Cover crop and phosphorus fertilizer management implications for water quality in a no-till corn-soybean rotation

by

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B.S., Virginia Polytechnic Institute and State University, 2012
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AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

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Abstract

Phosphorus (P) is an essential nutrient required for crop growth with finite global reserves. Although naturally occurring concentrations of total P in soils may greatly exceed crop demand, quantities of readily plant-available P in soil solution are typically very low. As such, agricultural producers regularly apply P-containing fertilizers to help optimize crop yields. While applications of P fertilizers may improve crop performance, losses of P from non-point agricultural sources are a known contributor to the degradation of surface water quality with excessive P inputs leading to eutrophication, harmful algal blooms, and increased water treatment costs. Acknowledging the importance of P in production agriculture and the role it plays in water quality it is imperative to develop agricultural management systems designed to promote crop yields while protecting water quality. This study explores the interplay between winter grown cover crops and P fertilizer management practice in relation to annual concentrations and loads of total suspended solids, total P, and dissolved reactive P in surface runoff generated by natural precipitation events for a no-till corn (*Zea mays*)-soybean (*Glycine max*) rotation located in the Central Great Plains. To explain the mechanisms behind the potential implications of altering cover crop and/or P fertilizer management practice in relation to water quality, this study examined temporal/seasonal variability in surface runoff water quality, changes in soil fertility status, and the impact of winter cereal cover crop species on potential P release and nutrient cycling.

The majority of this research was conducted at the Kansas Agricultural Watershed (KAW) field laboratory located near Manhattan, KS, USA, from September 2015 through September 2019. This study utilized three methods of P fertilizer management (no P, fall broadcast P, and spring injected P) each expressed with and without a winter grown cover crop.

The spring injected method of P fertilizer application consistently lost less total P and DRP compared to the fall broadcast method of applying P fertilizer highlighting the importance of using P fertilizer placement to protect water quality. Findings from this study show that the addition of a cover crop during a normally fallow period increased dissolved reactive P loss in 3 of 4 years representing an unintended consequence of a traditionally recognized conservation practice. Cover crops also decreased sediment loss with greater reductions in sediment loss coming from the P fertilized cover crop treatments. Soil test data for samples collected from KAW field lab found that spring subsurface placement of P fertilizer did not result in lesser concentrations of either Mehlich-III not total P in the top 0-5 cm compared to fall broadcast P. The spring injected P fertilizer without a cover crop treatment had lesser concentrations of water-extractable P (WEP) in the top 0-2.5 cm compared to the fall broadcast with and without cover crop treatments; however, when a cover crop was added to the spring injected treatment, WEP was found to be equal to the two fall broadcast treatments

The final portion of this research was conducted from fall 2019 through fall 2021 at locations near both Manhattan, KS, USA and Leonardville, KS, US, and examined the impact of six choices in winter cereal cover crops [included winter barley (*Hordeum vulgare*), winter oat (*Avena sterilis*), cereal rye (*Secale cereale*), triticale (X *Tritico-secale*), winter wheat (*Triticum aestivum*), and Cereal Killer Blend (1:1:1:1 of barley:oat:rye:triticale)] on P release from cover crop tissue, residue persistence, and the effect of cover crop choice on nutrient cycling throughout the cash crop growing season. This study found winter wheat to have the greatest potential for P release immediately following termination; however, after one week post termination, P concentrations in winter wheat residues were similar to other observed cover crops. Oats were observed to have lowest residue persistence and also to release assimilated nutrients faster than the remaining species. Marginal differences between winter barley, cereal rye, and triticale were observed with regards to P concentration, residue persistence, and nutrient cycling; however, these differences were not biologically significant. Results from this and the aforementioned studies highlight the importance and implications of management decisions when developing agricultural management practices to protect surface water quality.

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Approved by:

Major Professor
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Dedication

We loaded up the wagon in the year of sixteen
Headed across the Blue Ridge to a place we had not seen
They say opportunity is across the Missouri wide
Amidst the rolling Flint Hills, beneath prairie skies

Go west, young man! Is what the folks say
Take your little family and get along life's way
Live amongst the bluestem, the cottonwood, and grain
Go west, young man!
And make yourself a name

We rolled out of Virginia on a blue skied August day
Crossing hills and valleys, we went along our way
Through the bluegrass field of ol' Kentucky, and the flatlands of Illinois
Quite the change of scenery for this old mountain boy

Through the gateway to the West, we kept rolling on
Every mile, every day, a little further from our home
Thoughts filled with loved ones and friends left behind
Tore at our heartstrings and weighed heavy on our minds

Many years have passed since we reached the endless plains
A life we built amongst bluestem, cottonwood, and grain
Opportunity we did find across the Missouri wide
Amidst the rolling Flint Hills, beneath prairie skies

For Rial, thanks for loading up the wagon and heading west.

Chapter 1 - Role of Agriculture Management Practice in Relation to Phosphorus Loss in Surface Runoff

Introduction

Phosphorus (P) loss from non-point agricultural sources is a known contributor to the degradation of surface-water quality. When excessive quantities of P enter surface-waters, eutrophication may occur potentially causing an increase in both aquatic vegetative and algal growth resulting in decreased dissolved oxygen levels and increased cost of water treatment (Correll, 1998; Carpenter et al., 1998). Dodds et al. (2009) conservatively estimated increased water treatment cost due to harmful algal blooms and eutrophication at 2.4-4.6 billion U.S. dollars per year. In addition to increased water treatment cost, the aesthetic value of surface-waters may decrease as surface-waters undergo eutrophication resulting in a decrease in both recreational and property values (Dodds, 2002; Krysel et al., 2003).

Controlling non-point P pollution is not a localized challenge, and global net P storage for both aquatic and terrestrial ecosystems has increased over 75%, relative to pre-industrial levels, primarily due to phosphorus-based fertilizer application in agricultural soils (Bennet et al., 2001; Zhou et al., 2017). It has been estimated that up to 70% of all surface-water inputs of P can be associated with non-point agricultural sources (Havlin et al., 2005). Phosphorus plays an essential role in crop production. However, many soils are inherently low in readily plant-available P, and P-based fertilizers are regularly applied by producers around the world to help maximize crop yields (Hart & Quin, 2004). Acknowledging that non-point agricultural sources are the key contributor to excess P input into surface-waters, multiple agricultural best management practices (BMP) have been proposed to help curb P losses.

Agricultural management practices, or cropping systems, are among many factors which can impact agricultural nutrient loss (Liu et al., 2014a). An often-proposed agricultural BMP to reduce P loss is the promotion of crop residue retention on the soil surface plus the addition of a cover crop during normally fallow periods (Dumanski et al., 2006). This practice, in conjunction with no-till management is often considered a pivotal piece to the foundation of "Conservation Agriculture" (Dumanski et al, 2006).

Hartwig & Ammon (2002) define a cover crop as any living ground cover sown after, during, or prior to a main cash crop yet is terminated before planting the next cash crop. The addition of a cover crop during typical fallow periods has been proposed as a mechanism for reducing potential nutrient loss from agricultural fields (Sharply & Smith, 1991; Dabney et al, 2001; DeBaets et al., 2011; Blanco-Canqui et al., 2015; Ruffati et al., 2019).

Cover crops can benefit the soil in a variety of ways. Specifically, cover crops have been shown to reduce soil erosion, improve soil aggregate stability, decrease weed pressure, slow surface runoff, increase soil water storage, and decrease nutrient leaching and runoff (Dabney et al., 2001; Loss et al., 2015). Currently, cover crops play a key role in the reduction of nitrogen (N) leaching, with cover corps decreasing N leaching by 20-80%, dependent upon cover crop species (Dabney et al., 2001). Often, cover crops are also touted as a mechanism to help curb P loss (Sharpley & Smith, 1991; Dabney et al., 2001). However, as cover crops develop and mature, they can amass large quantities of P within the crop tissue creating a potential source of P release if accumulated P is not preserved within the crop tissue (Liu et al., 2014a, 2019). Additionally, the form of P accumulated in crop tissue can directly impact the rate of P release from the crop tissue (Casali et al., 2011). Understanding quantity and forms of P accumulated in cover crop tissue is critical to understanding P release from cover crops and potential impacts on both nutrient cycling and loss. However, the reported impacts of cover crops on P losses in surface runoff are both contrasting and inconsistent when examined across a variety of environmental conditions and agricultural management systems (Aronsson et al., 2016, Christianson et al., 2017; Kieta et al., 2018; Baulch et al., 2019). Additional field-scale data addressing the impacts of cover crops on P loss throughout the growing season is therefore needed before cover crops can be recommended as a BMP to reduce P losses.

In addition to utilizing residue retention and addition of a cover crop, producers can work to minimize potential losses of applied nutrients by employing various BMPs such as 4R Nutrient Stewardship, a method of fertilizer management which promotes the right source of nutrient applied at the right place, right rate, right time (Bruulsema et al., 2009). Implementation of fertilizer BMPs is important since most soil fertility recommendation systems for agricultural crops were developed to maximize crop yield and do not focus on minimizing potential environmental impacts (Withers et al., 2014).

Many studies have found that when P fertilizers are placed below the soil surface, both total P and dissolved P losses in surface runoff can be reduced compared to surface application of P fertilizers (Baker & Laflen, 1982; Mostaghimi et al., 1988; Zeimen et al., 2006; Kimmel et al., 2011; Yuan et al., 2018; Wiens et al., 2019). In addition, the timing of P fertilizer application in relation to precipitation events and associate surface runoff may impact P loss. Vadas et al (2008, 2011) and Sims & Kleinman (2005) all found, through extensive literature review, that application of P fertilizer during periods of high precipitation generally increases the likelihood of P loss. Therefore, both placement and timing of P fertilizer application may play a key role in understanding potential P loss from agricultural systems.

Across much of the Great Plains, seasonal rainfall is typically higher in the spring and summer compared to the fall and winter. Based on seasonal rainfall trends, applying P fertilizer in the fall, prior to soil freezing, would likely decrease the risk of P loss associated with surface broadcast fertilizer application. Fall broadcast application of P fertilizer offers producers additional advantages as fertilizers are generally less expensive, equipment and labor are more readily available, and the likelihood of interfering with other time sensitive field operations (e.g. planting) is minimal (Mallarino et al., 2009). While fall broadcast application of P fertilizer offers advantages, this method of P fertilizer application has not been compared against the currently recommended BMP of applying P fertilizer below the soil surface closer to planting (i.e., springtime). More specifically, additional information about the interaction between cover crops and P fertilizer management and the effects on P loss are needed to further develop agricultural BMPs to mitigate P loss.

This review of the literature aims to examine: i) P transport within and from the soil system; ii) how P fertilizer placement impacts P loss in surface runoff; iii) how cover crops influence P loss in surface runoff and P release from cover crops tissue, and (iv) dynamic changes in decomposition and P release from cover crop tissue.

Phosphorus Transport Within and From the Soil System

Phosphorus within the soil system may exist in a variety of chemical forms, commonly separated into inorganic P and organic P fractions, each of which exhibit different behaviors and fates within the soil system (Hansen et al, 2004; Turner et al., 2007; Shen et al., 2011). It is the nature of P forms present in the soil system in conjunction with biological activity, soil chemical properties, and environmental factors which ultimately influences the soil phosphorus cycle

(Pierzynski et al., 2005). However, both human and agricultural activities have heavily impacted the modern terrestrial P cycle (Oelkers & Valsami-Jones, 2008).

The concentration of P in soil solution is generally very low (<1% or <1 kg/ha) when compared to total amount of P in the soil (Pierzynski, 1991). This is in stark contrast to concentrations of P in crop tissue which can reach upwards of 3000 mg P/kg of crop tissue (Bieleski 1973). To account for low soil solution P concentrations and the inherent poor mobility of plant-available P in the soil, applications of P-based chemical fertilizers or P containing by-products are commonly needed to achieve optimal crops yields (Shen et al., 2011). However, maintaining a concentration of P in soil solution which is optimal for crop growth while minimizing potentially negative impacts of P movement into surface waters is challenging (Pierzynski et al., 2005).

Phosphorus removal via crop uptake is the major pathway for P removal from the soil system; however, surface runoff and erosion can also account for substantial quantities of P loss, and the quantity of P lost in surface runoff can be directly correlated to the form and concentration of P present in the soil, sediment levels in surface runoff, and surface runoff volume (Pierzynski et al., 2005; Sharpley et al., 1994). For agricultural systems, P loss occurs because of the interaction between site specific hydrological processes and characteristics, soil P, and supplemental supplied P (Osmond et al., 2019). The source areas of P loss are also highly variable and dependent upon soil physical properties, soil P levels, and erosion susceptibility (Kleinman et al., 2011; Withers & Bowes, 2018).

The transport of P is controlled via the following three main processes, each of which is directly affected by the intensity of drainage, hydraulic conductivity of the given soil, and soil infiltration capacity: surface runoff, erosion, and sub-surface flow (Heathwaite et al., 2005).

While sub-surface flow can carry P in course textured soils, organic soils, or tile drained systems, surface runoff is considered the predominant pathway for P transport in agricultural systems (Heathwaite & Dils, 2000; Vadas et al., 2005; King et al., 2015).

When soils become saturated or whenever infiltration capacity is reached, surface runoff may occur potentially carrying with it large amounts of sediment and P, especially when high intensity runoff events occur (Heathwaite et al., 2005). As P-enriched soil particles are carried by surface runoff, particulate-bound P may be carried to or deposited elsewhere in the field or potentially be deposited into surface waters (Osmond et al., 2019). The quantity of particulate-bound P removed from the field has been correlated to how much soil was eroded, the P levels of the eroded soil, and soil texture, with finer textured soil particles containing large amounts of P compared to coarser particles (Sharpley et al., 1985; Cox, 1994; Osmond et al. 2019).

As surface runoff moves across a field and interacts with the soil surface, P may become solubilized (i.e., dissolved) and carried away by surface runoff waters (Dunne & Black, 1970). The incorporation of P into surface runoff is generally controlled by diffusion, dissolution, and desorption reactions occurring in the top 5 cm of the soil (Sharpley, 1985; Hansen et al., 2002). As concentration of soil P near the soil surface increase, levels of dissolved P in surface runoff may also increase (Romkens & Nelson, 1974).

Phosphorus Fertilizer Management Practices' Impact on Phosphorus Loss

Management of P loss from agricultural systems is especially difficult due to P loss occurring in both dissolved and particulate-bound forms suggesting that BMPs which target both particulate-bound and dissolved P pathways are needed to help mitigate P loss. In broader terms, mitigating P loss from agricultural systems is best accomplished by developing management practices which target both P source and transport factors. Agricultural management practices which aim to minimize erosion and surface runoff or aim to decrease the amount of contact applied P has with surface runoff should thus result in decreased P transport away from the agricultural system (Pierzynski et al., 2005). Detailing every agriculture management practice and its impact on P loss is beyond the scale of this review. Therefore, discussion of agricultural management practices will be limited to P fertilizer management practices and cover crop management in no-till production systems.

When P fertilizers are added to an agricultural system, the concentration of P within the soil solution increases, increasing the amount of P potentially available for plant uptake and/or loss to the environment. As hydrological processes interact with soil P and supplemental P applied as fertilizer, P loss may occur (Osmond et al, 2019). The source, rate, placement, and timing of P fertilizer application in relation to precipitation intensity and duration may also directly impact P loss (Sharpley & Rekolainen, 1997).

Many fertilizer recommendation systems were derived from field-studies conducted during a time when extensive tillage was common and recommendations are often based upon an index of plant available P within the plow-layer (Vitosh et la., 1995; Smith et al., 2017). Incorporating surface applied P-based fertilizers by tillage is a known mechanism to reduce potential P loss in surface runoff (Sharpley et al., 1991; Smith et al., 1991). However, in no-till production systems, immobile P-based fertilizers are often broadcast across the soil surface without incorporation, resulting in high levels of P near the soil surface (Sims et al., 2000). Surface P levels can also further be increased through the deposition of assimilated P in crop residues upon the soil surface (Scheiner & Lavado, 1998). Additionally, the reduced cycling of sub-surface soil and decreased vertical integration of surface applied P may further increase P stratification under no-till management (Mallarino & Borges, 2006; Mallarino et al., 2009).

Subsurface placement of P fertilizer is currently recommended as a BMP to help curb P loss where injection serves as incorporation without tillage. Mostaghimi et al. (1988) found when P fertilizers are injected below the soil surface that P losses in surface runoff (via simulated rainfall) decrease by 39% compared to surface applied P-based fertilizers. Baker & Laflin (1982), also using a rainfall simulator, found when P fertilizer was subsurface applied there was no difference in the quantity of P lost compared to the unfertilized treatment. In no-till situations, subsurface application of P-based fertilizer has also been found to decrease bioavailable P losses by nearly 70% compared to broadcast application (Kimmel et al., 2001). Additional studies have shown increased P use efficiency, increased P uptake, and increased grain yield when P is subsurface applied compared to surface broadcast in no-till systems (Eckert & Johnson, 1985; Hairston et al., 1990; Lauson & Miller, 1997). However, the low cost and ease of surface broadcast application of P fertilizer contributes to broadcast application being the most widely implemented P fertilizer management strategy for no-till corn-soybean rotations across much of the Great Plains (Mallarino et al., 2009).

In addition to P fertilizer placement, producers must also select a P fertilizer source. Nutrient loss from fluid fertilizers has been shown to be lower compared to dry, granular fertilizers (Smith et al., 2017). When applied at the same rate, surface application of liquid single super phosphate (SPP) resulted in nearly 55% less soluble P loss compared to surface application of granular SPP (Sharpley & Syers, 1983). Surface application of fluid polyphosphate has been shown to decrease soluble P losses by 98% when compared to application of both granular monoammonium phosphate and diammonium phosphate fertilizers (Smith et al., 2016). Findings from these studies suggest application of fluid P-based fertilizer may result in lower levels of P loss. However, subsurface application of fluid fertilizer has not been compared to the common management practice in the Great Plains of fall, surface broadcast application of P fertilizer. To fully develop P fertilizer BMPs to reduce P loss, this comparison must be made.

Cover Crop Effects on Surface Runoff Losses of Phosphorus

Cover crops are often grown during normally fallow periods of the annual cropping cycle and provide a variety of benefits to both the agricultural and soil system. Addition of a cover crop during a normally fallow period increases carbon storage in soils, improves soil aggregate stability, and decreases negative effects of wind and water erosion (Cock, 1985; Reicosky & Forcella, 1998; Battany & Grismer, 2000). Cover crops may impact soil hydrological properties by either increasing infiltration capacity via the formation of channels from root decay or decreasing infiltration by chemically altering the rhizosphere in such a manner that it become hydrophobic (Hallett et al., 2003). Additionally, cover crops may deplete soil water, further potentially altering hydrological properties (Reicosky & Forcella, 1998).

Over 75% of P loss via surface runoff can be attributed to erosion (Sharpley & Rekolainen, 1997). As surface runoff moves across a field, both particulate and soluble P can be carried with it, thus, P loss can be directly linked to erosion (Gburek et al., 2005). Therefore, it can be inferred that practices which reduce erosion loss should decrease P loss via surface runoff.

In a cover cropped system, the soil surface remains under a “permanent” layer of vegetative cover. Surface vegetation is well-known for protecting soil from erosion through decreasing rainfall impact, disrupting surface runoff flow paths, and stabilizing soil due to plant root growth (Morgan, 2005; Gyssels et al., 2005). Cover crops decrease both interrill and splash erosion and protect again destruction of soil aggregates, surface sealing, and compaction of topsoil (Kaspar et al., 2001; Morgan, 2005). Blanco-Canqui (2018) reviewed thirteen articles examining sediment loss and found cover crops may reduce sediment losses by up to 100%

compared to fields with no cover crops; however, for one field examined field site, cover crops had no impact on sediment losses. The impacts of cover crops on erosion losses are well established in the literature (Kaspar et al., 2001; Morgan, 2005; Blanco-Canqui, 2018). However, cover crop effects on P loss are inconsistent, sometimes resulting in greater P loss sometimes less P loss compared to no cover (Aronsson et al., 2016, Christianson et al., 2017; Kieta et al., 2018; Baulch et al., 2019).

As cover crops grow and develop, they may accumulate large quantities of P within the cover crop tissue, creating a reservoir of P storage above the soil surface which may potentially serve as a P source for surface runoff (Liu et al., 2014b). The impact of assimilated P stored in cover crop tissue on water quality is therefore dependent upon the preservation of the assimilated P within the crop tissue (Liu et al., 2014b, 2019). Preservation of assimilated P can be influenced by management factors including cover crop species selection and/or termination method (Carver et al., 2020).

Noack et al (2012) found wide deviation in the concentration of inorganic-P within crop tissue across an array of species, suggesting cover crop species selection may influence potential P release from the cover crop residue. In addition to P concentration, frost tolerance amongst cover crop species varies, indicating tissue damage as a result of exposure to freezing temperatures will vary across crop species (Sturite et al, 2007). When exposed to freezing conditions, water within plant tissue can turn to ice resulting in expansion-induced lysis damaging the plant cell membrane and potentially causing soluble components, such as water-extractable P, to leak out of the plant tissue (Thomashow, 1990, Miller et al, 1994; Bechmann et al., 2005). Indeed, Øgaard (2015) found plant cells damaged by exposure to freezing conditions resulted in great P leaching from crop tissue compared to plants which had not been exposed to freezing, with freezing exposed plants losing between 20-50% of total biomass P after being frozen. Lozier & Macrae (2017) found similar results with field-grown crops losing up to 49% of total biomass P after exposure to freezing. Numerous other studies have also found that exposure of cover crop to freeze-thaw conditions increases water-extractable P concentrations released from cover crop tissue compared to non-freeze-thaw exposed cover crop tissue (Miller etl al., 1994; Sturite et al., 2007; Liu, 2014a, 2014b, 2019, Carver et al., 2020) While producers cannot control whether air temperatures will drop below freezing, they can adjust management practice through altering planting date and species selection to influence the quantity and characteristics of cover crop residue that may be exposed to freezing conditions.

Decomposition and Potential Phosphorus Release from Cover Crop Tissue

Decomposition of plant reside is influenced by a variety of factors including chemical and physical properties of the plant residue, interplay among soil fauna and microflora, and climate with climatic variation and accessibility of residue by microbes perhaps being the key drivers (Swift et al., 1979; Buchanan & King, 1993). Mellilo et al. (1982) and Muller et al. (1988) stated that nitrogen concentrations, lignin concentrations, and C/N ratio are each key characteristics for understanding rate of decomposition. The C/N ratio of crop residue is often considered a good index of the rate of litter decomposition, yet when the C/N ratio exceeds 75-100, the ratio of lignin to N may be a more appropriate decomposition rate predictor (Mafongoya et al., 2000; Heal et al., 1997).

The quantity of nutrient within crop tissue is correlated to physical and chemical nature of the plant, specifically, plant species, maturity, and overall plant health (Miller et al, 1994). Release of nutrients from crop residues during the decomposition process are controlled via three linked factors: quality of crop residue, physio-chemical environment, and decomposing organisms (Heal et al., 1997). Time after termination also directly impacts P released from decomposing cover crop tissue (Carver et al., 2020).

As cover crop tissue undergoes decomposition, P within the cover crop tissue may undergo a variety of fates: release from crop tissue and remain highly plant available in the soil; conversion into organic-P; immobilization by soil microbial community; or loss from the soil system via surface runoff, leaching, and/or erosion (Damon et al., 2014, Maltais-Landry & Frossard, 2015). Release of P from cover crop tissue is important if cover crops are to positively impact P cycling and potentially make assimilated P available for uptake by the subsequent cash crop (Damon et al., 2014). However, P released from cover crop tissue may serve as a potential source of P loss.

Proposed Research

Understanding the relationship between cover crops and P fertilizer management is important when developing agricultural BMPs to help curb P loss and preserve surface water quality. Additionally, understanding the roll cover crop species and time after termination play in potential phosphorus release from cover crop tissue will further help develop agricultural practices to mitigate P loss. This research aims to provide producers with flexible agricultural management options, which promote cash crop yields while reducing P loss and protecting surface waters.

Sediment and Phosphorus Concentrations and Loads in Surface Water Runoff

<u>Hypotheses</u>

1. Subsurface placement of phosphorus fertilizer will result in less phosphorus loss in surface runoff compared to surface-broadcast placement of phosphorus fertilizer.

2) Cover crops will decrease sediment and nutrient loss from the field and may negate any negative impacts of surface-broadcast placement of phosphorus fertilizer.

Research Objectives

Specific research objective for this proposed study are as follows;

1. Determine the interaction between cover crops and phosphorus fertilizer management practice on annual environmental measures (TSS concentration, TP concentration, DRP concentration, sediment load, TP load, DRP load) in a no-till, corn-soybean rotation.
2. Compare the impacts of fall broadcast P application to spring injected P application (currently recommended BMP) and no P fertilizer application on water quality for a no-till, corn-soybean rotation.
3. Determine temporal variability in patterns of sediment and nutrient loss across P fertilizer and cover crop management practices for a no-till corn-soybean rotation.

Changes in Soil Test nutrient levels as impacted by P fertilizer practice and cover crops

Hypotheses

1. Altering the placement of P fertilizer will influence the degree of P stratification.
2. Addition of a cover crop will increase P concentrations in the top portion of the soil even in plots not receiving P fertilizer

Objective

This research will measure changes in soil test levels for total C, total P, Mehlich-3 P, water-extractable P, potassium, and nitrate-nitrogen across a multiyear period at the Kansas Agricultural Watershed field laboratory and will determine the impact P fertilizer management and cover crops have on each soil test parameter.

Decomposition and nutrient cycling for winter cereals

Hypothesis

Choice in small grain cover crops will alter both nutrient cycling and dynamic changes in nutrient (N, P, K, and S) release from cover crop tissue throughout the growing season of the subsequent cash crop.

Research Objectives

Specific research objectives for this proposed study are as follows:

1. Determine total nutrient (N, P, K, and S), water-extractable nutrient concentrations, and biomass of small grain, winter sown cover crops in a no-till system and assess how these values change throughout the various stages of cover crop tissue decomposition.
2. Determine the impact of small grain, winter sown cover crops on nutrient cycling (i.e. nutrient accumulation and deposition) in a no-till system.

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Chapter 2 - Cover crop and phosphorus fertilizer management impacts on surface water quality from a no-till corn-soybean rotation

Citation

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Abstract

Best management practices that reduce potential phosphorus (P) loss and provide flexibility in P fertilizer management are needed to help producers protect water quality while maintaining crop yield. This study examined the impacts of P fertilizer management (no P, fall broadcast P, and spring injected P) and cover crop use on annual concentrations and loads of sediment, total P, and dissolved reactive P (DRP) in edge-of-field runoff from a no-till corn (*Zea mays*)-soybean (*Glycine max*) rotation in the Central Great Plains, USA, from September 2015 through September 2019. The spring injected P fertilizer treatment generally had 19% less total P and 33% less DRP loss compared to the fall broadcast treatment, confirming the importance of P fertilizer placement as a best management practice for reducing P loss. The addition of a cover crop had an inconsistent effect on total P loss, with no effect in 2016 and 2017, increasing loss in 2018 by 56%, and decreasing it in 2019 by 40%. The inconsistent impact of cover crops on total P loss was related to cover crop effects on sediment loss. Although cover crop impacts on total P losses were inconsistent, the addition of a cover crop increased DRP loss in three of four years. Cover crop use consistently reduced sediment loss, with greater sediment reduction when P fertilizer was applied. Results from this study highlight the benefit of cover crops for reducing

sediment loss and the continued need for proper fertilizer management to reduce P loss from agricultural fields.

Introduction

Phosphorus (P) is an essential nutrient for crop production, and producers apply P-based fertilizers to help achieve optimal crop yields. However, P loss from non-point agricultural sources contributes to the degradation of surface-water quality with excessive inputs of P potentially leading to eutrophication, harmful algal blooms, and the formation of hypoxic zones (Correll, 1998; Carpenter et al., 1998, Welch, 1978). Compared to pre-industrial levels, the net P storage of aquatic and terrestrial ecosystems has increased more than 75%, primarily due to the application of P fertilizers in agricultural systems (Bennett et al., 2001; Zhou et al., 2017). Thus, it is important to develop and evaluate agricultural best management practices (BMP) that reduce P losses.

Phosphorus fertilizer management plays a key role in 4R nutrient stewardship (right place, right time, right source, and right rate), and current BMPs recommend sub-surface application of P fertilizer close to planting-time (springtime) to reduce potential P loss (Johnston and Bruulsema, 2014). Across much of the Central Great Plains seasonal rainfall trends suggest the optimal time for P fertilizer application would be in the fall. Mallarino et al. (2009) stated that fall broadcast application of P fertilizer offers advantages to producers in several ways including typically lower fertilizer prices, greater availability of equipment/labor, and lack of interference with other field operations. In addition, fall broadcast application of P fertilizer is generally simpler and quicker than springtime sub-surface P fertilization; yet, when surface broadcast of P fertilizer is compared to sub-subsurface placement of P fertilizer in a no-till system, the sub-surface placement of P fertilizer may reduce total and dissolved P losses by 30 and 75%, respectively (Kimmell et al., 2001). Although sub-surface placement of P fertilizer has been shown to reduce both total and dissolved P losses across a variety of agricultural systems (Baker and Laflen, 1982; Mostaghimi et al., 1988; Zeimen et al., 2006; Yuan et al., 2018; Weins et al., 2019), development of BMPs for surface fall broadcast application of P fertilizer would be beneficial due to the economic, labor, and timing advantages of the fall broadcast system.

Addition of a cover crop may potentially reduce the environmental impacts of P fertilizer application by interrupting P transport pathways, decreasing erosion losses, and increasing water infiltration (Dabney, 1998; Dabney et al., 2001; Blanco-Canqui et al., 2015; Loss et al., 2015; Ruffati et al., 2019). Increasing infiltration and reducing runoff could translocate surface-applied P fertilizer into the soil where it could be retained by sorption mechanisms, thereby reducing P loss associated with fall-broadcast fertilizer application. If cover crops decreased the higher P loss associated with surface broadcast P application, producers would have greater flexibility in fertilizer management options while keeping P loss to a minimum and preserving surface water quality. Therefore, more information about the interactions between cover crops and P fertilizer management are needed to inform new agricultural BMPs.

Despite the ability of cover crops to potentially alter P transport pathways, the impacts of cover crops on P loss from agricultural systems are inconsistent, as the efficacy of cover crops in reducing total and dissolved P losses has been shown to be variable across several studies (Aronsson et al. 2016, Christianson et al., 2017; Kieta et al., 2018; Baulch et al., 2019). The majority of studies that have assessed the effect of cover crops on P loss have utilized simulated rainfall to measure P loss (Bechmann et al., 2005; Kleinmann et al., 2005; Kovar et al., 2011; Liu et al., 2013; Miller et al., 1994). Kleinmann et al. (2005) and Kovar et al. (2011) both examined the impacts of using a cover crop on P loss from fields receiving manure application. Both research teams found that using a cover crop reduced total P loss after application of manure, yet Kovar et al. (2011) found that cover crops increased dissolved reactive phosphorus (DRP) loss after they were terminated. Additionally, Bechmann et al. (2005) and Miller et al. (1994) found exposure of cover crop tissue to freeze-thaw cycles can increase the quantity of P leached from cover crop tissue. Increased P leaching from cover crop tissue because of exposure to freezing conditions could create a potential source of P loss from the field. Rainfall simulation studies are helpful for comparing management practices in controlled settings (i.e., rainfall intensity) at a specific time during the cropping cycle, but because cover crop effects on soil chemical and physical processes could change throughout the year (Hanrahan et al., 2021), additional information is needed from edge-of-field studies to determine cumulative effects of cover crops on P loss during the entire year. There are relatively few field-scale studies on cover crop effects on P loss in no-till systems and there are not any published studies that investigate the interactions between cover crop use and P fertilizer management on P loss.

The goal of this study is to provide farmers with flexible and sustainable agricultural management practices to help reduce P loss and preserve water quality. The specific objectives are to determine the effects of cover crops, method of P fertilizer application, and their interaction on total suspended solid, total P, and DRP concentrations and loads in surface runoff from natural precipitation events for a no-till corn (*Zea mays*)-soybean (*Glycine max*) rotation.

Materials and Methods

This field study was conducted at the Kansas Agricultural Watershed (KAW) field laboratory located near Manhattan, Kansas, from 1 October 2014 through 30 September 2019. This study monitored runoff volume, total P, DRP, and total suspended solids (TSS) concentration in edge-of-field surface runoff (caused by natural precipitation events) from a no-till corn (*Zea mays*)-soybean (*Glycine max*) rotation. Data are presented from the 2016, 2017, 2018, and 2019 harvest years, which ran from 22 September 2015 – 19 October 2016, 20 October 2016 – 20 September 2017, 21 September 2017 – 1 November 2018, and 2 November 2018 – 18 September 2019, respectively. Data from the first year of the study are not presented because the field was in transition from conventional tillage to no-till management.

Experimental Design

This study evaluated the effects of six agricultural management practices (treatments) on surface runoff water quality. Treatments were structured in a 3×2 complete factorial, arranged in a randomized complete block design (blocked by landscape position) with repeated measurements over time, and replicated thrice (*n* = 18) (Figure S1). Three levels of P fertilizer management practice were used: no P fertilizer control (CN); fall broadcast (FB, 61 kg P_2O_5/ha), spring sub-surface injected (SI, 61 kg P_2O_5/ha). Each level of P fertilizer management practice was expressed with two levels of cover crop: no cover (NC) and with cover crop (CC).

Field Site

The KAW field lab was established in 2014 and is comprised of eighteen, small-scale watersheds (i.e., plots), averaging approximately 0.5 ha in size, each fitted with a 0.46 m high H-flume and automated water sampler (ISCO Teledyne 6700 or 6712 series with a 730 bubbler unit, Lincoln, NE). All plots were separated from each other with berms and terraces. Soil ranges from an eroded to highly eroded Smolan silty clay loam (fine, smectitic, mesic Pachic Argiustoll) with 3-7% slope. Historically, the field site was under conventional tillage management in a winter wheat (*Triticum aestivum*)-soybean (*Glycine max*) rotation. The last tillage event occurred on 7 November 2014, when the site was cultivated with a chisel plow followed by a disc. Thirty-year average annual precipitation for this location was 889 mm/year (Figure S2).

Agricultural Management

Corn hybrids, soybean cultivars, and seeding rates were selected based on regional recommendations and the expected yield goals were 10 and 2.7 t/ha for corn and soybean, respectively. Soybean was grown in 2016 (325,000 seeds/ha) and 2018 (321,000 seeds/ha); corn was grown in 2017 and 2019 (64,000 seeds/ha).

Winter cover crops were sown immediately following harvest of the main crop and consisted of a small grain and brassica mix, with the vast majority of biomass production from the small grain. Cover crop species varied throughout the study depending on the planting time and main crop (Table S1). Cover crops were terminated with herbicide prior to planting in 2016 or immediately following planting for other years (Table S1).

Phosphorus fertilizer was applied annually to all P fertilized plots (FB and SI) at 61 kg P_2O_5/ha. Phosphorus fertilizer application rates were based on a 5-year build and maintain recommendation system and based on an average initial soil test of 17 mg P kg^{-1} Mehlich-III P (Leikem et al., 2003). Diammonium phosphate (18-46-0) was applied to the FB treatments with a 3.05-m wide drop spreader (Barber Engineering Co., Spokane, WA). Ammonium polyphosphate (10-34-0) was injected 5 cm below and 5 cm to the side of the seed at planting for the SI treatment.

During corn production (harvest years 2017 and 2019), nitrogen was applied as urea ammonium nitrate (28-0-0) to all plots using a coulter applicator and injected in 5-cm deep bands on 38-cm spacing. Nitrogen rates were balanced across all treatments during corn production so that each plot received identical total N application rates based on established university recommendations (Leikam et al., 2003).

Water Quality and Analysis

Flow-weighted composite water samples were collected from each runoff event throughout the study. Runoff (*Q*) was recorded year-round at 1-minute intervals using ISCO 730 bubbler modules. A 200-mL sample was collected for every 1 mm of surface runoff and composited in a 10 L Nalgene carboy. The majority of runoff samples were removed from the field and placed at 4^{o}C within 24 hours after runoff had ceased with occasional samples remaining in the field up to 48 hours after runoff. Every effort was made to complete chemical analysis of water samples within 7 days of collection, with maximum time to analysis of 21 days. Total suspended solid concentration was determined gravimetrically by vacuum filtration of a 50 to 100-mL aliquot through a pre-dried 0.45 µm filter (Csuros, 1997). Dissolved reactive P was determined by passing the sample through a 0.45 µm filter and analyzing the filtrate by the molybdate-blue colorimetric procedure with an Alpkem Rapid Flow Analyzer (Alpkem method A303-S200-13). Total P was determined by digesting a 1 to 10-mL sample at 120^{o}C for 60 minutes with potassium persulfate reagent followed by analysis as described for DRP (Nelson, 1987).

Data Processing

The total amount of surface runoff (mm) for each plot in each harvest year was calculated using Equation 1

$$Qi=\sum jQi,jQi=\sum jQi,j$$

(1)

where Q_i is the total amount of runoff in year *i* for a given plot and $Q_{i,j}$ is the amount of runoff for event *j* in year *i* for a given plot.

The total mass (load; kg/ha) of TSS, Total P and DRP exiting each plot in each harvest year was calculated using Equation 2

$$Li=(\sum jCi,jQi,j)/100Li=(\sum jCi,jQi,j)/100 \tag{2}$$

where L_i is the load of either TSS, Total P, or DRP for year i and $C_{i,j}$ is the concentration of the given water quality constituent in runoff for event j in year i (mg L^{-1}). The annual flow-weighed concentration (C_i; mg/L) of TSS, Total P and DRP for each plot in each harvest year was calculated as $C_i = 100(L_i/Q_i)$.

For DRP, five values were less than the quantification limit of 5 μg/L and were replaced by half of the quantification limit. Within a given runoff event, the missing response of a plot was replaced by the geometric mean of responses of other plots in the same treatment group. Only events with average runoff greater than 2.0 mm were included in the analysis.

Statistical Analysis

Data were first subjected to $\log_{10}$ transformation and then analyzed using the linear mixed model. Fixed effects of the model include replication, P fertilizer management practice, cover crop, harvest year, and all high order interactions among fertilizer practice, cover crop and harvest year. Plot was the error term vector whose elements corresponded to the 4 harvest years. Variance-covariance structure of the error term was taken as either compound symmetry, heterogenous compound symmetry, first-order autoregressive, heterogenous first-order autoregressive, ARMA(1,1) or unstructured according to model fitting criteria and convergence status. Interactions between model fixed effects were examined using type III tests at the 0.05 level. Back-transformed least squares (LS) means and standard errors for fixed effects are reported with transformed means and standard errors available in the supplemental materials

(Table S2). Pairwise comparisons between two levels of a fixed effect were performed based on the 2-sided test for non-zero difference in means. The protected LSD test with $\alpha = 0.05$ was used for mean separation within year. Statistical analysis was executed via Statistical Analysis Software (SAS version 9.4; Cary, NC) PROC MIXED with option DDFM=KR.

Results

Precipitation totals for harvest years 2016, 2017, 2018, and 2019 were 1141, 677, 813, and 1098 mm, respectively (Figure A2). There were 12, 7, 5, and 14 events with more than 2 mm of runoff in harvest years 2016, 2017, 2018, and 2019 that generated cumulative runoff of 162, 68, 73, and 244 mm in each year, respectively (Table A1).

Annual runoff was significantly impacted by the interaction between P fertilizer management practice and cover crop when averaged across all four harvest years with the FB-CC treatment having approximately 30% less runoff compared to both CN-CC and SI-NC treatments (Table 2.1; Figure 2.1a)A harvest year by cover crop interaction for annual runoff also was observed with the cover crop treatment resulting in 20% less runoff compared to the no cover treatment in 2019, but there was no effect of cover crop on runoff in the other years (Table 2.1; Figure 2.1b).

A three-way interaction between harvest year, P fertilizer management practice, and cover crop was observed for total suspended solids (TSS) concentration in runoff (Table 2.1). In harvest years 2016, 2017, and 2019, addition of a cover crop decreased TSS concentration in runoff regardless of P fertilizer management practice (Figure 2.2a). In harvest year 2018, for the no P fertilizer control, addition of a cover crop did not impact TSS concentration (Figure 2.2a), indicating cover crop implementation did not decrease TSS concentration unless P fertilizer was added. Furthermore, in 2017, the TSS concentrations of runoff from the FB-CC and SI-CC treatments were significantly less than from the CN-CC, indicating that the effect of including a cover crop on TSS concentration in runoff was enhanced by the addition of P fertilizer. The interaction is also evident in the way P fertilizer treatments affected TSS concentration for the no cover crop treatments in 2016 and 2017. In 2016, the TSS concentration in runoff from the SI-NC treatment was less than that from the CN-NC, but this effect was reversed in 2017 with the SI-NC having greater concentrations of TSS in runoff compared to CN-NC (Figure 2.2a). Averaged across all years, the addition of a cover crop reduced TSS concentration in runoff by 67% (Table 2.2).

Harvest year by P fertilizer management practice and harvest year by cover crop interactions on total P concentration in runoff were both observed (Table 2.1). The total P concentration in runoff from the SI treatment was less than that from the FB treatment in 2016 and 2017 but similar to that from the FB treatment in 2018 and 2019 (Figure 2.3a). The total P concentration in the runoff from the CN treatment was less than that from the FB treatment every year of the experiment and less than SI for every year except 2016 (Figure 2.3a). Addition of a cover crop had an inconsistent effect on total P concentrations in runoff, having no effect in 2016 and 2017, increasing total P concentration in 2018, and decreasing total P concentration in 2019 (Figure 2.3b).

For DRP concentration in runoff, a harvest year by P fertilizer management practice by cover crop interaction was observed (Table 2.1). Throughout this study, addition of a cover crop to the SI treatment consistently resulted in greater concentrations of DRP in runoff compared to when the cover crop was not present (Figure 2.4). This same effect was also observed for the FB treatment in 2017 and 2018 and for the CN treatment in the 2016, 2017 and 2018 harvest years (Figure 2.4). The presence of a cover crop did not have a significant effect on DRP concentration in runoff from the FB treatment in 2016 or 2019 or from the CN treatment in 2019, although in each of these cases the DRP concentration from the CC treatments was numerically greater than the NC treatments.

The harvest year by P fertilizer management practice by cover crop interaction can also be described based on how the cover crop treatment modified the effect of P fertilizer management on DRP concentration in runoff. In 2016, 2017, and 2019, the fertilizer effect was the same for both NC and CC treatments with the SI treatment having lesser DRP concentrations compared to FB. In 2018, the SI treatment decreased DRP concentration when no cover crop was present yet had no impact on DRP concentration when a CC was present (Figure 2.4), although the general trend was similar to other years where the DRP concentration in runoff from the SI-CC treatment was numerically less than that from the FB-CC treatment.

Similar to what was observed for TSS concentration, a three-way interaction between harvest year, P fertilizer management practice, and cover crop was observed for sediment load in runoff (Table 2.1). For the FB and SI P fertilizer treatments, addition of a cover crop consistently decreased sediment load approximately 70 and 80%, respectively, on average per year (Figure 2.2b). In harvest years 2016 and 2019, addition of a cover crop significantly decreased sediment load for the CN treatment, but this did not occur in 2017 and 2018 (Figure 2.2b). Also important to note is that across all years of the study, P fertilizer management did not affect sediment loss from the NC treatments; however, in the CC treatments, the FB and SI fertilizer treatments had less sediment loss than the CN treatment in 2017, and in 2018 the FB-CC treatment had less sediment loss than the CN-CC treatment (Figure 2.2b).

Both P fertilizer management practice by harvest year and cover crop by harvest year interactions were observed for total P load in runoff (Table 2.1). Patterns for treatment effects on total P load are similar to those for total P concentration, where total P load from the SI treatment was less than the FB treatment in 2016 and 2017 but similar to the FB treatment in 2018 and 2019 (Figure 2.3c). The total P load in runoff from the CN treatment was less than that from the FB treatment every year of the experiment and less than SI for every year except 2016. Similar to cover crop effects on total P concentration, addition of a cover crop had an inconsistent effect on total P load in runoff, having no effect in 2016 and 2017, increasing total P load in 2018, and decreasing total P load in 2019 (Figure 2.3c).

A harvest year by P fertilizer management interaction was observed for DRP load in runoff (Table 2.1). In three out of four years (2016, 2017, and 2019), the SI fertilizer treatment resulted in less DRP loss compared to the FB treatment (Figure 2.5a). The SI fertilizer treatment lost between 216 to 482 g/ha/yr less DRP compared to the FB treatment. Application of P fertilizer, regardless of management, resulted in greater DRP losses compared to the control (Figure 2.5a). A harvest year by cover crop interaction for DRP load also was observed with addition of a cover crop resulting in increased DRP losses ranging from 185 to 283 g/ha/yr in years 2016, 2017, and 2018 compared to the no cover treatment, but no differences were observed in 2019 (Table 2.1;Figure 2.5b).

Over the course of this study, the SI method of applying P fertilizer typically resulted in significantly smaller concentrations and loads of both total P and DRP compared to the FB treatment (Figure 2.3c and Figure 2.5a). For harvest years where differences between SI and FB management were not statistically significant, the SI treatment tended to have smaller concentrations and loads of both total P and DRP. Corresponding to these relatively consistent trends over time, there was a significant main effect of P fertilizer management practice on concentrations and loads of both total P and DRP (Table 2.1). The SI treatment decreased total P concentration and load by 31% and 21% respectively, compared to the FB treatment (Table 2.2). Similar trends were observed for DRP concentration and load with the SI treatment decreasing these values by 44% and 36% respectively, compared to the FB treatment (Table 2.2)

A main effect of cover crop on TSS concentration was observed with the addition of a cover crop decreasing TSS concentration in runoff by 67% (Table 2.1; Table 2.2). A similar trend was observed for sediment load with the addition of a cover crop tending to decrease sediment load by 68% (Table 2.2). Across all years, the addition of a cover crop typically resulted in greater DRP concentrations and loads in surface runoff compared to no cover (Figure 2.4 and Figure 2.5b), which resulted in a very strong main effect of cover crop on these parameters (Table 2.1). On average, use of a cover crop increased DRP concentration in runoff by 69% and increased the DRP load by 63% (Table 2.2).

Discussion

Phosphorus Fertilizer Management

Reductions in TSS concentration and sediment load from the P fertilized cover crop treatments are likely due to increased cover crop growth and surface residue resulting from P fertilizer application. Phosphorus fertilizer applications increased cover crop growth and biomass accumulation by 27% (Table A2). Mailapalli et al. (2013) and Ha et al. (2020) both found that increasing surface residue decreases sediment loss in runoff. Surface vegetation and residue is known to decrease erosion losses by protecting the soil surface from rainfall impact, disrupting runoff flow paths, and improving soil stability (Morgan, 2005; Gyssels et al., 2005).

Increased P losses from the P fertilized treatments is likely from P fertilization increasing the P concentration of surface soil or the applied P fertilizer serving as a potential P source to runoff (Romkens and Nelson, 1974; Kleinman et al, 2005). Multiple studies have identified a positive correlation between soil test P concentration and the concentration of total P and DRP in runoff (Sharpley et al., 1993; Pote et al., 1999; Cox and Hendricks, 2000). At the beginning of this study, Mehlich-III soil test P in the top 5 cm was equal among all treatments (31 ppm). After four years of fertilizer application to the FB and SI treatments, Mehlich-III soil test P in the top 5 cm for both the FB and SI treatments was 72 ppm, and the CN treatment was 18 ppm. Increased P loss associated with the application of P-containing fertilizers is widely documented in the literature with the addition of P fertilizer increasing P losses up to 1,500% compared to no P fertilizer controls depending on timing of runoff and soil conditions at time of fertilizer application (Sharpley and Rekolainen, 1997; Torbert et al., 1999; Smith et al, 2004a, Smith et al., 2004b, Smith et al. 2007; Li et al., 2020). Our study found application of P fertilizer increased P loss an average of 120% across all four years when compared to the control.

Decreased total P and DRP loss in the SI treatment relative to the FB treatment is likely a result of decreased interaction between runoff water and the P fertilizer. Subsurface placement of P fertilizer is a known management practice to reduce the risk of P loss in runoff and multiple studies confirm that subsurface placement or incorporation of applied fertilizers can help minimize nutrient loss (Sharpley et al., 1992; Baker and Laflen, 1982; Pote et al., 2006; Smith et al., 2016). Pote et al. (2006) found that incorporating P fertilizer decreased average total P concentration in runoff between 90-99% when compared to surface-broadcast P fertilizer application. Smith et al. (2016) found subsurface placement of P fertilizer also decreased total P load in runoff by approximately 97% compared to surface-broadcast P fertilizer application. These studies contrast with our study that found the SI treatment decreased total P loss an average of 20% compared to the FB treatment. Runoff in our study was from natural precipitation events, but Pote et al. (2006) utilized simulated rainfall to assess P loss from field plots at four days after P fertilizer application and Smith et al. (2016) utilized runoff boxes with simulated rainfall immediately following treatment implementation. Although looking at a single runoff event very close to fertilizer application and utilizing runoff boxes may provide mechanistic insight or serve as proof-of-concept, the data generated is not typical of actual field conditions that undergo dynamic changes over time as temperature and precipitation patterns vary relative to fertilizer timing, soil moisture, crop growth, and residue cover.

The decreased total P loss from the SI treatments relative to FB was mainly due to treatment effects on DRP loss. For example, in 2016 and 2017, the SI treatment had 560 and 210 g P/ha less total P loss, respectively, and 450 and 220 g P/ha less DRP loss, respectively, compared to FB. Baker and Laflen (1982) found that dissolved P concentrations from sub-surface applied P fertilizers were 86% less than from surface broadcast fertilizer. Kimmel et al (2001) found that sub-surface placement decreased DRP loss between 13% to 91% compared to surface broadcast. Zeimen et al. (2006) found sub-surface P placement decreased DRP loss by 0 to 82% relative to surface broadcast P. Our study found that annual DRP loss decreased by 5% to 51% over the 4-year period. Our fertilizer management treatments represent combined effects of timing, placement, and fertilizer source, which may explain why the DRP loss from the SI treatment was less than the effects of subsurface placement reported by other research studies. The first runoff event after P fertilizer application to the FB treatment ranged from 18 to 269 days whereas the first runoff occurring after P fertilizer application to the SI was 12 to 107 days. The longer time between fertilizer application and first runoff could decrease P losses from the FB treatment and thereby also potentially decrease the difference between P losses from FB and SI treatments.

There was not an observed effect of P fertilizer placement on DRP loss in 2018 because of the timing of precipitation and runoff relative to fertilizer application (Table S1). In the 2018 harvest year, fall broadcast fertilizer was applied on 28 November 2017, and spring injected fertilizer was applied on 9 May 2018, yet there were no runoff events from 16 October 2017 until 24 August 2018. As time after application increases, difference in nutrient loss from surface and subsurface applied soil amendments decreases (Mueller et al., 1984). Up to 75% of applied P fertilizer may adsorb to the soil and would therefore not be available for direct loss from fertilizer to runoff at 25 days post application with 50 to 65% of applied P being considered adsorbed within two days of application (Vadas et al., 2008; Williams, 1969).

