

Improving the sustainability of phosphorus fertility management in Kansas

by

Megan Ashley Bourns

B.Sc., University of Manitoba, 2017

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AN ABSTRACT OF A DISSERTATION

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Abstract

Phosphorus (P) is an essential nutrient for crop production, often required in fertilizer form for optimum agronomic productivity; however, P loss from agricultural fields in runoff water poses a substantial environmental threat. Lost P contributes to P loading, eutrophication, and development of harmful algal blooms in surface water bodies. Because of the consequences of P loss, agronomic management of P has been under scrutiny in recent years, in an effort to develop best management practices around P fertilization and fertility management. Strategies are required that align both agronomic productivity and environmental protection goals.

A long-term study was developed at Ashland Bottoms, KS, to investigate the interaction between P fertilizer management strategies and cover crop use to manage P loss, in a corn (*Zea mays*)-soybean (*Glycine max*) cropping system. The study began with a build phase wherein soil P was increased, focused on the placement and timing effects of P fertilizer. Treatments included a zero P control (CN), fall broadcast (FB), and spring injected (SI) P fertilizer. Each of these treatments was expressed with (CC) and without (NC) a cover crop. The study then transitioned to a maintenance/drawdown period from 2020-2022; the treatments during this time included the two levels of cover crop (CC and NC), CN P fertilizer management, drawdown (DD) and build and maintain (BM) management.

During the build phase, both FB and SI P fertilizer management increased P access and utilization for the main crop and cover crop. Cover crop did not affect main crop P uptake, removal in grain, or return to soil in crop residue, but CC treatment increased total P uptake and return in the system. Cover crop effects on P uptake, removal, and return were the same regardless of P fertilization treatments. Phosphorus fertilizer and CC treatments did not affect agronomic P use efficiency. Both FB and SI P fertilizer management decreased environmental P

use efficiency, although SI tended to decrease it less than FB. The cover crop significantly improved environmental efficiency only in 2019, when it reduced erosion losses. Therefore, cover crops were not consistently beneficial for reducing environmental effects of P fertilization, and their use cannot replace the importance of sound P fertilizer stewardship, including sub-surface P placement. However, cover crops play an important role in improving environmental efficiency in years with high erosion loss potential. During the maintenance/drawdown phase, CC decreased main crop biomass for all P fertilizer management treatments, but did not affect P access or use by corn or soybean. Phosphorus nutrition was generally similar for both DD and BM management, with the exception of grain P removal in corn under CC management; BM increased grain P removal in corn significantly when a cover crop was used, compared to DD management under CC treatment.

During the three years of the maintenance/drawdown phase, DD management under NC was consistently most profitable. This was true even when corn yield was significantly lower with DD management compared to BM; in other words, the increased corn yield was not enough to offset the increased cost of BM management compared to DD, for that year. While STP did decline under DD management and P fertilization was withheld, improvement in water quality relative to BM was not consistent across all metrics. The DD and CC combination reduced P losses in just one of three years. On the other hand, CN P fertilizer management consistently reduced P losses; however, CN management is not a profitable option for producers and substantial incentives would be required for adoption of CN management as a conservation option. Further research is needed to determine the feasibility of drawdown under initially high STP as a mode to improve annual return, reduce P inputs, and reduce P loss from the system over time.

Historical data analysis and new field studies were conducted in KS to determine the feasibility of a new P fertilizer management paradigm, sustainable sufficiency (SSF). The SSF paradigm is based on establishing a lower STP threshold for maintenance, maintained through routine applications of P fertilizer at crop removal rates. Historical data analysis revealed there is no clear STP threshold for maintenance based on existing P rate studies from the state; however, P fertilization rates greater than crop removal were only needed 9% of the time to obtain optimum yield. This suggests there is likely room to explore maintenance thresholds below the current critical threshold for yield response. Field studies were used to evaluate the relationship between initial STP and relative yield of corn and soybean with a maintenance rate of P fertilizer applied. Higher STP did not increase corn and soybean yield with a maintenance rate of P fertilizer, indicating it should be possible to lower the STP threshold for maintenance management.

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Major Professor
Nathan O. Nelson

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Dedication

“You are on a staircase, on step seven, looking up at step 26 and focusing so hard on getting there. If you don’t look down, you’re going to fall on your face and look like an idiot. Focus on step eight.” – Brendan Bourns

For my brother. ‘Step VIII’ is now a daily reminder. You are wise beyond your years, giver of sage advice, and a built-in best friend. I cannot imagine doing life without you.

Chapter 1 - Introduction

Phosphorus (P) management is critical agronomically, to sustain our productive capacity, and environmentally, to protect surface waterways from harmful effects of escaped agricultural P. While fertilizer P is commonly applied to benefit crop production in the Great Plains, P lost via surface runoff has negative consequences including contribution to eutrophication and development of harmful algal blooms (Welch, 1978; Correll, 1998; Le Noë et al., 2018). Engaging conservation action by producers to reduce P loss is a challenge, especially because the amount of P lost in runoff events is relatively inconsequential, agronomically, but can have substantial consequences environmentally (Hart et al., 2004). Best management practices for agronomic P have been a key focus of aligning productivity and conservation goals (Singh et al., 2020) but further development of management solutions that are attractive to producers are required for widespread adoption.

1.1 Agricultural Phosphorus: Importance and Consequences

Phosphorus is a critical nutrient for energy capture, transformation, and utilization in crop plants (Correll, 1998; Grant et al., 2001; Schneider et al., 2019), all critical for yield development and successful completion of the growth cycle. As crop yield potential increases, crop demand for P and the necessity to increase P supply increase (Hopkins and Hansen, 2019), making P management a critical aspect of successful high-yielding systems. Much of the P acquired by crop roots through the growing season is translocated to grain and harvested, thus removed from the field (Hopkins and Hansen, 2019). Given the importance of P in fundamental physiological processes and the removal of relatively large portions of available P, poor P fertility management can be yield-limiting (Boring et al., 2018).

Crops access P from soil P reserves and from P fertilizer applications. The total amount of P in soils can be quite large, upwards of 500 mg kg⁻¹, but only a small fraction is agronomically relevant at any given time (Hart et al., 2004; Pierzynski et al., 2005; Medinski et al., 2018; Schneider et al., 2019). Soil P exists in different pools, typically grouped based on relative availability of the P forms to crops; Hansen et al. (2002) characterize the soil P pools as soluble, reactive, and stable. The soluble pool consists of P in soil solution, while the reactive and stable pools characterize P associated with solid soil surfaces (Hansen et al., 2002). Crops pull P from the soluble pool, out of soil solution, and the quantity of P present in the soluble P pool is typically very small at any point. Reactive P exists in equilibrium with soluble P, such that the reactive pool replenishes the soluble pool as P is taken up by crop roots from soil solution. The stable pool does not contribute to plant available P in the short-term but can supply P to replenish the reactive and soluble pools over time (Pierzynski et al., 2005). Generally, the soluble P pool and the portion of the reactive pool in equilibrium with the soluble pool are the sources of soil P that will supply crop growth (Hansen et al., 2002); in other words, to quantify agronomically relevant soil P for annual management, characterization of the soluble P and a portion of the reactive P pool are necessary.

1.1.1 Characterizing agricultural phosphorus

Soil testing is an important tool to characterize agronomically relevant soil P to inform beneficial fertilization. Tests for agronomic STP, such as the Mehlich-III test used in Kansas, quantify P from the soluble and, to some extent, reactive P pools (Hansen et al., 2002). The supply of P to crop roots is governed by complex chemical interactions in the soil, mediated by environmental conditions. Rather than providing a discrete amount of P available for the crop year, STP provides an index of agronomically relevant P (Maguire et al., 2005). This index

amount of STP can then be used to provide P fertilizer recommendations based on correlation with crop response, from crop response studies.

Because of the importance of adequate P fertility to yield development, fertilizer P is often applied to supplement soil P to ensure crop demand is met (Hart et al., 2004). In fact, a history of over-application of P in agricultural production systems has resulted in accumulation of P in our soils (Daryanto et al., 2017; Cong et al., 2020), referred to as legacy P (Osmond et al., 2019; Guo et al., 2021). Legacy P can be a supply of P for present day crop production (Rowe et al., 2016; Blackwell et al., 2019; Cade-Menun, 2022; Pavinato et al., 2024), however, this source of P is somewhat difficult to manage as soils will differ in the rate of STP build-up and drawdown, depending on parent materials, environmental conditions, and other factors (Dunne et al., 2021).

1.1.2 Consequences of loss

Carefully managing STP and P fertilizer is critical to reduce the environmental impact of our agricultural systems. Soil P, whether geologically or from previous fertilizer applications, and P that is applied in a given year, are both at risk of loss (Bolster et al., 2019). Most of the P loss in KS soils occurs through surface transport; runoff water interacts with the surface layers of soil as it moves across the field and can pick up nutrients, like P, and transport them off-field (Daryanto et al., 2017). The major forms of P carried off-field are dissolved P and particulate P (Hansen et al., 2002; Maguire et al., 2005). Dissolved P is in runoff water solution. Particulate P is attached to soil particles that are carried off-field in runoff. Phosphorus loading in surface water ways enhances growth of microbes otherwise limited by P availability, ultimately leading to algal bloom development (Bolster et al., 2019). Through the development of algal blooms, or the overgrowth of algae from the surge of P availability, light penetration and oxygen production

are reduced (Correll, 1998; Bolster et al., 2019; Hanrahan et al., 2021), creating hypoxia and stimulating eutrophication (Haque, 2021). Algal blooms can lead to fish kills and harm biodiversity of the ecosystem (Carpenter et al., 1998).

All forms of lost P from agricultural fields are a threat to surface waterways, whether immediate in the case of dissolved P, or over time in the case of particulate and organic P forms (Correll, 1998; Hansen et al., 2002). For P loss to occur from a field, there must be a source of P (e.g., P available for loss) and transport of P from the field. Several things affect the source of P including P fertilizer management and STP concentration and transport of P off-field is affected by several factors such as runoff dynamics, connectivity of the field to surface waterways, and soil erosion potential (Bolster et al., 2019). Ultimately, we cannot eliminate the risk of P loss from agricultural fields entirely, given the importance of this nutrient agronomically, but there are several management strategies to mitigate the extent of P loss. These include 4R nutrient management and implementation of system additions such as cover crops, discussed below.

1.2 Agricultural Phosphorus Management

1.2.1 Managing with the 4R's

Agronomic management of P has a major role to play in reducing P loss from agricultural fields, mainly through the 4R's: right source, right rate, right time, and right place for P fertilizer management (Bolster et al., 2019). Nutrient management under the 4R's is aimed at improving sustainability of fertilizer management by bringing together considerations from social, economic, and environmental perspectives (Bruulsema et al., 2019a). The concepts of 4R nutrient management play into development of best management practices (BMPs) around P use. Best management practices are developed with the intention of promoting agronomic productivity and profitability while minimizing environmental impacts (Asci et al., 2015).

1.2.1.1 Phosphorus source

Typical sources of P fertilizer include mono- and diammonium phosphates in granular form or ammonium polyphosphate in liquid form (Johnston and Bruulsema, 2014).

Agronomically, these three sources of P fertilizer perform similarly to one another and most source decisions are driven by access, cost, and other system factors like equipment set up, rather than a selection based on agronomic purpose (Johnston and Bruulsema, 2014).

An underutilized and not commonly referenced form of P for crop production in source discussions is legacy P. Large quantities of legacy P (e.g., STP that is far in excess of agronomic optimums) are chronically susceptible to loss via surface runoff (Guo et al., 2021; Haque, 2021). Although losses from the legacy P pool may be small in any given year, they are consistent, and legacy P may contribute to high P loss over extended time periods. This contrasts with P loss from fertilizer sources that tend to be more episodic; where post-application precipitation can cause a large amount of loss from the applied P, but this threat is not consistently present over the growing season like the threat of loss from legacy P (Guo et al., 2021).

From a BMP perspective, fertilizer P source is not often a concern compared to rate, placement, and timing management, discussed below. However, there is growing discussion around the importance of tapping into legacy P reserves as a source of P fertility that is actively managed (Schneider et al., 2019), rather than passively accumulated. The role of legacy P as a source of P contributing to runoff losses has not been adequately accounted for in development of conservation practices (Sharpley et al., 2013). Developing management strategies targeted at utilization of legacy P as a contributor to P fertility will be critical for sustainability of P agronomics (Rowe et al., 2016).

Reliance on legacy P to supply crop P with reduced fertilizer supplementation is an avenue to decrease STP concentration over time and thereby reduce P loss (Schneider et al., 2019). However, a challenge of agronomic utilization of legacy P is managing STP drawdown. The effect of crop removal on post-harvest STP is difficult to predict (Hansen et al., 2002). There are several dynamics that contribute to available P and the effect of crop removal on the change in STP is not as simple as a 1:1 proportional relationship between crop export of P and STP drawdown. **Further research into management of legacy P as a predictable and reliable source of P fertility is needed, to capitalize on these P stocks and reduce P load in our environments.**

1.2.1.2 Phosphorus rate

Crop response, economic benefit, and environmental protection are all influenced by P rate decisions. Aligning P fertilizer inputs with crop demand is an important starting point for avoiding excessive applications (Carpenter et al., 1998). Systems with consistently higher applied rates will result in greater concentrations of P in the system, which increases likelihood of environmentally harmful loss (Sharpley, 1995). For this reason, reducing P fertilizer rates and ensuring alignment of P inputs with agronomic demand are key BMPs for P rate management (Singh et al., 2020).

There are two general philosophies that govern rate decisions for most crop production systems in the Great Plains: sufficiency and build and maintain (BM) management. These two contrasting strategies are sometimes thought of as “fertilizing the soil”, in the case of BM, and “fertilizing the crop” in the case of sufficiency (Olson et al., 1987). A BM approach prioritizes increasing soil test P (STP) above the critical threshold for crop yield response and maintaining it at a higher concentration, whereas a sufficiency approach aims to meet immediate crop demand

by fertilizing according to the critical soil test threshold for crop response (Leikam et al., 2010). Sufficiency is often thought to be more suitable for the short-term, under short land leases, land rentals, or years of tight cash-flow for example (Grant and Flaten, 2019).

There are few studies comparing the productivity differences between BM and sufficiency strategies and the limited data there are do not indicate a yield gain from a BM approach (Olson et al., 1987; Fabrizzi et al., 2017; Wortmann et al., 2018). Increasing STP above some level of plant available P is not going to contribute to increased yields (Medinski et al., 2018). Typically, the threshold level for crop response to P fertilization is the critical threshold for yield response (Rowe et al., 2016), 20 mg kg⁻¹ Mehlich-III P in Kansas (Ruiz Diaz et al., 2024). Under BM management, maintenance P fertilizer applications are still applied at STP at and above the critical threshold, even though crop response is not expected in the year of application. Regardless of the lack of evidence supporting the higher input BM strategy, it may be preferred over sufficiency as a risk mitigation approach to P fertilizer management (Osmond et al., 2019). Build and maintain is thought to reduce the risk of yield loss in areas of variable STP within a field and improve the overall productivity of the system by maintaining higher STP concentrations (Olson et al., 1987; Leikam et al., 2010; Rutan and Steinke, 2021). Phosphorus fertilizer responses can be sporadic and hard to predict, largely driven by environmental conditions and resulting changes in annual yield potential (Karamanos, 2007). Over-fertilizing to ensure more than enough P is supplied in any given year can mitigate the risk of missed yield under varying and unpredictable growing season conditions (Poulton et al., 2013). This strategy, although effective at reducing risk of missed yield opportunities for producers, does not align with BMPs for P rate management.

Soybean response to P fertilizer rate is often limited, particularly on soils testing above the low STP category (Buah et al., 2000; Culman et al., 2023). Corn is often more responsive; for example, Culman et al. (2023) found P fertilizer response in 30% of corn sites, but only 14% of soybean sites. Pedersen et al. (2023) found corn to respond to P fertilizer even at high STP, however, this study did not evaluate whether the yield response was economical. Corn response to P fertilization at high STP is not universal and generally speaking, although possible, yield response of corn to P fertilizer at STP above the critical threshold is not expected (Rutan and Steinke, 2021b).

1.2.1.3 Phosphorus placement and timing

Placement of P fertilizer is usually less important for productivity of the system compared to P rate and STP concentrations (Bordoli and Mallarino, 1998; Borges and Mallarino, 2000), but placement can have substantial environmental effects (Kimmell et al., 2001; Smith et al., 2017; Carver et al., 2022). Typically, subsurface banded and surface broadcast treatments perform similarly in crop yield (Buah et al., 2000) but subsurface placement reliably reduces P loss compared to surface broadcast (Kimmell et al., 2001; Smith et al., 2017). Even with incorporation, broadcast usually results in greater total P losses compared to subsurface banding; although dissolved reactive P (DRP) losses can be reduced with incorporation of fertilizer, soil disturbance from incorporation tends to increase particulate P loss, ultimately increasing total P loss (Smith et al., 2017). So, although broadcast application with incorporation can change the ratio of DRP and particulate P in runoff, total P losses are still greater compared to subsurface placement. For these reasons, subsurface placement of P fertilizer is a recognized BMP for managing P loss (Singh et al., 2020).

Tillage management often interplays with fertilizer placement, with cascading effects on P susceptibility to loss. No-till systems typically have either surface broadcast P fertilizer, without incorporation, or subsurface banded P fertilizer. Over time, with surface placement, P stratifies in the soil profile to a greater extent than it would with subsurface placement or incorporation of surface applications (Costa et al., 2010). The stratification increases the pool of P susceptible to loss in runoff (Baker et al., 2017). While practices like no-till can greatly reduce erosion losses, which are often accompanied by a reduction in particulate P loss (Macrae et al., 2021; Carver et al., 2022), the stratification increases risk of DRP loss (Daryanto et al., 2017; Baker et al., 2017; Grant and Flaten, 2019).

Placement and timing decisions for fertilizer management often come as a package deal. Phosphorus fertilizer is typically applied either in the fall, a few months prior to cash crop sowing, or at the time of planting in the spring. Crop response to P fertilizer applied in the fall and spring are typically similar throughout the Great Plains (Singh et al., 2020). Although spring subsurface P placement is a more efficient application method for crop access to fertilizer P (Eghball and Sander, 1989), yield increases with subsurface compared to broadcast placement are infrequent (Bordoli and Mallarino, 1998; Mallarino et al., 1999; Borges and Mallarino, 2000; Buah et al., 2000b; Schwab et al., 2006; Rosa et al., 2020).

1.2.2 What if best management practices are not ‘best’?

Key BMPs for P management that reliably reduce P loss include lower rates, in line with crop demand for P and subsurface placement of P fertilizer in the spring (Singh et al., 2020). **But these practices that are best for environmental protection are often not most desirable or feasible for producers.** Environmentally, greater quantities of P will increase the risk of P loss in surface runoff. Since a BM approach will maintain higher STP concentrations compared to

sufficiency management (Pierzynski & Logan, 1982), BM increases the risk of environmental P loss compared to sufficiency (Olson et al., 1987). Agronomically, for producers to manage their risk, higher STP is desirable. It is well known that lowering STP is an effective tool to reduce P loss from agricultural fields (Schneider et al., 2019; Sharpley, 1995), but producer willingness to adopt lower P management is often limited by their desire to mitigate risk (Osmond et al., 2019).

Environmentally, subsurface placement in the spring is an effective control measure to reduce P loss. Agronomically, producers often prefer a fall surface broadcast application. Increased availability of labor, time and more cost-effective fertilizer prices in the fall make this application placement and timing combination attractive to the farmer (Mallarino et al., 2009). Together, the feasibility of a fall broadcast application and the lack of yield response to subsurface placement, provide low incentive to choose the environmentally conscious BMP.

Phosphorus fertilizer rate and placement/timing decisions are two key examples of conservation BMPs and producer ‘BMPs’ being at odds. Discrepancy between management that best serves the environment and management that is favorable from a farm management perspective reduces the breadth of conservation management adoption. For sustainable improvement to occur, management practices need to be developed to bring agronomic, economic, and environmental outcomes in tandem with one another; there is currently a gap in P conservation management options that fill this niche.

1.3 Phosphorus Efficiency: We use it, but do we use it well?

Nutrient use efficiency is a manner of calculating the relative ability of crops to access and utilize nutrients under different management practices (Baligar et al., 2001). Calculations of nutrient use efficiency traditionally quantify utilization of an applied nutrient in the year of fertilization, either on a crop yield or nutrient uptake basis. Optimizing fertilizer use efficiency

should align economic optimum nutrient inputs and minimize environmental losses of nutrients (Fixen et al., 2015).

Phosphorus fertilizer use efficiency (PUE) is lower than other nutrients; P fertilizer use efficiency is typically between 5 and 25%, whereas potassium is usually closer to 40% and nitrogen is around 50% (Baligar et al., 2001; Syers et al., 2008). Upon addition to the soil, fertilizer P quickly undergoes a series of reactions that render a large portion of it unavailable to crop roots in the year of application (Roberts and Johnston, 2015; Rowe et al., 2016). For example, Roberts and Johnston (2015) found only 10-15% of applied P fertilizer was taken up in the year of application. While the balance of fertilizer P will not be available in the year it was applied, it will participate in P turnover dynamics among the soil P pools, increasing P supply over time.

A key aspect of promoting fertilizer use efficiency is aligning application rates with crop demand (Medinski et al., 2018; Blackwell et al., 2019). For example, high initial P fertility tends to reduce PUE compared to production under initially low P fertility conditions (Yu et al., 2021). Factors affecting nutrient supply and yield potential will also contribute to final P use efficiency; these factors include growing season conditions, soil type, and agronomic management (Yu et al., 2021). Increased nutrient use efficiency means we are utilizing more of the applied nutrients to produce yield, benefiting economic return on invested fertilizer, and reducing the quantity of nutrients susceptible to loss from the system; thus, management for improved nutrient use efficiency can play a role in conservation management. Management strategies that optimize and utilize P supplied by the soil, in conjunction with P fertilizer as needed, will reduce fertilizer demand over time and improve agronomic use efficiencies (Hopkins and Hansen, 2019).

There are several accepted ways to calculate agronomic use efficiency of nutrients (Fixen et al., 2015) but metrics to quantify the efficiency of nutrient use from an environmental perspective are limited. Quantifying nutrient use efficiency from an environmental perspective could provide important insight into the agronomic-environmental trade-offs of current vs. alternative management strategies. **Metrics indicating the efficiency of nutrient utilization, agronomically, relative to the quantity of those nutrients lost to the environment would be valuable in further refining BMPs to serve both production and conservation outcomes.**

1.3.1 Coupling conservation practices for more desirable outcomes

Clearly there is a gap between P fertilizer management practices that are best for environmental conservation and those that are favorable agronomically. The effect of conservation management strategies on P loss has frequently been discretely explored, however, there may be opportunity to couple conservation practices together that could provide benefit both environmentally and agronomically. **Cover crops are a conservation tool that could be explored for retaining P in the system in combination with P fertilizer management.**

1.3.1.1 Cover crops as a conservation tool

Cover crops are a conservation tool implemented for a system gain other than yield (Lal et al., 1991). Cover cropping can result in increased aggregate size and stability (Blanco-Canqui et al., 2015), increased soil organic matter content (Lal et al., 1991), improved soil aeration and water retention, and enhanced nutrient cycling (Snapp et al., 2005; Schneider et al., 2019). Cover crops may also be effective at improving runoff water quality metrics (Blanco-Canqui et al., 2015; Osmond et al., 2019; Carver et al., 2022). Because the physical biomass barrier from cover crop residue slows runoff flow across the soil surface, there is increased potential for runoff infiltration and reduction in sediment and particulate P loss with cover crops (Dabney et al.,

2001; Blanco-Canqui and Ruis, 2020). Improved aggregation imparts better physical stability of particles near-surface, also reducing the risk of sediment loss. So, cover crops reliably reduce total P losses, and this effect is amplified under conditions of high erosion potential (Carver, 2022).

Although cover crops are effective at reducing sediment and particulate P losses, they can increase dissolved P loss (Singh et al., 2018; Weyers et al., 2021; Hanrahan et al., 2021; Carver et al., 2022). The exact mechanism of increased DRP loss with cover crops is not well understood, but contributing factors include increased solubilization of nonlabile soil P under cover crops (Eichler-Löbermann et al., 2008; Schneider et al., 2019) and release of P from cover crop tissue and residue at the soil surface (Bechmann et al., 2005). Enhanced P accumulation at the soil surface is a concern particularly in systems under no-till management, where stratification already increases P concentration near the soil surface (Schwab et al., 2006; Sharpley & Smith, 1991). Increased concentration of P near-surface will increase the risk of P loss in runoff.

Beyond effects on runoff P loss, cover crops also influence P cycling through the soil-crop continuum. During growth, cover crops utilize nutrients and moisture for their biomass accumulation and this pulls resources from the pool available to the subsequent main crop (Lal et al., 1991; Dabney et al., 2001; Hanrahan et al., 2021). That said, the cover crop residue will decompose to return P to the soil; because cover crops may be able to solubilize and access sources of soil P that would not be otherwise available, P availability may be enhanced with cover crops (Eichler-Löbermann et al., 2008; Schneider et al., 2019; Pavinato et al., 2024). Release of P from cover crop tissue is rapid enough to provide P supply for the subsequent main crop (Carver et al., 2020; Maltis-Landry and Fossard, 2015). The effect of cover crops on

available P can be influenced by P fertilization in the system, as well; Soltangheisi et al. (2020) found that cover crops increased available P with P fertilization, but did not affect the size of the available P pool in an unfertilized system. On the contrary, there is potential for reduction in available P with cover crops, at least temporarily, due to conversion of mineral, available P, to organic, unavailable P (Blanco-Canqui et al., 2015). Nutrient cycling benefits of cover crops may be delayed, with yield boosts from improved availability of nutrients occurring after a couple of years of cover crop inclusion as more residue decomposes and recycles nutrients to the plant available pool (Dozier et al., 2017; Chim et al., 2022).

Cover crop effects on main crop yield are mixed, with soybean yield typically being less affected than corn yield (Acuña and Villamil, 2014; Pantoja et al., 2015; Behnke et al., 2020; Qin et al., 2021). Corn is more sensitive to resource competition, especially when the cover crop has used moisture under moisture-stressed conditions (Miguez and Bollero, 2005). This can be somewhat controlled by modifying termination timing, terminating cover crops earlier in the year to limit water use ahead of main crop planting (Unger and Vigil, 1998a). Cover crop effects on main crop yield and system productivity should be regionally evaluated because the outcomes will be influenced by environmental and management factors, such as precipitation patterns, tillage, and fertilizer management (Miguez and Bollero, 2005).

Although cover crops can provide a number of system benefits, depending on system goals, production costs increase with cover crop inclusion. The increased seed and sowing costs of planting a cover crop, as well as any potential decreases in main crop yield, should be considered prior to implementation of a cover crop, based on system-specific goals (Dabney et al., 2001). Often, the economic gains and losses from cover crop inclusion need to be weighed against system-specific goals to determine if cover crops are a logical conservation tool (Frye et

al., 1985). Concern over potential economic drawbacks of cover crops is a limitation to unincentivized producer adoption of this conservation practice (Plastina et al., 2020). Cover crops can provide a number of benefits to crop production systems, but those benefits do not come without drawbacks; therefore, cover crop implementation should be carefully considered based on system-specific goals.

1.4 Economic Outcomes Drive Agronomic Decisions

Phosphorus fertilization represents a substantial portion of fertilizer budgets for many production regions in the US (Boring et al., 2018). Given this, and the importance of P for crop yield development which affects gross returns, consideration for P management effects on the bottom line are critical in development of practical conservation management strategies. There is often a gap between development of best management practices for conservation and those that promote optimum economic gain for the producer (Asci et al., 2015). This gap can limit adoption of conservation practices if they are not viewed as feasible economically on the farm.

Sustainable conservation solutions require both efficacy from an environmental perspective and feasibility for farm production and economics (Lal et al., 1991; Grant and Flaten, 2019).

Investigating returns from conservation practices is a critical step in developing best management practices that will be widely adopted on-farm. Exploring the cost of incentivizing producers to adopt impactful conservation practices is an option as well (Nelson et al., 2023a). Ultimately, economic evaluation of conservation management outcomes is an important step toward informing recommendations for producer adoption.

1.5 Our Research

1.5.1 Improving BMPs

There is a clear divide between conservation management strategies for P fertilizer placement/timing and rate decisions, and those that are favored by producers. Our research explored coupling cover cropping with P management aligned with conservation BMPs and that aligned with practices that may be more feasible for producers. This facilitated investigation of cover crops as a conservation tool to accommodate agronomic P management that is outside of a known BMP for mitigating P loss. Additionally, we explored the agronomic efficiencies of these respective combined management approaches and developed a new metric to evaluate environmental efficiency. Economic analyses were conducted to determine feasibility of different management strategies and opportunities for producer incentives.

1.5.2 Tapping into legacy phosphorus

We agree with the importance of better managing legacy P reserves as a source of agronomic P year-to-year. We also understand producer hesitancy to adopt low P systems that impart greater risk of yield loss. Through a novel approach to historical data analysis and new field studies, we investigated feasibility of maintaining STP at a lower concentration than the current critical threshold for yield response. Our findings led us to propose further exploration of a novel P fertility management strategy, sustainable sufficiency (SSF). The SSF approach would combine crop response to P fertilizer applied annually, with reliance on legacy-P to supply complete crop demand each year. If successful, development of an SSF approach would improve utilization of legacy P, reduce total quantities of P in agricultural systems, and lower P loss in runoff, all while mitigating producer risk of yield loss compared to a traditional sufficiency

system. Our SSF project was aimed at aligning conservation and production goals in a producer-focused manner, to facilitate widespread and confident adoption of conservation P management.

