Cover crop and phosphorus fertilizer management effects on phosphorus loss and nutrient cycling

by

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Abstract

Phosphorus (P) loss from non-point agricultural sources has been identified as a main contributor to degraded surface water quality throughout the United States. Excessive P inputs to surface waters can lead to eutrophication, increased water treatment costs, and negative health impacts. Therefore, agricultural best management practices (BMP) that promote water quality, through minimizing P loss, must be identified. Studies outlined in this thesis aim to determine the impacts of cover crops and P fertilizer placement on P loss in surface runoff and nutrient cycling in a no-till corn (*Zea mays*)-soybean (*Glycine max*) rotation and provide insight into how cover crop species selection and termination method affects potential P loss from crop tissue. The first study examined combined effects of cover crop and P fertilizer placement on total P, dissolved reactive P (DRP) and sediment losses in surface runoff from natural precipitation events. This large-scale field study was conducted near Manhattan, Kansas, at the Kansas Agricultural Watershed (KAW) Field Laboratory during the 2016 and 2017 cropping years. Two levels of cover crop [no cover crop (NC) and cover crop (CC)] and three levels of P fertilizer management [no P (CN), fall broadcast P (FB), and spring injected P (SI)] were used. Flow-weighted composite water samples were collected from precipitation events generating greater than 2.0 mm of surface runoff. Results from this study found the CC treatment increased DRP losses compared to NC in both cropping years; however, CC reduced sediment loss by over 50% compared to NC. Application of P fertilizer increased DRP losses compared CN in both cropping years, although SI resulted in lower quantities of DRP loss compared to FB. In addition, this study found that CC reduced biomass and yield of corn compared to NC and therefore decreased nutrient uptake, removal, and deposition during the 2017 cropping year. However, no negative impacts of CC on biomass or yield were observed during the 2015 (corn) and 2016 (soybean) cropping years. Application of P fertilizer increased the concentration of Melich-3 P and total P in the top 0-5 cm of soil compared to CN; however, no differences between P fertilizer management practice were observed for concentrations of Melich-3 P at 5-15 cm. A greenhouse-based study determined the impacts of cover crop species (brassica, grass, and legume), termination method (clipping, freezing, and herbicide), and time after termination (1, 7, and 14 days after termination) on total P and water-extractable P (WEP) release from cover crop biomass. Freezing increased WEP concentration of crop tissue by more than 140% compared to clipping and herbicide. Additionally, at 7 and 14 days after termination, both concentration of WEP and fraction of WEP compared total P increased compared to 1 DAT. Findings from these studies suggest the use of cover crops may unintentionally result in greater DRP losses in surface runoff. However, addition of a cover crop can dramatically reduce erosion losses. In addition, cover crop species selection can directly impact the quantity of P being taken up and released by crop tissue. Understanding the impact of crop species selection may help create new BMPs which aim to reduce P loss.

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Dedication

Well many a mile a soul may wander
To fates and places yet unseen
But in the end, it's just a gamble
At least you chased a few dreams

You missed the ones that always love you
No matter whether right or wrong
Sometimes just a memory
Is all you have to call home

Home will always be Virginia
'tween the Blue Ridge and Chesapeake Bay
Atlantic to Appalachia
Home in my heart always

-Page Wilson

Chapter 1 - Mechanisms and Impacts of Phosphorus Loss from Agricultural Sources

Introduction

Phosphorus (P) loss from agricultural production is a significant contributor to surface water contamination. Excessive inputs of P to surface waters can lead to eutrophication, potentially causing an increase in algal and aquatic plant growth (Correll, 1998; Carpenter et al., 1998). Eutrophication, and associated harmful algal blooms, are conservatively estimated to cost the United States' economy 2.4-4.6 billon dollars a year (Dodds et al., 2009). In addition to severe economic impact, harmful algal blooms increase the risk of negative health impacts on both humans and animals (Hudnell, 2010). It is estimated that up to 70% of all P that reaches surface waters is linked to a nonpoint agricultural source (Havlin et al., 2005). The linkage between nonpoint agricultural P pollution and the degradation of surface water quality has created a need for new agricultural best management practices (BMP) to reduce P loss.

Cropping systems, among many factors, can influence nutrient loss from agriculture (Liu et al., 2014a). A commonly cited management practice to help reduce nutrient loss through erosion is planting cover crops during normal fallow periods (De Baets et al., 2011). A cover crop is any living ground cover that is sown before, during, or after a main crop and then terminated prior to planting the next crop (Hartwig & Ammon, 2002). The benefits of cover crops could include greater water infiltration, slower surface runoff and improved soil properties (Dabney et al., 2001). Cover crops also potentially benefit the soil by reducing soil erosion, decreasing nutrient leaching and runoff, and suppressing weeds (Dabney et al., 2001).

Currently, cover crops play an important role in reducing nitrogen leaching. Cover crops can decrease nitrogen leaching by 20-80%, depending on the plant species (Dabney et al., 2001).

While cover crops decrease nitrogen loss, they can also accumulate large amounts of P in their plant tissue creating a potential source of P loss when tissue is exposed to freezing-thawing cycles (Liu et al., 2014a). Therefore, cover crops could reduce P loss by reducing runoff and erosion or cover crops could increase P loss by acting as a source of P to runoff water. The role of cover crops as a BMP for reducing P loss needs further examination to sort out these potentially conflicting mechanisms of influence.

The objectives of this literature review are to examine how P is transported from the soil system to surface water, known causes of P loss from cover crops, and how agricultural management practices, such as species selection, can alter P loss.

Mechanisms of Phosphorus Loss

Phosphorus cycling within an agricultural system involves several factors. These factors include physical, chemical and biological processes, all of which interact with the agricultural production system (Pierzynski et al., 2005). In most agricultural systems, inorganic P fertilizers are used to achieve optimal yield. When applied to the soil, inorganic P fertilizers can quickly covert to orthophosphates (Havlin et al., 2005). The conversion of P fertilizer to orthophosphates in the soil makes P available for plants to uptake or potentially leach out of the soil system (Pierzynski et al., 2005). While some of the applied P will be taken up by plants, a large portion will be adsorbed by soil organic matter and soil colloids or precipitated as secondary minerals (Havlin et al., 2005).

The primary method of P removal from the soil is the uptake of P by plants; however, both erosion and surface runoff play a key role in understanding methods of P loss (Pierzynski et al., 2005). Sharpley et al. (1994) stated the amount of P lost in surface runoff is directly influenced by several factors, including surface runoff volume, sediment concentration of surface runoff, and form and concentration of P in the soil. Since both soluble and particulate P can be transported via surface runoff, erosion can be linked to P loss (Gburek et al., 2005).

To help combat erosion losses, many farmers have adapted conservation tillage practices in lieu of conventional tillage systems. Brady and Wiel (2002) define conservation tillage as a sequence of tillage practices which lead to a reduction in soil or water loss compared conventional tillage while leaving at least 30% of the soil surface covered by residuals, including practices such as stip-tillage, ridge-tillage, mulch-tillage, and no-tillage. As of 2011, nearly 40% of corn, soybean, wheat, and cotton acres in the United States were under no-till or strip-till management (Wade et al, 2015). A meta-analysis of P loss from no-till soils found that particulate P loss is lower with no-till production compared to conventional tillage; however, an increase in dissolved P loss is often observed (Daryanto et al., 2017).

When a plant accumulates P from the soil, it is incorporated in the plant’s biomass. This creates a temporary storage reservoir of P above the soil. Traditional harvest methods remove plant biomass from the soil surface, ultimately removing P from the soil system, but under a cover-cropped system, the non-harvested plant material remains on the soil surface creating an additional potential source of P that can be lost as the plant tissue decomposes. This is similar to a no-till system. However, when cover crops are added to a no-till system, surface residue levels increase.

Phosphorus Loss from Cover Crops

As previously discussed, cover crops have been shown to reduce nitrogen leaching from soil. However, Miller et al. (1994) found the use of cover crops could potentially increase the amount of nutrients lost in surface runoff because of nutrient release from tissue during rainfall events. In their study, the researchers conducted a simulated rainfall experiment to analyze the effect of freezing on NH_4-N, NO_3-N, and inorganic P loss from tissue of three common cover crop species: red clover (*Trifolium pretense*), annual ryegrass (*Lolium multiflorum*) and oilseed radish (*Raphanus sativus*). They found that exposing cover crops to freeze-thaw conditions and then exposing them to simulated rainfall significantly increased the amount of P in the collected runoff. During their study, they also examined the effects of freezing then drying the plant tissue. By drying the tissue in addition to freezing it, Miller et al. (1994) found that almost 30% of the total plant tissue P from oilseed radish and annual ryegrass was released into the runoff. Red clover lost approximately 20% of total its biomass P. The loss of P after exposure to freeze-thaw conditions is caused by the rupture of cell membrane when plant tissue is exposed to freezing temperature (White, 1973). This phenomenon is important in areas that experience freezing conditions.

Crop residue (both from cover crop and main crop) has been noted as a source of P loss from agricultural systems. As shown by Miller et al. (1994), the exposure of cover crop residue to freeze-thaw conditions can increase P loss. As the need for controlling nonpoint-source pollution from P loss associated with agriculture has grown, researchers have dug deeper into the effects of freeze-thaw condition on P loss from cover crops. It is commonly accepted in the literature that repeated exposure of cover crop tissue to freeze-thaw conditions greatly increases the quantity of P lost compared to that lost from non-frozen cover crop tissue (Bechmann et al., 2005; Liu et al., 2013). However, the quantity of P released from plant tissue exposed to freeze-thaw conditions may depend on several factors. These factors include the quantity of nutrient in plant tissue, how mobile the nutrient is, solubility of the nutrient, and the rainfall quantity and intensity to which the tissue is exposed (White, 1973).

Management Practices Impacts on Phosphorus Loss

Given that most cover-crop species have a low frost tolerance, they are susceptible to damage from freeze-thaw conditions (Sturite, 2007). Frost tolerance of cover crop varies among crop species and results in different species leaching varying amounts of P. (Liu et al., 2014b). This is of interest when cover crop species are chosen, specifically with respect to choosing annual or perennials, since annual cover crop species are known to leach greater levels of P (Øgaard, 2015). The greater leaching of P from annual cover crop species is correlated to their lower levels of frost tolerance than perennial cover crop species (Øgaard, 2015). The benefit of choosing a perennial over annual cover crop species can be negated if plant tissue is actively growing when exposed to freeze-thaw conditions (White, 1973). Apart from frost tolerance, the level of moisture in plant tissue at the time of freezing can contribute to amounts of P lost (Miller et al., 1994).

When developing a cover crop management plan to control the loss of P, it is important to carefully select which species of cover crops to be grown. Miller et al. (1994), Liu et al. (2013) and Øgaard (2015) extensively studied the effect of common cover crop species on P loss. In each of their studies, the researchers aimed to quantify observed differences in P loss from cover crop tissue exposed to freeze-thaw cycles. Miller et al. (1994) utilized red clover, annual ryegrass and oilseed radish. By exposing these plants' tissue to freeze-thaw conditions, they were able to determine that selection of cover crop species directly impacts the potential nutrient concentration lost to runoff. As previously stated, the use of oilseed radish statistically resulted in greater amounts of phosphorus loss. Radishes are members of the Brassicacaea family, which are known to mobilize non-soluble forms of phosphorus in the soil by changing the soil's pH via the exudation of organic acids (White & Weil, 2010). The ability of Brassicas to solubilize and take up recalcitrant forms of soil phosphorus is beneficial to farmers working with non-fertile soil. However, when Brassicas are used as a cover crop in areas susceptible to freeze-thaw conditions, the risk of phosphorus loss is increased due to the increased concentrations of phosphorus within the plant tissue (White & Weil, 2010). Liu et al. (2013) also found similar trends with respect to the amount of phosphorus lost after exposure to freeze-thaw conditions among members of the Brassicacaea family.

In several studies, Liu et al. (2013, 2014a, 2014b) worked with eight different cover crop species to determine the potential crop species on phosphorus loss from the crop tissue after exposure to freeze-thaw cycles. This study examined both perennials and annuals. Perennials included chicory (*Cichorium intybus* L.), cocksfoot (*Dactylis glomerata* L.), perennial ryegrass (*Lolium perenne* L.) and red clover. Annuals included phacelia (*Phacelia tanacetifolia* L.), white mustard (*Sinapis alba* L), oilseed radish, and white radish (*Raphanus longipinnatus*). Liu et al. (2013, 2014a, 2014b) worked at six sites across southern and central Sweden and analyzed the cover crops for biomass production and P content in both above ground (shoot) and below ground (root) tissues. In all three studies, they found that both shoot and total biomass varied significantly among different species of cover crops. For the perennial species studied, ryegrass and cocksfoot had the statistically higher biomass production. For the annual species studied, phacelia and white radish had the statistically highest shoot biomass. However, red clover developed the greatest amount of total biomass. Liu et al. (2013, 2014a, 2014b) also found that the concentration of P in the shoot tissue differed significantly among the cover-crop species. The three Brassicas studied (white mustard, white radish and oilseed radish) had the highest concentration of P in their tissue. Liu et al. (2013, 2014a, 2014b) also aimed to examine the influence of exposure to freeze-thaw conditions across the studied cover crop species. During the three studies, they found contradicting results when assessing P loss from cover crop tissue exposed to freeze-thaw conditions. In 2013, they found both radish species and white mustard had greater concentrations of soluble P compared to the other species. However, in 2014, the research team stated that both phacelia and white mustard had the statistically highest soluble P measured after being exposed to freeze-thaw cycles. Variations in P extracted after being exposed to freeze-thaw conditions show the need for further research regarding the behavior of different cover crop species.

The uptake of P by a cover crop can potentially reduce P loss only if the accumulated P is preserved in the plant's tissue (Liu et al. 2014a). As evident in the literature presented in this review, exposure of cover crop tissue to freeze-thaw conditions can increase the loss of P from the agricultural system. Hartwig and Ammon (2002) stated that cover crops are terminated prior to the planting of the next crop. Termination of cover crops can be classified into three categories: mechanical, natural, and chemical (Wayman et al. 2014). Freezing of cover crop tissues is classified as a natural termination method. Mechanical termination methods include, but are not limited to, mowing, crimping, and incorporation via tillage; chemical termination includes the use of herbicides (Wayman et al. 2014). Once a cover crop is terminated, the cover crop residue undergoes decomposition, which "is regulated by a number of variables, including the residue's physical and chemical properties, climate and the interactions between soil microflora and fauna" (Buchanan & King, 1991). During decomposition, nutrients stored within the plant tissue are recycled back into the soil system (1991). However, the effect of termination method on cycling nutrients back into the soil system is unclear. What happens to nutrients stored in the cover crop's tissue when plants undergo different methods of termination is also unclear. This gap in knowledge means that the potential nutrient loss from cover crops that experience different methods of termination also needs to be identified.

It is widely accepted in the literature that cover crops exposed to freeze-thaw conditions, commonly found in areas with frigid climates, can exhibit enhanced levels of P loss (Miller et al., 1994; Bechmann et al., 2005; Sturite et al., 2007; Liu et al., 2013, 2014a, 2014b; Øgaard, 2015). Bechmann et al. (2005) also found increasing the number of freeze-thaw cycles to which cover crop tissues are exposed can increase the levels of P lost from plant tissue up to 100-fold compared to tissues that had not been exposed to freeze-thaw conditions. This dramatic increase in the amount of P lost from plant tissue that has been exposed to additional freeze-thaw cycles warrants research into the effect of local climate on P loss from cover crop tissue.

The literature also shows that species selection can influence the amount of P lost from cover crop tissue dues to various frost sensitivities across cover-crop species (Liu et al. 2014a). Additionally, the ability of different cover crops to accumulate non-available nutrients from the soil can affect quantities of nutrients stored in the plant tissue that could potentially be lost to runoff (White & Wiel, 2010). These three factors all show the importance of cover crop species selection when an agricultural management plan is being developed.

While the importance of cover crop species selection is stressed throughout the literature, how termination method affects potential loss of nutrients from the cover crop tissue is not clear. The choice of termination method of cover crops is typically influenced by user preference (Wayman et al., 2014). Without adequate research into the implications on nutrients loss from different termination methods, growers may negate any positive impacts from using a cover crop.

In addition, Miller et al. (1994), Bechmann et al. (2005), Sturite et al. (2007), Liu et al. (2013, 2014a, 2014b), and Øgaard (2015) all conducted these research studies in the laboratory, utilizing rainfall simulation. Liu et al. (2013) and Bechmann et al. (2005) used greenhouse grown cover crop tissue, while Miller et al. (1994), Sturite et al. (2007), Liu et al. (2014a, 2014b), and Øgaard (2015) all used cover crop tissue collect from the field. However, each of these studies was only able to capture a single moment during the growth cycle. As plants grow and develop, nutrient concentrations in plant tissue can change (Jones et al., 2015). Changes in nutrient concentrations of plant tissue suggest that potential impact of cover crop tissue could change as a function of cover crop growth. In addition, extrapolation of data collected from small-scale samples using modern rainfall simulators to a larger field-scale has been deemed inaccurate (Ries et al., 2013). Natural rainfall has high temporal and spatial variability and modern rainfall simulators are not able to accurately represent this variability (Assouline, 2009; Reis et al., 2013). Therefore, to accurately determine how cover crops and P fertilizer management can impact P loss, data from large-scaled field studies using natural precipitation is needed.

To better understand the impacts of using a cover crop on P loss, further research needs to be performed assessing the interactions of cover crop species, termination method, and local climatic conditions on potential phosphorus loss. When reviewing the literature, I observed potential unintended consequences for establishing a cover-cropped agricultural system. As Dabney et al. (2001) stated, cover crops can decrease the amount of nitrogen loss from the agricultural system. However, cover crops may potentially increase the concentration of P that is lost from the agricultural system due to plant tissue leaching out P after being exposed to freeze-thaw conditions (Miller et al., 1994).

Increased levels of both nitrogen and P have contributed to the degradation of surface and ground waters in North America and Europe and have created a need for new agricultural BMPs (Bechmann et al., 2005). Further research pertaining to cover crop management needs to be performed to help combat unwanted trade-offs in nutrient loss and to help control nonpoint-source pollution of surface and groundwater.

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References

Assouline, S. 2009. Drop size distributions and kinetic energy rates in variable intensity rainfall. Water Resour. Res. 45:W1501

Buchanan, M. and L. King. 1993. Carbon and phosphorus losses from decomposing crop residues in no-till and conventional till agroecosystems. Agron. J.. 85:631-638.

Bechmann, M.E., P.J.A. Kleinman, A.N. Sharpley, and L.S. Saporito. 2005. Freeze-thaw effects on phosphorus loss in runoff from manured and catch-cropped soils. J. Environ. Qual. 34:2301-2309.

Brady, N.C. and R.R. Weil (eds.) 2002. Nature and property of soils. 13th ed. MacMillan, New York.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications. 8:559-568.

Correll, D. 1998. The role of phosphorus in the eutrophication of receiving waters: A review. J. Environ. Qual. 27:261-266.

Dabney, S.M., J.A. Delgado, and D.W. Reeves. 2001. Using Winter Cover Crops to Improve Soil and Water Quality. Communications in Soil Science and Plant Analysis. 32:1221–1250.

Daryanto, S., L. Wang, and P.A. Jacinthe. 2017. Meta-analysis of phosphorus loss from no-till soils. J. Environ. Qual. 46:1028-1037.

De Baets, S., J. Poesen, J. Meersmans, and L. Serlet. 2011. Cover crops and their erosion reducing effects during concentrated flow erosion. Catena. 85:237–244.

Dodds, W.K., J.L. Eitzmann, T.J. Pilger, K.L. Pitts, A.J. Riley, J.T. Schloesser and D.J. Thornburgh. 2009. Eutrophication of U.S. freshwaters: Analysis of potential economic damages. Environ. Sci. Technol. 43:12-19.

Gburek, W.J., E. Barberis, P.M. Haygarth, B. Kronvang and C. Stamm. 2005. Phosphorus mobility in the landscape. ASA-CSSA-SSSA. 46:941-979.

Hartwig, N. and H. Ammon. 2002. 50th anniversary - invited article - cover crops and living mulches. Weed Science. 50:688-699.

Havlin, J.L., J.D. Beaton, S.L. Tisdale and W.L. Nelson. 2005. Soil fertility and fertilizers: An introduction to nutrient management. Pearson Education, Upper Saddle River, New Jersey.

Hudnell, H.K. 2010. The state of U.S. freshwater harmful algal blooms assessments, policy and legislation. Toxicon. 55:1024-1034.

Jones, C., K. Olson-Ruts, and C. P. Dinkins. 2015. Nutrient uptake timing by crops to assist with fertilizing decisions. Montana State University Extension. EB0191

Liu, J., G. Bergkvist, and B. Ulen. 2014a. Biomass production and phosphorus retention by catch crops on clayey soils in southern and central Sweden. Field Crops Research. 171:130-137.

Liu, J., R. Khalaf, B. Ulen, and G. Bergkvist. 2013. Potential phosphorus release from catch crop shoots and roots after freezing-thawing. Plant Soil. 371:543-557.

Liu, J., B. Ulen, G. Bergkvist, and H. Aronsson. 2014b. Freezing-thawing effects on phosphorus leaching from catch crops. Nutrient Cycling Agroecosystems. 99:17-30.

Miller, M., E. Beuachamp, and J. Lauzon. 1994. Leaching of nitrogen and phosphorus from the biomass of 3 cover crop species. Journal of Environmental Quality. 23:267-272.

Pierzynski, G. M., R.W. McDowell, and T. Sims. 2005. Chemistry, cycling, and potential movement of inorganic phosphorus in soils. In J.T. Sims and A.N. Sharpley (Eds.), Phosphorus: Agriculture and the Environment. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Reis, J., T. Iserloh, M. Seeger, and D. Gabriels. 2013. Rainfall simulators – constraints, needs, and challenges for a future use in soil erosion. Geomorphology. 57:1-10.

Sturite, I., T.M. Henriksen, and T.A. Breland. 2007. Winter losses of nitrogen and phosphorus from italian ryegrass, meadow fescue and white clover in a northern temperate climate. Agriculture Ecosystems & Environment. 120:280-290.

Sharpley, A.N., S.C. Chapra, C.R. Wedepohl, J.T. Sims, T.C. Daniel and K.R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. J. Environ. Qual. 23:437-451.

Øgaard, A.F. 2015. Freezing and thawing effects on phosphorus release from grass and cover crop species. Acta Agriculturae Scandinavica Section B-Soil and Plant Science 65:529-536.

Wade, T., R. Classen and S. Wallander. 2015. Convservation-practice adoption rates vary widely by crop and region. Rep. EIB-147. U.S. Department of Agriculture.

Wayman, S., C. Cogger, C. Benedict, I. Burke, D. Collins, and A. Bary. 2015. The influence of cover crop variety, termination timing and termination method on mulch, weed cover and soil nitrate in reduced-tillage organic systems. Renewable Agriculture and Food Systems. 30:450-460.

White, C.M., and R.R. Weil. 2011. Forage radish cover crops increase soil test phosphorus surrounding radish taproot holes. Soil Science Society of America Journal. 75:121-130.

White, E. M. 1973. Water leachable nutrients from frozen or dried prairie vegetation. Journal of Environmental Quality. 2:104-107.

Chapter 2 - Cover crop and phosphorus fertilizer management effects on phosphorus loss in a no-till corn-soybean rotation

Introduction

Phosphorus (P) loss from non-point agricultural sources has been identified as a key contributor to decreased surface water quality. The excessive loss of P from non-point agricultural sources to surface waters can lead to eutrophication, harmful algal blooms, and hypoxic zones (Correll, 1998; Carpenter et al., 1998, Welch, 1978). Conservative estimates place water treatment cost due to eutrophication and harmful algal blooms between 2.4-4.6 billon dollars per year (Dodds et al., 2009).