Our initial hypothesis was that a cover crop may decrease P loss from fall broadcast P fertilizer; however, the addition of a cover crop to the fall broadcast P fertilizer treatment did not alleviate P loss associated with the surface broadcast application of P fertilizer, highlighting the importance of P fertilizer placement as a best management practice to reduce the risk of P loss.

Cover Crops

Decreased sediment loss from the cover crop treatment was likely due to increased soil cover and increased root biomass from the cover crop. From treatment establishment in fall 2014 through corn harvest in 2019, the cover crop treatment had a cumulative average of 6,378 kg/ha of additional residue deposited on the soil surface. A cover crop can decrease sediment loss and protect the soil surface through absorbing and dispersing raindrop energy, enhancing soil roughness, minimizing detachment of soil aggregates, postponing initiation time of runoff, slowing surface runoff velocity, and improving water infiltration (Blanco-Canqui et al., 2011). The benefits of utilizing a cover crop to reduce sediment loss are widely recognized in the literature, and cover crops are a frequently recommended BMP to help mitigate erosion losses (Kaspar et al., 2001; Morgan, 2005; Krutz et al., 2009; Blanco-Canqui, 2018).

It was noted through visual observation that previous corn and soybean residue had better retention in cover crop plots compared to the no cover plots. Cover crop biomass production in 2019 was the least of all four years (312 kg/ha), yet the minimal biomass produced likely improved residue retention and contributed to the smaller quantity of sediment lost from the cover crop treatment and may explain the decrease in total P loss observed in 2019. The decrease in erosion rate associated with adding a cover crop (69% reduction in erosion compared to NC) was the same in 2019 as in other years of this study (average reduction 68%) even though the cover crop produced little residue due to weather patterns plus planting and termination timing (Table S1). Although not quantified, it can be inferred that cover crop plots likely had greater root biomass, which may further have protected the soil from erosion. Although no-till is often regarded as a leading best management practice for reducing erosion (Siemans and Orschwald, 1976; Laflen et al., 1978; Mueller et al., 1984; Triplet and Dick, 2008; Verhulst et al., 2010), we found that adding a cover crop in a no-till system further reduced sediment loss by 60-80%. Findings from this study are similar to findings of Krutz et al. (2009) and Adler et al. (2020), where addition of cover crops in no-till systems decreased sediment loss by 65% and 41%, respectively. These results indicate that cover crops are an effective best management practice for reducing sediment loss even for situations where minimal sediment loss is expected, such as no-till production systems.

The effect of cover crops on annual total P loss was correlated to the sediment loss from the NC treatment (r^2=0.98; p=0.006), where cover crops decreased total P loss in 2019 when sediment loss was 4660 kg/ha, and cover crops increased total P loss in 2018 when sediment loss was 70 kg/ha but had no effect on total P loss in 2016 and 2017 when sediment loss was 1270 kg/ha and 180 kg/ha, respectively. The greater total P loss in 2018 and the smaller total P loss in 2019 resulted from the combination of cover crop effects on decreasing sediment loss while also increasing DRP loss. Phosphorus transport off agricultural fields can be generally categorized into dissolved P loss and particulate P loss, where less erosion typically results in less particulate P transport and loss. During the 2019 harvest year, significantly more sediment was lost compared to harvest years 2017 and 2018. Consequentially, the fraction of total P lost as DRP in harvest year 2019 was 23% for NC and 38% for CC, which was the least of all years in this study. However, in 2018, DRP loss was 68% and 77% of total P loss for NC and CC treatments, respectively. The greater total P loss in the cover crop treatment in 2018 is attributed to the greater DRP loss in runoff compared the small amount of sediment loss and subsequently small particulate P loss. This finding is similar to Aronsson et al. (2016) who linked lack of differences or increases in total P loss from multiple cover crop studies to higher losses of dissolved P in runoff.

The greater losses of DRP from the cover crop treatment in 2016, 2017, and 2018 demonstrate that the addition of a cover crop during normally fallow periods may have the unintended consequence of increasing DRP loading into surface waters. This is similar to multiple other studies that found cover crops increased DRP loss (Liu et al., 2013, 2014, 2019; Lozier and Macrae, 2017; and Kieta et al., 2018 but contrary to Adler et al. (2020) and Singh et al. (2018) who found cover crops decreased or had no effect on DRP loss. Those studies that had similar findings to our study attributed the effect to frozen cover crop biomass that released DRP into snowmelt runoff.

Numerous studies have focused on P loss in snowmelt runoff as a result of exposure of cover crop tissue to freeze-thaw conditions typical of northern climates where the research was conducted (Miller et al., 1994; Sturite et al., 2007; Riddle and Bergström, 2013, Liu et al., 2014 and 2019; Lozier and Macrae, 2017). When crop tissue is frozen, plant cells may experience expansion-induced lysis which damages the cell membrane resulting in an increase in potential P leaching from crop tissue (Thomashow, 1990; Øgaard, 2015). Miller et al. (1994) and Lozier and Macrae (2017) found that between 15-35% and up to 49% of total P within field-grown cold-acclimated cover crop tissue can be released as water extractable P after exposure to freeze-thaw conditions, respectively. These findings are similar to Carver et al. (2020) who examined non-cold acclimated, greenhouse-grown cover crops and found that approximately 30% of total P in the tissue may be released as water extractable P when tissue is exposed to one freezing event. These works highlight the potential impact of freezing conditions on cover crop contribution to DRP losses in runoff and suggest that freezing and thawing of cover crop tissue could explain observed increases in DRP loss when cover crops are added into an agricultural management system. However, climatic conditions at the KAW, and across much of the Central Great Plains, do not result in snowmelt runoff, and termination of small-grain cover crops, such as the triticale and winter wheat used in this study, via freezing is minimal.

Differences in DRP loss between the cover crop and no cover crop treatment for harvest years 2016, 2017, and 2018 could be explained by the cover crop tissue serving as a source of surface-applied P due to P release during the decomposition process since total P uptake of the cover crop (2016: 3.67 kg/ha; 2017: 6.37 kg/ha; 2018: 6.06 kg/ha) was greater than the increase in DRP loss between the cover crop and no cover crop treatments (2016: 0.288 kg/ha; 2017: 0.155 kg/ha; 2018: 0.251 kg/ha). Previously cited studies indicated that only a portion of total P within cover crop tissue may be released as water-extractable P. Liu et al. (2014) found the quantity of dissolved P in runoff to be only 12% of calculated dissolved P loss based on laboratory extracts of water-extractable P from cover crop tissue showcasing that only a fraction of water-extractable P released from cover crop tissue is exported from the field. Phosphorus in runoff may be adsorbed by the soil before it is transported out of the field (Elliott, 2013); therefore, it can be inferred that a portion of P released from cover crop tissue may also be adsorbed by the soil prior to transport out of the field.

There are other potential mechanisms that could explain the greater DRP loss from CC treatments such as cover crop effects on soil hydrological processes (Hallett et al., 2003). Cover crops may impact the quantity and/or duration of runoff from a field. Nelson et al. (2017) found that cover crops tended to increase the duration of runoff from a precipitation event suggesting increased contact time between runoff, soil, applied fertilizers, and crop tissue/residues. Increased time to runoff initiation has been linked to changes in subsurface soil properties along with greater surface residue associated with the addition of a cover crop (Krutz et al., 2009; Alberts and Neibling, 1994).

Water extractable P, an indicator of potential DRP concentration in runoff water, has been found to be directly influenced by the length of contact time with an extracting solution (Wang et al. 2010; Toor et al., 2006). Therefore, management practices that increase the length of runoff contact time with potential sources of P, such as soil, applied fertilizers, and/or crop tissue/residues, may result in greater concentrations of DRP in runoff and potential increased DRP losses from the field.

Results surrounding the impacts of cover crops on DRP losses are inconsistent across multiple studies suggesting the impact of cover crops on dissolved P loss may be influenced by a variety of factors including, but not limited to, climate, cover crop species, and management practices (Kleinman et al., 2005; Aronsson et al. 2016, Christianson et al., 2017; Kieta et al., 2018; Singh et al., 2018; Baulch et al., 2019). Our findings suggest that the observed increase in DRP loss from the cover crop treatment cannot solely be linked to P release from the cover crop tissue but is rather likely a reflection of the dynamic interplay between runoff, soils, applied fertilizers, and crop tissue/residue.

Conclusion

The sub-surface placement of P fertilizer at planting (SI treatment) reduced P loss from the field via surface runoff compared fall-broadcast fertilizer application (FB treatment), highlighting the importance of fertilizer management as a best management practice to reduce potential nutrient loss and protect water quality. Although the impact of fertilizer management on potential nutrient loss is well established, findings from this study re-emphasize the role that nutrient management practice plays in protecting surface water quality even when other conservation practices (such as no-till and cover crops) are implemented.

This study found that addition of a cover crop did not negate the potential negative impacts of broadcast P fertilizer application, suggesting that, although broadcast fertilizer application may offer producers a variety of advantages over sub-surface application, placing P fertilizer below the soil surface is a better option for reducing potential P loss compared to broadcast application with a cover crop.

A surprising finding from this study, and an unintended consequence of a widely recognized conservation practice, was the clear and consistent impact of cover crops on DRP concentrations and loads in runoff with cover crops increasing DRP loss in three out of four years of this study. Although the effect of cover crop on DRP loss was clear, cover crops had an inconsistent effect on total P loss. It is interesting to note that in years with high sediment loss (harvest year 2019), the cover crop treatment was able to decrease total P loss through reducing potential particulate P loss associated with erosion. This finding suggests that cover crops may serve as a practice to reduce P loss from areas highly susceptible to erosion. In areas where erosion is not a dominate concern, cover crops may unintentionally increase DRP loading into surface waters. Overall, cover crops should be viewed as a site- and task-specific conservation tool.

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Tables

Table 2.1 *P*-values for testing fixed effects for the analysis of data from Harvest Year 2016 through Harvest Year 2019. Table abbreviations include total suspended solids concentration (TSS), total phosphorus concentration (Total P), dissolved reactive phosphorus (DRP), annual sediment load (Sed Load), annual total phosphorus load (Total P Load), annual dissolved reactive phosphorus load (DRP Load), and total annual runoff (Q sum). Bolded values indicate signifiance at alpha = 0.05.

	Q sum	TSS	Total P	DRP	Sed Load	Total P Load	DRP Load
P Fertilizer Management	0.160	0.461	**<0.001**	**<0.001**	0.277	**0.001**	**<0.001**
Cover Crop	0.642	**<0.001**	0.478	**<0.001**	**<0.001**	0.910	**0.001**
P Fertilizer Management*Cover Crop	**0.032**	0.225	0.549	0.089	0.072	0.488	0.104
Harvest Year	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
P Fertilizer Management*Harvest Year	0.767	0.111	**<0.001**	**<0.001**	0.130	**<0.001**	**<0.001**
Cover Crop*Harvest Year	**0.006**	**<0.001**	**<0.001**	**<0.001**	0.143	**<0.001**	**<0.001**
P Fertilizer Management*Cover Crop*Harvest Year	0.713	**0.001**	0.590	**0.017**	**0.010**	0.891	0.218

Table 2.2 Main effects of phosphorus fertilizer management practice and cover crop on median concentrations of total suspended solids (TSS), total phosphorus (Total P), and dissolved reactive phosphorus (DRP) along with median sediment, Total P, and DRP loads in surface runoff. Values represent the back-transformed means. Letters represent differences within treatment at *p*<0.05.

Main Effect	TSS		Total P		DRP		Sediment		Total P Load		DRP Load	
	--------------------mg/L---------------------						---kg/ha---		--------------g/ha---------------			
Control	282	NS	0.49	C	0.16	C	348	NS	600	C	198	C
Fall Broadcast	239	NS	1.31	A	0.77	A	250	NS	1372	A	808	A
Spring Injected	250	NS	0.90	B	0.43	B	306	NS	1090	B	521	B
No Cover Crop	445	A	0.81	NS	0.29	B	525	A	959	NS	342	B
Cover Crop	148	B	0.85	NS	0.49	A	169	B	974	NS	557	A

Figures

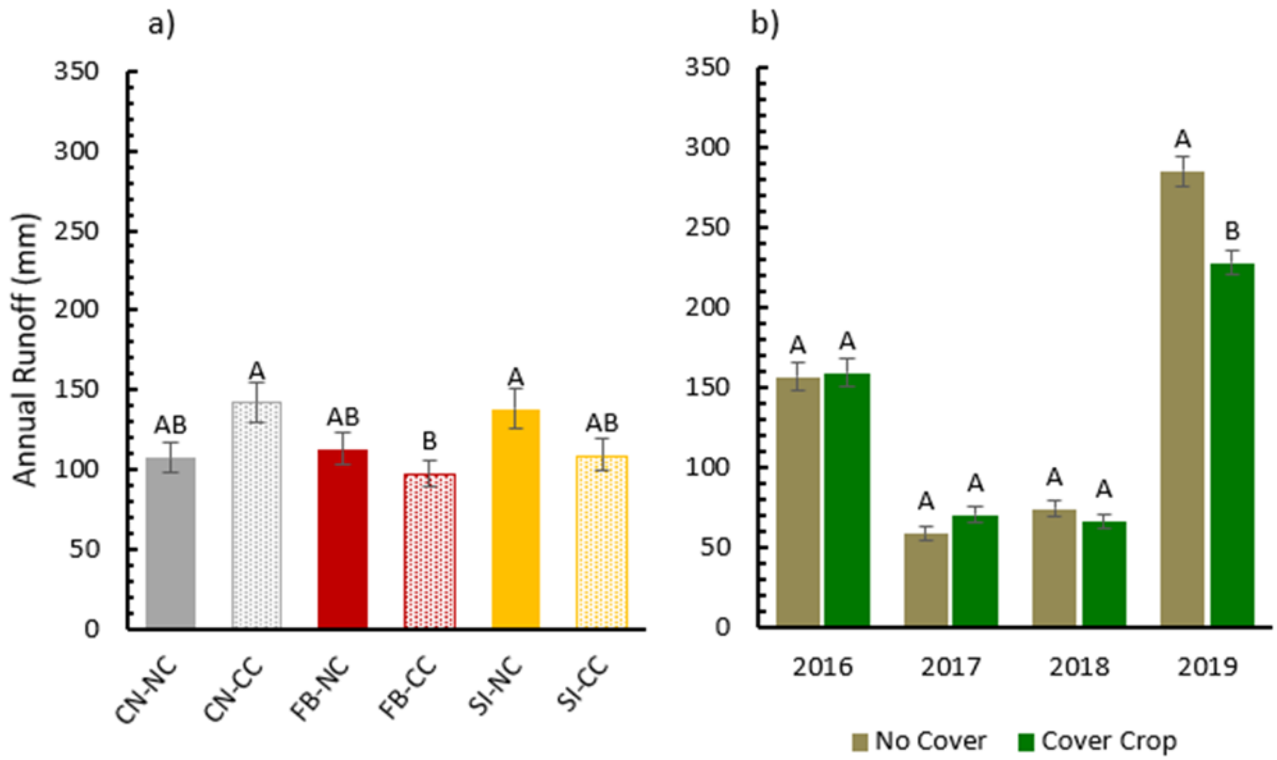

Figure 2.1 Phosphorus fertilizer management practice by cover crop interaction (a) and cover crop by harvest year interaction (b) for annual runoff. Letters represent differences between treatments (within year for b) at p<0.05 and error bars represent the standard error of the mean.

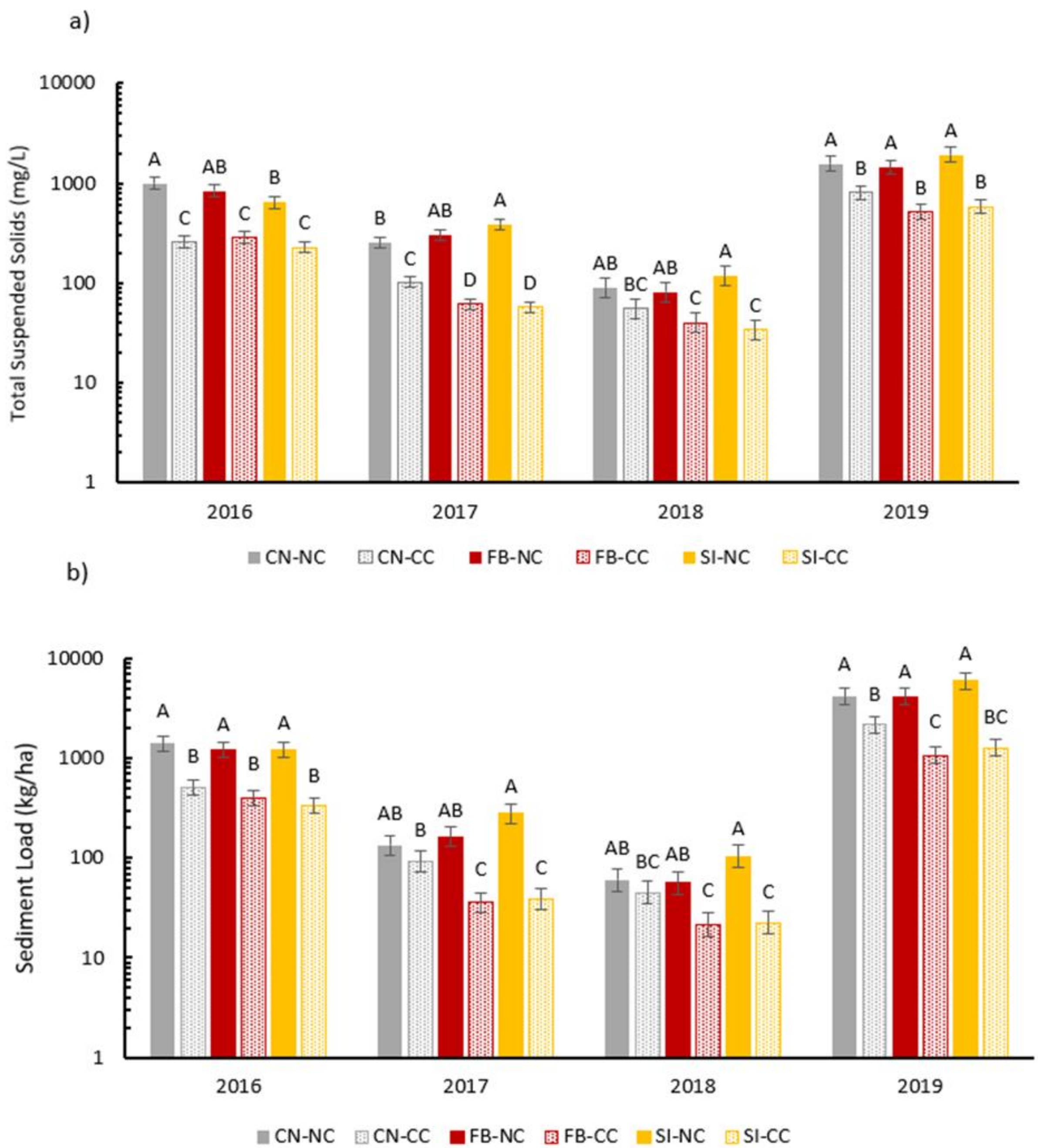

Figure 2.2 Phosphorus fertilizer by cover crop by harvest year interaction for flow-weighted annual average total suspended solids concentrations in surface runoff (a) and sediment load (b). Abbreviations include CN (control; 0 kg P_2O_5 /ha); FB (fall broadcast P fertilizer application; 61 kg P_2O_5/ha), SI (spring injected P fertilizer application, 61 kg P_2O_5/ha), NC (no cover crop), and CC (with cover crop). Letters indicated differences between treatments within harvest year at *p*<0.05 and error bars represent the standard error of the mean. Data depicted on log10 scale.

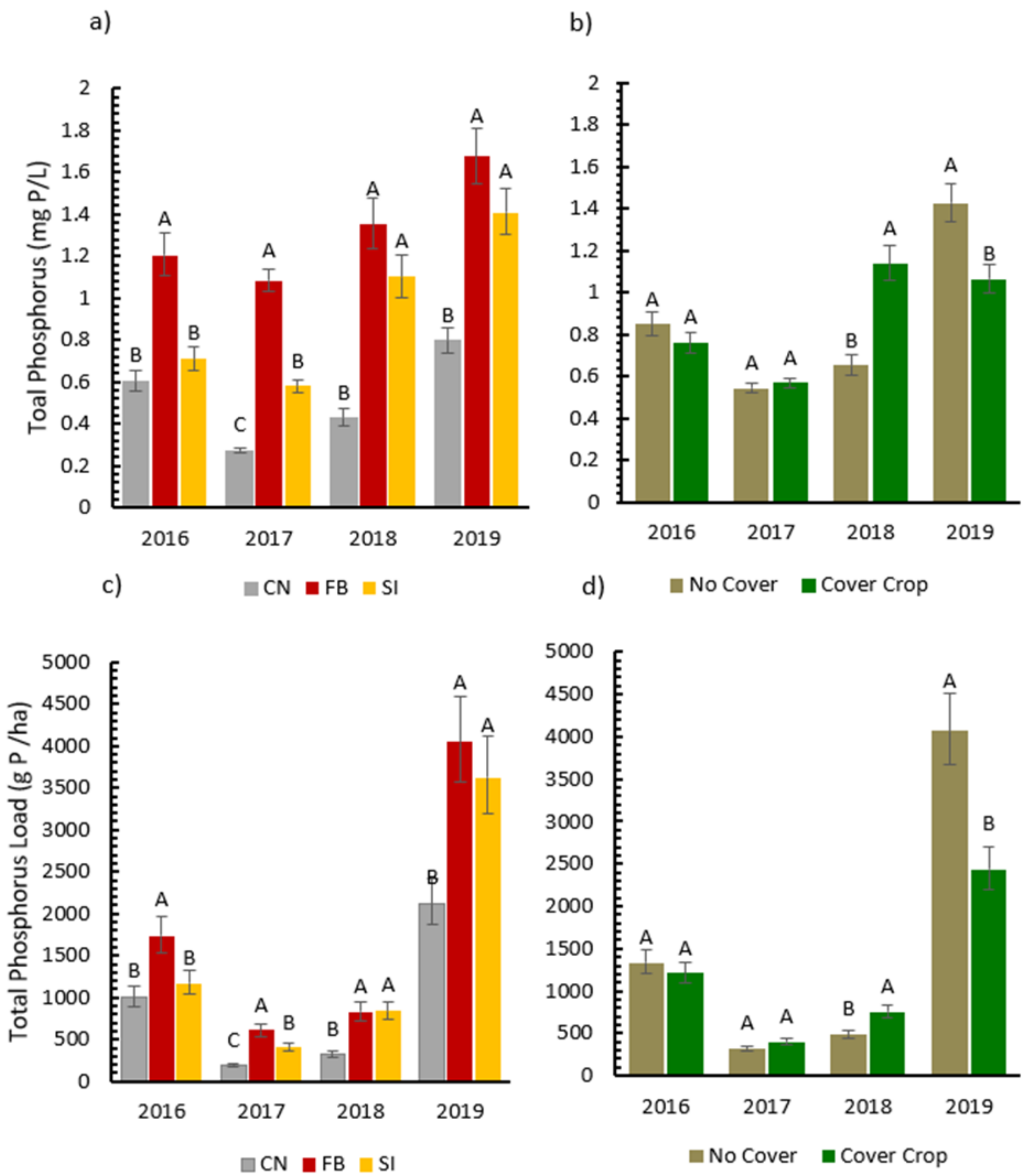

Figure 2.3 Phosphorus fertilizer management practice by harvest year interaction (a,c) and cover crop by harvest year interaction (b, d) on flow-weighted annual average total P concentration in surface runoff and total phosphorus load in runoff. Abbreviations include control (CN), fall broadcast (FB), and spring injected (SI). Letters represent differences between treatments within indicated harvest year at *p*<0.05 and error bars represent the standard error of the mean.

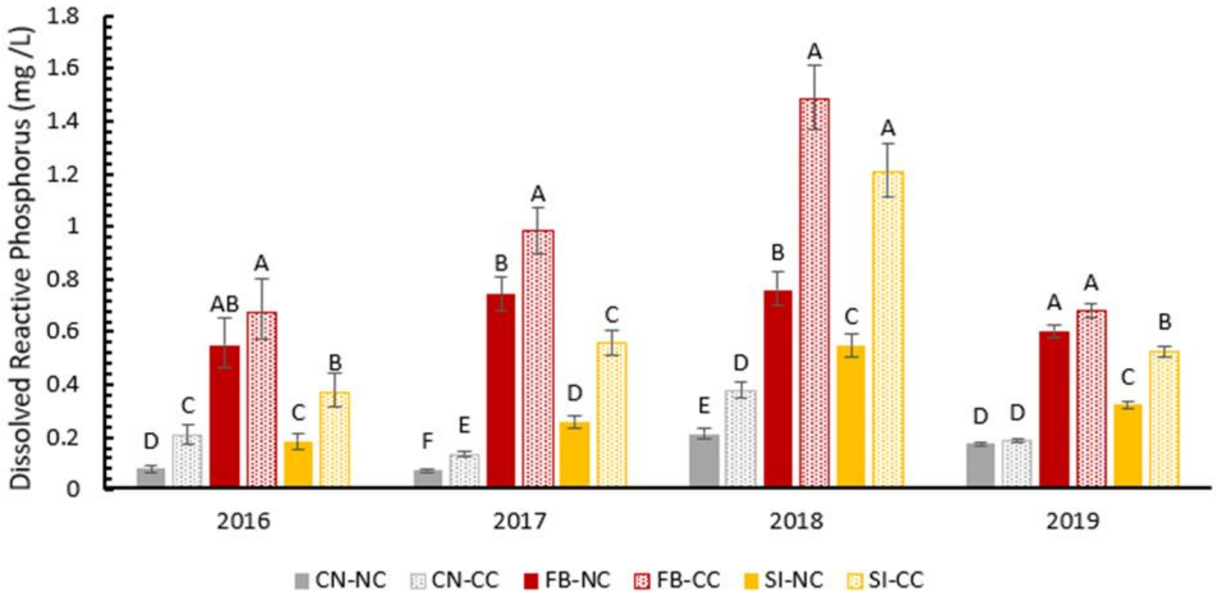

Figure 2.4 Phosphorus fertilizer management by cover crop by harvest year interaction for flow-weighted annual average dissolved reactive phosphorus concentration in surface runoff. Abbreviations include CN (control, 0 kg P_2O_5/ha), FB (fall broadcast, 61 kg P_2O_5/ha), SI (spring injected, 61 kg P_2O_5/ha), NC (no cover crop) and CC (with cover crop). Letters indicate differences between treatments within harvest year at *p*<0.05 and error bars represent the standard error of the mean.

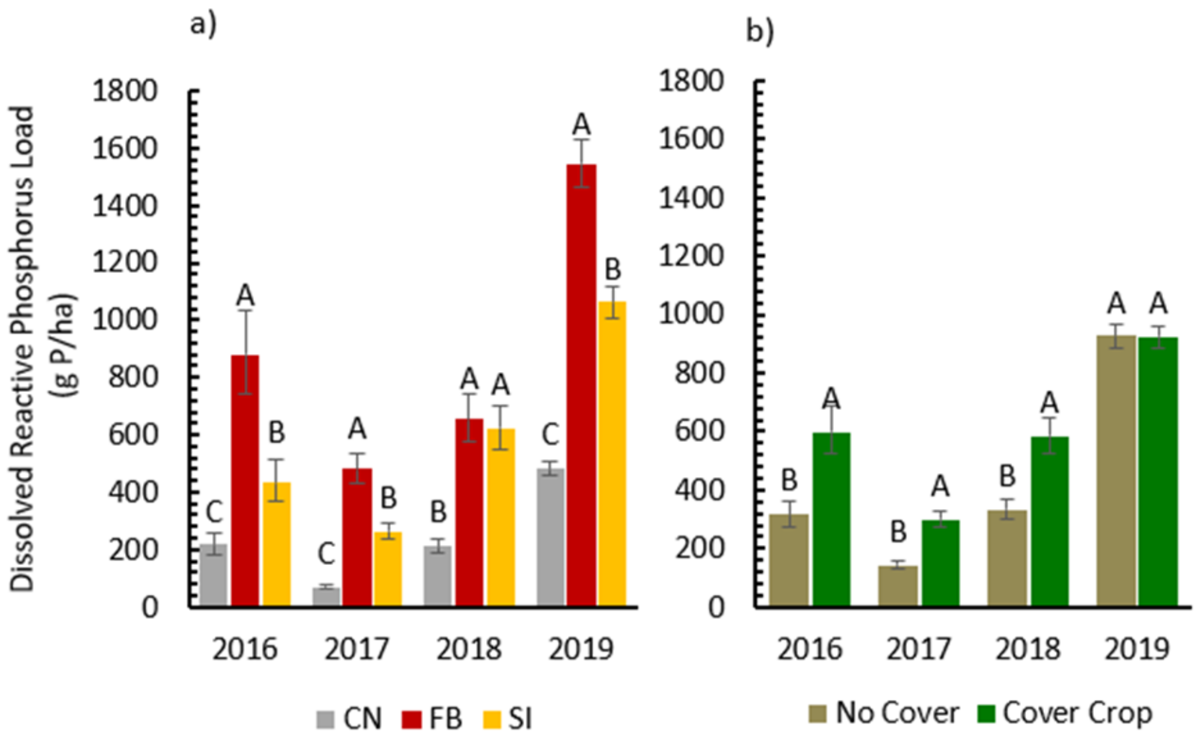

Figure 2.5. Phosphorus fertilizer management practice by harvest year interaction (a) and cover crop by harvest year interaction (b) on annual load of dissolved reactive phosphorus in surface runoff. Abbreviations used include: CN (control, 0 kg P_2O_5/ha), FB (fall broadcast, 61 kg P_2O_5/ha), SI (spring injected, 61 kg P_2O_5/ha). Letters represent differences between treatments within indicated harvest year at *p*<0.05 and error bars represent the standard error of the mean.

Chapter 3 - Temporal variations in surface runoff quality from a no-till corn-soybean rotation as impacted by phosphorus fertilizer management and a winter-grown cover crop

Introduction

Phosphorus (P) loss from agricultural production is a known challenge facing the environmental community. With an estimated 70% of all surface water inputs of P linked to non-point agricultural sources (Havlin et al., 2005), it is imperative to develop best management practices (BMP) which reduce the potential for P loss while protecting crop yields.

To help curb potential P loss from applied fertilizers, producers may choose to alter their application process and follow guidelines such as 4R Nutrient Stewardship which highlights the importance of selecting the right source, right rate, right placement, and right time of application of nutrients (Johnston and Bruulsema, 2014). Currently, recommendations for P fertilizer application suggest sub-surface applying P fertilizer close to planting-time can decrease the potential risk of loss commonly associated with unincorporated, surface applied nutrients (Johnston and Bruulsema, 2014). When compared to surface applied P fertilizer, the sub-surface application of P has shown to decrease both total and dissolved P loss by 30 and 75%, respectively (Kimmel et al., 2001). While sub-surface application of P fertilizer is known to reduce the potential for P loss, surface application of P fertilizer offers producers multiple advantages including lack of interference with other time sensitive field operations, greater equipment and labor availability, and cheaper fertilizer costs (Mallarino et al., 2009).

The Great Plains of the United States experience seasonal variation in precipitation with most of the precipitation occurring during the spring/summer growing season from April through

September (Rosenberg, 1987). The seasonal rainfall pattern across much of the Great Plains suggests that fall application of surface applied P fertilizer should decrease the risk of P loss due to low amounts of precipitation and, thus, a decrease in the potential transport of surface applied P away from the field. Recent work by Carver et al. (2022) comparing fall broadcast application of P fertilizer to spring injected application of P fertilizer found that fall broadcast applied P fertilizer exhibited greater annual P losses compared to spring injected P with the spring injected treatment having 19% less total P and 33% less DRP loss compared to the fall broadcast treatment. This work highlights the impact P fertilizer placement and timing may have on potential P loss and stresses importance of P fertilizer management in controlling P loss. Although Carver et al. (2022) demonstrated that spring injected application of P fertilizer decreased P loss compared to fall broadcast application, they found the spring injected treatment averaged approximately 67% greater P loss compared to the no P fertilizer control. To further develop fertilizer BMPs and better understand the dynamic changes of P loss throughout the growing season, additional information examining the temporal variability in surface runoff P concentrations is needed.

In addition to altering P fertilizer management practice to mitigate P loss, producers may choose to implement conservation practices such as the addition of a cover crop during a normally fallow period. Adding a cover crop may interrupt P transport pathways, improve water infiltration, and decrease erosion each of which may reduce potential P loss (Dabney, 1998; Dabney et al., 2001; Blanco-Canqui et al., 2015; Loss et al., 2015; Ruffati et al., 2019; Blanco-Canqui and Ruis, 2020) Findings from research investigating the impact of cover crops on P loss are inconsistent across the literature with multiple studies indicating that the addition of a cover crop increased P loss in both surface and/or sub-surface runoff (Liu et al., 2013, 2014, 2019;

Lozier and Macrae, 2017; Kieta et al., 2018; Hanrahan et al., 2021; Carver et al., 2022) while other studies indicate cover crops either decrease of have no impact on P loss (Her et al., 2017; Singh, et al., 2018; Adler et al., 2020). While the impacts of cover crops on P loss are variable across the literature, cover crops are a widely recognized BMP to help reduce erosion (Kaspar et al., 2001; Morgan, 2005; Krutz et al., 2009; Blanco-Canqui, 2018; Carver et al., 2022).

Carver et al. (2022) found the addition of a winter-grown cover crop to a no-till system reduced annual sediment loss by approximately 68%, but increased annual losses of DRP in three out of four years. As surface runoff moves across the field, smaller soil particulates are preferentially eroded compared to larger, more stable particulates (Yan et al., 2013). Fine soil particles often have enriched concentrations of P which may be more readily desorbed into surface runoff (Massey and Jackson, 1952; Sharpley, 1980). Since cover crops can decrease erosion, sediment lost from fields with cover crops may be dominated by finer soil particles with greater P concentrations which can maintain greater dissolved reactive P concentrations in runoff.

The loss of nutrients from a field is controlled by the combination of nutrient source and transport factors with the transport of nutrients being highly influenced by hydrologic processes that can vary across time based on site specific climatic conditions (Luo et al., 2008; Giri et al., 2014). Cover crops have variable impacts on soil chemical and physical properties throughout the year (Hanrahan et al., 2021), as such, it can be inferred that cover crops may have a variable effect on nutrient loss throughout the year. Multiple research studies assessing cover crop impacts on P loss have utilized simulated rainfall which only examines a specific timepoint during the cropping cycle (Bechmann et al., 2005; Kleinmann et al., 2005; Kovar et al., 2011; Liu et al., 2013; Miller et al., 1994). As such, research which examines the dynamic changes in runoff quality throughout the year resulting from cover crop addition is needed. Additionally, research examining the interactions between cover crops and P fertilizer management practice on a temporal scale would help producers develop BMPs to reduce P loss through identifying times of peak potential loss.

The objective of this research was to quantify the effects of P fertilizer management practice and a winter-sown cover crop on the temporal dynamics for concentrations of sediment and P in surface runoff generated by natural precipitation events for a no-till corn (*Zea mays*)-soybean (*Glycine max*) rotation.

Materials and Methods

Experimental Design

This study was conducted from 1 October 2014 through 31 September 2019 at the Kansas Agricultural Watershed (KAW) field laboratory located near Manhattan, KS, USA, and monitored surface runoff (Qt), total suspended solids (TSS), total phosphorus (total P), and dissolved reactive phosphorus (DRP) concentrations in edge-of-field surface runoff generated by natural precipitation events from a corn (*Zea mays*)-soybean (*Glycine max*) rotation. Three phosphorus fertilizer management practices, each with and without a winter-grown cover crop, were examined (CC: with cover crop; NC: without cover crop). Phosphorus fertilizer management practices included a no P fertilizer control (CN, 0 kg P_2O_5/ha), fall broadcast P (FB, 61 kg P_2O_5/ha) applied as diammonium phosphate (18-46-0), and spring injected P (SI, 61 kg P_2O_5/ha) applied as ammonium polyphosphate (10-34-0) placed 5 cm below and 5 cm to the side of the seed at planting. Treatments were structured in a 3 × 2 complete factorial, replicated three times (n = 18), and blocked by landscape position.

Field Site

Established in 2014, the KAW field lab contains eighteen, small-scale watersheds (i.e., plots) averaging 0.5 ha in size. Plots are delineated via the use of berms and terraces, are fitted with a 0.46-m H-flume and equipped with an automated water sampler (ISCO Teledyne 6700 or 6712 series with a 730 bubbler unit, Lincoln, NE). The dominant soil map unit is eroded Smolan silty clay loam (fine, smectitic, mesic Pachic Argiustoll) with 3-7% slope. The climate is hot, humid continental with a thirty-year average annual precipitation of 889 mm and a mean annual temperature of 12.9 °C. Over 95% off all precipitation events at this location occurred when mean temperature were above freezing. No surface runoff events resulting from snowmelt occurred during the course of this study.

Agricultural Management

The KAW field lab is managed under a no-till corn-soybean rotation where selections of corn hybrids, soybean cultivars, and seeding rates were based on regional recommendations. Historically, the KAW field lab was in a winter wheat (*Triticum aestivum*)-soybean rotation and managed using conventional tillage. The last tillage event occurred in November 2014. Soybean was grown during 2016 and 2018 while corn was grown during 2017 and 2019. Winter-grown cover crops were sown immediately following harvest of the main cash crop and were chemically terminated via herbicide application at/near planting of the following cash crop. Cover crop species varied throughout this study, based on time of planting and the following cash crop, and consisted of a small grain and brassica mix with the majority of cover crop biomass being produced by the small grain.

Application of P fertilizer to the P fertilized plots was performed annually at an application rate of 61 kg P_2O_5/ha. Application rate was calculated using a 5-year build and maintain P fertilizer recommendation with an average initial soil test of 17 ppm Mehlich-III P (Leikem et al., 2003). Further information outlining fertilizer application and agricultural management is detailed in Carver et al. (2022).

Water Quality and Analysis

Flow-weighted composite surface runoff samples were collected from all runoff events throughout the course of this study. For every 1 mm of runoff that passed through the H-flume, a 200 mL sample was collected and composted into a 10 L Nalgene carboy. All runoff samples were collected within 48 hours after runoff had ended with the vast majority of samples being collected within 24 hours of runoff cessation. After collection, all samples were stored a 4 °C until chemical analysis. All samples were analyzed within 21 days of collection with great effort to ensure chemical analysis was completed in less than 7 days after collection. A total of thirty-two precipitation events generating more than 2.0 mm of surface runoff were recorded during this study.

Concentration of TSS was determined gravimetrically via vacuum filtration of a 50-100 mL aliquot utilizing a pre-dried 0.45 µm filter (Csuros, 1997). A separate sub-sample was filtered using a 0.45 µm filter and the filtrate was then analyzed for DRP using the molybdate blue colorimetric procedure with an Alpkem Rapid Flow Analyzer (Alpkem method A303-S200-13). Concentration of total P was determined via potassium persulfate digest of a 1 to 10 mL sample at 120 °C for 60 minutes followed by the same analysis as detailed for DRP (Nelson, 1987).

Data Processing

Surface runoff samples were grouped into fertilization timespans and cover crop timespans to determine water quality effects of P fertilization management and cover crop management, respectively. The cover crop timespans were selected to examine the impacts of cover crop growth, termination, and decomposition on sediment and P concentrations within surface runoff. The three cover crop timespans were: i) cover crop planting until termination (cover crop growth timespan), ii) the 30 d following cover crop termination (termination timespan); and iii) from 30 d after cover crop termination to harvest of the main crop (corn or soybean) (decomposition timespan). The fertilization timespans were chosen to evaluate the effects of fertilizer application timing and method on surface runoff quality in systems with and without cover crops. The two fertilization timespans were: i) from application of the FB treatment until application of the SI treatment and ii) from application of the SI treatment until harvest of the main crop.

The flow-weighted mean concentration of TSS, Total P, and DRP in runoff for each timespan was computed for each experimental unit as follows. The total amount of runoff (Qt, mm) for each plot for a given timespan within harvest year was determined using the formula below.

$$\text{Qt at period i year j} = \sum_{\text{event k} \in \text{period i year j}} \text{Qt at event k}$$

The concentration (in mg/L) of TSS, Total P, and DRP for each plot for a given timespan within harvest year was derived using the formula below.

$$\text{Concentration at period i of year j} = \frac{\sum_{\text{event k} \in \text{period i year j}} \left(\text{Concentration at event k} \times \text{Qt at event k}\right)}{\sum_{\text{event k} \in \text{period i year j}} \text{Qt at event k}}$$

For DRP, five values were below quantification limit of 5 mg/L and were replaced by half of the quantification limit. Within a given event, the missing response of a plot was replaced by the geometric mean of responses of other plots in the same treatment group.

Data are presented from the 2016, 2017, and 2019 harvest years, which ran from September 22, 2015–October 19, 2016, October 20, 2016–September 20, 2017, and November 2, 2018–September 18, 2019, respectively. Due to drought in 2018, runoff did not occur for extended periods of time (no runoff events greater than 2.0 mm after 16 October 2018 until 24 August 2018) resulting in no data being collected for multiple cover crop and/or fertilizer timespans, therefore, data from the 2018 harvest year was removed from the analysis

Statistical Analysis

Data was first subjected to $\log_{10}$ transformation and then analyzed under the linear mixed model. Fixed effects of the model include replication, fertilizer management practice, cover crop, harvest year, timespan, and high order interactions among fertilizer practice, cover crop, harvest year and timespan except for those containing harvest-year-by-timespan interaction. Plot was the error term vector whose elements corresponded to the repeated measurements at three cover crop timespans (or two fertilizer timespans) over three harvest years. Variance-covariance structure of the error term was taken as the Kronecker product of the variance-covariance matric for harvest year (of type unstructured) and variance-covariance matrix for timespan (of type compound symmetry or unstructured) according to model fitting criteria and convergence status. Interactions between model fixed effects were examined using type III tests at the 0.05 level. Back-transformed least squares (LS) means and standard errors for fixed effects were reported. Pairwise comparisons between 2 levels of a fixed effect were performed based on the 2-sided test for non-zero difference in means (on the log scale). No multiplicity adjustment was applied. Statistical analysis was executed via Statistical Analysis Software (SAS version 9.4; Cary, NC) PROC MIXED with option DDFM=KR. Back-transformed means are presented in tables and figures.

Locally weighted regression was used to assess variability in DRP concentration in surface runoff relative to application of P fertilizer for the FB and SI treatments. Regression was performed using PROC LOESS in SAS.

Results

Cover Crop Timespans

Precipitation and Runoff

A total of 36 runoff events generating greater than 2.0 mm of surface runoff were analyzed during the course of this study. During the cover crop growth timespan, 8 runoff events were recorded with an average precipitation of 40.96 mm and average runoff of 15.26 mm (Table 3.1). Total runoff generated during the cover crop growth timespan was 122.08 mm. In the termination timespan, total of 12 events were recorded with an average precipitation amount of 36.85 mm and average runoff of 15.16 mm (Table 3.1). Total runoff received during the termination timespan was181.90 mm. For the decomposition timespan, 16 events were recorded with an average precipitation of 46.93 mm and average runoff of 14.54 mm (Table 3.1). Total runoff during the decomposition timespan was 232.67 mm. Runoff ratio (surface runoff measured:precipitation received) was determined for each cover crop timespan. The average runoff ratio for the cover crop growth timespan, termination timespan, and decomposition timespan were 0.33, 0.37, and 0.29, respectively (Table 3.1). The distribution of runoff events follows seasonal rainfall patterns of the Central Great Plains with fewer runoff events occurring during the dry-season of late-fall through winter and more runoff events occurring during the spring and summer.

Total Suspended Solids

Total suspended solids concentration was significantly impacted by cover crop timespan (Table 3.2). Concentrations of TSS during the termination timespan were approximately 108% greater than during the decomposition timespan and approximately 295% greater than during the cover crop growth timespan while TSS concentrations during the decomposition timespan were approximately 90% greater than during the cover crop growth timespan (Figure 3.1a). The addition of a cover crop decreased TSS concentrations by approximately 68% compared to the no cover crop treatment when surface runoff was grouped by cover crop timespan (Figure 3.1b).

Total Phosphorus

A two-way interaction between cover crop management practice and cover crop timespan was observed for total P concentrations in surface runoff (Table 3.2). During the cover crop growth timespan, the cover crop decreased concentrations of total P by approximately 42% compared to the NC treatment (Figure 3.2a). No differences between the NC and CC treatments were observed during the termination nor decomposition timespans.

Dissolved Reactive Phosphorus

A two-way interaction between cover crop management practice and cover crop timespan was observed for DRP concentrations in surface runoff (Table 3.2). Adding a cover crop increased DRP concentrations during the cover crop growth timespan, termination timespan, and decomposition timespan by approximately 57%, 92%, and 85%, respectively (Figure 3.4a). The two-way interaction is driven by the cover crop exhibiting a greater impact on DRP concentrations during the termination timespan compared to both the cover crop growth and decomposition timespans.

Fertilizer Timespans

Precipitation and Runoff

A total of 11 runoff events with greater than 2.0 mm of surface runoff were analyzed during the after FB and before SI timespan (Table 3.1). During post FB pre-SI timespan, the average precipitation received per runoff event was 41.25 mm and the average runoff generated was 14.86 mm (Table 3.1). Total generated runoff during the post FB pre-SI timespan was 163.51

mm. During the after-SI application through harvest timespan, a total of 25 runoff events were observed with an average precipitation amount of 42.95 mm and an average runoff of 14.93. (Table 3.1). For the after-SI application through harvest timespan, a total of 373.14 mm of runoff was measured. Average runoff ratios of the post-FB pre-SI timespan and the after-SI application through harvest timespan were calculated as 0.33 and 0.33, respectively.

Total Suspended Solids

A main effect of fertilizer timespan on concentrations of TSS was observed (Table 3.3). During the timespan from application of the SI treatment until harvest of the main crop, TSS concentrations were approximately 137% greater than the timespan from application of the FB treatment until application of the SI treatment (data not shown).

Total Phosphorus

The total P concentration in surface runoff was significantly impacted by a two-way interaction between P fertilizer management practice and fertilizer timespan (Table 3.3). This interaction showed that during the timespan after application of the FB treatment but prior to the application of the SI treatment, the FB treatment had approximately 187% greater total P concentrations compared to the SI treatment (Figure 3.2b). No differences between the FB and SI treatments were observed for the timespan after application of the SI treatment through harvest of the main crop. Total P concentrations from the CN treatment were less than those from the FB and SI treatments during both timespans; however, total P concentrations for the CN after application of the SI treatment through harvest of the main crop were approximately 75% greater than total P concentrations from the CN treatment during the timespan after FB application but prior to SI application (Figure 3.2b).

A two-way interaction between P fertilizer management practice and cover crop management practice was observed for total P concentration in surface runoff when data was averaged across fertilizer timespans (Table 3.3). Both the FB-NC and FB-CC treatments had approximately 66% greater total P concentrations in surface runoff compared both the SI-NC and SI-CC treatments (Figure 3.3). The addition of a cover crop to both the FB and SI methods of P fertilizer application did not impact total P concentration in surface runoff, yet the addition of a cover crop to the CN treatment reduced total P concentrations by approximately 32% (Figure 3.3).

Dissolved Reactive Phosphorus

A two-way interaction between P fertilizer management practice and fertilizer timespan was observed for DRP concentrations in surface runoff (Table 3.3). During both fertilizer timespans, the application of P fertilizer (FB and SI treatments) resulted in greater concentrations of DRP in surface runoff compared to the CN (Figure 3.4b). For the timespan after FB application but prior to SI application, the FB treatment had approximately 233% greater concentrations of DRP compared to the SI treatment while no difference in concentrations of DRP were observed between the FB and SI treatment during the timespan after SI application through harvest of the main crop (Figure 3.4b).

Days After Application

Local regression of DRP concentration in surface runoff relative to the number of days after P fertilizer application suggests the addition of a cover crop to both the FB and SI treatments may alter patterns of DRP concentration in surface runoff (Figure 3.5). For FB, the no cover crop treatment (FB-NC) appears to exhibit rapid decline in concentrations of DRP from 0 to 175 days after application with DRP concentrations then holding approximately steady (Figure

3.5). When a cover crop is added to the FB treatment (FB-CC), DRP concentrations appear to initially be lower than when a cover crop is not present (FB-NC), decline at a slower rate, yet, ultimately, maintain a greater concentration of DRP (Figure 3.5).

For the SI method of P fertilizer application, the addition of a cover crop also appears to increase concentrations and variability of DRP (Figure 3.5). The SI-NC treatment is the only treatment which exhibited a steady increase in predicted concentrations of DRP (Figure 3.5). Although the addition of a cover crop increased DRP concentration for the SI treatment, both the SI-NC and SI-CC treatments exhibited lower concentrations of DRP in surface runoff compared to the FB method of P fertilizer application

Discussion

Total Suspended Solids

The main effect of cover crop on reduced TSS concentrations can be linked to the demonstrated ability of cover crops to decrease raindrop erosivity, facilitate infiltration, and modify/obstruct preferential flow paths of surface runoff by increasing the amount of surface residue cover and root biomass (Endal et al., 2014; Blanco-Canqui, 2018; Carver et al., 2022). By the end of this study, the soil surface of the cover crop treatments received, on average, an additional cumulative 6378 kg/ha plant biomass compared to the no cover crop treatments. The deposition of additional residue likely resulted in increased surface roughness, slower runoff velocities, and decreased detachment of soil aggregates each of which are recognized as mechanisms to decrease erosion losses (Blanco-Canqui et al., 2011). Reduction in concentration of TSS within surface runoff resulting from the addition of a cover crop during a normally fallow period is widely document in the literature (Kaspar et al., 2001; Morgan, 2005; Krutz et al., 2009; Blanco-Canqui, 2018; Carver et al., 2022); however, it is interesting to note the addition of a cover crop further reduced TSS concentration in surface runoff even from the inherently low sediment loss no-till management system used at the KAW field laboratory. Sediment loading into surface waters is a leading cause of decreased surface water quality (U.S. EPA, 2003), and results from this study indicate that, for areas where sediment loss is a chief water quality concern, adding a cover crop may improve water quality.

The main effect of cover crop timespan on TSS concentration may be linked to seasonal variation in field conditions when runoff events occurred. In Kansas, and across much of the Central Great Plains, climatic conditions are such that soil may undergo freezing and thawing cycles as the temperature fluctuates. Concentrations of TSS in surface runoff are generally lower from fields undergoing freezing and thawing compared to runoff from times of the year when soils are not frozen and may partially explain the low TSS concentration during the cover crop growing period (Good et al., 2019).