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Chapter 2 – Cover Crops Impact Phosphorus Cycling and Environmental Efficiency in a Corn-Soybean System

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2.1 Abstract

Solutions to simultaneously meet crop phosphorus (P) demand and reduce P loss from agricultural systems are required to improve the sustainability of our production. Our objective was to determine the effect of cover crop addition [with cover crop (CC), and without cover crop (NC)] and P fertilizer management [zero P control (CN), fall broadcast (FB), and spring injected (SI)] on P cycling, agronomic P use efficiency (PUE), and environmental P use efficiency (EPUE), measured as the percent of P lost in runoff water, in a no-till corn–soybean rotation. The experiment was a 2x3 factorial. Both FB and SI increased P cycling through the main crop and cover crop tissue, compared to the CN. Cover crop did not affect main crop P uptake, removal in grain, or return to soil in crop residue, but CC treatment increased total P uptake and return in the system. Cover crop effects on P uptake, removal, and return were the same regardless of P fertilization treatments. Phosphorus fertilizer and CC treatments did not affect PUE. Both FB and SI P fertilizer management decreased EPUE, although SI tended to decrease EPUE less than FB. Cover crop significantly improved EPUE only in 2019, when CC reduced erosion losses. Therefore, cover crops were not consistently beneficial for reducing environmental effects of P fertilization, and their use cannot replace the importance of sound P fertilizer stewardship,

including sub-surface P placement. However, cover crops play an important role in improving EPUE in years with high erosion loss potential.

2.2 Introduction

Best management practices for phosphorus (P) fertilization have received growing attention in the last several years to reduce P loss from agricultural systems (Sharpley et al., 2018; Drohan et al., 2019; Singh et al., 2020) and improve phosphorus use efficiency (PUE). Efficient nutrient utilization provides agronomically and economically ideal nutrient levels to the crop, while reducing losses of nutrients from the field (Fixen et al., 2015). Increasing PUE in agricultural systems is recognized as an important step in protecting the sustainability of our production systems which rely on P inputs, largely from non-renewable phosphate rock fertilizer sources (Johnston et al., 2014). Due to the need to reduce P loss to the environment and the contrasting necessity of P inputs to maintain productivity of agricultural systems, management strategies that protect the environment while preserving or enhancing P cycling and P use efficiency are required.

The timing and placement of P fertilizer can affect P bioavailability, P uptake, and hence P use efficiency. Subsurface P fertilizer placement is often an effective means to reduce P loss compared to broadcast placement (Kimmell et al., 2001; Zeimen et al., 2006; Carver et al., 2022). Subsurface placement is also reported to have several agronomic benefits including easy crop access to fertilizer P due to root proximity (Johnston and Bruulsema, 2014), improved early season P nutrition (Grant et al., 2001), and improved root-fertilizer interactions (Eghball and Sander, 1989). Subsurface P fertilizer application has been found to increase P uptake compared to broadcast placement for both corn (*Zea mays*) and soybean [*Glycine max* (L.) Merr.] (Borges and Mallarino, 2000; Fernández and White, 2012), although increased P uptake with subsurface

placement is not consistent for soybean (Buah et al., 2000b). Phosphorus fertilization in spring at planting can improve early season crop access to the P fertilizer and reduce P fixation in the soil (Johnston and Bruulsema, 2014). However, a fall application may be advantageous due to lower fertilizer prices, more favorable environmental conditions for fertilizer application, and more available labor compared to spring (Mallarino et al., 2009).

Cover cropping is a conservation practice that can improve soil physical conditions, reduce surface runoff and sediment losses (Blanco-Canqui et al., 2015), increase soil organic matter (Lal et al., 1991b), improve soil aeration and water retention, and enhance nutrient cycling (Snapp et al., 2005). Cover crops require nutrients for growth, potentially affecting the quantity of nutrients immediately available to the succeeding cash crop (Lal et al., 1991b). Specific to P nutrition, cover cropping may increase available P for the main crop as a result of decomposition of cover crop tissue or through solubilization of otherwise non-available P forms through the action of cover crop root exudates (Eichler-Löbermann et al., 2008). Studies have found that P can be quickly released from cover crop tissue and can serve as a P source for subsequent crops (Carver et al., 2020; Maltis-Landry and Fossard, 2015). Soltangheisi et al. (2020) found that the effects of cover crops varied based on P fertilization, where cover cropping did not affect the size of the available P pool in an unfertilized system but cover crops increased available P in the surface soil with P fertilization. Increased accumulation of P in the surface soil could be beneficial for crop P accumulation; however, there could also be increased risk of P loss from the system, especially in no-till systems where P stratification is already a concern (Schwab et al., 2006; A. N. Sharpley & Smith, 1991). Although there are many studies that indicate cover crops can increase P availability, other literature cites a reduction in plant-available P with the

inclusion of cover crops in the system, which is attributed to conversion of highly available inorganic P to less available forms of organic P (Blanco-Canqui et al., 2015).

Traditional nutrient use efficiency calculations indicate the efficiency of applied nutrient in the year of application. Whereas nutrient use efficiencies of potassium (K) and nitrogen (N) are about 40 and 50%, respectively, in the year of application, P fertilizer use efficiency is only 10%, on average (Baligar et al., 2001). Field experiments using labelled P fertilizer found just 5 to 25% of applied P was taken up by a cereal crop in any given year (Syers et al., 2008). In a meta-analysis, Yu et al. (2021) found climate, soil, and crop management factors can influence the efficiency of P fertilizer use. Crops grown in soils with greater available P prior to P fertilization tend to have less efficient use of P fertilizer. Low P fertilizer use efficiency is a generally accepted reality for most field crops (Higgs et al., 2000; Johnston et al., 2014); however, improving P fertilizer use efficiency is an important advancement toward more sustainable fertilizer use because rock phosphate, the primary source for P fertilizers, is a non-renewable resource (Baligar et al., 2001; Johnston and Bruulsema, 2014; Fixen et al., 2015).

Evaluating the efficiency of the system to agronomically utilize nutrients while minimizing environmental loss is also valuable. A system that utilizes P more efficiently from an environmental perspective would have less P loss as a portion of total P leaving the field in a given year. Such a metric facilitates comparison of practices and systems through an environmentally focused lens and can help improve environmentally informed agronomic decision making.

Improved on-farm P management is critical to sustainable food production. Agronomic decisions, or combinations of agronomic decisions, should be evaluated weighing the advantages and disadvantages for the system of interest in relation to specific systems goals (Dabney et al.,

2001). Subsurface P placement and cover cropping provide conservation benefits that may promote productivity in some respects, and drawbacks in others. Our objectives were to investigate the effect of P fertilizer management and cover cropping on: i) P cycling (uptake, removal, and return) through the system; ii) agronomic P use efficiency; and iii) environmental P use efficiency (the portion of P leaving the system as P loss to the environment), in a no-till, corn-soybean system.

2.3 Materials and Methods

This study was conducted at the Kansas Agricultural Watershed field laboratory, located near Manhattan, KS (Carver et al., 2022). The site is under no-till management, in a corn-soybean rotation. Soil across the site is mapped as an eroded Smolan silty clay loam (fine, smectitic, mesic Pachic Argiustoll) with 3-7% slope. Prior to establishing the plots for this study, the field was managed as a conventionally tilled winter wheat (*Triticum aestivum*)-soybean rotation. The last tillage event took place in fall 2014. Thirty-year average annual precipitation is 889 mm, and the climate is continental, hot and humid, with a mean annual temperature of 12.9° C. For detailed precipitation and temperature data, refer to Carver et al. (2022).

This study was arranged as a randomized complete block experimental design, with a 2 x 3 factorial treatment arrangement. There were two levels of cover crop management: with a cover crop (CC) and without a cover crop (NC). There were three levels of P fertilizer management: a control with no added P (CN), a fall broadcast (FB) application, and a spring injected (SI) application. The P fertilizer management treatments represent different systems for P management due to differences in P source, timing, and placement including associated differences in the placement, source, and timing of up to 24 kg N ha⁻¹ yr⁻¹ (details provided

below). Each treatment combination was replicated three times ($n = 18$), with replications blocked by landscape position.

2.3.1 Agronomic management

Details on agronomic management can be found in (Nelson et al., 2023b). Briefly, the first cover crop was sown in fall 2014 and each year thereafter, following harvest of the main crop. Because the site was conventionally tilled prior to trial establishment in the fall of 2014, data from the 2015 growing season is omitted as this was a transition year to a no-till system. Cover crop species varied by season and preceding main crop, but included either winter wheat or winter triticale [$\times$ *Triticosecale* Wittm.], alone, or in combination with rapeseed (*Brassica napus* L.). However, in the years rapeseed was included in the cover crop mixture, it had very poor establishment and did not significantly contribute to cover crop biomass. The cover crop was planted in late September following corn (planting in fall 2015 and fall 2017), and in late October to early November following soybean (planting in fall 2016 and fall 2018), because soybean was harvested later in the growing season. The cover crop was drilled on 19.05-cm spacing, using a JD-1590 no-till drill, with single disc openers (John Deere, Moline, IL). Cover crop termination occurred either prior to planting (2016) or within three days after main crop planting (2017-2019) each year. Main crop alternated between soybean (2016 and 2018) and corn (2017, 2019). Corn planting rate was 64,000 seeds ha⁻¹, with a yield goal of 10 t ha⁻¹. Soybean planting rate was 325,000 and 321,000 seeds ha⁻¹ in 2016 and 2018, respectively, with a yield goal of 2.7 t ha⁻¹ in both years. Main crop planting was accomplished with a White 6200 series planter (AGCO Corp., Duluth, GA) with Yetter residue managers (Yetter Manufacturing Co., Colchester, IL).

Phosphorus fertilizer was applied to the FB and SI P treatments annually at a target rate of 61 kg P₂O₅ ha⁻¹ (27 kg P ha⁻¹), based on Kansas State University's build and maintain recommendations (Leikam et al., 2003a), for the initial site soil test P of 17 mg kg⁻¹ Mehlich III P. Fall broadcast P fertilizer was applied as diammonium phosphate (18-46-0 on a P₂O₅ basis), using a drop spreader (Barber Engineering Co., Spokane, WA.). Spring injected P fertilizer was applied as ammonium polyphosphate (10-34-0 on a P₂O₅ basis), at planting, 5 cm beside and 5 cm below the seed row. Nitrogen was applied in corn years according to university recommendations (Leikam et al., 2003a), using urea ammonium nitrate (UAN, 28-0-0). The UAN was placed under surface residue in a band, using a coulter injector, at 38.1 cm spacing. Nitrogen was balanced across the treatments, as part of the spring application, to ensure each plot received the same total N.

2.3.2 Data collection

Edge-of-field runoff samples were collected from each plot for each runoff event as flow-weighted composite samples, using 0.46-m H-flumes with ISCO 6700 and 6712 series water samplers collecting a 200-mL sample of runoff water for every 1-mm of runoff. Water depth was measured using ISCO 730 bubbler modules at each flume. Chemical analyses were completed on each water sample to determine total P loss in runoff from each natural precipitation event. Total P was analyzed using a potassium persulfate reagent for digestion at 120°C for 60 minutes, followed by analysis with the molybdate blue colorimetric procedure. For complete details on water quality data collection and chemical analyses, refer to Carver et al. (2022).

Cover crop and main crop biomass samples were collected from three georeferenced subsample points within each main plot. Cover crop biomass samples were collected as close to termination as possible, within two to ten days. An area of two rows by three meters was

collected from each subsample location for above ground cover crop biomass. Biomass was weighed, oven-dried, ground, and analyzed for total nutrient content. Soybean biomass samples were collected at soybean growth stage R6 to avoid loss of plant biomass due to leaf drop. In 2016, soybean aboveground biomass samples were collected from a one row by one meter area, from each subsample point in each main plot. Plants were cut at the soil surface. From that area, six plants were randomly selected to be dried and ground for nutrient analysis. In 2018, soybean aboveground biomass samples were collected from a two row by one meter area at each subsample point, and four plants were randomly selected from each subsample to be dried and ground for nutrient analysis. For corn, ears were collected from 2 rows by 9.1 m at physiological maturity to determine grain yield and biomass of cobs. Following removal of ears, 10 whole plants were randomly selected from the harvest area to determine biomass of stalks and leaves. Subsamples were dried, ground and analyzed for P using a sulfuric peroxide digest (Thomas et al., 1967) and inductively coupled plasma spectroscopy, for cover crop, corn, and soybean tissue.

Corn yield was determined from the hand-harvested ears, from which grain was shelled, weighed, and analyzed for moisture content. In both soybean years, a Gleaner E III plot combine (AGCO Corp., Duluth, GA) retrofitted with a calibrated weighing system was used to harvest 2 rows by 70-150 m length through the center of each plot, from which three grain samples were collected for analysis. The weight and moisture content from harvest in each plot were recorded. Yield was corrected to a standard moisture concentration of 133 g kg⁻¹ for soybean, and 155 g kg⁻¹ for corn. Grain samples were collected in each year, dried, ground and analyzed for P content using the same method as for plant tissue.

Calculations

Corn biomass was calculated, by subsampling point, calculated as:

$$B_{\text{Corn}} = B_{\text{Stover}} + B_{\text{Cob}} + B_{\text{Grain}} \quad (1)$$

where B_{corn} is the total biomass, found by summing the stover biomass (B_{Stover}), cob biomass (B_{Cob}), and grain biomass (B_{Grain}). Corn P uptake was calculated using a similar procedure, summing the uptake of the stover, cob and grain components.

Total P uptake was calculated, by plot, as follows:

$$U_{\text{Total}} = U_{\text{Cover Crop}} + U_{\text{Main Crop}} \quad (2)$$

where $U_{\text{Cover Crop}}$ is cover crop P uptake (kg P ha⁻¹) and $U_{\text{Main Crop}}$ is P uptake of the main crop (kg P ha⁻¹), in a given harvest year.

Total P return was calculated, by plot, as follows:

$$R_{\text{Total}} = U_{\text{Cover Crop}} + R_{\text{Main Crop}} \quad (3)$$

where $U_{\text{Cover Crop}}$ is cover crop P uptake (kg P ha⁻¹) and $R_{\text{Main Crop}}$ is the mass of P that remained in the main crop residue after grain harvest, in a given harvest year. For soybean, $R_{\text{Main Crop}}$ was calculated as the total soybean biomass P less the mass of grain P. For corn years, $R_{\text{Main Crop}}$ was calculated as the sum of the mass of P in stover and cobs.

Agronomic PUE was calculated for each plot in a given year as follows:

$$\text{PUE} = \frac{[Y - Y_0]}{F} \quad (4)$$

where Y is the yield with P fertilizer (kg grain ha⁻¹), Y_0 is the CN yield (kg grain ha⁻¹), and F is the mass of fertilizer P applied (kg P ha⁻¹) (Fixen et al., 2015). The CC-CN treatment was used as the Y_0 for CC plots and the NC-CN treatment was used as the Y_0 for NC plots.

Crop and fertilizer management may increase P uptake without affecting grain yield, therefore, we calculated Apparent Recovery Efficiency (ARE), which includes a direct measure

of P uptake by the crop. Apparent recovery efficiency was calculated for each plot in a given year as follows:

$$\text{ARE} = \frac{[U - U_0]}{F} \quad (5)$$

where U is the total P uptake with P fertilizer (kg P ha^{-1}), U_0 is the total P uptake of the CN treatment with no added P (kg P ha^{-1}), and F is the amount of fertilizer P applied (kg P ha^{-1}) (Fixen et al., 2015). The CC-CN treatment was used as the Y_0 for CC plots and the NC-CN treatment was used as the Y_0 for NC plots.

To investigate environmental phosphorus use efficiency (EPUE), we quantified the percent of P loss to the environment, relative to total P leaving the system, for each plot in a given year, as follows:

$$\%P_{\text{runoff}} = \frac{P_{\text{runoff}}}{P_{\text{runoff}} + P_{\text{grain removal}}} \times 100\% \quad (6)$$

where P_{runoff} is total P loss in runoff (kg P ha^{-1}) and $P_{\text{grain removal}}$ is the P leaving the system in the grain at harvest (kg P ha^{-1}). Calculated in this manner, an increase in $\%P_{\text{runoff}}$ is synonymous with decreased EPUE, as more P is lost in runoff, and a decrease in $\%P_{\text{runoff}}$ is synonymous with increases EPUE.

2.3.3 Statistical analysis

Response variables except PUE, ARE, and $\%P_{\text{runoff}}$ were calculated on a per-subplot basis and were analyzed using a linear mixed model. Fixed effects of the model included replication, cover crop, P fertilizer treatments, and year, as well as the two-way and three-way interactions among cover crop, P fertilizer treatments, and year. Because only one main crop was present in each year, the year and crop type were confounded. As a result, the year effect includes both

main crop and environmental effects. The random effect was plot (i.e., the error term vector whose elements corresponded to repeated measurements over year and at three subplots). Variance-covariance matrix for plot was taken as the direct product of the variance-covariance matrix for year (of type compound symmetry) and the variance-covariance for subplot (of type unstructured). Crop biomass, crop N uptake, crop N removal, cover crop biomass, and cover crop P uptake data, were not normally distributed and required a $\log_{10}$ transformation.

Response variables PUE, ARE, and $\%P_{\text{runoff}}$ were calculated on a per-plot basis. They were analyzed using the linear mixed model with fixed effects being replication, cover crop, P fertilizer treatment, and year, as well as all two-way and three-way interactions among cover crop, P fertilizer treatment and year. The random effect was plot, whose variance-covariance structure was taken as first-order autoregressive with diagonal elements heterogeneous with respect to year. Cover crop biomass and P uptake, as well as $\%P_{\text{runoff}}$ underwent the $\log_{10}$ transformation to better satisfy the model assumptions. Least squares means of the analysis output were back transformed into original units.

We used MIXED and GLIMMIX procedures of SAS ver. 9.4 for the statistical analyses. The Kenward-Roger method was employed to approximate the distribution of the test statistics (Kenward and Roger, 1997). All tests were two-sided. Significance was determined using $\alpha \leq .05$.

2.4 Results and Discussion

2.4.1 Phosphorus cycling

The main effects of P fertilizer and year significantly affected biomass and P uptake of the cover crop (Table 2.1). Cover crop biomass was greater in the FB treatment compared to the CN, and the SI treatment produced similar biomass to both the CN and FB treatments (Table

2.2). Cover crop biomass was significantly different for each year of the study due to variable growing season conditions and year-to-year differences in cover crop seeding and planting dates (Nelson et al., 2023b). Notably, 2019 had substantially less biomass compared to the other years. The 2019 cover crop was planted the latest out of all four cover crops in this study, and this likely impacted biomass accumulation in that year.

Phosphorus uptake by the cover crop was significantly greater with both FB and SI P fertilization, compared to the CN, and this effect was consistent across years (Tables 2.1 and 2.2). The increase in cover crop P uptake with P fertilization was driven largely by the increase in cover crop biomass for the FB and SI treatments compared to the CN, as all three of these treatments had similar P concentration in cover crop tissue in three of the four years in this study (Figure 2.1). Increased P uptake by the cover crop in treatments with P fertilization indicated cover crop can influence cycling of P fertilizer and potentially impact the forms of P in soil and hence availability for subsequent crops. Phosphorus uptake was similar for FB and SI treatments, so, although the FB treatment applied P and a small amount of N (as a component of the DAP) prior to the majority of cover crop growth, this did not significantly affect the cycling of P through cover crop tissue. Phosphorus uptake by the cover crop was greatest in 2017 and 2018, which were the years with the most biomass accumulation (Table 2.2). Our results are similar to other studies that found cover crop biomass and P uptake were greater in production systems where the main crop received P fertilizer (Maltais-Landry et al., 2014; Pavinato et al., 2017). Pavinato et al. (2017) also found that differences in cover crop P uptake were mainly caused by differences in cover crop biomass rather than changes in P concentration in the tissue.

Table 2.1 *P*-values for testing fixed effects of cover crop (cover), phosphorus (P) fertilizer management (Fert), year, and their interactions on cover crop biomass and P uptake; main crop biomass, P uptake, removal, and return; total P uptake and return of the system; agronomic phosphorus use efficiency (PUE), apparent recovery efficiency (ARE), and percent phosphorus loss in runoff (%P_{runoff})

	Cover Biom.	Cover P Conc.	Cover P Uptake	Crop Biom.	Crop P Conc.	Crop P Uptake	Crop Grain P Conc.	Crop P Removal	Crop P Return	Total P Uptake	Total P Return	PUE	ARE	%P _{runoff}
Cover	-	-	-	.0004^a	0.0190	.1485	0.2940	.0840	.0941	.0279	.0013	.5470	.3758	.3664
Fert	.0107	0.0088	.0034	.0115	<.0001	<.0001	0.0009	<.0001	<.0001	<.0001	<.0001	.6908	.7902	.0017
Year	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	.0006	.0023	.0119	<.0001
Cover*Fert	-	-	-	.9514	0.6710	.8445	0.5295	.3602	.8836	.9232	.2885	.6685	.9539	.5720
Cover*Year	-	-	-	.0016	0.0180	.2024	0.7763	.0837	.4367	.7807	.2086	.3933	.5680	<.0001
Fert*Year	.1585	0.0064	.3089	.8124	0.0698	.0750	0.1091	.2832	.3244	.0293	.1341	.5197	.4238	.0345
Cover*Fert*Year	-	-	-	.9726	0.8684	.9419	0.9592	.9047	.4767	.8113	.5101	.9234	.6102	.9929

^aBolded values indicate significance at $\alpha=.05$

Table 2.2 Effect of cover crop, phosphorus (P) fertilization treatment, and year on main crop biomass, P concentration, P uptake, removal, and return.

Effect	Cover Crop Biomass kg ha ⁻¹	Cover Crop P Uptake kg ha ⁻¹	Main crop biomass kg ha ⁻¹	Main crop biomass P conc. g kg ⁻¹	Main crop P uptake kg ha ⁻¹	Grain P conc. g kg ⁻¹	Grain P removal kg ha ⁻¹	Main crop P return to Soil kg ha ⁻¹	Total P Uptake kg ha ⁻¹	Total P Return kg ha ⁻¹
Cover Crop										
NC	—	—	12859a ^a	2.2b	28.6	4.0	19.0	10.3	28.6b	10.3b
CC	—	—	11307b	2.3a	27.0	4.1	17.9	9.0	31.3a	13.4a
Fertilizer										
CN	891b	2.42b	11222b	2.0b	22.2b	3.8b	15.9b	6.9b	23.8b	8.5b
FB	1471a	4.44a	12308a	2.4a	30.9a	4.1a	19.4a	11.3a	33.7a	14.2a
SI	1151ab	3.33a	12692a	2.4a	30.3a	4.3a	20.0a	10.8a	32.3a	12.8a
Year										
2016	1568b	3.33b	12309b	2.5b	31.6b	5.1b	21.4b	10.3a	33.3b	12.1a
2017	1753ab	6.09a	13009b	1.9c	24.7c	2.3d	15.1c	10.3a	28.1c	13.6a
2018	2302a	5.83a	6589c	2.7a	17.5d	6.2a	11.3d	6.3b	20.5d	9.2b
2019	273c	0.99c	20034a	1.9c	37.2a	2.7c	26.0a	11.9a	37.8a	12.5a

Note: Means followed by the same letter are not significantly different within main effect ($\alpha=.05$).

^aSee Figure 2 for the effect of the interaction between cover crop and year on main crop biomass.

Abbreviations: NC, no cover; CC, cover crop; CN, control; FB, fall broadcast; SI, spring injected.

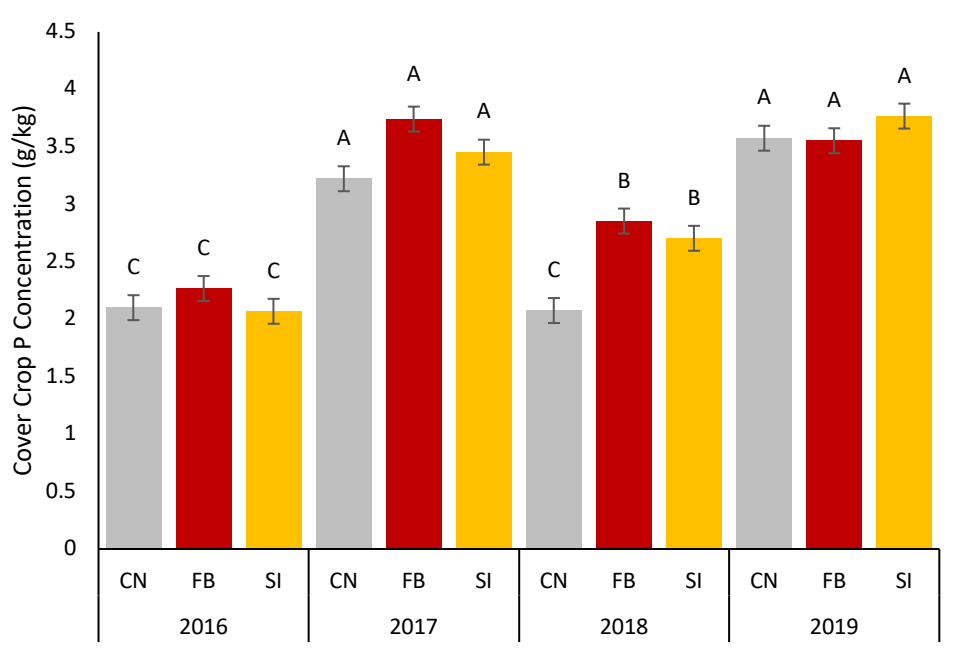


Figure 2.1 Effect of the interaction between phosphorus fertilizer management and year on phosphorus concentration of cover crop tissue. Abbreviations: CN=control; FB=fall broadcast P fertilizer; SI=spring injected P fertilizer. Bars with different letters are significantly different at $\alpha=.05$.

The effect of CC treatment on main crop biomass varied with year, as indicated by the significant cover*year interaction (Table 2.1). In 2016 and 2019, main crop biomass was similar for CC and NC treatments; however, in 2017 and 2018, CC reduced main crop biomass compared to NC (Figure 2.2). The 2017 and 2018 years had less precipitation during the time of main crop growth compared to the long-term average for the region (Carver et al. 2022) and potentially greater water use by the CC (as indicated by greater CC biomass; Table 2.2). This combination may have contributed to the reduction in main crop biomass for CC treatments in 2017 and 2018. Water use by a cover crop during the period of its active growth has been shown to restrict water availability to the subsequent main crop (Unger and Vigil, 1998b; Dabney et al., 2001). Although there were differences in main crop biomass between CC and NC treatments in

some years, addition of the cover crop did not affect main crop P uptake, removal, or return (Table 2.1). Greater main crop P concentration associated with the CC treatment compensated for the reductions in main crop biomass in uptake, removal, and return calculations (Table 2.3). These results indicate that the CC treatment did not have a detectable effect on P cycling through the main crop, and hence did not affect P bioavailability within the timeframe of our study despite P uptake and cycling through CC biomass (Table 2.2). This is in contrast to other studies that found CC to either restrict P availability due to P uptake and extraction from soil (Lal et al., 1991b), or improve P availability to the main crop via improved P mobilization pathways (Eichler-Löbermann et al., 2008). The different outcomes on P availability to the main crop are driven largely by cover crop species (Lal, et al., 1991; Eichler- Löbermann et al., 2008). Pavinato et al. (2017) found that cover crop species affected the P uptake of the subsequent corn crop, but this effect was not consistent. In one year they found ryegrass cover crop resulted in greater P uptake relative to the no-cover control and then found the opposite a few years later. It is possible that CC use in our study induced changes in soil biology which helped cycle the organic P in CC biomass back to bioavailable forms. For example, activity of P solubilizing enzymes was often greater in CC treatments compared to NC (Starr, 2021) hence the P uptake by the cover crop did not reduce P bioavailability to the main crop.

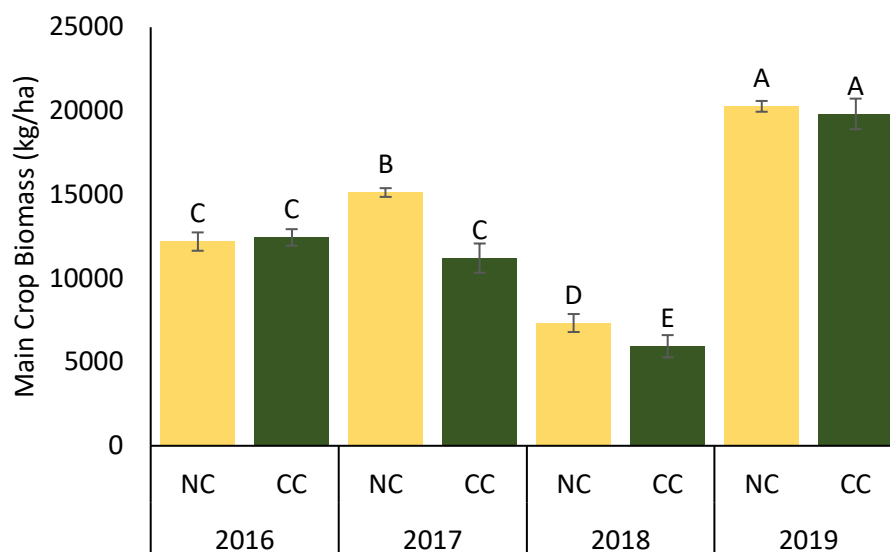


Figure 2.2 Cover crop by year interaction for main crop biomass. Letters represent significant differences among the eight combinations of cover crop and year, significant at $\alpha=0.05$ (NC=no cover crop; CC=with cover crop).

Both FB and SI treatments increased main crop P uptake, removal, and return compared to the CN (Table 2.3). This was because both biomass and P content for FB and SI treatments were greater than in the CN treatment (Table 2.3). Main crop grain P concentration also increased with FB and SI P fertilization, compared to the CN (Table 2.3). Increased biomass, P content, and P uptake in response to P fertilization was expected given the Mehlich III P soil test of 17 mg kg^{-1} at the beginning of the study. This is similar to other studies where corn and soybean have responded to P fertilization on soils with P concentrations below the critical threshold for yield response (Buah et al., 2000b; Edwards et al., 2013). There were no significant differences between FB and SI treatments for main crop P uptake, removal, and return, main crop biomass, or main crop P concentration (Table 2.3). This contrasts to other studies that found subsurface P fertilizer to increase P utilization (Borges and Mallarino, 2000; Fernández and White, 2012). The benefits of subsurface placement for increasing P access and utilization by the main crop are more important in cooler climates, where temperatures early in the season restrict

crop access to P fertilizer (Grant et al., 2001). This is less of a concern for P availability in KS, compared to more northern climates with cooler springs.