Bennett et al. (2001) state the net P storage of aquatic and terrestrial ecosystems has increased more than 75%, relative to pre-industrial levels, primarily due to the application of P fertilizers in agricultural. Phosphorus is an essential nutrient for crop production and producers around the globe apply P-based fertilizers to achieve optimal yield. However, P can be transported via runoff and often leads to mineral enrichment of surface waters (Correll, 1998). With acknowledgement that non-point agricultural sources of P can led to a decrease in water quality, many agricultural best management practices (BMP) have been proposed to curb P export from the field. An often proposed BMP is the combination of no-tillage management with cover crops. The increased surface residue level from no-till and addition of a cover crop during normal fallow periods have been proposed as a pillar for “conservation agriculture” (Dumanski et al., 2006).

Since approximately 1990, worldwide adoption of no-till management has grown rapidly, and in the United States, nearly 35% of total cropland is under no-till management with over ten million acres of cover crops (Tiplett & Dick, 2008; Dobberstein, 2014). While no-till acres continue to grow, inconsistent impacts of no-till on P loss, primarily due to various management and physiological factors, have been observed (Daryanto et al., 2017). In a meta-analysis of 27 publications, Duryanto et al. (2017) found that no-till can decrease particulate P concentration of agricultural catchment waters; however, dissolved P concentrations were not decreased.

Cover crops can potentially provide greater water infiltration, slower surface runoff and improved soil properties (Dabney et al., 2001). Cover crops also potentially benefit the soil by reducing soil erosion, decreasing nutrient leaching/runoff, and suppressing weeds (Dabney et al., 2001). An often cited benefit of cover crops is reduced P loss (Sharpley & Smith, 1991; Dabney et al., 2001). However, there is inconclusive evidence quantifying the effects of cover crops on P concentration in natural runoff from no-till cropping systems (Christianson et al., 2017). The few studies which 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). Both 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 as a result of exposure to freezing conditions could create a potential source of P loss from the field. However, in these studies, the researchers conducted a single, simulated rainfall event, which only provides insight into one point in time throughout the growing season. 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 researchers found using a cover crop reduced total P loss after application of manure; however, Kovar et al. (2011) found use of cover crops increased dissolved reactive phosphorus (DRP) loss after cover crops were terminated. The comprehensive effects of cover crops on P loss must be identified using field-scale projects with natural precipitation throughout a cropping-rotation.

Monitoring P loss throughout the entirety of the cropping year will account for variation in cover crop effect on P loss and runoff due to changes in cover crop growth.

The objective of this study was to examine the impacts of winter cover crops and P fertilizer placement on concentrations of total P, dissolved reactive P, and total suspended solids (TSS) in surface runoff from natural precipitation events in a no-till corn-soybean rotation. In addition, this study examines the effects of winter cover crops and P fertilizer placement on surface runoff volume and mass losses (load) of total P, dissolved reactive P, and TSS in surface runoff.

Materials and Methods

This field study was conducted at the Kansas Agricultural Watershed (KAW) field laboratory located near Manhattan, Kansas, from October 1, 2015 through September 30, 2017. This study monitored P concentration of edge-of-field runoff from natural precipitation events. Data is presented from the 2016 and 2017 cropping years. The 2016 cropping year ran from October 1, 2015-September 30, 2016, and the 2017 cropping year ran from October 1, 2016-September 30, 2017.

Field Site

The KAW field lab was established in 2014 and is comprised of eighteen small-scale watersheds (plots), averaging 0.5 ha in size, each fitted with a 0.46 m H-flume and automated water sampler. The soil is classified as an eroded Smolan silty clay loam (fine, smectitic, mesic Pachic Argiustoll) with 3-7% slope. Total research area is 14.8 ha including grass waterways, borders, and plots. Abel (2016) provides additional details concerning site history, construction, and equipment implementation.

Experimental Design

This study evaluated the effects of six agricultural management practices (treatments) on water quality. Treatments were structured in a 2x3 complete factorial arranged in a randomized complete block design with three replicates (Figure 2.1) Two levels of cover crop were used: no cover crop (NC) and cover crop (CC). Each level of cover crop was expressed with three levels of phosphorus management strategies: no P fertilizer control (CN), fall broadcast (FB), and spring sub-surface injected (SI).

Cropping System

The KAW is in a corn-soybean rotation with an expected yield goal of 7.5 t/ha for corn and 2.7 t/ha for soybean. This site is under no-till management, and the last tillage event occurred on November 7, 2014 when plots where cultivated with a chisel plow followed by a disk. All crops grown after the start of 2015 were under no-till management.

2016 Cropping Year

On September 22, 2015, one day after corn harvest, a winter wheat (*Triticum aestivum* var. *Overley*) cover crop was planted at a seeding rate of 146 kg ha^{-1} (Table 2.1). The cover crop emerged less than a week after planting (September 28, 2015). Throughout its growth and development, the winter wheat exhibit nitrogen (N) deficiency resulting in a possible reduction of biomass production.

Diammonium phosphate (DAP: 18-46-0) was broadcast, using a Barber Engineering drop fertilizer spreader (Spokane, Washington), at a target application rate of 56 kg P_2O_5 ha^{-1} on November 10, 2015. Due to equipment malfunctions (slipping gears and fertilizer spilling from the screws), fertilizer application was paused after finishing block 1. The fertilizer spreader was repaired and recalibrated prior to fertilizing blocks 2 and 3. The slipping gears caused an over application of P_2O_5 for block 1 (78 kg P_2O_5 ha^{-1}) while blocks 2 & 3 received an application rate of 52 kg P_2O_5 ha^{-1}.

On June 6, 2016, corresponding with soybean planting, the SI plots received an application of ammonium polyphosphate (APP: 10-34-0) placed approximately 5 cm below and 5 cm to the side of the soybean seed. To account for the higher fall broadcast application, block 1 received 78 kg P_2O_5 ha^{-1}. Blocks 2 & 3 received 56 kg P_2O_5 ha^{-1}.

All treatments received a spring burn down application of herbicide on April 12, 2016 (Table 2.1) For the CC treatment, herbicides were selected that would provide weed control but not kill the cover crop. The cover crop was terminated with glyphosate on May 6, 2016. A pre-emergence herbicide application was made on June 6, 2016. The NC plots received a post-emergence application of herbicide on June 29, 2016. The post-emergence herbicide was applied only to the NC treatments because weed pressure in the cover crop treatments was below the point that required herbicide. Full details of herbicide application are in Table 2.1.

Soybean (*Glycine max* var *KS3406*) was sown on June 6, 2016 at a seeding rate of 325, 000 seed ha^{-1}. Wet soil conditions due to spring rains, heavy corn residue, and cover crop biomass caused the delayed planting.

Plots were harvested on October 19, 2016 using a New Holland TR88 commercial combine fitted with a 7.3-m row-crop flex header. Once per plot, the grain bin was emptied into a weigh wagon, and the grain weight was recorded.

2017 Cropping Year

On October 19 & 20, 2016, a cover mixture of triticale (*x Triticosecale* var. *TriCal 780*) and rapeseed (*Brassica napus* var *Dwarf Essex*) was sown at a seeding rate of 68 kg ha^{-1} and 4.5 kg ha^{-1}, respectively, in all CC plots (Table 2.2). The triticale seeding rate was slightly higher than planned (63 kg ha^{-1}), but was deemed reasonable given the late planting date. Cover crop had strong emergence.

Diammonium phosphate was applied to all FB plots using a Barber spreader on December 2, 2016, at an application rate of 63 kg P_2O_5 ha^{-1}. Approximately 24-hours after the fall broadcast application of P, the KAW site received 8.9 mm of rainfall; however, there was no surface runoff. On April 24, 2017, the SI plots received 59 kg P_2O_5 ha^{-1} applied as APP in a 5 cm by 5 cm band in conjunction with corn planting. Nitrogen was balanced across all treatment at an application rate of 174 kg N ha^{-1}. Nitrogen was applied as urea ammonium nitrate (UAN: 28-0-0) with a disk-coulter injection unit within three days of corn planting. On June 12, 2017 (V8), all plots received an additional 45 kg N ha^{-1} applied as UAN with streamer bars.

The NC plots received a spring burndown application of herbicide on March 8, 2017 (Table 2.2). As seen in 2016, the cover crop again sufficiently controlled weed pressure enough not to warrant an early spring burndown application of herbicide. On April 24, 2017, the NC plots in block 1 received a pre-emergence herbicide application with the CC plots receiving the same application on April 25 (Table 2.2). Two days later (April 27, 2017), the entirety of the remaining plots (both NC and CC) received the same pre-emergence herbicide application.

Corn (*Zea mays* var *DKC53-56*) was sown at a seeding rate of 64,000 seed ha^{-1} on April 24, 2017. Plot areas near the H-flume were hand-seed to account for the planter not being able to get close to the H-flume.

On September 20, 2017, thirteen plots were harvested using a commercial New Holland TR88 combine mounted with an 8-row head. Harvest was stopped halfway through block 2 due to over-heating hydraulic fluid. The problem was fixed by replacing the recirculating fluid hose to the hydraulic fluid cooler. At this point, it was deemed too late to safely continue harvesting.

The remaining plots where harvest on September 21, 2017. The harvested grain from each plot was weighed using a weigh wagon.

Water Quality and Analysis

Each plot was fitted with a 0.46 m H-flume and an automated water sampler (ISCO Teledyne 6700 or 6712 series with a 730 bubbler unit). Flow-weighted composite water samples were collected for each runoff event. Runoff (Q) was recorded year-round at 1 minute intervals using ISCO 730 bubbler modules. Samplers were programmed to become "enabled" when runoff depth exceed 0.015 m in the H-flume. After enabling, a 200 mL sample was collected for every 1 mm of runoff . Water samples were collected in a 10 L Nalgene carboy housed within the sampler unit. Attempts were made to retrieve all runoff samples less than 24 hours after runoff had ceased. However, owing to timing of runoff events (weekends, holidays, etc) some events were not collected until after the 24-hour mark. Composite water samples were thoroughly mixed via shaking and a 500 mL aliquot was removed and submitted to the K-State Soil Testing Lab for analysis of total suspended solids (TSS), total nitrogen, total P, ortho-P nitrate (NO_3^-), and ammonium (NH_4^+). Samples were stored at 4°C prior to analysis.

Total suspended solids was determined by vacuum filtration through a 0.45 µm filter (Csuros, 1997). Before filtration, the filter paper was dried in a 60°C oven overnight and weighed. A 50-100 mL aliquot was collected while the sample was stirred and the aliquot was then filtered through the filter paper. Approximately 20 mL of filtrate was saved for additional chemical analysis. Collected sediment on the filter paper was dried overnight at 60°C and weighed. TSS was determined by the difference between filter dry weights (sediment filter minus clean filter) divided by the volume filtered. Dissolved reactive P (DRP) was measured in an aliquot of TSS filtrate using an Alpkem Rapid Flow Analyzer (RFA) with the ammoniummolybdate blue colorimetric procedure (Alpkem method A303-S200-13). A second aliquot of the TSS filtrate was collected and analyzed on the RFA for NO_3^- and NH_4^+ (Alpkem method A303-S021 & A303-S170). To measure total nitrogen and total P, a 1 to 10 mL sample was digested with potassium persulfate reagent and analyzed using the RFA according to Hosomi & Sudu (1986) and Nelson (1987).

Soil Sampling and Analysis

Initial soil samples were collected on October 28, 2014 at the three sub-plot locations (Figure 2.2) within each plots. Composite soil samples were collect from within a 3 m radius of each sub-plot point and contained twenty-one cores per composite. Soil cores were pulled to a depth of 15 cm and separated into 0-5 cm (surface) and 5-15 cm (sub-surface) depths. A total of 108 paired soil samples were collected. Soil samples were air dried and ground using a combination of a hammer-mill and mortar and pestle to pass through a 2 mm sieve. Once ground, soil samples were submitted to the Kansas State University Soil Testing Lab to be analyzed for pH, buffer pH, total P, Melich-3 P, potassium (K), nitrate ,total nitrogen, and total carbon.

Each year, soil sampling was performed in the same manner as described above. Sample collection for the 2015-2016 water year occurred on September 28, 2015 and collection for the 2016-2017 water year occurred between November 2 and November 14, 2017.

Soil test P levels from initial soil sampling were used to develop all P fertilizer application rates. P fertilizer rates are based on the Kansas State University build and maintain recommendation system (Leikam et al., 2003). Chemical soil analysis was performed according to methods outlined in “Recommended Chemical Soil Test Procedures for North Central Region” (University of Missouri, 1998).

Data Analysis

Nutrient concentration and load data were statistically analyzed in SAS version 9.4 using a PROC GLIMMIX procedure with repeated measures analysis of variance to examine treatment effects (Appendix A). To satisfy the assumption of normal distribution, all data required either square root or natural logarithm transformation to normalize residuals. For 2016, total P, total P load, DRP, DRP load, TSS, and TSS load required natural logarithm transformation, and runoff (Q) was square root transformed) For 2017, total P, TSS, TSS load, and Q were natural logarithm transformed, and DRP, DRP load, and total P load were square root transformed. All results are presented as back-transformed means. Error bars on graphs depict standard errors.

All runoff event dates presented in this thesis represent sample collection date and not date of precipitation event. In addition, only runoff events resulting in greater than 2.0 mm of runoff are reported.

Results

During the 2016 cropping year, a total of twenty-seven runoff events occurred resulting in 167.6 mm of runoff. Of these twenty-seven events, only twelve produced more than 2.0 mm of runoff (Table 2.3). These twelve events represented more than 93% of the total runoff generated in 2016. For the 2017 cropping year, eighteen runoff events occurred resulting in 77.6 mm of runoff with only seven events generating more than 2.0 mm of runoff (Table 2.4). These seven events represented more than 88% of total runoff for 2017. All presented results are derived from the analysis of precipitation events that generated more than 2.0 mm of average runoff.

Statistical analysis yielded significant two-way (cover*fertilizer & event*cover) and three-way (event*cover*fertilizer) interactions (Table 2.5 & Table 2.6). For parameters where significant interactions were found, the main treatment effect will not be discussed.

Precipitation

Cumulative precipitation in 2016 and 2017 was 21% above and 16% below the 30-year average for Ashland Bottoms, Kansas, respectively (Figure 2.3). Precipitation patterns were fairly consistent between 2016 and 2017 cropping years with May and June receiving the most rainfall. However, large precipitation events in late fall and early winter of 2016 along with a wetter than average spring caused precipitation levels to be greater in 2016.

Runoff Volume

A cover crop by fertilizer by runoff event interaction was seen in the 2016 cropping year with the CC-CN and NC-SI treatment having variable effects on runoff volume throughout the cropping year (Figure 2.4). In the 2017 cropping year, both a main effect of cover crop and a cover crop by event interaction was observed relating to runoff volume (Table 2.6). For the first four runoff events in the 2017 cropping year, CC had greater runoff volume compared to the NC treatment (Figure 2.5).

Total Suspended Solids

A cover crop by event interaction was found in both 2016 and 2017 cropping years (Table 2.5 & Table 2.6). In the 2016 cropping year, the NC treatment had greater TSS in surface runoff for ten out of twelve runoff events (Figure 2.7). The same trend was observed in the 2017 cropping year with the NC treatment having greater TSS levels for more than 80% of observed events (Figure 2.8). Fertilizer placement had no effect on TSS in either cropping year.

Sediment Load

As with TSS, a cover crop by event interaction was found for sediment load in both 2016 and 2017 cropping years (Table 2.5 & Table 2.6). For the 2016 cropping year, the NC treatment had greater sediment load in surface runoff for five out of twelve runoff events; however, on

12/15/15, the CC treatment had greater sediment load compared to the NC treatment (Figure 2.9). A similar trend was found in the 2017 cropping year with NC having greater sediment load in six out of seven (86%) of runoff events (Figure 2.10). A main effect of cover crop was also seen in both cropping years with cover crops reducing sediment load by over 45% and 60% in 2016 and 2017, respectively (**Error! Reference source not found.**). A fertilizer by event i nteraction was found for sediment load in the 2016 cropping year (Table 2.5). In the 2016 cropping year, fertilizer placement had an inconsistent effect sediment loss with the SI treatment having the greatest sediment loss on 12/01/2015 compared to the FB and CN treatments while one 8/20/2016, the SI treatment had the least sediment loss compared to both FB and CN treatments (Figure 2.11).

A cover crop by fertilizer management practice interaction was found for the 2017 cropping year (Table 2.6). In both SI and FB treatments, the use of a cover crop decreased sediment load from the field (Figure 2.12). However, for the CN treatment, no differences were observed between the cover cropped and non-cover cropped treatments.

Total Phosphorus Concentration

A cover crop by event interaction was observed in both cropping years (Table 2.5 & Table 2.6); however, the impact of cover crops on total P concentration was variable, increasing total P concentration in in some events and decreasing it in others (Figure 2.13 & Figure 2.14). Fertilizer management practice directly influenced the concentration of total P in runoff for both cropping years (Table 2.5 & Table 2.6). In the 2016 cropping year, the application of P fertilizer (regardless of method) increased total P concentration in more than 40% of runoff events (Figure 2.15). A similar trend was seen in the 2017 cropping year with P fertilizer application increasing total P concentration in more than 80% of runoff events (Figure 2.16). However, in both cropping years, prior to the spring application of P fertilizer (Table 2.1 & Table 2.2), the FB had the greatest total P concentration in surface runoff. After the SI application of P fertilizer, both SI and FB had the same total P concentration.

Dissolved Reactive Phosphorus Concentration

A cover crop by event interaction for dissolve reactive P (DRP) concentration in surface runoff was found for 2016 (Table 2.5). In the 2016 cropping year, the CC treatment had greater DRP concentrations in the runoff compared to the NC treatment for 83% of the runoff events (Figure 2.17). The FB fertilizer treatment had the greatest concentration of DRP in surface runoff for the first half of runoff events in the 2016 cropping year (Figure 2.18). During these same events, the concentration of dissolved reactive P was equal for the SI and CN treatments. In the second half of runoff events for 2016, the application of P fertilizer (FB and SI) had greater concentrations of DRP compared to the CN treatment.

In the 2017 cropping year, a three-way interaction between cover crop, fertilizer, and runoff event for dissolved reactive P concentration of surface runoff was found (**Error! Reference source not found.Error! Reference source not found.**). On 3/31/17, 4/3/17, and 4/6/17, the FB treatment, both with and without cover crop, had greater concentration of dissolved reactive P in surface runoff than the remaining treatments. However, on 5/20/17, 5/27/17, and 8/7/17 both FB with cover crop and SI with cover crop had greater dissolved reactive P concentrations compared to the other treatments. On the 5/20/17, 5/27/17, and 8/7/17 events, the CN with cover crop treatment had a greater DRP concentration compared to the CN without cover crop; whereas, the concentrations from these two treatments were equal for prior events. Between the 4/6/17 and 5/20/17 events, there was a striking change in the effect of CC on DRP concentration. On 5/20/17, both the SI and FB with cover crop had the greatest DRP concentration for all events in the 2017 cropping year. Prior to the termination of cover crop and the SI application of P fertilizer, cover crops had no impact on DRP concentration of surface runoff. However, after termination and application SI P fertilizer (Table 2.2) the CC treatment had greater DRP concentration in surface runoff for all P fertilizer management practice.

Total Phosphorus Load

The main effect of cover crop on total P load varied between cropping years. In 2016, no cover crop effect was observed (Table 2.5), but cover crops increased total P load in 2017 (Figure 2.19). Although no overall cover effect was detected in 2016, a cover crop by event interaction was found with three runoff events (12/15/15, 5/25/16 and 5/26/16) having greater total P loads from the CC plots compared to the NC plots (Table 2.5 & Figure 2.20).No event by cover interaction was found in 2017 (Table 2.6).

A fertilizer by event interaction was found for total P load in both cropping years (Table 2.5 & Table 2.6). In the 2016 cropping year, two runoff events (12/01/15 and 12/15/15) had no difference in total P load between the CN and SI treatments, but the FB treatment had greater total P loss (Figure 2.21). Also in the 2016 cropping year, 50% of runoff events showed no difference in total P loss among all fertilizer treatments (Figure 2.21). In 2017, the application of P fertilizer, regardless of method, increased total P loss from the field relative to the control in all events except one (Figure 2.22).

Dissolved Reactive Phosphorus Load

In the 2016 cropping year, a cover crop by event interaction was found with the CC treatment having greater DRP load for one-third of runoff events (Figure 2.23). In addition, a fertilizer by event interaction was found in the 2016 cropping year with the FB treatment having greatest DRP load in surface runoff for the first seven runoff events (Figure 2.24). Phosphorus fertilizer application, regardless of method, increased DRP loss compared to the control for four of the last five runoff events of the 2016 cropping year (5/27/16, 8/25/16, 8/26/16, 9/14/16, Figure 2.24).

A cover by fertilizer by event interaction was found during the 2017 cropping year for DRP load (Table 2.6 & Figure 2.25). In six of seven runoff events during the 2017 cropping year, addition of a cover crop increased DRP load compared to NC. However, on 10/11/2016, the CC treatment did not have any impact on DRP load. Between 04/06/2017 and 05/20/2017 there was a change in the impact of P fertilizer placement on DRP load. Prior to 05/20/2017 (except for 10/11/2016), the CC-FB treatment had a greater DRP load compared to the CC-SI, but from the 5/20/2017 event forward, no differences between the CC-FB and CC-SI treatments. Overall, the effect of cover crop changes after the cover crop was termination (Table 2.2). After termination, all P fertilizer management practices with cover crop had greater DRP load in surface runoff compared to NC.

Discussion

Cover Crop Effects

In both 2016 and 2017 cropping years, cover crops had an inconstant effect on runoff volume for individual precipitation events, increasing runoff in some events and decreasing it in other. However, all events in the 2017 cropping year where the CC treatment had greater runoff compared to the NC treatment occurred prior to termination of the cover crop (Table 2.2 & Figure 2.5). Similar to this study, Nelson et al. (2017) also found that cover crops have a variable effect on runoff volume. A likely reason behind this finding is that the cover crop kept the soil surface moister compared to the NC and therefore increased the volume of runoff in these events due to increased soil moisture saturation. Teasdale and Mohler (1991) stated that cover crop residue reduces the decline in soil moisture during dry periods, ultimately resulting in longer periods of wetter soil conditions. In addition, Penna et al. (2011) found that antecedent (0-30 cm) soil moisture levels can be directly correlated to surface runoff generation with greater soil moisture resulting in higher volumes of surface runoff.

Cover crops decreased sediment loss via erosion by more than 40% and more than 80% in the 2016 and 2017 cropping years, respectively. Nelson et al. (2017) found the use of a cover crop tended to increase the duration of surface runoff from a precipitation event suggesting a decrease in runoff velocity. As surface runoff velocity is increased, erosion rates also increase (Cogo et al., 1983). Cover crops also form a protective canopy over the soil surface that can decrease raindrop impact leading to decreased breakdown of soil aggregates and an overall reduction in soil erosion (Langdale et al., 1991).

In both 2016 and 2017 cropping years, cover crops had an inconsistent effect on total P concentration, increasing it in some events while decreasing it in others. The variability of runoff volume from one event to the next could influence trends in total P concentrations, with smaller runoff events having a greater total P concentration and large runoff events having lower total P concentration. In the 2017 cropping year, runoff events on 3/31/17 and 4/3/17 had greater total P concentration from the NC treatment compared to CC (Figure 2.14). However, when examining runoff volumes for these two events, the CC had greater runoff compared to the NC (Figure 2.5). The inconsistent effect of cover crops on runoff volume could have skewed P concentration data explaining why there is a cover crop by event interaction for total P concentration but not total P load.