The elevated TSS concentration observed for the 30 days following termination of the cover crop (termination timespan) may be linked to the frequency and/or intensity of rainfall events which occurred during this period. When frequent rainfall occurs, soils are more likely to become saturated compared to periods of time with less frequent rainfall events (Calvo-Cases et al., 2003). As hydrologic conditions in the soil change and soil saturation increases, fields may therefore become more susceptible to runoff and the subsequent transport of sediment (An et al., 2011; Lu et al., 2016). In the Central Great Plains, surface runoff is more likely to occur during springtime compared to fall due to springtime being typically wetter than the fall and soils being drier in the fall due to crop removal of soil moisture (Changnon et al., 2013; Yuan et al., 2018). The large concentrations of TSS during the termination timespan suggest that controlling sediment loss during this period is critical for protecting water quality.

Phosphorus

Elevated concentrations of total P during the termination timespan can be linked to the large concentrations of TSS also observed during this period. Phosphorus loss from agricultural fields can be grouped into soil-bound particulate and dissolved forms with soil-bound P often being considered the dominant from of P loss from the field via erosion (Sharpley and Rekolainen, 1997; Hart et al., 2004; Gburek et al., 2005). In a joint study, Carver et al. (2022) found that annual total P loss was directly correlated to sediment loss for the no cover crop treatment ($r^2 = 0.98$; $p = 0.006$) thus explaining the linkage between elevated TSS and elevated TP concentrations.

Lack of difference between the NC and CC treatment during the termination timespan for total P is likely due the impact of adding a cover crop (i.e., the CC treatment) on concentrations of DRP. This is similar to findings by Carver et al. (2022) and Aronnson et al. (2016) who each identified increased or lack of difference in total P loss resulting from the addition of cover crop to be linked to cover crop effects on DRP. During the termination timespan, DRP concentrations from the CC treatment account for approximately 35% of total P while DRP concentration from the NC treatment account for approximately 18% of total P concentration.

During the cover crop growth timespan, concentrations of total P from the CC treatment were directly driven by DRP concentrations with DRP accounting for nearly 100% of the total P concentration. This contrasts with NC treatment where DRP accounted for approximately 45% of the total P concentration. Since total P measures both dissolved and particulate-bound P, it can be inferred that the greater observed total P concentrations for the NC treatment is due to the presence of particulate-bound (i.e., sediment-bound) P. This finding suggests that the ability of a cover crop to decrease total P loss is driven by the cover crop impact on erosion. This is similar to findings by Carver et al. (2022) who demonstrated in years with high sediment loss, cover crops can decrease total P loss through reducing the quantity of sediment lost from the field. The effect of cover crop on DRP and TSS also explains why when runoff is grouped according to fertilizer timespan that the CC treatment has lesser concentrations of TP compared to the NC treatment during the time following FB application yet similar concentrations of TP after SI application throughout the remainder of the cash crop growing season.

Subsurface placement of P fertilizer is a known and commonly recommended practice to curb potential P loss associated with the application of P containing fertilizers (Johnson and Bruulsema, 2014; Kimmel et al., 2011), and Carver et al. (2022) found spring injected APP generally had 19% less total P and 33% less DRP loss compared to fall broadcast DAP. The work by Carver et al. (2022) found that annual runoff losses were the same between the FB and SI treatments indicating that differences in losses of total P and DRP must be related to differences in concentration of those variables within the surface runoff. For the termination timespan, decomposition timespan, and after SI application through harvest, concentrations of total P were similar between the FB and SI treatments. Differences in total P concentration between the FB and SI treatments were observed for the cover crop growth timespan and after FB application before SI. Concentrations of total P from the FB treatment during both the cover crop growth timespan and the period after FB before SI were found to be 187% and 232% greater than total P concentration from the SI treatment, respectively. The difference in total P observed between the FB and SI treatments during these two, over-lapping, late season timepoints can be inferred to be the driving force behind the identified differences in total P loss observed by Carver et al. (2022).

Days After Application

The use of both FB and SI treatments in this study present a unique opportunity to examine the “best-case scenario,” (in relation to precipitation patters, equipment specification, fertilizer costs, and labor availability) for each method of P fertilizer application and how these treatments may impact water quality. When comparing patterns of DRP concentration from the FB and SI treatment in relation to days after P fertilizer application, it is important to acknowledge that these two treatments represent changes in P placement, source, and timing.

The elevated concentrations of DRP for the FB treatment observed for the few months following application can be primarily explained by the fact that in no-till systems, surface applied fertilizers remain on the soil’s surface where they can readily interact with surface runoff and highlights the importance of P fertilizer placement in protecting water quality. Surface application of P in no-till systems can lead to elevated P concentrations near the soil surface and ultimately lead to greater potential P loss as surface runoff interacts with this zone of high P concentration (Gbruek and Sharpley, 1998; Ulèn et al., 2001). To help mitigate the potentially negative impact of surface broadcasting P fertilizers, producers may choose to place P fertilizers below the soil surface. The subsurface placement of P fertilizer is a widely recommended BMP to help curb potential P loss through decreasing the interaction of surface runoff with applied P fertilizers (Sharpley et al., 1992; Smith et al., 2016). Additionally, subsurface placement of P has shown to improve potential P availability for crop uptake and is considered a more efficient method of P fertilization (Randall and Hoeft, 1988; Alam et al., 2018).

Without a cover crop, the predicted concentration of DRP in surface runoff from the FB treatment is consistently greater than the SI treatment at equal points after application ranging from over 640% greater at 18 days after application to approximately 107% greater at 154 days after application (Figure 3.5). Similar trends are observed between the FB and SI treatments when a cover crop has been added, albeit differences between the two treatments are much less than without a cover crop; however, the 95% lower confidence interval for the FB and the 95% upper confidence interval overlap from 0 through 154 days after fertilizer application (Figure 3.5).

When a cover crop was added to the FB treatment (FB-CC), initial predicted concentrations of DRP were less than the FB-NC treatment and predicted levels of DRP decrease at a slower rate from 0 to 175 days after application. After approximately 175 days after application, change in DRP concentration for the FB-NC appears minimal possibly due to P uptake by the recently planted cash crop. Concentrations of DRP from the FB-CC treatment appear to be more variable compared to the FB-NC potentially due to cover crops' ability to modify the soil environment along with translocating and redepositing soil P from deeper within the profile (Kovar et al., 2011; Hallalama et al., 2019).

Lesser concentrations of DRP from the SI-NC compared to the FB-NC treatment is due to placement of the SI fertilizer with subsurface placement of P fertilizer being known to reduce concentrations of DRP in surface runoff compared to surface broadcast P application (Smith et al., 2017; Carver et al. 2022). As with the FB treatment, when a cover crop was added to the SI method of P fertilizer application, observed concentrations of DRP appear to be more variable. Additionally, the SI-CC treatment tended to have greater concentrations of DRP compared to the SI-NC treatment. The increased in DRP concentration for the SI-CC may be due to cover crops' ability to solubilize traditionally recalcitrant forms of P in the soil, modifying rhizosphere conditions, or release of compounds which may mineralize organic-P (Hallama et al., 2019).

Conclusion

Findings from this study emphasize the importance of P placement in protecting water quality and highlight the dynamic changes in concentrations of P and sediment in surface runoff throughout the year. The broadcast application of P in the fall, the time of year which should minimize potential P loss based on precipitation patterns in the Central Great Plains, led to greater concentrations of P in runoff compared to subsurface placement of P closer to cash crop plantings, suggesting that even in periods of low loss potential, surface application of P fertilizers in a no-till system still poses substantial environmental risk compared to subsurface placement.

The elevated concentrations of TSS observed during the 30 days following cover crop termination indicate this is a critical period and suggests that development of agricultural management practices specifically aimed at reducing sediment loss during this time may improve water quality and further mitigate erosion losses. Reduction of erosion losses during periods of heavy TSS concertation may also lead to decreased total P loss as sediment-bound P is retained in the field. The demonstrated ability of cover crops to reduce TSS concentration emphasizes their potential roll in curbing P loss in areas prone to erosion. However, in areas where erosion is not a primary concern, cover crops may unintentionally increase P loss through increased concentrations of DRP being carried with surface runoff.

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Tables

Table 3.1. Precipitation and runoff event descriptions separated by cover crop timespan and fertilizer timespan. Cover Crop Timespans include cover crop growing season (1); 30 days following termination of the cover crop (2); and from 30 days after cover crop termination until harvest of the main cash crop (3). Fertilizer Timespans include after fall broadcast application of P fertilizer prior to spring injected application of P fertilizer (1) and after spring injected application of P fertilizer until harvest of the main cash crop (2).

Cover Crop Timespan	Fertilizer Timespan	Date	Precipitation	Runoff	Runoff Ratio
			------------mm-------------		
1	1	1-Dec-15	16.51	5.00	0.30
1	1	15-Dec-15	57.15	18.70	0.33
1	1	25-Apr-16	52.32	18.02	0.34
1	1	27-Apr-16	74.93	40.65	0.54
1	1	31-Mar-17	54.61	20.73	0.38
1	1	3-Apr-17	18.29	4.46	0.24
1	1	6-Apr-17	32.26	12.15	0.38
1	1	25-Feb-19	21.59	2.37	0.11
2	1	25-May-16	34.67	2.15	0.06
2	1	26-May-16	20.45	4.34	0.21
2	1	27-May-16	50.88	34.94	0.69
2	2	20-May-17	17.02	5.31	0.31
2	2	27-May-17	19.05	4.42	0.23
2	2	7-Aug-17	84.58	20.68	0.24
2	2	7-May-19	23.37	18.53	0.79
2	2	8-May-19	50.29	47.05	0.94
2	2	9-May-19	42.67	4.62	0.11
2	2	13-May-19	16.26	2.81	0.17
2	2	19-May-19	55.37	17.60	0.32
2	2	22-May-19	49.02	19.45	0.40
3	2	13-Jul-16	50.80	10.70	0.21
3	2	20-Aug-16	46.74	3.27	0.07
3	2	25-Aug-16	37.59	8.34	0.22
3	2	26-Aug-16	26.92	11.22	0.42
3	2	14-Sep-16	57.91	2.13	0.04
3	2	11-Oct-16	17.02	2.17	0.13
3	2	24-Aug-18	45.21	14.88	0.33
3	2	3-Sep-18	75.18	23.86	0.32
3	2	6-Sep-18	22.35	6.98	0.31
3	2	10-Oct-18	58.93	17.77	0.30
3	2	27-May-19	17.78	4.91	0.28
3	2	24-Jun-19	65.79	28.13	0.43
3	2	5-Jul-19	51.56	4.54	0.09
3	2	16-Aug-19	44.70	19.24	0.43
3	2	26-Aug-19	50.04	18.53	0.37
3	2	30-Aug-19	82.30	56.00	0.68

Table 3.2. ***P*-values for the analysis of data collected during cover crop timespans throughout the 2016, 2017, and 2019 harvest years. Table abbreviations include total suspended solids concentration (TSS), total phosphorus concentration (TP), dissolved reactive phosphorus concentration (DRP), fertilizer management practice (Fertilizer), cover crop management practice (Cover), and. Bolded values indicate significance at alpha = 0.05.**

	Cover Timespan		
	TSS	TP	DRP
Cover	**<0.001**	0.345	**<0.001**
Timespan	**<0.001**	**<0.001**	**<0.001**
Fertilizer*Cover	0.327	0.094	**0.025**
Cover*Timespan	0.193	**0.023**	**0.025**
Fertilizer*Cover*Timespan	0.428	0.306	0.697

Table 3.3. ***P*-values for the analysis of data collected during fertilizer timespans throughout the 2016, 2017, and 2019 harvest years. Table abbreviations include total suspended solids concentration (TSS), total phosphorus concentration (TP), dissolved reactive phosphorus concentration (DRP), fertilizer management practice (Fertilizer), cover crop management practice (Cover), and. Bolded values indicate significance at alpha = 0.05.**

	Fertilizer Timespan		
	TSS	TP	DRP
Fertilizer	0.244	**< 0.001**	**< 0.001**
Timespan	**< 0.001**	**0.025**	**< 0.001**
Fertilizer*Cover	0.246	**0.047**	0.151
Fertilizer*Timespan	0.925	**< 0.001**	**< 0.001**
Fertilizer*Cover*Timespan	0.336	0.313	0.368

Figures

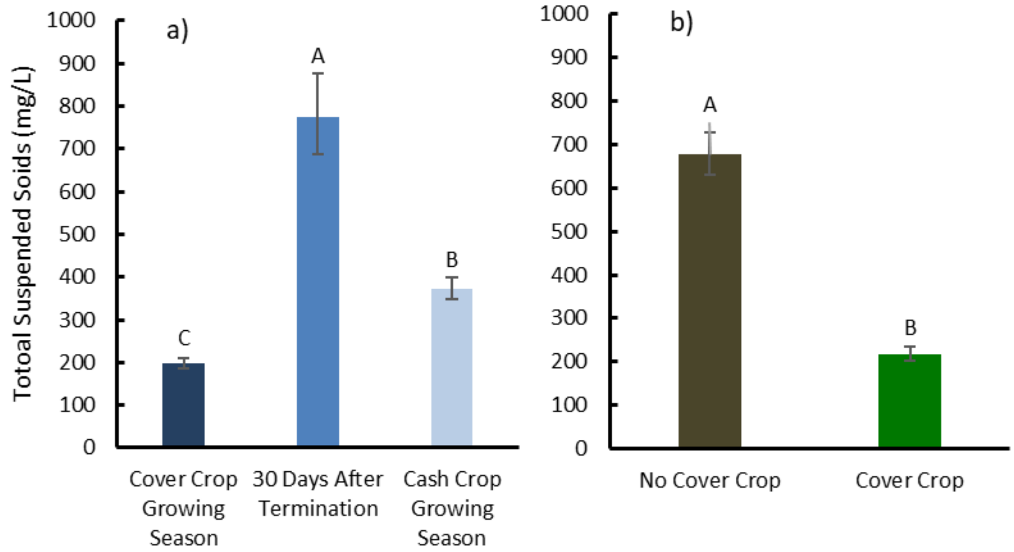

Figure 3.1 Main effects of cover crop timespan (a) and cover crop (b) on total suspended solids concentration in surface runoff at KAW field laboratory located near Manhattan, KS, USA. Letters represent significant differences at alpha = 0.05 and error bars represent standard error of the mean.

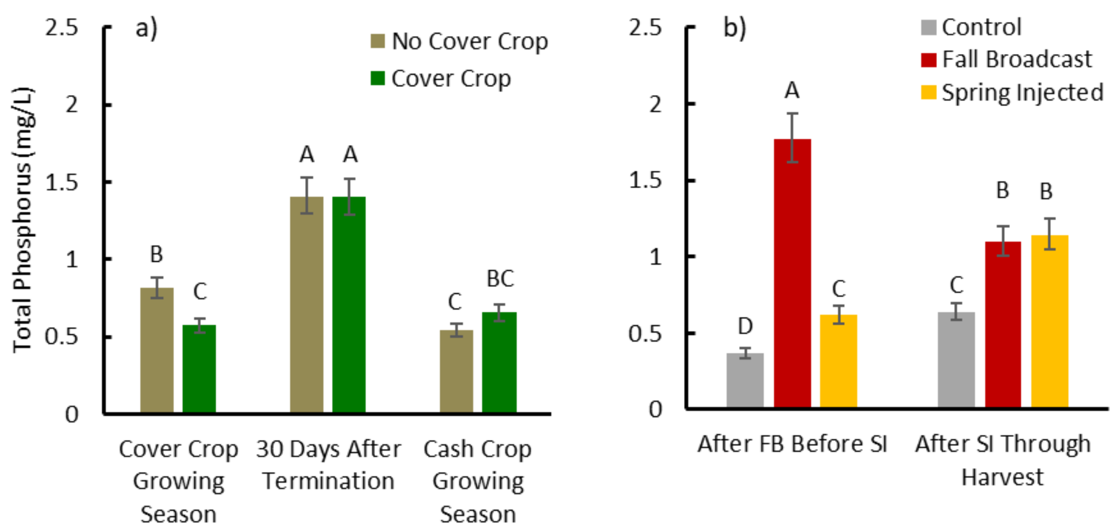

Figure 3.2 Cover crop management practice by cover crop timespan interaction (a) and fertilizer management practice by fertilizer timespan (b) interaction for total phosphorus concentration in surface runoff from the Kansas Agricultural Watershed field laboratory. Letters represent significant differences between treatments at alpha = 0.05 and error bars represent standard error of the mean.

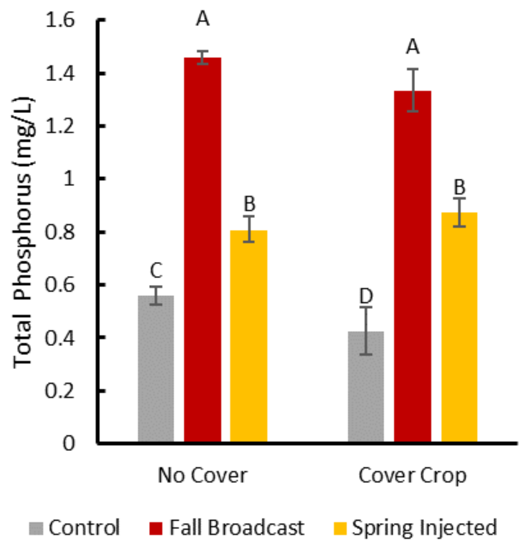

Figure 3.3 Fertilizer management practice by cover crop interaction for total phosphorus concentration in surface runoff from Kansas Agricultural Watershed field laboratory when grouped by fertilizer timespan. Letters indicate differences between treatments at alpha = 0.05 and error bars represent the standard error of the mean.

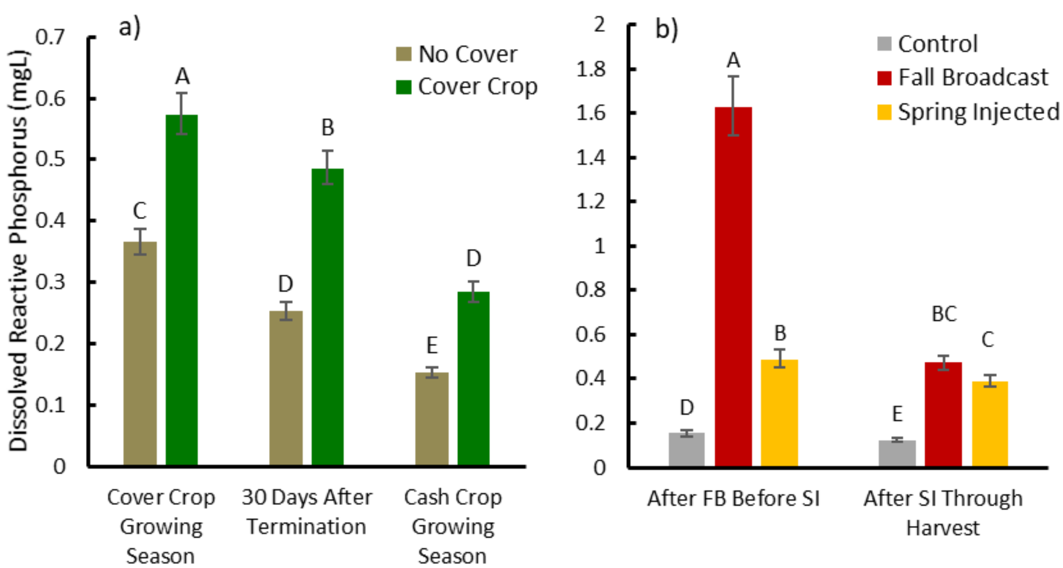

Figure 3.4 Cover crop management practice by timespan interaction for dissolved reactive phosphorus in surface runoff for cover crop timespans (a) and phosphorus fertilizer management practice by timespan interaction for fertilizer timespans (b). Letters represent significant differences at alpha = 0.05 and error bars represent the standard error of the mean.

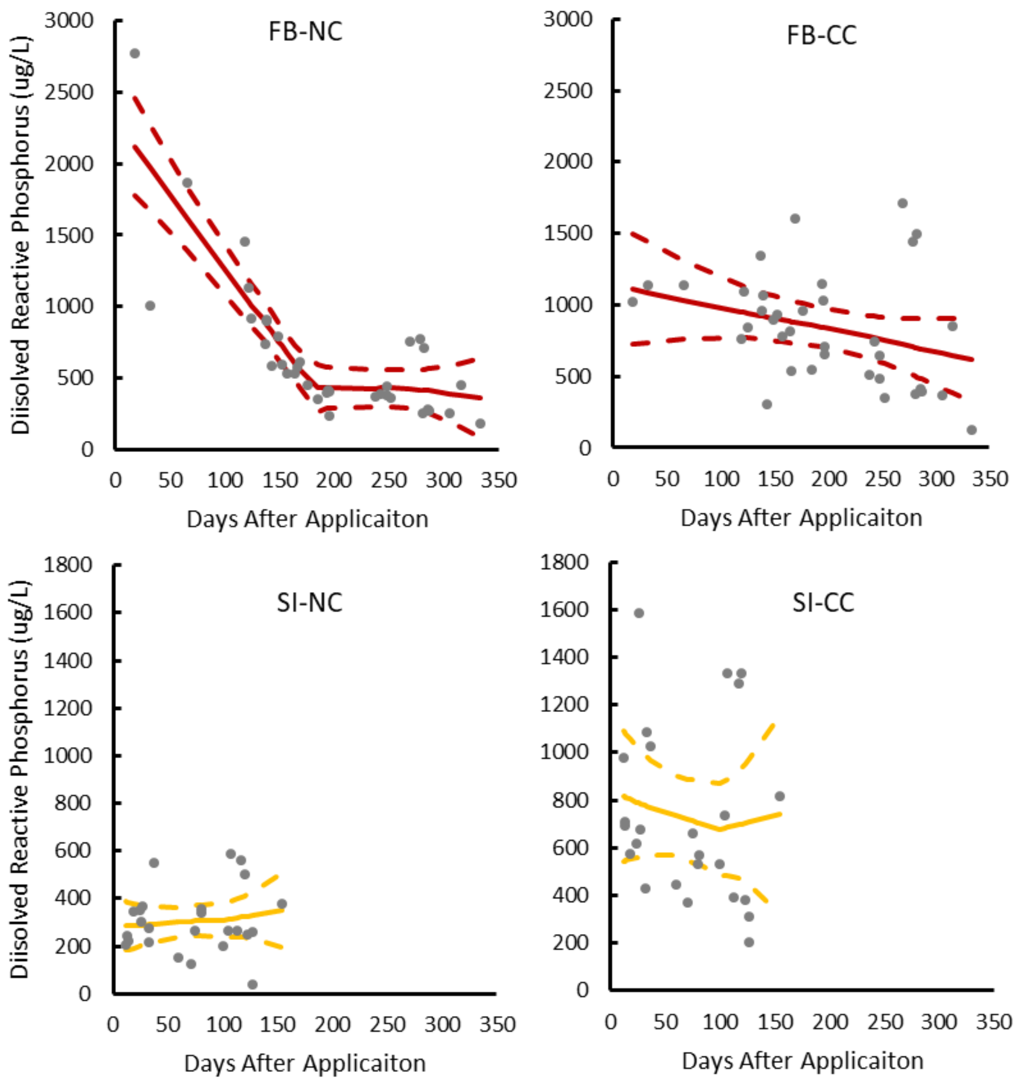

Figure 3.5 Effect of time after fertilizer application on concentration of dissolved reactive phosphorus in surface runoff from the Kansas Agricultural Watershed field lab. Dots represent actual measured concentration of surface runoff collected the indicated number of days after phosphorus fertilizer application, solid lines represent predicted concentration based on Loess regression, and dashed lines represent the 95% confidence interval of the predicted value. Abbreviated used include fall broadcast application of phosphorus fertilizer (FB), spring injected application of phosphorus fertilizer (SI), no cover crop (NC), and with cover crop (CC).

Chapter 4 - Phosphorus fertilizer management and cover crop impact on soil fertility in a no-till corn-soybean rotation

Introduction

When P fertilizers are applied to soils, soil test P (STP) concentrations may increase, increasing the potential risk of P loss from the field as particulate-bound P and dissolved P are carried away with surface runoff (Reddy et al., 1999; Withers et al., 2014; Hao et al., 2008). As STP concentrations near the surface increase, concentrations of P in surface runoff may also increase, leading to potentially greater losses of P from the field (Romkens and Nelson, 1974). Diffusion, dissolution, and desorption reactions within the top 0-5 cm of soil control the incorporation of P into surface runoff (Sharpley, 1985; Hansen et al., 2002). To mitigate potential P loss, producers may implement a variety of best management practices (BMP), including 4R Nutrient Stewardship, which emphasizes the importance of utilizing the right source, rate, placement, and timing of nutrient application (Bruulsema et al., 2009). Currently, P fertilizer BMPs recommend sub-surface application close to planting time to help reduce potential P loss (Johnston and Bruulsema, 2014). Numerous studies emphasize the role P fertilizer placement has in reducing potential P loss via surface runoff (Baker & Laflen, 1982; Mostaghimi et al., 1988; Zeimen et al., 2006; Yuan et al., 2018; Wiens et al., 2019, Carver et al., 2022). For no-till systems, the subsurface placement of P fertilizers may decrease bioavailable P losses by almost 70% compared to surface broadcast P fertilizer application (Kimmel et al., 2001).

While sub-surface placement of P close to planting (i.e., springtime for summer grown crop) offers potential reduction in P loss via surface runoff, surface-broadcast application of P during the fall offers producers a variety of benefits including typically lower fertilizer costs, increased labor and/or equipment availability, and minimal interference with other field operations (Mallarino et al., 2009). The majority of precipitation events in the Great Plains occurs between April and September with drier periods occurring throughout the fall and winter months suggesting that fall application of P fertilizer would likely minimize potential P loss via surface runoff.

To help curb the movement of soil and sediment-associated P away from the field, producers may include a cover crop as part of their agricultural management strategy. Adding a cover crop could alter P loss via improving water infiltration, disrupting P transport pathways, and minimizing erosion losses (Dabney, 1998; Dabney et al., 2001; Blanco-Canqui et al., 2015; Loss et al., 2015; Ruffati et al., 2019, Blanco-Canqui and Ruis, 2020). Data surrounding the impacts of cover crops on P loss are inconsistent and contrasting across the literature with some studies indicating addition of a cover crop had no effect on total and/or dissolved P loss, some observing increases, and others observing decreases (Aronsson et al. 2016, Christianson et al., 2017; Kieta et al., 2018; Baulch et al., 2019, Macrae et al., 2021; Carver et al., 2022). Cover crops have been found to potentially increase concentrations of bioavailable P near the soil surface, which may increase P loss via surface runoff (Cavigelli and Thein, 2003; Eichler-Löbermann, 2008; Wang et al, 2021). Information linking the relationship between cover crops and P fertilizer management with regards to STP concentrations is pivotal in developing agricultural BMPs to protect water quality.

While P fertilizer management practices and cover crop use have each been studied on an individual basis, information linking them and their potential impact on soil fertility is limited. Smith et al. (2017) examined effects of surface broadcast P fertilizer plus cover crop on soil test P compared to subsurface injection of P without cover crop; however, their study did not include a subsurface injected plus cover crop treatment. Understanding the interplay between P fertilizer management practice and cover crop use on soil fertility is needed to help develop agricultural BMPs to reduce potential surface runoff transport of nutrients through examining the soil as a key source factor in the nutrient loss equation.

The objective of this research was to quantify the impacts of P fertilizer management practices and the addition of a cover crop on Mehlich-III P (P_M), water-extractable P (P_W), total P (P_T), total nitrogen (N), and total carbon (C) concentrations at near-surface soil depths. We hypothesized that i) surface broadcast application of P fertilizer would increase surface concentrations of P compared to subsurface injection of P fertilizer, ii) addition of a cover crop would increase total P concentrations in surface soil depths, and iii) cover crops may modify the effect of P fertilizer management on concentrations of P_W.

Materials and Methods

This research was performed at the Kansas Agricultural Watershed (KAW) field laboratory located near Manhattan, Kansas, USA, from 1 October 2014 through 30 September 2019.

Experimental Design

This study examined the impact of six agricultural management practices (treatments) on soil test nutrient concentrations. The treatment structure was a 3×2 complete factorial arranged in a randomized complete block design. Each treatment combination was represented by three replicates. Treatments were blocked based on landscape position. Three levels of P fertilizer-management practice were evaluated in this study: no P fertilizer control (CN); fall broadcast (FB, 61 kg P_2O_5/ha); and spring injected (SI, 61 kg P_2O_5/ha). All P fertilizer treatments were expressed with two levels of cover crop: no cover crop (NC) and with cover crop (CC).

Field Site

Established in 2014, the KAW field lab consists of eighteen, approximately 0.5 ha, plots delineated with berms and terraces. Historically, this location was managed using conventional tillage in a winter wheat (*Triticum aestivum*)-soybean rotation. The last tillage event occurred on 7 November 2014 when the entire site location was cultivated using a chisel plow followed by a disc. The soils at the KAW field lab are mapped as eroded Smolan silty clay loam (fine, smectitic, mesic Pachic Argiustoll) with 3-7% slope. Climatic condition at the KAW field lab is hot, humid, continental with a mean annual temperature of 12.9°C and a thirty-year average annual precipitation of 889 mm.

Agricultural Management

Throughout the study, the KAW field lab was under no-till management. Yield goals for corn and soybean were 10 and 2.7 Mg ha^{-1}, respectively. Soybean was grown in 2016 and 2018, and corn was grown in 2015, 2017, and 2019.

Following harvest of the cash crop, a small grain and brassica mixed cover crop was sown (Table A.1.). Most plant biomass produced by the cover crop was attributed to the small grain. Selection of cover crop species varied throughout the study based on planting time and the following cash crop. In 2016, the cover crop was terminated via herbicide application prior to planting soybean, while in all other years, the cover crop was terminated soon after planting the cash crop.

Each year, P fertilizer was applied to both the FB and SI plots at a rate of 61 kg P_2O_5/ha. Application rate of P fertilizer was calculated using a 5-year build and maintain recommendation system based on an average initial Mehlich-III P soil test of 17 ppm at 0 to 15 cm deep (Leikem et al., 2003). For the FB treatment, diammonium phosphate (18-46-0) was applied to the soil surface using a 3.05-m wide drop spreader (Barber Engineering Co., Spokane, WA). The SI treatment received ammonium polyphosphate (10-34-0) injected approximately 5 cm below and 5 cm to the side of the seed at planting. During 2015, 2017, and 2019, nitrogen applications to the corn crop were balanced across all treatments with urea ammonium nitrate (28-0-0) injected 5 cm deep with 38-cm spacing using a coulter applicator. Total N application to corn, including N applied with the P fertilizer, was 174 kg N/ha/yr. Further details regarding agricultural management practice can be found in Carver et al. (2022).

Soil Sample Collection and Analysis

Composite soil samples, consisting of 21 cores per composite, were collected each fall after harvest and prior to application of the FB treatment from three geo-referenced subplot locations within each plot (Table A.1; Figure E.1) treatment effects on near-surface nutrient stratification. All soil samples were air dried then ground to pass through a 2 mm sieve.

Mehlich-III P was extracted using methods described by Mehlich (1984) with an extraction ratio of 1:10 (soil:solution) and a shake time of 5 minutes at 200 excursions per minute (epm). Concentrations of P_M in extract were analyzed colormetrically with the molybdate blue procedure using a Lachat QuickChem 8000 Series Automated Ion Analyzer and the QuickChem Method 12-115-01-1-A. Total P was determined by salicylic-sulfuric acid digestion and measured by an inductively coupled plasma (ICP) spectrometer (Bremner and Mulvaney, 1982). Total C and total N were determined by combustion using a LECO TruSpec CN Analyzer (TruSpec Method "Carbon and Nitrogen in Soil and Sediment). All soil samples were weighed for extraction. Chemical analyses were performed by the Kansas State University Soil Testing Lab (Manhattan, KS, USA).

Water-extractable ortho-P (P_W) was determined for the 2015, 2016, and 2017 0-5 cm samples and the 2017, 2018, and 2019 0-2.5 cm and 2.5-5 cm samples (Self-Davis et al., 2000). Water extractable ortho-P was determined by weighing 2.0 g of air-dried soil into a 40 mL conical tube to which 20 mL of deionized water was then added (1 soil:10 solution). Samples were placed on an end-to-end shaker for 1 hour at 180 epm. After shaking, samples were centrifuged at 10,000 rpm for 10 minutes and the supernatant filtered through a 0.45 µm syringe filter. Filtered extracts were stored at 5 °C until analysis. Water extractable ortho-P concentration in extracts were determined colormetrically using the Murphy and Riley molybdate reactive P method (1962). Extracts were analyzed using a Lachat QuickChem 8500 Series II Automated Ion Analyzer with the QuickChem Method 10-115-01-1-A.

Statistical Analysis

For each study endpoint, data collected from 2015-2019 (post treatment) were analyzed separately at each depth under the linear mixed model. Fixed effects of the model included replication, fertilizer management practice, cover crop, year, and all higher-order interactions among fertilizer-management practice, cover crop, and year. Random effect of the model was field plot, which is the error term vector whose elements correspond to repeated measurements at 3 points over 5 years. Data collected in 2014 (pre-treatment; baseline) served as the covariate. Variance-covariance matrix for field plot was taken as the Kronecker product of the variance-covariance matrix for point (of type unstructured) and the variance-covariance matrix for year (of type compound symmetry), according to model fitting criteria and convergence status.

In order to evaluate the effect of depth, data collected from 2017-2019 at depths 0-2.5 cm and 2.5 cm-5 cm was analyzed together under one model. Besides those fixed effects and covariate described in previous model, depth and its interaction with other fixed effects were included in the analysis. Random effects of the model included field plot and field-plot-by-year interaction, which is the error term vector whose elements correspond to repeated measurements at 3 points and at 2 depths. Variance-covariance matrix for field-plot-by-year interaction was taken as the Kronecker product of the variance-covariance matrix for point (of type unstructured) and the variance-covariance for depth (of type unstructured).

For P_M, post-treatment data were subjected to $\log_{10}$ transformation to better fulfill the normality assumption; the $\log_{10}$-transformed pre-treatment data served as the covariate. Interactions between model fixed effects were examined using type III tests at $\alpha = 0.05$. The least squares means and standard errors, back-transformed when applicable, were reported for fixed effects. Pairwise comparisons between 2 levels of a fixed effect were performed based on the 2-sided test for non-zero difference in means. Statistical analysis was executed via Statistical Analysis Software (SAS version 9.4; Cary, NC) PROC MIXED with option DDFM=KR.

Results

2015 through 2019: 0-5 cm & 5-15 cm

A fertilizer-management practice by year interaction for P_M in the top 0-5 cm of soil was observed where the application of P fertilizer, regardless of application method (FB or SI), increased P_M compared to the CN (Table 4.1, Figure 4.1a). From 2016 through 2019, no differences in P_M were observed between the FB and SI method of P fertilizer application in the top 0-5 cm, but in 2015, the FB treatment had approximately 67% greater P_M compared to the SI treatment. A main effect of cover crop on P_M concentration of 5-15 cm was observed with the NC treatment having approximately 21% greater P_M compared to the CC treatment (Figure 4.4a). A fertilizer management practice by year interaction for P_M was also observed for the 5-15 cm depth (Table 4.1). In 2015 and 2016, no differences in P_M were observed between either the FB or SI treatment and the CN, yet from 2017 through 2019, the CN had significantly lower P_M when compared to either FB or SI (Figure 4.1b). Mehlich-III P concentrations for the FB and SI treatments at 5-15 cm were the same from 2015 through 2018, but in 2019 the SI treatment had approximately 27% greater concentrations of P_M compared to FB (Figure 4.1b).

Main effects of both fertilizer and year were observed for P_W in the top 0-5 cm of soil (Table 4.1). The FB treatment had the greatest P_w (3.1 mg kg^{-1}) followed by SI (2.4 mg kg^{-1}) and CN with the least (0.7 mg kg^{-1}) ($p<0.05$). During 2015, 2016, and 2017, P_W in the top 0-5 cm of soil remained constant, at an average of 1.4 mg kg^{-1} when averaged across all treatments and years. Water extractable P increased to 3.2 mg kg^{-1} in 2018 and 2019 ($p<0.05$)

Total P in the top 0-5 cm was significantly impacted by the interaction between fertilizer and year (Table 4.1). The total P concentration at 0 to 5 cm deep in soils of the FB and SI were similar for all five years (Figure 4.2). For all years, total P in FB soils were greater than CN while SI was only greater than CN in 2016, 2018, and 2019 (Figure 4.2). Total P for both the FB and SI treatments increased approximately 17% throughout the course of this study, while concentrations of total P in the CN treatment remained constant (Figure 4.2). A year effect on total P was observed for the subsurface (5-15 cm) soils with total P decreasing approximately 6% over the course of this study (Table E.2).

A cover crop by year interaction was observed for total C in the top 0-5 cm (Table 4.1). Soils at 0-5 cm in the CC treatment had greater total C than the NC treatment for four out of five years (2016-2019) (Figure 4.3). Total C concentration in the top 0-5 cm, regardless of cover crop treatment, increased over time with total C concentrations starting at 12.7 g C/kg soil in 2015 and rising to 16.0 g C/kg soil in 2019 (Figure 4.3)

A main effect of cover crop on total N was also observed in the 0-5 cm depth (Table 4.1). The addition of a cover crop increased total N by approximately 5% compared to the NC treatment (Figure 4.4b). A year effect for both the 0-5 cm and 5-15 cm depths was observed with the 2018 and 2019 samples having 23% greater total N at the 0-5 cm depth and 17% greater total N at the 5-15 cm depth compared to the first three years of the study (Table E.1 and Table E.2).

A cover crop by year interaction was observed for soil pH at the 0-5 cm depth (Table 4.1). In 2017, pH for the NC treatment was 6.70 and for the CC treatment pH was 6.92 (Table E.4). No differences between cover crop treatments for soil pH were observed in other years. At the beginning of this study (2015), soil pH in the top 0-5 cm was measured to be 6.91 and by 2019, soil pH had dropped to 6.80 ($p\text{-}value<0.001$). A main effect of year on soil pH at the 5-15 cm depth was observed with pH at 5-15 cm starting at 6.52 in 2015 and rising to 6.84 in 2019 (Table 4.1; Table E.4).

2017 through 2019: 0-2.5 cm & 2.5-5 cm

A two-way interaction between cover crop and depth was observed for P_M (Table 4.2). For both the NC and CC treatment, the top 0-2.5 cm of soil had greater P_M when compared to the 2.5-5 cm depth with concentrations of P_M being approximately 150% greater in the 0-2.5 cm depth compared to the 2.5-5 cm depth (Figure 4.5a). The cover crop by depth interaction was because the effect of depth was greater in the CC treatment (31 mg kg^{-1}) compared to the NC treatment (30 mg kg^{-1}). Although this difference is statistically significant, the agronomic or environmental impact is likely negligible.

A fertilizer management practice by year interaction was also observed for P_M (Table 4.2). The P_M in the CN treatment decreased over time, while it remained constant in the FB treatment and increased in the SI treatment (Table E.3). Moving from 2017 through 2019, the difference between the fertilized treatments and the CN also increased with the 2017 fertilized treatments having approximately 35 mg kg^{-1} greater P_M compared to the CN and the 2019 fertilized treatments having approximately 50 mg kg^{-1} greater P_M compared to the CN (Table E.3)

An interaction between fertilizer management practice and depth was also identified for P_M where depth had a much greater impact for the FB and SI treatments than the CN. Concentration of P_M at 2.5-5 cm was 58 mg kg^{-1} less than at 0-2.5 for the FB treatment and 45 mg kg^{-1} less for the SI treatment (Figure 4.6a). No differences were observed between P_M concentrations for the SI and FB treatments at either depth.

For P_W, a three-way interaction between cover crop, fertilizer management practice, and depth was observed (Table 4.2). For the CN treatment, no effect of depth or cover crop was observed, with both cover crop treatments at both depths having an average of 0.74 mg kg^{-1} P_W (Figure 4.7). For the 0-2.5 cm depth, the FB-NC, FB-CC, and SI-CC each had the greatest P_W with an average of 6.46 mg kg^{-1}. The three-way interaction is caused by the SI-NC treatment having less P_W compared to the FB-NC, yet when a cover crop was added to both the FB and SI treatments no differences between FB and SI with regards to P_W were observed (i.e., FB-NC > SI-NC, yet FB-CC = SI-CC). Addition of a cover crop to the SI treatment at 0-2.5 cm resulted in an increase in concentration of P_W by approximately 41%. The P_W concentration at 0-2.5 cm was greater than P_W concentrations at 2.5-5 cm depth for all treatments that received P fertilizer (Figure 4.7). A year by depth interaction was also observed with the 0-2.5 cm depth consistently having greater P_W compared to the 2.5-5 cm depth regardless of treatment; although, soil samples collected in 2017 had lesser P_W at both depths when compared to both 2018 and 2019 (Table E.3).

Multiple two-way interactions were found for P_T including cover by year, cover by depth, fertilizer management practice by year, fertilizer management practice by depth, and year by depth (Table 4.2) For the cover by year interaction, the CC treatment had greater P_T compared to the NC treatment in both 2017 and 2018, but not in 2019 (Table E.3). With regards to depth, the CC treatment increased P_T in the top 0-2.5 cm by approximately 5% compared to the NC treatment while no differences between cover crop treatments were observed at 2.5-5 cm (Figure 4.5b). In 2017, the FB treatment had approximately 17% greater P_T compared to both the SI and CN treatments (Table E.3). For 2018 and 2019, no differences between the FB and SI treatments were observed with both P fertilizer treatments having approximately 25% greater P when compared to the CN treatment.

For total carbon, a cover crop by depth interaction was observed with the CC treatment exhibiting greater total C concentration compared to the NC treatment at both the 0-2.5 cm and 2.5-5 cm depths (Table 4.2; Figure 4.5c). The CC treatment had approximately 13% and 6% greater total C at the 0-2.5 cm depth and the 2.5-5 cm depth, respectively, when compared to the NC treatment. A fertilizer by depth interaction for total C was also found, where the FB and SI treatments had greater total C at 0-2.5 cm than the CN while there were not any P fertilizer management effects on total C at the 2.5-5 cm depth (Figure 4.6c). A year by depth interaction for total C showed the total C concentration in the 0-2.5 cm depth increased more over time than at the 2.5-5 cm depth (Table E.3).

A cover crop by depth interaction was observed for total N, where, similar to the CC effect on total C, the soil C concentration in CC treatment was greater than the NC treatment at 0-2.5 cm while there was no difference at 2.5-5 cm deep (Table 4.2; Figure 4.5d). The year by depth interaction for total N was also like that of total N, where the total N concentration in the 0-2.5 cm soil depth increased more over time than at the 2.5 to 5 cm depth (Table E.3).

A cover crop by year interaction was observed for soil pH where no differences in soil pH between the CC and NC treatments were observed across years although pH for the CC treatment in 2019 (pH 6.73) was less than pH for the CC treatment in 2017 (pH 6.89) (Table E.5.). A cover crop by depth interaction for soil pH was also observed where no differences in soil pH with regards to depth were observed for the NC treatment yet the pH at 0-2.5 cm for the CC treatment (pH 6.74) was found to be less than that of the pH for the CC treatment at 2.5-5 cm (pH 6.92) (Table E.5.) No differences in soil pH between the FB and SI treatments were observed (Table E.5)

Discussion

Phosphorus Fertilizer Management

Increased nutrient concentration near the soil surface due to the absence of soil mixing is a widely acknowledged challenge of no-till agricultural management (Robbins and Voss., 1991; Buah et al., 2000; Fernandez et al., 2012; Smith et al., 2017). As such, the subsurface placement of soil amendments is recommended to help reduce stratification (Robbins and Voss, 1991; Schwab et al., 2006). In our study, the application of P fertilizer in both FB and SI treatments increased both P_M and P_T concentrations near the soil surface (0-5 cm, 0-2.5 cm, and 2.5-5 cm), yet no differences were observed between the FB and SI treatments. This lack of difference between the FB and SI treatments is surprising given the subsurface placement of P in the SI treatment and the inherent immobility of P within the soil system and suggests that placing P fertilizer 5 cm below and 5 cm to the side of the seed at planting may not reduce the potentially greater near-surface concentrations of P in a no-till system. This finding is similar to Smith et al.

(2017) who also found no differences in P_M between surface applied DAP and polyphosphate applied 5 cm below and 5 cm to the side of the seed within a no-till system. Lack of difference in P_M and P_T between the FB and SI treatment may be due to variability in the placement depth of P fertilized applied as the SI treatment (i.e., the SI treatment not being consistently placed at 5 cm below and 5 cm to the side of the seed at planting) or from rapid cycling of P to the soil surface due to plant uptake followed by deposition and decomposition of residue.

Greater concentrations of P_M and P_T near the soil surface was also observed for the CN treatment likely because of soil P being assimilated by crop tissue and redeposited on the soil surface during the decomposition process (Scheiner and Lavado, 1998). Increased concentrations of P at the soil surface for the CN treatment due to lack of vertical mixing of soil and crop residue may lead to greater concentrations of dissolved P in surface runoff (Bordoli and Mallarino, 1998). Elevated concentrations of P near the soil surface are of particular concern for no-till systems, which have been found to have approximately 35% greater concentrations of dissolved P in surface runoff compared to conventionally tilled systems primarily due to increased concentrations of P near the soil surface (Daryanto et al., 2017).

Although the concentrations of P_M and P_T were similar for the FB and SI treatments, the P_W concentrations at 0-2.5 cm in the SI treatment were less than in FB. This contrasts with Smith et al. (2017) who found no differences in P_W between surface applied DAP and subsurface applied polyphosphate. Water extractable P has been identified as a potential predictor of dissolved reactive P concentration in surface runoff and may therefore provide insight into the potential impact P fertilizer management practice has on surface water quality (Torbert et al., 2002; Wang et al., 2010). In a joint study, Carver et al. (2022) found that the dissolved reactive P concentration in runoff from the SI treatment was 44% less than the FB treatment. This finding highlights the relationship between concentrations of P_W in the soil and DRP concentrations in surface runoff. Pote et al. (1996), and Torbert et al. (2002) each found P_W to be best correlated with dissolved P concentrations in surface runoff. This is in contrast with Sauer et al. (2000) who found that P_M in the top 0-2.5 cm of soil to be best correlated ($r^2 = 0.80$) with dissolved P in surface runoff.

Variation in P_W between the FB and SI treatment may be due to chemistry-based behavioral differences of DAP (FB treatment) and APP (SI treatment) within the soil. Work by Khasawneh et al. (1974) compared mobility of DAP to APP and found that one-week after application, concentrations of P from the DAP treatment was greatest at 3 mm away from the application point while concentrations of P for the APP treatment were greatest at 8 mm away from the application point. Fluid P fertilizers can diffuse greater distances within the soil and react with greater amounts of soils compared granular P fertilizers (Lombi et al., 2004). Decreased P_W for the SI treatment may be related to fluid P fertilizers, such as the APP used in the SI treatment, being less labile in soils compared to granular fertilizers and due to the form stronger surface complexes resulting from fluid fertilizers being disseminated across a greater volume of soil (Montalvo et al., 2014).

Condensed polyphosphates, such as those contained in APP, may exhibit greater affinity towards Al-oxides and/or Fe-oxides in soil compared to orthophosphates (Anderson et al., 1974; Taylor et al., 2001). Polyphosphates may also displace orthophosphates from Al- and/or Fe-oxides leading to potential transport of orthophosphates with surface runoff and subsurface flow (Guan et al., 2005). Pierzynski and Hettiarachchi (2018) stated that solubility of P may be controlled by the sorption of P on Al- and Fe-minerals. In work exploring X-ray absorption near edge structure of common P fertilizers, Pierzynski and Hettiarachchi (2018) found that APP had larger amounts of both Al-absorbed P and Fe-absorbed P compared to DAP suggesting that APP may form more recalcitrant forms of P in the soil after application when compared to DAP.

The addition of P fertilizer increased total C within the top 0-2.5 cm likely due to 27% greater crop biomass production and subsequent greater deposition of crop residue on the soil surface in the treatments receiving P fertilizer additions (FB and SI) compared to the CN (Carver et al., 2022). Potentially greater concentrations of root biomass associated with the larger concentrations of P near the soil surface may also explain increased total C concentrations for the FB and SI treatments (Ontl and Shulte, 2012).

Cover Crops

The ability of cover crop to modify the effect of the SI treatment on P_W in the top 0-2.5 cm is an interesting finding from this study. Cover crops have demonstrated the ability to solubilize and access more recalcitrant forms of soil P through the exudation of P solubilizing compounds, release of organic-P mineralizing compounds, and alteration of the rhizospheric microbial community (Hallama et al., 2019). The ability of cover crops to access traditionally insoluble sources of P may explain the increase in P_W at the 0-2.5 cm depth. Cover crops can alter forms of P present in the soil and, as such, may lead to competitive adsorption (Violante and Gianfreda, 1993). The increase in P_W at the 0-2.5 cm depth for the SI-CC treatment may also be in part associated with cover crops' ability to translocate P from deeper within the soil profile and redeposit it on the soil surface with cover crop residue (Kovar et al., 2011). Addition of a cover crop can also result in increased microbial biomass and elevated total C concentration (which were observed during this study) which may lead to an increase in mineralization of formerly recalcitrant forms of P in the soil (Starr, 2021). Cover crops may also increase availabilities of cations within the soil leading to enhanced hydrolysis of APP which may impact

P retention mechanisms (Wan et al., 2019). The observed increase in P_W for the SI-CC treatment contrasts with work by Christopher et al. (2020) who observed the addition of a cover crop had either no effect on P_W or decreased P_W.

Lack of difference between the FB-NC and FB-CC treatment with regards to P_W in the top 0-2.5 cm is likely due to the cover crop in the FB treatment accessing the surface applied P fertilizer therefore eliminating the need to translocate P from deeper within the soil. Since the cover crop may be accessing P from where P was applied and ultimately returning that P to the zone of acquisition, no interaction between the FB treatment and cover crop may be observed. A similar process may be occurring for the CN treatment and would explain a lack of difference in P_W between the 0-2.5 and 2.5-5.0 cm depth. Overall, the addition of a cover crop to the FB method of P fertilizer application did not impact P concentrations near the soil surface; however, adding a cover crop to the SI treatment resulted in increased concentrations of P_w near the soil surface. Increased concentrations of P_W in the top 0-2.5 cm may partially contribute to the consistent increase in dissolved reactive P concentration in surface runoff from the SI-CC treatment observed by Carver et al. (2022).

The increase in P_T at the soil surface (0-2.5 cm) for the CC treatment is likely due to surface deposition of translocated P from further down the soil profile. Cover crops have demonstrated greater ability to translocate P to the soil surface and access traditionally non-available P fractions through formation of symbiotic relationships with mycorrhizal fungi, secretion of P solubilizing root exudates, or altered root architecture (Hallama et al., 2019). Additionally, cover crops have shown to increase microbial activity in soils and to increase microbial biomass P (Hallama et al., 2019; Starr, 2021). The increase in P_T observed during this study is consistent with findings from Wang et al. (2021) and Dube et al. (2014) who each found addition of a cover crop to increase concentration of P_T in surface soils.