The main effects of fertilizer, cover crop, and year were significant for both total P uptake and total P return (Table 2.1). Cover crop increased the soil-plant P cycling, where CC increased total P uptake by 9% and total P return by 30%, relative to the NC treatment (Table 2.2). This has implications for the physical distribution of P in the system, which is of particular importance for no-till management where P from plant residue is deposited on the soil surface. Several studies have found increased runoff P losses with cover crops in the system (Carver et al., 2022; Hanrahan et al., 2021; Liu et al., 2019; Singh et al., 2018; Weyers et al., 2021) and an increase in P left on the soil surface could help explain increased risk of P loss with cover crops.

Both FB and SI increased total annual P uptake and total annual P return in the system, relative to the CN (Table 2.2). However, for total P uptake, the P fertilizer*year interaction indicates the effect of P fertilizer management varied year to year (Table 2.1). In 2017, SI led to less total annual P uptake compared to FB, but still increased total annual P uptake relative to the CN (Figure 2.3). In 2017, P uptake by both the cover crop and main crop tissue was greater numerically for the FB treatment compared to the SI treatment. Although those differences were not significant, when summed for total P uptake they resulted in a significantly greater P uptake for FB than SI in 2017. In the other years, total annual P uptake of the FB and SI treatments was similar (Figure 2.3). Increased P uptake could lead to increased yield and productivity of the system, whereas increased P return can increase the risk of P loss, particularly in a no-till system with residue accumulating on the soil surface.

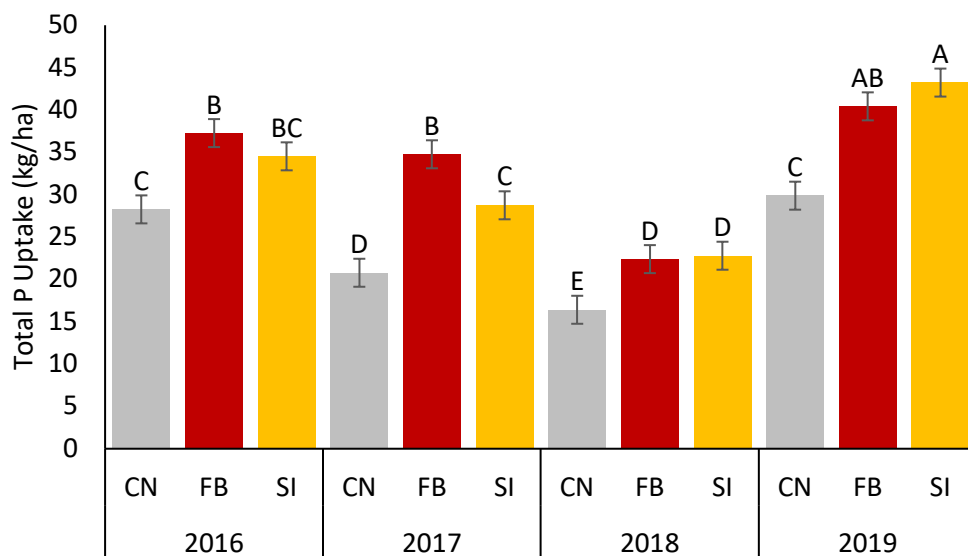


Figure 2.3 The interaction between phosphorus fertilizer management and year for total phosphorus uptake. Letters represent differences among the 12 combinations of phosphorus fertilizer management and year, significant at $\alpha=0.05$.

2.4.2 Agronomic efficiency

Agronomic PUE was not affected by cover crop or P fertilizer treatments (Table 2.1), averaging 25.3 kg kg⁻¹. It did, however, vary significantly by year, with more than three times the PUE in 2017 and 2019 (corn production), compared to 2016 and 2018 (soybean production; Table A.1). Similarly, only the main effect of year was significant for main crop ARE, where ARE was significantly greater in corn years, compared to soybean years (Table 2.1, Table A.1).

Yield results summarized by Nelson et al. (2023) indicate CC treatment decreased yield in 2017, driving the main effect of cover crop to be significant across years, on yield.

Additionally, SI significantly increased main crop yield compared to FB only in 2019; in all other years, the FB and SI treatments had a similar effect on main crop yield. Given the effect of our treatments on yield, we would have expected some effect of CC and P fertilizer on PUE. The lack of differences between treatments for PUE could be an artifact of our calculation; while comparing P fertilizer treatments within their respective cover crop treatments was critical to

make valid comparisons, the lack of significant treatment effects may be a result of using different control treatments for calculations of CC plots and NC plots.

On the other hand, the similarity of ARE across P fertilizer and cover crop treatments was expected as these treatments did not affect main crop P uptake. Although SI P fertilization is recommended to improve efficiency of P access and utilization by the crop (Eghball and Sander, 1989; Kovar and Claassen, 2005; Costa et al., 2010), it did not improve efficiency of P fertilizer use in our system, compared to FB. Our results agree with Pavinato et al. (2017), who found that cover crops did not affect corn yield or PUE.

2.4.3 Environmental efficiency

Both the cover*year and fertilizer*year interactions affected EPUE quantified as $\%P_{\text{runoff}}$ (Table 2.1). Cover crop treatment increased, decreased, or did not affect $\%P_{\text{runoff}}$ depending on differences in cover crop biomass, precipitation, and runoff dynamics year to year (Figure 2.4). In 2017, CC increased $\%P_{\text{runoff}}$ despite CC treatment having no effect on total P lost in runoff that year (Carver et al., 2022). Rather, increased $\%P_{\text{runoff}}$ with CC was driven by the decrease in the total amount of P leaving the system (i.e., P lost in runoff summed with P removed in grain) for CC plots, compared to NC, in 2017 (Table A.2). In 2018 CC increased $\%P_{\text{runoff}}$, whereas in 2019 the same treatment decreased $\%P_{\text{runoff}}$; both of these differences were driven by CC effect on runoff, directly. In 2018, CC significantly increased total P lost in runoff. This was the year with the greatest CC biomass (Table 2.2). Although beneficial to reduce sediment losses of P, increased biomass at the surface conversely increased risk of DRP loss. Several studies have found that cover crops increase DRP concentrations or loads in runoff (Singh et al., 2018; Liu et al., 2019; Weyers et al., 2021b; Hanrahan et al., 2021c). In our study, runoff losses in 2017 were

dominated by DRP (>70% DRP) (Carver et al., 2022), which could have been due to greater biomass-P at the soil surface in this year.

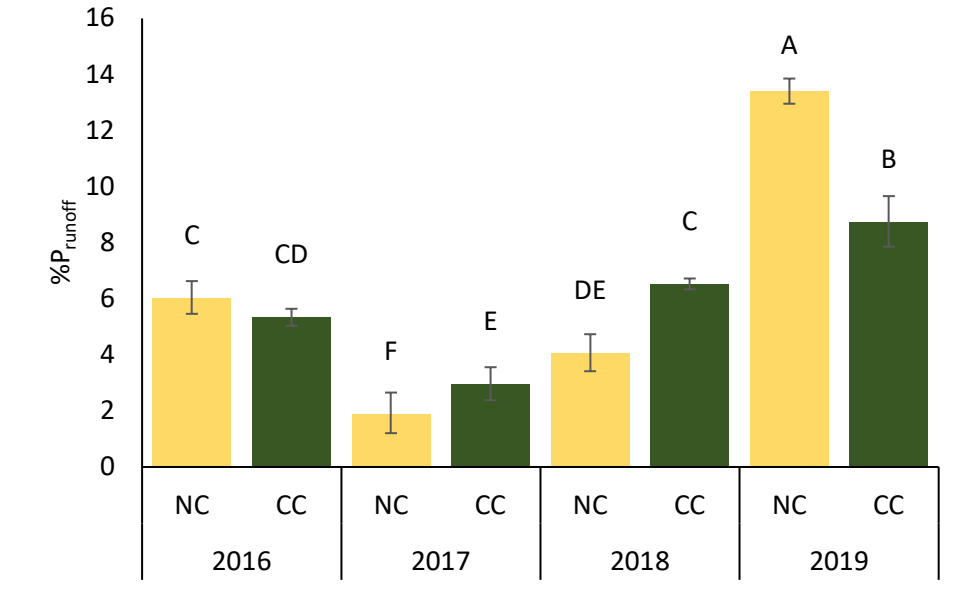


Figure 2.4 Cover crop by year interaction for percent phosphorus loss in runoff. Letters represent differences among the eight combinations of cover crop and year, significant at $\alpha=.05$.

On the other hand, there was a substantial reduction in total P runoff losses with CC, compared to NC, in 2019 (Carver et al. 2022), despite the relatively small amount of cover crop biomass that year (Table 2.2). This was caused by substantial reductions in sediment loss for CC treatments and the dominant role of particulate P on total P loss, where only 38% of the total P loss was DRP in 2019. This led to a smaller %P_{runoff} with CC treatment, compared to NC, in this year. Evidently, the addition of a cover crop did not consistently reduce %P_{runoff}, but there is potential for CC to positively impact EPUE, depending on runoff dynamics and dominant forms of P loss.

Except in 2016, both FB and SI P fertilizer treatments increased %P_{runoff} relative to the CN treatment and in 2017, FB increased %P_{runoff} more than the SI treatment (Figure 2.5). Thus, P fertilization reduced EPUE in all years except 2016. Although both FB and SI treatments

significantly increased the relative portion of P leaving the system as runoff losses over the control (Figure 2.5), the greater runoff losses from SI P fertilization were often less than for FB. The fertilizer*year interaction indicated %P_{runoff} was significantly less with SI compared to FB only in 2017, but the trend is clear across all four years of the study (Figure 2.5), as well as in the main effect of fertilizer on %P_{runoff}. Therefore, SI tended to improve EPUE by reducing %P_{runoff}, compared to FB, but these reductions were not consistently significant. Both FB and SI treatments reduced EPUE (or greater %P_{runoff}) because the application of P fertilizer, whether FB or SI, resulted in a relatively larger increase in P loss as compared to the relative increase in P removal in the grain. Agronomically, P fertilization increased main crop P removal in the grain for FB and SI treatments by 22% and 26% respectively, compared to the CN (Table 2.2). However, this increase in agronomic P use was not large enough to offset the increased runoff P loss for the FB and SI treatments of 129% and 82% respectively, compared to the CN (Carver et al., 2022).

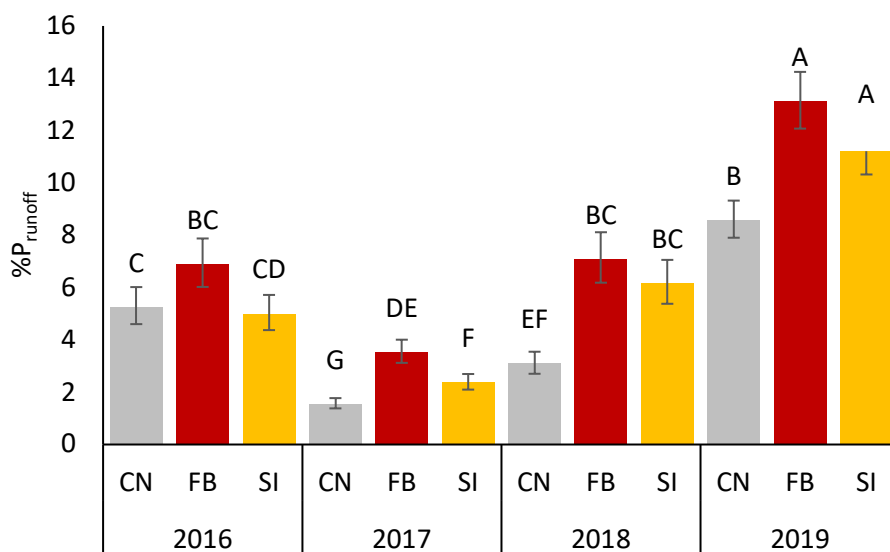


Figure 2.5 Phosphorus fertilizer by year interaction for percent phosphorus loss in runoff. Letters represent differences among the 12 combinations of phosphorus fertilizer and year, significant at $\alpha=.05$.

While there are several accepted metrics for evaluating PUE with an agronomic focus (Johnston et al., 2014; Fixen et al., 2015) and methods to assess P use efficiency at a whole systems-level, such as life cycle analyses (Suh and Yee, 2011) there are not well developed options to assess PUE from an environmentally focused lens, within the context of field production agriculture. These latter sorts of analyses can provide insight into PUE across the entirety of the food production system, and allow for modelling of certain systems-level changes in management (Sen and Bakshi, 2023); however, we are currently lacking a metric to assess PUE with an environmentally focused lens based on field-scale management changes. When using $\%P_{\text{runoff}}$ as an indication of EPUE, an efficient system loses a smaller fraction of P in runoff compared to the total P leaving the system in that year. Following this interpretation, both FB and SI P fertilization tended to reduce EPUE in our system, as they both increased the fraction of P leaving the field as runoff loss. Cover crop had a variable effect on EPUE, impairing EPUE in 2017 and 2018 but improving EPUE in 2019. Based on these data, addition of a cover crop may be effective at reducing $\%P_{\text{runoff}}$ in systems where DRP loss is a minor portion of total P loss, such as systems with high erosion potential. Overall, cover crop and P fertilizer treatment effects on P loss tended to drive $\%P_{\text{runoff}}$ outcomes. As a result, reducing P losses is an important control point for improving EPUE.

2.5 Conclusion

From an agronomic perspective, addition of a cover crop to the system did not limit main crop P uptake and removal despite the tendency of CC to decrease main crop biomass, and grain yield. Although other research has demonstrated that cover crops can be an effective tool to improve EPUE, this was not consistent in our study. Cover crop effect on EPUE depended on several annual factors including precipitation, cover crop biomass, and resulting runoff water

dynamics. The 30% increase in total P return to the soil surface with cover crops helps explain the increase in $\%P_{\text{runoff}}$ in some years, and is a probable contributing factor for observations of increased runoff P losses in other studies.

In almost every case, FB and SI P fertilizer management performed similarly from an agronomic perspective. There was no difference between the two management strategies in agronomic P use efficiency. Both FB and SI treatments increased $\%P_{\text{runoff}}$, although there was a clear trend for SI to have a smaller effect on this parameter. Cover crop treatment did not interact with P fertilizer treatment to affect main crop or total system P cycling parameters, PUE, or EPUE. Reducing P loss is a critical control point for improving EPUE, and cover crops can be an effective tool to manage P loss in systems with high erosion losses.

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Chapter 3 – Net Return and Water Quality Effects of Soil Test

Phosphorus Drawdown

3.1 Abstract

Developing conservation management options that are agronomically and economically feasible, with or without incentivization, and environmentally effective, is imperative for reducing phosphorus (P) loss from agricultural fields. To explore the effect of P fertilizer management and the use of cover crops on agronomics, economics, and environmental outcomes in a no-till, corn-soybean system, a long-term study was established at Ashland Bottoms, KS. This chapter includes results focused on the maintenance/drawdown years, when the treatments included: two levels of cover crop treatment (with, CC, and without, NC) and three levels of P fertilizer management (zero P control, CN; build and drawdown rate management, DD; and build and maintain rate management, BM). Both DD and BM management increased CC biomass compared to CN. Cover crop reduced corn yield by more than 1400 kg ha⁻¹ but did not affect soybean yield. Corn yield increased from CN, to DD, to BM management in a stepwise fashion. Fertilizer treatment effect on soybean yield was mixed, with BM increasing yield significantly in the 2020 soybean crop, compared to CN and DD, but not the 2022 crop. Consistently, net return was highest for the DD-NC treatment. Although DD did not receive applications of P fertilizer during these maintenance/drawdown years, water quality was not consistently improved for DD treatments compared to BM-NC. The CN-CC treatment was most consistent and effective at reducing P loss in runoff water; however, the cost of water quality improvement was high on a per kilogram basis with this management. Further research is needed to determine parameters of drawdown management as a mechanism for reduced P fertilizer use and P loss, and improvement of annual return.

3.2 Introduction

Mitigating phosphorus (P) loss from agricultural fields in runoff water is critical to improved sustainability. Phosphorus loss from agriculture contributes to eutrophication and development of harmful algal blooms (Welch, 1978; Correll, 1998; Le Noë et al., 2018; Haque, 2021), compromising surface water body quality and safety. The application of P in agricultural systems and best management practices for P use have received growing attention over the last several years to combat the environmental consequences of P loss (Drohan et al., 2019; Sharpley et al., 2018; Singh et al., 2020). Development of conservation strategies that reduce P loss while reliably meeting producer yield goals and profitability metrics is a hallmark challenge of mitigating P loss. Adoption of water quality conservation practices can be cost-prohibitive (Macrae et al., 2021), resulting in producer hesitancy for conservation adoption. Quantifying the costs and benefits of conservation practices are important to facilitate development of conservation systems and programs that meet goals for agronomic productivity, environmental protection, and economic sustainability.

Phosphorus fertilizer input and soil P fertility management are critical control points for reducing P loss in runoff. Reduced P fertilizer rates and reduced soil test P (STP) concentrations have long been recognized as consistent avenues to improve runoff water quality (Sharpley, 1995). Systems with consistently higher applied P rates have greater concentrations of P in the field, and therefore an increased likelihood of environmentally harmful P loss during runoff (Sharpley, 1995). Phosphorus fertilizer rate decisions are generally governed by two contrasting P fertilizer management strategies: build and maintain (BM) or sufficiency management. Build and maintain prioritizes increasing soil test P (STP) above the critical threshold for crop yield response, followed by maintenance of high STP with routine P fertilizer application. A

sufficiency approach, on the other hand, aims to meet immediate crop demand on an annual basis by fertilizing according to the critical soil test threshold for crop response (Leikam et al., 2010). Build and maintain will sustain higher STP concentrations compared to sufficiency management (Pierzynski & Logan, 1982) and thereby increase the risk of environmental P loss.

Producers frequently opt for high P BM systems, increasing STP to high or very high levels, followed by routine P fertilizer applications for maintenance (Osmond et al., 2019). Preference for this is often driven by a desire to mitigate risk. A field with high STP has greater potential to supply the crop with P compared to a field with low STP. A perceived benefit of this greater potential supply is greater crop yield, particularly for years with optimal growing conditions that maximize yield potential; this is thought to improve overall system productivity (Leikam et al., 2010; Olson et al., 1987; Rutan & Steinke, 2021). A BM system is also thought to reduce risk of yield loss due to variable STP within a field and unpredictable crop response under variable growing season conditions (Karamanos, 2007; Fabrizzi et al., 2017). Additionally, high STP under BM management allows fertilizer application to be forgone in years of high P fertilizer prices (Leikam et al., 2003). However, the extent to which producers capitalize on the opportunity to forgo P fertilizer application, partially or entirely, under high price conditions is not well understood. Nor are the cost-benefit tradeoffs of invested fertilizer dollars to build STP for this flexibility to be an option.

There are few studies comparing the productivity differences between BM and sufficiency strategies and the limited data do not indicate a yield gain from a BM approach compared to sufficiency (Olson et al., 1987; Fabrizzi et al., 2017; Wortmann et al., 2018). Whereas yield benefit from BM is not clear or consistent across these limited studies, the increased cost of a BM strategy is obvious. For example, Olson et al. (1987) found the cost of

BM to be almost double the cost of a sufficiency strategy. Despite the lack of evidentiary support, producers still opt for BM management with the non-data-based assumption that BM is a risk mitigation option. The perceived risk mitigation aspects of BM include ensuring adequate P supply from high STP to capture years of high yield potential and allowing flexibility to forgo P applications under years of high prices. The benefit of the risk mitigation aspect of BM will be variable year to year, based on environmental and price conditions, for example, but the perception of risk mitigation under BM is favorable for producers.

Accumulation of STP over time under P fertilizer additions in excess of crop demand is referred to as legacy P (Rowe et al., 2016). Legacy P may be a substantial source of P supply for crops and can reduce the need for fertilizer P inputs partially or completely (Sattari et al., 2012; Withers et al., 2019). Under high STP conditions, where inherent soil supply would meet crop demand without the help of P fertilization, legacy P can replace the need for P application; however, research and recommendations on pausing P application to utilize stocked soil P is lacking (Withers et al., 2019). Based on current knowledge, entering a period of STP drawdown, to supply crop P demand with existing soil P, will not compromise crop nutrition or productivity in the short-term (Rowe et al., 2016; Cade-Menun, 2022). But behavior of STP, system productivity, and profitability under drawdown need to be regionally explored. Making use of legacy P during a short drawdown period could play an important role in reducing P loss and improving eutrophication reduction targets (Withers et al., 2019).

Cover crops are a conservation practice that can provide system benefits and environmental protection. Cover crops can reduce sediment and particulate P loss (Carver et al., 2022), especially in high fertility systems (Sharpley & Smith, 1991), improve soil physical properties (Blanco-Canqui et al., 2015), soil fertility (Lal et al., 1991), and nutrient cycling

(Snapp et al., 2005). However, there may be limitations to overall system productivity and profitability with inclusion of a cover crop. The effect of cover cropping on main crop yield is mixed, often minimally affecting soybean [*Glycine max* (L.) Merr.] yield (Acuña and Villamil, 2014; Dozier et al., 2017), whereas corn (*Zea mays*) yield is often reduced with cover crop inclusion (Behnke et al., 2020; Qin et al., 2021). Other studies have identified the potential for improved yields and yield stability of the cropping system over time when cover crops are included (Snapp et al., 2005; Dozier et al., 2017; Chim et al., 2022).

Cover crops directly increase the cost of production through increased input cost (cover crop seed, planting, and termination) and often result in negative net returns, particularly under concurrence of increased costs and reduced main crop yields (Plastina et al., 2020; Nelson et al., 2023). Improved nutrient cycling with cover crops could reduce fertilizer inputs over time, reducing production costs. Herbicide inputs may also be reduced with the addition of cover crops to the system, as cover crops can reduce weed pressure, again offering a potential reduction in production costs (Qin et al., 2021). In addition to the effect on farm economics, the role cover crops may play in decreasing P loss to the environment can have economic benefits at a societal level. Thus, evaluation of the economic outcomes from addition of cover crops as a P loss mitigation strategy, in conjunction with P fertilizer management strategies, could inform the extent of incentives producers would require to widely adopt this practice.

Sustainable solutions to mitigate P loss require both efficacy from an environmental perspective and feasibility for farm production and economics (Lal et al., 1991; Grant and Flatten, 2019). Evaluation of management strategies and system modifications to mitigate loss, and their effect on agronomic and economic outcomes, are required to facilitate adoption of management strategies to reduce agricultural P loss. As such, investigating the effect of cover crops as a

conservation practice, in conjunction with P fertilizer management strategies on productivity and profitability of the system, will inform the feasibility of this approach to mitigate P loss, with or without the assistance of farm program funding. Our objectives were to i) determine the effect of contrasting P fertilizer management systems on no-till corn and soybean yield and economics, and ii) determine the opportunity cost of water quality improvement of potential conservation practices.

3.3 Materials and Methods

3.3.1 Site characteristics and experimental design

The Kansas Agricultural Watershed (KAW) field laboratory was established in 2014 to determine the effects of cover crops, P fertilizer management, and their interaction, on a no-till corn-soybean system. The research site consists of 18 individual plots, each about 0.5 hectare in size. Each plot is operated as a small-scale watershed from which surface runoff can be collected. The site was on a slightly to highly eroded Smolan silty clay loam (fine, smectitic, mesic Pachic Argiustoll), with 3-7% slope. The region is characterized by a hot, humid, continental climate, with an average annual temperature of 12°C and 875 mm of average annual precipitation, based on a 30-year average.

The experiment was set up as a 2x3 factorial, with two levels of cover crop treatment: with cover crop (CC) and without cover crop (NC), and three levels of P fertilizer management. The control (CN) treatment did not receive any P fertilizer, the build and maintain (BM) treatment received 61 kg P₂O₅ ha⁻¹ yr⁻¹ for five years (2015 to 2019 crop years) and an average of 55 kg ha⁻¹ yr⁻¹ for three years (2020 to 2022 crop years), and the build and drawdown (DD) treatment that received 61 kg P₂O₅ ha⁻¹ yr⁻¹ for five years (2015 to 2019 crop years) and 0 kg ha⁻¹ yr⁻¹ for three years (2020-2022 crop years). The P source for the BM treatment was ammonium

polyphosphate, applied at 5 cm below and 5 cm to the side of the seed at planting for all years. The P source for the DD treatment was diammonium phosphate broadcast on the surface during the fall prior to planting during the build years. The different P source and application methods for the DD treatment were selected to evaluate the effects of these two common P management systems (fall broadcast vs. spring injected) on P losses, efficiencies, crop yield, and economics during the build phase (Carver et al., 2022; Nelson et al., 2023; Bourns et al., 2024).

This study evaluates treatment effects during the drawdown/maintenance phase (2020, 2021, and 2022). Soil test P at the beginning of the project (2015) was 17 mg kg⁻¹. Soil test P after the build phase and for the three drawdown/maintenance years is found in Table 3.1. The three fertilizer management treatments were applied both with and without a small grain winter cover crop, comprised primarily of wheat (*Triticum aestivum* L.) or triticale ($\times$ *Triticosecale* Wittm.) from 2015 to 2019 or cereal rye (*Secale cereale* L.) from 2020 to 2022.

Table 3.1 Mehlich-III soil test phosphorus (P) from 0-15 cm depth for P fertilizer management treatments by year during the drawdown/maintenance phase. Soil test P was determined from samples collected the previous fall (e.g., 2020 soil test P was determined from samples collected in the fall of 2019, following harvest).

P fertilizer management	2020	2021	2022
	----- mg kg ⁻¹ -----		
CN	5	4	3
DD	27	16	14
BM	29	22	17

Abbreviations: CN, control; DD, build and drawdown; BM, build and maintain

3.3.2 Agronomic management

Details on agronomic management during the build period (2015 through 2019) can be found in Nelson et al. (2023). During the drawdown period (2020-2022), cereal rye (*Secale cereale*) was sown as the cover crop each year on 19.05 cm spacing, using a JD-1590 no-till drill with single disc openers (John Deere, Moline, IL). Corn and soybean were sown in alternating

years, beginning with soybean in 2020. Corn and soybean planting was done with a White 6200 series planter (AGCO Corp., Duluth, GA), at 76.2 cm spacing. Pre-emergent herbicides were used each season and post-emergent herbicides were applied as needed during the vegetative stages of crop growth. Specific agronomic management details are outlined in Table 3.2 and annual precipitation is summarized in Figure 3.1.

Table 3.2 Agronomic management for the 2020 through 2022 growing seasons at the KAW field site.

	Cropping Year		
	2020	2021	2022
Fertilizer management			
P application date (BM)	18 May 2020	29 Apr. 2021	15 Jun. 2022
P rate, kg P ₂ O ₅ ha ⁻¹ (BM)	40	71	53
N application date	-	22 Apr. 2021	-
N source and placement	-	UAN, injected	
N rate ^b	-	180	-
Annual precipitation^a	978 mm	725 mm	775 mm
Cover crop management			
Species	cereal rye	cereal rye	cereal rye
Seeding rate, kg ha ⁻¹	59.4	61.6	74
Planting date	29 Sept. 2019	13 Oct. 2020	24 Sept. 2021
Biomass collection date	9 May 2020	12 Apr. 2021	20 May 2022
Termination date	18 May 2020	13 Apr. 2021	20 May 2022
Main crop management			
Species	soybean	corn	soybean
Cultivar	Pioneer P38A49L	DEKALB DKC53-27RIB	Pioneer P39T61SE
Planting date	18 May 2020	29 Apr. 2021	15 Jun. 2022
Seeding rate, seeds ha ⁻¹	345,800	62,985	344,565
Harvest date ^c	7 Oct. 2020	8 Sept. 2021	17 Oct. 2022

^a30-year annual average precipitation = 875 mm

^bCumulative N rate across all fertilizer sources applied

^cHarvest dates for the subplot areas within the larger plot.

Abbreviations: BM, build and maintain.

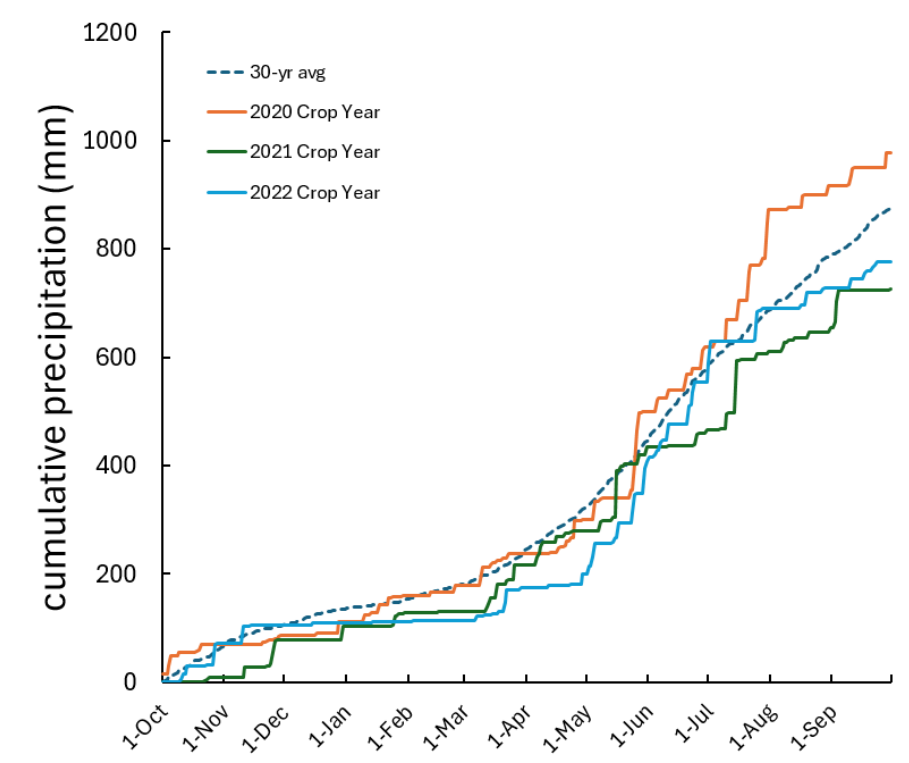


Figure 3.1 Cumulative annual precipitation for study years and 30-year average precipitation for the study region.