In 2016, an event by cover crop interaction was found for total P load (Table 2.5) with the CC having greater total P load for three out of twelve observed events (Figure 2.20). For these three events (12/15/15, 5/25/16, and 5/26/16), cover crops increased total P load by approximately 110% compared to the NC. For the 2017 cropping year, a main effect of cover crop was found with CC having 32% greater total P load compared to the NC (Figure 2.19). The increase in total P load from the CC treatment runs counter to the often touted benefits of cover crops' ability to reduce nutrient loss as an agricultural practice (Sharpley & Smith, 1991; Dabney et al., 2001).

Bechmann et al. (2005) stated that cover crops incorporate soil P into their tissue during their life cycle, concentrating increased levels of P above ground, potentially creating a source of P loss to surface runoff. Utilizing simulated rainfall and greenhouse grown crop tissue, Bechmann et al. (2005) found that exposing cover crop tissue to freeze-thaw cycles can increase the concentration of total P in runoff up to 100 times compared to non-freeze killed cover crop tissue. In both 2016 and 2017 cropping years, winter temperatures in Kansas dropped below minimal survival temperature for all cover crop species used (Figure 2.26 & Figure 2.27). Although cumulative time below minimal survival temperature was very limited (0-3 hours) at the KAW, some winterkill of the cover crop treatment was observed. However, the majority of cover crop tissue was not damaged. The exposure to sub-freezing temperatures and associated cell damage could have contributed to the increase in total P load from the CC treatment.

In both cropping years, the CC treatment had greater DRP losses compared to the NC treatment. The increase in DRP loss is vitally important from an environmental standpoint in that DRP is readily available to algae and aquatic plants (Wasley, 2007). Excessive inputs of P to surface waters can lead to eutrophication, increase algal and aquatic plant growth, and an overall drop in ecosystem health and water quality (Correll, 1998; Carpenter et al., 1998).

The increase in DRP loss from the CC treatment is an unintended consequence of adding a cover crop to this no-till system. In 2017, Nelson et al. found the use of a cover crop tended to increase the duration of surface runoff from a precipitation event. This increase in runoff time suggests a decrease in runoff velocity and an associated increase in runoff contact time with soil and crop residue. Toor et al (2006) stated that water extractable phosphorus (WEP) is directly related to the length of contact time with the extracting solution. Since cover crops increase the duration of runoff, the quantity of WEP may increase (Nelson et al., 2017; Toor et al., 2006). WEP is considered the most consistent predictor of DRP concentration (Wang et al., 2010). Therefore, the increased contact time could lead to the increase in dissolved reactive P losses from the CC treatment.

Fertilizer Effects

A cover crop by fertilizer by runoff event interaction was found for runoff volume in the 2016 cropping year (Table 2.5). When examining runoff data, two treatments stand out as having an inconsistent effect on runoff volume: CC-CN and NC-SI (Figure 2.4). As previously stated, the effect of cover crop on runoff was inconsistent across both cropping years and this inconstancy could explain the interaction between cover crop and fertilizer application methods. In addition, a cover crop by fertilizer interaction for runoff volume was also found in the 2016 cropping year (Table 2.5). Across the cropping year, the CC-SI and CC-FB treatments had the lowest surface runoff volume compared the NC-CN; however, no differences between CC and NC within the FB and SI treatments were observed (Figure 2.6). Further research is needed to determine the mechanisms behind this variation in runoff volume.

Phosphorus fertilizer application had a marginal impact on sediment loss from the field during both cropping years although a fertilizer by event interaction was observed during the

2016 cropping year. During 10 of 12 runoff events in the 2016 cropping year, the application of P fertilizer had no effect on sediment load. However, the SI treatment had an inconsistent effect on sediment load during two runoff events, increasing it on 12/01/15 and decreasing it on 8/20/16 (Figure 2.11). When looking at these events, the quantity of sediment being lost from the field is negligible compared to sediment loss during other runoff events. The reason behind the difference in sediment load because of the SI treatment cannot be explained at this time.

Each cropping year, the FB application of P fertilizer had greater total P concentration in surface runoff compared to both the SI and CN treatments from all runoff events prior to planting (Figure 2.15 & Figure 2.16). This finding is not surprising given the research field was under no-till management. In a no-till system, surface applied nutrients remain unincorporated into the soil and increase stratification of nutrients throughout the soil profile (Howard, et al., 1999). Increased soil test P at the soil surface could potentially result in greater concentrations of total P in surface runoff (Sharpley, 1995).

After planting, in both cropping years, the application of P fertilizer increased both total P and DRP load in runoff compared to the control. These findings run contradictory to Kimmel et al (2001) who stated that placement of P fertilizer below the soil surface in a no-till system can result in a decrease in P loss. However, Zeimen et al. (2009) found placing P fertilizer below the soil surface could result in P losses equal to or less than that of surface applied P fertilizer. In both cropping years, sediment loss appears to increase after field operations have occurred (Figure 2.9 & Figure 2.10). Increases in total P loads in surface runoff could be due to the increase in sediment being lost from the field, and because the fertilized plots had greater soil test P compared to the non-fertilized plots, the sediment could contain greater quantities of particulate bound P. Increases in DRP load were also likely because of increase soil test P levels.

A three-way interaction between cover, fertilizer, and runoff event was observed during the 2017 cropping year for both DRP concentration and DRP load. Findings from the 2017 cropping year indicate that application of P fertilizer can increase both DRP concentration and load in surface runoff, but these findings also suggest that a P fertilized cover crop will have greater DRP loss compared to a non-P fertilized cover crop. Additional research is needed to fully understand this three-way interaction.

Conclusions

Overall, this study found that the use of a winter cover crop in a no-till corn-soybean rotation increased the quantity of DRP being lost in surface runoff from the field. Although DRP losses were consistently greater from the CC plots across both cropping years, cover crops had an inconsistent effect on total P loss, increasing it in 2017 but having no effect in 2016. Although cover crops increased DRP losses, the CC treatment dramatically reduced erosion losses during both years.

The application of P fertilizer generally increased both total P and DRP concentrations and loads. However, injecting P fertilizer below the soil surface tended to result in less P loss compared to the surface broadcast application indicating that sub-surface placement of P fertilizer remains a BMP for minimizing P loss from agricultural fields.

References

Abel, D. 2016. Cover crops and fertilizer management impacts on water quality and cover crop effect on soil moisture. Master's of Science. Kansas State University, Manhattan, KS.

Bechmann, M.E., P.J.A. Kleinman, A.N. Sharpley and L.S. Saporito. 2005. Freeze-thaw effects on phosphorus loss in runoff from manured and catch-cropped soils. J. Environ. Qual. 34:2301-2309.

Bennett E.M., S.R. Carpenter, N.F. Caraco. 2001. Human impact on erodible phosphorus and eutrophication: a global perspective. Bioscience 51:227–234.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications. 8:559-568.

Correll, D. 1998. The role of phosphorus in the eutrophication of receiving waters: A review. J. Environ. Qual. 27:261-266.

Christianson R., J. Fox, C. Wong, D. Caraco, A. Daniels, N. Law, and B. Stack. 2017. Literature review and synthesis of the effectiveness of cover crops for water quality management in the upper Mississippi river basin (White Paper). Center for Watershed Protection, Inc., Ellicott City, Maryland.

Dabney, S., J. Delgado and D. Reeves. 2001. Using winter cover crops to improve soil and water quality. Commun. Soil Sci. Plant Anal. 32:1221-1250.

Daryanto, S., L. Wang, and P.A. Jacinthe. 2017. Meta-analysis of phosphorus loss from no-till soils. J. Environ. Qual. 46:1028-1037.

Dobberstein, J. 2014. No-till movement in U.S. continues to grow. Retrieved from https://www.no-tillfarmer.com/articles/489-no-till-movement-in-us-continues-to-grow?v=preview

Dodds, W.K., J.L. Eitzmann, T.J. Pilger, K.L. Pitts, A.J. Riley, J.T. Schloesser and D.J. Thornburgh. 2009. Eutrophication of U.S. freshwaters: Analysis of potential economic damages. Environ. Sci. Technol. 43:12-19.

Dumanski, J., R. Pieretti, J.R. Benites, D. McGarry, and C. Pieri. 2006. The paradignm of conservation agriculture. Proc. World Assoc. Soil and Water Conserv. P1:58-64.

Howard, D.D., M.E. Essington, and D.D. Tyler. 1999. Vertical phosphorus and potassium stratification in no-till cotton soils. Agron. J. 91:266– 269.

Kimmell, R.J., G.M. Pierzynski, K.A. Janssen, and P.L. Barnes. 2001. Effects of tillage and phosphorus placement on phosphorus runoff losses in a grain sorghum-soybean rotation. J. Environ. Qual. 30:1324-1330.

Kleinman, P., P. Salon, A.N. Sharpley, and L. Saporito. 2005. Effect of cover crops established at time of corn planting on phosphorus runoff from soils before and after dairy manure application. J. Soil Water Conserv. 60(6).

Kovar, J.L., T.B. Moorman, J.W. Singer, C.A. Cambardella, M.D. Tomer, and D.B. Beegle. 2011. Swine manure injection with low-disturbance applicator and cover crops reduce phosphorus losses. J. Environ. Qual. 40:329–336.

Liu, J., R. Khalaf, B. Ulen, and G. Bergkvist. 2013. Potential phosphorus release from catch crop shoots and roots after freezing-thawing. Plant Soil 371:543-557.

Miller, M., E. Beauchamp, and J. Lauzon. 1994. Leaching of nitrogen and phosphorus from the biomass of three cover crop species. J. Environ. Qual. 23:267-272.

Nelson, N.O, R.E. Carver, K.L. Roozeboom, G.J. Kluitenberg, P.J. Tomlinson, and J.R. Williams. 2017. Cover crop impacts on runoff hydrographs and edge-of-field surface water quality. Poster presented at ASSA-CSSA-SSSA Joint Meeting. Tampa, Florida.

Sharpley, A.N., and S.J. Smith. 1991. Effects of cover crops on surface water quality. p. 41–49. In W.L. Hargrove (ed.) Cover crops for clean water. Proc. Int. Conf., Jackson, TN. 9–11 April 1991. Soil and Water Conserv. Soc., Ankeny, IA.

Sharpley, A.N. 1995. Dependence off runoff phosphorus on extractable soil-phosphorus. J. Environ. Qual. 24:920-926.

Tripplet, G.B. and W.A. Dick. 2008. No-tillage crop production: a revolution in agriculture!. Agron. J. 100:S-153-S-165.

Welch, J.L. 1978. The impacts of inorganic phosphates in the environment. Rep. EPA 560/1-78 003. Office of Toxic Substances, Washington, DC.

Zeimen, M.B., K.A. Jannsen, D.W. Sweeney, G.M. Pierzynski, K.R. Mankin, D.L. Devlin, D.L Regehr, M.R. Langemeier, and K.A. McVay. 2006. Combining management practices to reduce sediment, nutrients, and herbicides in runoff. J. Soil Water Conserv. 61:258-267.

Table 2.1. 2015-2016 field operations. No cover crop (NC), Cover crop (CC), control application of phosphorus (P) fertilizer (CN), fall broadcast application of phosphorus fertilizer (FB), spring injected application of phosphorus fertilizer (SI), diammonium phosphate (DAP), ammonium polyphosphate (APP), ammonium sulfate (AMS).

Date	Activity	NC-CN	NC-FB	NC-SI	CC-CN	CC-FB	CC-SI	Notes
9/22/2015	Cover crop planting	NO	NO	NO	YES	YES	YES	winter wheat (Overley; 146 kg ha^{-1})
11/10/2015	P fertilizer application	NO	Block 1: 78 kg ha^{-1-} $P_2O_5^1$	NO	NO	Block 1: 78 kg ha^{-1-} P_2O_5	NO	DAP: 18-46-0; block 1
11/13/2015	P fertilizer application-	NO	Blocks 2 & 3: 52 kg ha^{-1} $P_2O_5^1$	NO	NO	Blocks 2 & 3: 52 kg ha^{-1} $P_2O_5^1$	NO	DAP: 18-46-0; blocks 2 & 3
4/12/2016	Herbicide application	Sterling Blue (0.58 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), glyphosate (3.51 L ha^{-1}), AMS	Sterling Blue (0.58 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), glyphosate (3.51 L ha^{-1}), AMS	Sterling Blue (0.58 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), glyphosate (3.51 L ha^{-1}), AMS	Sterling Blue (0.58 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), AMS	Sterling Blue (0.58 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), AMS	Sterling Blue (0.58 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), AMS	weed control
4/22/2016	Cover crop biomass harvest	NO	NO	NO	YES	YES	YES	*see text for details
5/5/2016	Cover crop biomass harvest	NO	NO	NO	YES	YES	YES	harvest repeated due to lag between herbicide application
5/6/2016	Herbicide application	NO	NO	NO	3.51 L ha glyphosate	3.51 L ha glyphosate	3.51 L ha glyphosate	cover crop termination
6/6/2016	Soybean planting, P fertilizer application, & herbicide application	Planting; Glyphosate (3.5 L ha^{-1}) and Fierce (0.26 kg ha^{-1})	Planting; Glyphosate (3.5 L ha^{-1}) and Fierce (0.26kg ha^{-1})	Planting; 78 or 56 kg ha P_2O_5; Glyphosate (3.5 L ha^{-1}) and Fierce (0.26 kg ha^{-1})	Planting; Glyphosate (3.5 L ha^{-1}) and Fierce (0.26 kg ha^{-1})	Planting; Glyphosate (3.5 L ha^{-1}) and Fierce (0.26kg ha^{-1})	Planting; 78 or 56 kg ha P_2O_5; Glyphosate (3.5 L ha^{-1}) and Fierce (0.26kg ha^{-1})	APP: 10-34-0; Block 1: 78 kg P_2O_5 ha^{-1}; Blocks 2 & 3: 56 kg P_2O_5 ha^{-1}
6/29/2016	Herbicide application	Glyphosate (3.51 L ha^{-1}), Cobra (0.91 L ha^{-1})	Glyphosate (3.51 L ha^{-1}), Cobra (0.91 L ha^{-1})	Glyphosate (3.51 L ha^{-1}), Cobra (0.91 L ha^{-1})	NO	NO	NO	weed control
9/19/2016	Soybean biomass harvest	YES	YES	YES	YES	YES	YES	*see text for details
10/17/2016	Plot combine harvest	YES	YES	YES	YES	YES	YES	*see text for details
10/19/2017	Combine harvest	YES	YES	YES	YES	YES	YES	*see text for details

Table 2.2. 2016-2017 field operations. No cover crop (NC), Cover crop (CC), control application of phosphorus (P) fertilizer (CN), fall broadcast application of phosphorus fertilizer (FB), spring injected application of phosphorus fertilizer (SI), diammonium phosphate (DAP), ammonium polyphosphate (APP), ammonium sulfate (AMS), urea ammonium nitrate (UAN), six-leaf vegetative growth stage (V6).

Date	Activity	NC-CN	NC-FB	NC-SI	CC-CN	CC-FB	CC-SI	Notes
10/19-20/2016	Cover crop planting	NO	NO	NO	YES	YES	YES	triticale (56 kg ha^{-1}), rapeseed (57 kg ha^{-1})
11/2-14/2016	Soil sampling	YES	YES	YES	YES	YES	YES	0-5 cm, 5-15 cm
12/2/2016	P application	NO	63 kg ha^{-1} P_2O_5	NO	NO	63 kg ha^{-1} P_2O_5	NO	DAP: 18-46-0
3/8/2017	herbicide application	Atrazine (1.12 kg ha^{-1}), dicamba (0.29 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), glyphosate (2.34 L ha^{-1}), AMS	Atrazine (1.12 kg ha^{-1}), dicamba (0.29 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), glyphosate (2.34 L ha^{-1}), AMS	Atrazine (1.12 kg ha^{-1}), dicamba (0.29 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), glyphosate (2.34 L ha^{-1}), AMS	NO	NO	No	spring burndown
4/17/2017	Cover crop biomass harvest	NO	NO	NO	YES	YES	YES	two, 3.05 m rows at each subplot location
4/24/2017	Corn planting & P fertilizer application	Planting Only	Planting Only	59 kg ha^{-1} $P_2O_5{}^1$	Planting Only	Planting Only	59 kg ha^{-1} $P_2O_5{}^1$	64,000 seeds ha, APP: 10-34-0
4/25-26/2017	herbicide application	Lumax (5.85 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), glyphosate (2.34 L ha^{-1}), AMS	Lumax (5.85 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), glyphosate (2.34 L ha^{-1}), AMS	Lumax (5.85 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), glyphosate (2.34 L ha^{-1}), AMS	Lumax (5.85 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), glyphosate (2.34 L ha^{-1}), AMS	Lumax (5.85 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), glyphosate (2.34 L ha^{-1}), AMS	Lumax (5.85 L ha^{-1}), 2,4-D LV6 (0.88 L ha^{-1}), glyphosate (2.34 L ha^{-1}), AMS	pre-emerge herbicide
4/24-27/2017	Nitrogen application	170 kg ha^{-1} N	170 kg ha^{-1} N	170 kg ha^{-1} N	170 kg ha^{-1} N	170 kg ha^{-1} N	170 kg ha^{-1} N	total N rate: 173.7 kg ha^{-1}
6/12/2017	Nitrogen application	44.8 kg ha^{-1} N	44.8 kg ha^{-1} N	44.8 kg ha^{-1} N	44.8 kg ha^{-1} N	44.8 kg ha^{-1} N	44.8 kg ha^{-1} N	V6, UAN: 28-0-0
9/7-8/2017	Hand harvest	YES	YES	YES	YES	YES	YES	*see text for details
9/20-21/2017	Combine harvest	YES	YES	YES	YES	YES	YES	*see text for details
9/21/2017	Cover crop planting	YES	YES	YES	YES	YES	YES	56 kg ha^{-1} titicale, 6 kg ha^{-1} rapeseed

Table 2.3. Runoff event summary from 2016 precipitation events generating more than 2.0 mm of surface runoff

Date when sample was removed from autosampler	Beginning date of precipitation event	Ending date of precipitation event	Precipitation (mm)	Average Runoff (mm)	Number of plots without a runoff sample
12/1/2015	11/26/2016	11/27/2016	38.10	4.8	5
12/15/2015	12/13/2016	12/14/2016	63.25	18.5	2
4/25/2016	4/24/2016	4/25/2016	52.92	17.8	2
4/27/2016	4/26/2016	4/27/2016	76.45	39.8	1
5/25/2016	5/24/2016	5/25/2016	14.39	2.1	1
5/26/2016	5/25/2016	5/26/2016	16.09	4.3	1
5/27/2016	5/26/2016	5/27/2016	62.57	34.5	2
7/13/2016	7/13/2016	7/13/2016	23.88	10.8	1
8/20/2016	8/19/2016	8/19/2016	46.61	3.1	3
8/25/2016	8/25/2016	8/25/2016	37.59	8.2	0
8/26/2016	8/26/2016	8/26/2016	26.86	11.13	0
9/14/2016	9/14/2016	9/14/2016	14.48	2.1	1

Table 2.4. Runoff event summary for 2017 precipitation events resulting in greater than 2.0 mm of runoff.

Date when sample was removed from autosampler	Beginning date of precipitation event	Ending date of precipitation event	Precipitation (mm)	Average Runoff (mm)	Number of plots without a runoff sample
10/11/16	10/10/16	10/10/16	17.3	2.1	0
03/31/17	03/28/17	03/30/17	64.2	20.51	3
04/03/17	04/01/17	04/03/17	21.5	4.42	2
04/06/17	04/04/16	04/05/17	31.6	12.02	1
05/20/17	05/19/17	05/19/17	17.9	5.16	0
05/27/17	05/27/17	05/27/17	17.8	4.47	1
08/07/17	08/05/17	08/05/17	85.9	20.05	3

Table 2.5. ANOVA table for analysis of events generating more than 2.0 mm of surface runoff in 2016 cropping year. Table abbreviations include total P concentration (TP), dissolved reactive P concentration (DRP), total suspended solid concentration (TSS), total P load (TP load), dissolved reactive P load (DRP load), sediment load (Sed), and runoff volume (Q).

	TP	DRP	TSS	TP load	DRP load	Sed	Q
Cover†	0.202	<0.001	<0.001	0.497	0.003	<0.001	0.953
Fert†	<0.001	<0.001	0.733	0.088	0.002	0.670	0.350
Event†	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cover*Fert†	0.398	0.213	0.326	0.534	0.175	0.326	0.031
Cover*Event†	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Fert*Event†	<0.001	<0.001	0.221	0.002	0.001	0.018	0.066
Cover*Fert*Event†	0.853	0.9	0.274	0.583	0.890	0.189	<0.001

†: Cover crop effect (Cover); Fertilizer effect (Fert); Event effect (Event); Cover by fertilizer interaction (Cover*Fert); Cover by event interaction (Cover*Event); Fertilizer by event interaction (Fert*Event); cover by fertilizer by event interaction (Cover*Fert*Event)

Table 2.6. ANOVA table for analysis of runoff events with more than 2.0 mm of surface runoff for 2017 cropping year. Table abbreviations include total P concentration (TP), dissolved reactive P concentration (DRP), total suspended solid concentration (TSS), total P load (TP load), dissolved reactive P load (DRP load), sediment load (Sed), and runoff volume (Q).

	TP	DRP	TSS	TP load	DRP load	Sed	Q
Cover†	0.988	<0.001	<0.001	0.043	<0.001	<0.001	0.043
Fert†	<0.001	<0.001	0.988	<0.001	<0.001	0.554	0.275
Event†	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cover*Fert†	0.072	0.028	0.143	0.596	0.815	0.022	0.095
Cover*Event†	<0.001	<0.001	0.002	0.278	0.002	<0.001	<0.001
Fert*Event†	<0.001	<0.001	0.848	<0.001	<0.001	0.857	0.239
Cover*Fert*Event†	0.724	0.031	0.516	0.089	0.003	0.718	0.262

†: Cover crop effect (Cover); Fertilizer effect (Fert); Event effect (Event); Cover by fertilizer interaction (Cover*Fert); Cover by event interaction (Cover*Event); Fertilizer by event interaction (Fert*Event); cover by fertilizer by event interaction (Cover*Fert*Event)

Table 2.7.Cover crop by fertilizer management practice by runoff event interaction for dissolved reactive phosphorus concentration in surface runoff in the 2017 cropping year. Different letters represent differences between treatments at $p<0.05$.

Event	NC-CN		CC-CN		NC-FB		CC-FB		NC-SI		CC-SI	
10/11/2016	10.20	v	12.31	uv	171.63	klmnp	125.95	npqr	25.66	stuv	202.70	klmnp
03/31/2017	138.07	lmnpq	106.67	pqr	1484.45	ab	1340.82	abc	277.54	ijk	374.93	hij
04/03/2017	132.19	mnpq	104.55	pqr	1154.53	bcd	1148.28	bcd	263.20	jklm	357.47	hij
04/06/2017	71.49	qrs	61.30	qrst	923.32	ed	873.97	ed	191.86	klmnp	289.99	hijk
05/20/2017	54.19	rstu	247.44	jklmn	593.31	gf	1601.32	a	292.98	hijk	1567.40	a
05/27/2017	20.74	tuv	123.02	pqr	457.25	gh	994.05	d	270.78	ijkl	1064.36	cd
08/07/2017	45.00	rstuv	221.91	jklmn	440.94	ghi	693.64	ef	267.15	jklm	700.76	ef

Table 2.8. Cover by fertilizer by runoff event interaction for dissolved reactive phosphorus load in the 2017 cropping year. Letters indicate differences between treatments at $p<0.05$.