The increase in total C resulting from the addition of a cover crop is likely due to an increase in total aboveground biomass production and associated C inputs (Blanco-Canqui et al., 2013). By the end of our study, the CC treatment had a cumulative average of 6,378 kg ha^{-1} of additional biomass deposited on the soil surface. Cover crops have also been found to impact the retention of carbon in soil through reducing erosion losses of soil (Blanco-Canqui et al, 2015). A decrease in observed erosions losses by Carver et al. (2022) at the study site showed that the addition of a cover crop resulted in a 68% less erosion losses compared to the NC treatment. The relatively quick increase in soil carbon during the course of the study (i.e., CC increased total C at 0-5 cm compared to NC in one year; Figure 4.3) contrasts with work by Blanco-Canqui et al., 2014 who found CC did not increase total C at 0-5 cm over three years of study. Acuna and Villamil (2004) also stated that increased total C concentration resulting from the addition of a cover crop may take several years to manifest; however, their study examined total C in the top 0-10 cm of soil.

Similar to total C, the observed increase in total N resulting from the addition of a cover crop can be linked to the increase in total plant biomass deposited on the soil surface. Hargrove (1996) and Kuo et al. (1997) each demonstrated that cover crops can increase soil N concentration through the production and accumulation of additional biomass.

Conclusion

Our initial hypothesis was that subsurface placement of P would decrease P concentrations near the soil surface; however, findings from this study indicate that placing APP fertilizer 5 cm below and 5 cm to the side of the seed at planting may not decrease P_M and P_T

concentrations in surface soils compared to broadcast application of DAP but could decrease P_W concentrations in surface soils. Results from this study highlight the need to evaluate multiple soil chemical properties (P_W in addition to P_M and/or P_T) when assessing the potential of a soil to serve as a P source to surface runoff through using STP as an indicator for risk of P loss.

Although no effect of cover crop was observed for P_M in the top 0-2.5 cm, addition of a cover crop resulted in greater concentrations of total P at the 0-2.5 cm depth suggesting that cover crops alter the forms of P present in the soil which could explain the observed increase in P_W for the SI treatment. These findings suggest that cover crops are modifying the soil environment in a way which may result in more readily soluble forms of P being present in the soil. To further explore cover crop impact on solubility of P in the soil, additional research examining the impact of cover crops on P speciation, fractionation, and adsorption in the soil is needed.

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Tables

Table 4.1 *P*-value for testing fixed effect for the analysis of data from 2015 through 2019. Table abbreviations in Mehlich-III P (P_M), water-extractable P (P_W), total P (P_T), total C (TC), total N (TN), cover crop management practice (cover), P fertilizer management practice (Fert). Bolded value indicate significant effect at alpha = 0.05.

Effect	P_M	P_W	P_T	TC	TN	pH
	----------------------------------*p* value------------------------------					
0-5 cm						
Cover	0.198	0.962	0.606	**< 0.001**	**0.015**	0.533
Fert	**< 0.001**	**< 0.001**	**< 0.001**	0.279	0.456	0.072
Year	**< 0.001**	**0.005**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Cover*Fert	0.303	0.970	0.328	0.339	0.737	0.807
Cover*Year	0.358	0.936	0.083	**< 0.001**	0.342	**0.001**
Fert*Year	**< 0.001**	0.650	**0.009**	0.264	0.753	0.279
Cover*Fert*Year	0.997	0.869	0.730	0.257	0.889	0.193
5-15 cm						
Cover	**< 0.001**	.	0.546	0.873	0.944	0.742
Fert	**< 0.001**	.	0.634	0.759	0.442	0.088
Year	**< 0.001**	.	**0.036**	0.123	**< 0.001**	**< 0.001**
Cover*Fert	0.165	.	0.971	0.637	0.936	0.615
Cover*Year	0.254	.	0.289	0.523	0.313	0.637
Fert*Year	**< 0.001**	.	0.661	0.742	0.286	0.334
Cover*Fert*Year	0.890	.	0.932	0.575	0.895	0.248

Table 4.2 ***P*-value for testing fixed effect for the analysis of data from 2017 through 2019. Table abbreviations in Mehlich-III P (P_M), water-extractable P (P_W), total P (P_T), total C (TC), total N (TN), cover crop management practice (cover), P fertilizer management practice (Fert). Bolded value indicate significant effect at alpha = 0.05.**

Effect	P_M	P_W	P_T	TC	TN	pH
		---------------------------------*p*-value----------------------------------				
Cover	0.182	0.583	0.112	< 0.001	**< 0.001**	0.766
Fert	**< 0.001**	**< 0.001**	**< 0.001**	0.076	0.109	0.136
Year	**0.010**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	0.053
Depth	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Cover*Fert	0.425	**0.036**	0.338	0.163	0.961	0.825
Cover*Year	0.443	0.166	**0.048**	0.050	0.992	**0.029**
Cover*Depth	**0.019**	0.088	**0.012**	**< 0.001**	**0.000**	**< 0.001**
Fert*Year	**< 0.001**	0.109	**0.011**	0.860	0.212	**0.024**
Fert*Depth	**0.012**	**< 0.001**	**< 0.001**	**0.003**	0.436	**0.001**
Year*Depth	0.174	**0.002**	**0.011**	**< 0.001**	**< 0.001**	**< 0.001**
Cover*Fert*Year	0.985	0.893	0.191	0.762	0.343	0.499
Cover*Fert*Depth	0.797	**0.041**	0.420	0.754	0.783	0.161
Cover*Year*Depth	0.176	0.266	0.124	0.055	0.670	0.107
Fert*Year*Depth	0.052	0.400	0.648	0.581	0.055	0.462
Cover*Fert*Year*Depth	0.845	0.860	0.682	0.849	0.686	0.530

Figures

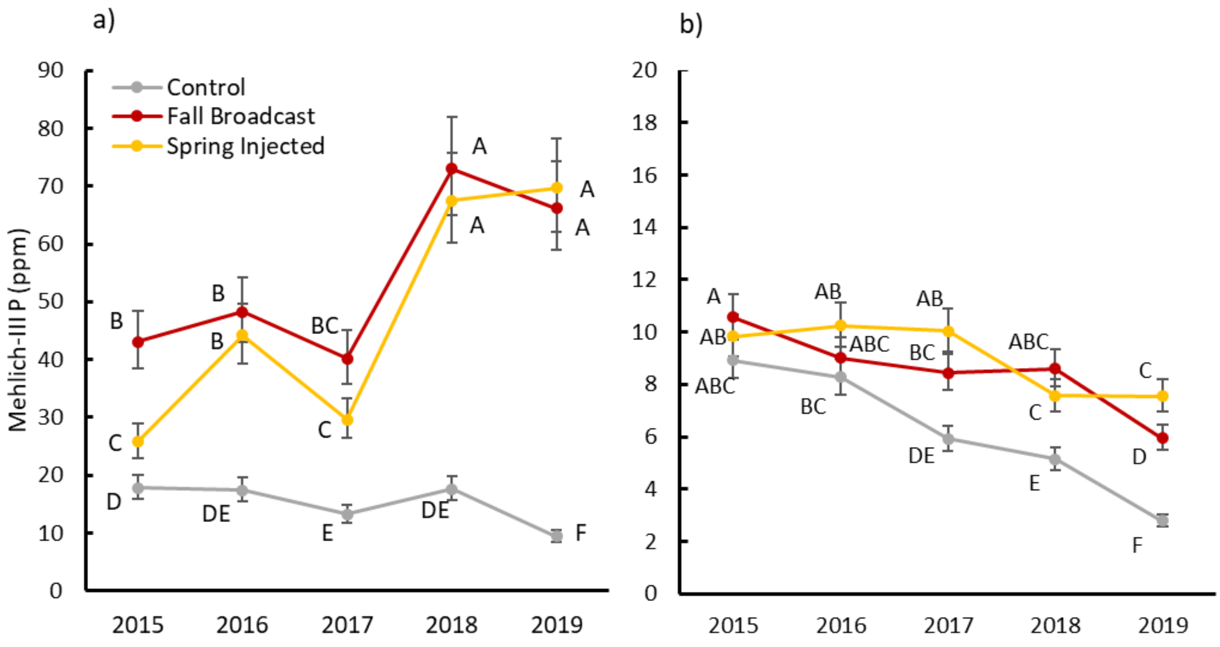

Figure 4.1 Phosphorus fertilizer management practice by year interaction for Mehlich-III P concentrations at 0-5 cm (a) and 5-15 cm (b). Letters represent significant differences between two combinations of year and management practice at *p* < 0.05 and error bars represent the standard error of the least squares mean.

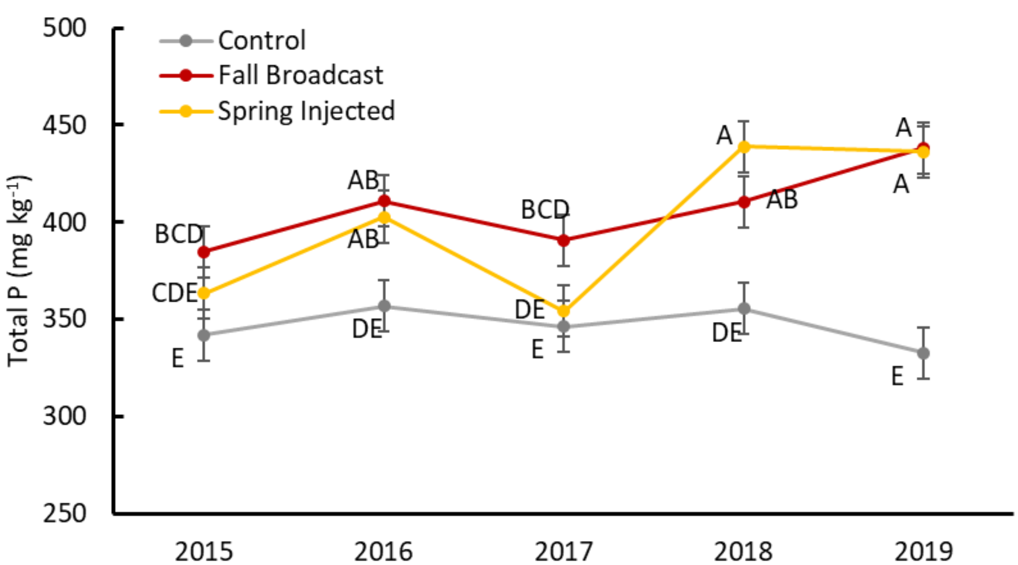

Figure 4.2 Phosphorus fertilizer management practice by year interaction for total P concentration at 0-5 cm. Letters represent significant differences between two

combinations of year and P fertilizer management practice at *p*<0.05 and error bars represent the standard error of the mean.

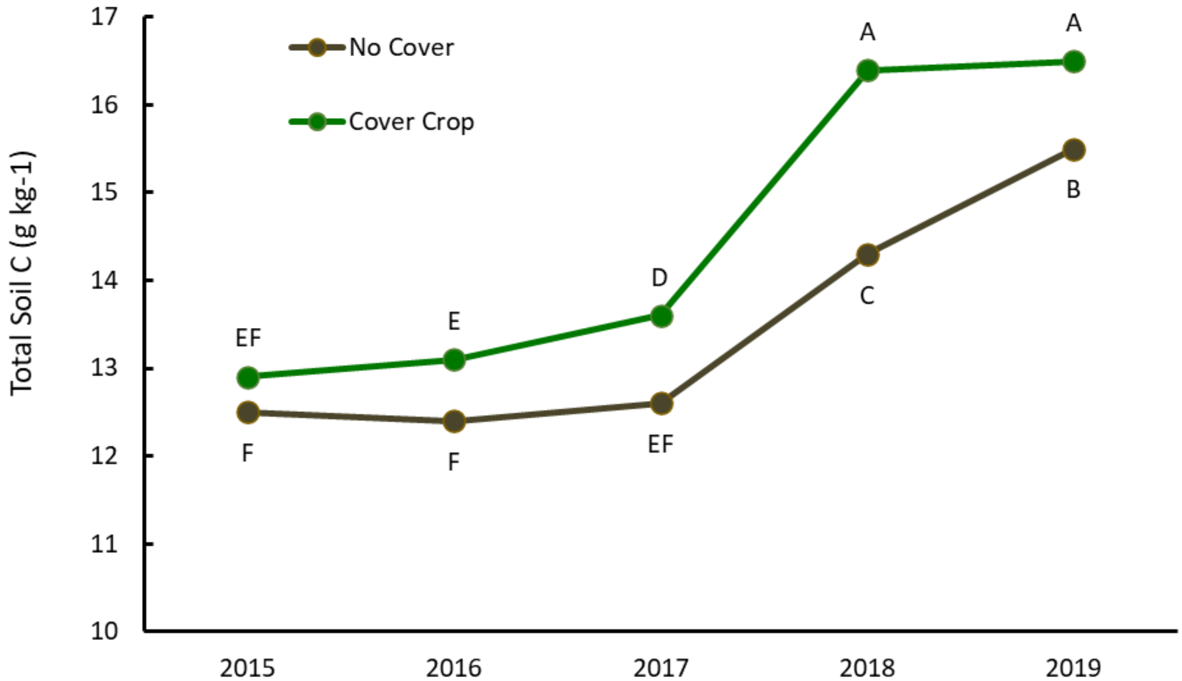

Figure 4.3 Cover crop by year interaction for total C measured in the top 0-5 cm for soil samples collected from 2015 through 2019. Letters indicate significance at alpha = 0.05.

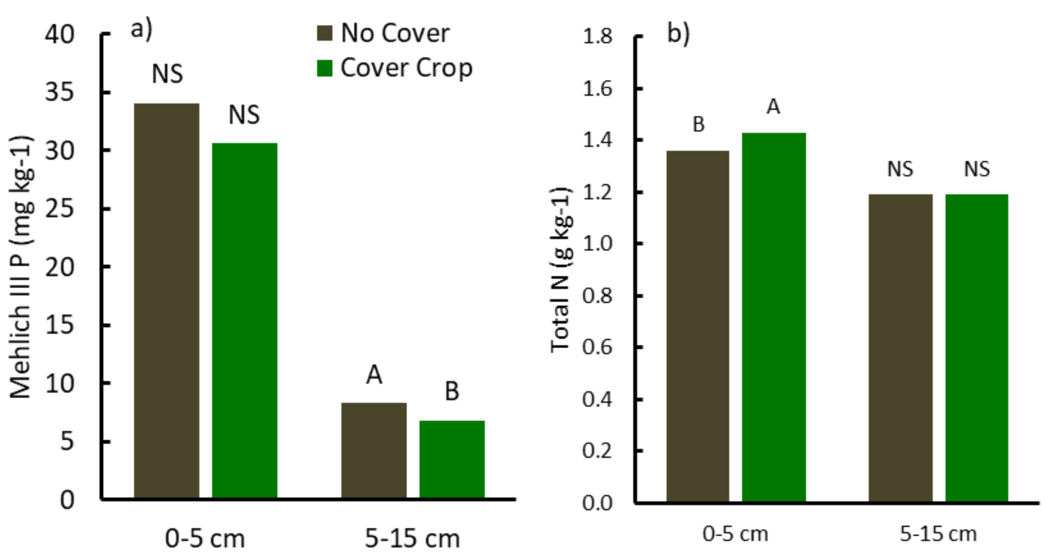

Figure 4.4 Main effects of cover crop for Mehlich-III P (a) and total N (b) for soil samples collected at 0-5 cm an 5-15 cm from 2015 through 2019. Letters represent significance at alpha = 0.05.

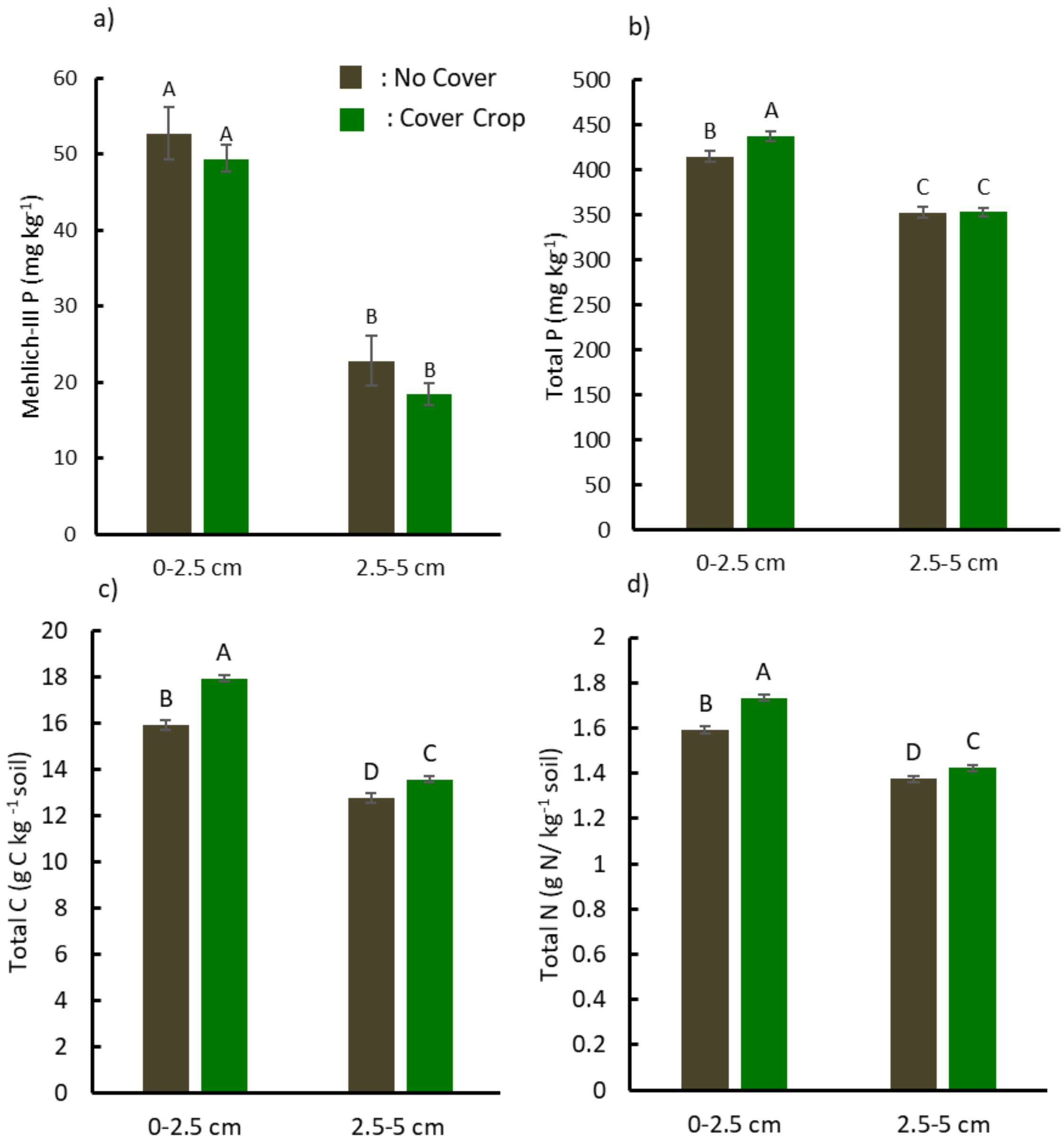

Figure 4.5 Cover crop by depth interaction for Mehlich-III P (a), total P (b), total C (c), and total N (d) for soil samples collected at 0-2.5 cm and 2.5-5 cm depths from 2017 through 2019. Letters indicate significant differences between treatment at alpha = 0.05 and error bars represent standard error of the mean.

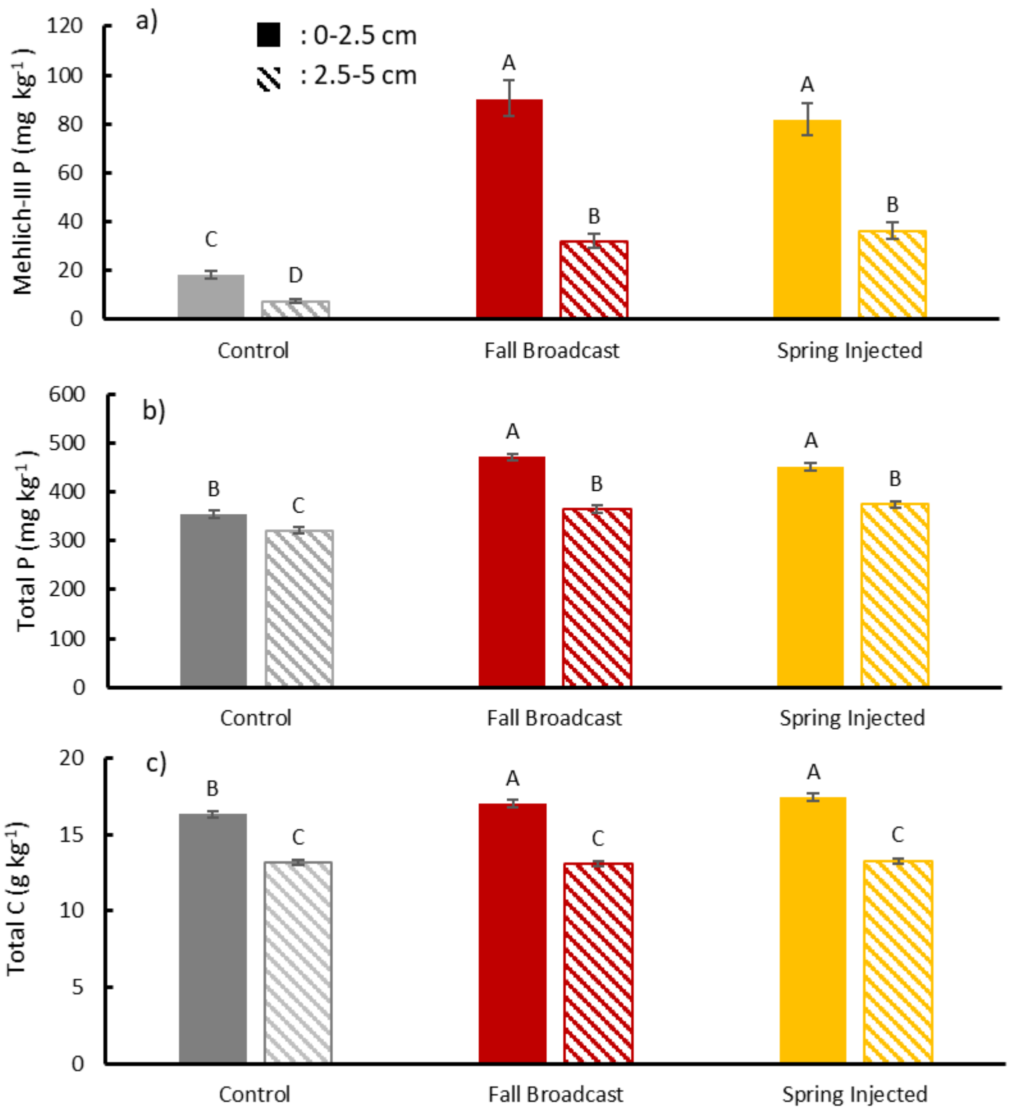

Figure 4.6 Phosphorus fertilizer management practice by depth interaction for Mehlich-III P (a), total P (b), and total C (c) for soil samples collected during 2017 through 2019. Letters indicate significance at alpha = 0.05 and error bars represent that standard error of the mean.

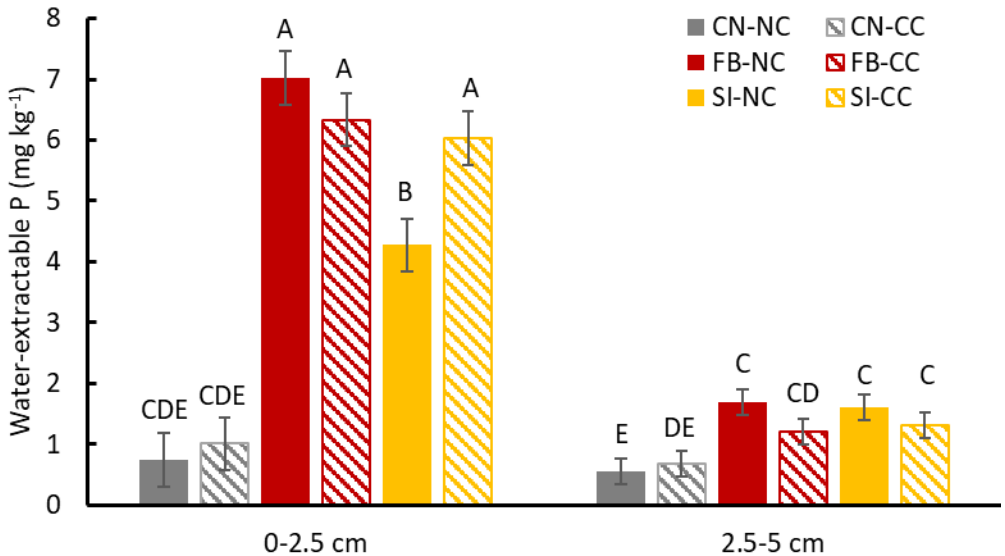

Figure 4.7 Cover crop by P fertilizer management practice by depth interaction for water-extractable P for soil samples collected during 2017 through 2019. Table abbreviation include control (CN), fall broadcast (FB), spring injected (SI), no cover crop (NC), and with cover crop (CC). Letters indicate significance at alpha = 0.05 and error bars represent the standard error of the mean.

Chapter 5 - Selecting winter cereal cover crop species to protect water quality and improve nutrient cycling

Introduction

Phosphorus loss associated with agricultural production is of national concern when discussing water quality, soil conservation, and soil health. As P moves out of agricultural systems and into surface waters, mineral enrichment, or eutrophication, of surface waters may occur. Eutrophication may result in increased occurrences of harmful algal blooms, a rise in water treatment costs, and an overall increase in potentially negative impacts to both human and animal health (Carpenter et al., 1998; Correll, 1998; Hudnell, 2010). To help protect and preserve agricultural and environmental resources, producers are encouraged to adopt conservation practices, such as no-till and the addition of cover crops, which are designed to protect environmental quality (NRCS, 2020b)

In a cover cropped system, the soil surface remains under a "permanent" layer of vegetative cover. Surface vegetation is well-known for protecting soil quality from negative effects of erosion through decreasing rainfall impact, disrupting surface runoff, and stabilizing the soil (Morgan, 2005; Gyssels et al., 2005). Cover crops have shown to decrease both interrill and splash erosion and protect against the destruction of soil aggregates, surface sealing, and compaction of topsoil (Kaspar et al., 2001; Morgan, 2005). Adding a cover crop during a normally fallow period can increase carbon storage in soils, improve soil aggregate stability, and decrease negative effects of wind and water erosion (Cock, 1985; Reicosky & Forcella, 1998; Battany & Grismer, 2000).

Blanco-Canqui (2018) reviewed thirteen articles examining sediment loss and found cover crops may reduce sediment losses by up to 100% compared to fields with no cover crops.

Research by Carver et al. (2022) found that even in low-erosion no-till systems, the addition of a cover crop reduced sediment losses consistently by 60 to 70%. Although impacts of cover crops on erosion losses are well established in the literature (Kaspar et al., 2001; Morgan, 2005; Blanco-Canqui, 2018), reported cover crop effects on P loss are inconsistent, sometimes resulting in greater P loss or sometimes less P loss when compared to no cover crop (Aronsson et al., 2016, Christianson et al., 2017; Kieta et al., 2018; Baulch et al., 2019; Carver et al., 2022). While cover crops exhibit inconsistent reductions in total P loss, there is increasing evidence that addition of a cover crop during a normally fallow period increases losses of dissolved reactive P (Liu et al., 2019; Hanrahan et al, 2021; Carver et al., 2022). These findings suggest additional research is needed to maximize the benefits of cover crops in promoting soil conservation and soil health while protecting water quality.

In Kansas, and across much of the Great Plains, winter cereals offer producers a cover crop option which overwinters well and generates large quantities of biomass prior to spring planting. The combination of winterhardiness and high biomass production ensures the soil surface remains under a protective layer of residue during a normally fallow period. While winter cereals are a promising conservation option for reducing erosion losses and decreasing weed pressure, Carver et al (2020) showed that up to 35% of total P within triticale crop tissue is readily water soluble. Work by Bechmann et al (2005), Cober et al. (2018), and Liu et al. (2019) also found that cover crop species directly impacted the quantity of water extractable P released from cover crop tissue. Rodehutscord et al. (2016) examined P concentration in the grain produced by multiple winter cereal species and found that winter cereal species directly impacts the concentration of P within the grain. Based on this finding, it can be inferred that concentrations of P within winter cereal tissue may also be variable across species. Quantifying the concentrations and amounts of P within the crop tissue for common winter cereal species would provide insight into the potential impact that selection of a particular winter cereal may have on water quality and nutrient cycling. With winter cereals offering producers multiple conservation advantages, it is imperative to identify winter cereal cover crop options that minimizes P release from cover crop tissue, therefore preserving the benefits of cover crops while decreasing potential P loss.

As cover crops grow and develop, they accumulate P within the crop tissue, creating a reservoir of P storage above the soil surface which may potentially serve as a P source into surface runoff (Liu et al., 2014b). The preservation in and/or release of P from crop residues can be influenced by management factors including species selection, termination method, and time after termination (Bechmann et al., 2005; Cober et al., 2018; Liu et al., 2019; Carver et al., 2020). While P is of major concern when dealing with water quality, it is also important to consider the behavior of other essential plant nutrients (e.g., N, K, and S) when evaluating the impacts of cover crops on potential nutrient availability to the subsequent cash crop.

The amount of nutrient released from crop residue is dependent upon the solubility, mobility, and quantity of the given nutrient in conjunction with rainfall amount and intensity (White, 1973). Substrate quality, microbial activity, and the physio-chemical environment also impact the decomposition process and subsequent release of nutrients (Heal et al., 1997). The quantity of nutrient within crop tissue is correlated to the physical and chemical nature of the plant, specifically, plant species, maturity, and overall plant health (Miller et al, 1994). Time after termination also directly impacts nutrient release from decomposing cover crop residue with P release significantly increasing as time after termination approaches two weeks post-termination (Carver et al., 2020). It is uncertain if P release continues to increase as time after termination increases; therefore, research identifying changes in P release during periods greater than two weeks post-termination is needed to fully understand P release from cover crop residue and its potential impact on water quality.

While P released from cover crop residue may impact water quality, release of P from cover crop residue is important if cover crops are to positively impact P cycling and potentially make assimilated P available for uptake by the subsequent cash crop (Damon et al., 2014). Additional research quantifying the changes in release of N, K, and S from cover crop tissue over time is also needed to provide producers and conservation agents necessary information for determining the impacts of winter cereal cover corps on nutrient cycling and soil health. Information examining the impact of winter cereal cover crop species and time after termination on nutrient release from cover crop tissue will enable further understanding of the potential of cover cropping as a conservation practice to protect water quality and promote soil health.

Information linking winter cereal cover crop species and time after termination to key processes which impact water quality (P loss), soil conservation (erosion/residue persistence), and soil health (nutrient cycling) is needed to allow producers to optimize conservation benefits of adding a winter cereal cover crop into their agricultural management system. Quantifying changes in total and water-extractable nutrient concentrations of cover crop residue and residue persistence will provide producers with decision-making tools when choosing to add a winter cereal cover crop to their agricultural management system. Specific objectives of this study were to determine the effects choice of winter cereal cover crop, on percent biomass remaining and total P, total N, K, S, and water extractable P (WEP) concentrations of cover crop residue over time.

Materials and Methods

This field study was conducted over the course of two years at two different locations in northeastern Kansas, USA, for a total of four growing environments. Field trials were located near Manhattan, KS, USA, and Leonardville, KS, USA and ran from 15 September 2019 through 25 August 2021

Experimental Design

This study evaluated the impacts of six choices of winter cereal cover crops on residue decomposition and nutrient release over time. Treatments were structured using a split-plot design and replicated four times (n = 24). Whole plot factor was choice of winter cereal cover crop and included winter barley (*Hordeum vulgare*), winter oat (*Avena sterilis*), cereal rye (*Secale cereale*), triticale (X *Tritico-secale*), winter wheat (*Triticum aestivum*), and Cereal Killer Blend (1:1:1:1 of barley:oat:rye:triticale). Sub-plot factor was time after termination: 7, 14, 28, 56, 84, and 112 d after termination.

Field Sites

Soil map unit at the 2020 Ashland Bottoms location (39.130174, -96.644313) is an eroded Smolan silty clay loam (fine, smectitic, mesic, Pachic Agriustoll) with 3-7% slope. Soil map unit at the 2021 Ashland Bottoms location (39.12971, -96.62351) is a Bismarkgrove-Kimo complex. Soil map unit at both the 2020 Leonardville location (39.32025, -96.86890) and 2021 Leonardville location (39.33939, -96.86864) is a Wymore silty clay loam with 0-1% slope. Climate at all locations is described as hot, humid, continental with a mean annual temperature of 12.9 °C.

Agricultural Management

In 2020 and 2021 at Ashland Bottoms, winter cereal cover crops were planted immediately following corn (*Zea mays*) harvest using a 3-m no-till grain drill with 19 cm row spacing and seeded a rate of 56 kg seed/ha (Table F.1). Cover crops were terminated via herbicide application prior to planting of soybean (*Glycine max*). In both 2020 and 2021, plots measured 3 m wide by 9.1 m long. Both Ashland Bottoms sites were under no-till management and used a corn-soybean rotation

In Leonardville, a 1.8-m no-till grain drill with 19 cm row spacing was used to plant cover crops for both the 2020 and 2021 growing seasons. Cover crops were plant at 56 kg seed/ha and were terminated via herbicide application prior to planting corn. During both 2020 and 2021, nitrogen was applied to all plots at a rate of 207 kg N/ha. In 2020, N was applied as urea ammonium nitrate (32-0-0) and in 2021, N was applied as urea (46-0-0). In both 2020 and 2021, plots measured 1.8 m wide by 3 m long. Both Leonardville locations were under no-till management and utilized a corn-soybean-wheat rotation

Cover Crop Biomass Collection

Cover crop tissue was harvested from an area 183 cm in length and 38 cm wide (two rows on 19 cm spacing) within the middle of plot for a total harvested area of 0.697 m^2 (approximately 9.8 times the surface area of one residue bag). Cover crop tissue was clipped at ground level, with care taken to not collect any previous crop residue or soil, and placed into a pre-weighed tote, homogenized, and weighed. The wet weight of the harvested cover crop biomass was then divided by 9.8 to determine the quantity of biomass to be placed in each residue bag. Six residue bags were filled with the calculated amount of cover crop biomass then sealed. An additional sample of harvest cover crop biomass was collected and weighed for moisture determination, nutrient analysis, and WEP at the time of cover crop harvest (1 d after termination). The remaining harvested cover crop biomass was then evenly spread out over the harvested area.

Residue Bag Construction, Placement, and Collection

This study utilized residue bags constructed of 18 x 16 weave fiberglass mesh (1.1 mm x 1.3 mm openings) measuring 30 cm x 30 cm in size. Residue bags were filled with a measured amount of harvested cover crop biomass based on the initial quantity of total biomass collected and sealed. The filled residue bags were then placed within the harvested plot area, randomized, and secured to the ground using landscape staples. Residue bags were collected at 7, 14, 28, 56, 84, and 112 d after termination of the cover crop. Collected residue bags were placed in a sealed tote for transport back to the laboratory.

Water-extractable Phosphorus

Concentration of WEP in the cover crop tissue was determined based on extraction procedures used by Carver et al. (2020). At the time of extraction (i.e., time after termination), approximately half of the cover crop tissue within the residue bag was removed, weighed, and placed into a 950 mL container filled with 500 mL of deionized water. The container was then sealed and placed on an end-to-end shaker for one hour at 180 oscillations per minute. After shaking, extracts were filtered through a 2-µm glass fiber pre-filter followed by a 0.45-µm nylon syringe filter. An approximately 15 mL aliquot of filtered extract was collected and stored at 4°C until analysis. Water-extractable P concentration of extracts was determining using the molybdate-blue colorimetric method with a flow-injection analyzer (QuickChem 8500 Series II; QuickChem Method 10-115-01-1-A, Lachat Instruments). Concentrations of WEP are expressed per unit of dry cover crop biomass.

Tissue Analysis for Phosphorus, Nitrogen, Potassium, and Sulfur

The remaining tissue within the residue bag was used for determination of moisture content and nutrient analysis. Cover crop tissue was dried using a forced air oven at 60 °C and then ground to pass through a 2.0 mm mesh sieve. Ground samples were then submitted to the Kansas State University Testing Laboratory for determination of total P, total N, K, and S concentrations within the cover crop tissue. Total P, total N, and K concentrations were determined using sulfuric peroxide digestion and measured using inductively coupled plasma (ICP) spectrometry (Linder & Harley, 1942; Thomas et al., 1967). Sulfur concentration was determined using perchloric digestion and ICP spectrometry (Gieseking et al., 1935).

The fraction of total P that is water-extractable (FracWEP) was determined by dividing the concentration of WEP by total P concentration and is reported as percentage of total P that is water extractable.

Residue Persistence

The remaining biomass was determined on a dry weight basis using moisture data from the day of collection (X d after termination). Residue persistence was calculated as the percentage of initial biomass remaining at the given collection timepoint.

Statistical Analysis

All data were analyzed using a linear mixed model with fixed effects of the model including winter cereal cover crop species, time after termination, and the interaction between winter cereal cover crop species and time after termination. Random effects of the model included replication, replication by winter cereal cover crop species, and replication by time after termination. Pairwise comparisons between two levels of a fixed were performed using a two-sided t-test for non-zero differences in means. Interactions between fixed effects of the model were examined at the α = 0.05 level. Statistical analysis was conducted using Statistical Analysis Software (SAS version 9.4; Cary, NC) PROC GLIMMIX with option DDFM = KR.

Data collected from the four unique growing environments were analyzed independently. For the 2020 Ashland Bottoms data, total C, WEP, FracWEP, mass of WEP, and C:N required natural logarithm transformation to satisfy the assumption of homogeneity of variance. For the 2021 Ashland Bottoms data, total C, WEP, FracWEP, and mass of WEP required natural logarithm transformation. For the 2020 Leonardville data WEP, FracWEP, and C:N required natural logarithm transformation and for the 2021 Leonardville data total C, WEP, FracWEP, mass of WEP, C:N, and C:P each required natural logarithm transformation. If transformation was required, data is presented as the back-transformed means.

Results

Residue Persistence

A main effect of time after termination on percent biomass remaining was observed in 2020 and 2021 for both the Ashland Bottoms and Leonardville locations (Table 5.1). For each growing environment, between 34.1-46.5% of the initial cover crop biomass was remaining at 112 d after termination (Figure 5.1). With the exception of 2021 Leonardville at 7 and 14 d after termination, rates of decomposition across growing environments followed similar trends with each measured timepoint having less cover crop biomass remaining than the timepoint prior. A main effect of cover crop species on percent biomass remaining was observed for 2020 Ashland Bottoms (Table 5.1) with triticale, winter wheat, and the cereal killer blend each exhibiting the greatest level of residue persistence with an average 57% of initial biomass remaining at 112 d after termination (Table 5.2). Across all growing environments, oat exhibited the lowest level of residue persistence with an average of approximately 34% initial biomass remaining at 112 d after termination (Table 5.2).

Phosphorous

A main effect of time after termination on total P concentration within cover crop tissue was observed for three of four growing environments (2020 Ashland Bottoms, 2021 Ashland Bottoms, and 2020 Leonardville, (Table 5.1). Each of these environments exhibited similar trends with total P concentration of cover crop tissue decreasing as time after termination increased (Table 5.3). Total P concentrations at 112 d after termination were between 228 and 616 mg P/kg less than initial total P concentrations (Table 5.3).

For 2020 Leonardville, a cover crop species effect was also observed with regards to total P concentration within the cover crop tissue (Table 5.1). For this growing environment, winter wheat was found to have the greatest total P concentration with 3129 mg P/kg cover crop tissue (Table 5.3). Concentrations of total P within winter wheat tissue were approximately 56% greater than both oat and rye (Table 5.3). For the 2021 Leonardville growing environment, oat had the significantly lowest concentration of total P of the examined species (Table 5.3).

A two-way interaction between winter cereal cover crop species and time after termination for total P concentration was observed for 2021 Leonardville (Table 5.1). The total P concentration for oat was significantly less than all other species at 14 d after termination and was among the least of all species for all other timepoints. With the exception of oat, the total P concentration of all other species were similar until 28 d after termination, at which point the total P concentration of triticale was greater than rye, cereal killer, and oat. The total P concentration of triticale biomass remained the greatest among species throughout the rest of the study (Table 5.3).

A two-way interaction between cover crop species and time after termination for FracWEP was observed in all four growing environments (Table 5.1). For 2020 Ashland Bottoms, at the initial sampling (pre-termination), winter wheat had the lowest FracWEP of all examined species (Table 5.3). This contrasts with all other examined growing environments where winter wheat had the greatest FracWEP at the initial sampling of all examined species. At 1 d after termination, each growing environment, with the exception of 2020 Ashland Bottoms, showed FracWEP for winter wheat to be between two to six times greater than all other species (Table 5.3). For all growing environments, from 7 through 112 d after termination, minute differences in FracWEP between winter cereal cover species were observed; however, these differences appear to be biologically inconsequential and suggest that FracWEP across winter cereal species is relatively consistent beyond 7 d after termination.

A main effect of time after termination on mass of P remaining in cover crop biomass was observed for both 2020 and 2021 Ashland Bottoms growing environments (Table 5.1). Both growing environments exhibited similar trends with regards to mass of P present where mass of P held constant from the initial sampling point until 28 d after termination at which point mass of P began to decrease (Figure 5.2). At 112 d after termination, the final mass of P present in cover crop biomass ranged from 60-62% less than mass of P present initially present (Table 5.4)

A two-way interaction between cover crop species and time after termination for mass of total P remaining was found for both the 2020 and 2021 Leonardville growing environments (Table 5.1). For 2020 Leonardville, the interaction is driven by the 14 d after termination data where rye had a similar mass of P remaining compared to winter wheat and greater than all other cover crop treatments (Figure 5.3a). Oat had the least P remaining, which was statistically similar to triticale, but less than all other cover crop treatments. For all other timepoints (with exception of 84 d after termination), rye, triticale, winter wheat, and the cereal killer blend all had similar masses of total P remaining and this mass was greater than oats (Table 5.4). The two-way interaction for 2021 Leonardville is driven by oat having the least mass of total P present for all cover crop species from 14 through 84 d after termination, yet at 112 d after termination, mass of total P present in oat is similar to that present in barley, triticale, and cereal killer blend (Table 5.4; Figure 5.3).

A main effect of time after termination was found for mass of WEP present for both 2021 Ashland Bottoms and 2020 Leonardville (Table 5.1). For both growing environments, mass of WEP exhibited a decrease over time with final masses of WEP present at 112 d after termination for both growing environments being approximately 60% less than that present at 7 d after termination (Table 5.5). For both the 2020 Ashland Bottoms and 2021 Leonardville growing environments, a two-way interaction between winter cereal cover crop species and time after termination was observed (Table 5.1). For the 2020 Ashland Bottoms growing environment, no differences between cover crop species were observed from 56 to 112 d after termination. The two-way interaction is driven by oat having less mass of WEP compared to rye at 14 d after termination, yet oat equals rye at all other timepoints (Table 5.5). For the 2021 Leonardville growing environment, final mass of WEP in cover crop tissue was relatively similar across all examined species except oat which had less WEP compared to triticale at both 14 and 56 d after termination, and less WEP than all other species at 84 d after termination (Table 5.5).

Nitrogen, Potassium, and Sulfur

A main effect of time after termination on mass of N remaining in cover crop tissue was observed for the 2020 and 2021 Ashland Bottoms growing environments along with the 2021 Leonardville growing environment (Table 5.1). For the 2021 Ashland Bottoms and 2021

Leonardville environments, the mass of N in the residue held constant from termination until 56 d after termination, where afterwards mass of N decreased each time point (Table 5.6). By 112 d after termination, the mass of N in residue at the 2021 Ashland bottoms and 2021 Leonardville environments was 19% and 32% less than at 7 d after termination respectively. The mass of N in residue at the 2020 Ashland Bottoms environment decreased at 56 and 84 d after termination, but then increased at 112 d after termination back similar to the mass of N present at 14 d after termination.

A two-way interaction between cover crop species and time after termination for mass of N during the 2020 Leonardville growing environment was also observed (Table 5.1). At 7 d after termination, no differences between winter cereal cover crop species were observed with each species having approximately 3.5 g N/m^2 (Table 5.6). As time after termination increased, subtle differences between cover crop species were observed with oat having the least mass of N compared to all other species at 84 d after termination. Although not always significant, oat tended to have the least mass of N compared to all other species at each timepoint. Across all examined species, mass of N decreased between 26-70% (Table 5.6).

A main effect of time after termination on mass of K present with the cover crop tissue was observed for the 2020 Ashland Bottoms growing environment (Table 5.1). At 112 d after termination, the mass of K present had decreased by approximately 88% compared to the mass of K present at 7 d after termination (Table 5.6). For all other growing environments, a two-way interaction between cover crop species and time after termination on mass of K in cover crop biomass was observed (Table 5.1). For both 2020 and 2021 Leonardville, oat tended to have the smallest mass of K present compared to other species (Table 5.6). Differences between species appeared at earlier times after termination for each of the three growing environments, but for the

2020 Ashland Bottoms growing environment, no differences in mass of K were observed between the examined species from 28 through 112 d after termination (Table 5.6). No differences between mass of K were observed from 84 to 112 d after termination for both 2020 and 2021 Leonardville. (Table 5.6).

A main effect of time after termination on mass of S present was observed for the 2021 Ashland Bottoms along with the 2020 and 2021 Leonardville growing environments (Table 5.1). Across these growing environments, mass of S present at 112 d after termination was found to be approximately 11-43 % less than the mass of S present at the first sampling date (Table 5.7). A main effect of winter cereal cover crop species was also observed for the 2020 Leonardville growing environment where rye was found to have greater S mass compared to both triticale and oat, yet a similar S mass as winter wheat and cereal killer blend (Table 5.1; Table 5.7). Oat was observed to have the lowest mass of S present on a per area basis (Table 5.7).

A cover crop species by time after termination interaction for mass of S was observed for the 2021 Leonardville growing environment (Table 5.7). For this growing environment, oat was found to have the statistically lowest mass of S at 7 d after termination and the numerically lowest mass of S at all other timepoints. Although not statistically different than the other winter cereal cover crop species, rye had the greatest mass of S present at each timepoint (Table 5.7).

Discussion

Soil Conservation

Residue persistence could be an important factor contributing to cover crop effects on soil erosion, where cover crop species that have less degradation would provide for more extended ground cover and soil protection. Residue persistence of the examined winter cereal cover crop species was found to be similar across species. Although the occasional effect of winter cereal species on percent biomass remaining was observed, differences between species were inconsistent and/or contrasting across growing environments. Decomposition rate of crop residue is known to be directly impacted by a variety of factors including physical and chemical properties of the crop residue, interactions between soil microflora and fauna, and climatic conditions with climatic variation and microbial accessibility perhaps being the chief drivers of the rate of decomposition (Swift et al., 1979; Buchanan & King, 1993). Climatic conditions at each growing environment were same and may partially explain the lack of variation between winter cereal species with regards to residue persistence.

The ratio of carbon to nitrogen (C:N) in plant tissue is also a known driver for the length of time require for crop residue decomposition and has long been recognized as a potential indicator of potential residue decomposition rate (Canalli et al., 2020; Salter, 1931). For the 2020 Ashland Bottoms and 2021 Leonardville growing environments, a two-way interaction between winter cereal species and time after termination was observed for C:N of collected material ($p < 0.05$, Table F.2), yet no differences were observed between choice in cover crop with regards to percentage of cover crop biomass remaining. A main effect of species on C:N was also observed for the 2020 Leonardville environment ($p < 0.001$, Table F.2), with oat and wheat having the lowest C:N compared to all other species, yet no differences in remaining cover crop biomass between species were observed. Ratios of carbon to nitrogen for each growing environment ranged from 23.6-33.4 at the time of initial sampling to 14.9-20.0 at 112 d after termination (Table F.2). The lack of differences between winter cereal cover crop species with regards to residue persistence when variations in C:N were observed suggests that exclusively using the C:N of crop tissue as an indicator of potential residue decomposition rate may not accurately reflect residue decomposition and, consequently, residue persistence. This conclusion is similar to those drawn by Reinertsen et al. (1984) and Smith and Peckenpaugh (1986) who each suggested that determining C:N based on available concentrations of C and N within crop tissue rather than using total C and N concentrations provides a better estimate of crop tissue decomposition in the field.

Phosphorus Loss

Addition of a cover crop into an agricultural management system may greatly alter P cycling through the cover crop's assimilation of P from the soil system and subsequent deposition upon the soil surface during the decomposition process (Noack et al., 2014; Damon et al., 2014). Ultimately, the impact of P contained in cover crop tissue on water quality is dependent upon the preservation of P within the crop tissue during times of high loss potential and synchronization of release with periods of crop uptake (Liu et al., 2014b, 2019; Nair, 1993).

In three out of four growing environments, at one d after termination, winter wheat had the statistically greatest FracWEP of all examined winter cereal cover crop species. Water-extractable P in cover crop tissue has been used as an indicator of potential dissolved reactive P in runoff (Toor et al., 2006; Wang et al., 2010; Carver et al., 2020) Several studies have recently identified increased concentrations of dissolved reactive P in surface runoff associated with the addition of a cover crop during a normally fallow period (Aronsson, et al. 2016; Hanrahan et al., 2021; Carver et al., 2022). Findings from this study suggest that choosing winter wheat over other winter cereals as a cover crop may increase the potential for dissolved reactive P release to surface runoff due to greater FracWEP in winter wheat residue.

For both 2020 and 2021 Leonardville growing environments, oat was found to have the least mass of total P of all examined winter cereals. The small mass of total P present for the oat treatment is likely a result of oat having the statistically lowest concentration of total P present within the cover crop tissue. Additionally, based on visual observation, oat appeared to have the smallest amount of total biomass produced during both the 2020 and 2021 Leonardville growing environments. The small biomass production of the oat treatment combined with its low concentrations of total P explains why oat had the least amount of total P present when compared to the other examined winter cereal species. This suggests that selecting oat as a winter-grown cover crop species may minimize the potential risk of P loss associated with adding a cover crop compared to selecting other winter cereals which were observed to have greater masses of P present.

Soil Fertility

The ability of a cover crop to contribute to soil fertility and plant nutrition is dependent on decomposition of plant tissue and the subsequent release of assimilated nutrients (Adediran et al., 2003). The mass of nutrients contributed by a cover crop is dependent on the concentration of nutrient within the cover crop tissue in conjunction with the total biomass produced by the cover crop (Griffin et al., 2000), and the rate at which those nutrients are released (i.e., decomposition rate). In this study, the mass of N, K, and S assimilated within cover crop residue and deposited on the soil surface was similar across the majority of the examined winter cereal species. Of the examined winter cereals, oat tended to have the lowest mass of N, K, and S for all growing environments and tended to exhibit the lowest level of residue persistence. The rapid decomposition of oat compared to the other examined winter cereal cover crops suggests that although the total quantity of nutrients released from oat may be less than other winter cereals, the rate at which the nutrients are released may be quicker; subsequently, the nutrients assimilated in oat may be more readily available for uptake by the following cash crop.

