anions in the soil are two additional factors affecting P fixation. Lower pH increases soil P fixation with Al and Fe while higher pH decreases P fixation with Al and Fe (Havlin et al., 2016). However, higher pH increases P fixation with Ca, which is discussed in the next section. A higher concentration of soil anions like sulfates, organic acids, and soil organic matter increases P fixation. They do this by competing with P for soil adsorption sites (Havlin et al., 2016). Organic acids from soil organic matter will also complex with Al and Fe thus reducing P fixation (Sible et al., 2021).

Physical and environmental factors like temperature, time, oxygen availability, and weathering are other factors that may affect P fixation. At higher temperatures and as more time passes, there tends to be greater P fixation (Havlin et al., 2016). But increased temperature can also increase plant root development and speed P diffusion in the soil, which allows crops to access more P during their growing cycle. So higher temperatures can lead to more or less fixation depending on the individual situation (Havlin et al., 2016). Similarly, oxygen availability may drive the fixation reaction in either direction. Lower oxygen availability in the soil may reduce Fe^{3+} to $Fe2^{+}$ which can result in more P sorption (Havlin et al., 2016). But P may also be mobilized in anoxic conditions as Fe releases P in reduced conditions (Brady & Weil, 2017). Finally, less weathered soils generally have much higher sorption capacities making it much more difficult to maintain adequate P in soil solution. (Brady & Weil, 2017)

Table 1. Factors Influencing P Fixation

Factor	**More likely to fix P**	**Less likely to fix P**
Mineralogy	1:1 clays	2:1 clays
Ratio of Al/Fe:P or Ca:P	High Al/Fe:P or Ca:P	Low Al/Fe:P or Ca:P
Soil Texture	Finer soil textures	Coarser soil textures
Soil pH	Acidic soil pH	Higher pH, especially in 6-6.5pH range
Competition for sorption sites from other anions (sulfates, organic acids, etc.)	Fewer other anions present	More other anions present
Soil organic matter (SOM)	Lower SOM concentration	Higher SOM concentration

Soil weathering	Less weathered soils	More highly weathered soils
Time	Longer time frame	Shorter time frame
Temperature*	*Higher temp*	*Lower temp*
Oxygen availability*	*Lower O_2 availability*	*Greater O_2 availability*

*Temperature and oxygen are factors that both increase and reduce P fixation.

Ca-P Precipitation or Dissolution

Neutral and calcareous soils fix around half the amount of P as acidic soils (Havlin et al., 2016). However, the cycle of precipitation and dissolution still applies in these situations. The plant-available anions, $H_2PO_4^-$ and HPO_4^{2-}, tend to react with Ca to form Ca-P minerals and precipitate out of the soil solution (Havlin et al., 2016). As with Al and Fe oxide surfaces in acidic soils, P may adsorb to calcium carbonate ($CaCO_3$) in calcareous soils and can become more tightly adsorbed over time into the inner sphere of the $CaCO_3$ surfaces. If soil pH is brought closer to 6.5 pH, Ca will release P and it will tend to dissolve into the soil solution (Havlin et al., 2016). The presence of 2:1 clays, a low Ca:P ratio, a coarse soil texture, more neutral soil pH, high competition for adsorption sites, high soil organic matter (SOM) concentration, shorter time frames, and the presence of more highly weathered soils will also reduce P fixation as with Al/Fe dominated soils (Havlin et al., 2016).

Organic P Immobilization or Mineralization

Soil biology is the key driver of organic P accessibility to crops (Alori et al., 2017). Microbes are constantly cycling nutrients in the soil as they reproduce, decompose organic matter, excrete waste, and die. Organic P is present in the soil most commonly as phytate, a compound produced by plants and bacteria, which is relatively resistant to decomposition (Alori et al., 2017). Nucleic acids and phospholipids also represent a portion of soil organic P, but they are present in smaller quantities because they are much more available to soil microbes, who assimilate these sources quickly (Schneider et al., 2019).

When microbes break down organic P, they either immobilize or mineralize the nutrient (Simpson et al., 2011). These processes can happen simultaneously in the soil (Havlin et al., 2016). During immobilization, organic P is made unavailable as the soil microbes use the P molecules for their metabolic processes. In mineralization, the microbes break down organic P into plant-available forms through the production of an enzyme called phosphatase, which produces HPO_4^{2-} from organic P (Simpson et al., 2011).

Several factors influence whether the microbial processes will immobilize or mineralize this pool of P. Nutrient ratios in the soil, the concentration of organic P, soil aeration, temperature, and moisture will all impact the rate of mineralization of organic P into plant-available P (Havlin et al., 2016). The ratio of P to C in the soil plays a large role. As microbes take up soil C during metabolic processes, they also take up some P a specific required proportion. Generally, P mineralization occurs when C:P is less than 200:1 and P immobilization occurs when C:P is greater than 300:1 (Havlin et al., 2016).

In addition to nutrient ratios, a higher concentration of organic P generally results in higher mineralization of P (Havlin et al., 2016). Further, the metabolic processes of the soil microbes are greater in an environment with a more neutral pH, access to adequate oxygen and moisture, and warmer temperatures so all these factors will increase the conversion of soil organic P into plant-available P (Havlin et al., 2016). Furthermore, fertilizer applications as well as tillage both increase organic P mineralization since they boost the P available to soil microbes either through direct addition or by exposing new surface area to microbial activities (Havlin et al., 2016).

Soil System Losses

The major P loss from the agroecosystem that is examined in this paper is the loss of dissolved P via runoff and, less commonly, leaching. As summarized in "The Phosphorus Cycle" above, P may be lost from the agroecosystem through runoff and leaching as well as harvest and removal of crop biomass and erosion. Erosion carrying sediment P with it has historically been the primary focus of P loss reductions due to the relatively high levels of P found on soil surfaces (Sharpley et al., 2013). However, the expected improvements in water quality in regions where Best Management Practices (BMPs) intended to curb this nutrient loss have not been realized (Jarvie et al., 2013). This illuminates the fact that dissolved P in runoff and water that infiltrates down the soil profile also significantly contributes to P pollution downstream (Qin & Shober, 2018) and is immediately available for uptake by plants, algae, and other eutrophying organisms, which can upset the delicate balance of nutrients in aquatic ecosystems (Penn et al., 2014).

P losses from the agroecosystem are determined by environmental and site-specific factors as well as present day and historic management decisions. In terms of environmental factors, the intensity of P losses from a farm field is greatly determined by climatic, edaphic, and geomorphic influences that play a major role in determining the magnitude of dissolved P losses (Buda et al., 2009). For example, extreme weather events characteristic of climate change accelerates the loss of dissolved P into waterways (Lucas et al., 2022). Slope also influences the degree of P losses because runoff occurs when rain or irrigation rates exceed the rate of infiltration, resulting in an increase in water flowing over the surface of a field (Dougherty et al., 2004) and potentially carrying dissolved P from P enriched soils along with it.

The historic overapplication of manure on cropland in regions like the Chesapeake Bay watershed has created legacy P hotspots, which are a primary concern for stemming the flow of dissolved P into water bodies. Repeated manure applications at rates that exceed crop requirements has reduced available P adsorption sites in the soil and resulted in an increased probability of P desorption and loss via runoff and leaching compared to commercial fertilizers (Jiao et al., 2007; Dou et al., 2009). The need to manage P losses from these legacy P hotspots, especially when the local hydrology makes fields susceptible to high levels of runoff (Kleinman et al., 2011), persists as a pressing concern for lawmakers, scientists, natural resource professionals, and farmers alike in the Chesapeake Bay (Steinzor & Havemann, 2014; Irby & Friedrichs, 2019; Aiken, 2019).

Testing for Soil P & Loss Risks

Determining the quantity of dissolved P that may be lost from an agroecosystem or the quantity of plant-available P in the soil is difficult to do accurately. Pools of P are not clearly delineated into categories that are “available” or “unavailable” (Frossard et al., 2000). Instead, P availability may be described best as existing on a continuum between P that is immediately available, the P present in solution, and mineral forms of P that range in their potential to resupply the soil solution (Frossard et al., 2000). But quantifying the continuum of P availability has proven to be a challenge both agronomically and environmentally.

Widely available agronomic soil tests used by field managers do not specifically measure the plant-available P in the soil. They have been developed by lab, greenhouse, and field experiments to predict nutrient availability, to determine the likelihood of a profitable yield response to fertilization, and to provide a recommended fertilizer application rate (Havlin et al., 2016). Although high soil test P (STP) results do correlate with the potential for P loss, they cannot be used to determine how much P will be lost from the agroecosystem (Kleinman, 2017). Instead, they provide an index for the soil’s buffering capacity, or its ability to resupply the soil solution with additional P (Hochmuth et al., 2017).