	NC-CN		CC-CN		NC-FB		CC-FB		NC-SI		CC-SI	
10/11/2016	0.1	v	0.4	uv	1.7	stuv	2.2	rstuv	0.7	uv	4.3	pqrstu
03/31/2017	14	lmnop	35	hijk	152	b	275	a	63	defg	82	cde
04/03/2017	3	qrstuv	8	nopqrs	22	klm	46	ghi	11	mnopq	18	klmn
04/06/2017	5	opqrstu	11	mnopq	63	defg	111	c	24	jklm	43	ghi
05/20/2017	3	qrstu	15	lmno	30	ijkl	58	efg	17	lmno	79	cdef
05/27/2017	1	tuv	7	nopqrst	18	lmn	41	ghij	13	mnop	45	ghi
08/07/2017	10	mnopqr	47	ghi	97	c	91	cd	54	fgh	100	c

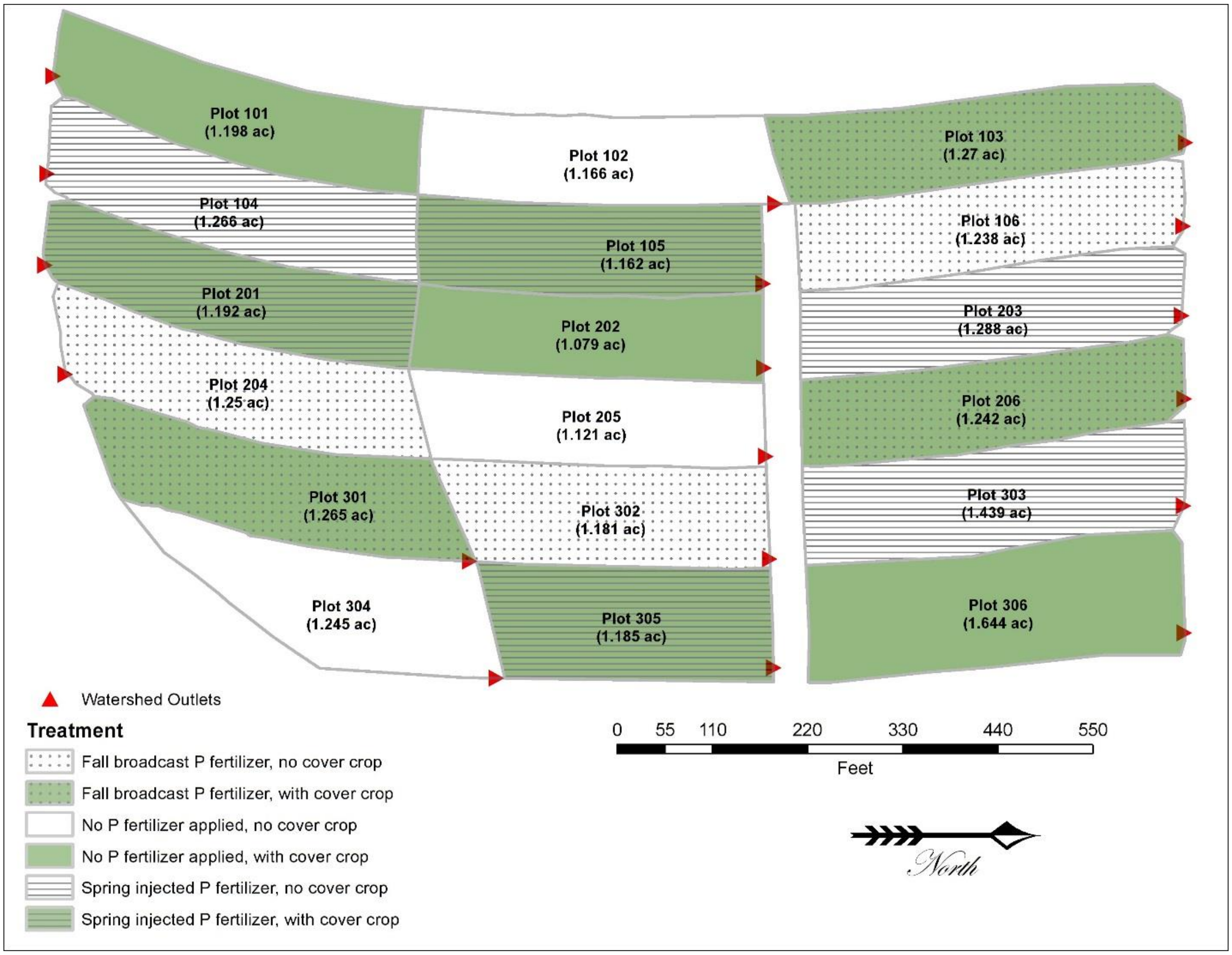

Figure 2.1. Plot map of Kansas Agricultural Watershed (KAW) field laboratory. Acre (ac), phosphorus (P).

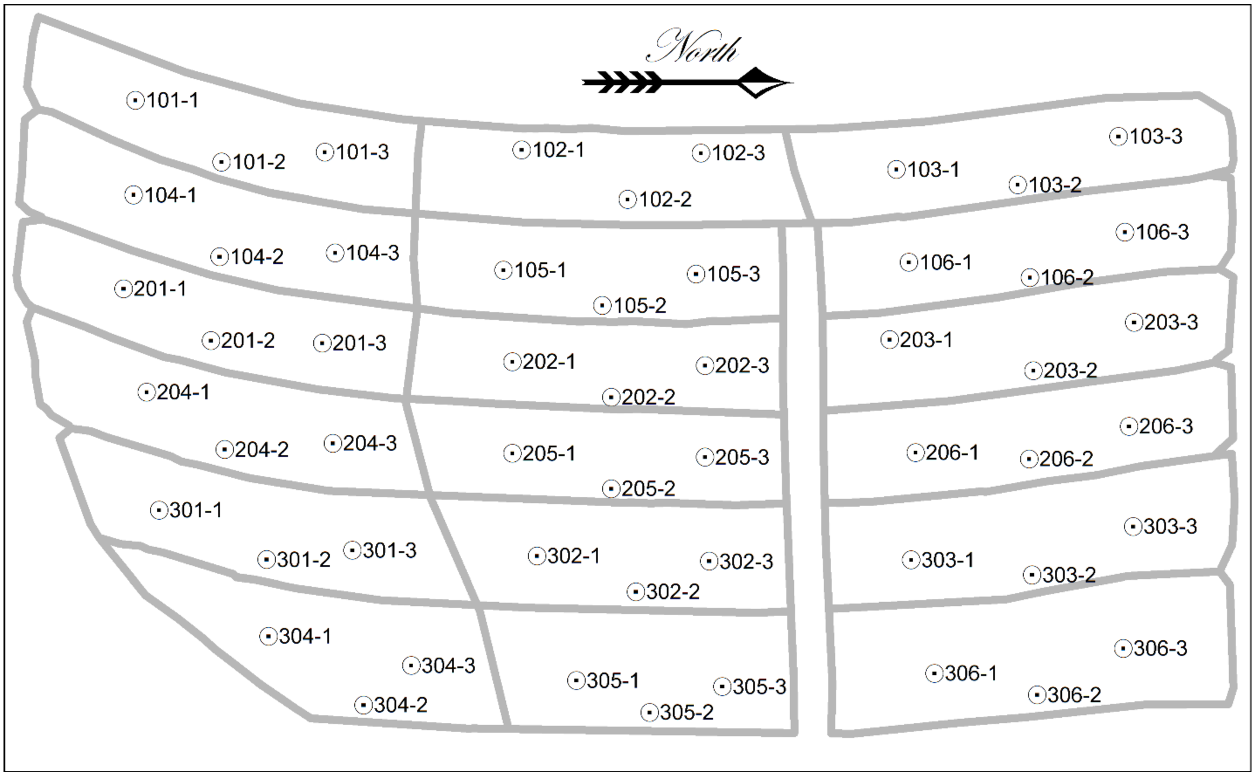

Figure 2.2. Sub-plot locations at KAW for soil sampling, biomass collection, and grain harvest. Sub-plot points 1 and 3 are located on the back-slope of the above terrace. Sub-plot point 2 is located approximately in the middle of each plot within the terrace channel

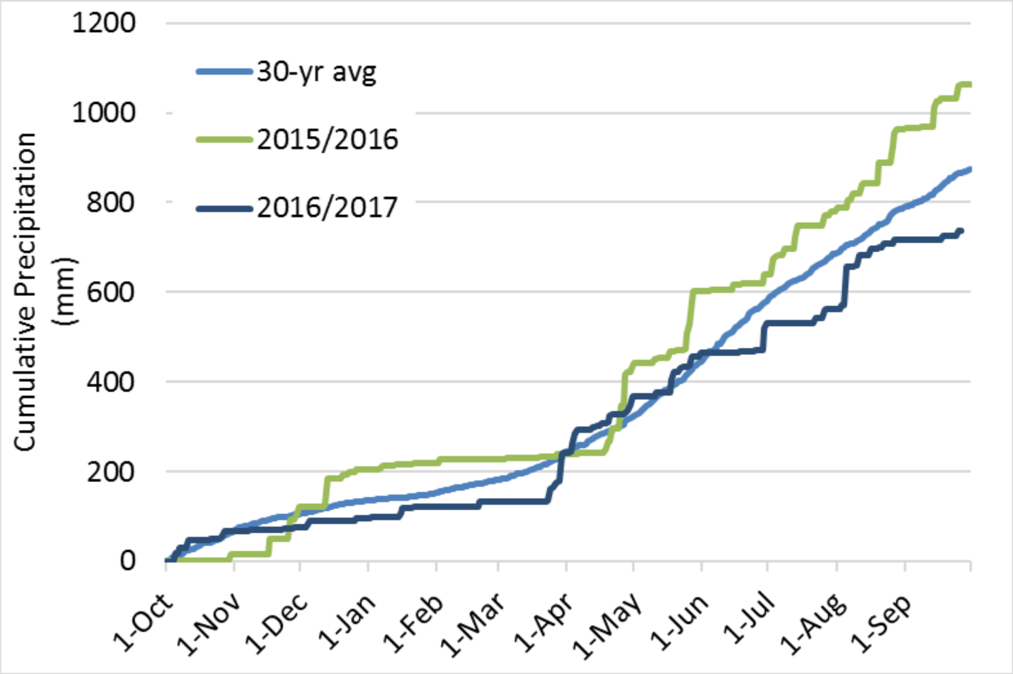

Figure 2.3. Cumulative rainfall for both 2016 and 2017 cropping years at the KAW compared to 30-year average for Manhattan, KS.

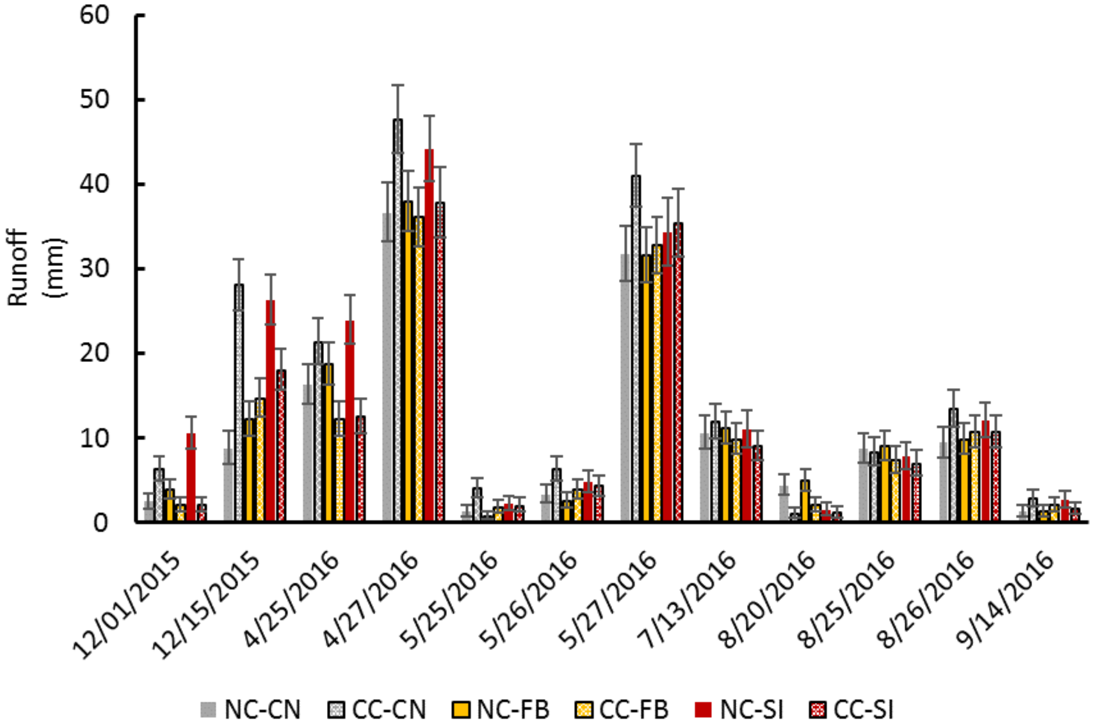

Figure 2.4. Cover by fertilizer by event interaction for runoff for the 2016 cropping year at ***p<0.05.***

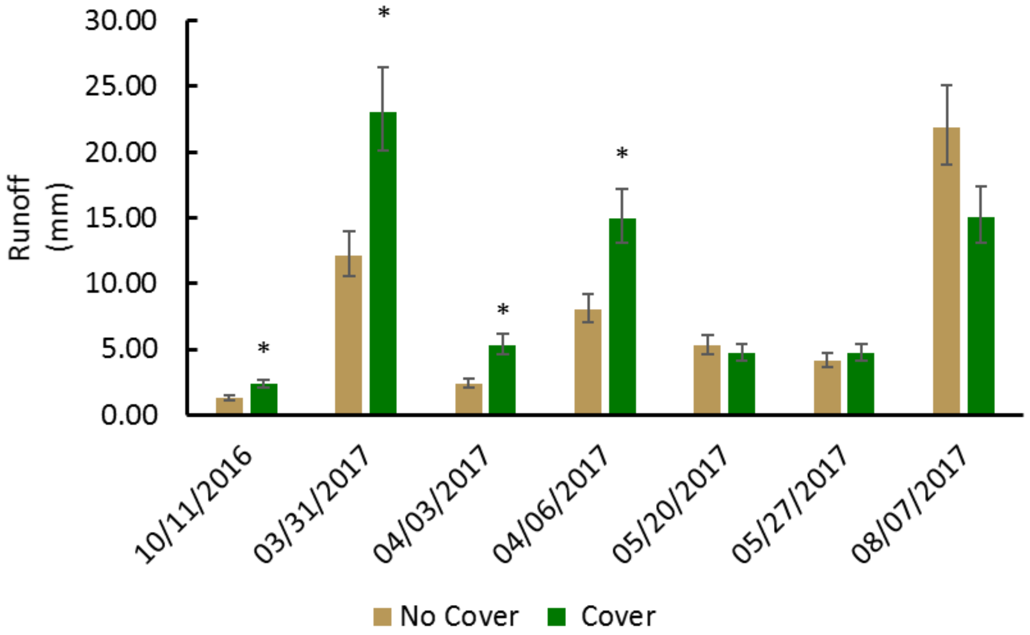

Figure 2.5. Winter cover crop effect on surface runoff volume for 2017 cropping year. Asterisk indicates difference between treatments within an event at ***p<0.05.***

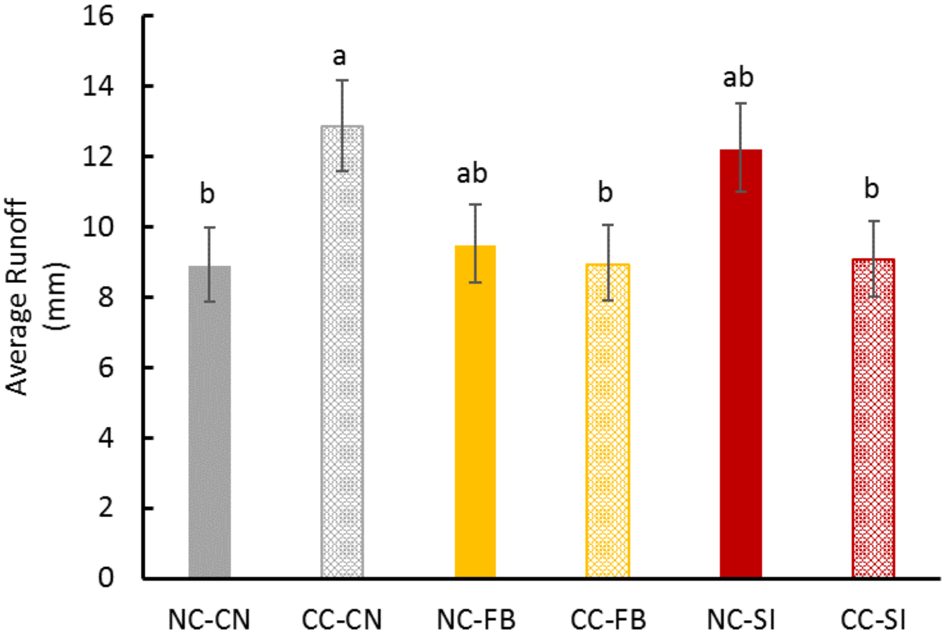

Figure 2.6. Cover crop by fertilizer interaction for runoff volume for 2016 cropping year. Letters represent difference between treatments at *p<0.05*.

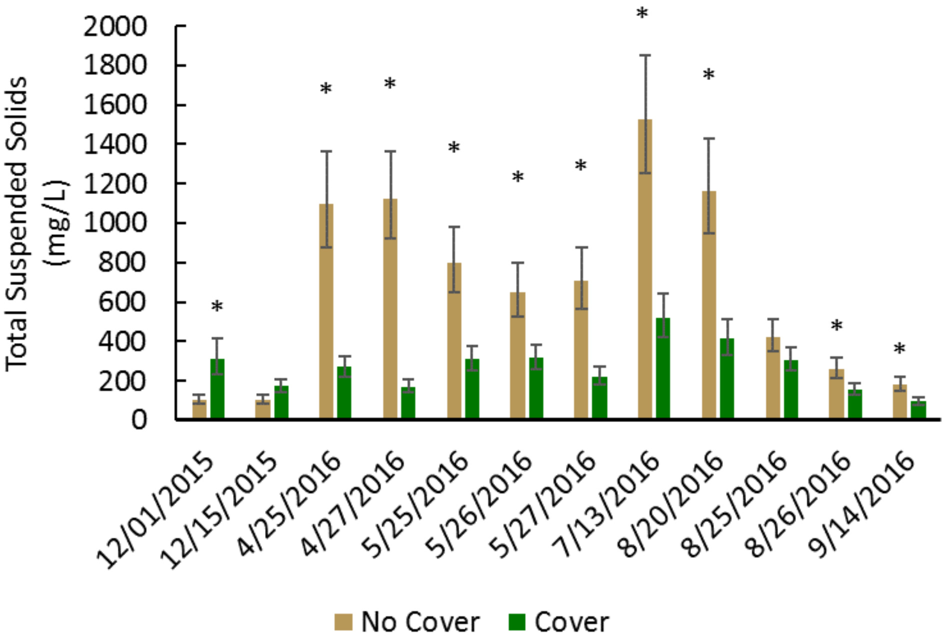

Figure 2.7. Event by cover interaction on total suspended solids concentration of surface runoff from 2016 cropping year. Asterisk indicates difference between treatments at *p<0.05*.

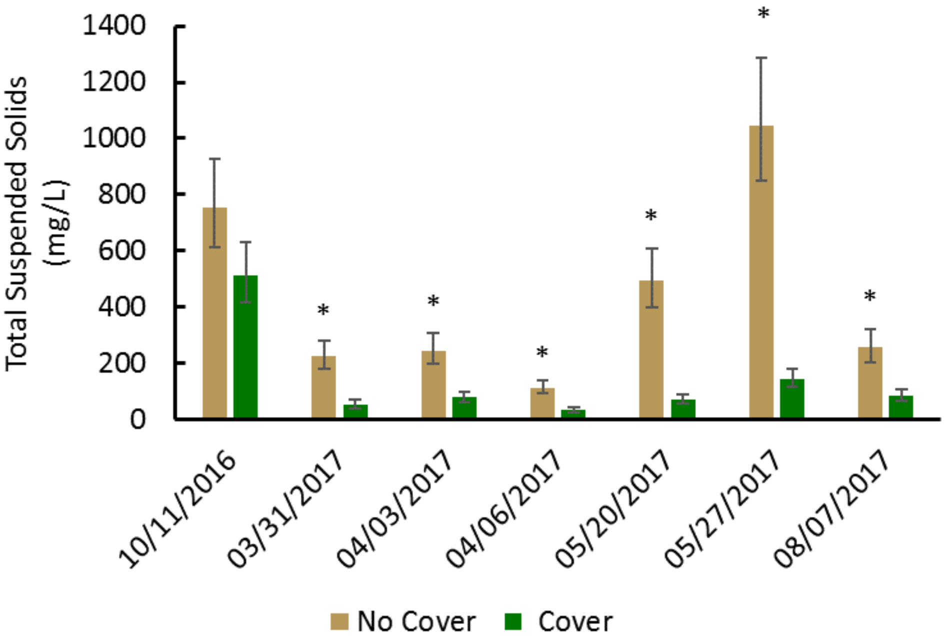

Figure 2.8. Winter cover crop effects on total suspended solids concentration in surface runoff for events with more than 2.0 mm of runoff for 2017 cropping year. Asterisk indicates difference between treatment within event at *p<0.05*.