During the course of this study, two growing environments (2020 and 2021 Ashland Bottoms) exhibited a clear effect of time after termination on mass of total P present, regardless of winter cereal species. For these growing environments, the mass of total P present held constant from the time of termination until 28 d after termination, at which point significant quantities of P began to release from the decomposing residue. This finding suggests that producers could termination their winter cereal cover corps approximately one month prior to planting of the subsequent cash crop to better synchronize P release from the decomposing residue with periods of cash crop uptake. This is similar to findings from Murungu et al. (2011) who compared P release from grazing vetch (*Vicia darsycarpa*), forage pea (*Pisum sativum*), and oats over time and demonstrated that P release from winter-sown cover crops began approximately one month after termination.

The decomposition of cover crop residue may provide a valuable source of P to both subsequent crops and the soil microbial community (Noack et al., 2012). The fate of P within cover crop residue is directly impacted by the C:P ratio of the tissue with C:P ratios of less than 200:1 resulting in the promotion of P mineralization (Dalal, 1977; Maltais-Landry et al., 2014). For both 2020 and 2021 Leonardville growing environments, a two-way interaction between choice in winter cereal cover and time after termination was observed with regards to C:P ratio of cover crop residue (Table F.2.), yet all calculated C:P ratios were less than 200:1 indicating that net mineralization of P within all examined choices in winter cereal cover crops should occur.

Conclusions

Data from this study indicate that cereal rye, triticale, barley, and the cereal killer blend each exhibit similar trends regarding residue persistence and their potential impacts on water quality and nutrient cycling. This finding suggests that when choosing a winter cereal cover crops these four choices should be interchangeable in the development a cover crop management strategy which promotes the longevity of residue retentions and promotes environmental quality. The large concentrations of total P present in winter wheat at/near termination suggest that winter wheat may have a greater negative impact on water quality early in the main crop growing season when compared to the other selections of winter cereal examined in this study. Of the examined species, oat offers producer the lowest level of residue persistence compared to the other examined winter cereals; although, oat may more readily release assimilated nutrients compared to other winter cereal options suggesting that nutrients assimilated by oat may be more readily available for uptake by the subsequent cash crop.

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Tables

Table 5.1 ANOVA table for data collected from both 2020 and 2021 Ashland Bottoms and both 2020 and 2021 Leonardville locations. Table abbreviations include sulfur present as sulfate (SO_4-S), water-extractable phosphorus (WEP), and percentage of total phosphorus that is water-extractable (FracWEP). Bolded values indicate significance at alpha = 0.05.

Location		Biomass Remaining	Total C	Total P	FracWEP	Mass P	Mass WEP	Mass N	Mass K	Mass SO_4-S
2020 Ashland Bottoms										
	Species	**<0.001**	**0.047**	0.091	0.655	0.466	0.343	0.397	0.28	**0.035**
	Time	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Species*Time	0.299	**0.037**	0.071	**0.02**	0.587	0.31	0.103	0.352	**<0.001**
2021 Ashland Bottoms										
	Species	0.388	**0.002**	0.174	0.807	0.599	0.319	0.679	0.454	0.593
	Time	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.005**	**<0.001**	**<0.001**
	Species*Time	0.387	**0.011**	0.499	**<0.001**	0.237	**0.03**	0.594	**0.022**	0.056
2020 Leonardville										
	Species	0.105	**<0.001**	**0.003**	**<0.001**	**0.020**	**0.013**	0.058	0.372	**0.036**
	Time	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Species*Time	0.096	**<0.001**	0.477	**0.014**	**<0.001**	0.213	**0.008**	**0.006**	0.16
2021 Leonardville										
	Species	0.413	**0.004**	**0.005**	**0.011**	**0.001**	0.076	0.269	**0.007**	0.501
	Time	**<0.001**	0.057	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.001**
	Species*Time	0.229	**<0.001**	**0.02**	**<0.001**	**0.005**	**0.002**	0.278	**0.005**	0.252

Table 5.2 Least square Means table for percent cover crop biomass remaining for all four growing environments. Letters represent significant differences between treatments at *p*-value < 0.05 and NS signifies no significant difference because the F-test for the main effect or interaction was not significant (*p*-value > 0.05).

Time	Species	Biomass Remaining (%)			
		Ashland Bottoms		*Leonardville*	
		2020	*2021*	*2020*	*2021*
Main effect of time					
Initial		.	.	.	.
1 d		.	.	.	.
7 d		.	91.9 A	96.6 A	92.4 A
14 d		73.6 A	84.3 B	85.7 B	92.2 A
28 d		65.0 B	76.7 C	78.6 C	79.0 B
56 d		53.4 C	66.5 D	63.0 D	68.4 C
84 d		50.4 C	51.8 E	51.8 E	59.0 D
112 d		41.3 D	46.5 F	34.1 F	45.3 E
Main effect of species					
	Barley	54.7 BC	70.8	-	70.6
	Oat	41.0 D	-	65.8	70.9
	Rye	48.3 CD	70.9	72.7	75.4
	Triticale	68.1 A	70.6	63.1	68.5
	Wheat	66.8 A	71.3	70.7	73.4
	Cereal Killer	61.5 AB	64.6	69.4	77.5
Time by species interaction					
7 d	Barley	.	92.5	.	92.1
7 d	Oat	.	.	95.4	86.6
7 d	Rye	.	89.1	97.0	94.6
7 d	Triticale	.	93.4	95.8	94.8
7 d	Wheat	.	93.2	96.8	95.2
7 d	Cereal Killer	.	91.2	98.1	90.8
14 d	Barley	69.2	86.8	.	93
14 d	Oat	62.0	.	85.0	88.6
14 d	Rye	63.4	84.5	92.4	94.3
14 d	Triticale	83.3	86.7	81.3	92.8
14 d	Wheat	86.7	86.7	90.2	90.9
14 d	Cereal Killer	76.9	76.7	79.7	93.8
28 d	Barley	58.8	79.6	.	75.6
28 d	Oat	51.1	.	76.1	72.1
28 d	Rye	55.6	81.4	81.5	83
28 d	Triticale	73.6	74.9	72.9	75.5
28 d	Wheat	77.4	73.5	81.5	78.2
28 d	Cereal Killer	73.2	74.3	81.1	89.9
56 d	Barley	53.6	66.5	.	69.7
56 d	Oat	27.8	.	59.7	62.8
56 d	Rye	43.2	68.9	64.3	74.2
56 d	Triticale	75.0	68.9	52.5	63.5
56 d	Wheat	58.9	66.1	65.9	65.1
56 d	Cereal Killer	62.0	62.3	72.8	75.2
84 d	Barley	40.8	54.2	.	51.5
84 d	Oat	27.8	.	52.0	77.0
84 d	Rye	34.7	48.2	57.3	58.4
84 d	Triticale	49.4	53.7	47.2	44.4
84 d	Wheat	51.6	56.6	50.4	58.2
84 d	Cereal Killer	43.4	46.5	52.3	64.3

Time	Species	Biomass Remaining (%)			
		Ashland Bottoms		*Leonardville*	
		2020	***2021***	***2020***	***2021***
112 d	Barley	50.9	45.3	.	41.8
112 d	Oat	36.2	.	26.5	38.1
112 d	Rye	44.4	53.0	43.5	47.7
112 d	Triticale	59.1	46.0	29.1	40.3
112 d	Wheat	59.5	51.7	39.2	53
112 d	Cereal Killer	52.1	36.8	32.5	50.9

Table 5.3. Least square means for total P concentration and percentage of total P that is water extractable for data collected from all growing environments. Means within an effect and environment followed by the same letter are not significantly different (p>0.05). Significant differences are only indicated for the effects with a significant F-test (see Table 5.1).

Time	Species	Total P				Fraction of total P that is water-extractable			
		Ashland Bottoms		Leonardville		Ashland Bottoms		Leonardville	
		2020	2021	2020	2021	2020	2021	2020	2021
		mg kg^{-1}				%			
Main effect of time									
Initial		1702 A	2245 A	3089 A	3110 C	0.3 D	0.3 D	1.0 E	0.7 D
1 d		1813 A	2080 AB	2833 BC	2831 D	1.3 D	0.2 D	3.1 E	0.6 D
7 d			2055 AB	2801 BC	2990 CD		16.7 A	18.1 B	16.3 B
14 d		1320 D	2085 AB	2683 C	3117 C	2.8 C	2.6 D	10.1 CD	18.3 AB
28 d		1351 CD	2175 A	2954 AB	3326 B	7.6 A	12.3 B	7.2 D	18.1 AB
56 d		1496 BC	1850 BC	2855 BC	3443 AB	6.8 B	12.1 B	11.6 CD	20.9 AB
84 d		1515 B	1840 BC	2797 BC	3310 B	8.5 AB	8.4 C	25.5 A	23.3 A
112 d		1474 BC	1762 C	2473 D	3617 A	4 C	11.9 B	19.4 B	2.8 C
Main effect of species									
	Barley	1678	2088		3318 AB	2.9	3.3		4.9 C
	Oat	1511		2616 C	2581 C	2.4		10.3 AB	6.4 B
	Rye	1549	1972	2600 C	3244 AB	2.8	4.1	6.6 C	6.6 B
	Triticale	1423	2072	2834 BC	3683 A	2.6	4.2	7.2 BC	6.5 B
	Wheat	1629	1847	3129 A	3385 AB	3.1	4.6	10.9 A	8.7 A
	Cereal Killer	1356	2078	2873 B	3096 B	3.6	3.5	7.8 BC	6.3 BC
Time by species interaction									
Initial	Barley	2018	2550		3010 A	0.4 A	0.15 BC		0.2 C
Initial	Oat	1545		2925	2388 B	0.4 A		1.7 A	0.7 B
Initial	Rye	1730	2400	2913	3423 A	0.3 A	0.29 BC	0.6 B	0.7 B
Initial	Triticale	1538	2325	3150	3562 A	0.3 A	0.43 B	1 AB	1 B
Initial	Wheat	1898	1800	3455	3292 A	0.1 B	2.11 A	1.7 A	2.3 A
Initial	Cereal Killer	1483	2150	3003	2985 AB	0.3 A	0.13 C	0.7 B	0.8 B
1 d	Barley	1970	2200		2768 AB	1.2 A	0.15 B		0.3 C
1 d	Oat	1455		2573	2178 B	1.4 A		4.1 AB	0.5 BC
1 d	Rye	2100	2050	2600	2977 A	0.8 A	0.15 B	2.3 B	0.6 BC
1 d	Triticale	1718	1975	2865	3123 A	1.3 A	0.21 B	2.4 B	0.6 BC
1 d	Wheat	2013	2050	3240	3057 A	1.9 A	1.04 A	5.6 A	1.5 A
1 d	Cereal Killer	1625	2125	2885	2885 A	1.3 A	0.18 B	2.4 B	0.6 B
7 d	Barley		2075		2888 A		17.05 A		15.6 B
7 d	Oat			2490	2173 B			27.3 A	31.5 A
7 d	Rye		2000	2665	3120 A		13.95 A	15.5 AB	16.9 AB
7 d	Triticale		2050	2793	3473 A		16.62 A	14 B	10.9 B
7 d	Wheat		2100	3213	3277 A		15.7 A	21.8 AB	18.3 AB
7 d	Cereal Killer		2050	2845	3008 A		20.96 A	15.1 AB	11.2 B
14 d	Barley	1505	2100		3140 A	2.4 ABC	2.77 A		17.4 A
14 d	Oat	1318		2310	2190 B	1.5 BC		11.7 AB	28.5 A
14 d	Rye	1198	2175	2618	3390 A	6.5 A	4.83 A	8.5 AB	14.5 A
14 d	Triticale	1005	2150	2690	3550 A	1.2 C	3.66 A	6.4 B	17.9 A
14 d	Wheat	1590	1775	2930	3412 A	4.1 A	0.59 B	11.8 AB	15.4 A
14 d	Cereal Killer	1308	2225	2865	3020 A	3.7 AB	3.84 A	13.6 A	18.8 A
28 d	Barley	1433	2200		3430 AB	4.8 BC	10.63 A		20.4 AB
28 d	Oat	1305		2770	2655 C	3.5 C		8.2 A	36.4 A
28 d	Rye	1350	2125	2643	3320 B	7.4 ABC	14.64 A	6.3 AB	16.8 B
28 d	Triticale	1355	2325	3238	4025 A	10.8 AB	12.25 A	4.1 B	11 B
28 d	Wheat	1425	1875	3185	3435 AB	7.4 ABC	10.33 A	9.5 A	20.4 AB
28 d	Cereal Killer	1238	2350	2933	3090 BC	19 A	14.15 A	9.8 A	12.5 B

Time	Species	Total P				Fraction of total P that is water-extractable			
		Ashland Bottoms		Leonardville		Ashland Bottoms		Leonardville	
		2020	2021	2020	2021	2020	2021	2020	2021
		mg kg^{-1}				%			
56 d	Barley	1735	1775		3723 AB	7.5 A	16.06 A		20 AB
56 d	Oat	1545		2928	2923 C	6.8 A		20 A	13 B
56 d	Rye	1545	1625	2570	3177 BC	5.6 A	14.84 A	9.3 B	22.4 AB
56 d	Triticale	1473	2000	2710	3958 A	5.2 A	14 A	15.5 AB	27 A
56 d	Wheat	1558	1825	3178	3415 ABC	9.1 A	8.95 A	8.4 B	23.2 AB
56 d	Cereal Killer	1120	2025	2890	3465 ABC	7.5 A	8.83 A	8.7 B	22.9 AB
84 d	Barley	1598	1975		3698 A	8.9 A	5.9 A		15.1 B
84 d	Oat	1708		2380	2840 B	7.8 A		20.3 B	13.9 B
84 d	Rye	1405	1775	2683	3057 B	5.9 A	11.27 A	20.1 B	27.9 AB
84 d	Triticale	1520	1925	2793	3830 A	8.6 A	10.67 A	22.6 B	30.5 A
84 d	Wheat	1480	1550	3188	3350 AB	12.4 A	6.17 A	45.7 A	26.1 AB
84 d	Cereal Killer	1380	1975	2940	3083 B	8.7 A	9.57 A	25.8 AB	34.6 A
112 d	Barley	1490	1833		3890 AB	4.5 A	13.12 A		3.7 A
112 d	Oat	1703		2550	3301 BC	2.9 A		16.9 A	1.5 B
112 d	Rye	1518	1625	2110	3491 ABC	3.8 A	11.48 A	17.2 A	3.7 A
112 d	Triticale	1353	1825	2435	3947 A	4 A	9.47 A	23.4 A	3.3 A
112 d	Wheat	1443	1800	2642	3840 AB	4.3 A	16.36 A	22.4 A	2.8 AB
112 d	Cereal Killer	1338	1725	2628	3233 C	4.9 A	10.04 A	18.2 A	2.6 AB

Table 5.4 Least square Means table for final mass of phosphorus present in cover crop tissue for all four growing environments. Letters represent significant differences between treatments at *p*-value < 0.05 and NS represents no significant difference because the F-test for the main effect or interaction was not significant (*p*-value > 0.05).

Time	Species	Mass P			
		Ashland Bottoms		Leonardville	
		2020	*2021*	*2020*	*2021*
		g/m^2			
Main effect of time					
Initial		.	.	.	.
1 d		.	.	.	.
7 d		.	0.36 A	0.71	1.49
14 d		0.21 A	0.36 A	0.61	1.56
28 d		0.2 A	0.34 A	0.60	1.39
56 d		0.17 B	0.24 B	0.48	1.23
84 d		0.12 C	0.19 C	0.37	0.93
112 d		0.15 B	0.16 C	0.23	0.85
Main effect of species					
	Barley	0.18	0.23	.	1.18
	Oat	0.13	.	0.31	0.62
	Rye	0.16	0.34	0.65	1.47
	Triticale	0.22	0.28	0.47	1.48
	Wheat	0.17	0.29	0.56	1.47
	Cereal Killer	0.17	0.23	0.52	1.24
Time by species interaction					
7 d	Barley	.	0.27	.	1.28 CD
7 d	Oat	.	.	0.44 B	0.83 D
7 d	Rye	.	0.46	0.9 A	1.73 ABC
7 d	Triticale	.	0.34	0.72 A	1.9 A
7 d	Wheat	.	0.39	0.77 A	1.84 AB
7 d	Cereal Killer	.	0.32	0.72 A	1.39 BC
14 d	Barley	0.22	0.32	.	1.53 AB
14 d	Oat	0.17	.	0.38 C	0.75 C
14 d	Rye	0.2	0.48	0.82 A	1.93 A
14 d	Triticale	0.24	0.37	0.56 BC	1.93 A
14 d	Wheat	0.22	0.34	0.69 AB	1.8 AB
14 d	Cereal Killer	0.21	0.3	0.58 B	1.43 B
28 d	Barley	0.21	0.3	.	1.26 B
28 d	Oat	0.17	.	0.38 B	0.66 C
28 d	Rye	0.21	0.42	0.73 A	1.67 AB
28 d	Triticale	0.23	0.37	0.65 A	1.74 A
28 d	Wheat	0.22	0.3	0.65 A	1.6 AB
28 d	Cereal Killer	0.18	0.29	0.6 A	1.42 AB
56 d	Barley	0.18	0.19	.	1.18 A
56 d	Oat	0.1	.	0.32 B	0.67 B
56 d	Rye	0.15	0.25	0.57 A	1.46 A
56 d	Triticale	0.26	0.25	0.37 B	1.42 A
56 d	Wheat	0.15	0.29	0.57 A	1.27 A
56 d	Cereal Killer	0.18	0.2	0.59 A	1.4 A
84 d	Barley	0.12	0.18	.	1 A
84 d	Oat	0.1	.	0.21 B	0.4 B
84 d	Rye	0.12	0.2	0.51 A	1.06 A
84 d	Triticale	0.15	0.21	0.35 AB	0.98 A
84 d	Wheat	0.12	0.19	0.41 A	1.14 A
84 d	Cereal Killer	0.12	0.16	0.39 AB	1 A

Time	Species	Mass P			
		Ashland Bottoms		Leonardville	
		2020	*2021*	*2020*	*2021*
		g/m^2			
112 d	Barley	0.15	0.14	.	0.81 AB
112 d	Oat	0.13	.	0.11 B	0.42 B
112 d	Rye	0.14	0.2	0.34 A	1 A
112 d	Triticale	0.2	0.16	0.19 AB	0.89 AB
112 d	Wheat	0.14	0.21	0.28 AB	1.15 A
112 d	Cereal Killer	0.16	0.1	0.22 AB	0.81 AB

Table 5.5 Least square Means table for final mass of water-extractable phosphorus (WEP) remaining in cover crop tissue for all four growing environments. Letters represent significant differences between treatments at *p*-value < 0.05 with NS standing for "Not Significant" because the F-test for the main effect or interaction was not significant (*p*-value > 0.05).

Time	Species	Mass of WEP			
		Ashland Bottoms		Leonardville	
		2020	*2021*	*2020*	*2021*
		g/m2			
Main effect of time					
Initial		.	.	.	.
1 d		.	.	.	.
7 d		.	0.059 A	0.133 A	0.251
14 d		0.012 B	0.013 D	0.066 B	0.277
28 d		0.020 A	0.045 AB	0.051 B	0.261
56 d		0.013 B	0.035 BC	0.057 B	0.286
84 d		0.012 B	0.019 D	0.110 A	0.257
112 d		0.007 C	0.022 CD	0.052 B	0.028
Main effect of species					
	Barley	0.011	0.027	.	0.202
	Oat	0.006	.	0.057	0.140
	Rye	0.012	0.043	0.086	0.268
	Triticale	0.017	0.033	0.061	0.247
	Wheat	0.014	0.030	0.111	0.269
	Cereal Killer	0.017	0.027	0.076	0.237
Time by species interaction					
7 d	Barley	.	0.043	.	0.223 AB
7 d	Oat	.	.	0.120	0.242 AB
7 d	Rye	.	0.064	0.152	0.301 AB
7 d	Triticale	.	0.061	0.105	0.210 AB
7 d	Wheat	.	0.060	0.180	0.341 A
7 d	Cereal Killer	.	0.066	0.109	0.188 B
14 d	Barley	0.009 AB	0.013	.	0.267 AB
14 d	Oat	0.004 B	.	0.046	0.200 B
14 d	Rye	0.023 A	0.022	0.072	0.300 AB
14 d	Triticale	0.012 AB	0.014	0.040	0.475 A
14 d	Wheat	0.010 AB	0.004	0.091	0.281 AB
14 d	Cereal Killer	0.012 AB	0.014	0.080	0.269 AB
28 d	Barley	0.013 C	0.037	.	0.269 A
28 d	Oat	0.007 C	.	0.039	0.213 A
28 d	Rye	0.016 C	0.072	0.056	0.288 A
28 d	Triticale	0.032 AB	0.044	0.032	0.206 A
28 d	Wheat	0.018 BC	0.031	0.065	0.333 A
28 d	Cereal Killer	0.035 A	0.041	0.062	0.259 A
56 d	Barley	0.013 A	0.036	.	0.234 BC
56 d	Oat	0.006 A	.	0.066	0.101 C
56 d	Rye	0.009 A	0.048	0.053	0.355 AB
56 d	Triticale	0.017 A	0.040	0.061	0.383 A
56 d	Wheat	0.018 A	0.032	0.053	0.314 AB
56 d	Cereal Killer	0.017 A	0.017	0.054	0.328 AB
84 d	Barley	0.011 A	0.012	.	0.188 BC
84 d	Oat	0.008 A	.	0.048	0.075 C

Time	Species	Mass of WEP			
		Ashland Bottoms		**Leonardville**	
		2020	*2021*	*2020*	*2021*
			———————— g/m2———————		
84 d	Rye	0.008 A	0.026	0.113	0.319 AB
84 d	Triticale	0.014 A	0.022	0.084	0.301 AB
84 d	Wheat	0.018 A	0.017	0.197	0.310 AB
84 d	Cereal Killer	0.011 A	0.018	0.107	0.351 A
112 d	Barley	0.007 A	0.020	.	0.030 A
112 d	Oat	0.005 A	.	0.022	0.007 A
112 d	Rye	0.006 A	0.029	0.068	0.042 A
112 d	Triticale	0.008 A	0.019	0.046	0.033 A
112 d	Wheat	0.008 A	0.034	0.080	0.031 A
112 d	Cereal Killer	0.009A	0.009	0.043	0.025 A

Table 5.6 Least square means for mass of nitrogen (N) and potassium (K) present in cover crop tissue for all four growing environments. Letters represent significant differences between treatments at *p*-value < 0.05. Values that are not significant different are indicated by NS because the F-test for the main effect or interaction was not significant (*p*-value > 0.05).

Time	Species	Mass N				Mass K			
		Ashland Bottoms		Leonardville		Ashland Bottoms		Leonardville	
		2020	2021	2020	2021	2020	2021	2020	2021
		g/m^2							
Main effect of time									
Initial		.							
1 d		.							
7 d		.	2.03 A	3.50 A	7.03 B	.	2.76 A	4.88 A	12.09 A
14 d		2.35 A	1.98 AB	3.49 A	7.89 A	2.20 A	2.08 B	3.78 B	12.53 A
28 d		2.28 A	2.08 A	3.48 A	6.27 C	1.42 B	1.53 C	2.39 C	9.87 B
56 d		1.97 B	1.72 BC	2.84 B	5.84 CD	0.57 C	0.89 D	1.87 D	7.68 C
84 d		1.74 C	1.56 C	2.56 B	5.10 DE	0.25 D	0.51 E	1.02 E	4.85 D
112 d		2.27 A	1.66 C	1.85 C	4.80 E	0.26 D	0.42 E	0.44 F	3.53 E
Main effect of species									
	Barley	2.05	1.68	.	5.58	0.67	1.00	.	9.32
	Oat	1.84	.	2.26	4.42	0.96	.	1.80	5.08
	Rye	1.99	2.16	3.51	7.04	0.92	1.85	2.88	9.53
	Triticale	2.69	1.80	2.66	6.78	1.21	1.52	2.43	9.74
	Wheat	2.03	2.15	3.39	7.04	0.77	1.33	2.34	8.30
	Cereal Killer	2.12	1.41	2.95	6.07	1.09	1.11	2.54	8.60
Time by species interaction									
7 d	Barley	.	1.89	.	5.58	.	2.01 B	.	12.22 AB
7 d	Oat	.	.	3.05 A	5.67	.	.	3.81 C	8.74 B
7 d	Rye	.	2.70	3.94 A	8.06	.	3.88 A	5.73 A	13.06 A
7 d	Triticale	.	1.84	3.30 A	8.33	.	2.73 AB	5.35 AB	15.07 A
7 d	Wheat	.	2.18	3.96 A	8.51	.	2.60 B	4.17 BC	12.01 AB
7 d	Cereal Killer	.	1.56	3.25 A	6.03	.	2.56 B	5.36 AB	11.47 AB
14 d	Barley	2.16	1.87	.	7.25	1.45	1.66 B	.	14.61 AB
14 d	Oat	2.27	.	3.23 B	5.51	2.65	.	2.90 B	7.85 C
14 d	Rye	2.14	2.56	3.73 AB	8.80	2.48	3.20 A	4.61 A	14.79 AB
14 d	Triticale	2.97	1.81	2.95 B	9.04	2.49	2.21 AB	4.27 A	15.28 A
14 d	Wheat	2.10	2.36	4.30 A	9.15	1.70	1.58 B	3.59 AB	11.15 BC
14 d	Cereal Killer	2.44	1.32	3.25 B	7.58	2.41	1.75 B	3.54 AB	11.52 ABC
28 d	Barley	2.19	1.88	.	5.51	1.18	1.26 A	.	10.74 A
28 d	Oat	2.41	.	2.79 B	4.73	1.45	.	1.62 A	5.55 B
28 d	Rye	2.09	2.47	3.97 A	6.91	1.14	1.99 A	2.65 A	10.53 A
28 d	Triticale	2.50	2.14	3.37 AB	7.36	1.60	1.97 A	2.75 A	12.35 A
28 d	Wheat	2.38	2.14	3.94 A	6.87	1.33	1.43 A	2.40 A	9.71 A
28 d	Cereal Killer	2.09	1.78	3.33 AB	6.22	1.80	1.00 A	2.56 A	10.35 A
56 d	Barley	1.94	1.45	.	5.50	0.28	0.53 A	.	8.00 AB
56 d	Oat	1.18	.	2.19 C	4.33	0.30	.	1.31 AB	4.68 B
56 d	Rye	2.01	1.85	3.24 AB	6.91	0.43	0.92 A	2.16 AB	8.84 A
56 d	Triticale	2.91	1.75	2.26 BC	5.89	1.16	1.02 A	1.14 B	8.88 A
56 d	Wheat	1.71	2.15	3.39 A	6.06	0.43	1.21 A	2.20 AB	6.40 AB
56 d	Cereal Killer	2.07	1.41	3.12 ABC	6.32	0.83	0.77 A	2.55 A	9.30 A

Time	Species	Mass N				Mass K			
		Ashland Bottoms		Leonardville		Ashland Bottoms		Leonardville	
		2020	2021	2020	2021	2020	2021	2020	2021
		g/m^2							
84 d	Barley	1.68	1.51	.	5.27	0.17	0.36 A	.	5.99 A
84 d	Oat	1.31	.	1.39 B	2.99	0.17	.	0.96 A	2.16 A
84 d	Rye	1.68	1.45	3.26 A	5.90	0.29	0.59 A	1.38 A	5.73 A
84 d	Triticale	2.15	1.68	2.50 A	5.31	0.48	0.68 A	0.79 A	3.92 A
84 d	Wheat	1.93	1.87	2.72 A	5.76	0.21	0.52 A	1.11 A	5.82 A
84 d	Cereal Killer	1.70	1.28	2.91 A	5.40	0.17	0.40 A	0.88 A	5.51 A
112 d	Barley	2.25	1.51	.	4.35	0.27	0.16 A	.	4.35 A
112 d	Oat	2.01	.	0.93 C	3.27	0.26	.	0.21 A	1.50 A
112 d	Rye	2.05	1.90	2.90 A	5.67	0.27	0.53 A	0.79 A	4.24 A
112 d	Triticale	2.94	1.56	1.59 BC	4.76	0.34	0.54 A	0.31 A	2.93 A
112 d	Wheat	2.06	2.17	2.02 AB	5.86	0.19	0.66 A	0.57 A	4.71 A
112 d	Cereal Killer	2.29	1.14	1.83 BC	4.86	0.25	0.20 A	0.32 A	3.43 A

Table 5.7 LS Means table for mass of sulfur (SO_4-S) present in cover crop tissue for all four growing environments. Letters represent significant differences between treatments at *p*-value 0.05 while NS signifies lack of significant difference between treatments because the F-test for the main effect or interaction was not significant (*p*-value > 0.05).

Time	Species	Mass SO_4-S			
		Ashland Bottoms		Leonardville	
		2020	*2021*	*2020*	2021
		g/m²			
Main effect of time					
Initial		.	.	.	.
1 d		.	.	.	.
7 d		.	0.14 A	0.25 A	0.55 A
14 d		0.15 A	0.14 A	0.23 AB	0.53 A
28 d		0.14 AB	0.14 A	0.21 BC	0.47 B
56 d		0.11 C	0.11 B	0.21 BC	0.46 B
84 d		0.1 C	0.1 B	0.19 C	0.39 C
112 d		0.13 B	0.12 B	0.14 D	0.37 C
Main effect of species					
	Barley	0.13	0.11	.	0.44
	Oat	0.12	.	0.15 C	0.44
	Rye	0.12	0.15	0.25 A	0.44
	Triticale	0.16	0.12	0.17 B	0.44
	Wheat	0.13	0.14	0.24 AB	0.44
	Cereal Killer	0.13	0.1	0.21 AB	0.44
Time by species interaction					
7 d	Barley	.	0.11	.	0.47 BC
7 d	Oat	.	.	0.21	0.42 C
7 d	Rye	.	0.19	0.3	0.66 A
7 d	Triticale	.	0.12	0.23	0.63 AB
7 d	Wheat	.	0.14	0.28	0.59 ABC
7 d	Cereal Killer	.	0.12	0.24	0.5 ABC
14 d	Barley	0.15	0.14	.	0.51 AB
14 d	Oat	0.15	.	0.19	0.35 B
14 d	Rye	0.14	0.19	0.27	0.65 A
14 d	Triticale	0.18	0.13	0.18	0.62 A
14 d	Wheat	0.13	0.16	0.3	0.56 A
14 d	Cereal Killer	0.15	0.11	0.21	0.51 AB
28 d	Barley	0.14	0.12	.	0.43 AB
28 d	Oat	0.15	.	0.17	0.32 B
28 d	Rye	0.12	0.19	0.25	0.58 A
28 d	Triticale	0.15	0.15	0.18	0.58 A
28 d	Wheat	0.16	0.14	0.25	0.48 AB
28 d	Cereal Killer	0.13	0.13	0.21	0.46 AB
56 d	Barley	0.12	0.09	.	0.45 AB
56 d	Oat	0.07	.	0.16	0.33 B
56 d	Rye	0.10	0.12	0.24	0.55 A
56 d	Triticale	0.17	0.11	0.16	0.49 AB
56 d	Wheat	0.10	0.14	0.26	0.42 AB
56 d	Cereal Killer	0.12	0.09	0.23	0.52 AB
84 d	Barley	0.10	0.1	.	0.42 A
84 d	Oat	0.09	.	0.12	0.22 B
84 d	Rye	0.10	0.11	0.24	0.46 A
84 d	Triticale	0.12	0.11	0.18	0.41 A
84 d	Wheat	0.11	0.11	0.2	0.41 A
84 d	Cereal Killer	0.10	0.09	0.21	0.43 A

Time	Species	Mass SO_4-S			
		Ashland Bottoms		Leonardville	
		2020	***2021***	***2020***	**2021**
112 d	Barley	0.14	0.11	.	0.34 AB
112 d	Oat	0.12	.	0.08	0.25 B
112 d	Rye	0.11	0.14	0.22	0.45 A
112 d	Triticale	0.17	0.12	0.12	0.36 AB
112 d	Wheat	0.13	0.15	0.17	0.44 A
112 d	Cereal Killer	0.13	0.08	0.14	0.38 AB

Figures

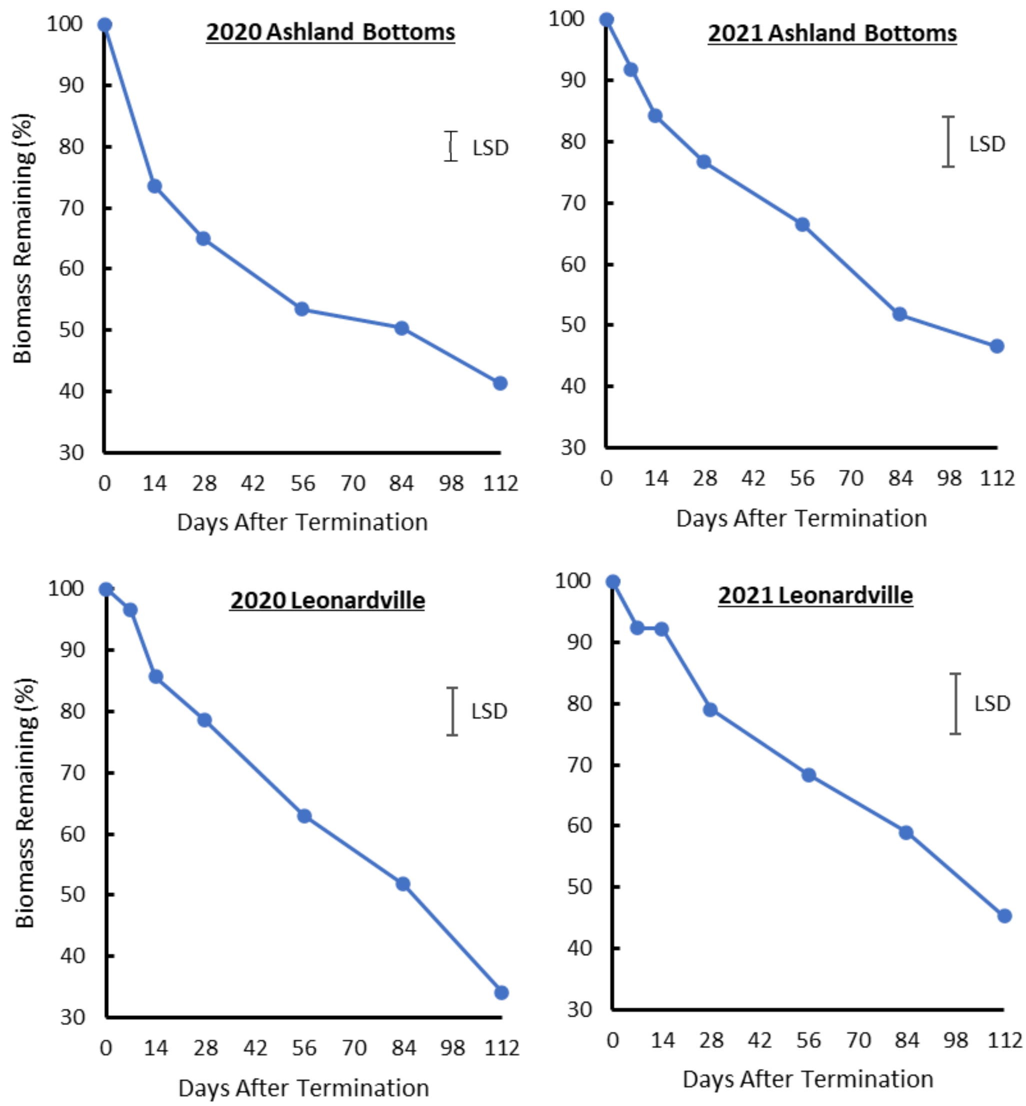

Figure 5.1 Main effect of time after termination on percent cover crop biomass remaining within residue bag. Abbreviations include least significant difference (LSD). Data points which fall outside the LSD indicate significant differences at *p*-value < 0.05.

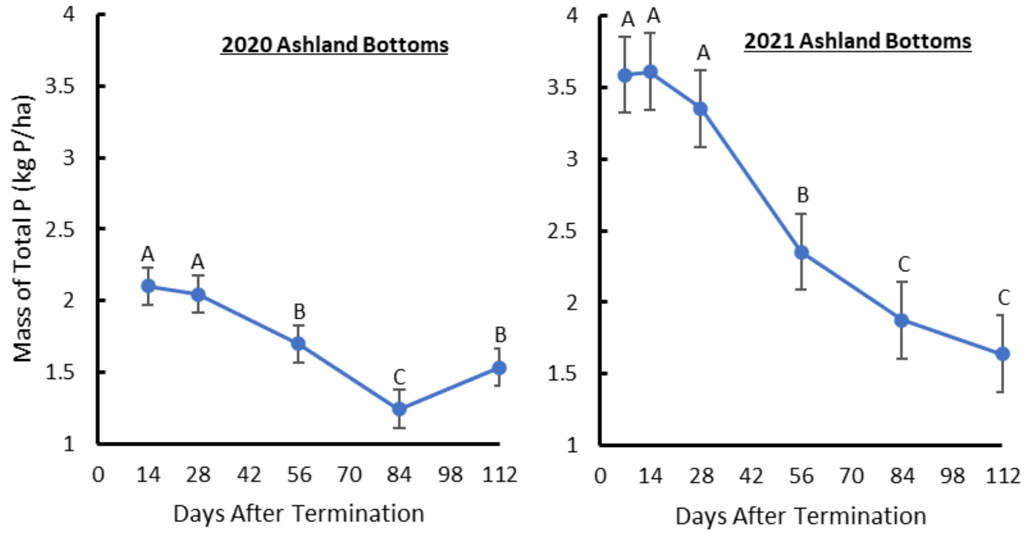

Figure 5.2 Main effect of days after termination on mass of total phosphorus present within cover crop biomass. Letters represent significant differences between timepoints at *p*-value < 0.05 and error bars represent standard error of the mean.

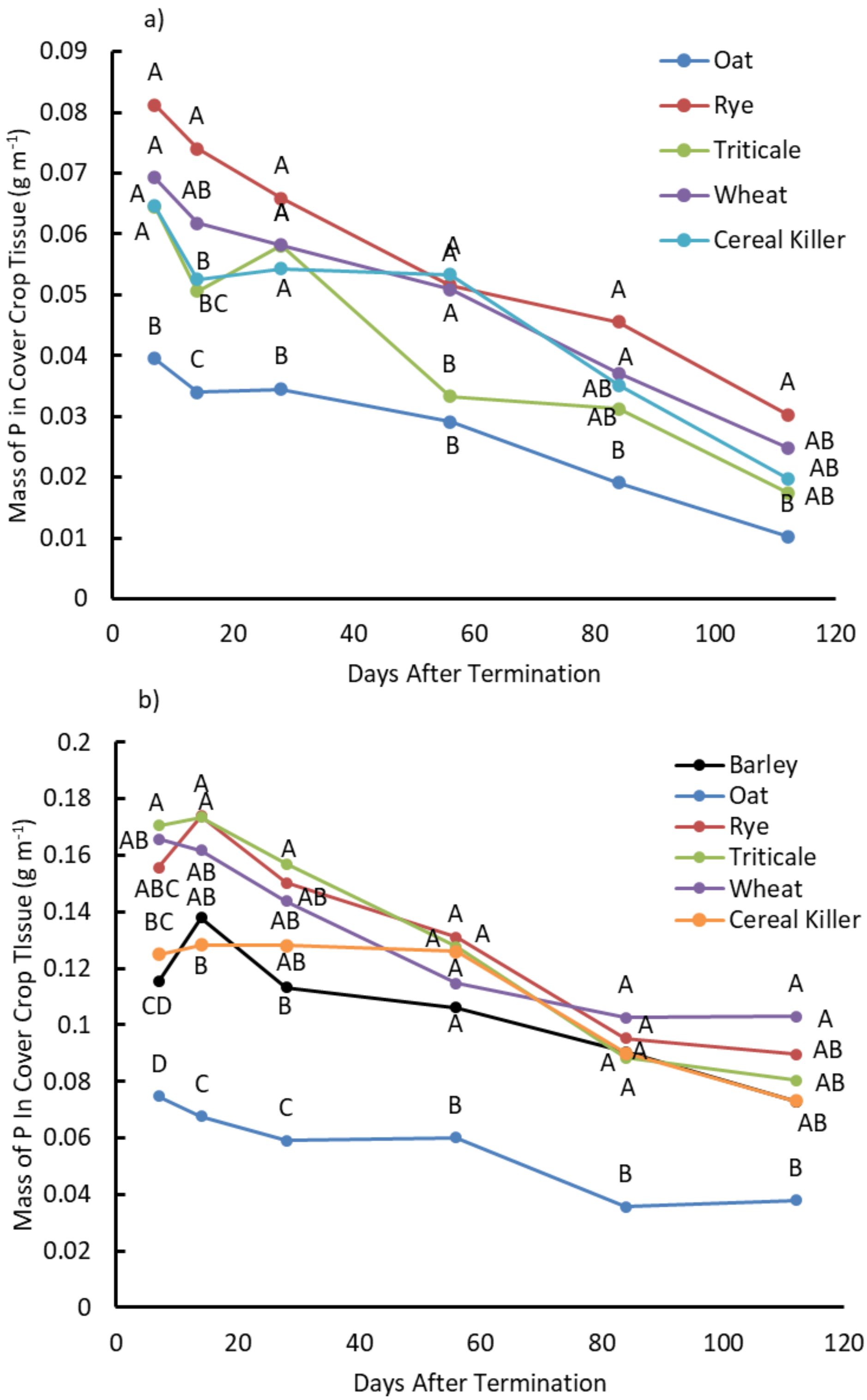

Figure 5.3 Cover crop by time after termination interaction for mass of P present in cover crop tissue for the 2020 Leonardville (a) and 2021 Leonardville (b) growing environments. Letters indicate significance at alpha = 0.05.

Chapter 6 - Summary

Loss of phosphorus associated with agricultural production is a key contributor to the deterioration and degradation of surface water quality throughout the world and will continue to be a challenge without the development of new agricultural managing practices. Current best management practices, such as no-till and 4R nutrient stewardship, offer producers management options which may reduce losses of both sediment and phosphorus, but other conservation practice, such as cover cropping, may unintentionally increase losses of dissolved reactive P into surface waters. While research conducted in part for this dissertation found the addition of a cover crop to a no-till corn-soybean during a normally fallow period increased concentrations and loads of dissolved reactive P in surface runoff in the majority of examined years, cover crops were able to dramatically decrease sediment lighting their importance in sediment control and the reduction of erosion losses. The impact of cover crops on sediment loss can extrapolated over to their variable impact on losses of total P observed during this research. For example, in areas where sediment loss is high, cover crops may be used to decrease losses of total P through the reduction in transport of sediment-bound particulate P. However, for areas where sediment loss or erosion risk is low, and subsequently the transport risk of sediment-bound P is low, adding a cover crop may unintentionally increase total P loss by increasing the loss of dissolved reactive P.

Placing P fertilizer below the soil surface at planting time resulted in significantly less P loss compared to broadcasting P fertilizer on the soil surface in the fall, even though the fall represented the ideal time to surface apply nutrients due to seasonal precipitation patters. Although not a novel result, this finding emphasizes the role P fertilizer placement plays in protecting water quality even when additional conservation practices (no-till and cover crops) are in place.

Originally, it was hypothesized that adding a cover crop to the fall broadcast method of applying P fertilizer would decrease losses of P or result in losses equal to the spring subsurface injection method of applying P fertilizer. The fall broadcast method of P fertilizer, regardless of the presence of a cover crop, consistently lost greater quantities of P compared to when P was subsurface applied at planting further reiterating the importance of P fertilizer placement.

Soil test analyses as the Kansas Agricultural Watershed field laboratory revealed that concentrations of total P and Mehlich-III P in the top 0-5 cm were identical between the fall broadcast and spring injected P treatments. Lack of difference at the 0-5 cm led to an alteration in sample methods to include 0-2.5 cm and 2.5-5 cm depths. After splitting the 0-5 cm depth, concentrations of Mehlich-III P and total P were revealed to still be identical between the fall broadcast and spring injected treatments. The addition of a cover crop, however, did result in increased concentrations of total P at the 0-2.5 depth suggesting that cover crops potentially modify the forms of P present in the soil. Additionally, the fall broadcast application of P fertilizer had greater concentrations of water-extractable P compared to the spring injected treatment when no cover crop was present, but when a cover crop was added concentrations of water-extractable P increased for the SI treatment to those equal to the fall broadcast indicating the cover crops modify the effect of P fertilizer treatment on water-extractable phosphorus.

The exploration of choice in winter cereal cover crop determined that cereal rye, barley, and triticale each exhibit similar trends with regards to rate of decomposition and concentration of nutrients present in the cover crop tissue. This findings suggests that these species my be interchangeable with potentially having variable impacts on soil conservation and water quality.

Winter wheat was observed to have the greatest concentrations of total P early in the main crop growing season suggesting that during that time period, a winter wheat cover crop may have a greater negative impact on water quality compared other winter cereals, however, moving further away from termination, winter wheat appeared to have similar nutrient concentrations to the other examined choices of winter cereal. Oat tended to have the quickest release of nutrients of all examined species and also had the lowest residue persistence. This finding suggests that oats may be able to quickly release assimilated to nutrients during the decomposition process that may be utilized by the subsequent cash crop, yet oats may not deliver the greatest erosion control compared to other choices in winter cereals.

Studies conducted for this dissertation highlight the implications that subtle changes in agricultural management practice may have on both the soil and the environment and underscore the importance of developing task-specific conservation strategies. Protecting and promoting water quality is a multi-faceted challenged which will require a multi-pronged, systems approach rather than a silver bullet.

Appendix A - KAW Annual Data: Supplemental Material

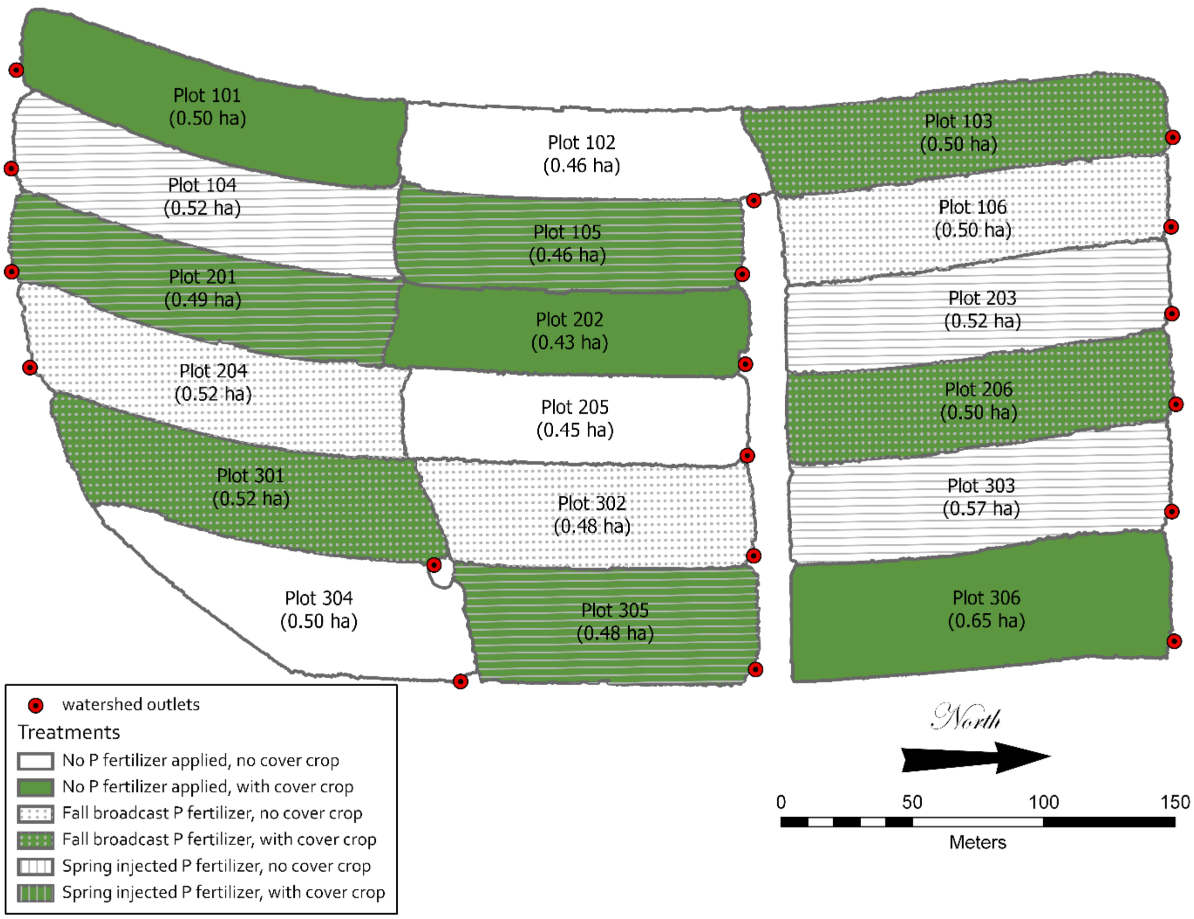

Figure A.1. Site map of Kansas Agricultural Watershed field laboratory located near Manhattan, KS, USA

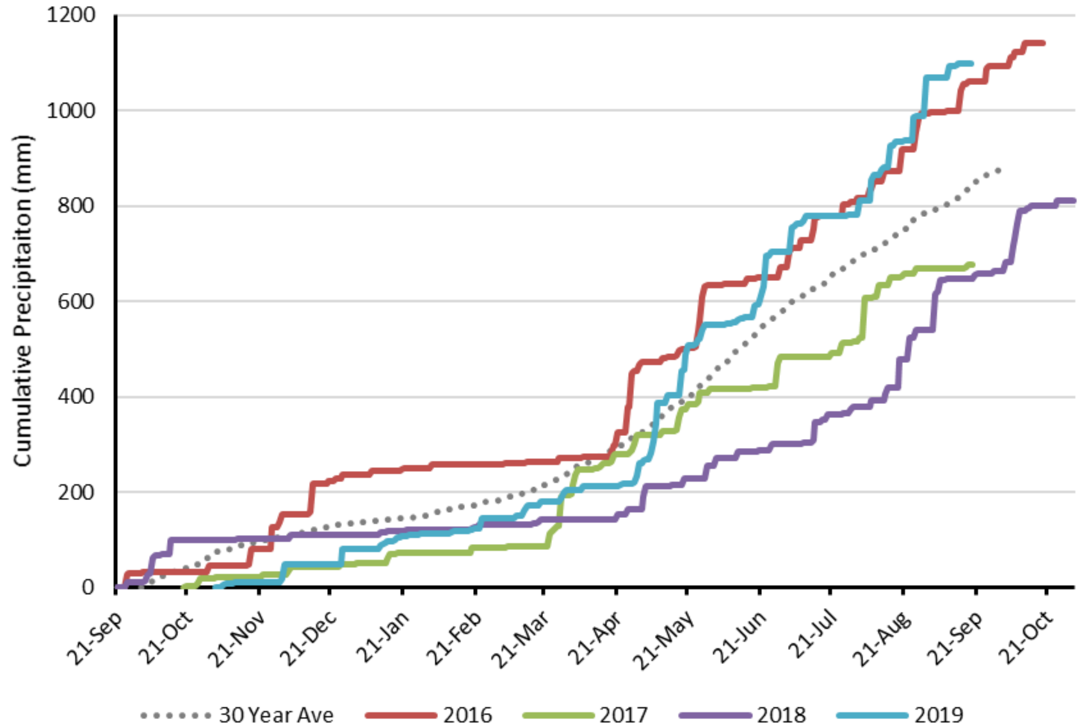

Figure A.2. Cumulative precipitation distribution for 30-year average and harvest years 2016-2019 at the Kansas Agricultural Watershed field laboratory located near Manhattan, KS, USA

Table A.1. Timing and descriptions of field operations and runoff events at the Kansas Agricultural Watershed field laboratory.