Agronomic soil P tests work by chemical extraction, which mimic the way that P might resupply the P available to plants in solution by removing Al or Ca from the soil solution in acidic or basic soils respectively (Havlin et al., 2016). There have been a range of soil test extractions developed for different soil types (e.g. Bray, Mehlich 1, or Mehlich 3 in acidic soils and Olsen in calcareous soils). Research is conducted to determine the most accurate soil test for different soil regions. One of the most common soil P tests in the Mid-Atlantic is the Mehlich-3P (M3-P) (Penn et al., 2018).

Since most managers test their soil with M3-P in the Chesapeake Bay watershed, attempts have been made to use M3-P soil test results as an indicator for the risk of P loss from an agroecosystem (Maguire & Simms, 2002; Vadas et al., 2005). STP typically correlates with high losses of soluble P (Withers et al., 2019). However, M3-P does not always accurately predict P loss. Environmental soil tests like those that measure water extractable P (WEP) may do a much better job of determining the likely levels of dissolved P lost via runoff especially when manures have been applied on the soil surface (Kleinman et al., 2007).

Isotopically exchangeable P and resin P may also be used to approximate the quantity of plant-available P more closely in a soil. P that is isotopically exchangeable is the main source of P for many agronomic crops (Demaria et al., 2005). Isotopically exchangeable P provides a closer prediction for the P that is likely to come into the soil solution from the mineral phase over a roughly 3-month time period (Frossard et al., 2000). The method uses isotopically labelled P that is added to a soil sample before applying an extractant and measuring the P in solution (Demaria et al., 2005). Resin P tests also appear to more accurately predicting plant-available P. These tests use membrane strips that are positively and/or negatively charged and attract P to their surfaces in a way that mirrors the P resupply process (Saggar et al., 1990). The mode of action of each soil test presents a range of benefits and drawbacks to quantifying soil P. Some researchers recommend that multiple tests be used to give a fuller picture of soil P availability (Kruse et al., 2015).

Unfortunately, resin P and isotopically exchangeable P tests are more time intensive than agronomic tests, and neither is widely available. Right now, the most accurate and accessible technology for plant available P testing comes from using the extractions most commonly used in the region in which the sample was taken and then conducting plant tissue testing to confirm the rates of P uptake (Silveira et al., 2011). As a result, it is a good practice to use M3-P soil test results in most Chesapeake Bay watershed soils. From an environmental standpoint, using M3-P in combination with WEP may help a manager to determine the risk of runoff losses from the agroecosystem (Penn et al., 2018; Lucas et al., 2021; Roswall et al., 2021). These risks may influence management decisions.

Management Techniques to Address Legacy Phosphorus

For over 40 years, soil conservation Best Management Practices (BMPs) have been promoted to managers of annual cropping systems to reduce the loss of agricultural nutrients to sensitive bodies of water (National Research Council, 2011; Hood et al., 2021). There has historically been a focus on BMPs developed in campaigns such as the Chesapeake Bay Program that set out to target soil particle P losses from legacy P soils (Kleinman et al., 2011). We now understand that P can also be lost from the agroecosystem as plant-available, dissolved P in much larger quantities than originally thought. As a result, the reduction in excess nutrients in waterways has not been as great as anticipated in part because the BMPs have not focused on techniques that would address the loss of dissolved P via runoff and leaching (Jarvie et al., 2013).

Clear management recommendations for how to reduce dissolved P losses from the agroecosystem have lagged behind our scientific understanding of the phenomenon (Qin & Shober, 2018). Scientific papers addressing the management issue of dissolved P loss often mix agricultural field-scale techniques with regional watershed strategies and infrastructure recommendations. The mix of scope and scale makes it difficult for managers of annual cropping systems to identify techniques they can implement.

This section seeks to highlight emerging management recommendations from the scientific literature that can guide farmers toward minimizing dissolved P losses while drawing down the large amounts of P in legacy P soils and maintaining yields. This paper highlights annual cropping system management strategies geared towards reducing dissolved P loss and classifies them into two categories: strategies that avoid or reduce P inputs and strategies that cycle the legacy P in the soil. An overview of how management strategies are organized are presented in Table 2. Summaries of the papers that present multi-pronged approaches for addressing dissolved P are summarized in Table 3.

Management strategies that are unlikely to be implemented by agricultural producers—including resource-intensive strategies such as the construction of P removal structures (Penn et al., 2017) and efforts requiring the resources of regional coalitions like identifying “critical source areas” (Qin & Shober, 2018) and conducting watershed assessments (Osmond et al., 2019)—are beyond the scope of this paper.

Avoid P Applications

This section discusses management techniques to eliminate or dramatically reduce P inputs in an annual cropping system.

Cease P Application

Perhaps the simplest yet most controversial management technique for continued cropping in legacy P soils is to cease further P applications until P levels have been drawn down to environmentally sound levels. This recommendation is most critical for soils with high P sorption capacity from which P losses can be highest (Klenman et al., 2017). Many papers and municipalities recommend aiming for STP levels that correlate with crop demands (Sharpley et al., 2015; Osmond et al., 2019; Schneider et al., 2019; Zhang et al., 2019; MDA, 2021). Managers accustomed to applying P regularly may be uncomfortable with this approach especially because P is less mobile in the cooler temperatures of the early season when crops are being established (Qin & Shober, 2018). But there is reason to believe that in some cases legacy P soils may be able to provide adequate P that will not result in a yield penalty (Withers et al., 2014; Rowe et al., 2016).

Several studies have demonstrated that drawdown through ceased P applications in Mid-Atlantic is a slow process (Fiorellino et al., 2017). Lucas et al. (2021) demonstrated that on three legacy P field sites in coastal plain soils in Maryland STP was high enough for sufficient yields of row crops 15 years after high manure applications had ceased. Another study in North Carolina's sandy coastal plain determined that M3-P indices would take around 18 years of continuous corn-soy to draw down STP from 100 mg kg$^{-1\ \mathrm{P}}$ to the agronomic critical level of 20 mg kg^{-1} P (McCollum, 1991).

The soil P index beyond which more P should not be applied will likely vary by agroecosystem and jurisdiction. In Maryland, the state extension service has developed an index to standardize the soil P test results arrived at by the many laboratories in the state. This index is known as the Fertility Index Value (FIV) (Coale & McGrath, 2001). Soils whose P FIV are over 150 are considered "very high" and managers of these soils are not permitted to apply any type of P fertilizers and are additionally required to participate in Maryland Department of Agriculture's Phosphorus Management Tool (PMT) (MDA, 2019). Other states in the Mid-Atlantic have similar tools for tracking and regulating soils with excessive STP.

Stopping P fertilization is best used in combination with recommendations from the second category of management technique: cycling the P that's already present in the soil. Because managers may be uncomfortable with the idea of ceasing all P applications, it will be important for research to continue to support effective strategies for repairing and recoupling the P cycling with other soil biogeochemical cycles to demonstrate the feasibility of this strategy.

Smart P Applications: The 4Rs of Nutrient Management and Stewardship

Based on the evidence of P drawdown in legacy P soils described above, it is important to carefully consider further P applications to high P soils. But given the possibility that there may be management situations in which some P applications are still required to achieve adequate yields despite high STP indices, guidance on how to do so with the least environmental impact is crucial. One example of a situation in which fertilization may still be required is when a row crop is seeded in the early spring and soil temperatures are too low for adequate P uptake from the bulk soil during the important early stages of growth (Rowe et al., 2016). However, it is important to note that P isotope studies have demonstrated that annual crops rarely use more than 25% of a P fertilizer application (Johnston et al., 2014). For comparison, between 30-50% of N fertilizer applications are taken up by cereal grain crops globally (Raun & Johnson, 1999). The inefficiency of this recovery rate drives home the point that P applications, if used, should follow the traditional 4Rs of nutrient management: Right rate, Right source, Right place, and Right time. Each of the 4Rs affect the others and decisions made under this framework should be considered holistically.

Right Rate

With the discovery of the environmental degradation that soil P excesses can cause, recommendations for P application rates to production fields have shifted. Previously, an "insurance" P application framework, which created the legacy P problem, focused on fertilizing the soil to subsequently feed the crop (Schneider et al., 2019; Zhang et al., 2019). Now, put succinctly by Withers et al., managers must "feed the crop not the soil (Withers et al., 2014)" to reduce the risk of compounding the legacy P soil problem.

The current recommendation for P applications to reduce environmental losses while achieving adequate yields is to set thresholds for STP (Kleinman et al., 2011) or, more specifically, to fertilize only up to the STP level equivalent to the rate of crop P removal (Johnston et al., 2014; Rowe et al., 2016; Grant & Flaten, 2019; Osmond et al., 2019; Schneider et al., 2019;). This rate of fertilization is often referred to as the "critical" level and is defined as a the minimum STP level required by a crop to still achieve 90-95% of that crop's maximum yield (Cox, 1992). To follow this guidance, managers now need access to extensive crop-, region-, and soil-specific STP data to know what the crucial level is for their cropping system (Davis et al., 2005). Until a more finely honed reference is developed, managers could opt to use STP and the average P recommendations for the crop they are growing to begin to follow the guidance to "feed the crop not the soil" when determining P applications.