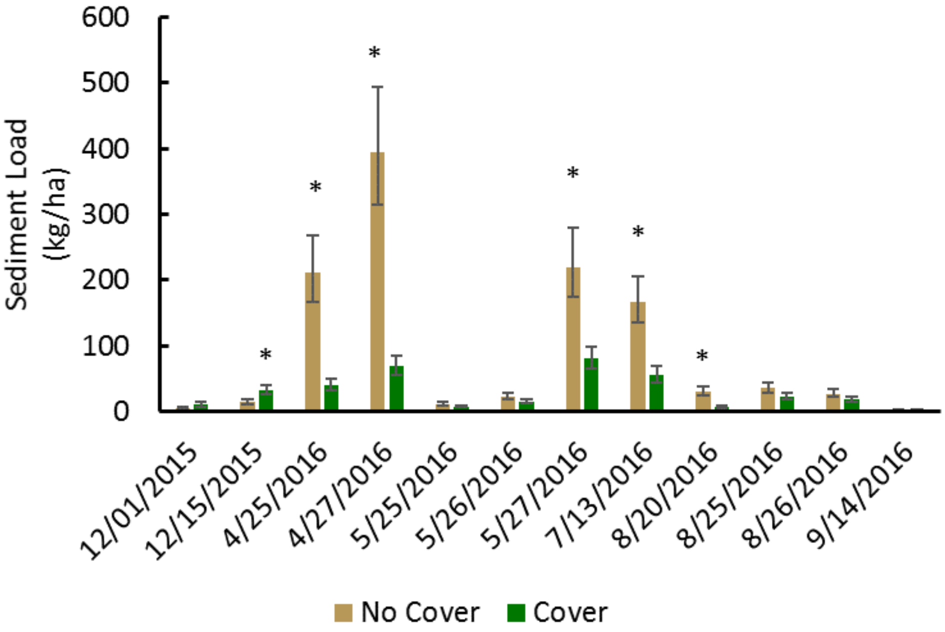

Figure 2.9. Cover crop effect on sediment load in surface runoff for 2016 cropping year. Asterisks indicate difference between treatments within an event at *p<0.05.*

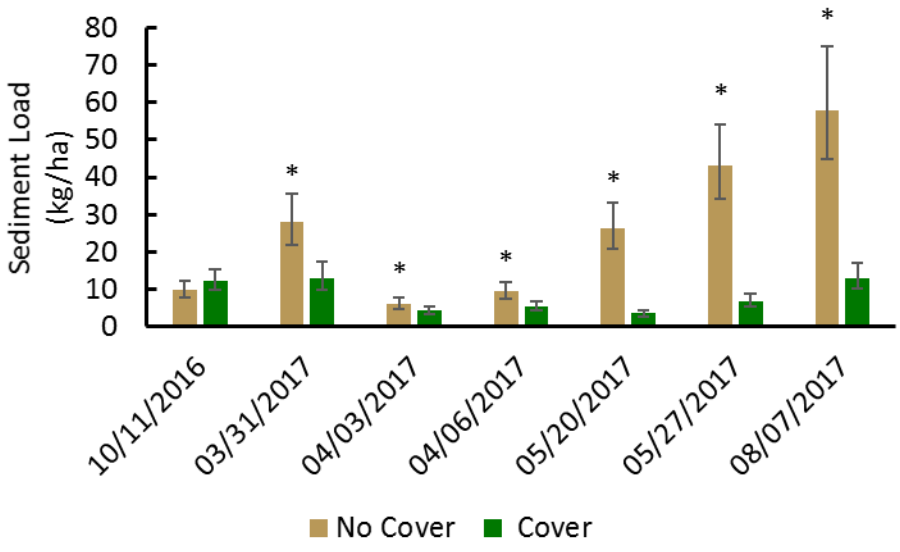

Figure 2.10. Cover crop effect on sediment load in surface runoff for events generating more than 2.0 mm of runoff in 2017 cropping year. Asterisks indicate difference between treatments within a runoff event at *p<0.05*.

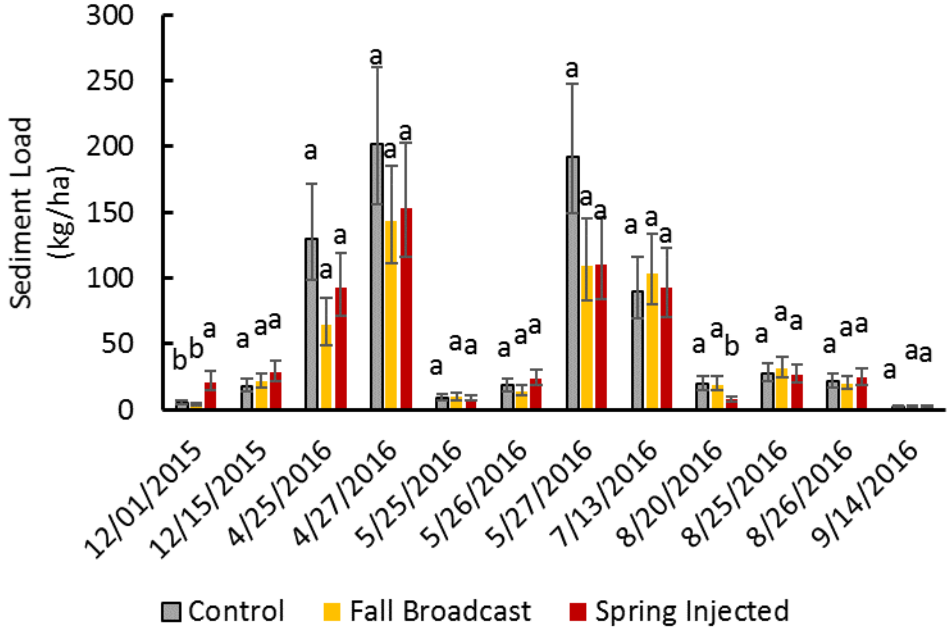

Figure 2.11. Fertilizer by event interaction for sediment load in 2016 cropping year. Letters represent differences between treatments within a runoff event a *p<0.05*.

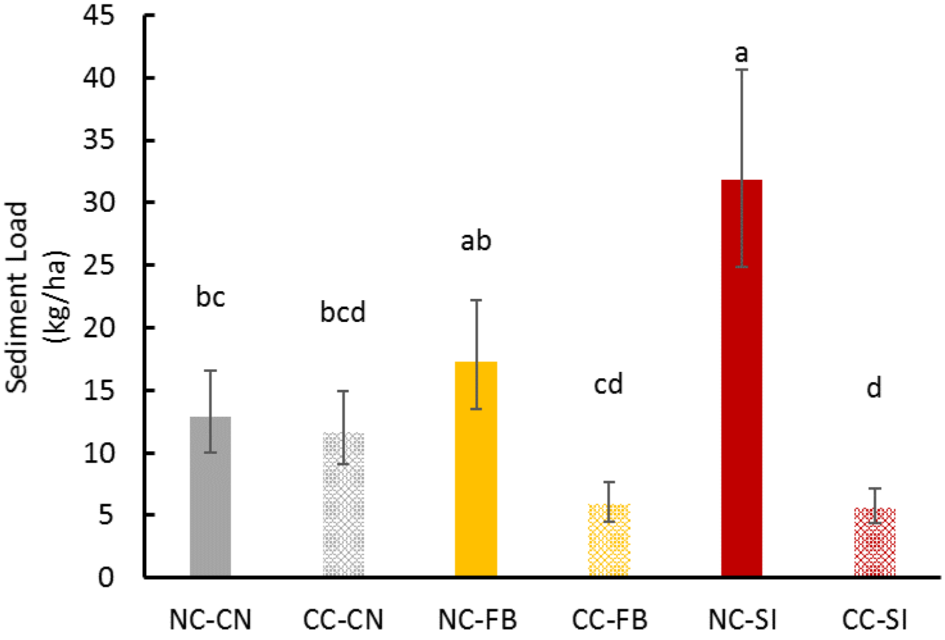

Figure 2.12. Cover by fertilizer interaction for sediment load in the 2017 cropping year. Data is averaged over all runoff events. Letters represent differences between treatments at *p<0.05.*

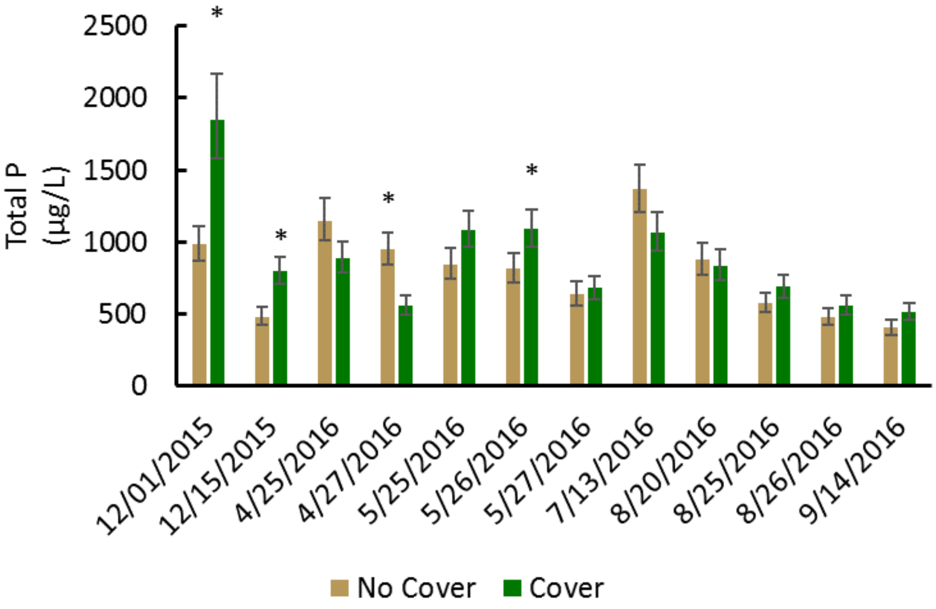

Figure 2.13. Effects of winter cover crops on total P concentration of surface runoff for events with more than 2.0 mm of runoff for 2016 cropping year. Asterisk indicates difference between treatment within an event at *p<0.05*.

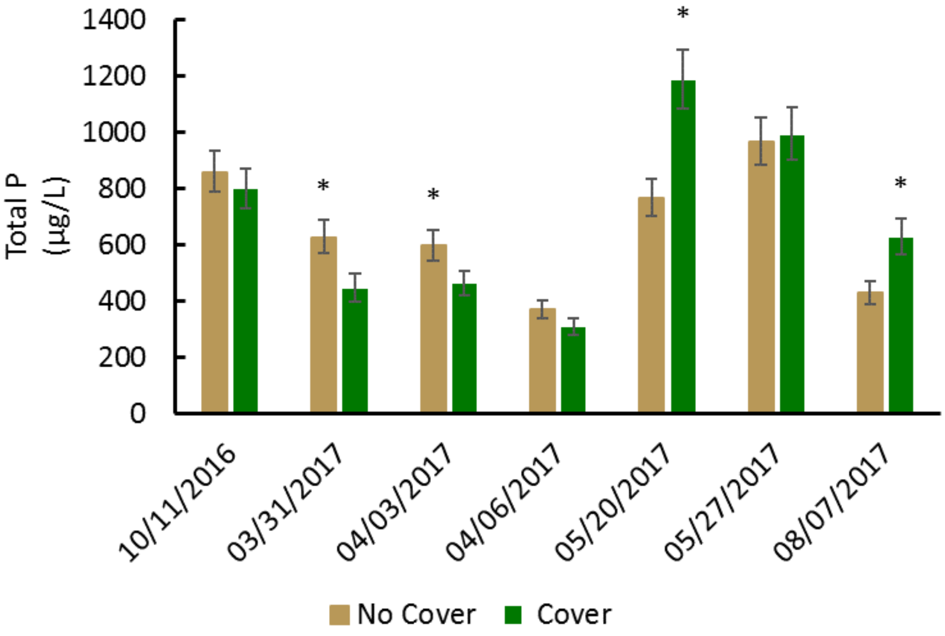

Figure 2.14. Winter cover crop effects on total P concentration in surface runoff for events with more than 2.0 mm of runoff for 2017 cropping year. Asterisk indicates difference between treatment within event at *p<0.05*.

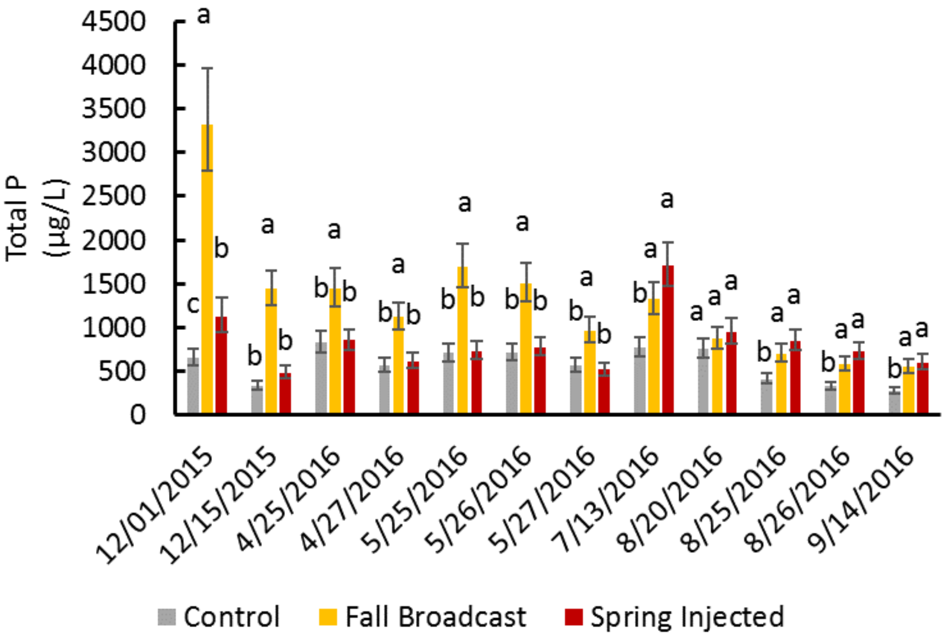

Figure 2.15. Impacts of P fertilizer management practice on total P concentration of surface runoff from precipitation events with more than 2.0 mm of runoff in 2016 cropping year. Letters represent differences between treatments within a runoff event at *p<0.05*.

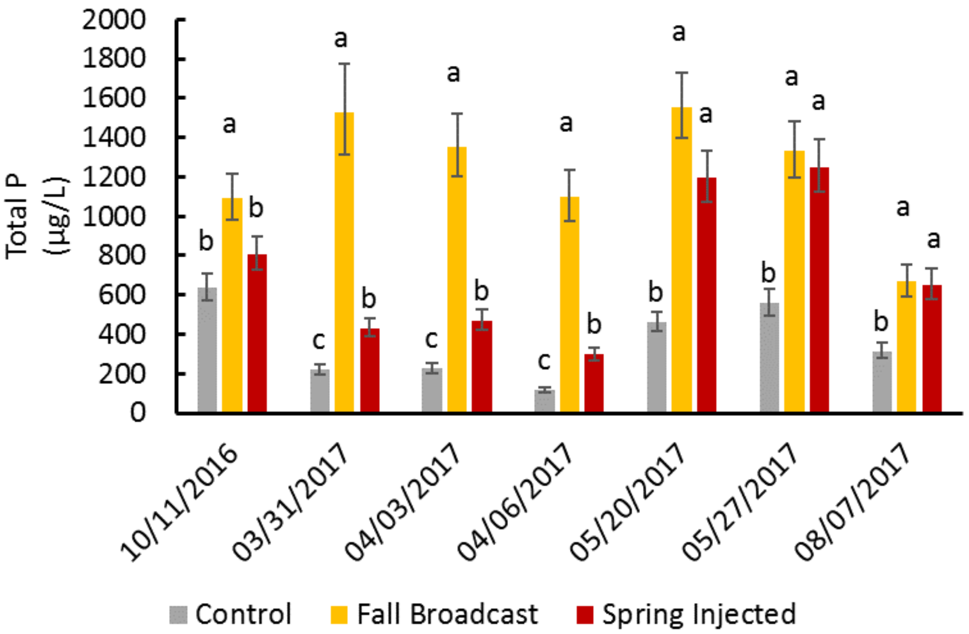

Figure 2.16. Impacts of P fertilizer management practice on total P concentration of surface runoff from precipitation events with more than 2.0 mm of runoff in 2017 cropping year. Letters represent differences between treatments within a runoff event at p<0.05.

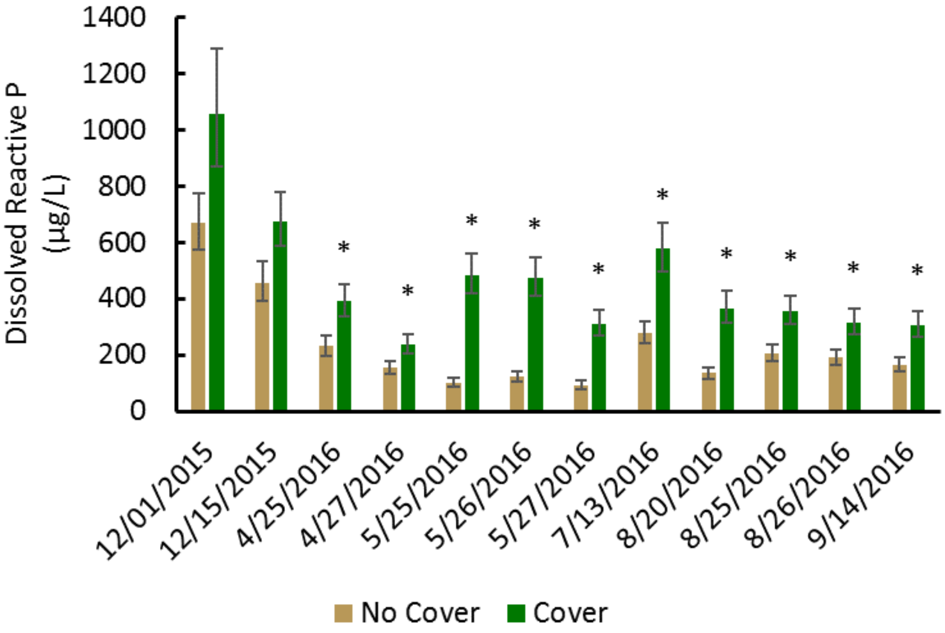

Figure 2.17. Effects of winter cover crops on dissolved reactive P concentration of surface runoff for precipitation events with more than 2.0mm of surface runoff in the 2016 cropping year. Asterisk indicates difference treatments within event at *p<0.05*.

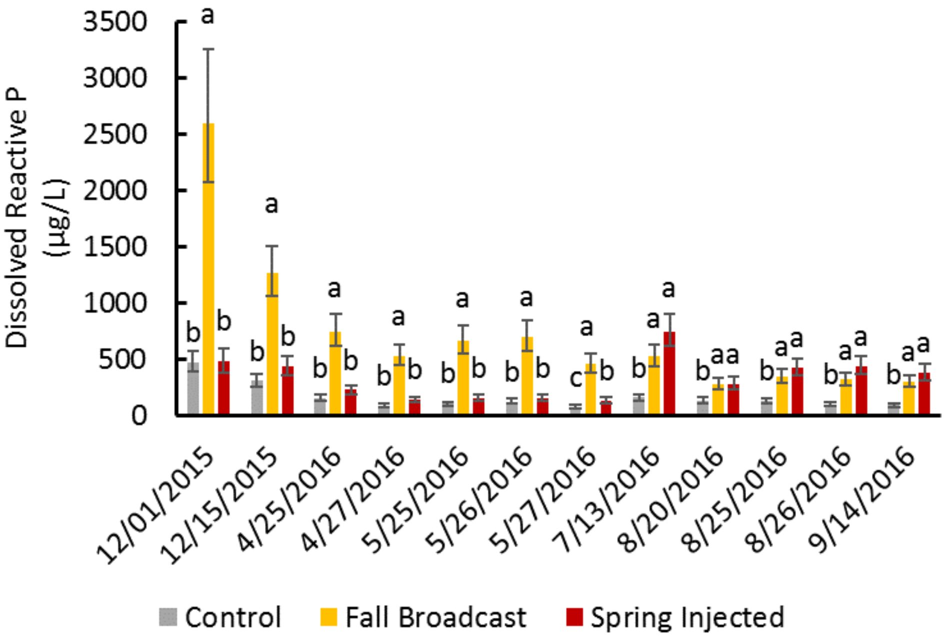

Figure 2.18. Fertilizer effects on dissolved reactive P concentration in surface runoff for events with more than 2.0 mm of runoff for the 2016 cropping year. Different letters indicate difference between treatment within event at *p<0.05*.

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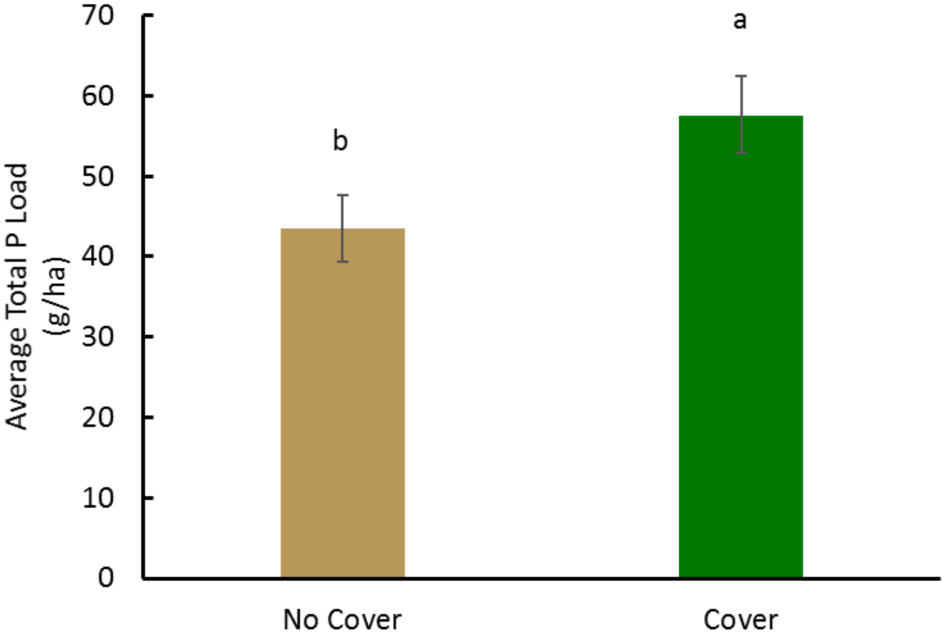


Figure 2.19. Main effect of cover crop on average total P load per runoff event for precipitations events with greater than 2.0 mm of surface runoff in 2017 cropping year. Letters indicates difference between treatments at *p<0.05*.