3.3.3 Data collection

Cover crop biomass was collected each spring as close to termination and main crop planting as possible. Biomass was collected from three geo-referenced subsample locations within each main plot, from a 3.05m x 2-row area. Main crop harvest data was collected differently for corn and soybean. Corn was hand harvested from a 9.14m x 2-row area, in each of the three subplots within each main plot. For soybean, a Gleaner E III combine (AGCO Corp., Duluth, GA) was used to harvest three, 10 to 20 m x 2-row subplot areas within each main plot. Yield data were adjusted to standard moisture contents of 133 g kg⁻¹ and 155 g kg⁻¹ for soybean and corn, respectively.

Surface runoff volume leaving each plot was measured with a 0.46-m H-flume. ISCO 6700 and 6712 series water samplers equipped with ISCO 730 bubbler modules were used to

measure water depth in the flumes. From each run-off event, the water samplers collected flow-weighted composite runoff samples. Water samples were removed from the samplers within 24 hours and analyzed for total P, dissolved reactive P (DRP), and total suspended solids concentrations following methods outlined by Carver et al. (2022).

Economic data were obtained from a variety of local sources. Costs for field operations were based on Kansas custom rates for 2020 and 2022 (Kansas Department of Agriculture and KSU Land Survey Program, 2020; Kansas Department of Agriculture and KSU Land Use Survey Program, 2022) and Kansas State University Farm Management Budgets (Ibendahl et al., 2020, 2021, 2022). Herbicide prices for weed control were obtained from Kansas State University (Kansas State University, 2020, 2021, 2022) as well as input suppliers. Price of seed was obtained from Kansas State University Farm Management Budgets (Ibendahl et al., 2020, 2021, 2022) and validated with input supply firms for accuracy. Field application and seeding rates were used to calculate total input costs.

Annual gross returns were calculated as yield*price for each year, with the same grain price allocated to each treatment within each year. Annual net return was calculated by subtracting the total costs from gross return for each treatment, in each crop year. The net returns used represent the net returns to land, management and risk as opportunity cost for land, management and risk characteristics were not included in the analysis. Potential Government payments were not included in net return calculations as these payments do not directly influence corn-soybean management.

3.3.4 Cost and water quality calculations

The change in water quality for management alternative to BM-NC was calculated by subtracting TP, DRP, or sediment loss of alternate management (CN-NC, CN-CC, DD-NC, DD-

CC, or BM-CC) from the loss of the BM-NC treatment. A negative change in water quality thereby indicates alternative management improved water quality compared to BM-NC. Our opportunity costs were calculated as the annual net return of the BM-NC treatment subtracted from the annual net return of our alternative management. A negative opportunity cost indicates the alternative management was less profitable than BM-NC.

We calculated the cost of water quality improvement ($\$ \text{ ha}^{-1}$) by dividing opportunity cost by change in water quality for TP, DRP, and sediment loss, for each alternative management strategy. Treatments that led to a negative opportunity cost and poorer water quality than BM-NC should not be considered as feasible alternative management options as they are more costly than BM-NC and decrease runoff water quality. Such treatments are marked as “NA” for cost of water quality improvement. Treatments that led to improved water quality and improved net profit compared to BM-NC have no associated cost of water quality improvement, as they both improve the bottom line and water quality metrics simultaneously. Such treatments are marked as “None” for cost of water quality improvement.

3.3.5 Statistical analysis

Statistical analysis was done using PROC GLIMMIX or PROC MIXED, in SAS version 9.4 with year, cover crop, P fertilizer and rep as fixed effects. Analysis of variance was used to determine treatment effects on cover crop biomass and main crop yield. Preplanned contrasts were used to determine if water quality metrics for a given treatment was significantly different from the optimal (or highest yielding) treatment each year.

In our models, the year factor includes both the effect of growing season conditions and crop, as only one crop was grown in each year. A 95% confidence level was used in assessing statistical significance. Residual panels were visually assessed to determine whether the

assumptions of normality were met; transformations were done on an as needed basis if the assumption of normality was violated. Sediment loss in 2020, 2021, 2022, and total P loss in 2021 required a log₁₀ transformation, as did cover crop biomass. Means and standard errors of transformed endpoints were backtransformed for presentation in tables and figures.

3.4 Results and Discussion

3.4.1 Crop yield

Both fertilizer ($p = 0.0224$) and year ($p = 0.0002$) significantly affected CC biomass (Table 3.3). Build and maintain and DD fertilizer treatments increased CC biomass compared to the CN. The CN treatment, which had STP in the very low category ($<8 \text{ mg kg}^{-1}$ Mehlich-III) all three years of the study was not sufficient to produce as much cover crop biomass as the DD and BM treatments. Cover crop biomass varied greatly among the three years due to variability in planting date and growing season conditions year-to-year. In 2021, cover crop biomass was almost eight times smaller than the cover crop biomass accumulated in 2020, and three times smaller than the 2022 cover crop. The smaller cover crop in 2021 was likely driven by later planting, following soybean harvest, and earlier termination ahead of corn planting. Moisture limitation may have played a role as well, with less-than-normal precipitation through the cover crop growth period in 2021 (Figure 3.1). Less than normal precipitation through the cover crop growth period was characteristic of the other two study years as well, so precipitation was not the only driving factor for reduced biomass in 2021.

Table 3.3 Main effect of phosphorus (P) fertilizer management treatment on cover crop biomass for the drawdown/maintenance phase.

Treatment	2020	2021	2022	Mean
----- kg ha ⁻¹ -----				
CN	2674	338	1225	1034b
DD	3885	506	1323	1375a
BM	4194	517	1600	1514a

Note: Means followed by the same letter within a column are not significantly different at $\alpha=.05$. Abbreviations: CN, control; DD, build and drawdown; BM, build and maintain.

Main crop yield was affected by the interactions between both cover crop by year ($p = 0.0002$), and fertilizer by year ($p = 0.0235$). Cover crop reduced main crop yield in corn by more than 1400 kg ha⁻¹, compared to NC, but did not affect soybean yield in either 2020 or 2022 (Figure 3.2). This is similar to other studies where corn yield is frequently reduced in the presence of a cover crop (Behnke et al., 2020; Qin et al., 2021), but soybean yield is usually minimally affected (Acuña and Villamil, 2014; Dozier et al., 2017). This was true for our corn even following relatively little biomass accumulation for the 2021 cover crop. Moisture and nutrient availability limitations are the main concern for corn production following a cover crop (Miguez and Bollero, 2005; Qin et al., 2021). The 2021 year was characterized by lower than long-term normal precipitation (Table 3.2). We found no effect of CC on P concentration or uptake in the corn (Chapter 4), so, corn yield reduction was not driven by reduced P availability under CC management. Restricted moisture availability under CC compared to corn under NC management could have played a role. In a year of already restricted moisture availability, from lower-than-normal precipitation, the effect of moisture competition on corn yield could be exacerbated.

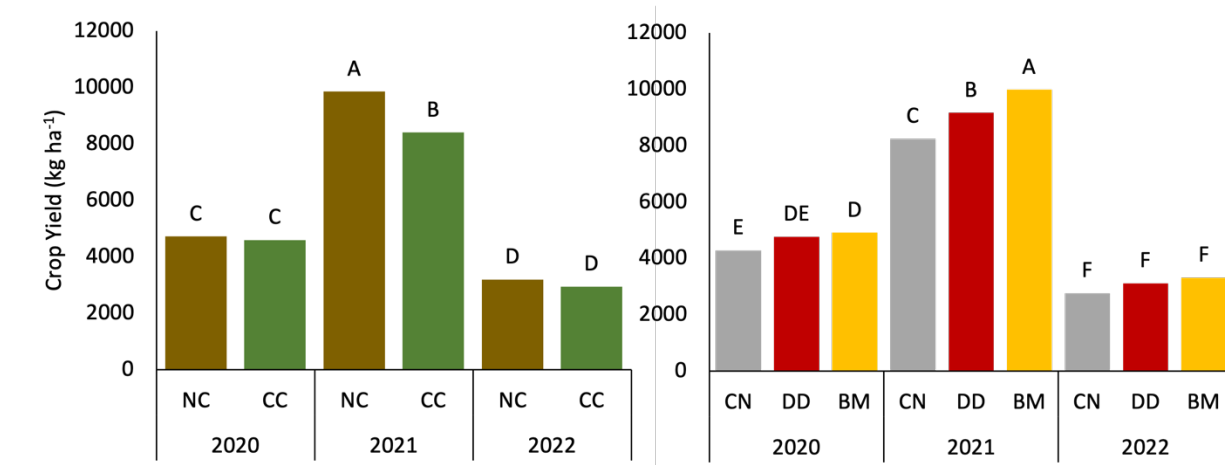


Figure 3.2 Effect of the cover crop by year (left) and fertilizer by year (right) interactions on main crop yield. Abbreviations: NC, without cover crop; CC, with cover crop; CN, control; DD, build and drawdown; BM, build and maintain. Bars with the same letter are not significantly different at $\alpha=.05$.

For soybean, CN and DD management resulted in similar yield in 2020 and 2022 (Figure 3.2). Build and maintain increased soybean yield compared to the CN in 2020, but all three P fertilizer treatments yielded similarly in 2022. Corn yield increased in a stepwise manner from CN to DD and DD to BM. Corn yield in the BM treatment was more than 1700 kg ha⁻¹ greater than the CN and more than 800 kg ha⁻¹ greater than DD. Even with STP at 4 mg kg⁻¹ (very low STP category) for the CN treatment in 2021, we were able to produce ~8200 kg ha⁻¹ of grain.

Yield spread between BM and CN in 2022 was the smallest of the three years, despite STP being nine times greater for BM compared to the CN (Table 3.2). Although soybean yield responses to P fertility and fertilizer are typically less frequent than for corn (Boring et al., 2018; Culman et al., 2023), we expected to see more separation in yield between the CN and DD and CN and BM treatments. Soil test P was more than four times greater for DD compared to CN, and nine times greater for BM compared to CN. Additionally, the BM treatment received P fertilizer and the other two treatments did not. So, the lack of yield separation among our P management treatments was surprising. The 2022 growing season followed a drier than normal

year in 2021, so we began the 2022 soybean season with a moisture deficit. Precipitation continued to be limited relative to normal, through the month of June (Figure 3.1). So, 2022 was also characterized by dry weather and this likely limited our overall yield potential. Lower yield potential reduces the demand for nutrients, and this could explain some of the similarity of soybean yield among our P fertilizer treatments in 2022.

Although growing season conditions may explain some of the unexpected yield similarities among our treatments, there was likely other factors at play – particularly related to soil P supply dynamics. The CN, with no P applied, yielded 87% of BM with 83% less STP in 2020, 82% of BM with 82% less STP in 2021, and effectively 100% of BM yield with 89% less STP in 2022. So, our soil was still supplying P at a rate great enough to achieve over 80% of the yield from our high P input system, with a fraction of the starting STP in each of the three drawdown years. We do not characterize the dynamic nature of P supply over the growing season with traditional agronomic soil tests (Steinfurth et al., 2024) and, evidently, soil P supply over the season can play a substantial role in yield development.

3.4.2 Costs and returns

All treatment combinations including a cover crop (CN-CC, DD-CC, BM-CC) had increased planting and seed costs compared to NC (Table 3.4, 3.5, 3.6). Phosphorus fertilizer and application costs in the BM treatments (BM-CC and BM-NC) increased total cost compared to the other treatments in all three years. During the drawdown/maintenance phase, DD plots did not receive any P fertilizer, so costs were similar between CN-NC and DD-NC treatments, and between CN-CC and DD-CC treatments.

In the 2020 soybean year gross return increased from CN to DD and DD to BM (Table 3.4). Under CN and DD, CC reduced gross return compared to the NC alternative. Under BM

management, BM-CC resulted in \$7.55 ha⁻¹ greater gross return than the BM-NC treatment in 2020 due to a slight numerical increase in soybean yield for BM-CC. However, once increased cost of production was factored in for CC seed and sowing, the gross benefit of BM-CC disappeared; net return of BM-NC was greater than that of BM-CC, and both were lower than net return of DD-NC. The DD-NC treatment was most profitable on a net return basis for 2020.

Table 3.4 Annual costs, yields, gross and net returns for soybean in 2020 as affected by phosphorus (P) fertilizer management and cover crop use.

	Treatment					
	CN-NC	CN-CC	DD-NC	DD-CC	BM-NC	BM-CC
<i>Soybean 2020</i>						
<i>Costs (\$ ha⁻¹)</i>						
Planting	\$43.83	\$84.57	\$43.83	\$84.57	\$43.83	\$84.57
Seed	\$116.35	\$152.35	\$116.35	\$152.35	\$116.35	\$152.35
Fertilizer						
Application	\$0.00	\$0.00	\$0.00	\$0.00	\$3.95	\$3.95
Fertilizer	\$0.00	\$0.00	\$0.00	\$0.00	\$55.43	\$55.43
Herbicide						
Application	\$18.59	\$18.59	\$18.59	\$18.59	\$18.59	\$18.59
Herbicides	\$47.20	\$47.20	\$47.20	\$47.20	\$47.20	\$47.20
Harvest	\$88.50	\$85.71	\$91.42	\$90.82	\$92.43	\$92.64
Interest	\$9.43	\$11.65	\$9.52	\$11.81	\$11.33	\$13.64
Total Costs	\$323.89	\$400.07	\$326.91	\$405.33	\$389.11	\$468.36
<i>Yield and Returns</i>						
Yield (kg ha ⁻¹)	4434	4122	4833	4695	4874	4946
Price (\$ kg ⁻¹)	\$0.32	\$0.32	\$0.32	\$0.32	\$0.32	\$0.32
Gross Return (\$ ha ⁻¹)						
¹⁾	\$1,436.04	\$1,334.99	\$1,565.26	\$1,520.57	\$1,578.54	\$1,601.86
Net Return (\$ ha ⁻¹)	\$1,112.14	\$934.92	\$1,238.35	\$1,115.24	\$1,189.43	\$1,133.49

Abbreviations: NC = no cover crop; CC = with cover crop; CN = no P fertilizer; DD =build and drawdown; BM = build and maintain.

In the corn year gross return was consistently greater for the NC treatment within each fertilizer management strategy (Table 3.5). This was expected based on the significant decrease in corn yield with CC compared to NC. Gross return in BM-NC was \$35.01 ha⁻¹ greater than DD-NC, which was the next highest grossing treatment. Although BM-NC grossed the most in the corn year, the increased cost of production from P fertilizer input and application costs compared to DD-NC diminished any gain from BM-NC for net return. The DD-NC treatment had the highest net return in 2021.

Table 3.5 Annual costs, yields, gross and net returns for corn in 2021 as affected by phosphorus (P) fertilizer management and cover crop use.

	Treatment					
	CN-NC	CN-CC	DD-NC	DD-CC	BM-NC	BM-CC
<i>Corn 2021</i>						
<i>Costs (\$ ha⁻¹)</i>						
Planting	\$45.93	\$86.67	\$45.93	\$86.67	\$45.93	\$86.67
Seed	\$164.96	\$204.89	\$164.96	\$204.89	\$164.96	\$204.89
Fertilizer						
Application	\$18.25	\$18.25	\$18.25	\$18.25	\$22.94	\$22.94
Fertilizer	\$227.21	\$227.21	\$227.21	\$227.21	\$325.68	\$325.68
Herbicide						
Application	\$37.19	\$37.19	\$37.19	\$37.19	\$37.19	\$37.19
Herbicides	\$68.41	\$68.41	\$68.41	\$68.41	\$68.41	\$68.41
Harvest	\$131.07	\$120.76	\$155.97	\$121.76	\$158.06	\$142.17
Interest	\$20.79	\$22.90	\$21.54	\$22.93	\$24.69	\$26.64
Total Costs	\$713.81	\$786.27	\$739.45	\$787.30	\$847.86	\$914.58
<i>Yield and Returns</i>						
Yield (kg ha ⁻¹)	8,573	7,824	10,380	7,897	10,532	9,379
Price (\$ kg ⁻¹)	\$0.23	\$0.23	\$0.23	\$0.23	\$0.23	\$0.23
Gross Return (\$ha ⁻¹)	\$1,977.42	\$1,804.71	\$2,394.38	\$1,821.51	\$2,429.39	\$2,163.29
Net Return (\$ha ⁻¹)	\$1,263.61	\$1,018.44	\$1,654.93	\$1,034.21	\$1,581.53	\$1,248.71

Abbreviations: NC = no cover crop; CC = with cover crop; CN = no P fertilizer; DD =build and drawdown; BM = build and maintain.

For the 2022 soybean year, gross return was greatest for the BM-NC treatment followed closely by BM-CC (Table 3.6). Although the CC treatment within each fertilizer treatment led to lower gross return than the NC alternative, both BM-NC and BM-CC had greater gross return than all other treatment combinations in 2022. However, again in 2022 DD-NC had the highest net return of all treatment combinations.

Table 3.6 Annual costs, yields, gross and net returns for soybean in 2022 as affected by phosphorus (P) fertilizer management and cover crop use.

	Treatment					
	CN-NC	CN-CC	DD-NC	DD-CC	BM-NC	BM-CC
<i>Soybean 2022</i>						
<i>Costs (\$ ha⁻¹)</i>						
Planting	\$55.14	\$106.99	\$55.14	\$106.99	\$55.14	\$106.99
Seed	\$155.01	\$199.01	\$155.01	\$199.01	\$155.01	\$199.01
Fertilizer						
Application	\$0.00	\$0.00	\$0.00	\$0.00	\$1.90	\$1.90
Fertilizer	\$0.00	\$0.00	\$0.00	\$0.00	\$154.52	\$154.52
Herbicide						
Application	\$54.81	\$54.81	\$54.81	\$54.81	\$54.81	\$54.81
Herbicides	\$266.71	\$266.71	\$266.71	\$266.71	\$266.71	\$266.71
Harvest	\$86.67	\$83.05	\$89.01	\$87.10	\$90.39	\$89.24
Interest	\$18.55	\$21.32	\$18.62	\$21.44	\$23.35	\$26.20
Total Costs	\$636.89	\$731.89	\$639.30	\$736.06	\$801.83	\$899.38
<i>Yield and Returns</i>						
Yield (kg ha ⁻¹)	2962	2560	3222	3010	3375	3248
Price (\$ kg ⁻¹)	\$0.55	\$0.55	\$0.55	\$0.55	\$0.55	\$0.55
Gross Return (\$ ha ⁻¹)	\$1,624.37	\$1,403.61	\$1,766.90	\$1,650.59	\$1,850.87	\$1,781.24
Net Return (\$ ha ⁻¹)	\$987.48	\$671.72	\$1,127.60	\$914.52	\$1,049.03	\$881.86

Abbreviations: NC = no cover crop; CC = with cover crop; CN = no P fertilizer; DD =build and drawdown; BM = build and maintain.

Overall, DD-NC was consistently most profitable on a net-return basis, even though STP declined the most for this treatment over the three-year study; DD STP began at 27 mg kg⁻¹ in 2020 and was down to 14 mg kg⁻¹ at the start of the 2022 growing season. Based on our yield

data, finding DD-NC to have the highest net return in the two soybean years was not surprising. However, DD-NC was also most profitable in the corn year, even when DD significantly reduced corn yield compared to BM. So, the yield increase with BM compared to DD for the corn year was not enough to offset the increased cost of production under BM management. We would have needed an additional 284 kg ha⁻¹ of corn yield to break even for the BM system. The 2021 growing season was drier than long-term normal, so it is possible that under more ideal growing season conditions BM-NC could have been more profitable than it was in the 2021 year.

Although there are not studies in the literature with the same treatments as our study (e.g., BM and DD systems), there have been studies investigating the economics of high P BM systems. A long-term study in Nebraska found the effect of P fertility maintained at high STP concentrations compared to medium and optimum, depended on growing season conditions (Patel et al., 2024); net return was significantly greater for the highest P fertility treatment under normal growing season conditions, characterized by precipitation, but not under dry or wet years. Other authors note the chance of yield increases in systems with STP maintained at high levels great enough to pay for the additional expenses are usually low (Fabrizzi et al., 2017; Rutan and Steinke, 2021a).

3.4.3 Cost of water quality improvement

Both DD and BM plots had similar STP at the start of the maintenance/drawdown phase in 2020 (27 and 29 mg kg⁻¹, respectively) and both were substantially greater than STP in the CN (5 mg kg⁻¹). This explains the significant decrease in TP and DRP loss for CN management, both with and without a cover crop, compared to BM-NC (Table 3.7). Decreased P loss is expected in conjunction with lower STP (Rowe et al., 2016; Schneider et al., 2019; Sharpley, 1995); however, there is no consensus on optimal STP concentration to reduce P losses and there is a

need to regionally determine threshold STP to reduce runoff losses (Macrae et al., 2021). The DD-CC treatment reduced TP loss compared to BM-NC, but DD-NC and BM-NC led to similar TP loss. This was likely because DD-CC substantially reduced sediment P loss compared to BM-NC, but DD-NC did not; with a reduction in sediment P loss typically comes a reduction in particulate, or “soil-bound”, P loss (Osmond et al., 2019; Carver et al., 2022). Due to similarity in crop biomass (Chapter 4) and starting STP, TP, DRP, and sediment loss were similar in 2020 between BM-NC and DD-NC. This was true even though BM plots received an application of P fertilizer and DD plots did not, likely because of the subsurface placement of the applied P. The presence of a cover crop substantially reduced sediment loss, up to 90% compared to BM-NC.

Table 3.7 Total phosphorus (P), dissolved reactive P (DRP), and sediment loss for cover crop and P fertilizer treatments with *p*-values from contrasts with BM-NC.

Treatment	Total P loss		DRP loss		Sediment loss	
	kg ha ⁻¹	<i>p</i> -value	kg ha ⁻¹	<i>p</i> -value	kg ha ⁻¹	<i>p</i> -value
2020						
BM-NC	3.78		1.52		1945	
CN-NC	1.79	<.0001	0.28	<.0001	1933	0.9801
DD-NC	3.59	0.5588	1.30	0.1196	1670	0.5485
BM-CC	3.54	0.4724	2.82	<.0001	210	<.0001
CN-CC	1.46	<.0001	0.71	<.0001	364	<.0001
DD-CC	2.40	0.0015	1.75	0.0962	200	<.0001
2021						
BM-NC	0.84		0.39		330	
CN-NC	0.42	0.0159	0.07	0.0001	312	0.8648
DD-NC	0.63	0.2677	0.31	0.1687	249	0.4105
BM-CC	1.64	0.0198	1.01	<.0001	52	0.0001
CN-CC	0.30	0.0016	0.06	0.0001	119	0.0096
DD-CC	0.48	0.0444	0.417	0.5924	53	0.0001
2022						
BM-NC	1.95		1.20		559	
CN-NC	0.70	<.0001	0.11	<.0001	684	0.6111
DD-NC	1.20	0.0019	0.59	<.0001	507	0.8032
BM-CC	2.65	0.0033	2.21	<.0001	154	0.0058
CN-CC	0.82	<.0001	0.36	<.0001	240	0.0481
DD-CC	1.47	0.0254	1.12	0.3645	152	0.0055

Note: Bolded values indicate significance at $\alpha = 0.05$

Abbreviations: NC = no cover crop; CC = with cover crop; CN = no P fertilizer; DD =build and drawdown; BM = build and maintain.

Again in 2021, all three treatments with a cover crop substantially reduced sediment loss, up to 84% compared to BM-NC (Table 3.7). Similar to 2020, the CN-CC and CN-NC treatments reduced both TP and DRP loss compared to BM-NC. The substantially lower STP for CN (4 mg kg⁻¹) compared to BM (22 mg kg⁻¹) in 2021 is the driver of reduced TP and DRP loss for CN compared to BM-NC. Both TP and DRP loss were similar between DD-NC and BM-NC

treatments but DD-CC reduced TP loss, likely due to sediment loss reduction with the CC.

Despite STP being 6 mg kg^{-1} less for DD plots compared to BM plots going into the 2021 crop year, both DD-CC and DD-NC had similar DRP loss to BM-NC.

Similar to 2020 and 2021, all CC treatments reduced sediment loss compared to BM-NC and both CN treatments reduced TP and DRP losses, as expected, in 2022. However, 2022 was the first year both DD-NC and DD-CC reduced TP loss compared to BM-NC (Table 3.7). The STP difference between DD and BM was greater in 2022, with DD starting the season at 14 mg kg^{-1} compared to BM STP of 27 mg kg^{-1} . This STP difference is more than double the difference between DD and STP in 2021; this could explain the significant reduction in TP for DD-NC in 2022, but not in 2020 or 2021. Drawdown of STP will be effective at reducing DRP loss, but those benefits will take time (Guo et al., 2021). Consistent with the other years, DD-CC did not decrease DRP loss compared to BM-NC. Because DD-NC decreased DRP loss in 2022, but DD-CC did not, perhaps the CC is contributing to increased DRP loss. Increased DRP loss in response to cover crop inclusion was noted in the build phase of this study, for 2016 through 2018 (Carver et al., 2022).

Based on annual net return, DD-NC was the most logical treatment option in each of these three drawdown years (Table 3.8). All other treatments decreased net return compared to BM-NC. Although DD-NC is the logical choice under our STP and growing season conditions for these three years based on economics, DD-NC did not consistently improve water quality metrics compared to BM-NC. Only CN P fertilizer management consistently reduced TP and DRP loss; however, CN P management represents a substantial loss in potential profit (negative opportunity cost in this case) to the producer compared to BM-NC. The effective cost of water

quality improvement from choosing CN P fertilizer management ranged from \$38.89 to \$1007.48 kg⁻¹ of P loss reduced (Table 3.8).

Table 3.8 Annual change in water quality and opportunity cost of alternative management to BM-NC, along with the cost of water quality improvement.

Alternative management	Change in water quality			Opportunity cost for selecting alternate	Cost of water quality improvement		
	TP loss	DRP loss	Sediment loss		TP reduction	DRP reduction	Sediment reduction
	kg ha ⁻¹	kg ha ⁻¹	kg ha ⁻¹	\$ ha ⁻¹	\$ kg ⁻¹	\$ kg ⁻¹	\$ kg ⁻¹
2020							
CN-NC	-1.99	-1.24	n.s.	-\$77.29	\$38.81	\$62.27	n.s.
DD-NC	n.s.	n.s.	n.s.	\$48.92	n.s.	n.s.	n.s.
BM-CC	n.s.	1.30	-1735	-\$55.94	n.s.	NA	\$0.03
CN-CC	-2.32	-0.81	-1581	-\$254.51	\$109.94	\$312.66	\$0.16
DD-CC	-1.38	n.s.	-1745	-\$74.19	\$53.79	n.s.	\$0.04
2021							
CN-NC	-0.42	-0.32	n.s.	-\$317.86	\$749.43	\$1,007.48	n.s.
DD-NC	n.s.	n.s.	n.s.	\$73.43	n.s.	n.s.	n.s.
BM-CC	0.80	0.62	-278	-\$332.83	NA	NA	1.20
CN-CC	-0.54	-0.32	-212	-\$563.06	\$1,327.54	\$1,740.78	2.66
DD-CC	-0.36	n.s.	-277	-\$547.28	\$1,524.79	n.s.	1.98
2022							
CN-NC	-1.25	-1.09	n.s.	-\$61.55	\$49.05	\$56.61	n.s.
DD-NC	-0.75	-0.61	n.s.	\$78.57	NONE	NONE	n.s.
BM-CC	0.69	1.01	-406	-\$167.18	NA	NA	\$0.41
CN-CC	-1.13	-0.84	-320	-\$377.31	\$334.33	\$448.11	\$1.18
DD-CC	-0.49	n.s.	-407	-\$134.51	\$277.33	n.s.	\$0.33

Abbreviations: NC = no cover crop; CC = with cover crop; CN = no P fertilizer; DD =build and drawdown; BM = build and maintain; n.s., indicates change in water quality of alternative management was not significant ($\alpha = .05$).

Cover crop addition consistently reduced sediment loss with the cost of sediment reduction ranging from just \$0.04 to \$2.66 kg⁻¹ (Table 3.8). Although the cost per kilogram of sediment reduction was minimal, the opportunity cost for CC management was often substantial,

up to a reduction of \$563.06 ha⁻¹. The only treatment to consistently reduce the water quality impact of both sediment and P loss was CN-CC (Table 3.8). However, the substantial opportunity cost compared to BM-NC is a barrier to adoption of CN-CC as a conservation practice, without incentive programs. Additionally, system productivity was lower for CN-CC, particularly in the corn year, reflected by a larger opportunity cost of CN-CC in 2021 compared to 2020 and 2022.

There is likely a need to further explore system effects on crop nutrition, productivity, profitability, and economics, when STP is maintained in the low category. Our DD treatment only reduced TP and DRP loss compared to BM-NC in 2022, when STP was under 15 mg kg⁻¹, or in the low STP category according to KSU recommendations (Ruiz Diaz et al., 2024) . Even under STP and environmental conditions that favored lower P losses from DD-NC compared to BM-NC, DD-NC was still the most profitable treatment. So, DD-NC would be a logical management option to explore for simultaneously achieving productivity, profitability and environmental protection goals.

3.5 Conclusion

Under our growing season conditions during drawdown and starting drawdown at 27 mg kg⁻¹ STP, DD-NC management was consistently most profitable. As such, there could be economic benefit for producers who have high STP to undergo a brief drawdown period, forgoing P fertilizer applications and capitalizing on soil P supply. Management to improve water quality, and its associated opportunity cost, depended on the metric of interest. Drawdown under initially high STP can reduce P loss in runoff depending on STP and growing season conditions; we had reduced losses of P with DD-NC management in one of three years. The CN-CC treatment reduced TP, DRP, and sediment loss in runoff most consistently compared to

farmer standard practice. Under CN-CC management, system productivity declined with reduced yields from CN management in both corn and soybean, and further reduction from CC management in corn. So, supplemental income in the form of incentives would be required for feasibility of this approach as there was a substantial opportunity cost of up to \$563.06 ha⁻¹. Further research is needed to determine the feasibility of drawdown under initially high STP as a mode to improve annual return, reduce P inputs, and reduce P loss from the system over time.