Another technique for managers of annual cropping systems to consider is the implementation of variable P applications, in which P is applied on a more granular scale instead of on a whole field or whole farm level (Simpson et al., 2011). A grid soil sampling system can be used by a manager to establish the various field blocks requiring different levels of P fertilization (Franzen & Peck, 1995). This ensures that only the areas that truly require a higher degree of P application receive those higher P applications.

In addition to P rates, it is important to reflect on the right rate for other applied agronomic nutrients as well. Because crop biomass production will be restricted by the most limiting nutrient, maximum P uptake cannot be achieved without balancing the other required crop nutrients (Simpson et al., 2011; Havlin et al., 2016). For example, adequate N fertilization improves the use of P present in soils in part through its impact on soil pH and in part through greater crop biomass production, which means more P uptake from the soil (Havlin et al., 2016; Rowe et al., 2016; Zhang et al., 2019). Ensuring adequate levels of crop nutrition ensures maximum biomass production and, thus, the greatest crop drawdown possible on P present in the soil (Dodd et al., 2014; Havlin et al., 2016).

Finally, the rates of P made available by organic P and soil biology activities have historically been difficult to quantify. However, field studies with reduced P applications indicate that biological P contributions may be larger than previously understood (Qin & Shober, 2018; Schneider et al., 2019). This is discussed more in the organic P fertilizer section. In general, more research is needed to be able to understand how to promote biological P cycling (Rowe et al., 2016; Schneider et al., 2019) and to better quantify the plant-available P that may be derived from organic P and microbial processes.

Right Source

There are many factors for a manager to consider when deciding on the most appropriate P fertilizer in high P soils. The decision is complex because adding more P fertilizer can start to fill the soil's P sorption capacity, bringing the soil closer to the threshold beyond which P losses dramatically increase (Kleinman et al., 2000). Factors such as the soil reactions that influence crop P uptake and the other nutrients present in a fertility source are important for determining an appropriate P source in legacy P soils.

The reactions the fertilizer will have in the soil are dependent on the type of source selected. Solubility varies depending on source and is a key reaction to consider. P fertilizer that dissolves more rapidly into the soil solution is also more readily lost via runoff (Sharpley et al., 2013) or fixation so the dissolution needs to be well calibrated to the uptake rates of the crop planted (Weeks & Hettiarachchi, 2019). Slow-release fertilizers may be the best choice for reducing losses (Withers et al., 2014; Sharpley et al., 2015). Additionally, the impact that a P fertilizer has on soil pH and salinity also varies and is important to consider. When a fertilizer begins to dissolve into the soil solution, the reaction may form a zone of higher salinity or lower pH around the granule, which may impact seedling development even though the impact is small on the bulk soil (Havlin et al., 2016).

The concentration of other nutrients in the chosen P fertilizer is another important consideration for getting the right balance of crop nutrition overall. For example, when a manager requires a Potassium (K) source as well as P, they may elect for a K phosphate fertilizer to supply both nutrients in one source. However, nutrient ratios need to be added in corresponding proportions to the needs of the crop. If a manager applies a fertilizer like manures, for example, which tend to have relatively low N:P ratios, applying them at a rate that meets crop N needs will result in much more P being applied than the crop can take up (Maltais-Landry et al., 2016). N:P and other nutrient to P ratios in a fertilizer need to be accounted for in the nutrient budgeting process to avoid worsening the legacy P issue by overapplying P.

P fertilizers are classified as inorganic or organic sources and within these two categories, soil dynamics for P availability are similar. Inorganic and organic fertilizers may be used separately or in combination in an agroecosystem. The merits and drawbacks of each are discussed in the following sections.

Inorganic P Fertilizers

Inorganic fertilizers contain higher concentrations of readily available forms of P than organic P fertilizers (Havlin et al., 2016). Additionally, ^{32}P isotope field studies using inorganic P fertilizers demonstrate that P uptake from that season's fertilizer application can be relatively low (Johnston et al., 2014). Only somewhere between 5% and 25% of the inorganic P applied is typically recovered by the crop (Johnston et al., 2014). The low uptake rate of P from inorganic P fertilizers, which are high in water soluble P (Havlin et al., 2016) can result in high rates of dissolved P loss from the soil (Sharpley et al., 2013).

There are a wide range of inorganic fertilizer sources to consider with different nutrient contents, and salinity and pH levels. Single superphosphate (SSP) and triple superphosphate (TSP) are two inorganic P fertilizers with high P availability that also supply Ca and have low salt indexes (Havlin et al., 2016), making them a good option for banding with salt-sensitive crops. But SSP and TSP are not commonly used on US farms today. Inorganic P fertilizers manufactured with ammonium such as monoammonium phosphate (MAP), diammonium phosphate (DAP), or ammonium polyphosphate (APP) are more common (Havlin et al., 2016). The dual nutrient application of N and P in these fertilizers has been shown to increase P uptake (Miller at al., 1970), which is key for reducing losses. MAP is very water soluble and generates an acidic band around the granule as it dissolves making it a source that may not be ideal for sensitive seedlings but that is more commonly used in high pH soils since it can reduce Ca P fixation (Grant & Flaten 2019). DAP generates less soil acidity than MAP, but its higher salt and ammonium content can be toxic to young seedlings (Allred and Ohlrogge, 1964). APP is a liquid fertilizer (Havlin et al., 2016) so it could be administered to crops through an irrigation system. However, its reaction in soils is quite variable and there is some concern that its behavior in acidic soils with a high concentration of Al and Fe would result in more P fixation when compared with other granular fertilizers (Montalvo et al., 2014).

Organic P Fertilizers

The use of organic P fertilizers such as manures, composts, and biosolids in legacy P soils may be counterintuitive at first because the problem of high P soils has commonly been created by the overapplication of manures. But some managers may, if legally permitted, still opt for organic fertilizers when choosing their P source. Although this carries significant risk of worsening the existing problem, organic fertilizers may still be favored because of their well-known beneficial influences on soil qualities like better water retention, reduced bulk density, more neutral pH, more soil aggregates, and higher yields over time (Tester, 1990; Ferreras et al., 2006; Ozores-Hampton et al., 2011; Adugna et al., 2016). Another reason to consider organic P fertilizers is that they add SOM which can increase the ability of crop roots to explore more of the soil volume and contributes to greater P uptake (Schröder et al., 2011). Additionally, SOM may contribute more plant-available P to an agroecosystem than previously thought (Schneider et al., 2019), which is discussed more below.

As mentioned previously, manures, composts, and biosolids tend to have low N:P ratios (Maltais-Landry et al., 2016). Non-ruminants like humans, swine, and poultry lack the enzyme phytase in their guts so there is a large amount of P in their excrement (Singh & Satyanarayana, 2015). Livestock diet and manure management can greatly impact the total P in manures used as an organic fertilizer source (Rayne & Aula, 2020). A manager will need the analysis of the N, P, and other nutrient concentration in the organic fertilizer to complete needed nutrient budgeting. Choosing an organic fertilizer with higher N:P ratios and high nutrient availability is one way for a manager to access the benefits of adding organic matter to the soil without applying excessive quantities of P.

It is commonly the case that crop systems that rely on organic fertilizers like manures and compost will exceed their P needs if the application rates are based on the crop systems' requirement for N (Nelson & Janke, 2007). This can cause detrimental environmental P losses of both organic and inorganic P via runoff (Sharpley et al., 2013). It may be better to calculate manure applications based on P requirements and then add additional N to avoid these P excesses. These N requirements could be provided through cover crop legumes, cash crop legumes, synthetic N fertilizer, or high N organic fertilizers like blood meal, or by selecting crops that require less N. In certain situations, a manager may even choose to forgo the additional N fertilizer expense and accept the yield penalty that arises from reduced N applications. However, as mentioned above, adequate rates of N and P are recommended to maximize a crop's ability to generate biomass and extract maximum P (Grant & Flaten, 2019). Using organic P fertilizer and supplementing with inorganic N fertilizer is a route that some managers may choose to access the benefits of both types of fertilizer (Sharpley et al., 2015; Maltais-Landry et al., 2016; Zhang et al., 2019).

Another final important understanding for which more research is required is that organic P may contribute more plant-available P to a crop than previously thought (Qin & Shober, 2018; Schneider et al., 2019). Some of this increased availability may be related to a higher SOM's ability to improve soil structure and thus a plant's root's ability to take up P (Johnston et al., 2014). Increased SOM via manure applications can also significantly increase organic P by growing the microbial P biomass in the soil (Dodd & Sharpley, 2015; Maltais-Landry et al., 2015). Since there is no clear consensus on how much soil available P we can account for from the organic P pool, likely because these rates vary from system to system, more research is needed on this topic so that managers can adjust their rates of P application to better account for the amount of P that will be made available to a crop.