Field Operation	Date	Ave. Runoff (mm)	Notes
START: Harvest Year 2016	22-Sep-2015		
Cover Crop Planted	22-Sep-2015		winter wheat (146 kg/ha)
Fall Broadcast Fertilizer Applied	13-Nov-2015		
Runoff	1-Dec-2015	5.00	1
Runoff	15-Dec-2015	18.70	1
Runoff	25-Apr-2016	18.02	1
Runoff	27-Apr-2016	40.65	1
Cover Crop Terminated	6-May-2016		
Runoff	25-May-2016	2.15	1
Runoff	26-May-2016	4.34	1
Runoff	27-May-2016	34.94	1
Spring Injected Fertilizer Applied, Soybeans Planted	6-Jun-2016		
Runoff	13-Jul-2016	10.70	2
Runoff	20-Aug-2016	3.27	2
Runoff	25-Aug-2016	8.34	2
Runoff	26-Aug-2016	11.22	2
Runoff	14-Sep-2016	2.13	2
Runoff	11-Oct-2016	2.17	2
Soybeans Harvested	19-Oct-2016		
END: Harvest Year 2016	19-Oct-2016		
START: Harvest Year 2017	20-Oct-2016		
Cover Crop Planted	20-Oct-2016		triticale (56 ha/ha) and rapeseed (5.6 kg/ha)
Fall Broadcast Fertilizer Applied	2-Dec-2016		
Runoff	31-Mar-2017	20.73	1
Runoff	3-Apr-2017	4.46	1
Runoff	6-Apr-2017	12.15	1
Spring Injected Fertilizer Applied, Corn Planted	24-Apr-2017		
Cover Crop Terminated	27-Apr-2017		
Runoff	20-May-2017	5.31	2
Runoff	27-May-2017	4.42	2
Runoff	7-Aug-2017	20.68	2
Corn Harvested	20-Sep-2017		
END: Harvest Year 2017	20-Sep-2017		
START: Harvest Year 2018	21-Sep-2017		

Field Operation	Date	Ave. Runoff (mm)	Notes
Cover Crops Planted	21-Sep-2017		triticale (56 kg/ha) and rapeseed (5.6 kg/ha)
Runoff	8-Oct-2017	2.05	
Runoff	16-Oct-2017	7.06	
Fall Broadcast Fertilizer Applied	28-Nov-2017		
Spring Injected Fertilizer Applied, Soybeans Planted	9-May-2018		
Cover Crop Terminated	10-May-2018		
Runoff	24-Aug-2018	14.88	2
Runoff	3-Sep-2018	23.86	2
Runoff	6-Sep-2018	6.98	2
Runoff	10-Oct-2018	17.77	2
Soybeans Harvested	1-Nov-2018		
END: Harvest Year 2018	1-Nov-2018		
START: Harvest Year 2019	2-Nov-2018		
Cover Crops Planted	2-Nov-2018		Winter wheat (56 kg/ha) and rapeseed (5.6 kg/ha)
Fall Broadcast Fertilizer Applied	21-Dec-2018		
Runoff	25-Feb-2019	2.37	1
Spring Injected Fertilizer Applied, Corn Planted	25-Apr-2019		
Cover Crop Terminated	26-Apr-2019		
Runoff	7-May-2019	18.53	2
Runoff	8-May-2019	47.05	2
Runoff	9-May-2019	4.62	2
Runoff	13-May-2019	2.81	2
Runoff	19-May-2019	17.60	2
Runoff	22-May-2019	19.45	2
Runoff	27-May-2019	4.91	2
Runoff	24-Jun-2019	28.13	2
Runoff	5-Jul-2019	4.54	2
Runoff	16-Aug-2019	19.24	2
Runoff	26-Aug-2019	18.53	2
Runoff	30-Aug-2019	56.00	2
Corn Harvested	18-Sep-2019		
END: Harvest Year 2019	18-Sep-2019		

Table A.2. . Least squared means from analysis of variance with SAS proc mixed and associated errors for runoff (Q), total suspended solids (TSS), total P (TP), dissolved reactive P (DRP), TSS load, TP load and DRP load. Note all data are in log10 transformed units

Effect	Fert	Cover	time	Q	TSS	TP	DRP	TSS load	TP load	DRP load
				log(mm)	log(mg/L)	log(µg/L)	log(µg/L)	log(kg/ha)	log(g/ha)	log(g/ha)
Fert	CN			2.091	2.450	2.688	2.206	2.541	2.779	2.297
Fert	FB			2.020	2.379	3.118	2.887	2.398	3.137	2.907
Fert	SI			2.088	2.397	2.951	2.631	2.485	3.039	2.719
standard error				0.028	0.041	0.026	0.023	0.060	0.049	0.043
Cover		NC		2.074	2.647	2.908	2.462	2.721	2.982	2.536
Cover		CC		2.059	2.170	2.930	2.687	2.229	2.988	2.746
standard error				0.023	0.033	0.021	0.019	0.049	0.040	0.035
Fert*Cover	CN	NC		2.031	2.636	2.695	2.087	2.667	2.726	2.118
Fert*Cover	FB	NC		2.051	2.616	3.111	2.819	2.667	3.162	2.870
Fert*Cover	SI	NC		2.139	2.690	2.918	2.481	2.829	3.058	2.621
Fert*Cover	CN	CC		2.151	2.265	2.680	2.324	2.416	2.832	2.476
Fert*Cover	FB	CC		1.988	2.141	3.125	2.956	2.129	3.112	2.944
Fert*Cover	SI	CC		2.037	2.104	2.984	2.781	2.141	3.021	2.817
standard error				0.039	0.058	0.036	0.033	0.084	0.069	0.060
time			2016	2.200	2.658	2.904	2.439	2.858	3.104	2.639
time			2017	1.811	2.172	2.745	2.505	1.983	2.555	2.315
time			2018	1.848	1.800	2.935	2.797	1.648	2.783	2.644
time			2019	2.407	3.005	3.091	2.559	3.412	3.498	2.966
standard error				0.010	0.029	0.020	0.007	0.034	0.032	0.013
Fert*time	CN		2016	2.223	2.703	2.781	2.113	2.926	3.004	2.336
Fert*time	FB		2016	2.158	2.688	3.081	2.786	2.846	3.239	2.944
Fert*time	SI		2016	2.218	2.584	2.851	2.418	2.802	3.069	2.637
Fert*time	CN		2017	1.842	2.204	2.437	2.002	2.046	2.279	1.844
Fert*time	FB		2017	1.750	2.135	3.035	2.931	1.885	2.784	2.681
Fert*time	SI		2017	1.840	2.177	2.763	2.580	2.017	2.604	2.420
Fert*time	CN		2018	1.872	1.845	2.633	2.453	1.716	2.504	2.324
Fert*time	FB		2018	1.788	1.754	3.131	3.027	1.542	2.919	2.815
Fert*time	SI		2018	1.884	1.802	3.042	2.910	1.685	2.925	2.794
Fert*time	CN		2019	2.427	3.050	2.900	2.255	3.477	3.328	2.682
Fert*time	FB		2019	2.383	2.937	3.224	2.806	3.320	3.607	3.189
Fert*time	SI		2019	2.411	3.026	3.149	2.615	3.437	3.559	3.026

Effect	Fert	Cover	time	Q	TSS	TP	DRP	TSS load	TP load	DRP load
				log(mm)	log(mg/L)	log(μg/L)	log(μg/L)	log(kg/ha)	log(g/ha)	log(g/ha)
standard error				0.018	0.050	0.034	0.012	0.058	0.055	0.023
Cover*time		NC	2016	2.196	2.909	2.929	2.304	3.105	3.125	2.500
Cover*time		CC	2016	2.203	2.407	2.880	2.574	2.611	3.083	2.777
Cover*time		NC	2017	1.771	2.491	2.735	2.385	2.262	2.505	2.156
Cover*time		CC	2017	1.850	1.853	2.755	2.624	1.704	2.606	2.474
Cover*time		NC	2018	1.873	1.976	2.814	2.649	1.849	2.687	2.522
Cover*time		CC	2018	1.823	1.625	3.056	2.944	1.447	2.879	2.766
Cover*time		NC	2019	2.455	3.213	3.154	2.511	3.669	3.610	2.966
Cover*time		CC	2019	2.358	2.796	3.028	2.607	3.154	3.386	2.965
standard error				0.014	0.041	0.028	0.010	0.048	0.045	0.018
Fert*Cover*time	CN	NC	2016	2.148	2.998	2.840	1.905	3.146	2.988	2.052
Fert*Cover*time	FB	NC	2016	2.169	2.920	3.114	2.742	3.089	3.283	2.911
Fert*Cover*time	SI	NC	2016	2.271	2.810	2.833	2.265	3.081	3.104	2.536
Fert*Cover*time	CN	CC	2016	2.298	2.408	2.722	2.321	2.706	3.020	2.619
Fert*Cover*time	FB	CC	2016	2.146	2.456	3.049	2.830	2.602	3.195	2.976
Fert*Cover*time	SI	CC	2016	2.165	2.358	2.870	2.572	2.523	3.035	2.737
Fert*Cover*time	CN	NC	2017	1.723	2.403	2.465	1.871	2.126	2.188	1.595
Fert*Cover*time	FB	NC	2017	1.736	2.478	3.009	2.870	2.214	2.745	2.606
Fert*Cover*time	SI	NC	2017	1.853	2.592	2.730	2.414	2.444	2.583	2.267
Fert*Cover*time	CN	CC	2017	1.960	2.005	2.409	2.133	1.966	2.369	2.093
Fert*Cover*time	FB	CC	2017	1.763	1.792	3.060	2.992	1.555	2.824	2.755
Fert*Cover*time	SI	CC	2017	1.828	1.762	2.797	2.746	1.590	2.624	2.574
Fert*Cover*time	CN	NC	2018	1.830	1.948	2.503	2.329	1.778	2.333	2.159
Fert*Cover*time	FB	NC	2018	1.842	1.907	3.024	2.882	1.750	2.866	2.724
Fert*Cover*time	SI	NC	2018	1.946	2.072	2.915	2.738	2.018	2.861	2.684
Fert*Cover*time	CN	CC	2018	1.913	1.741	2.763	2.576	1.654	2.676	2.490
Fert*Cover*time	FB	CC	2018	1.733	1.601	3.238	3.172	1.335	2.971	2.906
Fert*Cover*time	SI	CC	2018	1.821	1.531	3.168	3.083	1.352	2.989	2.904
Fert*Cover*time	CN	NC	2019	2.421	3.195	2.972	2.243	3.616	3.394	2.664
Fert*Cover*time	FB	NC	2019	2.458	3.159	3.296	2.781	3.616	3.754	3.239
Fert*Cover*time	SI	NC	2019	2.488	3.286	3.195	2.509	3.774	3.682	2.997
Fert*Cover*time	CN	CC	2019	2.433	2.905	2.828	2.267	3.338	3.262	2.701
Fert*Cover*time	FB	CC	2019	2.308	2.716	3.152	2.831	3.024	3.460	3.139
Fert*Cover*time	SI	CC	2019	2.334	2.767	3.103	2.722	3.100	3.436	3.056
standard error				0.025	0.071	0.048	0.017	0.082	0.078	0.032

Appendix B - SAS Code for KAW Annual Water Quality

Data Processing

```
%let path=C:\Users\Elliott\KAW\September 15 2020;
libname dat1 "&path\data";
PROC IMPORT OUT= WORK.SET1
            DATAFILE= "&path\Data\KAW_MasterData_Final.csv"
            DBMS=CSV REPLACE;
     GETNAMES=YES;
     DATAROW=2;
     GUESSINGROWS=2000;
RUN;

data dat1.runoff;format Event date.;set set1;
rename total_p__mg_l_=tp tss__mg_l_=tss;
label total_p__mg_l_='Total P (mg/L)' drp='DRP (mg/L)' tss__mg_l_='TSS
(mg/L)'
      harvest_year='Harv. Yr' fertilizer_timepoint='Fert Time'
cover_crop_timepoint='Cover Time';
Event=evid-42958+'11AUG17'd;
if plot=302 then cover='NC';
trt_comb=fert||' '||cover||' '||put(plot,3.0);
if plot=102 and event='27MAY17'd then drp__ug_l_=9;/*See email on July 21,
2020*/
if evID in (42958,43224,43379, 43436) then delete;
if drp__ug_l_<5 and drp__ug_l_^=. then drp__ug_l_=5/2;/*Replace values <LOD
with half of LOD*/
drp=drp__ug_l_/1000;
log10_tp=log10(total_p__mg_l_);
log10_drp=log10(drp);
log10_tss=log10(tss__mg_l_);
log10_qt=log10(qt);
where AvgQt>2;
drop drp__ug_l_ total_n__mg_l_ NH4_N__mg_l_;
run;

/*if ID=42958 then delete;
if ID=43224 then delete;
if ID=43249 then delete; (The data does not have this ID)
if ID=43332 then delete; (The data does not have this ID)
if ID=43436 then delete;
if ID=43637 then delete; (AvgQt<2)
if ID=43379 then delete; */

title 'Missing data pattern';
proc tabulate data=dat1.runoff;
class event plot harvest_year fertilizer_timepoint cover_crop_timepoint fert
cover;
table harvest_year*fertilizer_timepoint*cover_crop_timepoint*event,fert='
'*cover=' '*plot=' '*n=' '/Box='TSS/TP/DRP';
where harvest_year=2016 and tss^=.;
run;
proc tabulate data=dat1.runoff;
```

```
class event plot harvest_year fertilizer_timepoint cover_crop_timepoint fert
cover;
table harvest_year*fertilizer_timepoint*cover_crop_timepoint*event,fert='
'*cover=' '*plot=' '*n=' '/Box='Qt';
where harvest_year=2016 and Qt^=.;
run;
proc tabulate data=dat1.runoff;
class event evid plot harvest_year fertilizer_timepoint cover_crop_timepoint
fert cover;
table
harvest_year*fertilizer_timepoint*cover_crop_timepoint*event*evid,fert='
'*cover=' '*plot=' '*n=' '/Box='TSS/TP/DRP';
where harvest_year=2017 and tss^=.;
run;/*There was only one event in harvest_year=2017 and
fertilizer_timepoint=2 and cover_time=1*/
proc tabulate data=dat1.runoff;
class event plot harvest_year fertilizer_timepoint cover_crop_timepoint fert
cover;
table harvest_year*fertilizer_timepoint*cover_crop_timepoint*event,fert='
'*cover=' '*plot=' '*n=' '/Box='Qt';
where harvest_year=2017 and Qt^=.;
run;
proc tabulate data=dat1.runoff;
class event plot harvest_year fertilizer_timepoint cover_crop_timepoint fert
cover;
table harvest_year*fertilizer_timepoint*cover_crop_timepoint*event,fert='
'*cover=' '*plot=' '*n=' '/Box='TSS/TP/DRP';
where harvest_year=2018 and tss^=.;
run;
proc tabulate data=dat1.runoff;
class event plot harvest_year fertilizer_timepoint cover_crop_timepoint fert
cover;
table harvest_year*fertilizer_timepoint*cover_crop_timepoint*event,fert='
'*cover=' '*plot=' '*n=' '/Box='Qt';
where harvest_year=2018 and Qt^=.;
run;

proc tabulate data=dat1.runoff;
class event plot harvest_year fertilizer_timepoint cover_crop_timepoint fert
cover;
table harvest_year*fertilizer_timepoint*cover_crop_timepoint*event,fert='
'*cover=' '*plot=' '*n=' '/Box='TSS/TP/DRP';
where harvest_year=2019 and tss^=.;
run;/*There was only one event in harvest_year=2019 and
fertilizer_timepoint=2 */
proc tabulate data=dat1.runoff;
class event plot harvest_year fertilizer_timepoint cover_crop_timepoint fert
cover;
table harvest_year*fertilizer_timepoint*cover_crop_timepoint*event,fert='
'*cover=' '*plot=' '*n=' '/Box='Qt';
where harvest_year=2019 and Qt^=.;
run;


proc sort data=dat1.runoff;by event fert cover;
proc means data=dat1.runoff noprint;by event fert cover;
var log10_tss log10_tp log10_drp log10_Qt;
```

```
output out=trt_mean mean=log10_tss_m log10_tp_m log10_drp_m log10_Qt_m;
run;
/*Replace missing data with the average of data in the same treatment at the
same event time.

*/
data dat1.runoff;merge dat1.runoff trt_mean(drop=_type_ _freq_);by event fert
cover;
if tss=. then do;tss_=10**(log10_tss_m);freq=1;end;else tss_=tss;
if drp=. then do;drp_=10**(log10_drp_m);freq=1;end;else drp_=drp;
if tp=. then do;tp_=10**(log10_tp_m);freq=1;end;else tp_=tp;
if Qt=. then do;qt_=10**(log10_qt_m);freq_qt=1;end;else qt_=qt;
if harvest_year=2019 and fertilizer_timepoint='2' and
cover_crop_timepoint='1'
    and cover='NC' and Fert='CN' and TSS=. then do;
TSS_=.;TP_=.;DRP_=.;
END;
if harvest_year=2019 and fertilizer_timepoint='2' and
cover_crop_timepoint='1'
and cover='CC' and Fert='FB' and TSS=. then do;
TSS_=.;TP_=.;DRP_=.;
END;
if harvest_year=2017 and fertilizer_timepoint='2' and
cover_crop_timepoint='1'
and cover='CC' and Fert='FB' and TSS=. then do;
TSS_=.;TP_=.;DRP_=.;
END;
run;
data plot;set dat1.runoff;
blk=compress(harvest_year||"_FTime"||fertilizer_timepoint||"_CTime"||cover_cr
op_timepoint);
run;
options orientation=landscape nodate nonumber;
ods rtf file="&path\SASoutput\Data Processing_9_15_2020.doc"
style=monochromeprinter;
title;
ods graphics/width=10in height=6in noborder attrpriority=none outputfmt=png;
%macro plot(var,var_, label);
proc sgpanel data=plot noautolegend ;
panelby fert cover/layout=panel rows=6 onepanel novarname uniscale=row
noheader sort=data;
block x=event block=blk/transparency=0.9
      nooutline filltype=alternate fillattrs=(color=gray)
altfillattrs=(color=white) novalues;
series y=&var_ x=event/break group=plot lineattrs=(pattern=1 color=gray)
                     transparency=0.4;
scatter y=&var x=event/
                     markerattrs=(color=black symbol=circlefilled size=4)
transparency=0.4 name='b' legendlabel='Observed';
scatter y=&var_ x=event/ freq=freq
                     markerattrs=(color=red symbol=x) transparency=0.4
name='a' legendlabel='Imputed';
keylegend 'b' 'a'/noborder;
colaxis type=discrete label=' ' offsetmin=0.04;
inset cover fert/nolabel position=topleft;
rowaxis type=log logbase=10 logstyle=logexpand grid label=&label;
run;
```

```
%mend;
%plot(var=tp,var_=tp_,label='Total P(mg/L)');
%plot(var=drp,var_=drp_,label='DRP(mg/L)');
%plot(var=tss,var_=tss_,label='TSS(mg/L)');
proc sgpanel data=plot noautolegend ;
panelby fert cover/layout=panel rows=6 onepanel novarname uniscale=row
noheader sort=data;
block x=event block=blk/transparency=0.9
      nooutline filltype=alternate fillattrs=(color=gray)
altfillattrs=(color=white)
      novalues;
series y=qt_ x=event/break group=plot lineattrs=(pattern=1 color=gray)
                     transparency=0.4;
scatter y=qt x=event/
                     markerattrs=(color=black symbol=circlefilled size=4)
transparency=0.4 name='b' legendlabel='Observed';
scatter y=qt_ x=event/ freq=freq_qt
                     markerattrs=(color=red symbol=x) transparency=0.4
name='a' legendlabel='Imputed';
keylegend 'b' 'a'/noborder;
colaxis type=discrete label=' ' offsetmin=0.04;
inset cover fert/nolabel position=topleft;
rowaxis type=log logbase=10 logstyle=logexpand grid label='Qt';
run;


data dat1.runoff;set dat1.runoff;
QTSS=Qt_*TSS_; QTP=Qt_*TP_; QDRP=Qt_*DRP_;
drop log10_tp   log10_drp   log10_tss   log10_qt
     log10_tp_m log10_drp_m log10_tss_m log10_qt_m freq freq_qt ;
run;
proc sort data=dat1.runoff;by plot harvest_year fertilizer_timepoint
cover_crop_timepoint;
proc means data=dat1.runoff noprint;by plot harvest_year fertilizer_timepoint
cover_crop_timepoint ;
var qt_ qtss qtp qdrp;
output out=dat1.runoff_for_analysis sum(qt_ qtss qtp qdrp)=qt_sum qtss_sum
qtp_sum qdrp_sum
n(qt_)=N_events;
id rep fert cover trt_comb;
run;
data dat1.runoff_for_analysis;set dat1.runoff_for_analysis;
label tp='Total P (mg/L)' drp='DRP (mg/L)' tss='TSS (mg/L)'
      qtp_load='Load of Total P (g/ha)'
      qdrp_load='Load of DRP (g/ha)'
      qtss_load='Load of TSS (kg/ha)'
      qt_sum='Qt (mm)';
tss=qtss_sum/qt_sum;
tp=qtp_sum/qt_sum;
drp=qdrp_sum/qt_sum;
qtss_load=qtss_sum*0.01;
qtp_load=qtp_sum*0.01*1000;
qdrp_load=qdrp_sum*0.01*1000;
drop _type_ _freq_;
run;

data plot;set dat1.runoff_for_analysis;
```

```
time=compress(harvest_year||"_FTime"||fertilizer_timepoint||"_CTime"||cover_c
rop_timepoint);
run;
options orientation=portrait;
ods rtf;
ods graphics/width=6 in height=8in;
%macro plot1(var, label);
proc sgpanel data=plot noautolegend ;
panelby fert cover/layout=panel rows=6 onepanel novarname uniscale=row
noheader sort=data;
series y=&var x=time/break group=plot lineattrs=(pattern=1 color=gray)
                     transparency=0.4;
scatter y=&var x=time/
                     markerattrs=(color=black symbol=circlefilled size=4)
                     transparency=0.4 ;
colaxis type=discrete label=' ' offsetmin=0.1 offsetmax=0.1
        fitpolicy=splitalways splitchar='_';
inset cover fert/nolabel position=bottomright;
rowaxis type=log logbase=10 logstyle=logexpand grid label=&label
offsetmin=0.15;
run;
%mend;
%plot1(var=TSS,label='TSS(mg/L)');
%plot1(var=TP,label='TP(mg/L)');
%plot1(var=DRP,label='DRP(mg/L)');
%plot1(var=Qtss_load,label='Load TSS (kg/ha)');
%plot1(var=Qtp_load,label='Load TP (g/ha)');
%plot1(var=Qdrp_load,label='Load DRP (g/ha))');
%plot1(var=Qt_sum,label='Qt (mm)');
ods rtf close;
```

Data Analysis

```
%let path=C:\Users\Elliott\Documents\My SAS Files\9.4\Oct 5 2020;
libname dat1 "&path\data";
%let endpoint=tss;/*Enter either tp,qtp_load, drp, qdrp_load, tss,
qtss_load,qt_sum*/
ods listing gpath="C:\Users\Elliott\Documents\My SAS Files\9.4\gpath"; *must
indicate gpath for code to function;
data analysis;set dat1.runoff_for_analysis;
log_resp=log10(&endpoint);
time=harvest_year;
label time='Harvest Year'
run;
options orientation=landscape nodate nonumber;
*ods rtf file="&path\SASoutput\&endpoint_analysis.doc"
style=monochromeprinter;
proc tabulate data=analysis s=[just=c];
class fert cover time;
var &endpoint;
table time=' ',&endpoint*fert=' '*cover=' '*((min='Min' mean='Median'
max='Max' )*f=8.2);
run;

%macro fit(type=);
title "&type";
proc mixed data=analysis ;
class fert cover time plot rep;
model log_resp= rep fert cover fert*cover time fert*time cover*time
fert*cover*time/ddfm=kr;
repeated time/subject=plot type=&type;
ods select fitstatistics;
run;
%mend;
/***********
The following covariance structures where determined on 2/23/2021.
Qt: UN
TSS: CSH
TP: ARH(1)
DRP: UN
Qtss_load: CSH
QTP_load: CS
DQRP_load: CSH
************/
%fit(type=UN);
%fit(type=arh(1));
%fit(type=csh);
%fit(type=arma(1,1))
%fit(type=ar(1));
%fit(type=cs);
%let type=CSH;/*Pick the type based on the Fit Statistics (AIC/AICC/BIC)*/
ods graphics on;
title "&endpoint";
/*****************************
Variable Type
TP       CS
DRP         UN
```

```
TSS          CSH
Qtsum     CSH
TP Load      CS
DRP Load ARH(1)
TSS Load CS
***************************/

proc mixed data=analysis plots(only)=studentpanel(marginal) ;
class fert cover time plot rep;
model log_resp= rep fert cover fert*cover time fert*time cover*time
fert*cover*time/
      ddfm=kr residual;
lsmeans fert*cover*time fert*time cover*time fert*cover fert cover / diffs;
slice fert*time/sliceby=time pdiff lines;
slice cover*time/sliceby=time pdiff lines;
slice cover*fert*time/sliceby=time pdiff lines;
repeated time/subject=plot type=&type r;

/* The following contrast statements were added on Jan. 26, 2021 */
estimate "FB vs SI"                     fert 0 1 -1;
estimate "CN vs FB+SI"                  fert -2 1 1/divisor=2;
estimate "FB vs SI 2016"                fert 0 1 -1
                                        time 0 0 0 0
                                        fert*time 0 0 0 0 1 0 0 0 -1 0 0 0/
divisor=1;
estimate "FB vs SI 2017"                fert 0 1 -1
                                        time 0 0 0 0
                                        fert*time 0 0 0 0 0 1 0 0 0 -1 0 0/
divisor=1;
estimate "FB vs SI 2018"                fert 0 1 -1
                                        time 0 0 0 0
                                        fert*time 0 0 0 0 0 0 1 0 0 0 -1 0/
divisor=1;
estimate "FB vs SI 2019"                fert 0 1 -1
                                        time 0 0 0 0
                                        fert*time 0 0 0 0 0 0 0 1 0 0 0 -1 /
divisor=1;
estimate "CN vs FB+SI CC 2016"          fert -2 1 1
                                        time 0 0 0 0
                                        cover 0 0
                                        cover*time 0 0 0 0 0 0 0 0
                                        fert*time -2 0 0 0 1 0 0 0 1 0 0 0
                                        fert*cover -2 0 1 0 1 0
                                        fert*cover*time -2 0 0 0 0 0 0 0 1 0 0 0
0 0 0 0 1 0 0 0 0 0 0 0/divisor=2;
estimate "CN vs FB+SI CC 2017"          fert -2 1 1
                                        time 0 0 0 0
                                        cover 0 0
                                        cover*time 0 0 0 0 0 0 0 0
                                        fert*time 0 -2 0 0 0 1 0 0 0 1 0 0
                                        fert*cover -2 0 1 0 1 0
                                        fert*cover*time 0 -2 0 0 0 0 0 0 0 1 0 0
0 0 0 0 0 1 0 0 0 0 0 0/divisor=2;
estimate "CN vs FB+SI CC 2018"          fert -2 1 1
                                        time 0 0 0 0
                                        cover 0 0
                                        cover*time 0 0 0 0 0 0 0 0
```

```
                              fert*time 0 0 -2 0 0 0 1 0 0 0 1 0
                              fert*cover -2 0 1 0 1 0
                              fert*cover*time 0 0 -2 0 0 0 0 0 0 0 1 0
0 0 0 0 0 0 1 0 0 0 0 0/divisor=2;
estimate "CN vs FB+SI CC 2019"   fert -2 1 1
                              time 0 0 0 0
                              cover 0 0
                              cover*time 0 0 0 0 0 0 0 0
                              fert*time 0 0 0 -2 0 0 0 1 0 0 0 1
                              fert*cover -2 0 1 0 1 0
                              fert*cover*time 0 0 0 -2 0 0 0 0 0 0 0 1
0 0 0 0 0 0 0 1 0 0 0 0/divisor=2;
estimate "CN vs FB+SI NC 2016"   fert -2 1 1
                              time 0 0 0 0
                              cover 0 0
                              cover*time 0 0 0 0 0 0 0 0
                              fert*time -2 0 0 0 1 0 0 0 1 0 0 0
                              fert*cover 0 -2 0 1 0 1
                              fert*cover*time 0 0 0 0 -2 0 0 0 0 0 0 0
1 0 0 0 0 0 0 0 1 0 0 0/divisor=2;
estimate "CN vs FB+SI NC 2017"   fert -2 1 1
                              time 0 0 0 0
                              cover 0 0
                              cover*time 0 0 0 0 0 0 0 0
                              fert*time 0 -2 0 0 0 1 0 0 0 1 0 0
                              fert*cover 0 -2 0 1 0 1
                              fert*cover*time 0 0 0 0 0 -2 0 0 0 0 0 0
0 1 0 0 0 0 0 0 0 1 0 0/divisor=2;
estimate "CN vs FB+SI NC 2018"   fert -2 1 1
                              time 0 0 0 0
                              cover 0 0
                              cover*time 0 0 0 0 0 0 0 0
                              fert*time 0 0 -2 0 0 0 1 0 0 0 1 0
                              fert*cover 0 -2 0 1 0 10
                              fert*cover*time 0 0 0 0 0 0 -2 0 0 0 0 0
0 0 1 0 0 0 0 0 0 0 1 0/divisor=2;
estimate "CN vs FB+SI NC 2019"   fert -2 1 1
                              time 0 0 0 0
                              cover 0 0
                              cover*time 0 0 0 0 0 0 0 0
                              fert*time 0 0 0 -2 0 0 0 1 0 0 0 1
                              fert*cover 0 -2 0 1 0 1
                              fert*cover*time 0 0 0 0 0 0 0 -2 0 0 0 0
0 0 0 1 0 0 0 0 0 0 0 1/divisor=2;
ods output lsmeans=lsm Tests3=ANOVA SliceLines=slines slicediffs=spdiff;
ods exclude diffplot slicetests;
/*data slines; set slines (where=(effect is not missing)); keep effect slice
fert cover estimate line: ; */
run;
quit;
ods graphics off;

data plot;set lsm;
u=10**(estimate+stderr);l=10**(estimate-stderr);
median=10**(estimate);
REC_U= u-median;
REC_L= median-l;
```

```
comb=fert||'_'||cover;
run;
/*proc export data = WORK.plot DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_&endpoint._Feb2021.XLSX" replace;
     sheet=Data;
proc export data = WORK.ANOVA DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_&endpoint._Feb2021.XLSX" replace;
     sheet=ANOVA;
proc export data = WORK.spdiff DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_&endpoint._Feb2021.XLSX" replace;
     sheet=pdiff; */
ods graphics/height=6in width=8in attrpriority=none;
proc sgplot data=plot;
styleattrs datacontrastcolors=(red red green green blue blue)
datalinepatterns=(1 2 1 2 1 2);
series y=median x=time/group=comb groupdisplay=cluster clusterwidth=0.3
name='a';
scatter y=median x=time/ group=comb yerrorupper=u yerrorlower=l
groupdisplay=cluster
clusterwidth=0.1 noerrorcaps groupdisplay=cluster clusterwidth=0.3
markerattrs=(symbol=plus);
xaxis type=discrete label=' ' offsetmin=0.1 offsetmax=0.1
        fitpolicy=splitalways splitchar='_';
yaxis label='LSM+/-SE (Back-transformed)' type=log logbase=10 logstyle=linear
offsetmax=0.1;
keylegend 'a'/noborder title=' ';
where effect='Fert*Cover*time';
run;
ods graphics/height=6in width=8in;
proc sgplot data=plot;
styleattrs datacontrastcolors=(red green blue) datalinepatterns=(1 1 1);
series y=median x=time/group=fert groupdisplay=cluster clusterwidth=0.3
name='a';
scatter y=median x=time/ group=fert yerrorupper=u yerrorlower=l
groupdisplay=cluster
clusterwidth=0.1 noerrorcaps groupdisplay=cluster clusterwidth=0.3
markerattrs=(symbol=plus);
xaxis type=discrete label=' ' offsetmin=0.1 offsetmax=0.1
        fitpolicy=splitalways splitchar='_';
yaxis label='LSM+/-SE (Back-transformed)' type=log logbase=10 logstyle=linear
offsetmax=0.1;
keylegend 'a'/noborder title=' ';
where effect='Fert*time';
run;
ods graphics/height=6in width=8in;
proc sgplot data=plot;
styleattrs datacontrastcolors=(black black) datalinepatterns=(1 2);
series y=median x=time/group=cover groupdisplay=cluster clusterwidth=0.3
name='a';
scatter y=median x=time/ group=cover yerrorupper=u yerrorlower=l
groupdisplay=cluster
clusterwidth=0.1 noerrorcaps groupdisplay=cluster clusterwidth=0.3
markerattrs=(symbol=plus);
xaxis type=discrete label=' ' offsetmin=0.1 offsetmax=0.1
```

```
        fitpolicy=splitalways splitchar='_';
yaxis label='LSM+/-SE (Back-transformed)' type=log logbase=10 logstyle=linear
offsetmax=0.1
      ;
keylegend 'a'/noborder title=' ';
where effect='Cover*time';
run;
      *ods rtf close;
```

Appendix C - SAS Code for KAW Temporal Variations

Data Processing

```
%let path=C:\Users\Elliott\Documents\GRADUATE SCHOOL\KAW\Temporal Patterns;
libname dat1 "&path\data";
PROC IMPORT OUT= WORK.SET1
            DATAFILE= "&path\Data\KAW_TemporalPatterns.csv"
            DBMS=CSV REPLACE;
     GETNAMES=YES;
    DATAROW=2;
    GUESSINGROWS=2000;
RUN;

data runoff;format Event date.;set set1;
tp=total_p__mg_l_+0;tss=tss__mg_l_+0;
label tp='Total P (mg/L)' drp='DRP (mg/L)' tss='TSS (mg/L)'
      harvest_year='Harv. Yr' fertilizer_timepoint='Fert Time'
cover_crop_timepoint='Cover Time';
Event=evid-42958+'11AUG17'd;
if plot=302 then cover='NC';/*where AvgQt>2;*/
trt_comb=fert||' '||cover||' '||put(plot,3.0);
if plot=102 and event='27MAY17'd then drp__ug_l_=9;/*See email on July 21,
2020*/
If index(cover_crop_timepoint,'.') then delete;
if harvest_year=2018 then delete;/*See email on Jan. 14, 2022*/
if drp__ug_l_<5 and drp__ug_l_^=. then drp__ug_l_=5/2;/*Replace values <LOD
with half of LOD*/
drp=drp__ug_l_/1000;
log10_tp=log10(total_p__mg_l_);
log10_drp=log10(drp);
log10_tss=log10(tss__mg_l_);
log10_qt=log10(qt);
drop total_p__mg_l_ tss__mg_l_ drp__ug_l_ total_n__mg_l_ NH4_N__mg_l_
NO3_N__mg_L_ f19-f21 _2339 _;
run;


proc sort data=runoff;by event fert cover;
proc means data=runoff noprint;by event fert cover;
var log10_tss log10_tp log10_drp log10_Qt;
output out=trt_mean mean=log10_tss_m log10_tp_m log10_drp_m log10_Qt_m;
run;
/*Replace missing data with the average of data in the same treatment at the
same event time.
*/
proc format;
value $cc '3'='Cover Crop' '1'='Transition' '2'='Cash Crop';
value $fert '1'='Apply Fert' '2'='Plant & Harvest';
run;
data dat1.runoff;merge runoff trt_mean(drop=_type_ _freq_);by event fert
cover;
format cover_crop_timepoint $cc. fertilizer_timepoint $fert.;
if tss=. then do;tss_=10**(log10_tss_m);freq=1;end;else tss_=tss;
if drp=. then do;drp_=10**(log10_drp_m);freq=1;end;else drp_=drp;
```

```
if tp=. then do;tp_=10**(log10_tp_m);freq=1;end;else tp_=tp;
if Qt=. then do;qt_=10**(log10_qt_m);freq_qt=1;end;else qt_=qt;
QTSS=Qt_*TSS_; QTP=Qt_*TP_; QDRP=Qt_*DRP_;
if cover_crop_timepoint=1 then CCTorder=2;
else if cover_crop_timepoint=2 then CCTorder=3;
else if cover_crop_timepoint=3 then CCTorder=1;
trt=fert||' '||cover;
drop log10_tp   log10_drp   log10_tss   log10_qt
     log10_tp_m log10_drp_m log10_tss_m log10_qt_m ;
run;

options orientation=landscape nodate nonumber;
ods rtf file="&path\SASoutput\Data Processing_1_14_2022.doc"
style=monochromeprinter;
title;
proc sort data=dat1.runoff;by harvest_year CCTorder;
proc tabulate data=dat1.runoff order=data;
class event plot harvest_year fertilizer_timepoint cover_crop_timepoint trt;
table harvest_year=' '*cover_crop_timepoint=' ',
      trt='# of events where TSS,TP & DRP were measured'*plot=' '*n=' ';
where tss^=.;
run;
title ;
proc tabulate data=dat1.runoff order=data;
class event plot harvest_year fertilizer_timepoint cover_crop_timepoint trt;
table harvest_year=' '*cover_crop_timepoint=' ',
      trt='# of events where Qt was measured'*plot=' '*n=' ';
where Qt^=.;
run;
proc tabulate data=dat1.runoff order=data;
class event plot harvest_year fertilizer_timepoint cover_crop_timepoint trt;
table harvest_year=' '*fertilizer_timepoint=' ',
      trt='# of events where TSS,TP & DRP were measured'*plot=' '*n=' ';
where tss^=.;
run;
title ;
proc tabulate data=dat1.runoff order=data;
class event plot harvest_year fertilizer_timepoint cover_crop_timepoint trt;
table harvest_year=' '*fertilizer_timepoint=' ',
      trt='# of events where Qt was measured'*plot=' '*n=' ';
where Qt^=.;
run;

%macro plot_g3(var,var_, label,blk,freq=freq);
proc sgpanel data=dat1.runoff noautolegend ;
styleattrs datacolors=(red yellow blue);
panelby trt/layout=rowlattice rows=6 onepanel novarname uniscale=row
sort=data headerbackcolor=white;
block x=event block=&blk/transparency=0.9
      nooutline filltype=multicolor fillattrs=(color=gray)
altfillattrs=(color=white) ;
series y=&var_ x=event/break group=plot lineattrs=(pattern=1 color=gray)
                     transparency=0.4;
scatter y=&var x=event/
                     markerattrs=(color=black symbol=circlefilled size=4)
transparency=0.4 name='b' legendlabel='Observed';
scatter y=&var_ x=event/ freq=&freq
```

```
                         markerattrs=(color=red symbol=x) transparency=0.4
name='a' legendlabel='Imputed';
keylegend 'b' 'a'/noborder;
colaxis type=discrete label=' ' offsetmin=0.04;
rowaxis type=log logbase=10 logstyle=logexpand grid label=&label;
run;
%mend;
%macro plot_g2(var,var_, label,blk,freq=freq);
proc sgpanel data=dat1.runoff noautolegend ;
panelby trt/layout=rowlattice rows=6 onepanel novarname uniscale=row
sort=data headerbackcolor=white;
block x=event block=&blk/transparency=0.9
       nooutline filltype=altinate fillattrs=(color=gray)
altfillattrs=(color=white) ;
series y=&var_ x=event/break group=plot lineattrs=(pattern=1 color=gray)
                         transparency=0.4;
scatter y=&var x=event/
                         markerattrs=(color=black symbol=circlefilled size=4)
transparency=0.4 name='b' legendlabel='Observed';
scatter y=&var_ x=event/ freq=&freq
                         markerattrs=(color=red symbol=x) transparency=0.4
name='a' legendlabel='Imputed';
keylegend 'b' 'a'/noborder;
colaxis type=discrete label=' ' offsetmin=0.04;
rowaxis type=log logbase=10 logstyle=logexpand grid label=&label;
run;
%mend;
ods graphics/width=10in height=6in noborder attrpriority=none outputfmt=png;
%plot_g3(var=tp,var_=tp_,label='Total P(mg/L)',blk=cover_crop_timepoint);
%plot_g2(var=tp,var_=tp_,label='Total P(mg/L)',blk=fertilizer_timepoint);
%plot_g3(var=drp,var_=drp_,label='DRP(mg/L)',blk=cover_crop_timepoint);
%plot_g2(var=drp,var_=drp_,label='DRP(mg/L)',blk=fertilizer_timepoint);
%plot_g3(var=tss,var_=tss_,label='TSS(mg/L)',blk=cover_crop_timepoint);
%plot_g2(var=tss,var_=tss_,label='TSS(mg/L)',blk=fertilizer_timepoint);
%plot_g3(var=qt,var_=qt_,label='Qt',blk=cover_crop_timepoint,freq=freq_qt);
%plot_g2(var=qt,var_=qt_,label='Qt',blk=fertilizer_timepoint,freq=freq_qt);


proc sort data=dat1.runoff;by plot harvest_year cover_crop_timepoint ;
proc means data=dat1.runoff noprint;by plot harvest_year cover_crop_timepoint
CCTorder;
var qt_ qtss qtp qdrp;
output out=dat1.runoff_CCT_for_analysis sum(qt_ qtss qtp qdrp)=qt_sum
qtss_sum qtp_sum qdrp_sum
n(qt_)=N_events;
id rep fert cover trt;
run;
data dat1.runoff_CCT_for_analysis;set dat1.runoff_CCT_for_analysis;
label tp='Total P (mg/L)' drp='DRP (mg/L)' tss='TSS (mg/L)'
       qt_sum='Qt (mm)';
tss=qtss_sum/qt_sum;
tp=qtp_sum/qt_sum;
drp=qdrp_sum/qt_sum;
drop _type_ _freq_;
run;

options orientation=portrait;
```

```
ods rtf;
ods graphics/width=7 in height=9in attrpriority=none noborder;
proc sort data=dat1.runoff_CCT_for_analysis;by harvest_year CCTorder plot;
%macro plot_CCT(data,var, label);
proc sgpanel data=&data ;
styleattrs datasymbols=(circle square triangle)
datacontrastcolors=(red red red red red red green green green green green
green blue blue blue blue blue blue)
datalinepatterns=(1 1 1 2 2 2) ;
panelby harvest_year trt/layout=lattice novarname uniscale=row rows=6
headerbackcolor=white;
series y=&var x=cover_crop_timepoint/group=plot
                     name='b' markers markerattrs=(size=6);
colaxis type=discrete display=(nolabel) offsetmin=0.2 offsetmax=0.2
        fitpolicy=splitalways splitchar=' ' values=('Cover Crop' 'Transition'
'Cash Crop');
keylegend 'b'/noborder title='Plot';
rowaxis type=log logbase=10 logstyle=logexpand grid label=&label
offsetmin=0.15;
run;
%mend;
%plot_CCT(data=dat1.runoff_CCT_for_analysis,var=TSS,label='TSS(mg/L)');
%plot_CCT(data=dat1.runoff_CCT_for_analysis,var=TP,label='TP(mg/L)');
%plot_CCT(data=dat1.runoff_CCT_for_analysis,var=DRP,label='DRP(mg/L)');
proc sort data=dat1.runoff;by plot harvest_year fertilizer_timepoint;
proc means data=dat1.runoff noprint;by plot harvest_year
fertilizer_timepoint;
var qt_ qtss qtp qdrp;
output out=dat1.runoff_FT_for_analysis sum(qt_ qtss qtp qdrp)=qt_sum qtss_sum
qtp_sum qdrp_sum
n(qt_)=N_events;
id rep fert cover trt;
run;
data dat1.runoff_FT_for_analysis;set dat1.runoff_FT_for_analysis;
label tp='Total P (mg/L)' drp='DRP (mg/L)' tss='TSS (mg/L)'
      qt_sum='Qt (mm)';
tss=qtss_sum/qt_sum;
tp=qtp_sum/qt_sum;
drp=qdrp_sum/qt_sum;
trt=fert||' '||cover;
drop _type_ _freq_;
run;

options orientation=portrait;
ods rtf;
ods graphics/width=7 in height=9in attrpriority=none noborder;
proc sort data=dat1.runoff_FT_for_analysis;by harvest_year
fertilizer_timepoint plot;
%macro plot_FT(data,var, label);
proc sgpanel data=&data ;
styleattrs datasymbols=(circle square triangle)
datacontrastcolors=(red red red red red red green green green green green
green blue blue blue blue blue blue)
datalinepatterns=(1 1 1 2 2 2) ;
panelby harvest_year trt/layout=lattice novarname uniscale=row rows=6
headerbackcolor=white;
series y=&var x=fertilizer_timepoint/group=plot
```

```
                     name='b' markers markerattrs=(size=6);
colaxis type=discrete display=(nolabel) offsetmin=0.25 offsetmax=0.25
        fitpolicy=splitalways splitchar='&' splitcharnodrop ;
keylegend 'b'/noborder title='Plot';
rowaxis type=log logbase=10 logstyle=logexpand grid label=&label
offsetmin=0.15;
run;
%mend;
%plot_FT(data=dat1.runoff_FT_for_analysis,var=TSS,label='TSS(mg/L)');
%plot_FT(data=dat1.runoff_FT_for_analysis,var=TP,label='TP(mg/L)');
%plot_FT(data=dat1.runoff_FT_for_analysis,var=DRP,label='DRP(mg/L)');

      ods rtf close;
```

Data Analysis

```
%let path=C:\Users\Elliott\Documents\My SAS Files\9.4\KAW Temporal Patterns;
libname dat1 "&path\data";
proc format;
value $cc '3'='Cover Crop Growing' '1'='30 Days After CC Termination'
'2'='Remainder of Growing Season';
value $fert '1'='After FB Before SI' '2'='From SI Through Harvest';
run;
%let endpoint=DRP;/*Enter either tp,drp, tss*/
%let endpoint_label='DRP(mg/L)';/*Enter either 'TP(mg/L)','DRP(mg/L)',
'TSS(mg/L)'*/
%let time=FT;/*Enter either CCT or FT*/
data analysis;set dat1.runoff_&time._for_analysis;
log_resp=log10(&endpoint);
rename harvest_year=HY;
%if "&time"="CCT" %then %do;
format Time $cc.;
Time=cover_crop_timepoint;
label time='CCT';
%end;
%if "&time"="FT" %then %do;
Time=fertilizer_timepoint;
format Time $fert.;
label Time='FT';
%end;
run;
options orientation=landscape nodate nonumber;
ods rtf file="&path\SASoutput\&endpoint._&time._analysis.doc"
style=monochromeprinter;
%if "&time"="CCT" %then %do;proc sort data=analysis;by trt CCTorder;%end;
%if "&time"="FT" %then %do;proc sort data=analysis;by trt time;%end;
proc tabulate data=analysis s=[just=c] order=data;
class trt time;
var &endpoint;
table time=' ',&endpoint*trt=' '*((min='Min' mean='Median' max='Max'
)*f=8.2);
run;

%macro fit(type=);
proc mixed data=analysis order=data;
title "&type";
class fert cover time plot rep HY;
model log_resp= rep fert cover  HY time fert*cover fert*HY  cover*HY
fert*cover*HY
                    fert*time  cover*time fert*cover*time/ddfm=kr;
repeated HY time/subject=plot type=&type;
ods select fitstatistics;
run;
%mend;
%fit(type=un@cs);
%fit(type=un@un);
/***************************
Variable    Time  Type
TSS         Cover UN@UN
TP       Cover UN@CS
```

```
DRP         Cover UN@CS
TSS         Fert  UN@CS
TP       Fert  UN@CS
DRP         Fert  UN@UN
*****************************/
options orientation=portrait nodate nonumber;
ods rtf;
%let type=un@un;/*Pick the type based on the Fit Statistics (AIC/AICC/BIC)*/
ods graphics on/ reset;
ods graphics off;
title "&endpoint";
proc mixed data=analysis plots(only)=studentpanel(marginal) order=data;
class fert cover time plot rep HY;
model log_resp= rep fert cover  HY time fert*cover fert*HY  cover*HY
fert*cover*HY
                    fert*time  cover*time fert*cover*time/ddfm=kr residual;
lsmeans fert*cover*time fert*time cover*time fert*cover fert cover time /
diffs;
slice fert*time/sliceby=fert lines; *pdiff; *adjust=tukey  ADJDFE=ROW lines;
slice cover*time/sliceby=cover lines; *pdiff;
slice fert*cover*time/sliceby=fert lines; *pdiff;
repeated HY time/subject=plot type=&type r;
ods output lsmeans=lsm Tests3=ANOVA diffs=pdiffs slicelines=slines;
*slicediffs=spdiff;
*ods exclude diffplot slicetests;
run;
ods graphics off;

data plot1;format fert $6.;set lsm;
u=10**(estimate+stderr);l=10**(estimate-stderr);
median=10**(estimate);
if effect='Cover*Time' then fert='Across';
run;
data plot1; set plot1;
PError=u-median; Nerror=median-l;
run;
proc export data = WORK.analysis DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_&time._&endpoint._Temp.XLSX" replace;
     sheet=Data;
proc export data = WORK.plot1 DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_&time._&endpoint._Temp.XLSX" replace;
     sheet=LSMeans;
proc export data = WORK.ANOVA DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_&time._&endpoint._Temp.XLSX" replace;
     sheet=ANOVA;
proc export data = WORK.pdiffs DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_&time._&endpoint._Temp.XLSX" replace;
     sheet=pdiff;
proc export data = WORK.slines DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_&time._&endpoint._Temp.XLSX" replace;
     sheet=SliceLines;
run;
```

```
options orientation=landscape nodate nonumber;
ods rtf style=htmlblue;
title "LSM+/-SE (Back-transformed)";
ods graphics/height=6in width=9in attrpriority=none outputfmt=png noborder;
proc sgpanel data=plot1;
styleattrs datacolors=(green brown) datacontrastcolors=(green brown) ;
panelby fert/layout=columnlattice novarname headerbackcolor=white sort=data
columns=4 headerbackcolor=white;
vbarparm response=median category=time/group=cover groupdisplay=cluster
clusterwidth=0.7 transparency=0.3 name='a'
         limitlower=l limitupper=u  limitattrs=(color=black) filltype=solid ;
%if "&time"="CCT" %then %do;
colaxis type=discrete label=' ' offsetmin=0.2 offsetmax=0.2
        fitpolicy=splitalways splitchar=' ';
%end;
%if "&time"="FT" %then %do;
colaxis type=discrete label=' ' offsetmin=0.3 offsetmax=0.3
        fitpolicy=splitalways splitchar=' ';
%end;
rowaxis label=&endpoint_label offsetmax=0.1;
keylegend 'a'/noborder title=' ';
where effect='Fert*Cover*Time' or effect='Cover*Time';
run;

data plot2;format cover $6.;set lsm;
u=10**(estimate+stderr);l=10**(estimate-stderr);
median=10**(estimate);
if effect='Fert*Time' then cover='Across';
run;

proc sgpanel data=plot2;
styleattrs datacolors=(white white white) datacontrastcolors=(gray red
orange) datafillpatterns=(r2 l2 l2) ;
panelby cover/layout=columnlattice novarname headerbackcolor=white sort=data
columns=3 headerbackcolor=white;
vbarparm response=median category=time/group=fert groupdisplay=cluster
clusterwidth=0.7 transparency=0.3 name='a'
         limitlower=l limitupper=u  limitattrs=(color=black)
         fillpattern ;
%if "&time"="CCT" %then %do;
colaxis type=discrete label=' ' offsetmin=0.2 offsetmax=0.2
        fitpolicy=splitalways splitchar=' ';
%end;
%if "&time"="FT" %then %do;
colaxis type=discrete label=' ' offsetmin=0.3 offsetmax=0.3
        fitpolicy=splitalways splitchar=' ';
%end;
rowaxis label=&endpoint_label offsetmax=0.1;
keylegend 'a'/noborder title=' ';
where effect='Fert*Cover*Time' or effect='Fert*Time';
run;

      ods rtf close;
```