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Chapter 4 – Phosphorus use and efficiencies under drawdown management

4.1 Abstract

Phosphorus (P) is an essential nutrient for crop growth but causes harmful consequences to the environment when lost in runoff. Solutions are required to more efficiently utilize P agronomically and environmentally, reducing P losses while protecting crop P nutrition and system productivity. A history of over-application of P fertilizer with respect to crop P demand has resulted in accumulation of legacy P, now a reserve source of P for crop nutrition. An ongoing challenge of P fertility management is understanding the utility of legacy P for year-to-year P fertilizer management. A long-term study at Ashland Bottoms, KS, has been investigating the effect of P fertilizer management and cover cropping on crop P nutrition and efficiencies in a no-till, corn-soybean system. This chapter includes results focused on three maintenance/drawdown years, when the treatments included: two levels of cover crop treatment (with, CC, and without, NC) and three levels of P fertilizer management (zero P control, CN, build and drawdown rate management, DD, and build and maintain rate management, BM).

The CC treatment reduced main crop biomass but did not affect corn or soybean crop nutrition. Build and maintain management did not consistently increase crop P nutrition compared to DD, although the higher P BM system did support greater grain P removal under CC management in corn. Agronomic efficiency was similar between DD and BM management on a P use efficiency (PUE) PUE and apparent recovery efficiency (ARE) basis, but PFP was increased for DD compared to BM, as expected. Build and drawdown management improved environmental efficiency, once STP decreased under no fertilizer addition. Drawdown

management from initially high STP seems to be a viable option for conservation P management, with limited impacts on crop P nutrition and improvement of environmental efficiency; however, further research is needed to develop region-specific recommendations for drawdown management.

4.2 Introduction

Phosphorus is an essential macronutrient for crop growth (Grant et al., 2001) and fertilizer P is often required to achieve target yields of corn and soybean in the Great Plains. Application of P in cropping systems and development of best management practices (BMPs) around its use have received growing attention over the last several years (Drohan et al., 2019; Sharpley et al., 2018; Singh et al., 2020). Agricultural P entering surface water bodies via runoff contributes to eutrophication and development of harmful algal blooms, both major environmental concerns affecting quality and safety of surface water bodies (Welch, 1978; Correll, 1998; Le Noë et al., 2018; Haque, 2021). Mitigating P loss from our agricultural systems is necessary for the sustainability of our production; however, sustainability demands both protection of the environment and preservation, or even promotion, of agronomic productivity (Lal et al., 1991). Therefore, innovative solutions which reduce P loss to the environment while preserving or enhancing crop P utilization and nutrient use efficiency, are required.

Phosphorus fertilizer management in no-till corn (*Zea mays*)-soybean [*Glycine max* (L.) Merr.] systems of the Great Plains tends to align with one of two distinct strategies: 1) sufficiency-based management wherein P fertilizer decisions are made annually, based on current soil test P (STP) and yield goals, or, 2) build and maintain (BM) management that includes increasing STP above the critical threshold for crop response and then maintaining high STP with routine applications of P fertilizer (Leikam et al., 2010). Build and maintain sustains

higher STP (Pierzynski & Logan, 1982) with more P susceptible to environmental loss compared to a sufficiency system (Osmond et al., 2019; Sharpley, 1995).

Build and maintain is thought to reduce the risk of yield loss in areas of variable STP within a field and improve the overall productivity of the system (Leikam et al., 2010; Olson et al., 1987; Rutan & Steinke, 2021). With more available P, there is also a greater opportunity for producers to capitalize on years of high yield potential under varying, unpredictable, environmental conditions (Karamanos, 2007). The risk mitigating potential of BM is a perceived benefit of this strategy compared to sufficiency; however, data supporting this high P input strategy are limited. A long-term study in Nebraska found maintaining higher STP concentrations increased grain P but did not consistently provide highest return on P fertilizer or highest yield (Patel et al., 2024). Other research does not indicate a clear benefit of BM for crop P nutrition, yield, or return on investment (Olson et al., 1987; Fabrizzi et al., 2017; Wortmann et al., 2018; Culman et al., 2023).

Generally, producers tend to opt for high P systems because of the perceived risk mitigation benefits (Osmond et al., 2019). This preference contributes to accumulation of large stocks of soil test P as annual application of fertilizer exceeds crop demand and soil P reserves increase; this reserve soil P is often referred to as legacy P and is often an underutilized source of P in the system for agronomic gain (Rowe et al., 2016). Legacy P may contribute substantially to crop nutrition in a given year and as such can reduce the need, partially or completely, for P fertilizer inputs (Sattari et al., 2012; Withers et al., 2019). Entering a period of STP drawdown, forgoing fertilizer applications and relying on legacy P supply, may be particularly prudent in years of high P fertilizer prices or tight budgets (Leikam et al., 2003). Additionally, under land management changes (e.g., move from long-term to short-term land rental) there may be a desire

to move away from BM management and capitalize on STP supply from initially high P concentrations (Grant and Flaten, 2019) under drawdown. The opportunity to rely on soil P supply is a delayed benefit of investment in STP building.

Regionally, recommendations to optimize BM systems are ubiquitous; however, recommendations for entering drawdown to utilize legacy P are greatly lacking (Withers et al., 2019). Usually, short-term (a few years) reliance on legacy P in systems with STP greater than the critical threshold for yield response does not compromise crop nutrition or productivity (Rowe et al., 2016; Cade-Menun, 2022); however, drawdown P fertilizer management and use of legacy P need to be regionally explored. The ability to lower STP via drawdown, utilizing legacy P stocks is an important environmental conservation tool; reducing STP to levels equivalent or less than critical agronomic thresholds would help achieve eutrophication reduction targets (Withers et al., 2019).

Cover crops are a conservation tool that can improve P cycling and utilization (Snapp et al., 2005; Pavinato et al., 2017). Depending on the type of cover crop and growing season conditions, cover cropping may lead to greater P uptake of the main crop compared to fallow (Pavinato et al., 2017). Cover crop residue releases P as it decomposes (Eichler-Löbermann et al., 2008) and this process is relatively quick, with cover crop residue P potentially available for use by the subsequent main crop (Carver et al., 2020; Maltis-Landry and Fossard, 2015). If cover crops effectively improve P cycling and availability for the main crop, P fertilizer inputs could be reduced over time (Snapp et al., 2005); however, increased P utilization by the main crop is not consistent in all systems with cover cropping (Chim et al., 2022). The effect of cover crops on P use in the system should be regionally explored.

Cover crops consistently reduce sediment and particulate P loss (Carver et al., 2022), particularly in high fertility systems (Sharpley & Smith, 1991). As such, cover crops can have a substantial impact on runoff water quality improvement; however, the efficacy of cover crops to reduce dissolved P loss in runoff water solution are mixed (Kleinman et al., 2022). Although increased concentration of P near the soil surface from cover crop residue may improve crop P access and utilization, any management that increases P concentration near the soil surface will increase the risk of P loss in runoff water. This is especially true under no-till management in which near-surface nutrient stratification will be further exacerbated (Schwab et al., 2006; Sharpley & Smith, 1991). The effect of cover cropping on available P may also interact with P fertilization practices; for example, cover crops may lead to increased P availability under fertilized conditions, but not under unfertilized conditions (Soltangheisi et al., 2020).

Calculations of nutrient use efficiency traditionally quantify utilization of an applied nutrient in the year of fertilization. Typically, P fertilizer use efficiency is low compared to other nutrients like potassium or nitrogen; P fertilizer use efficiency is typically between 5 and 25%, whereas potassium is usually closer to 40% and nitrogen is around 50% (Baligar et al., 2001; Syers et al., 2008). Under high initial P fertility, P fertilizer use efficiency on an annual basis may be lower than for similar production under initially low P fertility conditions (Yu et al., 2021). Factors affecting nutrient supply and yield potential will also contribute to final P use efficiency; these factors include growing season conditions, soil type, and agronomic management (Yu et al., 2021).

An accepted reality of P fertilizer management is the low PUE for most production conditions on an annual basis (Higgs et al., 2000; Johnston et al., 2014); however, P fertilization and P fertility management is often done with a longer-term scope in mind. For example, under

BM management application of P fertilizer each year is not solely intended to meet crop nutrient demand in the year of application, but rather be an investment into soil P building for use in future seasons. So, assessing agronomic phosphorus use efficiency over a longer period may be more telling as to differences in P fertilizer use under variable P fertilizer management.

Our objectives were to investigate the effect of cover cropping and P fertilizer management systems, including drawdown and maintenance, on i) crop P use; ii) agronomic P use efficiency; and iii) environmental P use efficiency (the portion of P leaving the system as P loss to the environment), in a no-till, corn-soybean system.

4.3 Materials and Methods

4.3.1 Site Characteristics and Experimental Design

A long-term study was established at the Kansas Agricultural Watershed (KAW) field laboratory in 2014 to investigate the effect of P fertilizer management and cover cropping on no-till corn-soybean production. The KAW site was comprised of 18 plots, approximately 0.5 ha in size. Runoff was collected from each individual plot, so, each plot serves as an individual watershed. The site was on a slightly to highly eroded Smolan silty clay loam, with 3-7% slope. The region where the study was located is characterized by a hot, humid, continental climate, with an average annual temperature of 12° C and 875 mm of average annual precipitation.

The experiment was set up as a 2x3 factorial with two levels of cover crop treatment (with and without) and three levels of P fertilizer management. The three P fertilizer treatments included a control (CN) that did not receive any P fertilizer, a build and maintain (BM) treatment that went through a build period from 2015-2019, followed by maintenance, and a build and drawdown (DD) treatment that went through a build period from 2015-2019, followed by drawdown where no P fertilizer was applied. During the five-year build period, both BM and DD

plots received an average of 27 kg P ha⁻¹ year⁻¹. From 2020-2023, the DD treatment did not receive any P fertilizer. During that same time, BM plots received an average of 24 kg P ha⁻¹ year⁻¹. Phosphorus sources for the build period were ammonium polyphosphate applied 5 cm beside and 5 cm below the seed row at planting for the BM treatment and diammonium phosphate broadcast in fall for the DD treatment. These two different management approaches were used to investigate the effects of placement and timing management systems on P losses, P cycling and efficiency, and yield and economics during the build phase (Carver et al., 2022; Nelson et al., 2023; Bourns et al., 2024). The CN, BM, and DD P fertilizer treatments were applied with (CC) and without (NC) a cover crop; the cover crop was comprised primarily of wheat (*Triticum aestivum* L.) or triticale ($\times$ *Triticosecale* Wittm.) from 2015 to 2019 or cereal rye (*Secale cereale* L.) from 2020 to 2022.

4.3.2 Agronomic Management

Build phase agronomic management can be found in detail in Nelson et al. (2023). From 2020 through 2022, the cover crop was sown as fall rye on 19.05 cm spacing with a JD-1590 no-till drill with single disc openers (John Deere, Moline, IL). Cover crop sowing immediately followed harvest of main soybean or corn crop each year. The cover crop was terminated with herbicide prior to planting of the subsequent main crop (Table 4.1).

Soybean was sown in 2020 and 2022, and corn was sown in 2021. Both main crops were planted with a White 6200 series planter, sown at 76.5 cm spacing (AGCO Corp., Duluth, GA). Herbicides were used as required for weed control, pre- and post-emergent. Nitrogen was applied in the corn year as liquid urea ammonium nitrate placed under the surface, banded with a coulter injector at 38.1 cm spacing. Nitrogen was balanced across the three P fertilizer treatments to

ensure total applied N from all fertilizer sources was equivalent. Specific agronomic details for the drawdown years are outlined in Table 4.1.

Table 4.1 Agronomic management for 2020-2022 growing seasons at the KAW field site.

	Cropping Year		
	2020	2021	2022
Fertilizer management			
P application date (BM)	18 May 2020	29 Apr. 2021	15 Jun. 2022
P rate, kg P ₂ O ₅ ha ⁻¹ (BM)	40	71	53
N application date	-	22 Apr. 2021	-
N source and placement	-	UAN, injected	
N rate ^b	-	180	-
Annual precipitation^a	978 mm	725 mm	775 mm
Cover crop management			
Species	cereal rye	cereal rye	cereal rye
Seeding rate, kg ha ⁻¹	59.4	61.6	74
Planting date	29 Sept. 2019	13 Oct. 2020	24 Sept. 2021
Biomass collection date	9 May 2020	12 Apr. 2021	20 May 2022
Termination date	18 May 2020	13 Apr. 2021	20 May 2022
Main crop management			
Species	soybean	corn	soybean
Cultivar	Pioneer P38A49L	DEKALB DKC53-27RIB	Pioneer P39T61SE
Planting date	18 May 2020	29 Apr. 2021	15 Jun. 2022
Seeding rate, seeds ha ⁻¹	345,800	62,985	344,565
Harvest date ^c	7 Oct. 2020	8 Sept. 2021	17 Oct. 2022

^a30-year annual average precipitation = 875 mm

^bCumulative N rate across all fertilizer sources applied

^cHarvest dates for the subplot areas within the larger plot.

Abbreviations: BM, build and maintain.

4.3.3 Data Collection

Edge-of-field runoff from each plot was measured by monitoring water depth in a 0.46-m H-flume with an ISCO 730 bubbler module at 1-min time intervals. Flow-weighted composite

water samples were collected for each runoff event using ISCO 6700 and 6712 series water samplers, which collected a 200-mL sub-sample of runoff water for every 1 mm of runoff. Water samples were analyzed for total suspended solids, total P, and dissolved reactive P following methods described by Carver et al. (2022).

Composite soil samples were collected in the fall, following harvest of the previous crop, from three georeferenced points within each plot. Each composite sample was comprised of 21 soil cores at a sample depth of 15 cm. Soil samples were air dried, ground to pass a 2 mm sieve, and analyzed for Mehlich-III P with a 1:10 soil to solution extraction ratio and a shake time of five minutes.

Cover crop biomass was collected at the three georeferenced points within each plot prior to termination by clipping biomass from a 2-row (0.38 m) by three meter area (Table 4.1). Soybean biomass was collected by cutting plants at the soil surface from a 2-row by one meter area at the same three georeferenced locations used for cover crop biomass collection. Soybean biomass collection was targeted for peak R6 to avoid biomass loss due to leaf drop. The entire sample was weighed to estimate biomass and four plants were then randomly selected from each sample for determination of moisture and nutrient analysis. Soybean grain yield was determined using a Gleaner E III plot combine (AGCO Corp., Duluth, GA) retrofitted with a calibrated weighing system. Two rows by 82-172 m length were collected through the center of each plot. Three grain samples were collected during harvest of each plot, for nutrient analysis. Grain yield was adjusted to standard moisture of 133 g kg⁻¹.

Corn grain and biomass yield were determined by harvesting ears from 2-rows by 9.1 m length from each georeferenced subsample location at physiological maturity. After ear removal, 10 whole plants were randomly selected from the sampling area and collected for leaf and stem

biomass determination. The grain, cob, and stalk/leaf biomass components were summed to get total corn biomass. Grain yield was adjusted to standard moisture of 155 g kg⁻¹. All plant biomass and grain samples were dried, ground, and analyzed for nutrient content with sulfuric peroxide digest (Thomas et al., 1967) and inductively coupled plasma spectroscopy.

Calculations

Agronomic PUE of the DD and BM systems was calculated for each plot as follows:

$$PUE = \frac{[Y_{FT} - Y_{0T}]}{F_T} \quad (2)$$

where Y_{FT} is the cumulative yield (kg grain ha⁻¹) from 2015 through 2022 for the DD or BM treatments, Y_{0T} is the cumulative control yield from 2015 through 2022 (kg grain ha⁻¹), and F_T is the total amount of fertilizer applied from 2015 through 2022 (kg P ha⁻¹) for the DD or BM treatments. The CC-CN treatment was used as the Y_0 for CC plots and the NC-CN treatment was used as the Y_0 for NC plots.

To investigate the effect of P fertilizer management and cover crops on P uptake, we used Apparent Recovery Efficiency (ARE). Cumulative apparent recovery efficiency was calculated for each plot as follows:

$$ARE = \frac{[U_{FT} - U_{0T}]}{F_T} \quad (3)$$

where U_{FT} is the cumulative P uptake (kg P ha⁻¹) from 2015 through 2022 for DD or BM treatments, U_{0T} is the cumulative P uptake of the CN treatment with no added P (kg P ha⁻¹) from 2015 through 2022, and F_T is the total amount of fertilizer P applied from 2015 through 2022 (kg P ha⁻¹) for the DD or BM treatments. The CC-CN treatment was used as the U_{0T} for CC plots and the NC-CN treatment was used as the U_{0T} for NC plots.

Partial factor productivity (PFP) was calculated to determine amount of productivity per unit of P fertilizer applied for the DD versus BM systems, as follows:

$$PFP = \frac{[Y_{FT}]}{F_T} \quad (4)$$

where Y_{FT} is the cumulative yield (kg grain ha⁻¹) from 2015 through 2022 for DD or BM treatments and F_T is the total fertilizer applied (kg P ha⁻¹) from 2015 through 2022 (kg P ha⁻¹) for the DD or BM treatments.

Percent of P lost in runoff was calculated as a metric for environmental phosphorus use efficiency (EPUE). Percent of P loss in runoff was determined as the amount of P lost in runoff relative to the total amount of P leaving the field each year of the maintenance/drawdown period (2020-2022), as follows:

$$\%P_{\text{runoff}} = \frac{P_{\text{runoff}}}{P_{\text{runoff}} + P_{\text{grain removal}}} \times 100\% \quad (6)$$

where P_{runoff} is total P loss in runoff (kg P ha⁻¹) and $P_{\text{grain removal}}$ is the P leaving the system in the grain at harvest (kg P ha⁻¹). So, increased $\%P_{\text{runoff}}$ represents decreased EPUE, with a greater portion of total exported P leaving as P lost in runoff. Similarly, then, decreased $\%P_{\text{runoff}}$ represents an increase in EPUE.

4.3.3.1 Statistical analysis

Analysis of variance was conducted using PROC MIXED or PROC GLIMMIX in SAS ver. 9.4 for each of these end points. Our mixed model included replication, cover crop, P fertilizer treatment, and year as fixed effects. The two-way and three-way interactions among cover crop, P fertilizer treatment, and year were also considered fixed effects. Year and main crop type were confounded in this study, since only one main crop type was present each year; therefore, the year effect includes both growing season environmental condition effects and crop type effects. Plot was the random effect in our model (i.e., the error term vector whose elements corresponded to repeated measurements over year and at three subplots). Cover crop biomass,

cover crop P uptake, and crop removal were not normally distributed and were $\log_{10}$ transformed. Results included for these end points have been back transformed to original units.

Each of PUE, ARE, and $\%P_{\text{runoff}}$ endpoints were calculated on a per-plot basis. They were analyzed with PROC GLIMMIX in SAS ver. 9.4 with fixed effects of replication, cover crop, P fertilizer treatment, and year. All two- and three-way interactions among fixed factors were also considered fixed. Plot was the random effect in our model. For all statistical analyses, the Kenward-Roger method was used for test statistic distribution approximation (Kenward and Roger, 1997). An alpha of 0.05 was used to determine significance and all statistical tests were two-sided.

4.4 Results and Discussion

4.4.1 Soil test phosphorus

At the start of the maintenance/drawdown years, going into the 2020 growing season, DD and BM had similar STP (Table 4.2). After the first maintenance/drawdown year, CN, DD, and BM had significantly different STP within the other two crop years. Over the maintenance/drawdown phase, CN STP stayed very similar and was consistently in the very low ($<8 \text{ mg kg}^{-1}$) STP category. After one year of drawdown, STP dropped significantly from 27 to 16 mg kg^{-1} . The second year of drawdown had less of an effect on DD STP, with similar STP in fall 2020 and fall 2021. Build and maintain STP was lower in fall 2020 than for both other years, but BM STP was consistently in the high STP category ($20\text{-}30 \text{ mg kg}^{-1}$) for the duration of the maintenance/drawdown phase.

Table 4.2 Mehlich-III soil test phosphorus (P) from 0-15 cm depth for P fertilizer management treatments by year during the drawdown/maintenance phase. Soil test P (STP) was determined from samples collected the previous fall.

P fertilizer management	Fall 2019	Fall 2020	Fall 2021
----- mg kg ⁻¹ -----			
CN	5d	4d	3d
DD	27a	16c	14c
BM	29a	22b	27a

Abbreviations: CN, control; DD, build and drawdown; BM, build and maintain.

Note: Means followed by the same letter are not significantly different ($\alpha=.05$).

There was a small, but significant effect of CC on Mehlich-III STP (Table 4.3). Soil test P was slightly greater on average for the NC treatment, compared to the CC treatment. This is not surprising from the perspective of additional utilization of soil P with cover crop growth (Lal et al., 1991a); however, several authors cite the potential for cover crops to improve P supply to the main crop over time (Snapp et al., 2005; Eichler-Löbermann et al., 2008; Pavinato et al., 2017), and this was not the case during maintenance/drawdown in this study. Our results better align with Chim et al. (2022), with a small effect of cover crop on overall STP; although significantly different, statistically, a 2 mg kg⁻¹ STP difference is not likely to be agronomically meaningful.

Table 4.3 Main effect of cover crop treatment on Mehlich-III soil test phosphorus (P) from 0-15 cm depth during the drawdown/maintenance phase.

Cover Crop Treatment	Fall 2019
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	mg kg ⁻¹
NC	17a
CC	15b

Abbreviations: CC, with cover crop; NC, without cover crop.

Note: Means followed by the same letter are not significantly different ($\alpha=.05$).

4.4.2 Phosphorus Nutrition

For treatments with a history of P fertilization (DD and BM treatments) CC biomass was 40% greater compared to the long-term CN (Table 4.4). Greater CC biomass can be both a positive system outcome for reducing sediment loss, competing with weeds, and increasing the rate of soil health improvements (Lal et al., 1991a; Snapp et al., 2005; Blanco-Canqui and Ruis, 2020) or a negative outcome due to increased water and nutrient use that may inhibit main crop productivity (Lal et al., 1991a). Phosphorus concentration in the CC tissue tended to increase with both DD and BM for all three years, significantly for 2021 and 2022 (Figure 4.1). The effect of P fertilizer management on CC P uptake was similar across all three years and both P fertilizer management strategies increased P uptake compared to the CN (Table 4.3). Despite lower STP for the DD treatment compared to BM as the study went on (Table 4.2), P uptake was similar for all three years of the study.

Generally, CC P uptake will increase under higher concentrations of available soil P (Pavinato et al., 2017). In the case of our study, the supply of P from the DD treatment was enough to facilitate CC P uptake similar to the higher P BM treatment. Additionally, cover crop biomass typically mediates P uptake more than P concentration in a given year (Pavinato et al., 2017), and this is reflected in the similarity of biomass and P uptake responses in our cover crop data.

Table 4.4 P-values for testing fixed effects of cover crop (cover), phosphorus (P) fertilizer management (Fert), year, and their interactions on cover crop biomass and P uptake; main crop biomass, P uptake, removal, and return; agronomic phosphorus use efficiency (PUE), apparent recovery efficiency (ARE), partial factor productivity (PFP), and percent phosphorus loss in runoff (%P_{runoff}).

	Soil Test P	Cover Biom.	Cover P Conc.	Cover P Uptake	Crop Biom.	Crop P Conc.	Crop P Uptake	Crop Grain P Conc.	Crop P Removal	Crop P Return	Long- term PUE	Long- term ARE	PFP	%P _{runoff}
Cover	.0411	-	-	-	.0320	.0530	.9448	.2634	.1023	.9107	.6142	.5632	.0019	.5575
Fert	<.0001	.0116	<.0001	.0005	.0017	<.0001	<.0001	<.0001	<.0001	.1022	.8800	.1913	<.0001	.0009
Year	<.0001	<.0001	.0009	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	-	-	-	<.0001
Cover*Fert	.3372	-	-	-	.3516	.5057	.4449	.5979	.1793	.6998	.4842	.8018	.0917	.2828
Cover*Year	.7409	-	-	-	.1444	.2747	.4456	.2082	.6400	.8236	-	-	-	.0020
Fert*Year	.0047	.5349	.0046	.2983	.6442	.0005	.0014	.7120	.0080	.1543	-	-	-	.0401
Cover*Fert*Year	.9332	-	-	-	.1083	.2522	.4873	.8782	.0498	.9672	-	-	-	.4881

^aBolded values indicate significance at $\alpha=.05$.

Table 4.5 Effect of fertilizer and year on cover crop biomass and phosphorus (P) uptake.

Effect	Cover Crop Biomass kg ha ⁻¹	Cover Crop P Uptake kg P ha ⁻¹
Fertilizer		
CN	1034b	2.4b
DD	1375a	4.0a
BM	1514a	4.5a
Year		
2020	3519a	9.2a
2021	445c	1.3c
2022	1374b	3.5b

Note: Means followed by the same letter are not significantly different ($\alpha=.05$).
Abbreviations: CN, control; DD, build and drawdown; BM, build and maintain.

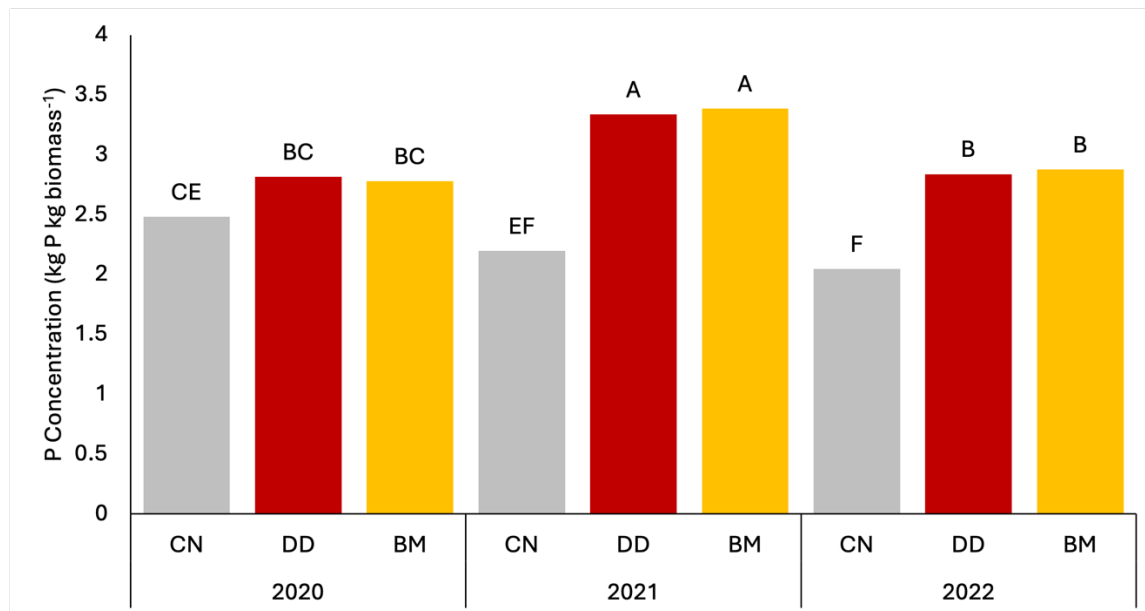


Figure 4.1 Effect of interaction between P fertilizer management and year on P concentration in the cover crop. Abbreviations: CN, control; DD, build and drawdown; BM, build and maintain. Bars with the same letters are not significantly different at $\alpha=.05$.

Main crop biomass was reduced by an average of 7% with CC treatment compared to NC (Figure 4.2). Cover crops can prohibit successive main crop access and utilization of water (Unger and Vigil, 1998b; Dabney et al., 2001). Both 2021 and 2022 were characterized by drier than normal growing season conditions (Table 4.1), so moisture restriction from cover crop growth could have played a key role in reduced main crop biomass. Typically, corn production is more limited by cover crop inclusion than soybean (Qin et al., 2021). Although we did not see a cover crop by year interaction for main crop biomass, indicating the effect of cover crop on soybean and corn growth was similar for our maintenance/drawdown years, we did find a significant cover crop by year interaction for yield (Chapter 3), wherein cover crop decreased corn yield but did not affect soybean yield. Cover crop treatment did not affect main crop P concentration or uptake (Table 4.4), indicating CC did not affect main crop P nutrition in our study. Cover crops can increase P supply to the main crop (Eichler-Löbermann et al., 2008) and this can increase P uptake by the subsequent main crop (Pavinato et al., 2017) but CC did not have these effects in this study. The lack of CC effect on tissue P concentration and uptake indicate CC treatment did not improve P access or utilization compared to the NC treatment. Alternatively, lack of CC effect on tissue P concentration and uptake indicate a neutral effect of CC on main crop P nutrition status; that is, the decrease in main crop biomass with CC did not result from a restriction in P availability to the main crop.

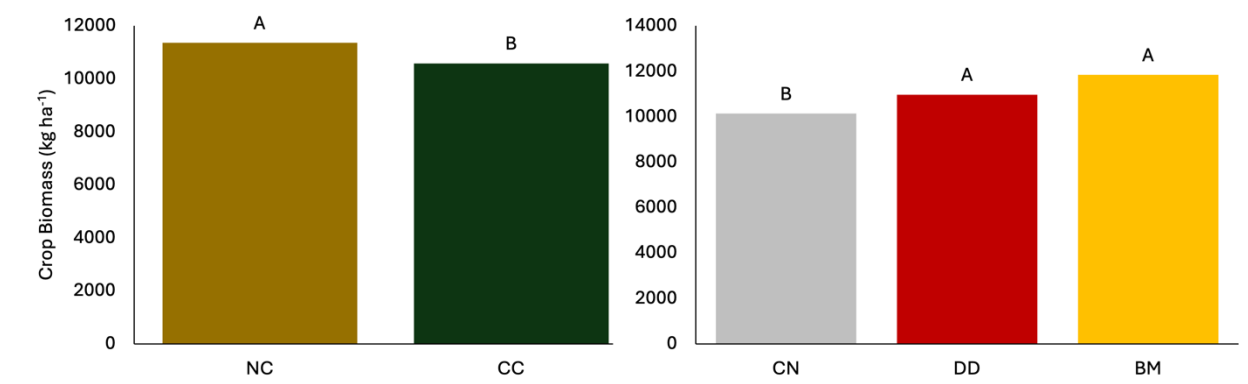


Figure 4.2 Effect of cover crop (left) and P fertilizer management (right) on main crop biomass. Abbreviations: NC, no cover crop; CC, cover crop; CN, control; DD, build and drawdown; BM, build and maintain. Bars with the same letters are not significantly different.