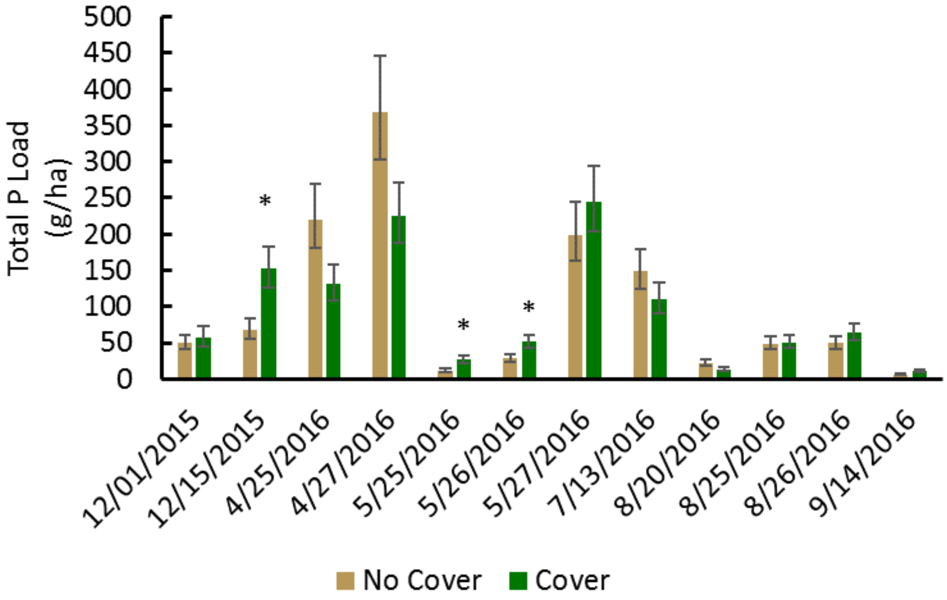


Figure 2.20. Event by cover interaction on total P load for precipitation events generating greater than 2.0 mm of surface runoff in 2016 cropping year. Asterisk indicates difference between treatments within an event at *p<0.05.*

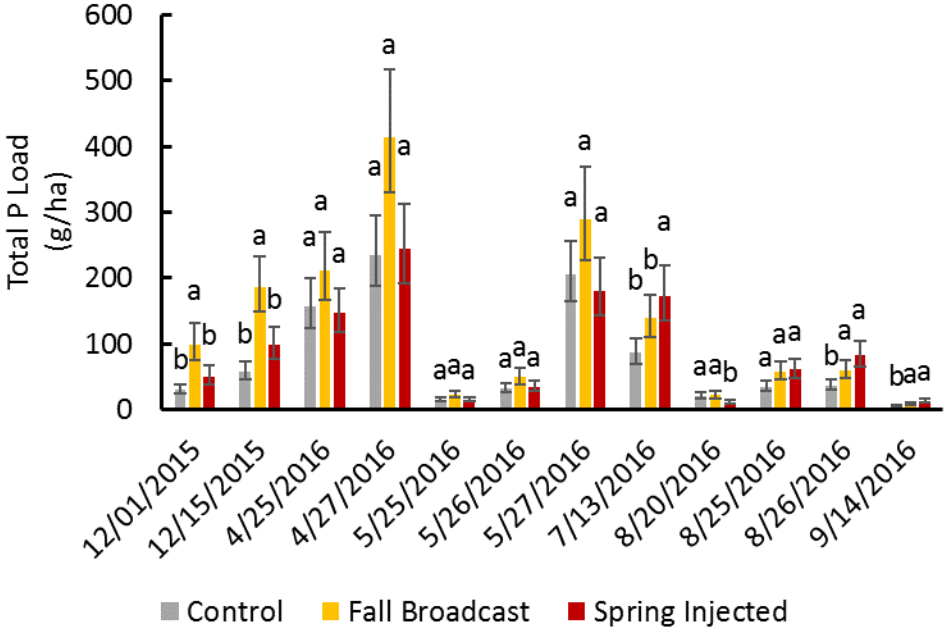


Figure 2.21. Fertilizer by event interaction for total P load in 2016 cropping year. Different letters indicate differences between treatments within a runoff event at *p<0.05.*

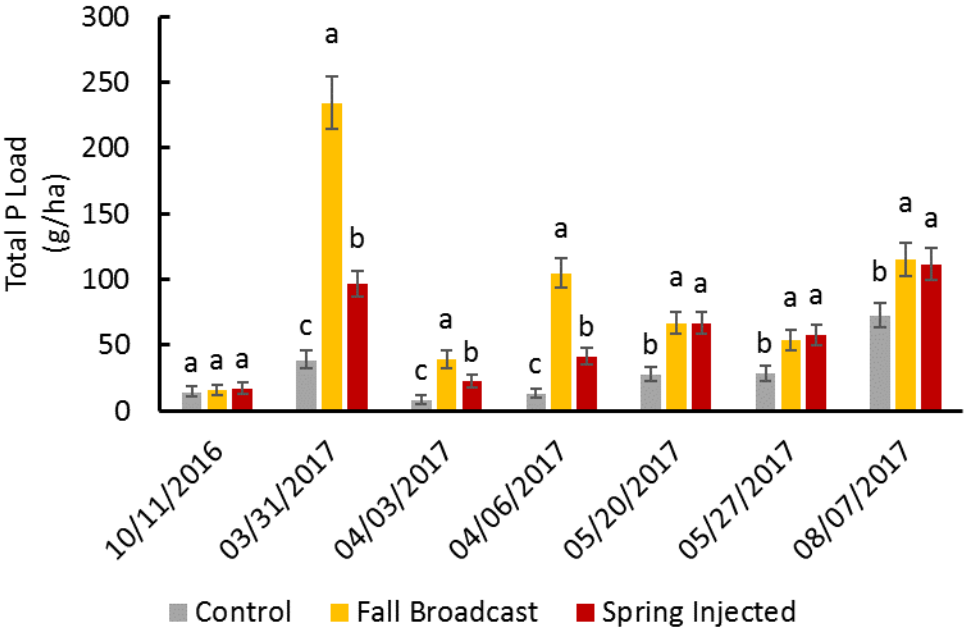


Figure 2.22. Fertilizer by event interaction for total P load in 2017 cropping year. Different letters indicate differences between treatments within a runoff event at *p<0.05*.

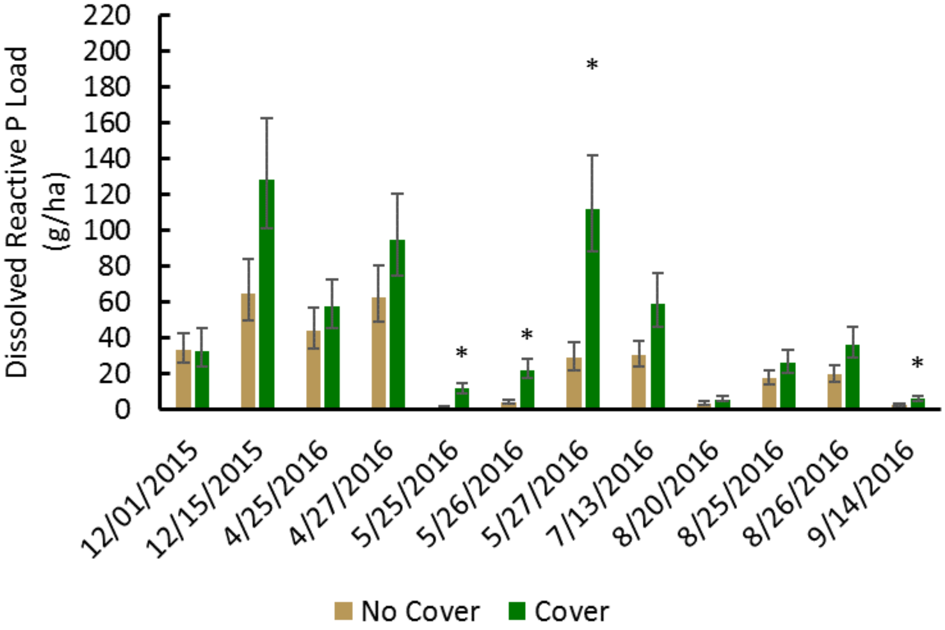


Figure 2.23. Cover crop by event interaction for dissolved reactive P load in surface runoff from precipitation events generating greater than 2.0 mm of surface runoff during the 2016 cropping year. Asterisk indicates difference between treatments within an event at *p<0.05*.

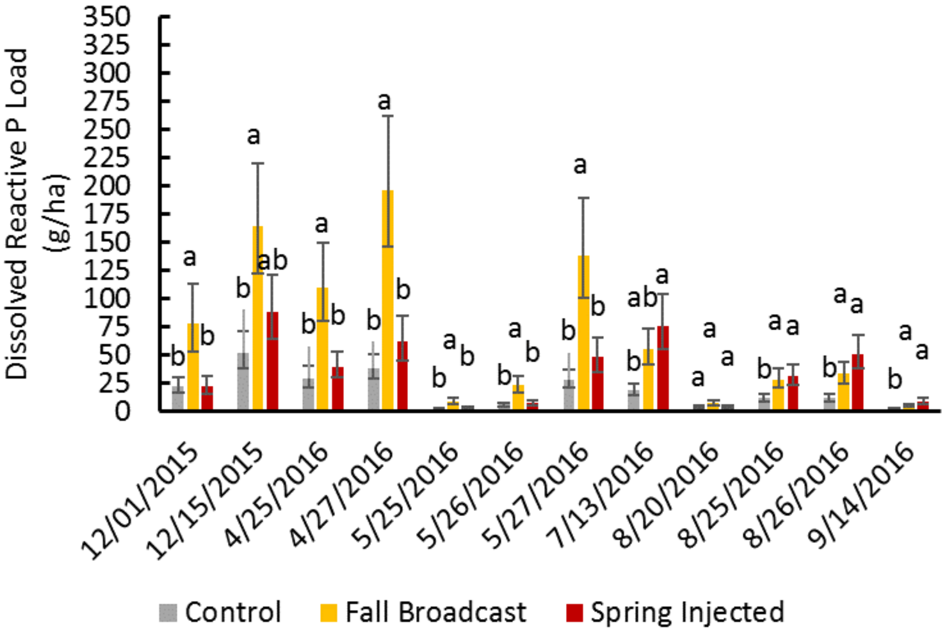


Figure 2.24. Event by fertilizer interaction on dissolved reactive P load for runoff events with greater than 2.0 mm of surface runoff in 2016 cropping year. Letters represent differences between treatments within an event at *p<0.05.*

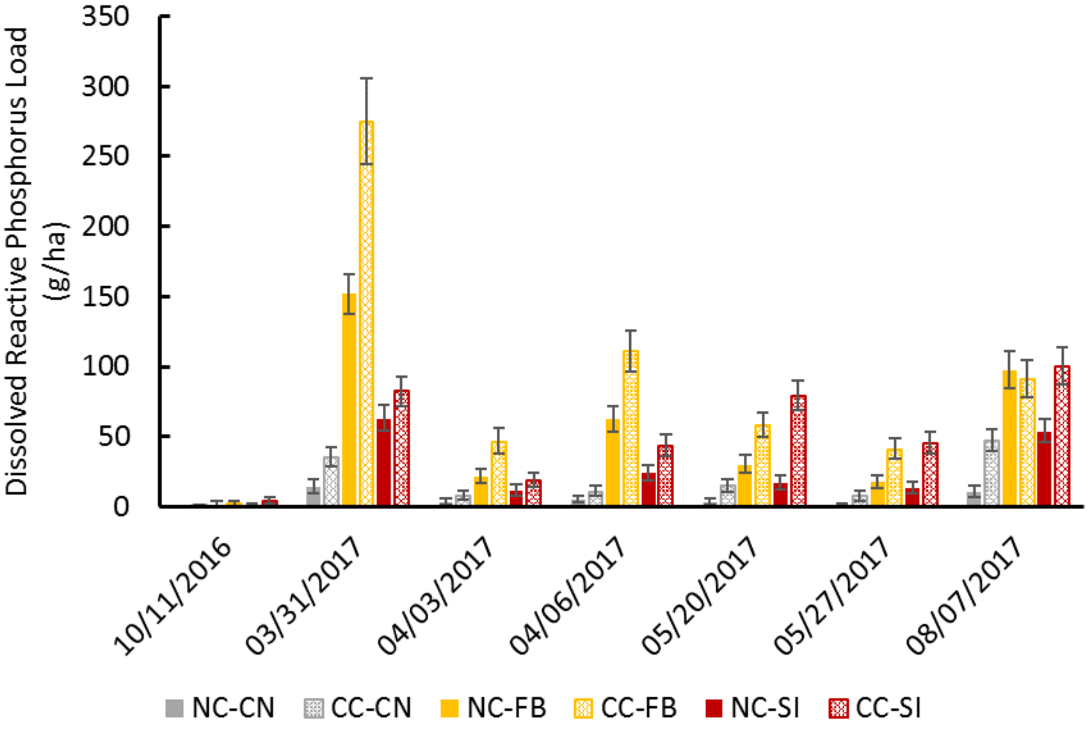


Figure 2.25. Cover by fertilizer by runoff event interaction for dissolved reactive phosphorus load in the 2017 cropping year. Statistical differences can be seen in Table 2.7.

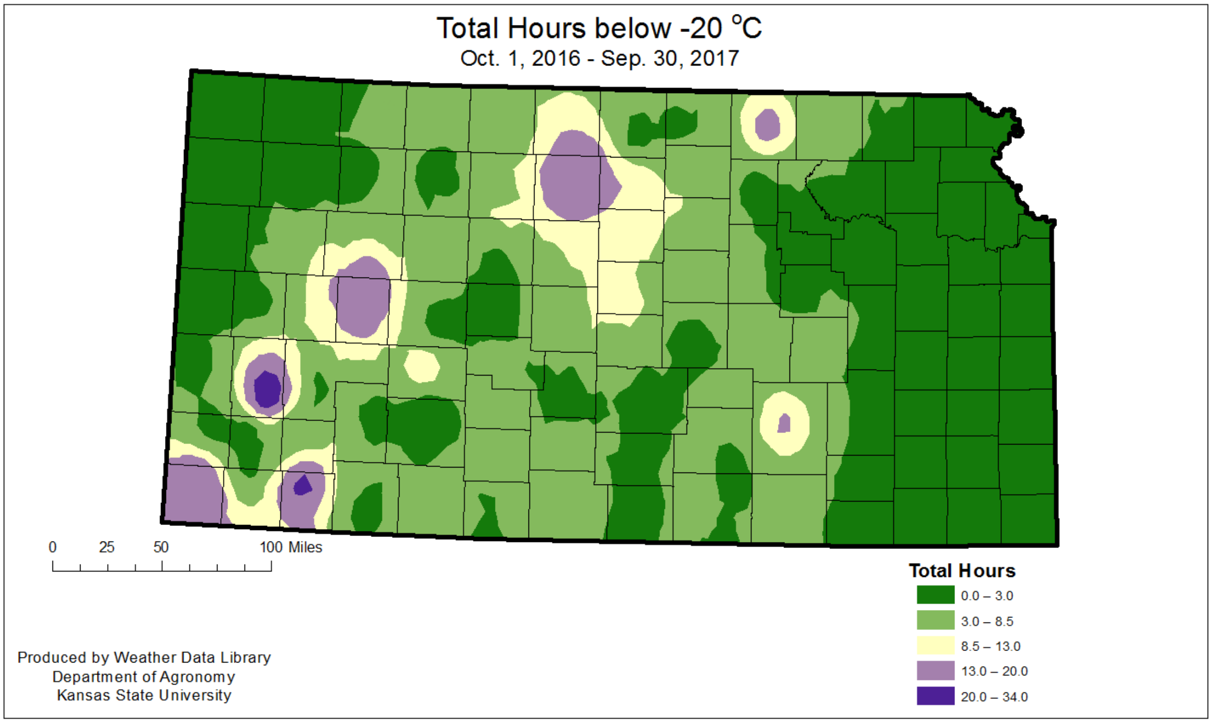


Figure 2.26. Cumulative hours below -20 °C across Kansas during the 2017 cropping year.

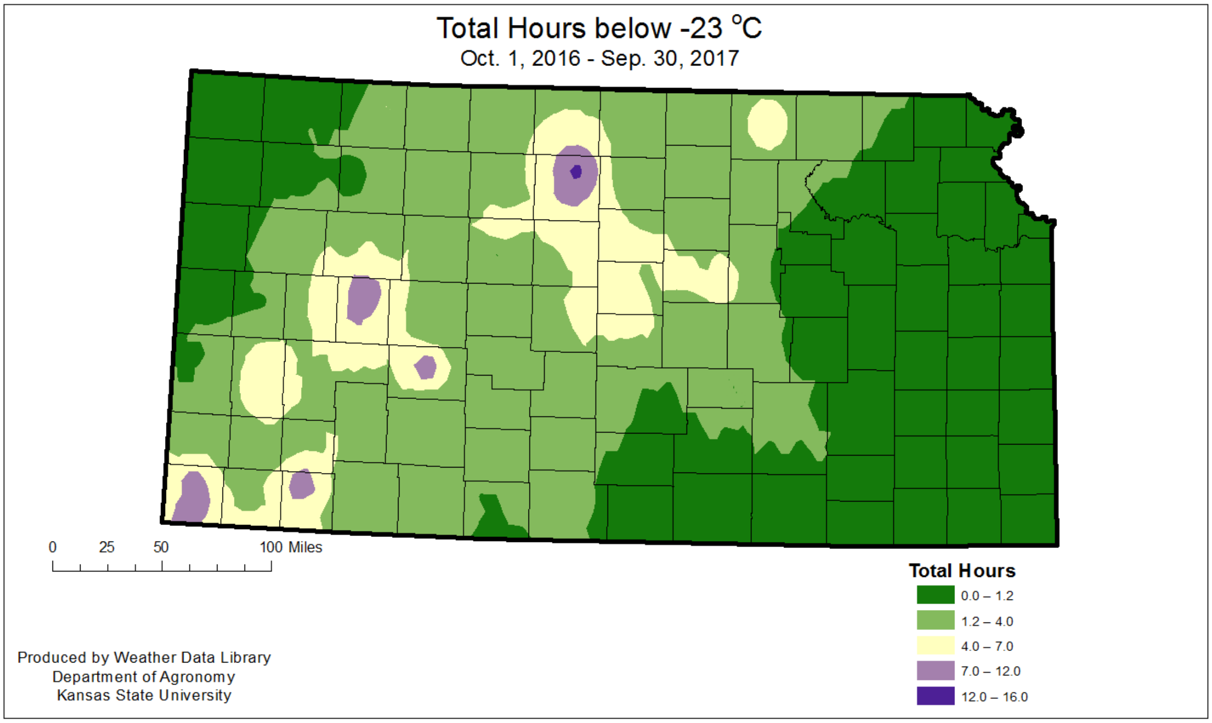


Figure 2.27. Cumulative hours below -23 °C across Kansas during the 2017 cropping year

Chapter 3 - Cover crop and phosphorus fertilizer management effects on nutrient uptake, removal, and deposition in a no-till corn-soybean rotation

Introduction

The combination of no-till, cover crops, and crop rotation serve as the foundation of conservation agriculture (Dubanski et al., 2006). When these practices are combined, the soil surfaces remains under a near constant organic layer that protects the soil from wind, precipitation, and sunlight (Hobbs et al., 2008). In addition to protecting the soil surface, benefits of cover crops include decreased erosion, reduced weed pressure, and greater water infiltration (Dabney et al., 2001). Cover crops may also potentially reduce P losses and increase P cycling efficiency through the accumulation of P in plant tissue during normally fallow periods (Maltis-Landry & Frossard, 2015; Bechmann et al., 2005).

Cover crops can accumulate significant amounts of nutrients during their lifecycle and as the cover crop decomposes, the accumulated nutrients are released at the soil surface, providing a potential nutrient source for subsequent crops (Calegari et al., 2013). Research suggest that when cover crops decompose, nutrient availability, such as P, can increase (Maltis-Landry & Frossard, 2015). Since cover crops are terminated in the field and not harvested, it is important to determine the impact they may have nutrient cycling and soil test levels (Hartwig & Ammon, 2002).

While understanding the impacts of cover crops on nutrient cycling can help provide better justification for new agricultural best management practices (BMP), it is also important to understand how fertilizer placement and timing of application affects cycling as well.

Phosphorus fertilizer placement and timing of application play a key role in 4R nutrient stewardship (right place, right time, right source, and right rate), and current BMPs recommend sub-surface application of fertilizer close to planting (springtime). However, in Kansas, seasonal rainfall trends suggest the optimal time for P fertilizer application would be in the fall (Figure 2.3). Mallarino et al. (2009) stated that fall broadcast application of P fertilizer offers advantages to producers in several ways including typically lower fertilizer prices, increased availability of equipment/labor, and lack of interference with other field operations. Since each P fertilizer management practice appears to offer its own advantages, differences in the effects of P fertilizer application method and timing on nutrient cycling and soil test P levels need to be determined. In addition, more information about the interactions between cover crops and P fertilizer management is needed to help develop new agricultural BMPs.

The objective of this study was to compare the impact of two winter cover crop (no cover and with cover crop) and three phosphorus (P) fertilizer management practices (no phosphorus fertilizer, fall broadcast, and spring injected) on nutrient uptake, removal, and surface deposition. This study also aimed to quantify effect of agricultural management strategy on soil test levels of P.

Materials and Methods

This study was conducted at the Kansas Agricultural Watershed (KAW) field laboratory in conjunction with the experiment described in Chapter 2. Experimental design and sampling equipment is identical across both studies. Full details on field site, cropping systems, and treatments can be found in Chapter 2. The following methods highlight any specifics pertaining to this study that differ from the study discussed in Chapter 2. This study includes data from the

2015 cropping year at the KAW. Full details on field operations for the 2015 cropping year can be found in Abel (2016).

2016 Cropping Year

On September 19, 2016, when soybeans were at the R6 development stage, whole plant (all above ground tissue) biomass samples were harvested. Biomass samples were collect from each of the three sub-plot locations (Figure 2.2). To perform biomass collection, 1 m of row (0.5 m to each side of GPS marked sub-plot location) of soybean plants where clipped at ground level. The total weight of plants in 1 m of row was recorded and a sub-sample of six plants was randomly collected. The six sub-samples were weighed independently and placed in a 60℃ forced-air oven for several days. Dry tissue weight was recorded and then the samples were ground using a Wiley mill. A sub-sample of ground tissue was collected and submitted to the K-State Soil Testing Lab for analysis of N, P, potassium (K), calcium (Ca), magnesium (Mg), sulfate-sulfur (SO_4^{-2}), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn).

A plot combine was used to harvest 2-rows across each plot (north to south) on October 17, 2016. Using real time kinematic (RTK) positioning, the exact distance the plot combine traveled was measured. The weigh bin was dumped three times per plot and grain weight was recorded. A sub-sample of grain was collected each time the weigh bin was dumped. Grain samples were ground using a Rancilio Rocky Doserless Coffee Grinder and submitted to the K-State Soil Testing Lab for nutrient analysis of N, P, potassium (K), calcium (Ca), magnesium (Mg), sulfate-sulfur (SO_4^{-2}), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn)..

2017 Cropping Year

Corn ears and stalks were hand harvested from block 1 on September 7, 2017. At this time all plots were at black layer (black layer first identified on 8/31/17). Blocks 2 and 3 were harvested on September 8, 2017.

All ears were harvested from two, 9.1-m sections of row at each sub-plot location within each plot and placed into a labeled burlap sack to be processed later. Ten stalks from each sub-plot location were cut at ground level and weighed to the nearest 0.01 kg. The stalks were then run through a wood chipper and a 200-300 g sub-sample was collected and weighed to the nearest 0.1 g. Shredded stalk samples were placed in a 60°C forced-air oven to dry. Samples were dried for four days. After four days, dry weights were recorded and the samples were then ground using a Wiley mill. A sub-sample of stalk tissue was collected and submitted to the K-State Soil Testing Lab for analysis.

Corn ears where shelled using an Ear Corn Sheller (ALMACO, Nevada, Iowa) and approximately 150-200 g of grain was sub-sampled to be ground for nutrient analysis. Wet weight of whole ears, wet weight of grain, % moisture, test weight, and weight of four cobs were all recorded. After shelling, grain samples were ground using a Rancilio Rocky Doserless Coffee Grinder (Villastanza di Parabiago, Milan, Italy) and submitted to the Kansas State University Soil Testing Lab for nutrient analysis. In addition, the sub-sample of four shelled corncobs were dried at 60 °C and then ground using a Wiley mill.

Grain, stalk, and cob samples were analyzed for N, P, potassium (K), calcium (Ca), magnesium (Mg), sulfate-sulfur (SO_4^{-2}), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn).

Soil Sampling

Soil samples were collected each year after harvest of the main cash crop and prior to fertilizer application. Soil samples were collected following the procedure outlined in Chapter 2. Collection dates for both 2016 and 2017 cropping year are also found in Chapter 2. Samples for the 2018 cropping year were collected between October 31, 2017-November 7, 2017. All soil samples were analyzed for pH, buffer pH, Melich-3 P, potassium (K), nitrate-nitrogen (NO_3^--N), total P, and total carbon. Chemical soil analysis for pH, buffer pH, Melich-3 P, K, and NO_3^--N was performed according to standard soil testing methods (Peters et al., 2012; Geldermann & Beegle, 1998; Warncke &Denning, 1998). Total carbon and total P were measured using a LECO TruSpec CN combustion analyzer (LECO, 2005).

Changes in soil test nutrient levels were determined by examining the difference between the most recent (2018 cropping year) and the initial soil test levels (2015 cropping year). A positive value for change in nutrient level indicates an increase in the soil test level while a negative value for change in nutrient level indicates a decrease in the soil test level.

Plant Tissue Analysis

Concentrations of N, P, and K in the plant tissue, cobs, and grain were analyzed by sulfuric peroxide digest (Linder & Harley, 1942; Thomas et al., 1967). The digest containing ammonia was analyzed via the indophenol blue colorimetric procedure on a RFA-300 Rapid Flow Analyzer (RFA Methodology No. A303-S072). Phosphorus and K concentrations were measured using an inductively coupled plasma (ICP) spectrometer (Model 720-ES ICP Optical Emission Spectrometer).