New P Fertilizers

In addition to the various inorganic fertilizers mentioned above, it is worth highlighting the newer inorganic P fertilizers that might be good options for agroecosystems with legacy P soils. Struvite is one such inorganic fertilizer option that shows promise with agronomic and ecological significance (Withers et al., 2014, Rowe et al, 2016; Schneider et al., 2019). It is a wastewater-derived substance comprised of magnesium ammonium phosphate (Grant & Flaten, 2019) so it is manufactured without mining more rock phosphate (RP). Research has shown that it can reduce the risk of P leaching and runoff compared with conventional fertilizers because it supplies the soil solution with a more slow-release form of P (Ahmed et al. 2016; Talboys et al., 2016; Hertzberger & Margenot, 2020). It is not as soluble as MAP, for example (Ackerman et al., 2013; Degryse et al., 2017). But soil type and the source from which the struvite is derived produce variable fertility results. And since few studies have investigated the impact of struvite on soil biology (Schneider et al., 2019) there are some gaps in our understanding of this source. More research is needed to develop clear guidance for managers on how to use struvite in their operations.

Other new P fertilizers may also improve crop P uptake. Weeks and Hettiarachchi (2018) have classified these new technologies based on their mechanism for improving efficiency: "inducers," which stimulate a crop's ability to access P, "blockers," which disrupt P fixation, "slow releasers," to encourage greater plant uptake and reduce fixation, or "alternative P sources," which are non-orthophosphate sources that are more likely to stay in soil solution (Weeks & Hettiarachchi, 2018). However, studies indicate that many of these new technologies may not work as well as hoped such as slow-release maleic-itaconic polymer coatings (Chien et al., 2014). Newly developed fertilizers still require more honing and testing until they can be definitively recommended to managers of annual cropping systems (Weeks & Hettiarachchi, 2018).

More questions than solutions remain for managers when it comes to determining the best source of P fertility when STP is already high. The development of slow-release P fertilizers and a better understanding of how new P fertilizers impact soil dynamics are needed (Sharpley et al., 2015). Finally, there is still much to be learned regarding the plant availability of organic P in the soil and determining the quantity of P made available to plants varies widely between cropping systems making it difficult to create accurate P budgeting (Schneider et al., 2019).

Right Place

Another nutrient management consideration when applying P fertilizer is the way that P is administered. Subsurface banding of dry or liquid fertilizer is most commonly mentioned in the literature to address the concern of dissolved P losses (Withers et al., 2014). Subsurface banding is a technique in which a tractor implement places a strip of inorganic P fertilizer under the soil surface in row or right next to a seeded crop (Havlin et al., 2016). Organic P fertilizer like liquid manure can also be applied in subsurface bands with a range of tractor implements that inject the P source into the soil (Maguire et al., 2011).

Subsurface banding of fertilizer at the time of seeding can be used to reduce P losses (Rowe et al., 2016, Zhang et al., 2019) and is a management technique thoroughly explored by Grant & Flaten (2019) in the northern Great Plains. Another study showed that chisel injected liquid swine manure reduced P runoff losses by 94% when compared with broadcast manure applications (Daverede et al., 2004). Subsurface banding is an environmentally sound and agronomically efficient way to apply P since it concentrates the fertilizer source right in the root zone where it is needed most by young crops (Withers et al., 2014; Jarvie et al., 2019). This is key in the early season when temperatures are low, P diffusion is slower, and crops need P in adequate amounts so that their growth trajectory gets off on the right foot and no yield penalties are suffered at harvest time (Zhang et al., 2019). As the plants grow, their root systems will explore a wider volume of bulk soil and can begin to draw down on other preexisting pools of soil P (Grant & Flaten, 2019). Another major benefit of banding is that less P fertilizer is typically required than the rates required to achieve adequate application rates when using the broadcast fertilization method. Additionally, concentrating P in one location also tends to reduce P fixation. However, its effectiveness is higher in soils with low P (Randall and Hoeft, 1986). For pH sensitive crops like canola, flax, or soybean, the seed and banded P must be kept a safe distance apart if electing to use inorganic fertilizers like MAP and APP, which lower the soil pH as they dissolve into solution (Grant & Flaten, 2019).

Keeping the banded fertilizer below the soil surface is key to ensuring that this technique is successful in its goals of environmental protection and agronomic efficiency. The fertilizer should be applied between 2 and 8 inches deep depending on the requirements of the crop being seeded with the band of P fertilizer (Havlin et al., 2016). If the band is placed too close to the surface, it may become inaccessible to the crop if the soil surrounding the band dries out leaving it "stranded" and unavailable to the intended crop recipient (Grant & Flaten, 2019).

Foliar feeding is a less common recommendation for P delivery to a crop although Rowe et al. (2016) and Withers et al. (2014) both mention its potential use for meeting crop P needs without adding much additional P to the soil. A review of a range of cropping systems demonstrated that results are variable on a crop-by-crop basis, so more information is needed before this technique is widely used (Withers et al., 2014). Another novel technique that requires more research is the application of P fertilizer via irrigation water, also known as fertigation. Its use for reducing P losses is only briefly mentioned in Sharpley et al. (2015).

Right Time

The timing of P fertilizer application involves important environmental and agronomic considerations for the reduction of P losses and the efficient use of P applied to fields or already present in the bulk soil. From an agronomic standpoint, the most critical time for adequate access to soil nutrients is in the early growth and development stages of a crop. For this reason, fertilizing at seeding is often recommended (Zhang et al., 2019). P access is important in the early growth stages because plant growth, biomass production, root elongation, and thus P uptake, can be restricted later in a crop's life cycle without adequate growth in the early phases (Grant et al., 2001; Zhang et al., 2019). However, this phase of early development often takes place in the early season when P mobility is slower because soil temperatures are lower resulting in less P uptake (Sheppard & Racz, 1984). So, ensuring crop access to P, especially shortly after germination, is important (Grant & Flaten, 2019).

From an environmental perspective, the periods of time when greatest nutrient losses can occur is during high precipitation seasons (Buda et al., 2009). In more northern climates, P fertilizer is lost in largest quantities as runoff during snowmelt (Tiessen et al., 2010). So, in these regions timing P applications for after snowmelt in spring is a key recommendation to reduce environmental losses (Osmond et al., 2019). For this same reason, fall applications of fertilizer in regions that experience winter snow cover is discouraged (Grant & Flaten, 2019).

Cycle P Already Present

The second major category of management recommendations are those that cycle and more effectively use the P in legacy P soils. For the sake of conceptual organization, these management strategies are separated into three scales: field, crop, and rhizosphere, although most management tools can work at multiple agroecosystem scales.

Field Level

At the field level, available management tools for improving P cycling relate to irrigation, soil amendments, and tillage.

Irrigation Management

In a legacy P soil system where a manager is attempting to access as much of the legacy P present in the soil as possible while reducing dissolved P losses, irrigation management should be considered. The first irrigation goal of accessing as much of the soil P as possible is primarily achieved through consistent crop access to soil moisture. Adequate soil moisture ensures that water or nutrient transport via soil water is not the limiting factor for maximum biomass generation, which creates the opportunity for maximum P uptake by the crop. Soil moisture is also important for stimulating biological activity (Havlin et al., 2016), which can contribute to increased P mineralization (Schneider et al., 2019).

The second goal of reducing losses involves a closer examination of irrigation type. Choosing an irrigation management strategy that does not contribute to runoff is key for legacy P soils since this is a major pathway for P loss. In vegetable annual cropping systems, for example, drip irrigation is ideal to provide water to crops without contributing to losses such as runoff (Wallace, 2000), since the system delivers water right to the crop root zone. The best option for reducing losses in a fertigated system is the inclusion of a soil moisture sensor that shuts the irrigation off when the soil moisture reaches a predetermined critical concentration (Prathyusha & Suman, 2012). Overall, irrigation management can play a role in legacy P soils by improving P drawdown through optimal crop biomass and yield generation while reducing the need for P inputs and reducing the P losses by careful technique selection and monitoring.

Soil Amendments

There are a wide range of soil amendments to consider that may either solubilize or increase the precipitation and adsorption capacity of P in legacy P soils depending on the control a manager needs to exert on the P in the soil. One of the most well-known soil amendments used to improve a crop's access to soil P and other nutrients is lime or other such amendments whose primary purpose is to alter soil pH such that the optimal range for nutrient uptake is achieved. As discussed previously, keeping soil pH in the 6 to 6.5 range is ideal. Below 5.4 pH or above pH 7.0, P will more readily precipitate with Al or Fe and Ca minerals respectively and move out of the soil solution (Brady & Weil, 2017; Kleinman, 2017). In the Mid-Atlantic, the primary management concern is to raise soil pH because the soils are commonly acidic (Fanning et al.., 2010). Calcitic lime containing calcium carbonate ($CaCO_3$) or dolomitic lime containing magnesium carbonate ($CaMg(CO_3)_2$) can be used to raise the soil pH by neutralizing the hydrogen ions (H+) in the soil solution (Havlin et al., 2016).