Data Analysis: Loess Regression

```
data aaa; infile 'C:\Users\Elliott\Documents\GRADUATE SCHOOL\KAW\Temporal
Patterns\Data\TimeAfterApplication.csv'
          dlm=','  dsd  missover firstobs=2;
input fert$ cover$ EventID$ Days QtSUM QTSSSUM QTPSUM QDRPSUM WtAve_TSS
WtAve_TP WtAve_DRP;
ods listing gpath="C:\Users\Elliott\Documents\My SAS Files\9.4";
proc sort data=aaa; by fert cover;
run;
proc sgplot data=aaa;
scatter y=WtAve_DRP x=Days;
run;
ods graphics on;
proc loess data=aaa; by fert cover;
model WtAve_DRP=Days / all;
score data=aaa;
ods output OutputStatistics=aaastats FitSummary=Summary;
run;
proc loess data=aaa; by fert cover;
model WtAve_TP=Days / all;
score data=aaa;
ods output OutputStatistics=TPstats FitSummary;
run;
proc export data = WORK.aaastats DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS
Files\TimeAfterApp_KAW.XLSX" replace;
     sheet=DRPStats;
proc export data = WORK.TPstats DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS
Files\TimeAfterApp_KAW.XLSX" replace;
     sheet=TPstats;
     run;
      quit;
```

Appendix D - SAS Code for Soils Analysis

Data Import and Processing

```
%let path=C:\Users\Elliott\Documents\GRADUATE SCHOOL\KAW\Soils;
libname dat "&path\Data";
proc import out=set1 datafile="&path\Data\Soils_July21_2021.xlsx" dbms=xlsx
replace;
sheet="Ave 0-2.5 & 2.5-5";
getnames=yes;
datarow=2;
run;
proc sort data=set1; by year plot rep cover fert point tdepth_cm bdepth_cm
thick;
proc transpose data=set1
     out=set2(rename=(_label_=ep) );
   var ph M3_P var12 var13 TP__ppm_ WEP AveDepth M3_PStrat TNstrat TCstrat
TPstrat WEPstrat;
   by year plot rep cover fert point tdepth_cm bdepth_cm thick;
run;
proc format;
value dp 1='0~2.5cm' 2='2.5~5cm' 3='0~5cm' 4='0~5cm (Avg)' 5='5~15cm';
value pt 1='Point 1' 2='Point 2' 3='Point 3';
run;
data set2;set set2;
format depth dp.;
resp=col1+0;drop col1;
if thick=10 then depth=5;
else if tdepth_cm=0 and bdepth_cm=2.5 then depth=1;
else if tdepth_cm=2.5 and bdepth_cm=5 then depth=2;
else if tdepth_cm=0 and bdepth_cm=5 then depth=3;
else if tdepth_cm=1 and bdepth_cm=6 then depth=4;
run;
data baseline;set set2;
rename resp=baseline;
where year=2014 ;
run;
proc print data=baseline;
where plot=206 and depth=3;
run;
proc means data=baseline  mean  nway noprint;by plot depth;class ep;
var baseline;
output out=missing_data mean=baseline;
where plot=206 and depth=3 and baseline^=.;
run;
data missing_data;set missing_data;
point=1;
drop _type_ ;
run;
proc sort data=missing_data; by plot point ep depth;
proc sort data=baseline;by plot point ep depth;
data dat.baseline;merge baseline missing_data;by plot point ep depth;
logbaseline=log(baseline);
drop year;
run;
```

```
proc sort data=set2;by plot point ep depth;
data analysis;merge set2 dat.baseline;by plot point ep depth;
if year=2014 then delete;
logresp=log(resp);
run;
data baseline_adj;set dat.baseline;
do year=2017,2018,2019;
do depth=1,2,4;
output;
end;
end;
where depth=3;
drop tdepth_cm bdepth_cm thick;
run;
proc sort data=baseline_adj;by plot point ep year depth;
proc sort data=analysis;by plot point ep year depth;
data dat.analysis;merge analysis baseline_adj;by plot point ep year depth;
run;

title 'Baseline Summary Statistics';
%macro Baseline_summary_stat(ep,fmt);
proc tabulate data=dat.baseline; where ep="&ep";
format point pt.;
class cover fert point depth ep ;
var baseline;
table cover='Cover'*fert='Fertilizer', baseline='Baseline'*ep=' '*depth='
'*(point=' ' all)*(n (mean min max)*f=&fmt);
run;
%mend;
%baseline_summary_stat(ep=M3-P, fmt=6.1);
%baseline_summary_stat(ep=TC (%), fmt=6.2);
%baseline_summary_stat(ep=TN (%), fmt=6.3);
%baseline_summary_stat(ep=TP (ppm), fmt=6.0);
%baseline_summary_stat(ep=pH, fmt=6.1);

title 'Assessing Baseline Effect: Original scale';
proc sort data=dat.baseline;by ep depth;
proc mixed data=dat.baseline order=data;by ep depth;
class cover fert rep plot point;
model baseline=rep cover fert cover*fert/ddfm=kr;
repeated point/subject=plot type=un;
ods exclude all;
ods output tests3=t3;
run;
title 'Assessing Baseline Effect: Log scale';
proc mixed data=dat.baseline order=data;by ep depth;
class cover fert rep plot point;
model logbaseline=rep cover fert cover*fert/ddfm=kr;
repeated point/subject=plot type=un;
ods exclude all;
ods output tests3=t3_log;
run;
ods select all;
data t3_baseline;merge t3 t3_log(rename=(probf=prof_log));
run;
proc report data=t3_baseline spanrow;
column ep depth effect probf prof_log;
```

```
define ep/'Endpoint' group;
define depth/'Depth' group;
define effect/'Effect' group order=data;
run;

title 'Post-Treatment Summary Statistics';
%macro Treatment_summary_stat(ep,fmt);
proc tabulate data=dat.analysis; where ep="&ep";
format point pt.;
class cover fert point depth year ep;
var resp;
table year='Year'*cover='Cover'*fert='Fertilizer', ep=' '*resp=' '*depth='
'*(n (mean std min max)*f=&fmt);
run;
%mend;
%Treatment_summary_stat(ep=M3-P, fmt=6.1);
%Treatment_summary_stat(ep=TC (%), fmt=6.2);
%Treatment_summary_stat(ep=TN (%), fmt=6.3);
%Treatment_summary_stat(ep=TP (ppm), fmt=6.0);
%Treatment_summary_stat(ep=pH, fmt=6.1);


/*
Comments:
---Baseline, or log(baseline), should be included as a covariate.
---In 2017, the difference between '0-5cm' and average of '0-2.5cm','2.5-5cm'
was within 1 SD;
---In 2017, the SD of '0-5cm' was not always larger then the SD of the
average of '0-2.5cm','2.5-5cm'.
      */
```

Analysis for 2015 through 2019 Data

```
%let path=C:\Users\Elliott\Documents\GRADUATE SCHOOL\KAW\Soils;
libname dat "&path\Data";
ods listing gpath="C:\Users\Elliott\Documents\My SAS Files\9.4"; *This line
added in on 8/22/21. Without it, each time the code ran an error message
stating "GPHAT or PATH is invalid" would come up
/*
This analysis focuses on depth '0~5cm' and '5~15cm' from 2015-2019.
For 2017, depth '0~2.5cm' and '2.5~5cm' was excluded from the analysis.
For 2018 and 2019, the average of depth '0~2.5cm' and '2.5~5cm' was used to
impute the depth '0~5cm'.
For 2017, the average of depth '0~2.5cm' and '2.5~5cm' was excluded from the
analysis.
*/
proc format;
proc format;
value dp 1='0~2.5cm' 2='2.5~5cm' 3='0~5cm' 4='0~5cm (Avg)' 5='5~15cm';
value pt 1='Point 1' 2='Point 2' 3='Point 3';
run;
data analysis;set dat.analysis;
if depth in (1,2) then delete;
if year in (2018, 2019) and depth=4 then depth=3; *replaces value of depth
variable from 4 to 3 for 2018 and 2019;
if year in (2017) and depth=4 then delete;
run;
proc tabulate data=analysis;
class depth year;
var resp;
table year, n*depth=' '*resp=' ';
run;

%macro modeling(y,covariate);
proc sort data=analysis;by ep depth;
proc mixed data=analysis order=data;by ep depth;
class cover fert rep plot point year;
model &y=&covariate rep cover fert cover*fert year cover*year fert*year
cover*fert*year/ddfm=kr;
random plot;/*Whole plot error*/
repeated year/subject=plot*point type=cs;/* Subplot error vector*/
ods exclude all;
ods output fitstatistics=cs;
run;

/* The previous model is equivalence to the following one*/

/*proc mixed data=analysis order=data;by ep depth;
class cover fert rep plot point year;
model &y=&covariate rep cover fert cover*fert year cover*year fert*year
cover*fert*year/ddfm=kr;
random plot;
random plot*point;
ods select covparms fitstatistics;
run; */
proc mixed data=analysis order=data;by ep depth;
class cover fert rep plot point year;
```

```
model &y=&covariate rep cover fert cover*fert year cover*year fert*year
cover*fert*year/ddfm=kr;
random plot;
repeated year/subject=plot*point type=ar(1);
ods exclude all;
ods output fitstatistics=ar1;
run;

proc mixed data=analysis order=data;by ep depth;
class cover fert rep plot point year;
model &y=&covariate rep cover fert cover*fert year cover*year fert*year
cover*fert*year/ddfm=kr;
repeated point year/subject=plot type=un@ar(1);/*Multivariate repeated
measurement*/
ods exclude all;
ods output fitstatistics=un_ar1;
run;
proc mixed data=analysis order=data ;by ep depth;
class cover fert rep plot point year;
model &y=&covariate rep cover fert cover*fert year cover*year fert*year
cover*fert*year/ddfm=kr;
repeated point year/subject=plot type=un@cs;
ods exclude all;
ods output fitstatistics=un_cs;
run;
data fs;set cs(in=a) ar1(in=b) un_ar1(in=c) un_cs(in=d);
if a then type='CS    ';
if b then type='AR1   ';
if c then type='UN@AR1';
if d then type='UN@CS ';
where index(descr,'AIC (Smaller is Better)');
run;
proc sort data=fs;by ep depth type;
proc transpose data=fs out=fs_;by ep depth;
var value;
id type;
run;
ods select all;
title2 'AIC(Samller is Better)';
proc print data=fs_(drop=_name_) noobs;
run;
title2;
%mend;
title 'Orginal data';
proc sort data=analysis;by ep depth;
data Original; set analysis; if ep in ('M3-P') then delete;

*%modeling(y=resp,covariate=baseline);
ods graphics off; *added in on 8/23/21 since slines will not output;
proc mixed data=Original order=data plots=(studentpanel) ;by ep depth;
class cover fert rep plot point year;
model resp=baseline rep cover fert year cover*fert cover*year fert*year
cover*fert*year/ddfm=kr;
lsmeans cover fert year cover*fert cover*year fert*year
cover*fert*year/pdiff;
repeated point year/subject=plot type=un@cs;
slice fert*year/sliceby=year lines;
```

```
slice cover*year/sliceby=year lines;
slice cover*fert*year/sliceby=year lines;
* The following contrast states were added on Spetember 13, 2021;
contrast "Linear"                 year -2 -1 0 1 2;
contrast "Linear Control"         year -2 -1 0 1 2

                            fert*year -2 -1 0 1 2 0 0 0 0 0 0 0 0 0 0;
contrast "Linear Fall Broadcast"     year -2 -1 0 1 2

                            fert*year 0 0 0 0 0 -2 -1 0 1 2 0 0 0 0 0;
contrast "Linear Spring Injected"    year -2 -1 0 1 2

                            fert*year 0 0 0 0 0 0 0 0 0 0 -2 -1 0 1 2;
contrast "Linear Cover Crop"      year -2 -1 0 1 2

                            cover*year -2 -1 0 1 2 0 0 0 0 0;
contrast "Linear No Cover"           year -2 -1 0 1 2

                            cover*year 0 0 0 0 0 -2 -1 0 1 2;
estimate "Linear"                 year -2 -1 0 1 2;
estimate "Linear Control"         year -2 -1 0 1 2

                            fert*year -2 -1 0 1 2 0 0 0 0 0 0 0 0 0 0;
estimate "Linear Fall Broadcast"     year -2 -1 0 1 2

                            fert*year 0 0 0 0 0 -2 -1 0 1 2 0 0 0 0 0;
estimate "Linear Spring Injected"    year -2 -1 0 1 2

                            fert*year 0 0 0 0 0 0 0 0 0 0 -2 -1 0 1 2;
estimate "Linear Cover Crop"      year -2 -1 0 1 2

                            cover*year -2 -1 0 1 2 0 0 0 0 0;
estimate "Linear No Cover"           year -2 -1 0 1 2

                            cover*year 0 0 0 0 0 -2 -1 0 1 2;
*ods select tests3 covparms studentpanel lsmeans diffs slices slicelines;
ods output lsmeans=lsm Tests3=ANOVA diffs=pdiffs SliceLines=slines;
run;
data lsm;set lsm;
u=(estimate+stderr);l=(estimate-stderr);
median=(estimate); *median is actually the mean;
REC_U= u-median;
REC_L= median-l;
comb=fert||'_'||cover;
run;


data slines; set slines (where=(effect is not missing)); keep ep effect slice
fert cover depth estimate line: ;
run;
data slines; set slines; array dx line:; call sortc(of line:); x = catt(of
line:); *This sorts the letters alphabetically and stores them as a single
variable.;
run;

proc sort data=slines; by ep depth effect slice fert descending cover;
```

```
data slines; retain ep depth effect slice fert cover estimate x; set slines;
*places effect slice fert cover estimate x as the first columns, followed by
other variable follow in order as is;
run;
/*proc print data=ANOVA;
where effect='Cover*Fert';
run; */
title 'Log-transformed data';
data transformed; set analysis; if ep in ('TC (%)', 'TN (%)', 'TP (ppm)',
'WEP', 'pH') then delete;
*%modeling(y=logresp,covariate=logbaseline);
proc mixed data=transformed order=data plots=(studentpanel) ;by ep depth;
class cover fert rep plot point year;
model logresp=logbaseline rep cover fert year cover*fert cover*year fert*year
cover*fert*year/ddfm=kr;
lsmeans cover fert year cover*fert cover*year fert*year
cover*fert*year/pdiff;
repeated point year/subject=plot type=un@cs;
slice fert*year/sliceby=year lines;
slice cover*year/sliceby=year lines;
slice cover*fert*year/sliceby=year lines;
*ods select covparms tests3 lsmeans studentpanel;
* The following contrast states were added on Spetember 13, 2021;
contrast "Linear"       year -2 -1 0 1 2;
contrast "Linear Control"  year -2 -1 0 1 2

               fert*year -2 -1 0 1 2 0 0 0 0 0 0 0 0 0 0;
contrast "Linear Fall Broadcast"    year -2 -1 0 1 2

               fert*year 0 0 0 0 0 -2 -1 0 1 2 0 0 0 0 0;
contrast "Linear Spring Injected"   year -2 -1 0 1 2

               fert*year 0 0 0 0 0 0 0 0 0 0 -2 -1 0 1 2;
contrast "Linear Cover Crop"     year -2 -1 0 1 2

               cover*year -2 -1 0 1 2 0 0 0 0 0;
contrast "Linear No Cover"          year -2 -1 0 1 2

                  cover*year 0 0 0 0 0 -2 -1 0 1 2;
estimate "Linear"                year -2 -1 0 1 2;
estimate "Linear Control"        year -2 -1 0 1 2

               fert*year -2 -1 0 1 2 0 0 0 0 0 0 0 0 0 0;
estimate "Linear Fall Broadcast"    year -2 -1 0 1 2

               fert*year 0 0 0 0 0 -2 -1 0 1 2 0 0 0 0 0;
estimate "Linear Spring Injected"   year -2 -1 0 1 2

               fert*year 0 0 0 0 0 0 0 0 0 0 -2 -1 0 1 2;
estimate "Linear Cover Crop"     year -2 -1 0 1 2

               cover*year -2 -1 0 1 2 0 0 0 0 0;
estimate "Linear No Cover"          year -2 -1 0 1 2

               cover*year 0 0 0 0 0 -2 -1 0 1 2;
ods output lsmeans=lsm2 Tests3=ANOVA2 diffs=pdiffs2 SliceLines=slines2;
run;
```

```
data slines2; set slines2 (where=(effect is not missing)); keep ep effect
slice fert cover depth estimate line: ;
run;
data slines2; set slines2; array dx line:; call sortc(of line:); x = catt(of
line:); *This sorts the letters alphabetically and stores them as a single
variable.;
run;

proc sort data=slines2; by ep depth effect slice fert descending cover;

data slines2; retain ep depth effect slice fert cover estimate x; set
slines2; *places effect slice fert cover estimate x as the first columns,
followed by other variable follow in order as is;
run;
data lsm2;set lsm2;
u=exp(estimate+stderr);l=exp(estimate-stderr);
median=exp(estimate);
REC_U= u-median;
REC_L= median-l;
comb=fert||'_'||cover;
run;
data combinedlsm; set lsm lsm2;
run;
proc sort data=combinedlsm; by effect depth cover fert year;
proc transpose data=combinedlsm out=lsmtable;
by effect depth cover fert year;
id ep;
var median;
run;
data lsmtable; set lsmtable;
if cover='NC' then csort=1;   if cover='CC' then csort=2;
if effect='cover' then esort=1; if effect='fert' then esort=2; if
effect='Year' then esort=3;
if effect= 'cover*fert' then esort=4; if effect='cover*Year' then esort=5; if
effect='fert*Year' then esort=6; if effect='cover*fert*Year' then
esort=7;*need to add in if statments for interacitons;
run;
proc sort data=lsmtable out=lsmtable;
by depth esort year fert descending cover;
run;
proc export data = WORK.lsmtable DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS Files\KAW_SOILS_2015-
2019_August2021.XLSX" replace;
     sheet=LSMeans;
proc export data = WORK.ANOVA DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS Files\KAW_SOILS_2015-
2019_August2021.XLSX" replace;
     sheet=ANOVA;
proc export data = WORK.pdiffs DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS Files\KAW_SOILS_2015-
2019_August2021.XLSX" replace;
     sheet=pdiff;
proc export data = WORK.slines DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS Files\KAW_SOILS_2015-
2019_August2021.XLSX" replace;
     sheet=slines;
proc export data = WORK.ANOVA2 DBMS=XLSX
```

```
     outfile = "C:\Users\Elliott\Documents\My SAS Files\KAW_SOILS_2015-
2019_August2021.XLSX" replace;
     sheet=ANOVA2;
proc export data = WORK.pdiffs2 DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS Files\KAW_SOILS_2015-
2019_August2021.XLSX" replace;
     sheet=pdiff2;
proc export data = WORK.slines2 DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS Files\KAW_SOILS_2015-
2019_August2021.XLSX" replace;
     sheet=slines2;
run;
quit;

/*data plot;set plot;
l=estimate-stderr;u=estimate+stderr;
run;
title 'LSM+/-SE';

%macro plot(data,y,depth,title);
ods graphics/height=9in width=6in outputfmt=png attrpriority=none noborder;
proc sgpanel data=&data;
title2 "&title";
where depth=&depth;
styleattrs datacontrastcolors=(red green blue);
panelby ep/novarname layout=rowlattice uniscale=column rowheaderpos=left
headerbackcolor=white noheaderborder
        rows=5;
scatter x=year y=&y/group=fert yerrorupper=u yerrorlower=l noerrorcaps
groupdisplay=cluster
       markerattrs=(symbol=plus) clusterwidth=0.1;
series x=year y=&y/group=fert groupdisplay=cluster clusterwidth=0.1 markers
markerattrs=(symbol=plus)
       lineattrs=(pattern=1) name='a';
rowaxis display=(nolabel);
keylegend 'a'/noborder title='Fertilizer';
run;
%mend;
%plot(data=plot, y=estimate,depth=3,title=0~5cm);
%plot(data=plot,y=estimate,depth=5,title=5~15cm);
data plot_log;set plot_log;
l=exp(estimate-stderr);u=exp(estimate+stderr);
median=exp(estimate);
run;
title 'Back-transformed LSM+/-SE';
%plot(data=plot_log,y=median,depth=3,title=0~5cm);
%plot(data=plot_log,y=median,depth=5,title=5~15cm);
/*
Comments:
---Model for multivariate repeated measurements with type=UN@CS generally
provided the best fit.
---Log transformation is needed for modeling M3-P.
---Baseline, or log(baseline), should be included as a covariate.
*/
```

Analysis for 2017 through 2019 0-5 cm Data

```
%let path=C:\Users\Elliott\Documents\GRADUATE SCHOOL\KAW\Soils;
libname dat "&path\Data";
/*
This analysis focuses on depth '0~2.5cm' and '2.5~5cm' from 2017-2019.
*/
title;
proc format;
value dp 1='0~2.5cm' 2='2.5~5cm' 3='0~5cm' 4='0~5cm (Avg)' 5='5~15cm';
value pt 1='Point 1' 2='Point 2' 3='Point 3';
run;
data analysis;set dat.analysis;
if depth in (3,4,5) then delete;
if year<2017 then delete;
run;
proc tabulate data=analysis;
class depth year;
var resp;
table year, n*depth=' '*resp=' ';
run;
ods graphics/reset;
proc sort data=analysis;by ep ;
ods graphics off;
*The following lines of code are only for M3-P since it requires log10
transformation;
proc mixed data=analysis order=data plots=(studentpanel);where ep='M3-P';
by ep;
class cover fert rep plot point year depth;
model logresp=logbaseline rep cover|fert|year|depth/ddfm=kr;
random plot;
repeated point depth/subject=plot*year type=un@un;
lsmeans cover|fert|year|depth/pdiff;
slice cover*depth/sliceby=depth lines;
slice fert*depth/sliceby=depth lines;
slice fert*year/sliceby=year lines;
slice fert*depth*year/sliceby=year lines;
* The following contrast states were added on Spetember 16, 2021;
contrast "Linear"                year -1 0 1;
contrast "Linear Control"        year -1 0 1

                           fert*year -1 0 1 0 0 0 0 0 0;
contrast "Linear Fall Broadcast"    year -1 0 1

                           fert*year 0 0 0 -1 0 1 0 0 0;
contrast "Linear Spring Injected"   year -1 0 1

                           fert*year 0 0 0 0 0 0 -1 0 1;
contrast "Linear Cover Crop"     year -1 0 1

                           cover*year -1 0 1 0 0 0;
contrast "Linear No Cover"          year -1 0 1

                           cover*year 0 0 0 -1 0 1;
estimate "Linear"                year -1 0 1;
estimate "Linear Control"        year -1 0 1
```

```
                              fert*year -1 0 1 0 0 0 0 0 0;
estimate "Linear Fall Broadcast"    year -1 0 1

                              fert*year 0 0 0 -1 0 1 0 0 0;
estimate "Linear Spring Injected"   year -1 0 1

                              fert*year 0 0 0 0 0 0 -1 0 1;
estimate "Linear Cover Crop"     year -1 0 1

                              cover*year -1 0 1 0 0 0;
estimate "Linear No Cover"          year -1 0 1

                              cover*year 0 0 0 -1 0 1;
*ods select tests3 covparms studentpanel lsmeans diffs slices slicelines;
ods output lsmeans=lsm Tests3=ANOVA diffs=pdiffs SliceLines=slines;
run;
data slines; set slines (where=(effect is not missing)); keep effect slice
fert cover depth estimate line: ;
run;
data slines; set slines; array dx line:; call sortc(of line:); x = catt(of
line:); *This sorts the letters alphabetically and stores them as a single
variable.;
run;

proc sort data=slines; by effect slice fert descending cover depth;

data slines; retain effect slice fert cover depth estimate x; set slines;
*places effect slice fert cover estimate x as the first columns, followed by
other variable follow in order as is;
run;
*Lines 49-55 backtransform the log10 transformed data and also generate the
upper and lower limits for error bars;
data lsm;set lsm;
u=exp(estimate+stderr);l=exp(estimate-stderr);
median=exp(estimate);
REC_U= u-median;
REC_L= median-l;
comb=fert||'_'||cover;
run;
*Lines 57-74 analyze all variable other than M3-P since they do not require
log10 transformation;
proc mixed data=analysis order=data plots=(studentpanel);where ep^='M3-P';
by ep;
class cover fert rep plot point year depth;
model resp=baseline rep cover|fert|year|depth/ddfm=kr;
random plot;
repeated point depth/subject=plot*year type=un@un;
lsmeans cover|fert|year|depth/pdiff;
*lsmeans cover fert year depth cover*year cover*fert fert*year cover*depth
fert*depth/pdiff;
slice cover*depth/sliceby=depth lines;
slice fert*depth/sliceby=depth lines;
slice fert*year/sliceby=year lines;
slice cover*year/sliceby=year lines;
slice depth*year/sliceby=year lines;
slice fert*depth*year/sliceby=year lines;
```

```
slice cover*fert*depth/sliceby=depth lines;
* The following contrast states were added on Spetember 16, 2021;
contrast "Linear"                year -1 0 1;
contrast "Linear Control"        year -1 0 1

                         fert*year -1 0 1 0 0 0 0 0 0;
contrast "Linear Fall Broadcast"    year -1 0 1

                         fert*year 0 0 0 -1 0 1 0 0 0;
contrast "Linear Spring Injected"   year -1 0 1

                         fert*year 0 0 0 0 0 0 -1 0 1;
contrast "Linear Cover Crop"     year -1 0 1

                         cover*year -1 0 1 0 0 0;
contrast "Linear No Cover"          year -1 0 1

                      cover*year 0 0 0 -1 0 1;
estimate "Linear"                year -1 0 1;
estimate "Linear Control"        year -1 0 1

                      fert*year -1 0 1 0 0 0 0 0 0;
estimate "Linear Fall Broadcast"    year -1 0 1

                      fert*year 0 0 0 -1 0 1 0 0 0;
estimate "Linear Spring Injected"   year -1 0 1

                         fert*year 0 0 0 0 0 0 -1 0 1;
estimate "Linear Cover Crop"     year -1 0 1

                         cover*year -1 0 1 0 0 0;
estimate "Linear No Cover"          year -1 0 1

                         cover*year 0 0 0 -1 0 1;
*ods select tests3 covparms studentpanel lsmeans diffs slices slicelines;
ods output lsmeans=lsm2 Tests3=ANOVA2 diffs=pdiffs2 SliceLines=slines2;
run;
data slines2; set slines2 (where=(effect is not missing)); keep ep effect
slice fert cover depth estimate line: ;
run;
data slines2; set slines2; array dx line:; call sortc(of line:); x = catt(of
line:); *This sorts the letters alphabetically and stores them as a single
variable.;
run;

proc sort data=slines2; by effect slice ep fert descending cover depth;

data slines2; retain effect slice fert cover depth estimate x; set slines2;
*places effect slice fert cover estimate x as the first columns, followed by
other variable follow in order as is;
run;
data lsm2;set lsm2;
u=(estimate+stderr);l=(estimate-stderr);
median=(estimate); *median is actually the mean;
REC_U= u-median;
REC_L= median-l;
comb=fert||'_'||cover;
```

```
run;
/* The following lines (85-101) are designed to generate an organized,
complete LSmeans table to be use in either journals or dissertation */
data combinedlsm; set lsm lsm2;
run;
proc sort data=combinedlsm; by effect depth cover fert year; *when running
this line, all data duplicates in the table. I added noduplicates, but that
does not eliminate the error;
run;
proc transpose data=combinedlsm out=lsmtable;
by effect depth cover fert year;
id ep;
var median;
run;
data lsmtable; set lsmtable;
if effect='cover' then esort=1; if effect='fert' then esort=2; if
effect='Year' then esort=3; if effect='depth' then esort=4;
if effect= 'cover*fert' then esort=5; if effect='cover*Year' then esort=6; if
effect='cover*depth' then esort=7;
if effect='fert*Year' then esort=8; if effect='fert*depth' then esort =9; if
effect='Year*depth' then esort=10;
if effect='cover*fert*Year' then esort=11; if effect='cover*fert*depth' then
esort=12; if effect='cover*Year*depth' then esort=13; if
effect='fert*Year*depth' then esort=14; if effect='cove*fert*Year*depth' then
esort=15;*need to add in if statments for interacitons;
run;
proc sort data=lsmtable out=lsmtable;
by esort depth year fert descending cover;
run;
proc export data = WORK.lsm DBMS=XLSX
      outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_SOILS_August2021.XLSX" replace;
      sheet=LSMeans;
proc export data = WORK.ANOVA DBMS=XLSX
      outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_SOILS_August2021.XLSX" replace;
      sheet=ANOVA;
proc export data = WORK.pdiffs DBMS=XLSX
      outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_SOILS_August2021.XLSX" replace;
      sheet=pdiff;
proc export data = WORK.slines DBMS=XLSX
      outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_SOILS_August2021.XLSX" replace;
      sheet=slines;
proc export data = WORK.lsm2 DBMS=XLSX
      outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_SOILS_August2021.XLSX" replace;
      sheet=LSMeans2;
proc export data = WORK.ANOVA2 DBMS=XLSX
      outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_SOILS_August2021.XLSX" replace;
      sheet=ANOVA2;
proc export data = WORK.pdiffs2 DBMS=XLSX
      outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_SOILS_August2021.XLSX" replace;
      sheet=pdiff2;
```

```
proc export data = WORK.slines2 DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_SOILS_August2021.XLSX" replace;
     sheet=slines2;
proc export data = WORK.lsmtable DBMS=XLSX
     outfile = "C:\Users\Elliott\Documents\My SAS
Files\KAW_SOILS_August2021.XLSX" replace;
     sheet=CombinedLSM;
run;
quit;
```

Appendix E - KAW Soils: Supplemental Material

Tables

Table E.1. Means table for soils data from 2015-2019 0-5cm. Table abbreviations include Mehlich-III P (P_M), water-extractable P (P_W), total P (P_T), total C (TC), and total N (TN), no cover crop (NC), cover crop (CC), control (CN), fall broadcast (FB), and spring injected (SI). Levels of an effect that were significantly different at *p*-value < 0.05 were marked with different letters.

Effect	Cover	Fert	Year	P_M (ppm)	P_W (ppm)		P_T (ppm)	TC (%)	TN (%)	
				---------------------------ppm---------------------------				---------------%----------------		
Cover										
	NC			34.1	2.07		382	1.34	0.136	B
	CC			30.6	2.10		386	1.45	0.143	A
Fert										
		CN		14.7	0.74	C	347	1.38	0.138	
		FB		52.6	3.14	A	407	1.39	0.141	
		SI		43.6	2.38	B	399	1.42	0.141	
Year										
			2015	27.1	1.02	B	363	1.27	0.122	B
			2016	33.3	1.78	B	390	1.27	0.125	B
			2017	25.1	1.29	B	364	1.31	0.139	A
			2018	44.3	3.32	A	402	1.53	0.151	A
			2019	35.1	3.02	A	402	1.60	0.163	A
Cover*Fert										
	NC	CN		14.8	0.67		338	1.33	0.134	
	CC	CN		14.6	0.80		356	1.43	0.141	
	NC	FB		60.7	3.28		412	1.32	0.136	
	CC	FB		45.6	3.00		402	1.46	0.146	
	NC	SI		44.0	2.25		397	1.39	0.139	
	CC	SI		43.3	2.50		401	1.46	0.143	
	NC		2015	27.6	1.03		371	1.25	0.120	
	CC		2015	26.5	1.01		356	1.29	0.123	
	NC		2016	35.1	1.84		396	1.24	0.122	
	CC		2016	31.7	1.72		385	1.31	0.128	
	NC		2017	28.9	1.22		357	1.26	0.136	
	CC		2017	21.7	1.36		370	1.36	0.142	
	NC		2018	43.1	3.05		383	1.43	0.146	
	CC		2018	45.5	3.58		421	1.64	0.157	
	NC		2019	38.0	3.20		405	1.55	0.159	
	CC		2019	32.5	2.83		400	1.65	0.168	

Effect	Cover	Fert	Year	P_M (ppm)		P_W (ppm)	P_T (ppm)		TC (%)		TN (%)
				--------------------------ppm--------------------------					---------------%----------------		
Cover*Year											
	NC		2015	27.6		1.03	371		1.25	F	0.120
	CC		2015	26.5		1.01	356		1.29	EF	0.123
	NC		2016	35.1		1.84	396		1.24	F	0.122
	CC		2016	31.7		1.72	385		1.31	E	0.128
	NC		2017	28.9		1.22	357		1.26	EF	0.136
	CC		2017	21.7		1.36	370		1.36	D	0.142
	NC		2018	43.1		3.05	383		1.43	C	0.146
	CC		2018	45.5		3.58	421		1.64	A	0.157
	NC		2019	38.0		3.20	405		1.55	B	0.159
	CC		2019	32.5		2.83	400		1.65	A	0.168
Fert*Year											
		CN	2015	17.8	D	0.55	342	E	1.27		0.119
		FB	2015	43.1	B	1.65	385	BCD	1.23		0.122
		SI	2015	25.8	C	0.86	363	CDE	1.31		0.124
		CN	2016	17.4	DE	0.91	357	DE	1.28		0.123
		FB	2016	48.3	B	2.34	411	AB	1.27		0.126
		SI	2016	44.2	B	2.08	403	AB	1.27		0.125
		CN	2017	13.2	E	0.45	346	E	1.28		0.139
		FB	2017	40.2	BC	1.81	391	BCD	1.31		0.138
		SI	2017	29.6	C	1.60	354	DE	1.34		0.141
		CN	2018	17.6	DE	0.95	355	DE	1.50		0.147
		FB	2018	73.0	A	5.61	411	AB	1.55		0.156
		SI	2018	67.5	A	3.40	439	A	1.55		0.150
		CN	2019	9.4	F	0.83	333	E	1.57		0.160
		FB	2019	66.2	A	4.28	438	A	1.59		0.163
		SI	2019	69.7	A	3.95	436	A	1.64		0.167
Cover*Fert*Year											
	NC	CN	2015	16.5		0.43	343		1.22		0.116
	CC	CN	2015	19.3		0.67	341		1.32		0.122
	NC	FB	2015	50.5		1.83	401		1.21		0.122
	CC	FB	2015	36.8		1.47	369		1.25		0.122
	NC	SI	2015	25.3		0.84	370		1.31		0.123
	CC	SI	2015	26.2		0.89	357		1.31		0.124
	NC	CN	2016	18.0		0.95	357		1.25		0.120
	CC	CN	2016	16.8		0.86	356		1.31		0.127

Effect	Cover	Fert	Year	P_M (ppm)	P_W (ppm)	P_T (ppm)	TC (%)	TN (%)
				---------------------------ppm---------------------------			---------------%----------------	
	NC	FB	2016	54.8	2.36	419	1.22	0.120
	CC	FB	2016	42.5	2.31	403	1.32	0.132
	NC	SI	2016	43.7	2.19	412	1.25	0.125
	CC	SI	2016	44.6	1.97	394	1.29	0.125
	NC	CN	2017	15.2	0.46	332	1.27	0.136
	CC	CN	2017	11.5	0.43	361	1.29	0.141
	NC	FB	2017	48.9	1.88	382	1.23	0.135
	CC	FB	2017	33.0	1.75	400	1.38	0.141
	NC	SI	2017	32.4	1.31	359	1.29	0.137
	CC	SI	2017	27.1	1.90	350	1.39	0.144
	NC	CN	2018	15.9	0.67	328	1.41	0.143
	CC	CN	2018	19.5	1.23	383	1.60	0.152
	NC	FB	2018	79.4	5.60	416	1.40	0.147
	CC	FB	2018	67.1	5.61	405	1.69	0.164
	NC	SI	2018	63.3	2.89	403	1.48	0.147
	CC	SI	2018	72.0	3.91	474	1.62	0.153
	NC	CN	2019	9.9	0.85	329	1.51	0.155
	CC	CN	2019	9.0	0.81	336	1.63	0.165
	NC	FB	2019	76.6	4.72	443	1.52	0.158
	CC	FB	2019	57.1	3.85	433	1.66	0.169
	NC	SI	2019	72.4	4.04	442	1.61	0.163
	CC	SI	2019	67.1	3.85	431	1.66	0.170

Table E.2. Means table for soils data collected from 2015-2019 at 5-15 cm. Table abbreviations include Mehlich-III P (P_M), water-extractable P (P_W), total P (P_T), total C (TC), and total N (TN), no cover crop (NC), cover crop (CC), control (CN), fall broadcast (FB), and spring injected (SI). Letters represent significant differences between treatments at *p*-value < 0.05.

Effect	Cover	Fert	Year	P_M		P_T		TC		TN	
				----------------ppm---------------				------------------%-----------------			
Cover											
	NC			8.33	A	317		1.10		0.119	
	CC			6.85	B	322		1.10		0.119	
Fert											
		CN		5.74		315		1.09		0.119	
		FB		8.37		321		1.10		0.117	
		SI		8.96		323		1.10		0.121	
Year											
			2015	9.75		330	A	1.09		0.110	B
			2016	9.14		330	A	1.09		0.107	B
			2017	7.94		311	B	1.08		0.125	A
			2018	6.94		318	AB	1.10		0.127	A
			2019	5.00		309	B	1.12		0.127	A
Cover*Fert											
	NC	CN		5.90		312		1.08		0.120	
	CC	CN		5.59		318		1.09		0.119	
	NC	FB		9.73		320		1.09		0.117	
	CC	FB		7.20		322		1.10		0.117	
	NC	SI		10.07		320		1.11		0.121	
	CC	SI		7.97		326		1.09		0.122	
Cover*Year											
	NC		2015	10.10		335		1.08		0.109	
	CC		2015	9.41		324		1.09		0.110	
	NC		2016	10.78		331		1.11		0.110	
	CC		2016	7.76		330		1.08		0.105	
	NC		2017	9.01		307		1.08		0.126	
	CC		2017	7.00		314		1.08		0.124	
	NC		2018	7.35		305		1.09		0.127	
	CC		2018	6.55		331		1.11		0.127	
	NC		2019	5.57		308		1.11		0.125	
	CC		2019	4.49		309		1.13		0.130	
Fert*Year											
		CN	2015	8.92	ABC	320		1.07		0.108	
		FB	2015	10.56	A	329		1.10		0.112	

Effect	Cover	Fert	Year	P_M		P_T	TC	TN
				----------------ppm---------------			------------------%-----------------	
		SI	2015	9.84	AB	340	1.09	0.110
		CN	2016	8.28	BC	327	1.10	0.109
		FB	2016	9.02	ABC	335	1.08	0.103
		SI	2016	10.24	AB	329	1.10	0.109
		CN	2017	5.92	DE	306	1.06	0.126
		FB	2017	8.43	BC	321	1.08	0.120
		SI	2017	10.05	AB	305	1.11	0.130
		CN	2018	5.14	E	323	1.10	0.124
		FB	2018	8.60	ABC	305	1.10	0.128
		SI	2018	7.56	C	327	1.10	0.128
		CN	2019	2.78	F	298	1.12	0.129
		FB	2019	5.95	D	315	1.12	0.124
		SI	2019	7.55	C	314	1.12	0.129
Cover*Fert*Year								
	NC	CN	2015	8.59		320	1.06	0.109
	CC	CN	2015	9.27		320	1.07	0.106
	NC	FB	2015	12.01		333	1.08	0.109
	CC	FB	2015	9.28		325	1.12	0.114
	NC	SI	2015	9.98		352	1.11	0.110
	CC	SI	2015	9.70		327	1.08	0.109
	NC	CN	2016	8.60		333	1.09	0.113
	CC	CN	2016	7.96		321	1.11	0.106
	NC	FB	2016	11.20		332	1.09	0.107
	CC	FB	2016	7.26		338	1.06	0.099
	NC	SI	2016	12.99		328	1.14	0.110
	CC	SI	2016	8.07		330	1.07	0.109
	NC	CN	2017	6.47		304	1.08	0.128
	CC	CN	2017	5.41		308	1.03	0.124
	NC	FB	2017	10.21		316	1.06	0.122
	CC	FB	2017	6.96		327	1.09	0.118
	NC	SI	2017	11.08		302	1.09	0.128
	CC	SI	2017	9.10		308	1.12	0.131
	NC	CN	2018	5.33		306	1.09	0.123
	CC	CN	2018	4.95		340	1.11	0.125
	NC	FB	2018	9.35		303	1.08	0.127
	CC	FB	2018	7.92		307	1.13	0.130
	NC	SI	2018	7.96		306	1.11	0.130
	CC	SI	2018	7.17		347	1.09	0.126

Effect	Cover	Fert	Year	P_M	P_T	TC	TN
				----------------ppm---------------		------------------%-----------------	
	NC	CN	2019	2.81	295	1.10	0.127
	CC	CN	2019	2.76	300	1.15	0.131
	NC	FB	2019	6.79	316	1.11	0.122
	CC	FB	2019	5.21	313	1.13	0.126
	NC	SI	2019	9.04	313	1.12	0.125
	CC	SI	2019	6.30	315	1.12	0.132

Table E.3. Means table for soils data collected from 2017-2019 at both 0-2.5 cm and 2.5-5 cm. Table abbreviations include Mehlich-III P (PM), water-extractable P (PW), total P (PT), total C (TC), and total N (TN), no cover crop (NC), cover crop (CC), control (CN), fall broadcast (FB), and spring injected (SI). Letters represent significant differences between treatments at p-value < 0.05.

Effect	Cover	Fert	Year	Depth	P_M		P_W	P_T		TC		TN	
					---------------------ppm---------------------------					----------------%-----------------			
Cover													
	NC				34.6		2.65	384		1.43		0.148	
	CC				30.2		2.76	396		1.57		0.158	
Fert													
		CN			11.6		0.75	338		1.47		0.150	
		FB			53.7		4.06	418		1.50		0.154	
		SI			54.3		3.30	413		1.54		0.155	
Year													
			2017		30.8		2.09	368		1.38		0.145	
			2018		36.4		3.13	401		1.54		0.151	
			2019		30.0		2.89	401		1.60		0.164	
Depth													
				0-2.5 cm	51.0		4.24	427		1.69		0.166	
				2.5-5 cm	20.5		1.17	353		1.32		0.140	
Cover*Fert													
	NC	CN			12.0		0.65	326		1.41		0.145	
	CC	CN			11.2		0.84	350		1.54		0.155	
	NC	FB			63.0		4.36	419		1.41		0.149	
	CC	FB			45.7		3.77	417		1.60		0.159	
	NC	SI			55.0		2.94	407		1.49		0.150	
	CC	SI			53.7		3.67	420		1.58		0.159	
Cover*Year													
	NC		2017		33.7		2.06	367	D	1.32		0.140	
	CC		2017		28.1		2.12	368	C	1.44		0.149	
	NC		2018		37.2		2.82	382	B	1.43		0.146	
	CC		2018		35.7		3.44	419	A	1.64		0.156	
	NC		2019		33.0		3.06	403	AB	1.55		0.159	
	CC		2019		27.3		2.72	399	AB	1.65		0.168	
Cover*Depth													
	NC			0-2.5 cm	52.7	A	4.02	415	B	1.59	B	0.159	B
	CC			0-2.5 cm	49.4	A	4.46	438	A	1.79	A	0.173	A
	NC			2.5-5 cm	22.7	B	1.28	353	C	1.28	D	0.137	D
	CC			2.5-5 cm	18.4	B	1.06	353	C	1.36	C	0.142	C
Fert*Year													

Effect	Cover	Fert	Year	Depth	P_M		P_W		P_T		TC		TN	
					---------------------ppm--------------------------						---------------%----------------			
		CN	2017		13.0	C	0.52		326	B	1.35		0.143	
		FB	2017		49.1	AB	3.06		407	A	1.37		0.143	
		SI	2017		45.6	B	2.69		370	B	1.42		0.148	
		CN	2018		14.7	C	0.83		356	B	1.50		0.147	
		FB	2018		57.4	AB	4.99		411	A	1.55		0.155	
		SI	2018		57.3	AB	3.58		435	A	1.55		0.149	
		CN	2019		8.1	D	0.89		332	B	1.57		0.161	
		FB	2019		54.9	AB	4.14		436	A	1.59		0.163	
		SI	2019		61.4	A	3.65		435	A	1.63		0.167	
<u>Fert*Depth</u>														
		CN		0-2.5 cm	18.1	C	0.88		355	B	1.63	B	0.163	
		FB		0-2.5 cm	90.1	A	6.68		472	A	1.70	A	0.167	
		SI		0-2.5 cm	81.5	A	5.15		453	A	1.74	A	0.169	
		CN		2.5-5 cm	7.4	D	0.61		321	C	1.31	C	0.138	
		FB		2.5-5 cm	32.0	B	1.45		364	B	1.31	C	0.141	
		SI		2.5-5 cm	36.2	B	1.46		374	B	1.33	C	0.141	
<u>Year*Depth</u>														
			2017	0-2.5 cm	47.0		3.44	B	395	B	1.48	C	0.152	C
			2018	0-2.5 cm	59.6		5.17	A	442	A	1.74	B	0.162	B
			2019	0-2.5 cm	47.3		4.11	B	443	A	1.85	A	0.184	A
			2017	2.5-5 cm	20.2		0.74	C	341	D	1.28	E	0.137	E
			2018	2.5-5 cm	22.3		1.09	C	359	C	1.33	D	0.139	E
			2019	2.5-5 cm	19.1		1.68	C	360	C	1.34	D	0.144	D
<u>Cover*Fert*Year</u>														
	NC	CN	2017		14.1		0.49		322		1.30		0.137	
	CC	CN	2017		12.1		0.55		329		1.39		0.150	
	NC	FB	2017		59.4		3.40		401		1.29		0.141	
	CC	FB	2017		40.6		2.72		414		1.44		0.144	
	NC	SI	2017		45.9		2.30		378		1.36		0.142	
	CC	SI	2017		45.3		3.09		362		1.47		0.154	
	NC	CN	2018		14.3		0.61		328		1.40		0.144	
	CC	CN	2018		15.2		1.05		384		1.59		0.151	
	NC	FB	2018		63.5		5.04		415		1.41		0.147	
	CC	FB	2018		51.9		4.95		406		1.70		0.163	
	NC	SI	2018		56.7		2.82		403		1.49		0.146	
	CC	SI	2018		57.9		4.33		468		1.62		0.153	
	NC	CN	2019		8.5		0.86		328		1.52		0.156	
	CC	CN	2019		7.6		0.93		336		1.63		0.165	
	NC	FB	2019		66.4		4.63		441		1.52		0.158	

Effect	Cover	Fert	Year	Depth	P_M	P_W		P_T	TC	TN
					---------------------ppm--------------------------				----------------%-----------------	
	CC	FB	2019		45.4	3.64		431	1.67	0.169
	NC	SI	2019		63.9	3.69		440	1.61	0.163
	CC	SI	2019		58.9	3.60		430	1.66	0.171
Cover*Fert*Depth										
	NC	CN		0-2.5 cm	18.2	0.75	CDE	334	1.53	0.155
	CC	CN		0-2.5 cm	17.9	1.01	CDE	376	1.73	0.170
	NC	FB		0-2.5 cm	102.5	7.02	A	471	1.57	0.159
	CC	FB		0-2.5 cm	79.3	6.33	A	473	1.84	0.175
	NC	SI		0-2.5 cm	78.4	4.27	B	440	1.67	0.162
	CC	SI		0-2.5 cm	84.7	6.03	A	465	1.81	0.175
	NC	CN		2.5-5 cm	7.9	0.55	E	318	1.28	0.136
	CC	CN		2.5-5 cm	7.0	0.67	DE	323	1.35	0.141
	NC	FB		2.5-5 cm	38.7	1.69	C	367	1.24	0.138
	CC	FB		2.5-5 cm	26.4	1.21	CD	361	1.37	0.143
	NC	SI		2.5-5 cm	38.6	1.60	C	373	1.30	0.138
	CC	SI		2.5-5 cm	34.0	1.31	C	375	1.35	0.143
Cover*Year*Depth										
	NC		2017	0-2.5 cm	51.7	3.44		393	1.41	0.146
	CC		2017	0-2.5 cm	42.7	3.43		396	1.55	0.159
	NC		2018	0-2.5 cm	57.4	4.51		412	1.59	0.155
	CC		2018	0-2.5 cm	62.0	5.83		472	1.90	0.170
	NC		2019	0-2.5 cm	49.2	4.09		440	1.77	0.176
	CC		2019	0-2.5 cm	45.5	4.12		446	1.94	0.191
	NC		2017	2.5-5 cm	22.0	0.68		341	1.23	0.134
	CC		2017	2.5-5 cm	18.5	0.81		341	1.32	0.140
	NC		2018	2.5-5 cm	24.1	1.13		352	1.27	0.137
	CC		2018	2.5-5 cm	20.6	1.06		366	1.38	0.141
	NC		2019	2.5-5 cm	22.2	2.03		366	1.32	0.142
	CC		2019	2.5-5 cm	16.4	1.32		353	1.37	0.146
Fert*Year*Depth										
		CN	2017	0-2.5 cm	18.6	0.76		333	1.43	0.150
		FB	2017	0-2.5 cm	76.7	5.20		447	1.48	0.152
		SI	2017	0-2.5 cm	72.7	4.34		405	1.52	0.155
		CN	2018	0-2.5 cm	24.6	1.27		381	1.68	0.161
		FB	2018	0-2.5 cm	101.1	8.41		472	1.78	0.166
		SI	2018	0-2.5 cm	85.3	5.82		474	1.78	0.161
		CN	2019	0-2.5 cm	12.9	0.61		351	1.78	0.177
		FB	2019	0-2.5 cm	94.4	6.42		497	1.86	0.184
		SI	2019	0-2.5 cm	87.3	5.29		479	1.93	0.190

Effect	Cover	Fert	Year	Depth	P_M	P_W	P_T	TC	TN
					---------------------ppm---------------------------			----------------%-----------------	
		CN	2017	2.5-5 cm	9.2	0.27	318	1.26	0.136
		FB	2017	2.5-5 cm	31.4	0.92	368	1.26	0.134
		SI	2017	2.5-5 cm	28.6	1.04	335	1.31	0.141
		CN	2018	2.5-5 cm	8.8	0.38	331	1.32	0.134
		FB	2018	2.5-5 cm	32.6	1.57	349	1.33	0.145
		SI	2018	2.5-5 cm	38.5	1.33	397	1.33	0.138
		CN	2019	2.5-5 cm	5.0	1.18	313	1.36	0.144
		FB	2019	2.5-5 cm	31.9	1.86	375	1.33	0.143
		SI	2019	2.5-5 cm	43.1	2.00	391	1.34	0.144
Cover*Fert*Year*Depth									
	NC	CN	2017	0-2.5 cm	20.1	0.74	320	1.38	0.143
	CC	CN	2017	0-2.5 cm	17.2	0.79	346	1.48	0.157
	NC	FB	2017	0-2.5 cm	93.3	5.96	443	1.39	0.147
	CC	FB	2017	0-2.5 cm	63.1	4.44	450	1.56	0.156
	NC	SI	2017	0-2.5 cm	73.6	3.64	417	1.45	0.148
	CC	SI	2017	0-2.5 cm	71.8	5.05	392	1.60	0.162
	NC	CN	2018	0-2.5 cm	22.7	1.01	342	1.54	0.154
	CC	CN	2018	0-2.5 cm	26.6	1.53	419	1.82	0.167
	NC	FB	2018	0-2.5 cm	109.0	8.21	469	1.57	0.154
	CC	FB	2018	0-2.5 cm	93.8	8.61	475	1.98	0.177
	NC	SI	2018	0-2.5 cm	76.3	4.31	426	1.68	0.156
	CC	SI	2018	0-2.5 cm	95.4	7.33	522	1.88	0.166
	NC	CN	2019	0-2.5 cm	13.1	0.50	341	1.69	0.169
	CC	CN	2019	0-2.5 cm	12.6	0.72	362	1.88	0.185
	NC	FB	2019	0-2.5 cm	105.9	6.90	501	1.75	0.176
	CC	FB	2019	0-2.5 cm	84.1	5.94	494	1.97	0.191
	NC	SI	2019	0-2.5 cm	85.9	4.87	477	1.89	0.183
	CC	SI	2019	0-2.5 cm	88.7	5.72	481	1.96	0.197
	NC	CN	2017	2.5-5 cm	9.9	0.23	325	1.23	0.130
	CC	CN	2017	2.5-5 cm	8.5	0.31	312	1.30	0.143
	NC	FB	2017	2.5-5 cm	37.8	0.84	359	1.19	0.136
	CC	FB	2017	2.5-5 cm	26.1	0.99	377	1.32	0.132
	NC	SI	2017	2.5-5 cm	28.7	0.95	338	1.28	0.136
	CC	SI	2017	2.5-5 cm	28.6	1.12	333	1.35	0.146
	NC	CN	2018	2.5-5 cm	8.9	0.20	315	1.27	0.133
	CC	CN	2018	2.5-5 cm	8.7	0.56	348	1.36	0.135
	NC	FB	2018	2.5-5 cm	37.0	1.86	362	1.25	0.140
	CC	FB	2018	2.5-5 cm	28.7	1.28	336	1.42	0.150
	NC	SI	2018	2.5-5 cm	42.1	1.33	380	1.31	0.136

Effect	Cover	Fert	Year	Depth	P_M	P_W	P_T	TC	TN
					---------------------ppm---------------------------			----------------%-----------------	
	CC	SI	2018	2.5-5 cm	35.1	1.32	413	1.35	0.139
	NC	CN	2019	2.5-5 cm	5.5	1.22	316	1.35	0.143
	CC	CN	2019	2.5-5 cm	4.6	1.14	310	1.38	0.145
	NC	FB	2019	2.5-5 cm	41.6	2.37	381	1.29	0.139
	CC	FB	2019	2.5-5 cm	24.5	1.35	369	1.37	0.147
	NC	SI	2019	2.5-5 cm	47.5	2.52	402	1.33	0.143
	CC	SI	2019	2.5-5 cm	39.1	1.48	380	1.35	0.145

Table E.4. Means table for soils pH data collected from 2015 –2019 at both 0-5 cm and 5-15 cm. Table abbreviations include no cover crop (NC), cover crop (CC), control (CN), fall broadcast (FB), and spring injected (SI). Letters represent significant differences between treatments at p-value < 0.05.