Main crop P concentration increased for both DD and BM treatments each year, compared to the CN. In 2020 and 2021, both DD and BM led to similar P concentration (Figure 4.3). In the final year of drawdown, P concentration was greater for BM than DD, although DD still increased P concentration compared to the CN. Phosphorus uptake was similar between DD and BM treatments each year, although BM tended to be numerically greater (Figure 4.3). In 2022, P uptake was similar between CN and DD; this was the only year DD did not increase P uptake compared to the CN.

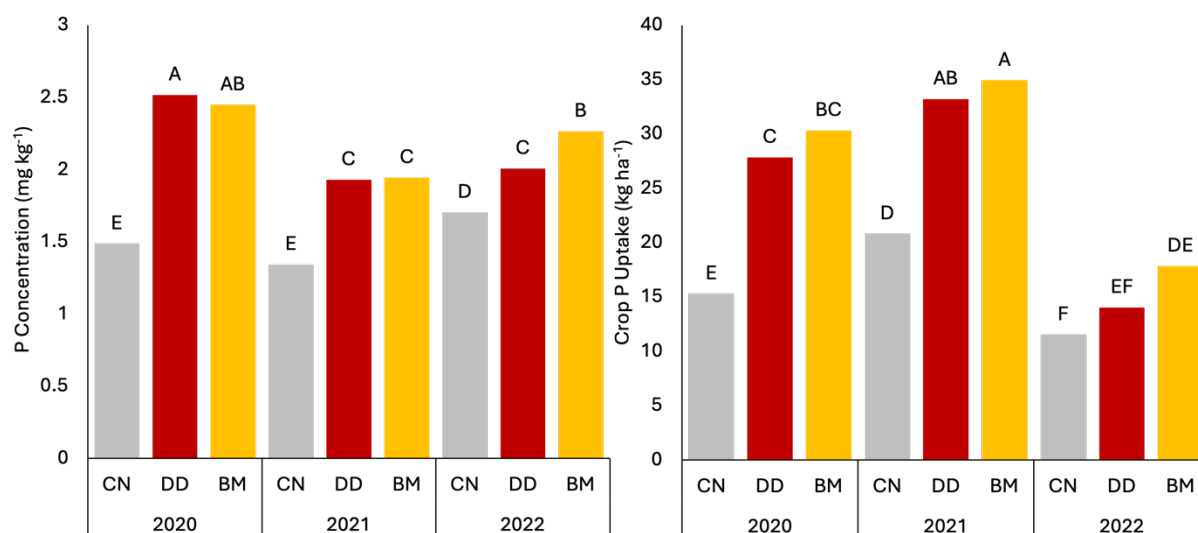


Figure 4.3 Fertilizer by year interaction effect on main crop tissue P concentration (left) and main crop P uptake (right). Abbreviations: CN, control; DD, build and drawdown, BM, build and maintain. Bars with the same letters are not significantly different at $\alpha=0.05$.

Our data indicate a greater difference in P nutrition over time between DD and BM, as STP continues to decline in the DD treatment. In 2021, P nutrition as indicated by both concentration and uptake were similar between the DD and BM treatments, at which time the STP for DD was 6 mg kg⁻¹ less than BM, but by 2022, the STP difference had increased to 13 mg kg⁻¹ and the P concentration was significantly greater for the higher P system and numerically greater for crop P uptake.

Grain P concentration increased for both BM and DD treatments compared to the CN, but BM and DD grain P concentration were similar to one another (Table 4.6). This contrasts with the recent findings of Patel et al. (2024), who found an increase in grain P concentration with higher STP. Phosphorus removal by the grain was affected by the three-way interaction between cover, fertilizer, and year (Figure 4.4). Generally, under both NC and CC treatments, DD and BM led to greater P removal compared to the CN. For corn, under cover crop management BM led to greater crop P removal compared to DD. Greater P supply and/or higher P inputs could be

important for P nutrition in corn when a cover crop is present. Corn is generally more sensitive to both cover crop (Qin et al., 2021) and P fertility (Culman et al., 2023) than soybean.

Table 4.6 Effect of fertilizer and year on grain phosphorus (P) concentration.

Effect	Grain P Concentration kg kg ⁻¹
Fertilizer	
CN	3.75b
DD	4.56a
BM	4.66a
Year	
2020	5.46a
2021	2.73c
2022	4.76b

Note: Means followed by the same letter are not significantly different ($\alpha=.05$).
Abbreviations: CN, control; DD, build and drawdown; BM, build and maintain.

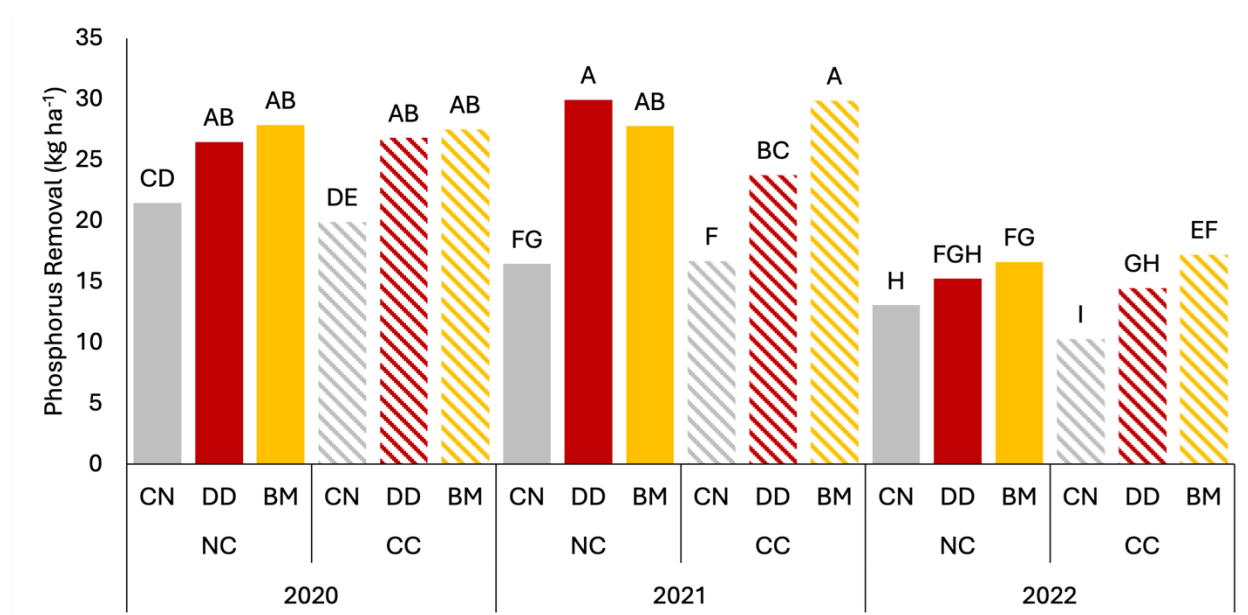


Figure 4.4 Cover crop, fertilizer, and year three-way interaction effect on main crop P removal. Abbreviations: CN, control; DD, build and drawdown; BM, build and maintain. Bars with the same letters are not significantly different at $\alpha=.05$.

Consistently, studies indicate no benefit of STP greater than the critical threshold for yield response on corn or soybean P utilization and productivity (Olson et al., 1987; Fabrizzi et al., 2017; Wortmann et al., 2018; Culman et al., 2023). The current critical soil test threshold for

corn and soybean in Kansas is 20 mg kg⁻¹ Mehlich-III (Ruiz Diaz et al., 2024). Our DD treatment fell below the critical threshold after the 2020 crop year, starting the 2021 season at 16 mg kg⁻¹. During the 2021 and 2022 crop years, P concentration and uptake were still similar between DD and BM treatments, even though STP under DD was within the traditional crop responsive range of STP; that is, we would have anticipated DD to result in poorer crop P nutrition than BM under STP conditions for DD in 2021 and 2022, but this was not the case, statistically. There may, therefore, be potential in exploring the boundaries of STP for drawdown management as a conservation tool to reduce total system P inputs and lower risk of environmental P loss.

Crop P use was statistically similar between DD and BM for most parameters except P concentration in the tissue in 2022 and P removal in the grain in 2021 under CC management. The overwhelming similarities between DD and BM exemplifies the role of legacy P in crop nutrition as well as the ability to reduce or forgo fertilizer inputs for a period of time (Sattari et al., 2012; Withers et al., 2019). Although we can make use of legacy P during drawdown to meet crop P demands (Blackwell et al., 2019), year-over-year drawdown will limit agronomic P availability to subsequent crops. This is evident by the reduced crop P nutrition status under CN management in this study; the CN plots have been in drawdown (i.e., have not received P fertilizer) since fall of 2014. Control STP has stabilized in the very low category and supply of legacy P under extended drawdown in CN plots was not great enough to meet crop P demand. Currently, there is a lack of data for determining optimal drawdown duration and STP parameters to guide drawdown management.

4.4.3 Agronomic Efficiency

Long-term PUE of the system was not affected by cover crop or P fertilizer management treatment (Table 4.7). On average, PUE was 27.5 kg additional yield kg P fertilizer⁻¹ (Table 4.5).

Generally, where over-fertilization occurs, efficiency of fertilizer use is expected to increase as fertilizer inputs decrease (Medinski et al., 2018). So, we expected to find increased PUE for DD compared to BM on the basis of continued yield production under DD with a fraction of the P fertilizer inputs, having withheld application during the three drawdown years. By the end of the 2022 growing season, the BM treatment had received 1.5 times the amount of P fertilizer the DD treatment had. Therefore, the denominator of the BM PUE calculation was 1.5 times larger than for DD. This alone would have led to increased PUE for DD compared to BM, if the yield difference between fertilized and control treatments (i.e., the numerators of the PUE calculations) were similar. However, the increased production with BM management compared to CN management was 1.5 times greater than the increased production with DD management compared to CN. In other words, the increased P fertilizer input with BM compared to the DD system was proportionally offset by the increased yield with BM management for our system.

Similarly, cover crop and P fertilizer management treatments did not affect ARE (Table 4.7). Snapp et al. (2005) proposed cover crops could lead to reduced demand for P fertilizer if they are effective at improving P cycling and P supply to the main crop. The lack of cover crop by fertilizer interaction for ARE suggests this was not the case for these data; CC did not affect main crop uptake of P fertilizer and this was consistent for both DD and BM P management.

Overall average ARE was 0.34 kg P uptake kg P fertilizer⁻¹ (Table 4.7). The ARE numerator for BM was not proportional to the increased cumulative fertilizer applied compared to DD; the BM numerator was about 1.1 times greater than the DD numerator. Numerically, BM ARE is less than DD (Table 4.7); however, ARE was not consistent enough from plot to plot within treatments to render this difference statistically significant.

Table 4.7 Effect of cover crop and phosphorus (P) fertilizer management on phosphorus use efficiency (PUE), apparent recovery efficiency (ARE), and partial factor productivity (PFP) for 2015 through 2022.

Effect	PUE	ARE	PFP
	kg additional yield kg P fertilizer ⁻¹	kg additional P uptake kg P fertilizer ⁻¹	kg yield kg P fertilizer ⁻¹
Cover Crop			
NC	29.5 (16-43) ¹	0.36 (0.24-0.48)	309a (300-318)
CC	25.4 (12-39)	0.32 (0.19-0.44)	282b (273-291)
Fertilizer			
DD	26.9 (14-40)	0.39 (0.27-0.51)	348a (339-357)
BM	28.1 (15-41)	0.29 (0.16-0.41)	244b (235-252)

Note: Means followed by the same letter are not significantly different ($\alpha=.05$).

Abbreviations: NC, no cover crop; CC, cover crop; DD, build and drawdown; BM, build and maintain.

¹Values in parentheses are 95% confidence intervals of the means.

Both cover crop and fertilizer treatments affected PFP, or the amount of yield produced per kg of fertilizer applied over the 8-year study period (Table 4.7). Overall, CC led to almost 30 kg yield kg fertilizer⁻¹ less than NC. Generally, CC treatment yield did tend to be lower than NC yield, although this was only significant in the corn year (Chapter 3). The DD treatment led to over 100 kg of yield more, per kg of fertilizer applied, compared to BM. Yield was similar between DD and BM treatments in both soybean years, but DD reduced yield compared to BM in the corn year (Chapter 3).

4.4.4 Environmental Efficiency

Both cover*year and fertilizer*year interactions affected EPUE, quantified as %P_{runoff} (Table 4.3). The effect of CC treatment on %P_{runoff} varied by year. There was no significant difference between CC and NC treatments in 2020 and 2021, but a significant increase in %P_{runoff} with CC treatment in 2022 (Figure 4.5). Cover crops consistently reduce particulate P loss, mediated by sediment loss, loss (Carver et al., 2022), but have a mixed effect on dissolved P losses (Kleinman et al., 2022). The effect of cover crop on total P loss is affected by the relative effects of cover cropping on particulate and dissolved P losses, and these effects will vary with

precipitation and runoff water dynamics. The trend in %P_{runoff} differences between NC and CC treatments within year follow the effect of CC and NC on total P, with total P loss being significantly greater for CC compared to NC in 2022, due to a large increase in dissolved P loss with CC compared to NC (unpublished data). This was similar to findings from the build phase of the study, where CC effect on %P_{runoff} was closely related to CC effect on total P loss (Bourns et al., 2024).

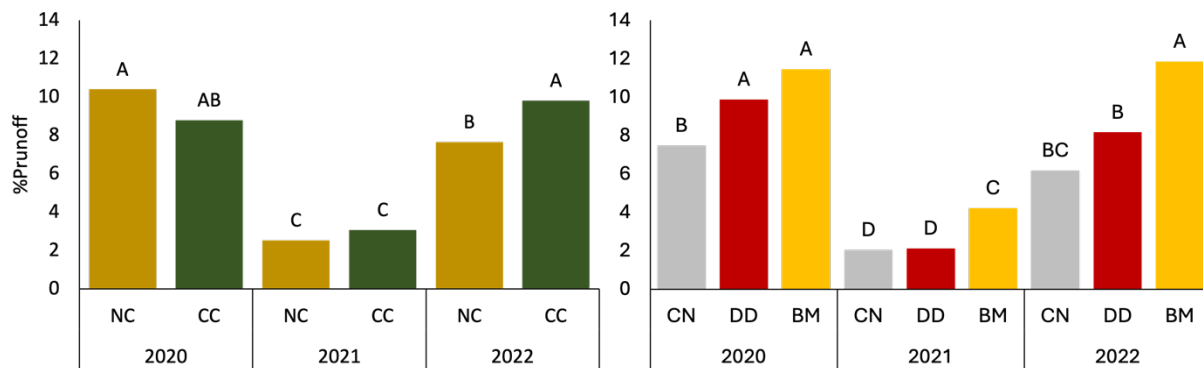


Figure 4.5 Cover crop by year (left) and fertilizer by year (right) interaction effects on environmental phosphorus use efficiency as %P_{runoff}. Abbreviations: NC, no cover crop; CC, cover crop; CN, control; DD, build and drawdown; BM, build and maintain. Bars with the same letters are not significantly different at $\alpha=.05$

In 2020, both DD and BM led to similar %P_{runoff} and both P fertilization treatments increased %P_{runoff} with respect to the CN (Figure 4.5). However, in both 2021 and 2022 BM led to significantly greater %P_{runoff} compared to both the CN and DD treatments, with the latter two resulting in similar %P_{runoff} within 2021 and 2022 crop years. At the start of the study, DD and BM plots had similar STP of 27 and 29 mg kg⁻¹ Mehlich-III, respectively. By the start of the 2022 crop year, BM had an average of 13 mg kg⁻¹ greater STP than DD. This increased STP, in combination with annual fertilization for the BM plots, played a key role in increased %P_{runoff} for the BM treatment, as expected based on the known relationship between increased STP and/or P

fertilizer rates and increased P loss (Sharpley, 1995; Carpenter et al., 1998; Osmond et al., 2019; Schneider et al., 2019; Guo et al., 2021).

Blackwell et al. (2019) note the importance of a change in attitude around P fertility management, including a shift toward optimal fertilization of the crop rather than simply a mentality of building STP, for simultaneously meeting agronomic and environmental system goals. In our system, our DD treatment decreased %P_{runoff} to levels similar to the zero-P CN in 2021 and 2022, as STP continued to decline. This indicates a greater portion of exported P was leaving the field in the grain, compared to leaving as P in runoff water and supports Withers et al. (2019) suggestion that reducing STP below critical thresholds for yield response will result in improved water quality metrics. There was no improvement agronomic efficiency on a PUE or ARE basis for DD management compared to BM; however, entering a DD period to make use of legacy P can improve environmental efficiency compared to continued maintenance under BM management because the decline in P loss in runoff is greater than the decline in P exported in grain.

4.5 Conclusion

Cover crop P use was similar between DD and BM management. The CC treatment decreased main crop biomass, on average, but did not interfere with main crop P access or utilization. This was consistent across P fertilizer management strategies. Phosphorus uptake was similar for both DD and BM, suggesting DD management can meet crop P nutrition needs. A notable exception was the decline in grain P removal for corn under CC management with DD compared to BM; the interaction between cover crop and P fertilizer management for grain P removal suggests separate recommendations for drawdown management may be required for cover crop systems, to ensure adequate crop nutrition. Agronomic use efficiency on a PUE and

ARE basis was not improved with DD management compared to BM, but DD did improve EPUE once STP dropped to 16 mg kg^{-1} .

Drawdown management, with forgone fertilization and reliance on legacy P to supply crop P demand, is a viable option to explore for conservation management. Refined recommendations are needed, though, to determine specific recommendations for STP concentrations at which to start and end drawdown management. Additionally, research is needed to determine the effect of runoff duration on STP concentrations over time, and crop nutrition and efficiencies under different growing season conditions and soil types.

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Chapter 5 – Sustainable Sufficiency: An alternative P fertility management paradigm

5.1 Abstract

Agronomic and economic outcomes are often at odds with environmental protection benefits of conservation practices to improve runoff water quality. Conservation practices that are not feasible for producer adoption will not successfully improve environmental protection as adoption will be limited. Therefore, innovative solutions to agronomic management problems are required, with alignment of agronomic productivity, economic profitability, and environmental protection goals. Current phosphorus (P) rate management is governed by two contrasting paradigms: sufficiency or build and maintain management. While sufficiency management tends to reduce system P levels, lowering environmental risk from P loss in runoff, this paradigm is often viewed as unsustainable over the long-term by producers. A build and maintain paradigm, on the other hand, is often favored for risk mitigation and protection of yield potential. However, a build and maintain system sustains higher soil test P (STP), increasing the risk of P loss to the environment.

Through novel field studies and a new approach to historical data analysis, proof-of-concept for a new management paradigm, sustainable sufficiency, was carried out. Sustainable sufficiency is based on the principle of maintaining a certain STP concentration with routine maintenance application of P fertilizer, however, we contend that the threshold STP for maintenance can be less than the current critical threshold for yield response. Corn and soybean yield response to P fertilizer rate was less frequent than predicted by Mehlich-III STP. A P fertilizer rate greater than maintenance was required just 4% of the time to optimize crop yield. Overwhelmingly, corn and soybean response to a maintenance rate of P fertilizer was similar

across STP, even when STP was low. Continued development of a sustainable sufficiency paradigm is a valid option to explore for alignment of agronomic and environmental outcomes, preserving yield productivity while reducing system P.

5.2 Introduction

As demand for agricultural products continues to expand, protection of our productive capacity through improved sustainability is critical. Sustainable practices must not just be environmentally conscious, but also economically viable and agronomically productive to promote widespread adoption (Lal et al., 1991; Grant and Flaten, 2019). Agronomic and economic outcomes are often at odds with environmental protection benefits of conservation practices. Therefore, development of conservation tools that are attractive to producers agronomically and economically offer an opportunity to increase adoption of practices that will advance the sustainability of our agricultural systems. Critical research is needed to align agronomic productivity and environmental protection goals, to enable adoption of sustainable conservation practices, right now.

Agricultural management of P plays a vital role agronomically in the success of our production and environmentally in the quality and safety of our surface water bodies. Phosphorus is an essential macronutrient for crop growth (Grant et al., 2001) and inputs of P fertilizer are usually applied to meet crop demand and achieve target yields of corn and soybean in the Great Plains. Phosphorus lost in surface runoff from agricultural fields can contribute to eutrophication and development of algal blooms (Welch, 1978; Correll, 1998; Le Noë et al., 2018; Haque, 2021). This severely affects the health and safety of surface water bodies and can greatly limit access and utilization of recreational spaces, negatively impacting communities.

Phosphorus fertilizer management is a well-established control point for reducing agricultural P loss (Kimmell et al., 2001; Zeimen et al., 2006) and work to develop beneficial management practices (BMPs) to reduce P loss has been a focus in recent years (Sharpley et al., 2018; Drohan et al., 2019; Singh et al., 2020). From an environmental protection point of view, BMPs to reduce P loss include reducing the total quantity of P available for loss and limiting the opportunity for P to interact with surface runoff water (Kimmell et al., 2001; Zeimen et al., 2006; Carver et al., 2022).

Currently, P fertilizer recommendations fall under two distinct categories: build and maintain (BM) or sufficiency. Fertilizer rates for both recommendation systems in Kansas are described in Leikam et al. (2003a). The central goal of a BM system is to increase STP above the threshold for crop yield response in the year of fertilization, and then maintain STP at this high level. In Kansas, this means increasing STP above 20 ppm Mehlich III with annual P fertilizer applications, generally over a four-to-eight-year build period, and then maintaining STP in the 20-30 ppm Mehlich III range, also with annual applications. In other words, BM is a high input, high STP system, with regular P fertilizer applications even when STP is above the threshold where we would expect any crop response to the fertilizer in the year of application. Not considering maintenance of any level of STP on the other hand, a sufficiency approach currently recommends P fertilizer rates based on the likelihood of crop response to P fertilizer in the year it is being applied, calculated using current STP and target yield. Sufficiency rate recommendations are often less than crop removal rates at harvest, and a SF system will generally lead to drawdown of STP over time, as a result. Therefore, a BM system will sustain higher STP than a sufficiency system (Pierzynski and Logan, 1982), and we know from research

conducted in other places (Sharpley, 1995; Torbert et al., 2002; Andraski and Bundy, 2003; Schroeder et al., 2004; Osmond et al., 2019) that higher STP is a greater risk to the environment.

Recent work at the Kansas Agricultural Watershed Field laboratory found that sufficiency management under drawdown from initially high STP decreased dissolved reactive P loss in runoff water by 46% and 29% compared to BM for corn-soybean production with and without cover crops, respectively (Figure 5.1). In the same study, sufficiency management reduced total P loss by 45% from plots with a cover crop (Figure 5.1). This illustrates that using a sufficiency P management system is even more important in systems that use soil health building practices like cover crops.

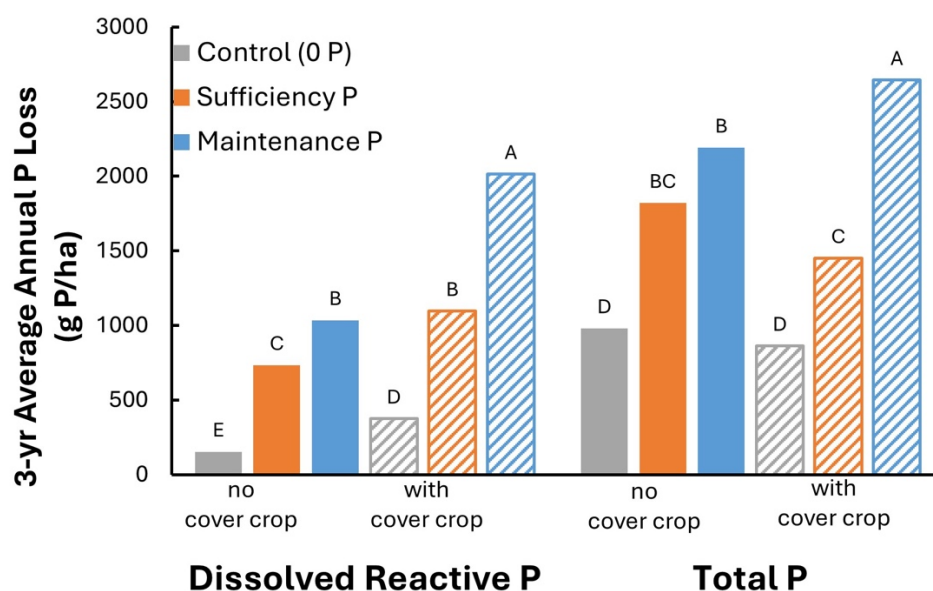


Figure 5.1 Effect of sufficiency P management on dissolved reactive P and total P losses from corn-soybean rotation without cover crop and with cover crop. Data are from the 2020, 2021, and 2022 crop years at the Kansas Agricultural Watershed field laboratory (N.O. Nelson, personal communication, October 16, 2024)

Although the current sufficiency recommendations offer a low input option for P fertilizer management, which is environmentally favorable, the higher input, higher environmental risk strategy of maintaining high STP may be preferred by producers (Osmond et

al., 2019). Sufficiency tends to be viewed as a short-term approach to P fertilizer management (Havlin et al., 2013; Grant and Flaten, 2019), since it will drawdown STP over time. Build and maintain may be favored by producers as it is viewed as more agronomically sustainable over the long term since (Grant and Flaten, 2019) and reduces risk of missed yield opportunities in years of high yield potential, by having the extra P supply in the soil (Karamanos, 2007; Fabrizzi et al., 2017). Phosphorus fertilizer responses can be sporadic and hard to predict, largely driven by environmental conditions and resulting yield potential (Karamanos, 2007). Over-fertilizing to ensure more than enough P is supplied in any given year can mitigate the risk of missed yield under varying and unpredictable growing season conditions (Poulton et al., 2013).

High STP concentrations are thought to improve overall productivity of the system (Olson et al., 1987; Leikam et al., 2010; Rutan and Steinke, 2021a). Even in precision systems, with the opportunity to manage areas of the field uniquely, producers seek to build their STP in all areas of their fields, and maintain STP at high levels. A recent survey of 19 agricultural retailers in the Milford Lake watershed indicated that all but one location-based recommendations on the BM philosophy, with 50% of the locations continuing to recommend >20 lb P₂O₅/ac for fields with STP>35 ppm (N.O. Nelson, unpublished data, 2020). Application of P in quantities over and above what is agronomically required by our crops reduces soil health; we end up with a system that very readily leaks P, potentially in large quantities, to the environment and harms water quality as a result.

Increasing STP above some level of plant available P is not going to contribute to increased yields (Medinski et al., 2018). Typically, the threshold level for crop response to P fertilization is the critical threshold for yield response (Rowe et al., 2016), 20 mg kg⁻¹ Mehlich-III P in Kansas (Ruiz Diaz et al., 2024). Corn is not expected to respond to P fertilization above

the critical threshold (Rutan and Steinke, 2021a) and soybean rarely responds to P fertilization for STP above the low category (Buah et al., 2000a; Culman et al., 2023), which is less than 8 mg kg⁻¹ in KS. Historically, long-term research in Nebraska found no benefit to corn yield using BM fertilizer recommendations, compared to SF, over a 12-year period (Olson et al., 1987). More recent work has also indicated no benefit to corn yield with a BM approach compared to SF (Fabrizzi et al., 2017; Wortmann et al., 2018). Despite a lack of data supporting the high input BM system, it is frequently recommended to, and preferred by, producers as a risk mitigation strategy to cope with the unpredictability of crop response to P fertilizer (Karamanos, 2007; Bruulsema et al., 2019b) and to support high yielding systems.

We believe that our P fertilizer recommendations should better align environmental conservation and agronomic productivity goals. We are proposing a new paradigm for P management: sustainable sufficiency (SSF). This paradigm would be based on maintaining STP with traditional maintenance rates of P fertilizer applied routinely, like under BM management, but at a STP below the critical threshold for yield response. From our perspective, the lack of yield data in favor of the high input BM system does not support the increased environmental risk this paradigm poses. Our contention is that there is a STP threshold lower than 20 mg kg⁻¹ Mehlich-III that will sustain target yields when it is maintained with annual P fertilization. We recognize the somewhat erratic nature of crop P response, a producer's desire to mitigate their risk, and the value of maintaining some level of P fertility to accomplish this and increase the likelihood of capitalizing on high yielding environmental conditions.

Our specific objectives are to: i) determine the theoretical threshold for SSF management through analysis of historical P rate response data for corn and soybean, and ii) evaluate the STP threshold for SSF management using corn and soybean response data from new field studies. If

successful, our research will provide proof of concept for a SSF approach. Future development of recommendations based on this new paradigm will reduce P loss from agriculture fields while protecting productivity, bridging the gap between agronomic and environmental goals.

5.3 Materials and Methods

This project utilized a combination of a novel approach to historical P rate response data and new field studies. The first objective, to determine the theoretical threshold for SSF management was carried out through historical data analysis and calculation of a new metric, ΔP_2O_5 . The second objective was met using data from new field studies, implemented in the 2023 and 2024 crop years, to investigate the effect of STP on corn and soybean response to maintenance rates of P fertilizer. Both aspects of the project are outlined below.