The application of silicon (Si) may also improve the availability of P already present in the soil. Si has been shown to mobilize more P from the soil into annual crops. Si field trials have also demonstrated a clear promise in the amendment's ability to bring the soil P into solution by substituting for P on the soil matrix. For annual cropping systems with legacy P soils, Si could provide a solution to the common issue where soil dynamics and low early season temperatures prevent the mobilization of P in the soil for early seedling growth (Qin & Shober 2018). Si amendments have been shown to reduce disease instance (Heckman et al., 2003), buffer abiotic stressors (Owino-Gerroh & Gascho, 2004), and increase P concentrations in plant tissues (Fisher, 1929; Owino-Gerroh & Gascho, 2004). Taken together, these factors overall contribute to a healthier crop that is more able to take up P from the soil.

In the situation where a manager needs to dramatically reduce P losses, amendments that increase sorption capacity are a potential option requiring more investigation. One novel approach recommended in the literature for increasing P adsorption to prevent losses is the application of industrial biproducts that increase P sorption capacity in the soil. Field studies indicate that applying chemical substances high in Al, Fe, Ca, or Mg such as alum, gypsum, ferrihydrite, water treatment residuals and fly ash from coal burning like bituminous refuse ash can be successful at removing P from the soil solution (Kleinman et al., 2011; Rowe et al., 2016; Kleinman et al., 2017; Qin & Shober, 2018; Osmond et al., 2019). As a sidenote, some studies suggest that the chemical compounds may also be mixed with composted manures to reduce P loss when they are field applied (Warren et al., 2006; Huang et al., 2016; Kleinman et al., 2017). In soils with extremely high STP and great risk of dissolved P loss due to site hydrology, these chemicals may be used to mitigate the loss of dissolved P. However, little is known about the risk of unforeseen soil contamination from heavy metal presence or the long-term fate of P that is sorbed by some of these materials (Penn et al., 2011), so more research is needed before their use is more broadly recommended.

A second novel approach for increasing the P sorption capacity of a legacy P soil is the use of biochar as a soil amendment (Sharpley et al., 2015). In principle, biochar addresses high soil P in the same way as the industrial residuals: by increasing the P sorption capacity of the soil. Biochar is produced by heating a carbon source in the partial or total absence of oxygen (Spokas et al., 2012). Biochar seems to exhibit a strong ability to adsorb P, which could reduce dissolved P losses from a soil system (Zheng et al., 2020). However, its ability to reduce P loss from the soil system seems to diminish in mineral soils when compared to organic soils (Riddle et al., 2019). Soil pH may also determine a biochar's capacity to adsorb P. In one study, biochar application on alkaline soils increased desorption (Xu et al., 2014). In the same study, acidic soils that received biochar applications significantly increased P adsorption only when P additions were high (Xu et al., 2014). Additionally, the carbon source used to make the biochar results in a wide range of P-sorbing abilities. Biochar made from cassava straw and banana straw, which are high in magnesium (Mg) seem to show the highest potential for P adsorption (Wu et al., 2019). Questions still remain about the best strategies for implementing biochar as a P-sorbing soil amendment and if the practice is scalable.

Tillage

Tillage is a complex management decision in legacy P soils because no-till and conservation tillage systems tend to reduce the quantity of P lost via erosion but increase the quantity of P lost via dissolved P. In no-till systems, P accumulates close to the soil surface and can therefore be more easily lost via runoff in higher quantities than tillage systems (Kleinman et al., 2011; Kleinman et al., 2019). The planting of cover crops, a BMP typically associated with a reduction in P loss from an agroecosystem, in concert with no-till may further concentrate organic P at the soil surface and, thus, further exacerbate the loss of dissolved P (Jarvie et al., 2017). Unfavorable hydrology can worsen this problem and cause even more dissolved P to be lost from no-till systems in legacy P soils (Buda et al., 2009; Qin & Shober, 2018). In a highly controlled experiment, Sharpley (2003) showed that overall, tilling legacy P soils might actually reduce overall P losses from a soil system because of reduced dissolved P losses in runoff. And various papers recommend periodic tillage as a potential management option in legacy P soils to adsorb more P in the soil and to reduce surface P concentrations through the soil mixing generated by tillage (Kleinman et al., 2011; Kleinman 2017). More research is likely needed to understand when this might be more helpful than harmful to reducing P losses.

Other papers present counterarguments to using tillage as a P loss mitigation (Qin & Shober, 2018; Grant & Flaten, 2019). No-till may still be preferred because field studies have demonstrated that while dissolved P losses may be elevated under a no-till regime, P losses via erosion are commonly greatly reduced such that overall P loss is reduced (Sharpley & Smith 1994). Eliminating all tillage from a cropping system may not be possible. But simply reducing tillage typically improves soil health (Qin & Shober, 2018) and enhances soil biology (Grant & Flaten, 2019). Soil health and biology enhancement overall indicates that conservation tillage is likely better for P management. Conservation tillage should be the top choice but a dramatic increase in dissolved P loss from a system may require a manager to revisit this decision on a case-by-case basis (Osmond et al., 2019).

Crop Level

At the crop level, available management tools relate to cover crops, crop selection, and cropping system.

Cover Crops

The incorporation of cover crops in an annual cropping system has traditionally been used as a nutrient management BMP because their use reduces soil erosion (Fageria et al., 2005). They may also be used for reducing dissolved P losses. A large body of research on the relationship between cover crops and dissolved P focuses on their ability to trap P in an agroecosystem. And many of the papers summarized in Table 3 promote their use to reduce P losses (Sharpley et al., 2015, Rowe et al., 2016; Osmond et al., 2019; Schneider et al., 2019). Overall, cover crops may be used in a diversity of ways and the best strategy for implementation to minimize dissolved P losses and receive some of cover crops' other benefits will need to be decided by a manager on a case-by-case basis.

There are many reasons why planting cover crops may reduce dissolved P losses. Cover crops can take up more P from the soil solution because of their extensive root architectures, which can explore and intercept more P in the soil when compared with many cash crops (Fageria et al., 2005). Additionally, cover crop grasses such as barley can be used to augment the presence of AMF (Hontoria et al., 2019), which is widely recognized as a soil microbe that improves plant P uptake. Just like many types of plants, cover crops that develop symbioses with AMF can take advantage of AMF's vast mycelial networks with high turnover rates that rapidly explore a greater soil volume to intercept and transport P to a crop's roots (Smith & Smith 2011).

Planting mixes of different cover crop species can magnify the overall impact of cover crops. For example, cover crop mixes that include legumes as well as cereals have been shown to mobilize more soil P than a leguminous cover crop planted alone (Maltais-Landry, 2015). Diverse cover crop mixes strengthen AMF associations, build better soil structure, and add more organic matter when compared with single species cover crop stands (Rowe et al., 2016). Finally, cover crop mixtures often increase soil microbial diversity and biomass production more than a single cover crop species (Hallama et al., 2019).

In addition to our understanding of cover crops as nutrient management BMPs and soil biological stimulants, more recent research suggests that cover crops may make P available for uptake by a subsequent crop. From a microbial perspective, cover crops can grow the soil's microbial P biomass and P enzymatic activity, which may increase their ability to take up and cycle P (Hallama et al., 2019). Buckwheat planted as a cover crop is worth specifically highlighting for its unique ability to cycle soil P. In high Al soils especially, buckwheat secretes organic acids, which can solubilize previously fixed P (Zheng et al., 1998). In a field study, buckwheat took up over 20 kg ha^{-1} more inorganic P than spring wheat, and more P was found in plant-available P pools in the soil after harvest (Teboh & Franzen, 2011). However, the ability of the buckwheat-mobilized P to be taken up by a subsequent crop was not demonstrated (Teboh & Franzen, 2011). Many other types of cover crop may bring P into the soil solution as well. A greenhouse study on cover crops demonstrated that a wide range of cover crop residues resulted in a similar amount of P uptake by a subsequent wheat crop to the amount of P taken up by the wheat crop planted with mineral P fertilizer (Maltais-Landry & Frossard, 2015).

Overall, leguminous cover crops may also increase subsequent crop P uptake by maximizing N availability. Legumes support biological nitrogen fixation (BNF) thus improving the chances of maximizing biomass production and P uptake by making N available at higher rates (Vance, 2001). Further, leguminous cover crops like white lupin are known to exude organic acids into the soil, which may bring more P into the soil solution for subsequent plant uptake (Neumann et al., 1999). And in another greenhouse P isotope study, Noack et al. (2014) demonstrated that a pea cover crop can supply agronomically significant quantities of P to a subsequent wheat crop. Between 9 and 44% of the P in the wheat crop was supplied by the pea with the highest levels of P provided when the cover crop residues were incorporated into the soil (Noack et al., 2014).