A perchloric digest, as outlined by Gieseking et al. (1935) was used for Ca, Mg, SO_4^{-2}, Cu, Fe, Mn, and Zn. Concentrations of Ca, Mg, SO_4^{-2}, Cu, Fe, Mn, and Zn were measured using the same Model 720-ES ICP Optical Emission Spectrometer as for the N, P, and K analysis.

Calculations for Nutrient Uptake, Removal, and Deposition

All nutrient uptake, removal, and deposition values for P and K are elemental.

2016 Cropping Year: Soybeans

Nutrient uptake (α) was calculated based on whole plant biomass (β_w) collected from soybeans at the R6 development stage and nutrient content (μ_t) of the plant tissue (Equation 4.1). Whole plant biomass included all above ground tissue (stems, leaves, pods, and seeds). Nutrient removal (λ) is comprised of the quantity of nutrients taken out of the field with harvested grain (Equation 4.2). Where μ_g is the nutrient concentration in the grain and YIELD is grain yield (kg ha^{-1}). Nutrients returned to the soil surface with crop and cover crop residue, hereafter referred to as deposition (π), was calculated by determining the quantity of nutrient from crop biomass being deposited on the soil surface and adding the total nutrient uptake of the cover crop (ρ_{cc}) (Equation 4.3 & Equation 4.4).

$$\alpha = \beta_w \times \mu_t$$ **Equation 4.1.**

$$\lambda = YIELD\ x\ \mu_g$$ **Equation 4.2.**

$$\pi = (\alpha - \lambda) + \rho$$ **Equation 4.3.**

$$\rho_{cc} = \beta_{cc}\ x\ \mu_{cc}$$ **Equation 4.4**

2015 & 2017 Cropping Years: Corn

Calculations for nutrient uptake were similar from 2015 and 2017 compared to the 2016 cropping year; however, slight differences in biomass collection occurred due to the difference in crop species being grown. For corn, above ground biomass was separated into two portions: stalks (β_s) and cobs (β_c). To calculated total nutrient uptake the sum of nutrient uptake in the stalks, cobs, and grain was calculated (Equation 4.5). As with soybeans, the quantity of nutrient removed was determined by Equation 4.2. Nutrient deposition was also determined by adding the nutrient uptake of stalks, cobs, and cover crop (Equation 4.6)

$$\alpha = (\beta_s\ x\ \mu_s) + (\beta_c\ x\ \mu_c) + (YIELD\ x\ \mu_g)$$ **Equation 4.5.**

$$\pi = (\beta_s\ x\ \mu_s) + (\beta_c\ x\ \mu_c) + \left(YIELD\ x\ \mu_g\right) + \ \rho$$ **Equation 4.6.**

Cumulative Nutrient Removal and Deposition

Cumulative nutrient removal ($\lambda_{\text{cumulative}}$), and deposition ($\pi_{\text{cumulative}}$) was determined by summing the respective values for the 2015, 2016, and 2017 cropping years (Equation 4.7 and Equation 4.8).

$$\lambda_{cumulative} = \ \lambda_{2015} + \lambda_{2016} + \lambda_{2017}$$ **Equation 4.7.**

$$\pi_{cumulative} = \ \pi_{2015} + \pi_{2016} + \pi_{2017}$$ **Equation 4.8.**

For cumulative nutrient cycling, all data from plot 305 (spring injected with cover crop) for the 2015 cropping year was missing. To account for this, average nutrient uptake, removal, and deposition from plots 105 and 201 (both spring injected with cover crop) was calculated and used as the nutrient cycling values for plot 305 during the 2015 cropping year.

Statistical Analysis

Nutrient uptake, removal, and deposition data were statistically analyzed in SAS version 9.4 using a PROC GLIMMIX procedure with repeated measures analysis of variance to examine treatment effects. Soil test data also were analyzed in SAS using a PROC GLIMMIX procedure with repeated measures analysis of variance where year was treated as a sub-plot and depth was treated as a sub-sub-plot. Treating year and depth in such manner was done to not over specify the replication in the design.

For the soil test data, both Melich-3 P and NO_3^--N required natural logarithm transformation to satisfy the assumption of normal distribution. All interpretations of these data are depicted as back-transformed means.

Error bars on graphs represent standard error. For non-transformed data, standard error of the mean was calculated using SAS version 9.4. Standard error the transformed soils data were calculated using Equation 4.9, where $s.e.(\hat{\mu}^*)$ represents the standard error of the back-transformed mean and $\hat{\mu}$ represents the transformed mean. Complete means of all soil test data can be seen in Appendix B.

$$s.e.(\hat{\mu}^*) = \exp(\hat{\mu})\ x\ s.e.(\hat{\mu}) \qquad \textbf{Equation 4.9.}$$

Results

Biomass and Yield

In 2016, a main effect of P fertilizer management practice was found with the fall broadcast (FB) application of P fertilizer increased soybean yield by 12% or 475 kg/ha compared to the non-fertilized control (CN) (Table 3.1; Figure 3.1). The spring injected (SI) yield was similar to the FB; however, yields in the SI plots were not different when compared to the CN (Figure 3.1).

For the 2017 cropping year, cover crop (CC) reduced corn biomass by 36% compared to no cover crop (NC) (Table 3.2 & Figure 3.2). A decrease in corncob biomass was also found for the CC plots with the CC plots producing 26% less cob biomass compared to the NC (Figure 3.2). Similar trends were seen with corn grain production where CC plots produced 39% less corn grain compared to the NC plots (Table 3.1 & Figure 3.2.)

Variable impacts of P fertilizer management practice on cover crop biomass production were observed across both 2016 and 2017 cropping years (Table 3.1). In 2016, no impact of P fertilizer was observed, but in 2017, the SI treatment had the most amount of cover crop biomass produced compared to both FB and CN (Figure 3.3).

Nutrient Uptake

A main effect of P fertilizer application was found for both 2016 and 2017 cropping years for P uptake (Table 3.2). In both cropping years, the application of P fertilizer, regardless of application method, caused greater P uptake by the main crop (Figure 3.4). For 2016, P uptake increased an average of 22% compared to the CN when P fertilizer is applied, and in 2017, P uptake increased an average of 39% when P fertilizer was applied.

In 2017, a main effect of cover was observed for the uptake of nitrogen (N), phosphorus (P), and potassium (K) (Table 3.2). The CC plots accumulated 35% less N, 25% less P, and 35% less K compared to the NC plots (Figure 3.5).

Nutrient Removal

Across both 2016 and 2017 cropping years, P fertilizer application significantly affected N, P, and K removal (Table 3.3). For both 2016 and 2017, applying P fertilizer (regardless of application method) increased P removal in the harvested crop grain (Figure 3.6). The application of P fertilizer caused a 25% and 37% increase in P being removed with the grain in 2016 and 2017, respectively (Figure 3.6). In 2016, the SI application of P fertilizer increased N removal by 13% compared to the control (Figure 3.7) The FB application of P fertilizer in 2016 resulted in N removal that was the same as SI but not different compared to the CN. For the 2017 cropping year, application of P fertilizer increased N removal from the field by 20% compared to the CN (Figure 3.7). The application of P fertilizer, regardless of application method, also increased K removal in the 2016 and 2017 cropping years at 16% and 26%, respectively (Figure 3.8).

In the 2017 cropping year, a main effect of cover was found on the removal of N, P, and K (Table 3.3). For all three nutrients (N, P, and K), the CC plots had roughly 20% less removal compared to the NC plots (Figure 3.9).

When examining cumulative nutrient removal (2015, 2016, and 2017 cropping years), a main effect of P fertilizer application was found for both cumulative P and K removal (Table 3.4). The application of P fertilizer increased cumulative P removal an average of 17% compared to the CN (Figure 3.10). In addition, applying P fertilizer increase K removal an average of 13% compared to the CN (Figure 3.11).

Nutrient Deposition

In both 2016 and 2017 cropping years, a main effect of cover crop on nutrient deposition was found to be significant (Table 3.5). For 2016, cover crops increased deposition of P on the soil surface with the CC plots having 33% greater P deposition (approximately 3.5 kg/ha additional P) compared to the NC (Figure 3.12). Although cover crop increased P deposition in

2016, the use of a cover crop decreased N and K deposition in 2017 by 14% and 11%, respectively (Figure 3.13).

A main effect of cover crop on cumulative nitrogen deposition was found in this study (Table 3.4). Cumulatively, the CC plots had 52 kg/ha less N deposited on the soil surface compared to the NC plots (Figure 3.14). Overall, the use of a cover crop decreased nitrogen deposition by 13% versus the NC plots.

Soil Test Levels

A fertilizer application method by year interaction was found for Melich-3 phosphorus (M3P) concentration in the soil (Table 3.6). In general, the application of P fertilizer resulted in higher M3P soil test levels with the 2016 SI plots having to greatest M3P soil test level and the 2017 control being the lowest (Figure 3.15). In 2015, the addition of P fertilizer had no effect on raising M3P soil test concentrations; however, in both 2016 and 2017, adding P fertilizer increased M3P soil test concentrations. A fertilizer by depth interaction was also found (Table 3.6). Fertilizer management practice had no impact on M3P soil test levels at the 5-15 cm depth; however, at the 0-5 cm depth, both FB and SI increased soil test P levels over the control (Figure 3.16). On average, the application of P fertilizer increase M3P soil test levels of the 0-5 cm samples by 150% compared to the CN (Figure 3.16).

A fertilizer application method by depth interaction was also found for total P (Table 3.6). Similar stratification trends were found for total P with respect to depth as were found for M3P (Figure 3.17). Both FB and SI application methods of P fertilizer increased total P concentration of the surface sample compared to the control, and no differences were found between the sub-surface samples (Figure 3.17). In addition to the fertilizer by depth interaction, a year by depth interaction was found for total P (Table 3.6). The surface samples for all cropping years had a greater concentration of total P compared to the sub-surface samples (Figure 3.18).

A interaction between cover and cropping year was found for soil test NO_3^--N levels (Table 3.6). For 2015 and 2016, no differences between CC and NC were observed; however, in 2017, the NC plots had a greater NO_3^--N soil test level compared to the 2017 CC (Figure 3.19). A cover by depth interaction was also found for NO_3^--N soil test level (Table 3.6). The NC surface samples had a greater $NO3^-$-N concentration compared the CC surface and both NC and CC sub-surfaces samples (Figure 3.20). The CC surface samples were found to have the same NO_3^--N concentration as the NC subsurface samples (Figure 3.20).

A cover crop by depth interaction was found for total C (Table 3.6). Surface (0-5 cm) soil samples, regardless of cover, had a greater percentage of total C compared to the sub-surface (5-15 cm) samples (Figure 3.21). No effect of cover crop on total C was observed.

Discussion

During the 2017 cropping year, the CC plots consistently had lower levels of nutrient uptake, removal, and deposition on to the soil surface (Figure 3.5; Figure 3.9; Figure 3.13). This consistency in negative impact of cover crops on these parameters can be explained by the lower biomass (stalk and cob) and grain production of the CC plots during the 2017 cropping year (Figure 3.2).

Throughout the 2017 cropping year, CC plots seemed to lag behind the NC plots. Although not quantified, soil in the CC plots at planting appeared to be cooler and wetter than the NC plots resulting in visually uneven and slower germination. On June 26, 2017, plant height was recorded, and the CC plots were found to have shorter plants (Figure 3.22). In addition, on

July 6, 2017, percent of plants at R1 (silking) was measured, and the CC plots again had lower values compared to the NC plots (Figure 3.23). These findings confirm earlier visual observed differences in plant growth between CC and NC.

The negative impact of the CC treatment could possibly be linked to allelopathic effects of using triticale (*x Triticosecale* var. *TriCal 780*) as part of the cover crop treatment. Triticale is a hybrid grass resulting from a cross between rye (*Secale)* and wheat (*Triticum*) (Oelke et al., 1989). Studies using cereal rye as a cover crop have found that cereal rye residue is able to reduce weed pressure through the release of allelochemicals as residue decomposes (Barnes & Putnam, 1983; Akemo et. al, 2000). Research suggests the impact of allelochemicals is greater on plants with small seeds; therefore, "the large seed of corn and its relatively deep planting depth should minimize the impact of any chemicals released by the cover crop," yet negative impacts of rye on corn have still been observed (Hartzler, 2014). In addition to allelopathy, possible reasons behind the negative impact of rye-based cover crop residue could include tie up of nitrogen by decaying cover crop biomass, alteration of the soil environment that creates unfavorable conditions for corn growth, or decomposing cover crop residue may serve as a host for potential corn pathogens (Hartzler, 2014). Although cover crop soils had lower soil nitrate at the end of the 2017 cropping season (Figure 3.20), N stress was not observed in CC treatments during the 2017 growing year and the N application rate was more than adequate for the yield potential.

As the 2017 cropping year progressed, all plots experienced water stress, specifically during grain-fill, owing to a month-plus long drought (Figure 2.3). However, the CC plots exhibited greater visual drought stress. Unger and Vigil (1998) stated that cover crops deplete soil water levels as they are growing and can negatively impact yield of the subsequent crop if inadequate soil water recharge time is not provided. In semiarid regions, such as the Great Plains, dramatic yield reductions can occur as a result of water use by cover crops (Unger & Vigil, 1998). The drawdown of available soil water by the cover crop along with the drought during grain-fill could explain decreased yield and biomass production in the CC plots and therefore reduced the quantities of nutrient uptake, removal, and deposition.

Increased stratification of P (both Melich-3 P and total P) within the soil profile was observed as a result of adding P fertilizer (Figure 3.16 & Figure 3.17). As P fertilizer was added, regardless of placement (FB or SI), the concentration of Melich-3P and total P in the top 0-5 cm of soil increased. However, P fertilizer application did not affect Melich-3P or total P concentrations in the sub-surface (5-15 cm) samples (Figure 3.16 & Figure 3.17). The increased concentration of P in the surface samples is likely caused by the lack of soil mixing associated with no-tillage management. Costa et al. (2010) found similar trends in P stratification with the top 0-5 cm of soil having greater soil test P levels for soils under no-tillage management. However, these findings run contrary to Baker et al.'s (2017) findings which stated that sub-surface placement of P fertilizer will decrease P stratification compared to surface broadcast application of P fertilizer.

Conclusions

Overall, this study found the use of a cover crop had an inconsistent effect on nutrient uptake, removal, and deposition, increasing these variables in some years and decreasing them in others. Findings from this study detail the importance of crop biomass and grain production when assessing nutrient cycling. As seen in the 2017 cropping year, cover crops may negatively affect nutrient cycling when main crops are grown during years with low or infrequent rainfall. While benefits of cover crops on erosion, weed pressure, and water infiltration have been established, results from this study are inconclusive as to how cover crops impact nutrient cycling. An additional cycle through the crop rotation is needed to determine how cover crops impact nutrient cycling before new BMPs can be developed.

The application of P fertilizer, regardless of application methods, caused an increase in soil test P levels (both M3P and total P) compared to the control. However, P fertilizer application method did not influence the stratification of P within the soil profile, i.e., no differences between FB and SI were observed for soil test P levels in either the 0-5 cm or 5-15 cm samples.

References

Abel, D. 2016. Cover crops and fertilizer management impacts on water quality and cover crop effect on soil moisture. Master's of Science. Kansas State University, Manhattan, KS.

Akemo, M.C., E.E. Regnier, and M.A. Bennett. 2000. Weed suppression in spring-sown rye (*Secale cereal)*-pea (*Pisum sativum)* cover crop mixes. Weed Technol. 14:545-549.

Alpkem Corporation. 1986a. RFA methodology. Rep. A303-S072. Clackamas, OR 97015.

Baker, D.B, L.T. Johnson, R.B. Confesor, and J.P. Crumrine. 2017. Vertical stratification of soil phosphorus as a concern from dissolved phosphorus runoff in the Lake Erie basin. J. Environ. Qual. 46:1287-1295.

Barnes, J.P and A.R. Putnam. 1983. Rye residues contribute to weed suppression in no-tillage cropping systems. J. Chem. Ecol. 9:1045-1057.

Bechmann, M.E., P.J.A. Kleinman, A.N. Sharpley and L.S. Saporito. 2005. Freeze-thaw effects on phosphorus loss in runoff from manured and catch-cropped soils. J. Environ. Qual. 34:2301-2309.

Calegari, A., T. Tiecher, W.L. Hargrove, R. Ralisch, D. Tessier, S. Tourdonnet, M.F. Guimaraes, and D.R. Santos. 2013. Long-term effect of different soil management systems and winter crops on soil acidity and vertical distribution of nutrients in a Brazilian Oxisol. Soil & Tillage Research. 133:32–39.

Costa, S.E.V.G.A., E.D. Souza, I. Anghnomi, J.P.C. Flores, F.C.B. Viera, A.P. Martins, and E.V.O. Ferreira. 2010. Patterns in phosphorus and corn root distribution and yield in long-term tillage systems with fertilizer applications. Soil and Tillage Research. 109:41-49.

Dabney, S., J. Delgado and D. Reeves. 2001. Using winter cover crops to improve soil and water quality. Commun. Soil Sci. Plant Anal. 32:1221-1250.

Dumanski, J., R. Pieretti, J.R. Benites, D. McGarry, and C. Pieri. 2006. The paradignm of conservation agriculture. Proc. World Assoc. Soil and Water Conserv. P1:58-64.

Frank , K., D. Beegle, and J. Denning. 1998. Phosphorus. pp. 21-26 in: J.R. Brown (ed.) Recommended chemical soil test procedures for North Central Region. North Central Reg. Res. Publ. 221 (Rev.). SB 1001. Missouri Agric. Exp. Stn. Columbia.

Geldermann, R.H. and D. Beegle. 1998. Nitrate-nitrogen pp. 23-25 in: J.R. Brown (ed.) Recommended chemical soil test procedures for North Central Region. North Central Reg. Res. Publ. 221 (Rev.). SB 1001. Missouri Agric. Exp. Stn. Columbia.

Hartwig, N. and H. Ammon. 2002. 50th anniversary - invited article - cover crops and living mulches. Weed Sci. 50:688-699.

Hartlzer, B. 2014. Cereal rye cover crops, allelopathy and corn. Iowa State University. 05-05-2018. https://crops.extension.iastate.edu/cropnews/2014/04/cereal-rye-cover-crops-allelopathy-and-corn

Hobbs, P.R., K. Sayre and R. Gupta. 2008. The role of conservation agriculture in sustainable agriculture. Food and Agriculture Organization of the United Nations 369:543–555.

LECO Corporations. 2005. Carbon and nitrogen in soil and sediment. St. Joseph, MI.

Mallarino, A.P., S.R. Barcos, J.R. Prater, and D.J Wittry. 2009. Timing of broadcast phosphorus fertilizers for no-till corn and soybeans. Soi Sci. Soc. Am. J. 73:2143-2150.

Maltais-Landry, G. and E. Frossard. 2015. Similar phosphorus transfer from cover crop residues and water-soluble mineral fertilizer to soils and a subsequent crop. Plant Soil 393:193-205.

Oelke, E.A., E.S. Oplinger and M.A. Brinkman. 1989. Triticale. *In* Alternative field crops. University of Wisconsin Cooperative Extension.

Peters, J., M. Nathan, and C. Laboski. 2012. pH and lime requirments. pp. 18-21 in: J.R. Brown (ed.) Recommended chemical soil test procedures for North Central Region. North Central Reg. Res. Publ. 221 (Rev.). SB 1001. Missouri Agric. Exp. Stn. Columbia.

Warncke, D. and J. Denning. 1998. Potassium and other basic cations. pp. 36-38 in: J.R. Brown (ed.) Recommended chemical soil test procedures for North Central Region. North Central Reg. Res. Publ. 221 (Rev.). SB 1001. Missouri Agric. Exp. Stn. Columbia.

Table 3.1. ANOVA table showing *p-values* for 2016 soybean grain yield and biomass production, and 2017 corn yield and biomass production. Table abbreviations include: Stalk (stalk biomass), Cob (cob biomass), Cover (cover crop) and Fert (fertilizer management practice).

	2016			2017			
	Soybean Yield	Soybean Biomass	Cover Crop Biomass	Corn Yield	Corn Stalk	Corn Cob	Cover Crop Biomass
Fert	0.040	0.265	0.272	0.183	0.146	0.546	0.008
Cover	0.833	0.961	N/A	0.002	<0.001	0.005	N/A
Fert*Cover	0.656	0.886	N/A	0.954	0.724	0.671	N/A

Table 3.2. ANOVA table depicting *p-values* for nutrient uptake in both 2016 (soybean) and 2017 (corn) cropping years. Table abbreviations include: Fert (fertilizer management practice), cover (cover crop), N (nitrogen), P (phosphorus), and K (potassium).

	2016			2017		
	Soybean N Uptake	Soybean P Uptake	Soybean K Uptake	Corn N Uptake	Corn P Uptake	Corn K Uptake
Fert	0.2934	0.020	0.180	0.149	0.015	0.365
Cover	0.493	0.572	0.662	<0.001	0.020	0.000
Fert*Cover	0.941	0.649	0.754	0.770	0.419	0.958

Table 3.3. ANOVA table showing *p-values* for nutrient removal in both 2016 and 2017 cropping years. Table abbreviations include: N (nitrogen), P (phosphorus), K (potassium) Cover (cover crop) and Fert (fertilizer management practice).

	2016			2017		
	Soybean N Removal	Soybean P Removal	Soybean K Removal	Corn N Removal	Corn P Removal	Corn K removal
Fert	0.042	0.001	0.005	0.046	0.007	0.015
Cover	0.628	0.443	0.410	0.002	0.014	0.008
Fert*Cover	0.867	0.701	0.731	0.947	0.744	0.498

Table 3.4. ANOVA table showing *p-values* for cumulative nutrient removal across 2015, 2016 and 2017 cropping years. Table abbreviations include: N (nitrogen), P (phosphorus), K (potassium), Fert (fertilizer management practice), Cover (cover crop).

	N Removal	N Deposition	P Removal	P Deposition	K Removal	K Deposition
Fert	0.055	0.409	0.005	0.124	0.007	0.472
Cover	0.139	0.026	0.330	0.646	0.841	0.228
Fert*Cover	0.714	0.894	0.952	0.544	0.978	0.815

Table 3.5. ANOVA table showing *p-values* for nutrient deposition in both 2016 and 2017 cropping years. Table abbreviations include: N (nitrogen), P (phosphorus), K (potassium) Cover (cover crop) and Fert (fertilizer management practice).