Effect	Cover	Fert	Year	pH			
				0-5 cm		5-15 cm	
				--------------	-log[H+]	------------	
Cover							
	NC			6.88		6.60	
	CC			6.90		6.61	
Fert							
		CN		6.96		6.65	
		FB		6.84		6.63	
		SI		6.87		6.55	
Year							
			2015	6.91		6.52	CD
			2016	7.03		6.58	BC
			2017	6.81		6.48	D
			2018	6.88		6.62	B
			2019	6.80		6.84	A
Cover*Fert							
	NC	CN		6.93		6.64	
	CC	CN		6.99		6.65	
	NC	FB		6.84		6.64	
	CC	FB		6.83		6.61	
	NC	SI		6.86		6.52	
	CC	SI		6.88		6.58	
Cover*Year							
	NC		2015	6.91	BC	6.52	
	CC		2015	6.92	BC	6.52	
	NC		2016	7.00	AB	6.59	
	CC		2016	7.07	A	6.56	
	NC		2017	6.70	D	6.44	
	CC		2017	6.92	BC	6.52	
	NC		2018	6.92	BC	6.62	
	CC		2018	6.85	CD	6.63	
	NC		2019	6.85	CD	6.83	
	CC		2019	6.76	D	6.84	

Effect	Cover	Fert	Year	pH	
Fert*Year					
		CN	2015	6.95	6.54
		FB	2015	6.84	6.54
		SI	2015	6.96	6.49
		CN	2016	7.11	6.68
		FB	2016	7.01	6.56
		SI	2016	6.98	6.49
		CN	2017	6.84	6.51
		FB	2017	6.76	6.47
		SI	2017	6.82	6.47
		CN	2018	6.95	6.62
		FB	2018	6.83	6.68
		SI	2018	6.88	6.57
		CN	2019	6.95	6.89
		FB	2019	6.75	6.89
		SI	2019	6.71	6.74
Cover*Fert*Year					
	NC	CN	2015	6.90	6.50
	CC	CN	2015	7.00	6.58
	NC	FB	2015	6.91	6.56
	CC	FB	2015	6.76	6.53
	NC	SI	2015	6.92	6.52
	CC	SI	2015	7.00	6.46
	NC	CN	2016	7.15	6.69
	CC	CN	2016	7.07	6.67
	NC	FB	2016	6.96	6.61
	CC	FB	2016	7.06	6.50
	NC	SI	2016	6.89	6.47
	CC	SI	2016	7.06	6.51
	NC	CN	2017	6.72	6.56
	CC	CN	2017	6.97	6.47
	NC	FB	2017	6.65	6.41
	CC	FB	2017	6.88	6.53
	NC	SI	2017	6.73	6.36
	CC	SI	2017	6.91	6.57
	NC	CN	2018	6.94	6.61
	CC	CN	2018	6.95	6.63
	NC	FB	2018	6.88	6.70
	CC	FB	2018	6.77	6.66
	NC	SI	2018	6.92	6.55
	CC	SI	2018	6.83	6.58
	NC	CN	2019	6.93	6.85

Effect	Cover	Fert	Year	pH	
	CC	CN	2019	6.98	6.92
	NC	FB	2019	6.80	6.94
	CC	FB	2019	6.70	6.83
	NC	SI	2019	6.82	6.71
	CC	SI	2019	6.60	6.78

Table E.5. Means table for soils pH data collected from 2017-2019 at both 0-2.5 cm and 2.5-5 cm depths. Table abbreviations include no cover crop (NC), cover crop (CC), control (CN), fall broadcast (FB), and spring injected (SI). Letters represent significant differences between treatments at p-value < 0.05.

Effect	Cover	Fert	Year	Depth	pH - log[H+]	
Cover						
	NC				6.85	
	CC				6.83	
Fert						
		CN			6.92	
		FB			6.77	
		SI			6.82	
Year						
			2017		6.85	
			2018		6.88	
			2019		6.79	
Depth						
				0-2.5 cm	6.77	
				2.5-5 cm	6.90	
Cover*Fert						
	NC	CN			6.90	
	CC	CN			6.94	
	NC	FB			6.79	
	CC	FB			6.75	
	NC	SI			6.85	
	CC	SI			6.80	
Cover*Year						
	NC		2017		6.80	AB
	CC		2017		6.89	A
	NC		2018		6.89	A
	CC		2018		6.86	A
	NC		2019		6.84	AB
	CC		2019		6.73	B
Cover*Depth						
	NC			0-2.5 cm	6.81	AB
	CC			0-2.5 cm	6.74	B
	NC			2.5-5 cm	6.88	A
	CC			2.5-5 cm	6.92	A

Effect	Cover	Fert	Year	Depth	pH	
Fert*Year						
		CN	2017		6.88	BC
		FB	2017		6.76	BCD
		SI	2017		6.90	ABC
		CN	2018		6.93	AB
		FB	2018		6.81	ABCD
		SI	2018		6.88	ABC
		CN	2019		6.95	A
		FB	2019		6.74	CD
		SI	2019		6.68	D
Fert*Depth						
		CN		0-2.5 cm	6.88	
		FB		0-2.5 cm	6.66	
		SI		0-2.5 cm	6.78	
		CN		2.5-5 cm	6.96	
		FB		2.5-5 cm	6.88	
		SI		2.5-5 cm	6.86	
Year*Depth						
			2017	0-2.5 cm	6.71	C
			2018	0-2.5 cm	6.88	B
			2019	0-2.5 cm	6.73	C
			2017	2.5-5 cm	6.98	A
			2018	2.5-5 cm	6.87	B
			2019	2.5-5 cm	6.85	B
Cover*Fert*Year						
	NC	CN	2017		6.85	
	CC	CN	2017		6.90	
	NC	FB	2017		6.69	
	CC	FB	2017		6.83	
	NC	SI	2017		6.87	
	CC	SI	2017		6.94	
	NC	CN	2018		6.93	
	CC	CN	2018		6.94	
	NC	FB	2018		6.86	
	CC	FB	2018		6.76	
	NC	SI	2018		6.89	
	CC	SI	2018		6.87	
	NC	CN	2019		6.94	
	CC	CN	2019		6.96	
	NC	FB	2019		6.81	
	CC	FB	2019		6.66	
	NC	SI	2019		6.78	
	CC	SI	2019		6.58	

Effect	Cover	Fert	Year	Depth	pH
Cover*Fert*Depth					
	NC	CN		0-2.5 cm	6.92
	CC	CN		0-2.5 cm	6.84
	NC	FB		0-2.5 cm	6.70
	CC	FB		0-2.5 cm	6.62
	NC	SI		0-2.5 cm	6.82
	CC	SI		0-2.5 cm	6.74
	NC	CN		2.5-5 cm	6.89
	CC	CN		2.5-5 cm	7.03
	NC	FB		2.5-5 cm	6.87
	CC	FB		2.5-5 cm	6.89
	NC	SI		2.5-5 cm	6.87
	CC	SI		2.5-5 cm	6.85
Cover*Year*Depth					
	NC		2017	0-2.5 cm	6.68
	CC		2017	0-2.5 cm	6.75
	NC		2018	0-2.5 cm	6.93
	CC		2018	0-2.5 cm	6.84
	NC		2019	0-2.5 cm	6.83
	CC		2019	0-2.5 cm	6.62
	NC		2017	2.5-5 cm	6.93
	CC		2017	2.5-5 cm	7.04
	NC		2018	2.5-5 cm	6.86
	CC		2018	2.5-5 cm	6.88
	NC		2019	2.5-5 cm	6.85
	CC		2019	2.5-5 cm	6.85
Fert*Year*Depth					
		CN	2017	0-2.5 cm	6.78
		FB	2017	0-2.5 cm	6.59
		SI	2017	0-2.5 cm	6.76
		CN	2018	0-2.5 cm	6.96
		FB	2018	0-2.5 cm	6.77
		SI	2018	0-2.5 cm	6.92
		CN	2019	0-2.5 cm	6.90
		FB	2019	0-2.5 cm	6.62
		SI	2019	0-2.5 cm	6.66
		CN	2017	2.5-5 cm	6.97
		FB	2017	2.5-5 cm	6.93
		SI	2017	2.5-5 cm	7.04
		CN	2018	2.5-5 cm	6.91
		FB	2018	2.5-5 cm	6.85
		SI	2018	2.5-5 cm	6.85
		CN	2019	2.5-5 cm	7.00

Effect	**Cover**	**Fert**	**Year**	**Depth**	**pH**
		FB	2019	2.5-5 cm	6.86
		SI	2019	2.5-5 cm	6.69
Cover*Fert*Year*Depth					
	NC	CN	2017	0-2.5 cm	6.80
	CC	CN	2017	0-2.5 cm	6.76
	NC	FB	2017	0-2.5 cm	6.50
	CC	FB	2017	0-2.5 cm	6.69
	NC	SI	2017	0-2.5 cm	6.73
	CC	SI	2017	0-2.5 cm	6.80
	NC	CN	2018	0-2.5 cm	6.99
	CC	CN	2018	0-2.5 cm	6.94
	NC	FB	2018	0-2.5 cm	6.86
	CC	FB	2018	0-2.5 cm	6.68
	NC	SI	2018	0-2.5 cm	6.94
	CC	SI	2018	0-2.5 cm	6.89
	NC	CN	2019	0-2.5 cm	6.96
	CC	CN	2019	0-2.5 cm	6.84
	NC	FB	2019	0-2.5 cm	6.74
	CC	FB	2019	0-2.5 cm	6.49
	NC	SI	2019	0-2.5 cm	6.80
	CC	SI	2019	0-2.5 cm	6.53
	NC	CN	2017	2.5-5 cm	6.89
	CC	CN	2017	2.5-5 cm	7.05
	NC	FB	2017	2.5-5 cm	6.88
	CC	FB	2017	2.5-5 cm	6.98
	NC	SI	2017	2.5-5 cm	7.01
	CC	SI	2017	2.5-5 cm	7.08
	NC	CN	2018	2.5-5 cm	6.87
	CC	CN	2018	2.5-5 cm	6.94
	NC	FB	2018	2.5-5 cm	6.86
	CC	FB	2018	2.5-5 cm	6.84
	NC	SI	2018	2.5-5 cm	6.84
	CC	SI	2018	2.5-5 cm	6.85
	NC	CN	2019	2.5-5 cm	6.91
	CC	CN	2019	2.5-5 cm	7.08
	NC	FB	2019	2.5-5 cm	6.88
	CC	FB	2019	2.5-5 cm	6.83
	NC	SI	2019	2.5-5 cm	6.76
	CC	SI	2019	2.5-5 cm	6.63

Figures

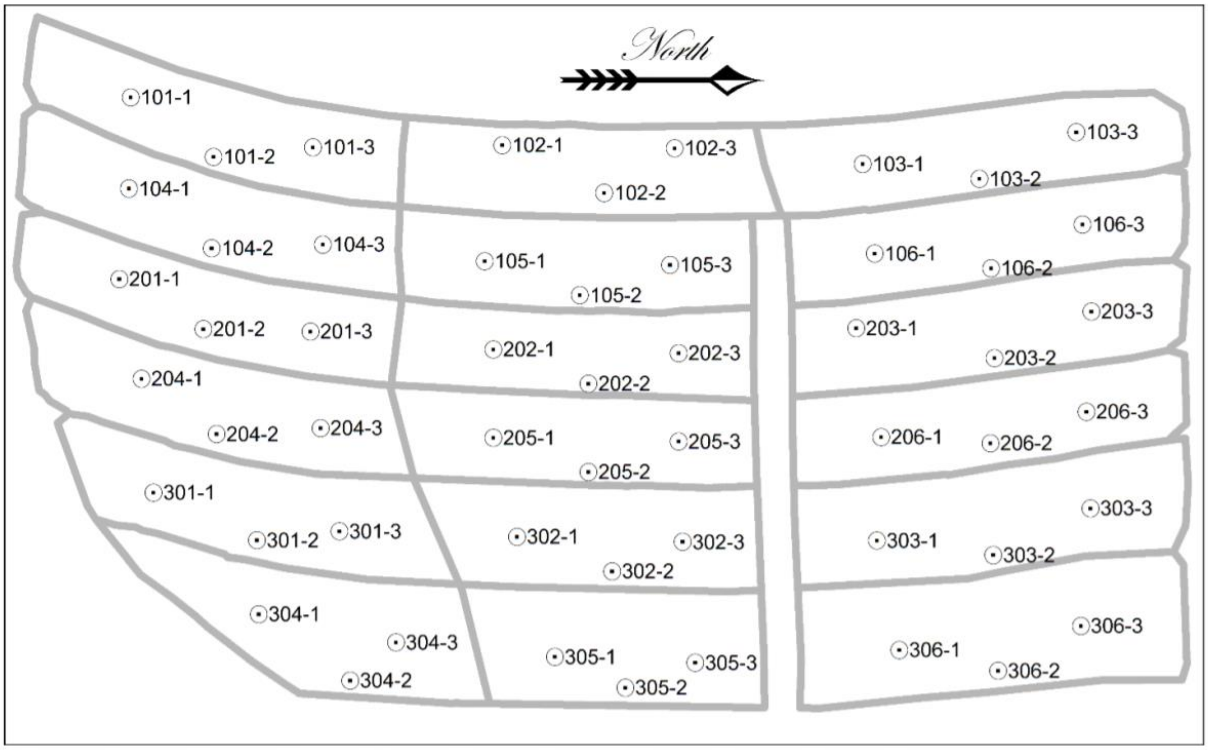

Figure E.1. Plot map at Kansas Agricultural Watershed field laboratory detailing the location of georeferenced sub-plots from where soil samples were collected each year. Sub-plot points 1 and 3 are located on the backslope of the above terrace while sub-plot 2 is located approximately in the middle of the terrace channel

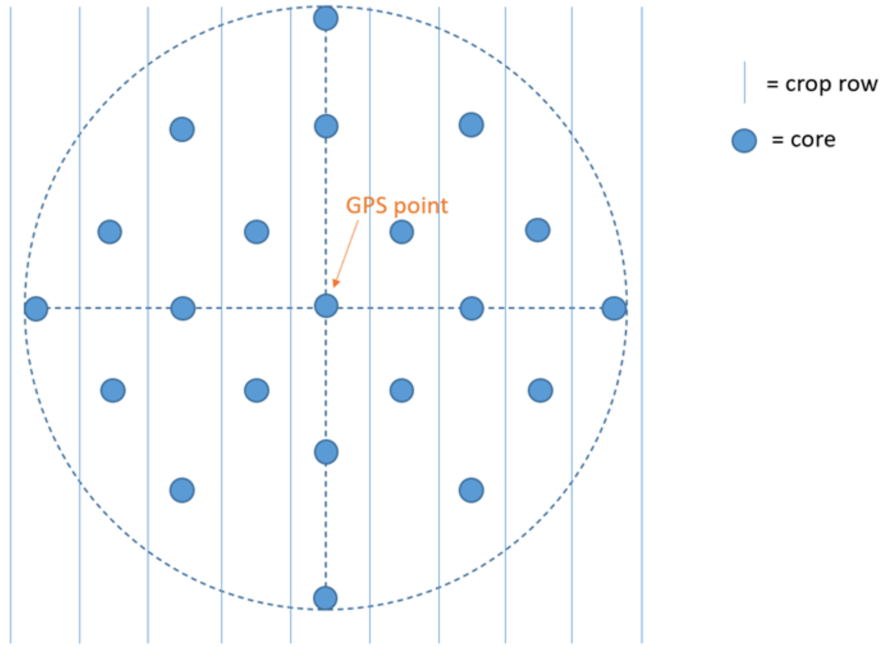

Figure E.2. Plot map at Kansas Agricultural Watershed field laboratory detailing the location of georeferenced sub-plots from where soil samples were collected each year. Sub-plot points 1 and 3 are located on the backslope of the above terrace while sub-plot 2 is located approximately in the middle of the terrace channel

Appendix F - Selecting Winter Cereals: Supplemental Material

Table F.1. Field operations and sample collection dates for the four examined growing environments.

Location	Event	Date
2020 Ashland Bottoms		
	Cover crop planting	9/27/2019
	Initial biomass sampling	5/18/2020
	Cover crop termination	5/18/2020
	1 day post termination biomass collection and filling of residue bags	5/19/2020
	1 week post termination residue bag collection	5/26/2020
	2 weeks post termination residue bag collection	6/2/2020
	4 weeks post termination residue bag collection	6/16/2020
	8 weeks post termination residue bag collection	7/14/2020
	12 weeks post termination residue bag collection	8/11/2020
	16 week post termination residue bag collection	9/8/2020
2020 Leonardville		
	Cover crop planting	9/15/2021
	Initial biomass sampling	4/28/2020
	Cover crop termination	4/29/2020
	1 day post termination biomass collection and filling of residue bags	4/30/2020
	1 week post termination residue bag collection	5/7/2020
	2 weeks post termination residue bag collection	5/14/2020
	4 weeks post termination residue bag collection	5/28/2020
	8 weeks post termination residue bag collection	6/25/2020
	12 weeks post termination residue bag collection	7/23/2020
	16 week post termination residue bag collection	8/20/2020
2021 Ashland Bottoms		
	Cover crop planting	10/2/2020
	Initial biomass sampling	5/4/2021
	Cover crop termination	5/5/2021
	1 day post termination biomass collection and filling of residue bags	5/6/2021
	1 week post termination residue bag collection	5/12/2021
	2 weeks post termination residue bag collection	5/19/2021
	4 weeks post termination residue bag collection	6/2/2021
	8 weeks post termination residue bag collection	6/30/2021
	12 weeks post termination residue bag collection	7/28/2021
	16 week post termination residue bag collection	8/25/2021

Location	Event	Date
2021 Leonardville		
	Cover crop planting	9/18/2020
	Initial biomass sampling	4/28/2021
	Cover crop termination	4/29/2021
	1 day post termination biomass collection and filling of residue bags	4/30/2021
	1 week post termination residue bag collection	5/6/2021
	2 weeks post termination residue bag collection	5/13/2021
	4 weeks post termination residue bag collection	5/27/2021
	8 weeks post termination residue bag collection	6/24/2021
	12 weeks post termination residue bag collection	7/22/2021
	16 week post termination residue bag collection	8/19/2021

Table F.2. Least square means for C:N and C:P ratios for data collected from all growing environments. Letters represent significance at alpha = 0.05.

Time	Species	C:N								C:P							
		Ashland Bottoms				Leonardville				Ashland Bottoms				Leonardville			
		2020		*2021*		*2020*		*2021*		*2020*		*2021*		*2020*		*2021*	
Initial		23.6		33.4	B	20.7	D	24.5		254	C	352		131		130	
1 Day		23.3		38.1	A	27.6	AB	28.7		241	C	196		144		143	
7 Days		.		37.9	A	29.1	A	28.8		.	.	201		147		137	
14 Days		28.9		37.2	A	26.0	B	25.2		332	A	192		154		130	
28 Days		25.0		30.6	C	23.0	C	25.8		291	B	187		137		121	
56 Days		21.8		29.2	C	22.2	CD	24.1		263	BC	214		134		118	
84 Days		17.9		24.4	D	16.1	E	20.9		258	C	204		113		120	
112 Days		16.3		20.0	E	14.9	E	18.5		248	C	203		127		110	
	Barley	19.3		30.0		.	.	25.1		242	C	188		.		119	
	Oat	18.9		.		17.9	C	21.1		252	BC	.		135		153	
	Rye	24.1		34.6		28.2	A	25.8		276	AB	212		157		128	
	Triticale	22.9		31.5		23.1	B	23.4		287	A	191		134		109	
	Wheat	22.7		28.8		18.8	C	24.2		254	BC	312		116		118	
	Cereal Killer	25.0		31.7		23.1	B	26.8		306	A	191		137		132	
Initial																	
	Barley	19.8	A	30.5		.	.	27.0	A	211	NS	162		.	.	130	BC
	Oat	24.7	A	.		17.4		24.7	AB	271	NS	.		138	A	168	A
	Rye	26.1	A	37.4		25.3		21.6	B	257	NS	175		142	A	119	BC
	Triticale	23.4	A	34.9		21.5		24.5	AB	277	NS	176		124	AB	112	C
	Wheat	24.5	A	31.4		19.0		25.4	AB	223	NS	1054		113	B	135	BC
	Cereal Killer	23.5	A	32.8		21.2		24.1	AB	288	NS	194		137	A	121	B

Time	Species	C:N						C:P						
1 Day														
	Barley	19.3	B	39.2	.	32.0	A	219	NS	190	.	.	144	B
	Oat	23.3	AB	.	24.1	27.3	AB	291	NS	.	159	A	185	A
	Rye	24.5	AB	40.4	35.6	29.4	AB	209	NS	201	161	A	140	B
	Triticale	22.9	AB	38.1	29.0	28.3	AB	254	NS	204	140	AB	126	B
	Wheat	23.6	AB	33.6	22.2	26.0	B	209	NS	195	120	B	130	B
	Cereal Killer	26.7	A	39.2	28.7	29.6	AB	264	NS	188	142	A	141	B
7 Days														
	Barley	.	.	36.3	.	31.5	A	.	.	200	.	.	137	B
	Oat	.	.	.	23.6	28.5	A	.	.	.	165	A	189	A
	Rye	.	.	39.4	35.7	28.8	A	.	.	207	157	AB	133	B
	Triticale	.	.	38.0	32.6	26.4	A	.	.	202	146	AB	115	B
	Wheat	.	.	34.3	23.7	26.7	A	.	.	194	125	C	122	B
	Cereal Killer	.	.	41.4	31.7	31.5	A	.	.	201	143	BC	136	B
14 Days														
	Barley	27.9	A	36.1	.	26.3	A	334	NS	191	.	.	124	BC
	Oat	25.5	A	.	20.4	25.2	A	330	NS	.	176	A	185	A
	Rye	31.3	A	38.5	36.1	26.6	A	327	NS	191	162	AB	121	BC
	Triticale	26.7	A	38.2	29.1	23.7	A	336	NS	188	152	BC	111	C
	Wheat	32.0	A	31.5	20.6	23.0	A	301	NS	214	132	C	118	BC
	Cereal Killer	30.3	A	41.7	26.7	26.5	A	364	NS	178	147	BC	135	B
28 Days														
	Barley	21.2	BC	30.3	.	26.2	AB	246	NS	182	.	.	115	BC
	Oat	18.8	C	.	18.1	20.2	C	268	NS	.	133	B	150	A
	Rye	26.7	AB	33.2	30.1	29.7	A	276	NS	198	164	A	125	B
	Triticale	27.1	AB	30.2	23.8	23.2	BC	304	NS	173	125	B	97	C
	Wheat	25.5	AB	30.0	19.6	26.5	AB	274	NS	210	121	B	115	BC
	Cereal Killer	33.1	A	29.4	25.2	30.7	A	376	NS	174	141	B	133	AB
56 Days														
	Barley	18.5	BC	28.0	.	22.8	AB	213	NS	216	.	.	107	B
	Oat	18.0	C	.	16.9	19.8	B	220	NS	.	115	C	134	A
	Rye	22.5	ABC	33.0	28.1	27.3	A	304	NS	252	161	A	131	A
	Triticale	24.1	AB	27.0	23.0	24.2	A	282	NS	191	142	AB	101	B
	Wheat	23.7	ABC	29.8	19.1	25.3	A	265	NS	214	116	C	119	AB
	Cereal Killer	25.2	A	28.0	25.8	26.0	A	296	NS	196	137	BC	118	AB

Time	Species	C:N						C:P						
84 Days														
	Barley	15.6	BC	21.9	.	19.9	B	233	NS	182	.	.	105	B
	Oat	13.9	C	.	14.0	15.6	C	191	NS	.	93	C	128	A
	Rye	19.3	AB	30.3	21.7	24.1	A	261	NS	231	141	A	136	A
	Triticale	21.1	A	24.7	15.5	19.4	B	304	NS	196	110	BC	105	B
	Wheat	16.9	ABC	22.6	14.4	23.2	AB	255	NS	222	99	C	118	AB
	Cereal Killer	22.1	A	22.6	16.1	24.9	A	304	NS	186	121	AB	135	A
112 Days														
	Barley	15.2	BC	17.8	.	18.6	A	240	NS	183	.	.	100	C
	Oat	12.5	C	.	12.0	13.0	B	194	NS	.	98	C	108	ABC
	Rye	20.3	A	24.9	18.6	20.8	A	302	NS	240	168	A	121	AB
	Triticale	16.8	AB	20.8	16.0	19.3	A	251	NS	197	134	B	103	BC
	Wheat	16.4	ABC	17.7	13.7	19.5	A	250	NS	189	102	C	102	C
	Cereal Killer	17.4	AB	18.5	15.0	21.3	A	250	NS	207	129	B	128	A

Table F.3. *P*-value for testing the fixed effects of the analysis of nutrient release from cover crop tissue data collected from the 2020 Ashland Bottoms, 2021 Ashland Bottom, 2020 Leonardville, and 2021 Leonardville growing environments. Bolded values indicate significance at alpha = 0.05.

Location		Change in P	Change in WEP	Change in N	Change in K	Change in SO4-S
2020 Ashland Bottoms						
	Species	**0.017**	0.206	**0.022**	0.106	**0.021**
	Time	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Species*Time	0.906	**0.038**	0.285	0.126	0.269
2021 Ashland Bottoms						
	Species	0.671	0.303	0.590	0.881	0.367
	Time	**<0.001**	**<0.001**	**0.003**	**<0.001**	**0.001**
	Species*Time	0.648	0.677	0.376	0.515	**0.050**
2020 Leonardville						
	Species	**0.042**	0.310	0.106	**0.001**	0.182
	Time	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Species*Time	**0.020**	0.290	**0.040**	**0.015**	0.334
2021 Leonardville						
	Species	**0.016**	0.137	**0.021**	0.152	0.154
	Time	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Species*Time	**<0.001**	**0.022**	**0.043**	**<0.001**	**0.020**

Table F.4. Least square means for mass of phosphorus and mass of water-extractable phosphorus (WEP) released from cover crop tissue at all four growing environments. Negative values indicate a release of nutrient from cover crop tissue. Letters indicate significant differences between treatment at alpha = 0.05.

Time	Species	Change in P				Change in WEP			
		Ashland Bottoms		*Leonardville*		*Ashland Bottoms*		*Leonardville*	
		2020	*2021*	*2020*	*2021*	*2020*	*2021*	*2020*	*2021*
					---------*g/m2*--------				
Main effect of time									
Initial									
1 d									
7 d			-0.056 A	-0.033 A	-0.011 A	.	0.056 A	0.111 A	0.244 A
14 d		-0.178 A	-0.222 C	-0.133 B	0.044 A	0.011 B	0.011 D	0.044 B	0.267 A
28 d		-0.178 A	-0.256 C	-0.133 B	-0.100 B	0.011 A	0.044 AB	0.022 B	0.244 A
56 d		-0.211 B	-0.078 A	-0.278 C	-0.256 C	0.011 B	0.033 BC	0.033 B	0.278 A
84 d		-0.256 C	-0.089 A	-0.356 D	-0.556 D	0.011 B	0.022 D	0.089 A	0.244 A
112 d		-0.233 B	-0.156 B	-0.522 E	-0.622 D	0.000 C	0.022 CD	0.022 B	0.022 B
Main effect of species									
	Barley	-0.211 A	-0.144 A	-	-0.200 AB	0.000 AB	0.022 A	-	0.200 AB
	Oat	-0.189 A	-	-0.189 A	-0.144 A	0.000 B	-	0.033 A	0.133 B
	Rye	-0.178 A	-0.167 A	-0.244 AB	-0.289 BC	0.011 AB	0.044 A	0.067 A	0.256 A
	Triticale	-0.344 B	-0.111 A	-0.289 B	-0.322 C	0.011 A	0.033 A	0.044 A	0.233 A
	Wheat	-0.167 A	-0.156 A	-0.267 B	-0.300 BC	0.011 AB	0.022 A	0.067 A	0.233 A
	Cereal Killer	-0.178 A	-0.133 A	-0.233 AB	-0.244 ABC	0.011 A	0.022 A	0.056 A	0.222 AB
Time by species interaction									
7 d	Barley	-	-0.067 A	-	-0.056 A	-	0.044 A	-	0.222 A
7 d	Oat	-	-	-0.044 A	-0.044 A	-	-	0.100 A	0.233 A
7 d	Rye	-	-0.078 A	0.000 A	-0.022 A	-	0.067 A	0.133 A	0.289 A

Time	Species	Change in P				Change in WEP			
		Ashland Bottoms		*Leonardville*		*Ashland Bottoms*		*Leonardville*	
		2020	*2021*	*2020*	*2021*	*2020*	*2021*	*2020*	*2021*
					---------*g/m2*--------				
7 d	Triticale	-	-0.033 A	-0.056 A	0.100 A	-	0.056 A	0.089 A	0.200 A
7 d	Wheat	-	-0.022 A	-0.022 A	0.033 A	-	0.056 A	0.133 A	0.311 A
7 d	Cereal Killer	-	-0.056 A	-0.022 A	-0.089 A	-	0.067 A	0.089 A	0.178 A
14 d	Barley	-0.178 A	-0.078 A	-	0.078 AB	0.000 B	0.011 A	-	0.267 AB
14 d	Oat	-0.133 A	-	-0.122 AB	-0.089 B	0.000 B	-	0.022 A	0.189 B
14 d	Rye	-0.300 B	-0.056 A	-0.056 A	0.167 A	0.022 A	0.022 A	0.056 A	0.289 AB
14 d	Triticale	-0.133 A	-0.033 A	-0.178 B	0.089 AB	0.011 AB	0.011 A	0.022 A	0.333 A
14 d	Wheat	-0.144 A	-0.111 A	-0.156 AB	0.033 AB	0.000 B	0.000 A	0.044 A	0.256 AB
14 d	Cereal Killer	-0.156 A	-0.078 A	-0.156 AB	-0.022 AB	0.011 AB	0.011 A	0.067 A	0.256 AB
28 d	Barley	-0.167 A	-0.089 A	-	-0.078 A	0.011 B	0.033 B	-	0.267 A
28 d	Oat	-0.144 A	-	-0.100 A	-0.089 A	0.000 B	-	0.022 A	0.211 A
28 d	Rye	-0.300 B	-0.089 A	-0.144 A	-0.089 A	0.011 B	0.067 A	0.033 A	0.278 A
28 d	Triticale	-0.144 A	-0.067 A	-0.144 A	-0.056 A	0.022 A	0.044 AB	0.011 A	0.200 A
28 d	Wheat	-0.133 A	-0.156 A	-0.167 A	-0.222 A	0.011 B	0.022 B	0.022 A	0.300 A
28 d	Cereal Killer	-0.189 A	-0.078 A	-0.122 A	-0.056 A	0.033 A	0.044 AB	0.044 A	0.244 A
56 d	Barley	-0.222 A	-0.167 A	-	-0.100 A	0.011 A	0.033 AB	-	0.233 BC
56 d	Oat	-0.189 A	-	-0.167 A	-0.122 A	0.000 A	-	0.044 A	0.100 C
56 d	Rye	-0.356 B	-0.200 A	-0.322 BC	-0.356 BC	0.000 A	0.044 A	0.033 A	0.344 AB
56 d	Triticale	-0.133 A	-0.111 A	-0.378 C	-0.356 BC	0.011 A	0.044 AB	0.044 A	0.378 A
56 d	Wheat	-0.200 A	-0.178 A	-0.289 BC	-0.456 C	0.011 A	0.022 AB	0.000 A	0.289 AB
56 d	Cereal Killer	-0.178 A	-0.133 A	-0.222 AB	-0.156 AB	0.011 A	0.011 B	0.033 A	0.322 AB
84 d	Barley	-0.256 A	-0.189 A	-	-0.467 B	0.011 A	0.011 A	-	0.189 BC
84 d	Oat	-0.211 A	-	-0.278 A	-0.222 A	0.000 A	-	0.022 C	0.067 C
84 d	Rye	-0.389 B	-0.267 A	-0.344 AB	-0.678 CD	0.000 A	0.022 A	0.089 AB	0.311 AB
84 d	Triticale	-0.233 A	-0.178 A	-0.411 B	-0.833 D	0.011 A	0.022 A	0.067 BC	0.289 AB
84 d	Wheat	-0.222 A	-0.244 A	-0.400 B	-0.656 BCD	0.011 A	0.011 A	0.144 A	0.278 AB
84 d	Cereal Killer	-0.233 A	-0.211 A	-0.344 AB	-0.478 BC	0.011 A	0.022 A	0.089 AB	0.344 A
112 d	Barley	-0.242 A	-0.256 A	-	-0.567 B	0.000 A	0.022 A	-	0.022 A
112 d	Oat	-0.193 A		-0.400 A	-0.289 A	0.000 A	-	0.000 A	0.000 A
112 d	Rye	-0.182 B	-0.289 A	-0.578 B	-0.778 CD	0.000 A	0.033 A	0.044 A	0.033 A
112 d	Triticale	-0.384 A	-0.211 A	-0.589 B	-0.889 D	0.000 A	0.022 A	0.022 A	0.022 A
112 d	Wheat	-0.192 A	-0.256 A	-0.567 B	-0.556 B	0.000 A	0.033 A	0.033 A	0.000 A
112 d	Cereal Killer	-0.205 A	-0.267 A	-0.511 B	-0.644 BC	0.000 A	0.011 A	0.022 A	0.011 A

Table F.5. Least square means for mass of nitrogen and mass potassium released from cover crop tissue at all four growing environments. Negative values indicate a release of nutrient from cover crop tissue. Letters indicate significant differences between treatment at alpha = 0.05.

Time	Species	Change in N				Change in K			
		Ashland Bottoms		*Leonardville*		*Ashland Bottoms*		*Leonardville*	
		2020	*2021*	*2020*	*2021*	*2020*	*2021*	*2020*	*2021*
						---------g/m2--------			
Main effect of time									
Initial									
1 d									
7 d			-0.078 A	-0.278 A	-0.389 B	.	-0.222 A	-0.233 A	-0.244 A
14 d		-1.611 A	-0.256 A	-0.300 A	0.444 A	-2.689 A	-1.056 B	-1.311 B	0.100 A
28 d		-1.667 A	-0.133 A	-0.289 A	-1.033 C	-3.456 B	-1.578 C	-2.700 C	-2.278 B
56 d		-1.989 B	-0.311 AB	-1.056 B	-1.478 C	-4.300 C	-1.956 D	-3.378 D	-4.500 C
84 d		-2.211 C	-0.544 B	-1.189 B	-2.133 D	-4.633 D	-2.433 E	-4.033 E	-7.244 D
112 d		-1.722 A	-0.500 B	-2.011 C	-2.378 D	-4.656 D	-2.600 E	-4.778 F	-8.456 E
Main effect of species									
	Barley	-2.356 BC	-0.189 A	-	-0.611 A	-3.744 AB	-1.500 A	-	-3.533 AB
	Oat	-2.089 BC	-	-0.978 B	-0.733 AB	-4.811 B	-	-2.522 A	-3.211 A
	Rye	-2.467 C	-0.322 A	-0.511 A	-1.367 BC	-4.667 B	-1.800 A	-2.489 A	-3.433 AB
	Triticale	-1.567 AB	-0.300 A	-1.000 B	-1.300 BC	-3.833 AB	-1.633 A	-3.600 B	-4.511 B
	Wheat	-1.067 A	-0.289 A	-1.044 B	-1.822 C	-2.711 A	-1.689 A	-2.322 A	-3.489 AB
	Cereal Killer	-1.500 AB	-0.422 A	-0.722 AB	-1.111 AB	-3.911 AB	-1.567 A	-2.778 A	-4.444 B
Time by species interaction									
7 d	Barley	-	0.156 A	-	-0.422 AB	-	-0.300 A	-	-0.244 A
7 d	Oat	-	-	-0.111 A	-0.222 AB	-	-	-0.400 AB	0.100 A
7 d	Rye	-	0.033 A	-0.156 A	-0.267 AB	-	-0.089 A	0.256 A	-2.278 B
7 d	Triticale	-	-0.156 A	-0.411 A	0.267 A	-	-0.300 A	-0.756 B	-4.500 C
7 d	Wheat	-	-0.211 A	-0.300 A	-0.567 AB	-	-0.211 A	-0.311 AB	-7.244 D
7 d	Cereal Killer	-	-0.222 A	-0.411 A	-1.122 B	-	-0.189 A	0.067 A	-8.456 E
14 d	Barley	-2.367 C	-0.144 A	-	0.733 A	-3.078 A	-1.022 A	-	-0.256 AB
14 d	Oat	-1.611 ABC	-	-0.056 A	-0.156 A	-3.078 A	-	-1.478 AB	-0.744 AB
14 d	Rye	-2.156 BC	-0.078 A	-0.267 A	0.411 A	-2.900 A	-0.733 A	-0.733 A	0.233 AB
14 d	Triticale	-1.233 AB	-0.344 A	-0.578 A	0.789 A	-2.489 A	-1.056 A	-1.533 B	0.867 A
14 d	Wheat	-1.100 A	-0.200 A	-0.200 A	0.322 A	-1.900 A	-1.433 A	-1.133 AB	-0.056 AB
14 d	Cereal Killer	-1.233 AB	-0.489 A	-0.378 A	0.578 A	-2.656 A	-1.044 A	-1.711 B	-1.522 B
28 d	Barley	-2.033 B	-0.089 A	-	-0.522 A	-3.056 AB	-1.367 A	-	1.078 AB
28 d	Oat	-1.656 AB	-	-0.367 A	-0.311 A	-4.533 B	-	-2.600 A	-1.256 C
28 d	Rye	-2.344 B	0.000 A	0.011 A	-1.444 AB	-4.411 B	-1.689 A	-2.644 A	1.844 A
28 d	Triticale	-1.611 AB	-0.167 A	-0.422 A	-0.733 A	-3.256 AB	-1.522 A	-3.478 B	0.733 ABC
28 d	Wheat	-0.778 A	-0.433 A	-0.422 A	-2.233 B	-2.211 A	-1.611 A	-2.189 A	-0.589 BC
28 d	Cereal Killer	-1.567 AB	0.033 A	-0.233 A	-0.956 A	-3.256 AB	-1.700 A	-2.600 A	-1.200 C
56 d	Barley	-2.578 D	-0.300 A	-	-0.256 A	-4.244 AB	-1.789 A	-	-1.778 A
56 d	Oat	-2.500 CD	-	-1.067 A	-0.978 AB	-5.122 B	-	-3.022 A	-2.544 A
56 d	Rye	-2.467 BCD	-0.356 A	-0.789 A	-1.733 BC	-5.178 B	-2.367 A	-3.244 A	-2.356 A
56 d	Triticale	-1.511 AB	-0.189 A	-1.322 A	-2.056 BC	-4.078 AB	-1.933 A	-4.756 B	-1.911 A
56 d	Wheat	-1.344 A	-0.522 A	-1.211 A	-2.611 C	-3.000 A	-1.944 A	-2.633 A	-2.389 A

Time	Species	Change in N				Change in K			
		Ashland Bottoms		*Leonardville*		*Ashland Bottoms*		*Leonardville*	
		2020	*2021*	*2020*	*2021*	*2020*	*2021*	*2020*	*2021*
		---------*g/m2*--------							
56 d	Cereal Killer	-1.556 ABC	-0.200 A	-0.889 A	-1.233 AB	-4.189 AB	-1.722 A	-3.267 A	-2.678 A
84 d	Barley	-2.589 BC	-0.344 A	-	-1.344 A	-4.111 AB	-2.122 A	-	-3.956 A
84 d	Oat	-2.711 BC	-	-1.844 C	-1.211 A	-5.744 C	-	-3.367 A	-3.856 A
84 d	Rye	-2.844 C	-0.856 B	-0.589 A	-2.400 ABC	-5.367 BC	-2.844 A	-3.778 AB	-4.489 A
84 d	Triticale	-2.100 BC	-0.400 AB	-1.156 AB	-2.833 BC	-4.556 ABC	-2.456 A	-5.222 C	-5.133 A
84 d	Wheat	-1.133 A	-0.656 AB	-1.656 BC	-3.222 C	-3.233 A	-2.456 A	-3.500 A	-5.144 A
84 d	Cereal Killer	-1.867 AB	-0.456 AB	-0.678 A	-1.767 AB	-4.756 ABC	-2.289 A	-4.322 B	-4.400 A
112 d	Barley	-2.222 BC	-0.422 A	-	-1.844 AB	-4.211 AB	-2.422 A	-	-7.767 B
112 d	Oat	-1.956 BC	-	-2.433 BC	-1.556 A	-5.578 B	-	-4.278 A	-4.589 A
112 d	Rye	-2.500 C	-0.533 A	-1.256 A	-2.789 BC	-5.433 B	-3.100 A	-4.767 A	-7.044 B
112 d	Triticale	-1.378 AB	-0.467 A	-2.144 BC	-3.233 C	-4.767 AB	-2.533 A	-5.844 B	-10.444 C
112 d	Wheat	-0.978 A	-0.500 A	-2.489 C	-2.656 ABC	-3.211 A	-2.489 A	-4.167 A	-6.144 AB
112 d	Cereal Killer	-1.278 AB	-0.589 A	-1.756 AB	-2.178 ABC	-4.689 AB	-2.478 A	-4.856 A	-7.489 B

Table F.6. Least square means for mass of sulfur (SO4-S) released from cover crop tissue at all four growing environments. Negative values indicate a release of nutrient from cover crop tissue. Letters indicate significant differences between treatment at alpha = 0.05.

Time	Species	Change in SO4-S			
		Ashland Bottoms		*Leonardville*	
		2020	*2021*	*2020*	*2021*
		---------*g/m2*--------			
Main effect of time					
Initial					
1 d					
7 d			-0.022 A	-0.022 A	-0.022 A
14 d		-0.122 A	-0.056 B	-0.044 AB	-0.033 A
28 d		-0.133 AB	-0.044 B	-0.067 B	-0.078 B
56 d		-0.167 C	-0.022 A	-0.078 BC	-0.100 B
84 d		-0.178 C	-0.022 A	-0.089 C	-0.167 C
112 d		-0.144 B	-0.044 B	-0.144 D	-0.178 C
Main effect of species					
	Barley	-0.211 B	-0.033 A	-	-0.067 A
	Oat	-0.122 A	-	-0.100 B	-0.078 A
	Rye	-0.200 B	-0.044 A	-0.078 AB	-0.144 B
	Triticale	-0.122 A	-0.044 A	-0.078 AB	-0.100 AB
	Wheat	-0.111 A	-0.022 A	-0.056 A	-0.078 A
	Cereal Killer	-0.122 A	-0.033 A	-0.067 A	-0.111 AB
Time by species interaction					
7 d	Barley	-	-0.022 A	-	-0.022 A
7 d	Oat	-	-	-0.033 A	-0.022 A
7 d	Rye	-	-0.022 A	-0.033 A	-0.033 A
7 d	Triticale	-	-0.011 A	-0.022 A	0.011 A
7 d	Wheat	-	-0.022 A	-0.011 A	0.011 A
7 d	Cereal Killer	-	-0.033 A	-0.033 A	-0.067 A
14 d	Barley	-0.200 B	-0.022 A	-	-0.022 A
14 d	Oat	-0.089 A	-	-0.067 B	-0.078 A
14 d	Rye	-0.156 AB	-0.022 A	-0.056 AB	-0.044 A
14 d	Triticale	-0.100 A	-0.022 A	-0.056 AB	-0.011 A
14 d	Wheat	-0.111 A	-0.022 A	-0.011 A	0.000 A
14 d	Cereal Killer	-0.100 A	-0.044 A	-0.056 AB	-0.044 A

Time	Species	Change in SO4-S			
		Ashland Bottoms		*Leonardville*	
		2020	***2021***	***2020***	***2021***
		---------*g/m2*--------			
28 d	Barley	-0.189 B	-0.033 A	-	-0.067 A
28 d	Oat	-0.100 A	-	-0.078 A	-0.067 A
28 d	Rye	-0.189 B	-0.011 A	-0.078 A	-0.111 A
28 d	Triticale	-0.122 AB	-0.011 A	-0.067 A	-0.033 A
28 d	Wheat	-0.078 A	-0.033 A	-0.044 A	-0.100 A
28 d	Cereal Killer	-0.122 AB	-0.022 A	-0.056 A	-0.111 A
56 d	Barley	-0.233 B	-0.044 A	-	-0.022 A
56 d	Oat	-0.156 AB	-	-0.100 A	-0.067 AB
56 d	Rye	-0.211 B	-0.056 A	-0.089 A	-0.167 C
56 d	Triticale	-0.122 A	-0.033 A	-0.089 A	-0.111 ABC
56 d	Wheat	-0.133 A	-0.044 A	-0.056 A	-0.133 BC
56 d	Cereal Killer	-0.133 A	-0.044 A	-0.067 A	-0.089 ABC
84 d	Barley	-0.222 C	-0.044 A	-	-0.122 AB
84 d	Oat	-0.156 ABC	-	-0.133 B	-0.100 A
84 d	Rye	-0.222 BC	-0.078 B	-0.067 A	-0.233 C
84 d	Triticale	-0.156 ABC	-0.044 A	-0.067 A	-0.211 BC
84 d	Wheat	-0.122 A	-0.056 AB	-0.100 AB	-0.156 ABC
84 d	Cereal Killer	-0.144 AB	-0.056 AB	-0.056 A	-0.144 ABC
112 d	Barley	-0.200 B	-0.044 AB	-	-0.167 AB
112 d	Oat	-0.122 A	-	-0.189 B	-0.122 A
112 d	Rye	-0.211 B	-0.056 AB	-0.122 A	-0.256 B
112 d	Triticale	-0.111 A	-0.022 A	-0.133 A	-0.244 B
112 d	Wheat	-0.100 A	-0.033 A	-0.144 AB	-0.111 A
112 d	Cereal Killer	-0.111 A	-0.067 B	-0.122 A	-0.189 AB