The topic of incorporation brings up the important management consideration of cover crop termination. When a manager needs to prepare a field for cash crop planting, the cover crop will need to be terminated, which can be done during a range of cover crop growth stages and in a variety of ways such as spraying herbicide, mowing and incorporating (i.e. tilling) into the soil, roller crimping, or waiting for a killing frost. All of these factors introduce a wide range of variability in the impact of a cover crop. For example, nutrient ratios in the cover crop biomass will vary greatly depending on the timing of termination, which will impact the mineralization or immobilization of soil nutrients to a subsequent crop (McClelland et al., 2021). In the greenhouse experiment mentioned above, the incorporation of the crop residues, which mimics tillage, was beneficial to the transfer of P to a subsequent crop (Noack et al., 2014). Managers who opt for no-till systems will use equipment like a roller crimper or, commonly, a chemical control to terminate a cover crop. These strategies do not require that any soil be inverted, which may be desirable because leaving the cover crop roots in place and the soil undisturbed can augment the biological activity generated by a cover crop planting. For example, a meta-analysis of cover crop and tillage techniques indicates that reducing tillage in annual cropping systems that maintain a cover crop stand in the winter increases AMF associations for a summer cash crop (Bowles et al., 2017).

However, some managers may prefer to use non-chemical termination methods or be concerned with the environmental implications of using glyphosate or other herbicides. In the case of glyphosate, a phosphoric acid, its use may contribute to greater dissolved P losses in runoff and leaching (Hébert et al., 2019) and the persistence of the herbicide in the soil (Mamy et al., 2016). To terminate a cover crop without a chemical control in a no-till system, managers may use tractor-mounted implements like flail mowers, roll-choppers, or roller crimpers that kill the cover crop and lay it down as a mulch layer on the soil surface (Hallama et al., 2019). However, some studies indicate that this technique may actually immobilize P and other soil nutrients and reduce microbial activity in the soil (Hefner et al., 2020). To complicate things further, one last cover crop termination option is to let a killing frost handle the job. Seen through a certain lens, this may go against the soil health principle of maximizing the presence of living roots. However, in one field experiment, frost-killed cover crop produced higher rates of soil carbon than rolled cover crop or cover crops treated with herbicide (Romdhane et al., 2019). But a review of 41 cover crop studies in cold climates revealed that in certain conditions, freeze-thaw cycles and killing frosts generally promote the release of dissolved P via runoff and leaching in the winter months (Liu et al., 2019). This P may come from both the release of P from the microbial biomass generated by the cover crop as well as the rupture of the cover crop plant cells that can then lose nutrients when water washes over their leaves (Liu et al., 2019). Overall, these are complex issues for managers to weigh when deciding on the best cover crop termination strategy.

The recommendation to incorporate cover crops into a cropping system is backed by a well-established body of research for improving soil health and reducing nutrient losses via soil erosion (Sarrantonio & Gallant, 2003). But even more research is still needed to better understand their impact on dissolved P losses and P cycling within an agroecosystem. It is possible, for example, that cover crop planting may increase dissolved P losses due to increased rates of infiltration (Osmond et al., 2019). On the other hand, some P budget models that suggest that cover crop residues incorporated into the soil may provide enough P for the next crop (Damon et al., 2014), which could diminish the need for fertilizer inputs. However, a cover crop's ability to mobilize P so that it is taken up by a subsequent crop is highly variable and not always successful (Maltais-Landry et al., 2014; Hallama et al., 2019). Some fertilization in an annual cropping system whose goal it is to achieve maximum yields will likely still be required (Horst et al., 2001; Hansen et al., 2022). Gaining a better understanding for the rates and time frames in which cover crop species take up and mineralize P will allow managers to reduce dissolved P losses and to develop more accurate P budgets and potentially reduce reliance on additional P inputs (Dodd & Sharpley, 2015).

Crop Selection

Crop breeding for increased P uptake is often recommended by authors promoting solutions to reduce agroecosystem P losses (Schneider et al., 2019). While breeding is commonly beyond the scope of work for a manager of an annual cropping system, crop selection is an important decision made when a farmer is planning what they will plant. In legacy P soils, a manager may decide what crops to grow in legacy P soil based on their unique ability to utilize the P already present without any starter P fertilization (Rowe et al., 2016).

When identifying annual crops that can increase P uptake from legacy P soils, required STP levels, root architecture, biological symbioses, and P mining abilities are important to consider. Annual vegetables often require P in relatively high STP levels. For example, both tomato and lettuce crops require soil P concentration to be relatively high when compared with other row crops (Havlin et al., 2016) yet do not take up much P from the soil (Johnstone et al., 2005; Maltais-Landry et al., 2016). Therefore, vegetables are likely not the right crop for managing legacy P soils. However, it is worth noting that in a field study, some cucurbit species like cucumbers and yellow squash accumulated relatively high rates of P in high P soils (Sharma et al., 2007). In some cases, the dry weight P in these crops were as high as 1.4% P (dry weight) in vegetative and fruit biomass (Sharma et al., 2007).

Though pasture and forage crops are beyond the scope of this paper, it is worth noting that there are numerous field studies that indicate a heightened ability to draw down legacy P in pasture or forage cropping systems that are grazed or harvested for hay when compared with grain production (Dodd et al., 2014; Kleinman, 2017; Fiorellino et al., 2017). This shift in management regime is worth considering in situations where annual cropping systems need more extreme remediation to confront the legacy P issues.

In general, root architecture plays a role in a crop's ability to take up P (Havlin et al., 2016). For example, the root architectures of maize and legumes like beans and soybean (Zhang et al., 2019) are optimal for exploring topsoil for available P, making them excellent crop selections in no-till and other systems where organic P and applied P fertilizer are present in large quantities closer to the soil surface (Richardson et al., 2011). Additionally, associations with AMF are important to consider as AMF may be able to access pools of P not readily available to a crop (Richardson et al., 2011; Schneider et al., 2019). Cereal grains are a promising selection for increased P uptake because they often host strong beneficial associations with AMF. Leguminous crops also benefit from symbiotic relationships with AMF (Richardson et al., 2011). And as mentioned in the cover crop section, legumes can increase P solubility in their rhizosphere by secreting organic acids (Ae et al., 1991), though this ability varies greatly by legume type (Pearse et al., 2006). For managers of legacy P soils hoping to boost P drawdown through crop uptake, regular communications on the latest understandings of P uptake rates from specific crops and varieties will be needed from research institutions.

Cropping System

Intercropping, crop rotation, and crop intensity are three cropping system considerations that can play a role in the cycling or reduction of losses of the P present in legacy P soils. Intercropping has been shown to be a strong system for P cycling and crop uptake especially in cereal-legume systems (Tang et al., 2014; Rowe et al., 2016; Zhang et al., 2016). Schneider et al. (2019) promotes intercropping for its potential to improve the uptake of P present in agricultural soils through the occupation of different sections of the soil profile by complementary crop roots and the facilitation of improved microbial dynamics.

Recent studies suggest that the intercropping of cereals and legumes improves P cycling in the soil relative to monocrop systems. In a maize-faba bean intercrop field study, maize root length was longer and faba bean increased the quantity of organic acids secreted into the soil both of which improved crop P acquisition in comparison to the monocropped fields (Zhang et al., 2016). Another recent field study ties the efficient cycling of P to the improved P dynamics in the rhizosphere of an intercropped system. Tang et al. (2014) observed that P availability in durum wheat-lentil and durum wheat-chickpea intercrops significantly increased available P in the rhizosphere when compared to the bulk soil. Relatedly, the pool of microbial biomass of P increased in the rhizospheres of both the durum wheat and the chickpea when intercropped and in the lentil rhizosphere when intercropped with the durum wheat in comparison to the bulk soil (Tang et al., 2014). Research into the crops and varieties whose rooting systems develop an advantageous niche partitioning of soil nutrient resources is an important area for further study.

Crop rotation is another tool for improving soil P cycling (Sharpley et al., 2015; Schneider et al., 2019). One consideration for this framework is the contribution that a crop has to the proliferation of AMF in the soil. Grant & Flaten (2019) suggest that crops highly reliant on associations with AMF, such as corn and flax, should not be placed in rotation immediately after brassica crops like canola, which diminish AMF soil presence in an agroecosystem. Another practice is the addition of a legume cover or cash crop into the rotation for the benefits previously described related to legumes and P uptake (Zhang et al., 2019). Legumes' strong association with AMF (Richardson et al., 2011), secretion of organic acids that can dissolve P into the soil solution (Ae et al., 1991; Neumann et al., 1999), and ability to assimilate P into their biomass so that it may be decomposed and mineralized for a subsequent crop (Noack et al., 2014) make them an excellent crop to include in a rotation for improved P cycling. Additionally, newer research indicates that organic P is perhaps a larger pool of available P than previously believed so more research is needed to better understand other ways that crop rotation may contribute to greater organic P pools in the soil (Schneider et al., 2019).