5.3.1 Historical data analysis – ΔP_2O_5

Data were compiled from corn and soybean P rate response studies in KS. Data were accessed from published and unpublished studies. The minimum requirements to be included in our dataset included studies conducted more recently than 1980 and with a minimum of four P rate treatments, including a control. Included studies also had to have available information on site locations, soil type, STP at the start of the study, treatment details and pertinent agronomic management details. The final dataset included 35 corn studies and 14 soybean studies (Appendix Table B.1).

Data were grouped and analyzed by crop. Crop response to P fertilizer rate was determined from each site-year of data using ANOVA. For those studies already published, ANOVA results from the publication were used to determine if the crop responded to P fertilization ($\alpha = 0.05$). For site-years not yet published, ANOVA was conducted by site-year using PROC GLIMMIX in SAS ver. 9.4 with P fertilizer rate as the fixed effect and rep as a

random effect. For site-years that were not responsive to P fertilizer, the optimum P fertilizer rate (P_O) was set to zero. To determine P_O for responsive site-years, PROC NLMIXED was used to fit a linear-plateau model. The changepoint was determined to be P_O . Crop removal at P_O , P_R , (i.e., crop removal at the plateau yield from our analysis) was calculated using standard expected removal values of 0.0059 kg P_2O_5 kg corn⁻¹ and 0.0133 kg P_2O_5 kg soybean⁻¹ (Ruiz Diaz et al., 2024). Delta P_2O_5 was then calculated for each site-year, as follows:

$$\Delta P_2O_5 = P_O - P_R$$

These ΔP_2O_5 values were then plotted against initial STP for each site-year.

Price ratios were used to investigate corn price conditions at which P_O would be economical. To do this, we established a range of corn prices from \$0.08-0.22 kg⁻¹. These were multiplied by the slope of the linear portion of the model used to describe the relationship between P fertilizer and crop yield, for each site-year with positive P_O , to generate the breakeven cost of P fertilizer on a \$ kg⁻¹ P_2O_5 basis.

5.3.2 Maintenance Rate Field Study

To investigate the effect of STP on corn and soybean yield with a maintenance rate of P fertilizer, we applied a single rate of P fertilizer on a crop removal basis to sites with a range in STP. To do this, our study required sites with an established, known range of STP. We established these locations by applying a range of P fertilizer rates to our soils in a preparation year, similar to a standard P rate response trial. Site-years were no-till managed from the start of the preparation year through the end of the maintenance year. Site-years followed a corn-soybean rotation; if the preparation year crop was soybean, the maintenance year crop at that same site was corn, and vice versa. Specific preparation and maintenance year methods are outlined below.

5.3.2.1 Preparation: Establishing a STP Gradient

Preparation site-years were selected based on their STP, with a preference for locations with very low to medium STP concentrations, based on KSU classification (Ruiz Diaz et al., 2024) (Table 5.1). Pre-preparation STP was determined for the whole site-year area, typically using composite 0-15 cm soil samples by replication. Twelve to fifteen cores were taken in each replicate and composited to characterize site starting STP. At some locations the STP at the start of the study was simply communicated as being low (e.g., studies with “<” symbol in Table 5.1).

In the preparation year, a range of P fertilization rates from zero to 134 kg P₂O₅ ha⁻¹ were applied in a standard small plot (3 m x 12 m) P rate experiment, set up as a RCBD with four replications. All P fertilizer was applied as granular, surface broadcast in the spring. Nitrogen was balanced across all plots using urea. Some site-years included an additional control plot in the preparation year to use as an unfertilized check in the following maintenance year, to investigate P responsiveness of the site-year.

After harvest of the preparation crop, soil samples were collected by plot to determine STP gradient established with the prep treatments. Post-harvest soil samples were collected by plot. Twelve 0-15 cm soil cores were taken in the plot area: four cores from within the harvested rows for yield determination, four cores in the midrow space, and four cores adjacent to the crop row. Soil samples were air dried and ground to pass through a 2 mm sieve and analyzed for Mehlich-III P, pH, SOM by combustion, and ammonium acetate extractable cations.

Table 5.1 Site-year details for preparation and maintenance years.

Site-year	Initial STP mg kg ⁻¹	Prep Crop	Prep Rates kg P ₂ O ₅ ha ⁻¹	Maintenance Crop	Anticipated Yield kg ha ⁻¹	Maintenance Rate kg P ₂ O ₅ ha ⁻¹
Manhattan-2023s^a	13	Corn	0, 34, 67, 101, 134	Soybean	4033	54
Ottawa-2-23s	4	Corn	0, 34, 67, 101, 134	Soybean	3361	45
Hutchinson-2023s	6	Corn	0, 34, 67, 101, 134	Soybean	4369	58
Scandia-2023c	2	Soybean	0, 45, 90, 134	Corn	14117	83
Ashland-2024s	3	Corn	0, 17, 34, 67, 134	Soybean	3361	45
Manhattan-2024s	10	Corn	0, 17, 34, 67, 134	Soybean	4033	54
Ottawa-2024s	<10	Corn	0, 17, 34, 67, 134	Soybean	3361	45
Hutchinson-2024s	8	Corn	0, 17, 34, 67, 134	Soybean	4369	58
Scandia-2024s	<10	Corn	0, 17, 34, 67, 134	Soybean	4369	58
Manhattan-2024c	6	Soybean	0, 17, 34, 67, 134	Corn	8784	52
Ottawa-2024c	<10	Soybean	0, 17, 34, 67, 134	Corn	8784	52
Hutchinson-2024c	8	Soybean	0, 17, 34, 67, 134	Corn	12548	74
Scandia-2024c	<10	Soybean	0, 17, 34, 67, 134	Corn	15685	92
Smith-2024c	<15	Soybean	0, 17, 34, 67, 134	Corn	9411	55

Note: bolded site-years are included in this version of the dissertation, with yield data only. Grain and post-harvest STP, as well as the remaining yield data, will be added as the data are available.

^aThe year indicates the maintenance study year, followed by either a “c” indicating the maintenance year crop was corn, or an “s” indicating the maintenance year crop was soybean.

5.3.2.2 Maintenance Rate Response

Maintenance rates were determined based on expected crop removal for each location, using standard crop removals of 0.0059 kg P₂O₅ kg corn⁻¹ and 0.0133 kg P₂O₅ kg soybean⁻¹ (Ruiz Diaz et al., 2024). Expected yield to determine expected removal was based on target yield by location, informed by yield history (Table 5.1). All maintenance rates were applied as MAP (11-52-0) and N was balanced for sites with a maintenance year control plot using urea (46-0-0). Maintenance rates and urea were applied to each plot by hand, broadcast in the spring within one week of planting. Variety or hybrid, planting rate, and agronomic management beyond P fertilization were at the discretion of each location and done according to routine agronomic management for each site.

Most locations had a small plot combine equipped with a grain weight and moisture system to determine plot yield based on two rows by 10-11 m. At some corn site-years, hand harvest was required (Scandia-2023c, Hutchinson-2024c, Manhattan-2024c, and Smith-2024c). Cobs were picked from a two-row by six-meter area in each plot and threshed to remove grain. Grain weight and moisture were recorded at the time of threshing. All yield data was corrected to standard moisture contents of 15% for corn and 13% for soybean. Grain samples were collected from each plot, air dried, ground, and analyzed for P content using a sulfuric peroxide digest (Thomas et al., 1967) and inductively coupled plasma spectroscopy. Post-harvest soil samples were collected from each plot following the same methods as described above for the preparation year.

5.3.3 Statistical Analysis

Linear regression using PROC REG in SAS ver. 9.4 was used to determine the relationship between establishment P fertilizer rate and STP at the end of the site establishment

year. Relative yield from each experimental unit that received a maintenance rate of P was plotted against STP to explore the relationship between STP and relative yield with a maintenance rate of P fertilizer applied. Relative yield was calculated using the MAX method outlined by Pearce et al. (2022) where the denominator of the relative yield calculation is the maximum yield within a site-year. The changepoint was determined using PROC NLMIXED to fit a linear-plateau model, where appropriate based on the data and model fit. The change-point represents the STP where a maintenance rate of P fertilizer maximized yield. This is similar to the traditional method of determining critical STP concentration except the traditional method determines the critical STP *in absence of any P fertilizer application*. Our novel methodology investigated potential critical STP when P fertilizer is applied at a maintenance rate.

5.4 Results and Discussion

5.4.1 Delta P₂O₅

5.4.1.1 Corn

Only 8/35 site-years significantly responded to P fertilization. Responsive site-years included a range of yield potential from 6290-16037 kg ha⁻¹ and varied in starting STP from 3-17 mg kg⁻¹ (Table 5.3). Based on KSU recommendations for corn P fertilization, we would have expected crop response to P fertilizer at 21/35 locations (Ruiz Diaz et al., 2024); however, only 8/35 site-years responded to P fertilizer. Generally, greater corn responsiveness to P fertilization is expected at low STP. For example, Drescher et al. (2021) found 80% of corn sites were responsive to P fertilization at Mehlich-III STP between 9-16 mg kg⁻¹, 60% responsive at soil tests between 17-24 mg kg⁻¹, 33% responsive between 25-32 mg kg⁻¹ and 0% responsive when STP was above 33 mg kg⁻¹. Adjusting these categories slightly to suite our KS categorization of STP, we had 35% respond in when STP was in the very low-low category (<15 mg kg⁻¹, n=17),

35% respond in the medium category (15-20 mg kg⁻¹, n=6), and 0% respond in the high-very high category (>30 mg kg⁻¹). Overall, for this dataset, we would have expected greater responsiveness to P fertilizer rate, particularly for site-years with STP <15 mg kg⁻¹.

Table 5.2 Starting soil test phosphorus (STP), optimum phosphorus (P), fertilizer rate (P_O), grain yield, estimated P removal (P_R) at P_O, and yield with zero P based on the fitted model, for site-years where corn grain yield was responsive to P fertilizer.

Site-Year	STP	P _O	Slope ^a	Yield at P _O	P _R at P _O	Yield at 0 P
	mg kg ⁻¹	kg P ₂ O ₅ ha ⁻¹	kg yield kg P ₂ O ₅ ⁻¹	kg ha ⁻¹	kg P ₂ O ₅ ha ⁻¹	kg ha ⁻¹
Stevens-2004c^b	6	118	46	14180	84	8740
Ottawa-2022c	5	110	9	6290	37	5307
Manhattan-2023c	15	85	16	15081	89	13695
Greeley-2004c	17	74	36	13929	82	11252
Greeley-2005c	17	57	50	10446	62	7592
Greeley-2006c	9	56	91	12925	76	7835
Scandia-2021c	5	56	83	16037	95	11352
Scandia-2022c	3	48	72	15589	91	12125

^aThe slope of the linear relationship between STP and yield.

^bBolded values indicate site-years where P_O was greater than P_R.

The additional yield gained per unit of P fertilizer added ranged from 9 to 91 for the responsive site-years (Table 5.2). There were only two responsive site-years where ΔP₂O₅ was positive, indicating optimal P fertilizer rate (P_O) exceeded the P rate for crop removal (P_R) only 6% of the time (Figure 5.2). Both site-years with positive ΔP₂O₅ had P_O over 100 kg P₂O₅ ha⁻¹ and started with very low STP; however, the slopes describing yield gain per unit of P fertilizer added were dramatically different. At Stevens-2004c, there was an additional 46 kg yield kg P₂O₅⁻¹ added, whereas there was only an additional 9 kg yield kg P₂O₅⁻¹ added for Ottawa-2022c (Table 5.2).

Crop demand would have been satisfied by a maintenance rate of P fertilizer, based on crop removal, more than 90% of the time for these site-years. This includes site-years with very low STP and high yield potential. For example, the Scandia-2021c and Scandia-2022c site-years yielded more than 15500 kg ha⁻¹ and had STP <6 mg kg⁻¹. Yet, ΔP_2O_5 was negative, indicating P_O was less than P_R .

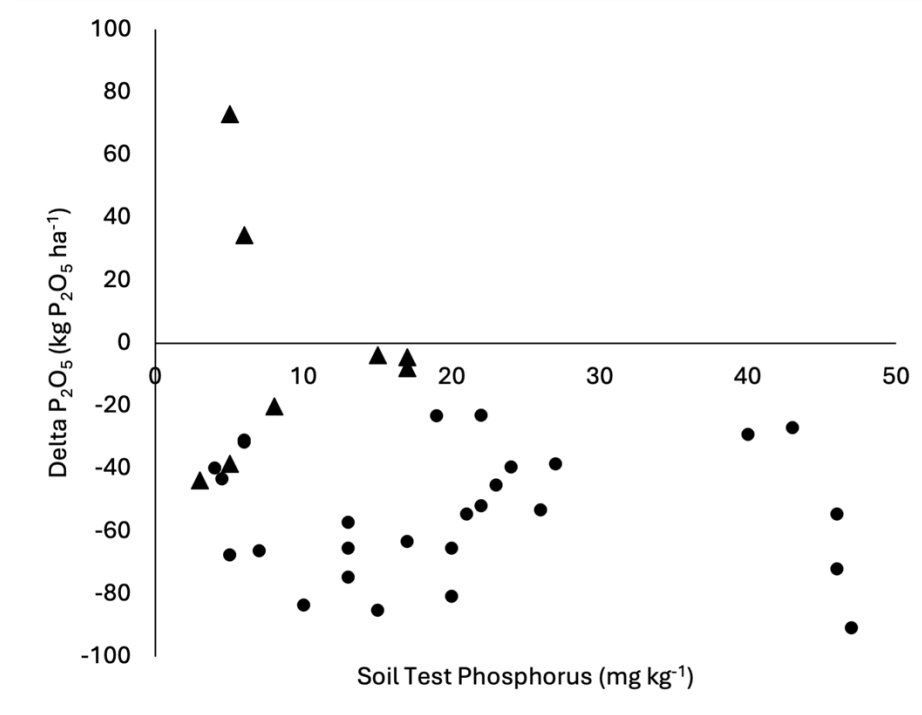


Figure 5.2 Relationship between soil test phosphorus (STP) and ΔP_2O_5 (the difference between optimum P fertilizer rate (P_O) and crop P removal (P_R) for corn yield. Triangular data points indicate site-years with significant response to P fertilization.

With all the site-years compiled there is no clear pattern in the data or relationship between STP and ΔP_2O_5 . That is, model fitting to attempt determination of a threshold STP concentration that would support crop P demand under maintenance fertilization is not justified. Additionally, the ability to use STP to evaluate ΔP_2O_5 did not improve when site-years were grouped based on factors like initial STP, yield potential, production region, or P responsiveness (Figure B.1). pH is another factor that may be logical to group site-years, although pH effects on

P fertility dynamics are largest for strongly acidic and strongly basic/highly calcareous soils (J.Pierzynski & Hettiarachchi, 2018). Most of our site-years were classified as near-neutral pH of 6.0-7.5 (Yu et al., 2021) (Table B.1) and inherent soil supply tends to be greater from near-neutral soils compared to strongly acidic or strongly basic soils. So, pH is not likely to be a grouping factor of significance for this dataset.

The only combination of factors, from the information available, that suggest there may be a relationship between ΔP_2O_5 and STP was for high yield potential site-years that were irrigated (Figure 5.3). However, this relationship was not significant at $\alpha = 0.05$; the P -value was 0.08.

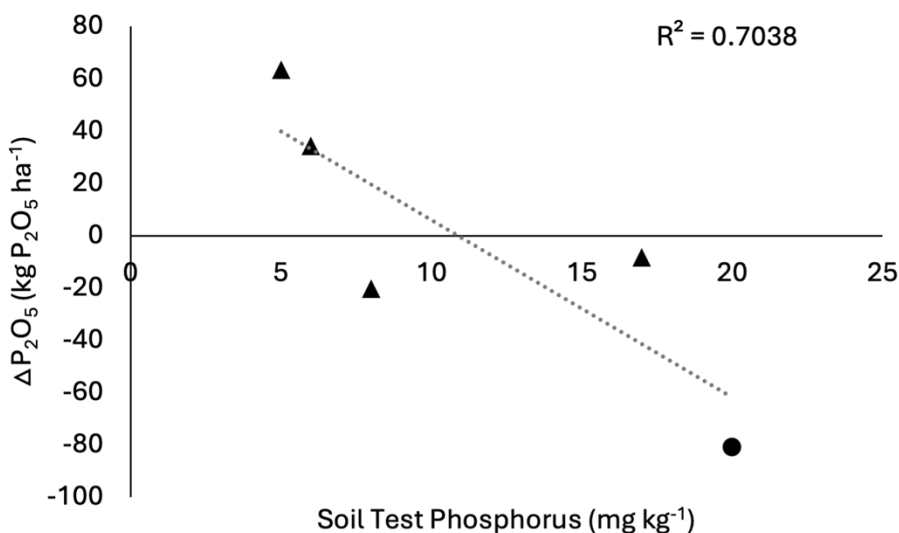


Figure 5.3 Relationship (not significant) between ΔP_2O_5 and soil test phosphorus for site-years with high yield potential ($>12,548$ kg ha⁻¹, or >200 bu ac⁻¹). Triangular points indicate site-years that were responsive to phosphorus fertilization.

5.4.1.2 Soybean

All soybean site-years included in the dataset had starting STP concentrations less than 20 mg kg⁻¹. Only 1/14 soybean site-years was responsive to P fertilization, with a P_0 of 36 kg

P_2O_5 ha^{-1} and a yield of 4334 $kg\ ha^{-1}$ at that rate (Figure 5.4). Yield at P_O ranged from 1278-4457 $kg\ ha^{-1}$ across the site-years. None of the soybean sites required P fertilizer rates greater than P_R to achieve optimum yield.

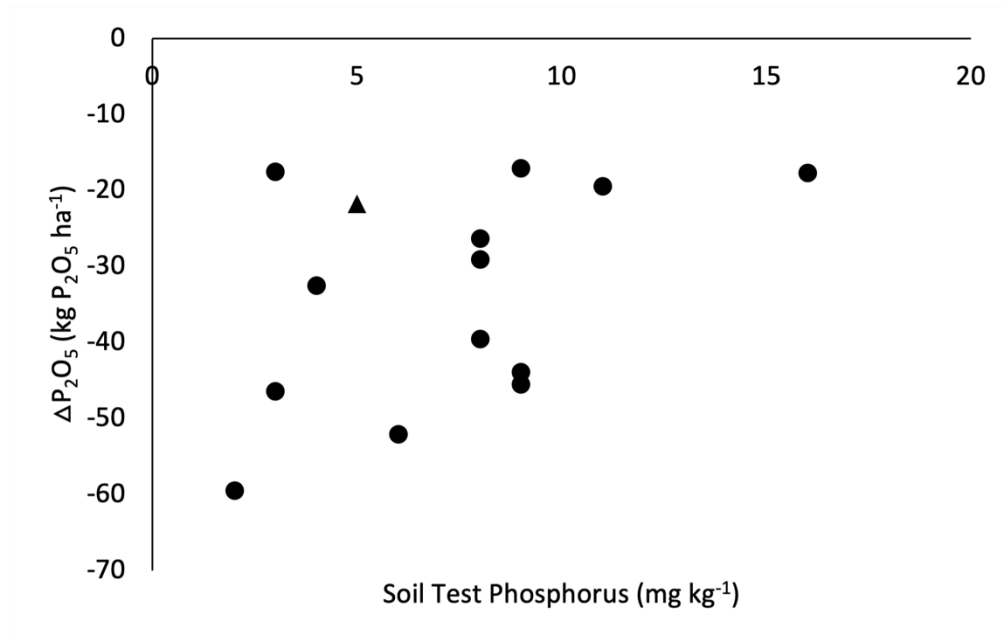


Figure 5.4 Relationship between soil test phosphorus (STP) and the difference between optimum phosphorus (P) fertilizer rate and crop removal for soybean yield at optimum rate (ΔP_2O_5). Triangular data points indicate site-years with significant response to P fertilization. Circular data points indicate site-years with no yield response to P fertilization.

Soybean response to P fertilization tends to be less consistent than for corn (Webb et al., 1992), rarely responding to P fertilization if STP is above the very low category (S. Buah et al., 2000; Culman et al., 2023). So, just 7% responsiveness to P fertilization in the soybean dataset compared to 23% total responsiveness in the corn dataset is not too surprising. However, it is worth noting 13 of these soybean site-years had initial STP in the very low-low category. Compared to 35% of corn site-years responding to P fertilization at very low STP, soybean only responded 8% of the time for the same STP category. This highlights the difficult nature of managing P fertility for yield and economic gain. Crop P response is highly variable and

unpredictable (Karamanos, 2007) and that unpredictability is clear in this dataset, where Mehlich-III STP did not reliably predict crop response to P fertilization. Similar to the corn dataset, grouping data based on factors like yield potential, initial STP, region, and pH did not clarify a pattern in the relationship between STP and ΔP_2O_5 . There were not enough irrigated soybean site-years to try grouping in that manner.

Some form of relationship, even a weak one, was anticipated between STP and ΔP_2O_5 , particularly for soils testing low in P. Instead, there was no clear pattern or predictable relationship between ΔP_2O_5 and STP for corn or soybean. In other words, STP was not a good indicator of the magnitude of ΔP_2O_5 . Rather, the highly site-year-specific nature of corn and soybean response to P fertilization and P fertility was evident for these data. Even for site-years with similar initial STP, ΔP_2O_5 values could be vastly different; there was site-year to site-year variability in the behavior of crop responsiveness, yield potential, and crop removal at optimum yield, even when P_O was zero.

Overwhelmingly, a maintenance rate of P fertilizer would have been more than enough to satisfy corn and soybean requirements, regardless of STP, in most cases. While these findings cannot be used to suggest a STP threshold or range where maintenance management would be best suited, they do highlight the opportunity for maintenance management across a wide range of STP. However, there is a clear gap in our ability to characterize crop response to P fertility and fertilizer using Mehlich-III STP alone. Mehlich-III and similar agronomic extractions provide a snapshot in time of potentially available P, but do not account for P dynamics, turnover, or supply capacity through the growing season (Steinfurth et al., 2024). Clearly, based on the lack of consistent P response in the low and very low STP site-years in this dataset, Mehlich-III P is not working well on its own to characterize P supply to our crops over the

growing season. Further research into characterization of soil P dynamics and supply of P to the crop is needed to refine STP-based P recommendations.

5.4.2 Maintenance Rate Crop Response

5.4.2.1 Soil Test P Response to Preparation Treatments

There was a significant relationship between preparation year treatments and resulting STP at 8/10 site-years (Table 5.4). For these seven site-years, preparation treatment described between 81 and 96% of the variability in STP after harvest in the preparation year.

Table 5.3 Soil test P (STP) range established at each location in response to preparation treatments, slope, *P*-value, and *R*² for linear regression analysis of establishment treatment on soil test P at maintenance rate site-years.

Site-Year	STP Range	Slope	<i>P</i> -value	<i>R</i> ²
	mg kg ⁻¹			
Ashland-2024s	11-39 (8.9) ^a	-0.4	0.8637	0.01
Hutchinson-2023s	7-29 (3.2)	4.9	0.0366	0.81
Hutchinson-2024s	5-19 (2.3)	8.7	0.0015	0.98
Manhattan-2023s	17-40 (4.5)	4.4	0.0193	0.88
Ottawa-2023s	10-15 (4)	10.7	0.3903	0.25
Scandia-2024s	3-16 (5.2)	18.7	0.0303	0.83
Manhattan-2024s	9-30 (3.3)	5.5	0.0061	0.92
Hutchinson-2024c	6-23 (3.8)	6.2	0.0069	0.94
Manhattan-2024c	10-46 (5.9)	3.1	0.0030	0.96
Scandia-2023c	4-31 (4.2)	4.1	0.0194	0.96

Note: Bolded values indicate significance at $\alpha=0.05$.

^aValues in parentheses are standard errors of the means for STP by preparation treatment

At Ashland-2024s preparation treatments established a wide range of STP from the low to very high categories, but plot-to-plot variability was large (Table 5.4). This variability drove the insignificant relationship between preparation treatment and STP for this location. At Ottawa-2023s, the other location where STP was not significantly related to preparation

treatment, variability was not likely the driver. At this site-year preparation treatments resulted in the smallest range of STP concentrations, most likely driven by soil type differences that influence P dynamics and agronomic STP concentrations. Clay content, soil pH/calcium carbonate content, amount of organic matter, and oxide content are soil factors that can influence the amount of P fertilizer that is retained (e.g., not extractable immediately by agronomic soil test extractants like Mehlich-III) (Doyle and Cowell, 1993). The major difference between Ottawa-2023s and the other site-year locations is likely clay content. Soils in the Ottawa region are characterized by higher clay content than soils in the other regions where our site-years were located. Higher clay content will result in higher retention of fertilizer P (Havlin et al., 2013) and this could explain the lesser range of STP established by the preparation treatments for this location.

5.4.2.2 Crop Response to Maintenance Across STP

5.4.2.2.1 Corn

Relative yield of corn with a maintenance rate of P fertilizer did not respond to initial STP (Figure 5.5). Based on the flat nature of this relationship, our data suggest that corn yield is not limited by STP, even in the very low category ($<8 \text{ mg kg}^{-1}$) when a maintenance rate of P fertilizer is applied.

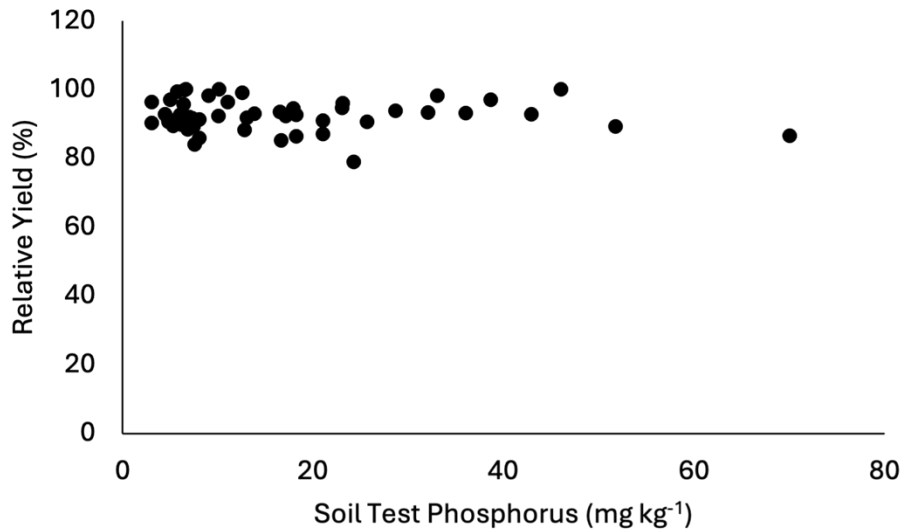


Figure 5.5 Relative yield of corn with a maintenance rate of P fertilizer applied in relation to soil test P.

Based on current KSU sufficiency recommendations (Ruiz Diaz et al., 2024) the removal rates based on expected yield for these three corn site-years were at or above sufficiency recommendations (Table B.4). The lack of STP influence on corn yield with the maintenance rate applied was then not unexpected, at least for two of the three site-years where yield was at or below expected yield targets. For Manhattan-2024c, target yield was 1.5 times expected yield. Even with this higher P demand from greater crop yield potential, the relationship between STP and relative yield with a maintenance rate applied based on expected yield was flat (Figure 5.6).

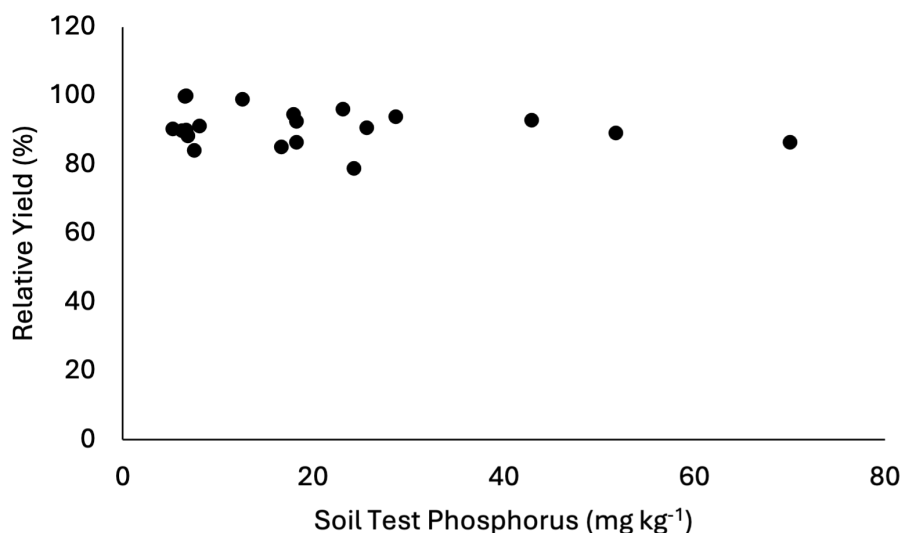


Figure 5.6 Relative yield of corn with a maintenance rate of P fertilizer at Manhattan-2024c, in relation to initial soil test P.

5.4.2.2.2 Soybean

There is no clear relationship that would suit model fitting to determine a changepoint for the data relating soybean relative yield with a maintenance rate of P fertilizer and initial STP, when all site-years are grouped into one dataset (Figure 5.7). Based on the appearance of more variability in the soybean data across the range of STP, compared to the corn data, site-years were broken out and assessed individually for potential model fit to determine a change-point. Only one site-year, Hutchinson-2024, had data suited to model fitting (Figure 5.8). The change-point was 9 mg kg⁻¹, indicating this is the STP at which a maintenance rate of P fertilizer would maximize yield for this site-year. However, the model only described about 30% of the relative yield variability for this location.