Finally, it may be important to consider the intensity of operation that can be environmentally supported in an agroecosystem with legacy P soils. Sharpley et al., 2015 suggests that if soil P levels are increasing, a manager might need to use a less intensive production system to reduce significant nutrient losses that can cause very long-term environmental degradation. For example, though there may be many barriers to successful implementation, it may be worth considering a transition from annual cropping to pasture as mentioned in the previous section.

Rhizosphere Level

The rhizosphere dynamics in an agroecosystem is an area of crop production that is currently of great interest and one for which much more study is required. Rhizosphere level management considerations to promote plant-microbial P interactions in the root zone as well as use of biostimulants to improve P uptake are discussed below.

Promoting Plant-Microbial P Interactions

There is still much to learn about the impact that plant-microbe interactions can have on cycling P in an agroecosystem. A growing body of evidence suggests that P made available via biological soil processes and their correlated organic pools of P can have a greater contribution to available P than once thought (Schneider et al., 2019). Both fungi and bacteria are important to making P available to crops.

As explored in previous sections, most plant species have some type of association with AMF, which can improve P mobilization and crop uptake (Rowe et al., 2016; Grant & Flaten, 2019; Schneider et al., 2019). Plants alone may also secrete organic acids to bring P into solution (Sharpley et al., 2015). Soil bacteria are another important category of plant-microbe interaction to consider for improved P cycling. A wide range of P solubilizing microorganisms (PSM) are known to mineralize P through the excretion of organic acids and enzymes into the soil solution (Khan et al., 2009). There is no consensus on what soil temperature produces the highest rates of P solubilizing by soil microbes but, in general, warmer temperatures contribute to higher P mineralization (Alori et al., 2017).

The main way that managers can increase soil microbial biomass is through the addition of organic matter to an agroecosystem (Dodor and Tabatai, 2003; Simpson et al., 2011; Schneider et al., 2019). Therefore, the addition of cover crops, organic P fertilizers, and tillage decisions can all contribute to the growth of microbial biomass in the soil. Additionally, crop rotation can also increase the presence of PSM because of the diversity of organic matter it introduces to the agroecosystem through diverse crop residues (Azziz et al., 2012). More crop- and microbe-specific research is needed to understand more specific ways that managers may foster greater plant-microbe P interactions in the agroecosystems that they manage.

Biostimulants

Managers may also attempt to influence soil P dynamics in the rhizosphere through the application of biostimulants (Withers et al., 2014; Sharpley et al., 2015; Zhang et al., 2019). Biostimulant is an umbrella term for substances and microbes that are applied in some way to the soil or a crop for the purposes of enhancing crop growth (Calvo et al., 2014). There are a range of ways a manager might use biostimulants. Commercially available biostimulants may be sold as amendments to be mixed with seed, compost, potting soil, or field soil (Calvo et al., 2014; Mehta et al., 2014). They are of growing interest in the realm of sustainable agriculture for their potential to enhance ecosystem services without the need for nutrient inputs that can be easily lost to waterways and cause pollution (Sharpley et al., 2015). Biostimulants may also be combined with fertilizers to improve their uptake by a crop (Zhang et al., 2019).

Biostimulants include a wide range of organic acids, protein-based plant stimulants, seaweed extracts, and microbial inoculants (Calvo et al., 2014). We know little scientifically about the mode of action of many of these biostimulants (Sible et al., 2021). But those that seem to play the largest role in terms of P availability include organic acids and phosphorus solubilizing microbes (PSM) (Sible et al., 2021).

Organic acids (i.e. humic acids and oxalic acids) appear to dissolve mineral and organic P into the soil solution for plant uptake by competing for soil adsorption sites (Guppy et al., 2005). Additionally, humic acids may contribute to increased microbial biomass, increased crop root and shoot growth, and increased soil N and P (Sible et al., 2021). Mixing organic acids with inorganic fertilizers at a rate of 1:5 by weight may also increase crop yields and P uptake while reducing P fixation (Shen et al., 2023). But the impact that an organic acid has on a crop may depend on the source from which the organic acid is derived. Humic acid produced from compost may be more effective than humic acid produced from peat or lignite, for example (Sible et al., 2021).

PSM likely mineralize P into the soil solution by secreting organic acids that compete for P sorption sites in the soil matrix and that dissolve Ca-P into the soil solution (Sible et al., 2021). There are many PSM that have been identified as improving P availability to a crop. AMF, which have already been discussed in previous sections, form symbiotic relationships with a plant's roots, explore a larger soil volume than that plant, and supply P in exchange for sugars. Other fungi such as *Aspergillus* and *Penicillium* may also serve as efficient PSM (Sible et al., 2021). Gram negative bacteria seem to be better at making P available compared to gram positive bacteria (Sible et al., 2021). *Bacillus*, *Pseudomonas*, and *Rhizobium* bacteria have also been shown to solubilize P (Sible et al., 2021). *Bacillus megaterium M3* was identified in field trials as a very promising PSM for its ability to increase phosphatase activity, microbial biomass, and crop P uptake (Sible et al., 2021). However, it had less effect on sterile greenhouse soil than on native soil indicating it may have a unique ability to enhance overall native PSM activities (Sible et al., 2021).

In general, the use of organic acids and PSM present promising options for increasing the quantity of plant-available P. But there is still a lot to learn about the best ways to commercialize effective biostimulants as well as the ways that biostimulants impact rhizosphere dynamics. Moreover, the variability in the intensity of response to biostimulants indicates that much more research is needed to better understand their impact before they are widely recommended to field managers (Grant & Flaten, 2019).

Economic Impacts of Legacy P Management

An in-depth analysis of the economic impact of adopting the management strategies described above is beyond the scope of this paper. However, it is worth noting that from an agronomic perspective, many of these management recommendations may not be economically feasible for a farm business to shoulder without support. So, it is worth noting, that these management strategies may increase costs or, as in the case of reducing P applications, result in yield penalties.

Spending money on new types of fertilizers, fertilizer application technology, irrigation systems, tractor implements, seeds, soil amendments, and biostimulants may increase the overall operational expenses, at least initially. In these cases, management strategies that have sound potential for reducing dissolved P losses regionally ought to be promoted by state and local governments via subsidies to increase the likelihood of adoption. In the case of cover crops, which have already been promoted to reduce erosion, the practice has been more widely adopted in Maryland than in Pennsylvania (Kleinman et al., 2019). This is likely because the Maryland state government has provided more financial support to farmers for adopting the use of cover crops (Kleinman et al., 2019).

Shifts in management may also contribute to a reduction in farm income or higher costs. For example, if a manager decides to produce a new crop that increases P uptake such as cucumbers, the agronomic value of the crop may be less than the income that they could earn on a crop that takes up less P (Fiorellino, 2017). In the extreme example of shifting from annual crop production to a pasture rotation, there may be numerous expenses related to infrastructure, inputs, and professional development involved in the change. Finally, without the insurance-based P applications commonly implemented in annual cropping systems, it is possible that even managers of high P soils may experience yield penalties because of the slow rate of P diffusion and root interception of the crop root with the nutrient (Withers et al., 2014; Qin & Shober, 2018).

Conclusion

The issue of legacy P soils is a complex environmental and agronomic concern, which impacts ecologically sensitive waterways as well as managers of annual cropping systems. Historically, P has been overapplied via insurance-based approaches to soil P fertilization. This previous practice stemmed from the geographic concentration of livestock operations needing to offload an abundance of manures as well as a misunderstanding of the many ways that P can be lost from the agroecosystem. In addition to addressing P on a regional level via coalition work and watershed studies, clear management strategies need to be developed to better use the P in legacy P soils for agronomic benefit and to reduce particulate P as well as dissolved P losses from agroecosystems. Presently, managers of annual cropping systems have few tools to specifically address dissolved P loss, which has prevented initiatives like the Chesapeake Bay Program from achieving anticipated reductions in nutrient pollution. This paper summarizes some of the various recent recommendations to address dissolved P loss. Further efforts to collect and organize management techniques will be needed as scientific understanding of managing legacy P soils improves.

Table 2. Management of Dissolved P Loss in Annual Cropping Systems

See supplementary document

Table 3. Avoid & Cycle P Management Strategies

See supplementary document

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Table 2. Management Strategies to Avoid & Cycle P

Avoid P		Cycle P		
Eliminate P applications	**Smart P Applications (4Rs)**	**Field scale**	**Crop scale**	**Rhizosphere scale**
Cease P applications	Use RIGHT rate: - Work towards STP levels equivalent to crop removal rate - Apply fertilizer at "critical" level for region and crop * - Use variable application rates - Apply adequate rates of fertilization for other crop nutrients	Irrigation: - Ensure adequate soil moisture to stimulate soil microbes, maximize crop biomass, and P drawdown - Choose strategy that does not contribute to runoff (e.g. drip irrigation) - Irrigation shut-off by moisture sensors is optimal	Cover Crops: - Plant cover crops to mobilize P for subsequent crop * - Incorporate legumes and grasses to augment P uptake - Use cover crop mixes to magnify cover crops' P uptake abilities - Use Buckwheat to take up and cycle P in higher quantities than other cover crops (and in high Al soils)	Promote Plant-Microbial (P-M) P Interactions: - Promote management strategies to support AMF, PSB, and other Phosphate solubilizing microorganisms (e.g. Add SOM, reduce tillage, consider crop rotation) *
	Use RIGHT source: - Choose carefully from wide range of options. Consider soil reactions. - One option: inorganic fertilizer banded at seeding - Another option: boost SOM with organic fertilizers; only to crop P	Soil Amendments to increase P availability: - Control soil pH by applying lime - Use amendments that mobilize P (e.g. Si)* Soil Amendments to adsorb P/decrease availability for severe circumstances:	Crop selection: - Select crops with optimal root architecture (e.g. Corn, beans, soybean) - Select crops with strong AMF associations (e.g. Cereal grains) - Consider incorporating	Biostimulant applications may be used to promote microbial activities that solubilize soil P*

	requirements and supplement with inorganic fertilizers for remaining N needs - Use struvite * - Use new fertilizer technologies (e.g. SR polymer coatings) *	- Use amendments that increase sorption capacity (e.g. industrial biproducts, alum, biochar) *	legumes (strong AMF relationship and P solubility capacity)	
	Use RIGHT place: - Apply subsurface band - Apply through foliar feeding *	Tillage: - Weigh the +/- of each system type given the local soil type, hydrology, fertilizer application systems, etc. (Conservation tillage may increase dissolved P losses but decrease P losses overall) *	Cropping/planting system: - Intercrop (e.g. Cereal grains and legumes) - Rotate crops (e.g. Consider which crops promote or require higher AMF associations) * - Consider cropping intensity (e.g. Is pasture a better option than annual cropping?)	
	Use RIGHT time: - Apply in early spring - Apply after snowmelt - Avoid heavy precipitation windows - Avoid fall applications			

*** More research needed before impact on dissolved P is fully understood**

Table 3. Holistic Recommendations from the Literature for Management of Dissolved P Loss in Annual Cropping Systems

	AVOID P		**CYCLE P**			**RECOMMENDATIONS UNRELATED TO DISSOLVED P LOSS MANAGEMENT**
Article	**Cease P applications**	**Smart P Applications (4Rs)**	**Field scale**	**Crop scale**	**Rhizosphere scale**	
Kleinman et al., 2011. "Soil controls of phosphorus in runoff: Management barriers and opportunities."		Right Rate: - Set thresholds and maintain for STP levels *	Soil Amendments: - Apply P sorption materials (PSMs) (e.g. Alum, gypsum, ferrihydrite) Tillage: - Till soils with enriched P *			- Management of sediment-bound P - Hydrology considerations - Identification of "critical source areas"
Withers et al, 2014. "Feed the crop not the soil: rethinking phosphorus management in the food chain.	Eliminate "insurance"-based approach to P fertility	Right Rate: - Target the crop P needs - Maintain crop yields at lower STP * Right Source: - Use slow release fertilizers - Use struvite * Right Place: - Use foliar feeding			Plant-Microbe interactions/ biostimulants: - Use biostimulants *	- Public awareness campaigns on environmental consequences of dietary choice - Crop breeding - Waste product P recycling
Sharpley et al., 2015. "Future agriculture with minimized phosphorus losses to	Avoid excessive P applications	Right Source: - Use slow-release fertilizers - Mix mineral and organic P fertilizers	Soil Amendments: - Apply PSMs (e.g. biochar) *	Cover Crops: - Plant cover crops Cropping system: - Use diverse crop rotations	Plant-Microbe interactions/ biostimulants:	Policy and research initiatives related to: - Crop breeding - Waste management - Hydrology

waters: Research needs and direction."		Right Place: - Apply P via fertigation *		- Reduce cropping intensity on vulnerable landscapes	- Engineer the rhizosphere with root exudates * - Use biostimulants *	- Livestock systems - P loss monitoring, modeling, and communication - Techniques to measure microbial P processes - BMPs efficacy evaluation
Rowe et al., 2016. "Integrating legacy soil phosphorus into sustainable nutrient management strategies for future food, bioenergy and water security."	Draw down on STP to agronomic optimum	Right Rate: - Keep applications low to promote biological P cycling * - Consider N fertilizer soil reactions and how that may affect P uptake Right Source: - Use struvite * Right Place: - Use Seed dressings - Apply "placed" P - Use foliar feeding *	Soil Amendments: - Apply PSMs * Tillage: - In some situations, targeted tillage may reduce dissolved P losses *	Cover Crops: - Plant diverse cover crop mixes Crop selection: - Choose crops that draw down on legacy P (e.g. white clover, high yielding crops) * Crop System: - Include legumes in crop rotation	Plant-Microbe interactions/ biostimulants: - Promote AMF presence - Manage system to promote soil P biological processes *	Policy and research initiatives related to: - Crop breeding - P recovery and recycling
Kleinman, et al. 2017. "The persistent environmental relevance of soil phosphorus sorption saturation."	Cease P applications on soils with high P sorption saturation		Soil Amendments: - Apply lime to maximize P availability - Apply PSMs (e.g. those rich in Al and Fe to acidic soils) * - Amend compost/manures with alum Tillage: - Use selective tillage in "critical			Policy and research initiatives related to: - Promotion of use of P sorption capacity tests as environmental risk indicator - Forage cropping system STP draw down - Fertility recommendation revisions to account for PUE of modern varieties and current understanding of soil P dynamics.

			source" areas to reduce soluble P *			
Qin & Shober, 2018. "The challenges of managing legacy phosphorus losses from manure-impacted agricultural soils."	Draw down on legacy P	Use 4R nutrient stewardship Right Rate: - Account for biological P contributions *	Soil Amendments: - Phosphorus sorbing materials may be used but need more research * - Use Si and organic acids to increase P solubility * Tillage: - Use no-till and CT			- Buffer strips - Constructed wetlands - Hydrology - Construction of P removal structures (PSMs)
Osmond et al., 2019. "Increasing the effectiveness and adoption of agricultural phosphorus management strategies to minimize water quality impairment."	Reduce STP as low as agronomically possible	Right Rate: - Maintain crop yields at lower STP * Right Time: - Apply fertilizer(s) after snowmelt	Soil Amendments: - Apply PSMs (e.g. industrial biproducts and gypsum) Tillage: - Include CT (but consider increased dissolved P loss management)	Cover Crops: - Plant cover crops (but consider subsurface P losses because of increased infiltration)		- Watershed-scale conservation - Buffer strips, wetlands, and stormwater P filters - Hydrologic transport pathway considerations - Financial incentives for farmers
Schneider et al., 2019. "Options for improved phosphorus cycling and use in agriculture at the field and regional scales."	Eliminate "insurance"-based approach to P fertility	Right Rate: - Maintain crop yields at lower STP * - Keep applications low to promote biological P cycling * Right Source: - Use struvite *		Cover Crops: - Plant cover crops Crop selection: - Select crop/cultivar for P uptake Crop System: - Intercrop & use crop rotations * - Plant grains and legumes in rotation	Plant-Microbe interactions/ biostimulants: - Promote AMF presence - Manage system to promote soil P biological processes * - Increase SOM to promote organic P mineralization	- Regional P cycling (5Rs promoted by Withers et al., 2015) - P recovery and recycling technologies - Crop breeding - Research to update "critical" STP concentrations for soil type and crop

Zhang et al., 2019. "Management strategies to optimize soil phosphorus utilization and alleviate environmental risk in China."	Eliminate "build up and maintain" approach to P fertility	Right Rate: - Maintain crop yields at lower STP * - Apply sufficient N Right Source: - Use organic fertilizers in combination with inorganic fertilizers * Right Place: - Use banded applications Right Time: - At seeding		Crop selection: - Incorporate legume plantings for superior P uptake root architecture Crop System: - Use intercropping (e.g. cereal grains and legumes) - Use crop rotations (e.g. cereal grains and legumes)	Plant-Microbe interactions/ biostimulants: - Plant legumes for increased P mobilization * - Apply biostimulants * - Apply biostimulants in combination with fertilizers *	- Improve farmer outreach - Research specific P recommendations for wide range of cropping systems

* More research needed to delineate specific guidance for managers