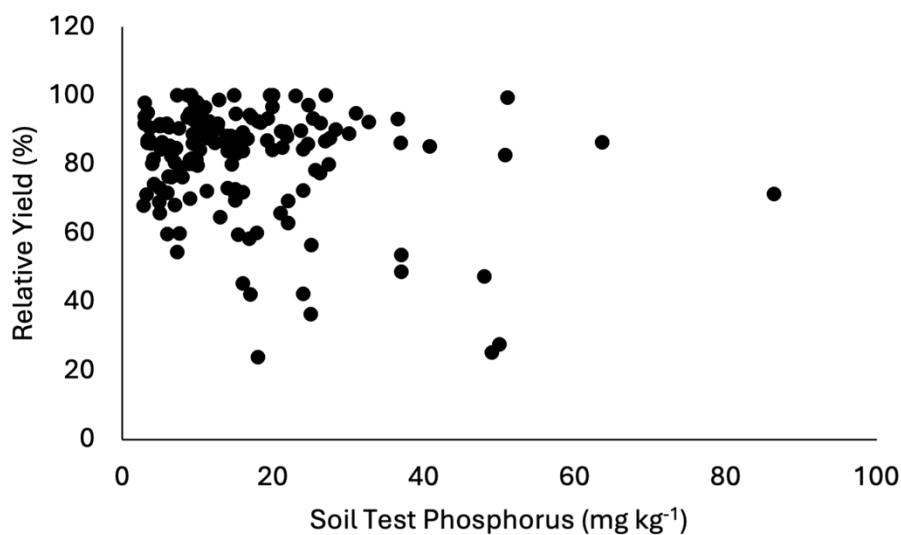


Figure 5.7 Relative yield of soybean with a maintenance rate of P fertilizer applied in relation to soil test P.

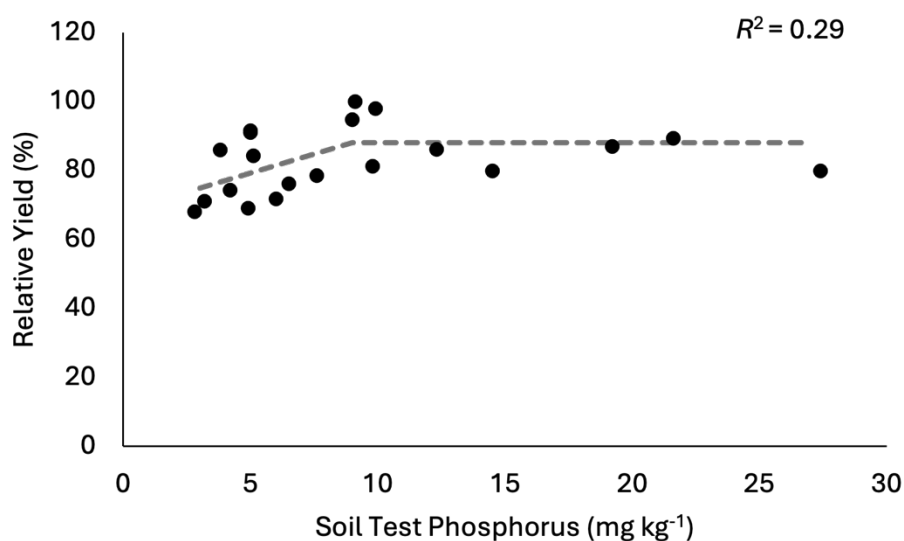


Figure 5.8 Relative yield of soybean with a maintenance rate of P fertilizer applied at Hutchinson-2024.

In comparing our maintenance rates applied based on expected crop removal and KSU sufficiency recommendations, maintenance rates were less than sufficiency recommendations when STP was in the very low category ($<8 \text{ mg kg}^{-1}$) (Table B.2). Very low STP was present at two site-years, Hutchinson-2023s and Hutchinson-2024s, the latter of which has a critical STP

for maintenance fertilization of 9, according to the linear-plateau model fit (Figure 5.8). The remaining five soybean site-years had STP in the low category, and above, and maintenance rates based on expected crop removal were greater than KSU sufficiency recommendations.

Sufficiency recommendations are based on meeting crop demand in the year of fertilizer application, based on expected yield and initial STP (D. Leikam et al., 2003). If application at a maintenance rate based on expected crop removal results in P fertilizer rates greater than, or close to, sufficiency recommendations, we can then assume those rates of P fertilizer would be sufficient to meet crop demand in the year of application. To further develop the SSF paradigm, determine the critical STP threshold for maintenance P fertilizer applications, and preservation of yield potential with this approach, more research is needed specifically on very low testing soils.

A main perceived benefit of traditional BM, wherein medium-high STP is sustained over time with routine maintenance applications, is reduction of yield loss risk from variable growing season conditions (Karamanos, 2007; Poulton et al., 2013; Fabrizzi et al., 2017). Based on our preliminary work to explore the option of a SSF paradigm, our data do not support the concept of higher STP resulting in greater yield under years of high yield potential. We had a corn year with 1.5 times expected yield, and three soybean years with 1.1, 1.3, and 1.3 times expected yield. The relationship between relative yield with a maintenance rate and STP for these site-years did not indicate an increase in relative yield under high yield potential with higher STP (Figures B.2 and B.3).

5.5 Conclusion

The ΔP_2O_5 corn and soybean datasets indicate three key findings: i) response of both corn and soybean to P fertilizer are limited and not consistent even when STP is very low; ii) a maintenance rate of P fertilizer would have been sufficient to meet soybean demand 100% of the

time and corn demand 91% of the time based on our site-years; and, iii) we lack the ability to understand the role of soil P supply over the growing season using agronomic STP methods alone.

Because our maintenance rate site-years did not have a consistent relationship between STP and relative yield with a maintenance rate of P fertilizer, we cannot achieve our initial objective of evaluating a potential threshold STP for maintenance. However, we identified that further research is needed specifically into responsiveness of relative yield with a maintenance rate of P fertilizer applied for very low STP compared to STP $>8 \text{ mg kg}^{-1}$. Additionally, our data indicate maintenance management based on expected crop removal does frequently support crop yield across the whole range of STP categories, and reliably supports crop yield for STP above the very low category. Therefore, further development of a SSF paradigm is justified to reduce the threshold STP for maintenance, lowering system P and reducing the threat of P loss to the environment while preserving yield productivity.

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Chapter 6 - Synthesis

Ultimately, our primary research goal was to investigate agronomic management options to improve the sustainability of phosphorus (P) fertilizer management in Kansas. Specifically, our research: i) investigated the coupling of cover cropping as a conservation tool with P fertilizer management strategies on P agronomics, economics, and efficiencies in a no-till corn-soybean system; and ii) outlined the premise of a new P fertilizer management paradigm, sustainable sufficiency (SSF) and explored further research needed to develop a SSF recommendation system.

6.1 Cover Crops and Phosphorus Management

While cover cropping had a neutral effect on main crop P access and utilization in corn and soybean, cover crops did sometimes lead to net negative effects on environmental P use efficiency. In other cases, when erosion losses were substantial, cover crops were an effective tool to improve environmental P use efficiency (EPUE). Cover crops are valuable for certain desired outcomes, but their use is not without tradeoffs and implementation of cover cropping should be done on a case-by-case basis, based on system-specific goals.

Following known best management practices (BMPs) of P fertilizer management, like spring injecting rather than fall broadcast, and reduced STP concentration/reduced P fertilizer rates, consistently improved EPUE. Clearly, reducing the amount of P in the system and/or reducing the opportunity for fertilizer P to interact with surface runoff is critical for managing P loss. Cover crops were not effective when coupled with practices producers may prefer, like fall broadcast or build and maintain management, to improve EPUE. As such, cover crop inclusion cannot replace BMP management of P fertilizer.

6.2 Sustainable Sufficiency

Drawdown management, relying on legacy P to meet crop demand in the absence of fertilizer, was most profitable on a net return basis in our study. However, drawdown did significantly decrease yield one year, and the conditions of our experiment were limited to one site over a three-year period. Although P fertilizer was not applied, P loss was not consistently improved compared to build and maintain management. Rather, it was only as STP continued to decline after year-over-year drawdown that water quality metrics improved.

Our proof-of-concept approach to investigating the feasibility of SSF as an alternative P fertilizer management paradigm indicated there is merit to further research for development of SSF recommendations. Maintenance rates of P fertilizer supported crop P demand far more often than not, and did not require STP above the critical threshold for crop response to do so. While we could not propose a clear threshold STP for maintenance applications, we have clearly identified further need for research into maintenance rate performance on soils testing in the very low STP category to determine a potential threshold.

6.3 Implications for Producers

Conservation management to reduce P lost in runoff can be challenging for producers, particularly when conservation strategies are at odds with practices most feasible or least risk inducing. Following BMPs, particularly utilizing spring subsurface placement where possible, will reliably reduce P runoff losses without implicating crop nutrition and system productivity. Drawdown, utilizing soil P reserves, could be considered under high STP conditions, but refinement of drawdown management recommendations would be helpful to facilitate confident adoption of drawdown management. Similarly, SSF may be a great option for producers to retain

their yield potential while reducing overall P inputs, and thereby load to the environment, but further research is needed to establish SSF recommendations.

6.4 Future Research Needs

Regional research into drawdown management at initially high STP would be valuable to establish parameters for producer guidance and better understand implications for water quality. Studies evaluating drawdown management under varying initial STP concentrations, across several environments and soil types would be most valuable.

Future research to support SSF recommendation development would provide producers with an alternative to their current sufficiency and build and maintain recommendation systems, offering a lower P system alternative to build and maintain and a risk-reducing alternative compared to traditional sufficiency. Specifically, further investigation of crop yield response to very low STP compared to STP >8 mg kg⁻¹, with a maintenance rate of P fertilizer applied, would facilitate establishment of a maintenance STP threshold.

Beyond research further to our specific objectives, the SSF project outcomes indicate the shortcomings of Mehlich-III STP for understanding agronomic P supply over a growing season. The P fertility research area, and P fertilizer management industry, could benefit greatly from development of methods to characterize the dynamic nature of soil P supply in a manner that complements Mehlich-III and can be used to refine P fertility management.

Appendix A Chapter 2

Table A.1. Main effects of phosphorus fertilization, cover crop and year on agronomic phosphorus use efficiency (PUE) and apparent recovery efficiency (ARE)

Effect	PUE	ARE
Cover Crop	kg grain kg ⁻¹ P applied	kg tissue P kg ⁻¹ P applied
NC	27.2	.32
CC	23.4	.24
P Fertilization		
FB	22.4	.27
SI	28.2	.29
Year		
2016	12.8b	.20b
2017	39.8a	.31a
2018	6.9b	.20b
2019	41.7a	.41a

Note: Means followed by the same letter are not significantly different ($\alpha=.05$).

Abbreviations: NC, no cover; CC, cover crop; FB, fall broadcast; SI, spring injected.

Table A.2. Effect of phosphorus fertilization, cover crop and year on the sum of phosphorus leaving the field in a given year (sum of P in grain and P in runoff).

Effect	P Leaving the System
Cover	kg P year ⁻¹
NC	20.7
CC	19.2
P Fertilization	
CN	16.8b
FB	21.4a
SI	21.7a
Cover*Year Interaction	
NC-2016	22.4b
CC-2016	22.9b
NC-2017	17.2c
CC-2017	14.1d
NC-2018	12.3de
CC-2018	11.7e
NC-2019	30.9a
CC-2019	28.1a
Fertilizer*Year Interaction	
CN-2016	19.3c
FB-2016	25.2b
SI-2016	23.5b
CN-2017	12.4de
FB-2017	17.5c
SI-2017	17.1c
CN-2018	10.5e
FB-2018	11.8de
SI-2018	13.7d
CN-2019	24.9b
FB-2019	31.1a
SI-2019	32.4a

Note: Means followed by the same letter are not significantly different ($\alpha=.05$).

Abbreviations: NC, no cover; CC, cover crop; FB, fall broadcast; SI, spring injected.

Appendix B Chapter 5

Delta P₂O₅

Table B.1. Delta P₂O₅ site-year information including optimum P fertilizer rate (Po), crop removal at Po (Pr), soil test P (STP) and category. Blank cells indicate information was not available.

Site	Crop	Year	County	pH	irrigation	Po	yield at Po	Pr at Po	STP category	Site Starting STP	delta P ₂ O ₅
						kg P ₂ O ₅ ha ⁻¹	kg ha ⁻¹	kg P ₂ O ₅ ha ⁻¹		mg kg ⁻¹	kg P ₂ O ₅ ha ⁻¹
JewlS	Corn	2022	Jewell	5.2	no	0	3931.1	23.2	medium	19	-23.2
SmiX	Corn	2022	Smith	5.3	no	0	6535.1	38.5	high	27	-38.5
Salina21	Corn	2021	Saline	5.4	no	0	4574.0	27.0	very high	43	-27.0
OTTC5	Corn	2022	Franklin	5.6	no	110	6290.0	37.1	very low	5	72.9
MHKMAP	Corn	2023	Riley	5.7	no	0	14447.3	85.1	low	15	-85.1
MHKTSP	Corn	2023	Riley	5.7	no	85	15081.0	88.9	low	15	-3.9
Abilene21	Corn	2021	Dickinson	6	no	0	7692.5	45.3	high	23	-45.3
Ottawa23	Corn	2023	Franklin	6	no	0	5375.0	31.7	very low	6	-31.7
Scd1	Corn	2023	Reno	6	yes	0	11452.3	67.5	very low	5	-67.5
OttF3	Corn	2022	Franklin	6.1	no	0	6767.8	39.9	very low	4	-39.9
Scandia_dry21	Corn	2021	Reno	6.1	no	0	11239.9	66.2	very low	7	-66.2
Gove_G21	Corn	2021	Gove	6.2	no	0	4947.6	29.2	very high	40	-29.2
Ashland21	Corn	2021	Riley	6.3	no	0	12221.7	72.0	very high	46	-72.0
Hiawatha21	Corn	2021	Brown	6.3	no	0	15408.3	90.8	very high	47	-90.8
Logan_46021	Corn	2021	Logan	6.4	no	0	8816.8	52.0	high	22	-52.0
Scan	Corn	2022	Republic	6.4	no	48	15589.0	91.9	very low	3	-43.9
Smi280	Corn	2022	Smith	6.4	no	0	3917.8	23.1	high	22	-23.1
MHK	Corn	2022	Riley	6.5	no	0	12658.8	74.6	low	13	-74.6
parsons23	Corn	2023	Labett	6.5	no	0	7352.0	43.3	very low	4.5	-43.3
ScIrr21	Corn	2021	Reno	6.5	yes	56	16037.0	94.5	very low	5	-38.5
Gove_T21	Corn	2021	Gove	6.6	no	0	9034.0	53.2	high	26	-53.2
Ashl	Corn	2023	Riley	6.7	no	0	9256.1	54.5	very high	46	-54.5
JewlN	Corn	2022	Jewell	6.7	no	0	11098.2	65.4	low	13	-65.4
Par2	Corn	2022	Reno	6.9	yes	0	6708.9	39.5	high	24	-39.5

Site	Crop	Year	County	pH	irrigation	Po	yield at Po	Pr at Po	STP category	Site Starting STP	delta P ₂ O ₅
JewlNW	Corn	2022	Jewell	7	no	0	9712.8	57.2	low	13	-57.2
Oska	Corn	2022	Jefferson	7.1	no	0	11113.5	65.5	medium	20	-65.5
Gove_1221	Corn	2021	Gove	7.2	no	0	9248.7	54.5	high	21	-54.5
Parl	Corn	2022	Reno	7.4	yes	0	5262.2	31.0	very low	6	-31.0
Rossville21	Corn	2021	Shawnee	7.6	yes	0	13714.9	80.8	medium	20	-80.8
Hutch23	Corn	2023	Reno	7.7	no	0	14171.5	83.5	low	10	-83.5
Greel04	Corn	2004	Greeley		yes	74	13929.0	82.1	medium	17	-8.1
Greel05	Corn	2005	Greeley		yes	57	10446.0	61.6	medium	17	-4.6
Greel06	Corn	2006	Greeley		yes	56	12925.0	76.2	very low	8	-20.2
Republic04	Corn	2004	Republic		yes	0	10741.4	63.3	medium	17	-63.3
Stev04	Corn	2004	Stevens		yes	118	14180.0	83.6	very low	6	34.4
nfarm23	soybean	2023	Riley	6.2	no	0	3289.1	43.9	low	9	-43.9
ottC	soybean	2023	Franklin	6.6	no	0	1278.0	17.0	low	9	-17.0
Scanhq	soybean	2023	Reno	6.8	no	0	3899.0	52.0	very low	6	-52.0
Scdr	soybean	2022	Reno	6.9	no	0	3473.0	46.3	very low	3	-46.3
Scan	soybean	2023	Reno	7	no	36	4334.0	57.8	very low	5	-21.8
Scirr	soybean	2022	Reno	7	yes	0	4457.0	59.4	very low	2	-59.4
hutch23	soybean	2023	Republic	7.8	no	0	2962.0	39.5	very low	8	-39.5
Goff12	soybean	2012	Nemaha		no	0	1310.9	17.5	very low	3	-17.5
leonard12	soybean	2012	Riley		no	0	1322.1	17.6	medium	16	-17.6
NFarm12	soybean	2012	Riley		no	0	2173.5	29.0	very low	8	-29.0
Pringle11	soybean	2011			no	0	2433.5	32.4	very low	4	-32.4
Sleep1	soybean	2011			no	0	1452.0	19.4	low	11	-19.4
Yates2	soybean	2012	Woodson		no	0	3406.0	45.4	low	9	-45.4
YCMeadow12	soybean	2012	Woodson		no	0	1971.9	26.3	very low	8	-26.3

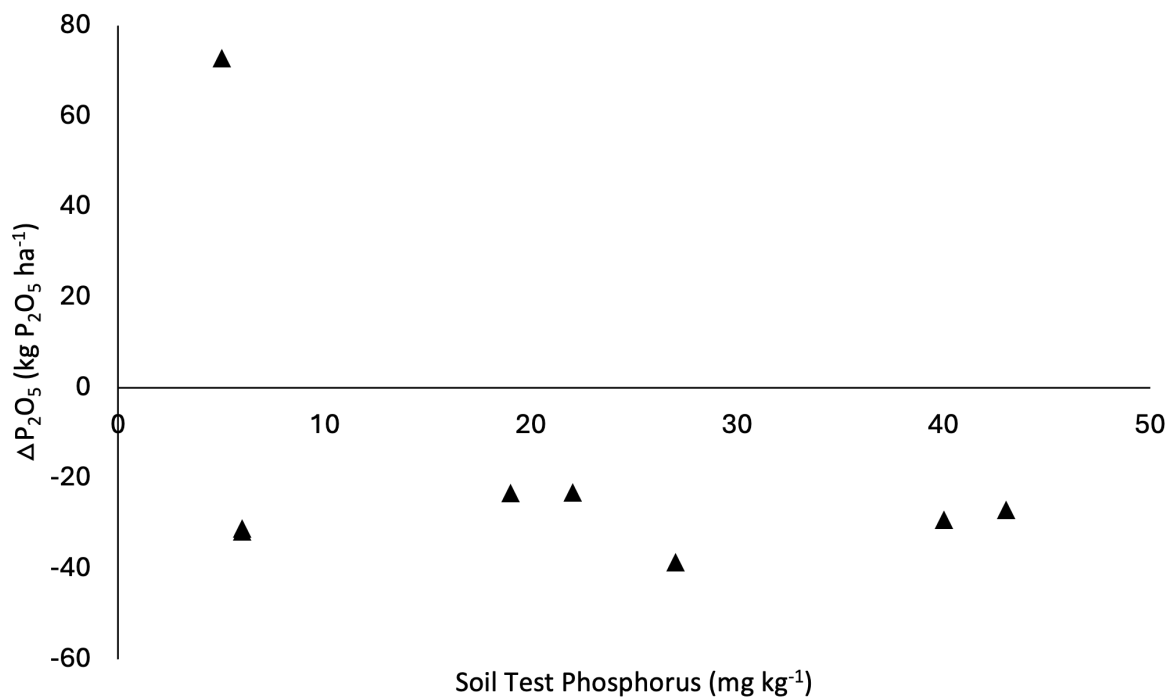


Figure B.1a. Delta P₂O₅ for corn site-years with significant response to P fertilizer, as related to site soil test P.

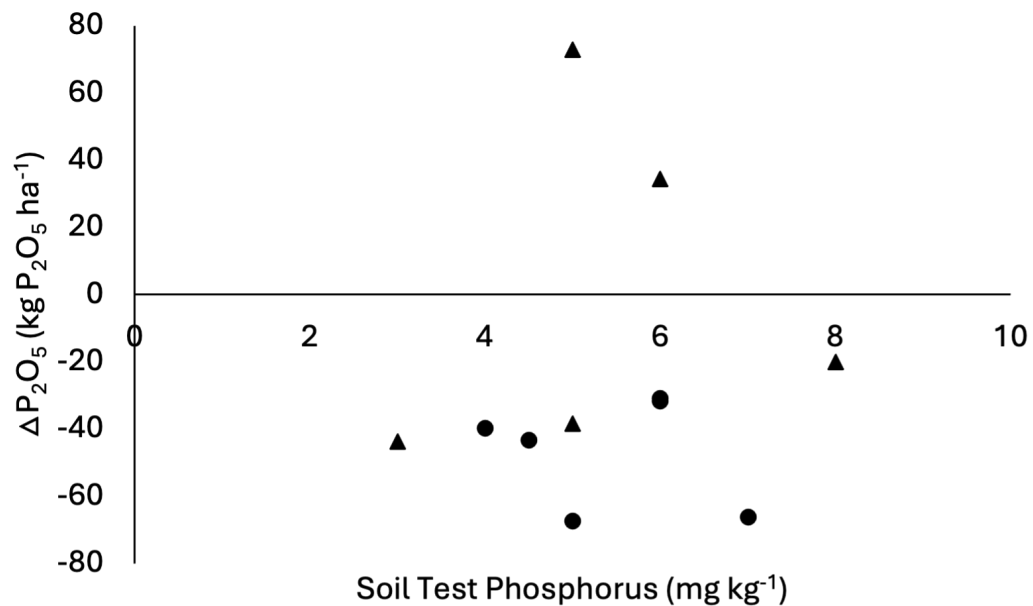


Figure B.1b. Delta P₂O₅ for corn site-years with very low soil test P.

Relative Yield by Site-Year

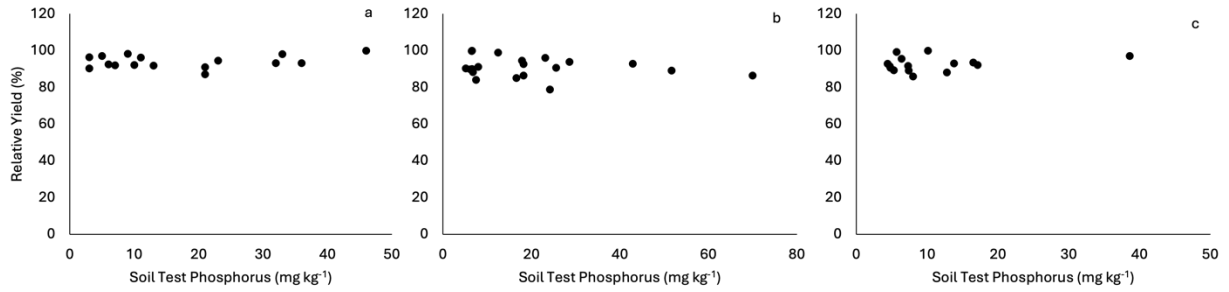


Figure B.2. Relative yield in relation to STP for corn site-years at Scandia-2023 (a), Manhattan-2024 (b), and Hutchinson-2024 (c).

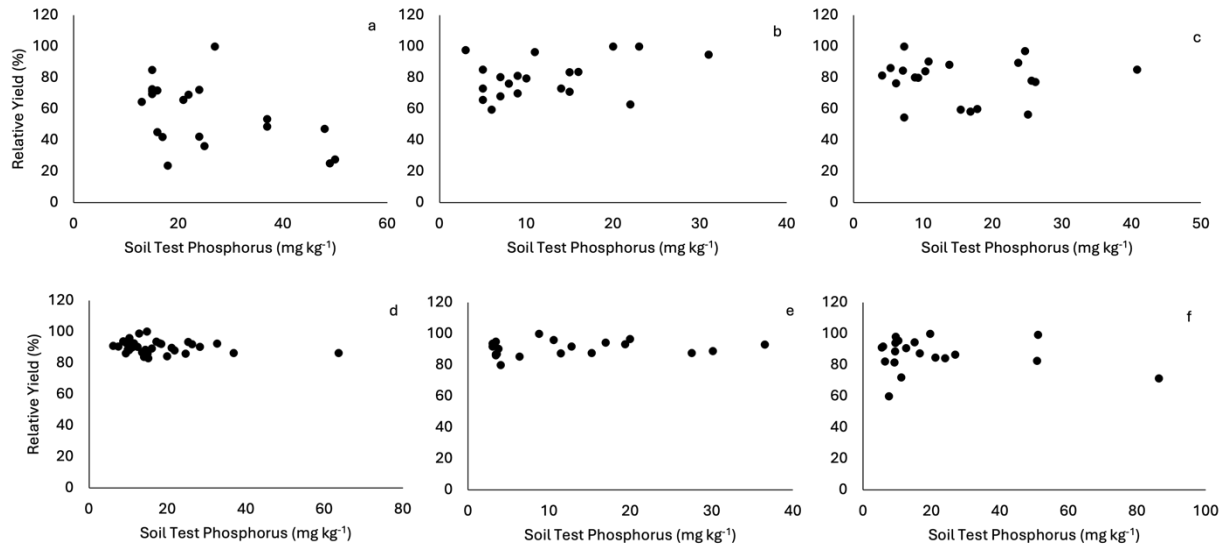


Figure B.3. Relative yield in relation to STP for soybean site-years at Manhattan-2023 (a), Ottawa-2023 (b), and Hutchinson-2023 (c), Manhattan-2024 (d), Scandia-2024 (e), and Ashland Bottoms-2024 (f).

Table B.3. Removal rate applied in our study at corn site-years relative to KSU sufficiency recommendations.

Site-yr	STP	Expected yield		KSU Suff. Rec.		Our maintenance rate
	mg kg ⁻¹	kg ha ⁻¹	bu ac ⁻¹	lb P ₂ O ₅ ac ⁻¹	kg P ₂ O ₅ ha ⁻¹	kg P ₂ O ₅ ha ⁻¹
MHK-2024c	45.625	8784	140.0042082	-99.93857835	-111.96863	52
MHK-2024c	21.225	8784	140.0042082	-4.777551551	-5.3526469	52
MHK-2024c	13.5	8784	140.0042082	25.35027353	28.4017997	52
MHK-2024c	10.875	8784	140.0042082	35.587884	39.8717573	52
MHK-2024c	9.5	8784	140.0042082	40.95044186	45.8798303	52
Sc-23c	30.5	14117	225.0044863	-49.87547106	-55.879205	83
Sc-23c	25	14117	225.0044863	-23.75022431	-26.609145	83
Sc-23c	10	14117	225.0044863	47.50044863	53.2182907	83
Sc-23c	4.25	14117	225.0044863	74.81320659	83.8188079	83
Hutch-24c	6	12548	199.996904	62.99956656	70.583107	74
Hutch-24c	22.6333	12548	199.996904	-11.84976847	-13.276178	74
Hutch-24c	6.5	12548	199.996904	60.74958204	68.0622818	74
Hutch-24c	5.5	12548	199.996904	65.24955108	73.1039323	74
Hutch-24c	13.6667	12548	199.996904	28.49965392	31.9302851	74

Table B.4. Removal rate applied in our study at soybean site-years relative to KSU sufficiency recommendations.

Site-year	STP	Expected Yield		KSU Suff. Rec.		Our maintenance rate
	mg kg ⁻¹	kg ha ⁻¹	bu ac ⁻¹	lb P ₂ O ₅ ac ⁻¹	kg P ₂ O ₅ ha ⁻¹	kg P ₂ O ₅ ha ⁻¹
hutch-23s	29.25	4369	65.0	-41.6	-46.6	58
hutch-23s	16.75	4369	65.0	14.3	16.0	58
hutch-23s	14.25	4369	65.0	25.4	28.5	58
hutch-23s	9.5	4369	65.0	46.7	52.3	58
hutch-23s	6.75	4369	65.0	59.0	66.1	58
hutch-24s	18.5	4369	65.0	6.4	7.2	58
hutch-24s	10	4369	65.0	44.4	49.8	58
hutch-24s	7.25	4369	65.0	56.7	63.6	58
hutch-24s	6	4369	65.0	62.3	69.8	58
hutch-24s	5.25	4369	65.0	65.7	73.6	58
sc-2024s	11.5	4369	65.0	37.7	42.3	58
sc-2024s	15.75	4369	65.0	18.7	21.0	58
sc-2024s	10	4369	65.0	44.4	49.8	58
sc-2024s	10.5	4369	65.0	42.2	47.3	58
sc-2024s	13	4369	65.0	31.0	34.8	58
mhk-2023s	16.5	4033	60.0	15.0	16.8	54
mhk-2023s	18.25	4033	60.0	7.4	8.2	54
mhk-2023s	19.5	4033	60.0	1.9	2.2	54
mhk-2023s	32	4033	60.0	-52.3	-58.6	54
mhk-2023s	39.75	4033	60.0	-86.0	-96.3	54
mhk-2024s	9.4	4033	60.0	45.8	51.3	54
mhk-2024s	10	4033	60.0	43.2	48.4	54
mhk-2024s	16	4033	60.0	17.1	19.2	54
mhk-2024s	16	4033	60.0	17.1	19.2	54
mhk-2024s	30	4033	60.0	-43.7	-48.9	54
ashland-24s	10.5	3361	50.0	38.6	43.3	45
ashland-24s	12	3361	50.0	32.5	36.4	45
ashland-24s	15.5	3361	50.0	18.2	20.4	45
ashland-24s	39.25	3361	50.0	-78.8	-88.3	45
ashland-24s	25.5	3361	50.0	-22.7	-25.4	45
ott-2023s	10.5	3361	50.0	38.6	43.3	45
ott-2023s	12.5	3361	50.0	30.4	34.1	45
ott-2023s	9.5	3361	50.0	42.7	47.8	45
ott-2023s	15.25	3361	50.0	19.2	21.5	45
ott-2023s	12.5	3361	50.0	30.4	34.1	45