	2016			2017		
	Soybean N Deposition	Soybean P Deposition	Soybean K Deposition	Corn N Deposition	Corn P Deposition	Corn K Deposition
Fert	0.326	0.455	0.401	0.321	0.017	0.164
Cover	0.370	0.042	0.011	0.013	0.718	0.032
Fert*Cover	0.981	0.730	0.470	0.838	0.310	0.818

Table 3.6. ANOVA table for soil test data across 2015, 2016 and 2017 cropping years. Table abbreviations include: M3P (Melich-3 Phosphorus), NO3 (Nitrate-Nitrogen), K (Potassium), TP (Total Phosphorus), TC (Total Carbon), and Fert (Fertilizer Management Practice).

	pH	M3P	NO3	K	TP	TC
Fert	0.158	0.001	0.571	0.604	0.012	0.630
Cover	0.163	0.288	0.003	0.242	0.519	0.431
Fert*Cover	0.658	0.551	0.752	0.928	0.222	0.318
Year	<0.001	0.041	<0.001	<0.001	0.012	0.315
Fert*Year	0.182	0.048	0.473	0.133	0.769	0.325
Cover*Year	0.027	0.319	0.007	0.117	0.212	0.598
Fert*Cover*Year	0.222	0.740	0.642	0.527	0.963	0.051
Depth	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Fert*Depth	0.651	<0.001	0.380	0.371	0.001	0.805
Cover*Depth	0.089	0.948	0.035	0.381	0.993	0.001
Fert*Cover*Depth	0.942	0.501	0.616	0.171	0.284	0.263
Year*Depth	0.054	0.156	<0.001	<0.001	0.023	0.119
Fert*Year*Depth	0.807	0.750	0.817	0.848	0.506	0.209
Cover*Year*Depth	0.537	0.714	0.091	0.771	0.582	0.347
Fert*Cover*Year*Depth	0.140	0.962	0.557	0.709	0.680	0.639

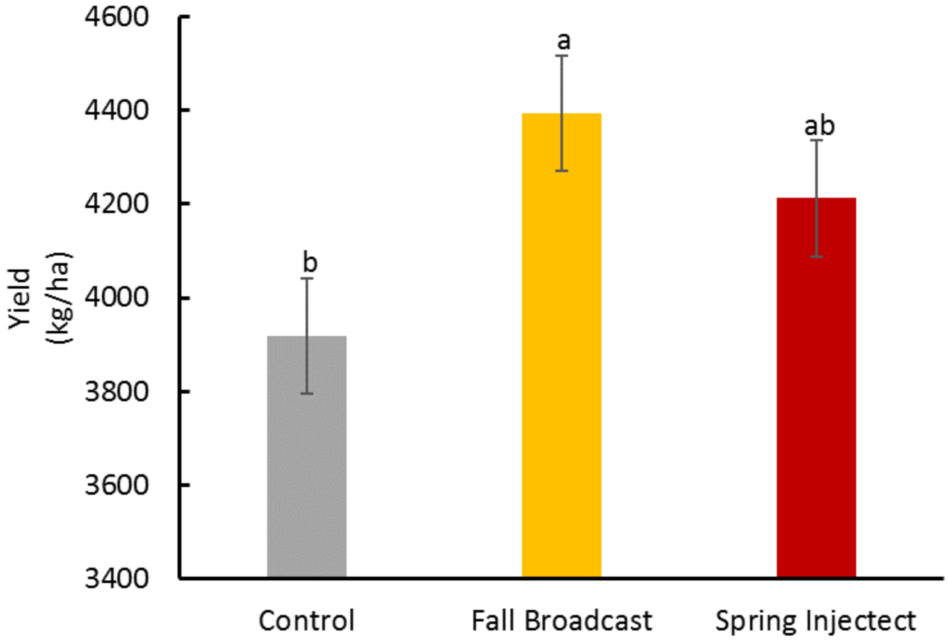


Figure 3.1. Main effect of fertilizer management practice on soybean grain yield in the 2016 cropping year. Letters indicate differences between treatments at *p<0.05*.

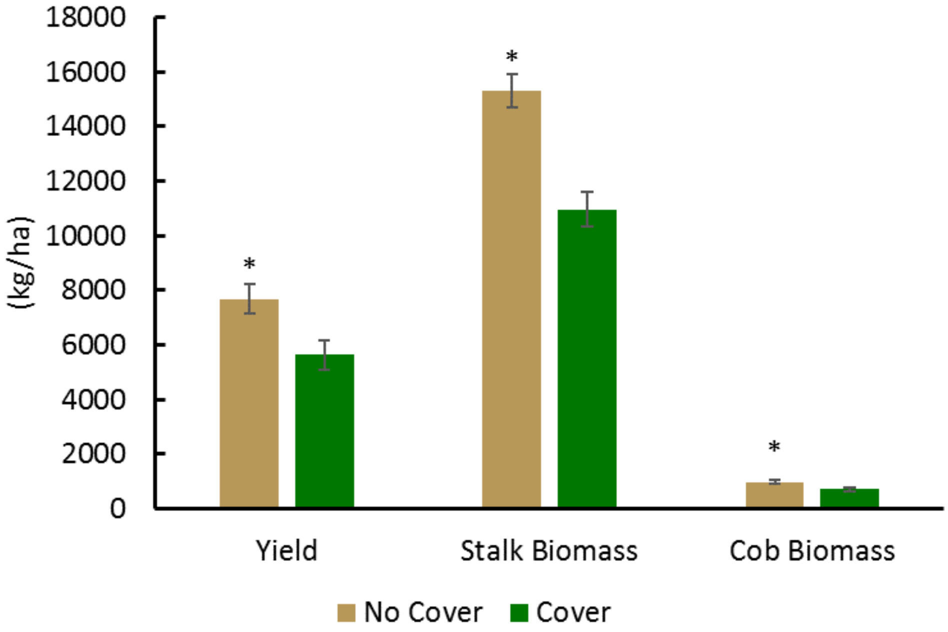


Figure 3.2. Effect of cover on yield, stalk biomass, and cob biomass production in the 2017 cropping year. Asterisk indicates difference between treatments for given parameter at *p<0.05*.

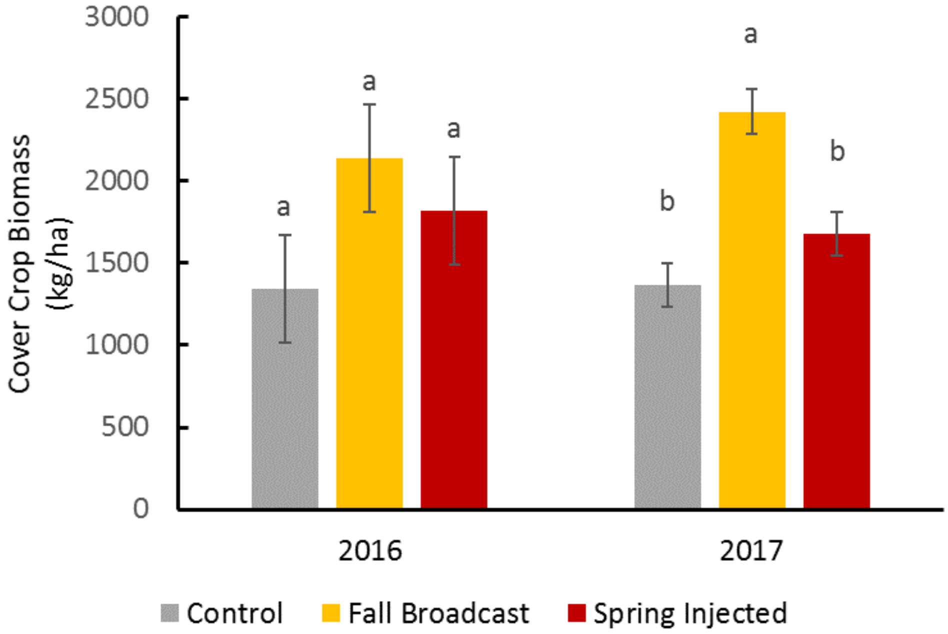


Figure 3.3. Effect of phosphorus fertilizer management on cover crop biomass production in both 2016 and 2017 cropping years. Letters indicate differences between treatments within given cropping year at *p<0.05.*

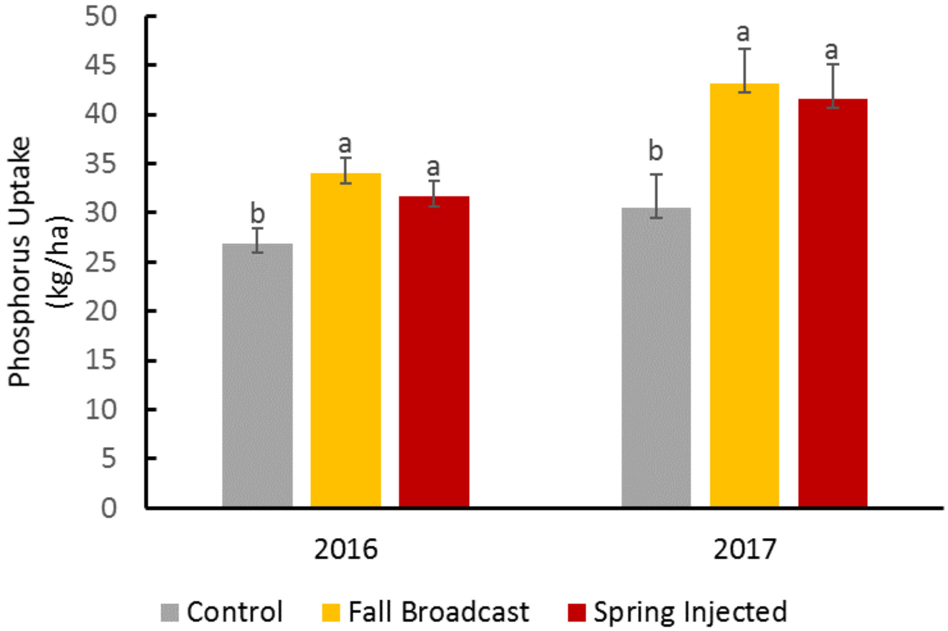


Figure 3.4. Impact of phosphorus fertilizer management practice on phosphorus uptake in both 2016 and 2017 cropping years. Differences in letters represent differences between treatment within cropping year at *p<0.05.*

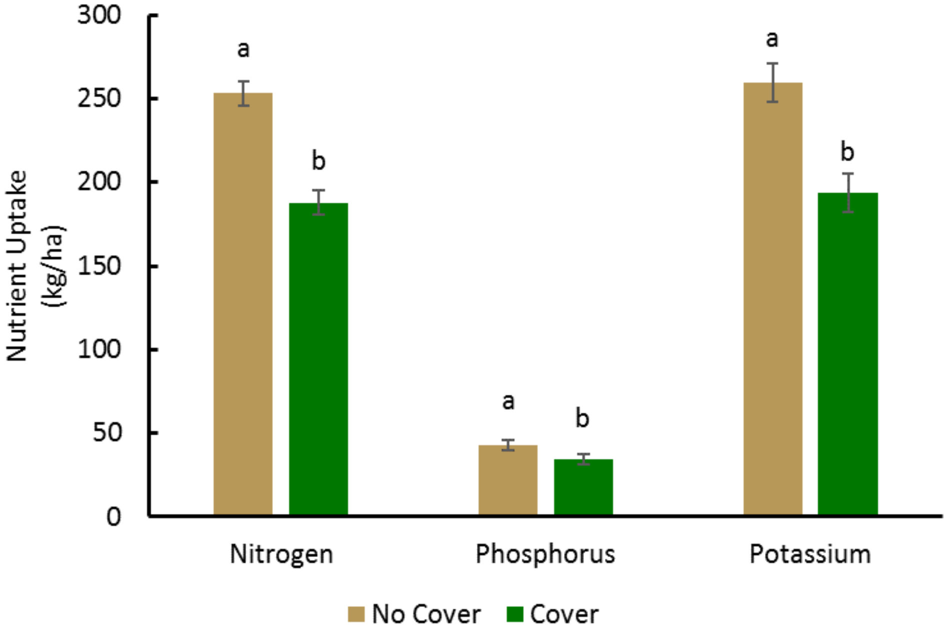


Figure 3.5. Main effect of cover on 2017 total nutrient uptake for corn. Differences in letters represent differences between treatments within group at *p<0.05.*

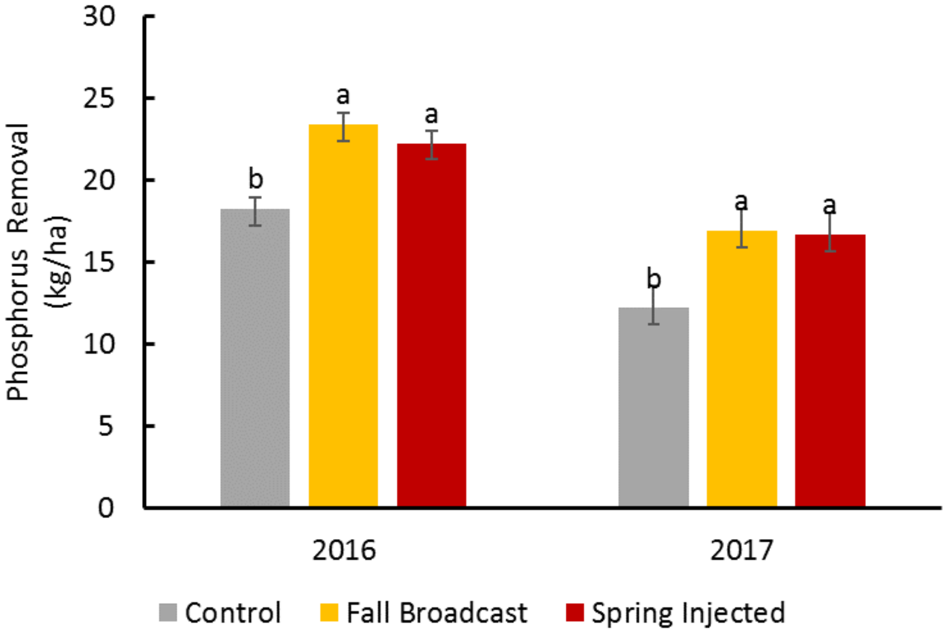


Figure 3.6. Fertilizer placement effect on phosphorus removal from the field for both 2016 and 2017 cropping years. Different letters represent a difference between treatments within the given cropping year at *p<0.05.*

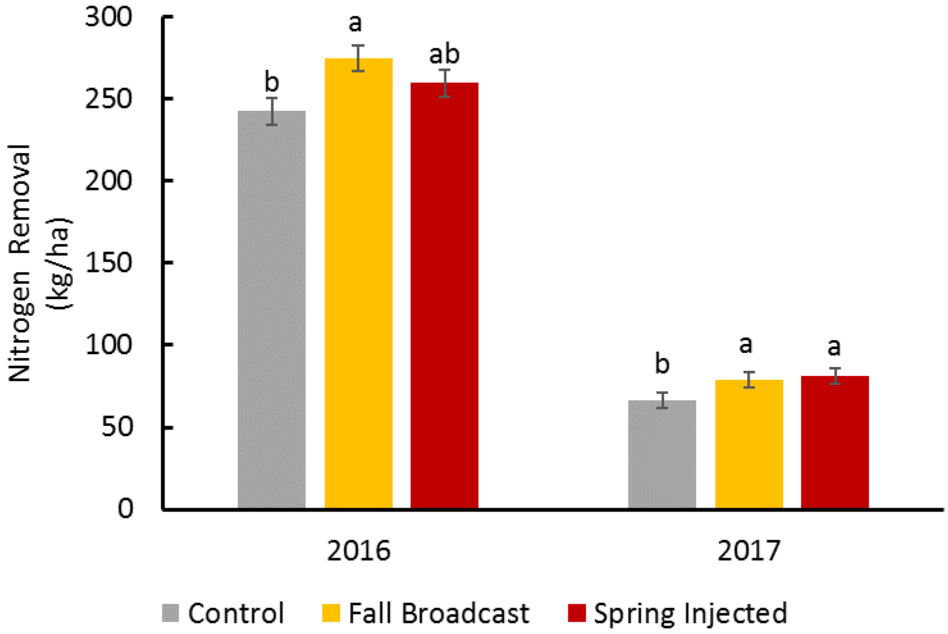


Figure 3.7. Fertilizer placement effect on nitrogen removal from the field for both 2016 and 2017 cropping years. Different letters represent a difference between treatments within the given cropping year at p<0.05.

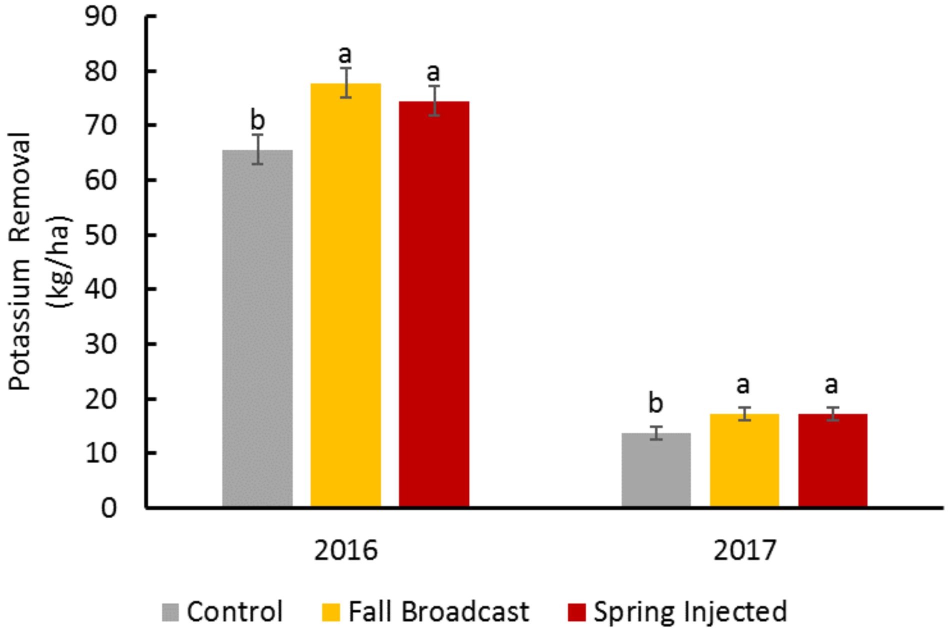


Figure 3.8. Fertilizer placement effect on potassium removal from the field for both 2016 and 2017 cropping years. Different letters represent a difference between treatments within the given cropping year at p<0.05.

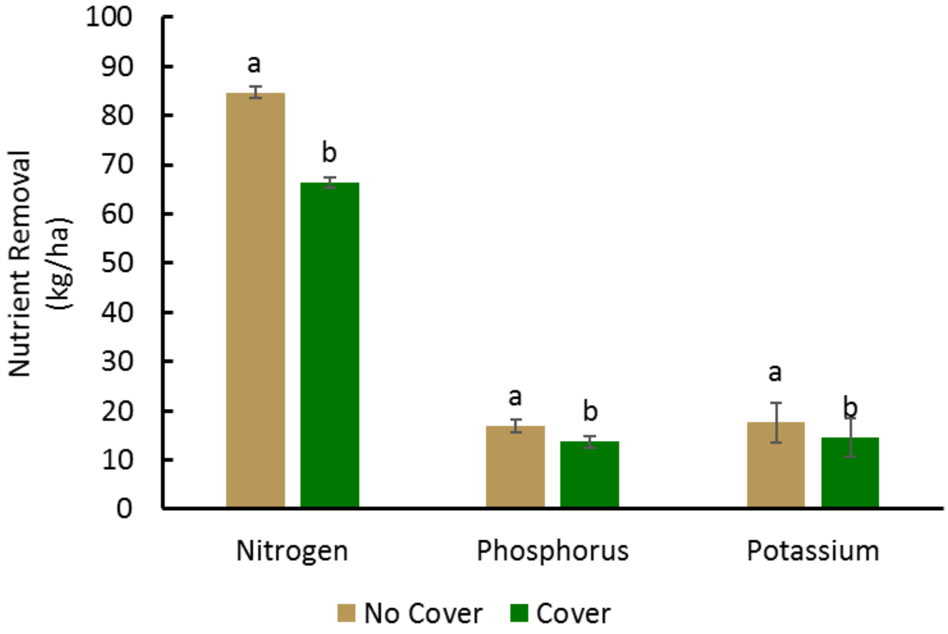


Figure 3.9. Main effect of cover on nutrient removal for 2017 cropping year Phosphorus and potassium both in elemental forms. Letters represent differences between treatments at *p<0.05*

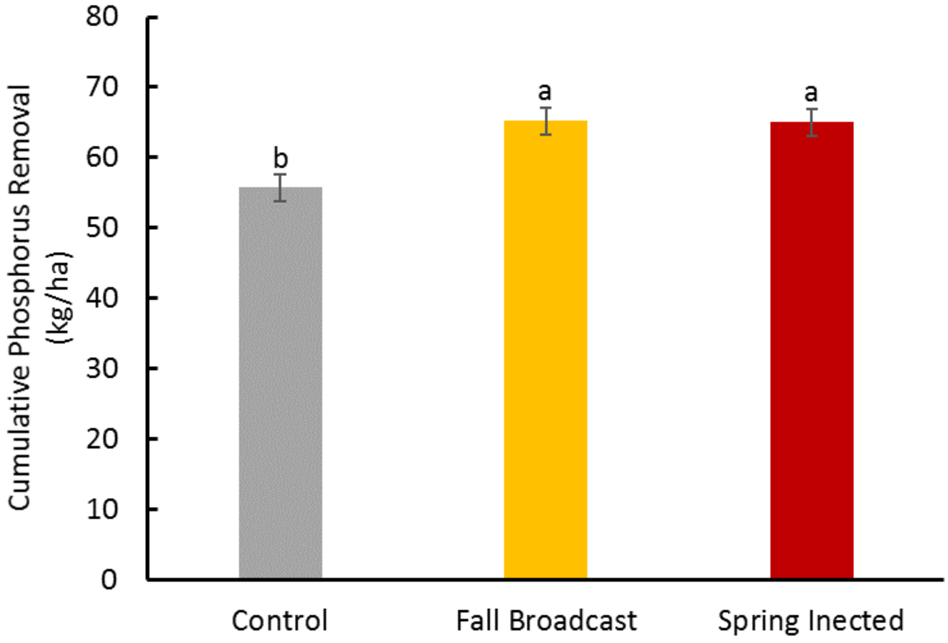


Figure 3.10. Fertilizer placement effect on cumulative phosphorus removal from 2015, 2016 and 2017 cropping years. Letters indicate differences between treatments at *p<0.05*.

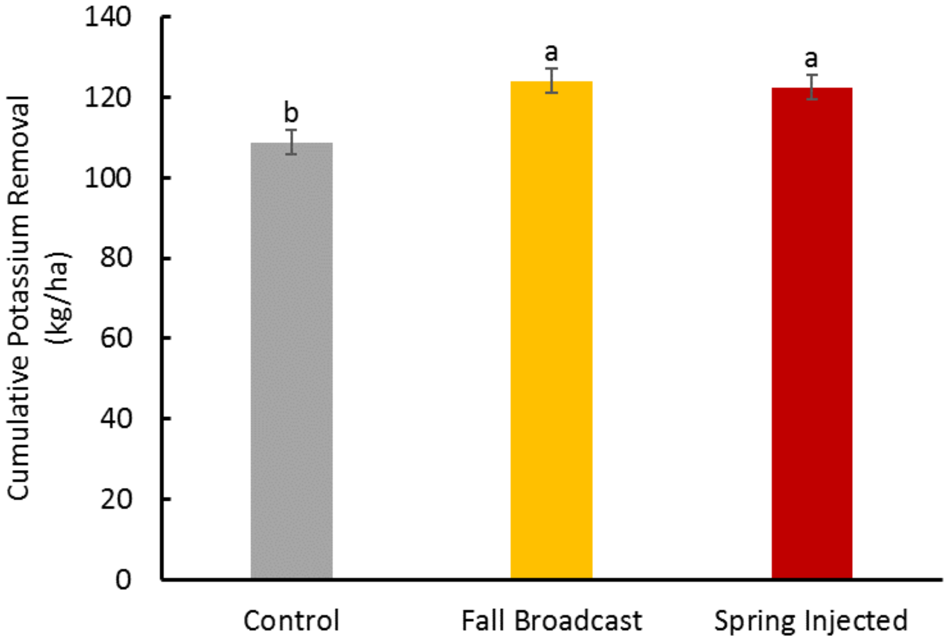


Figure 3.11. Main effect of phosphorus fertilizer placement on cumulative potassium removal from 2015, 2016, and 2017 cropping years. Letters indicate difference between treatments at *p<0.05.*

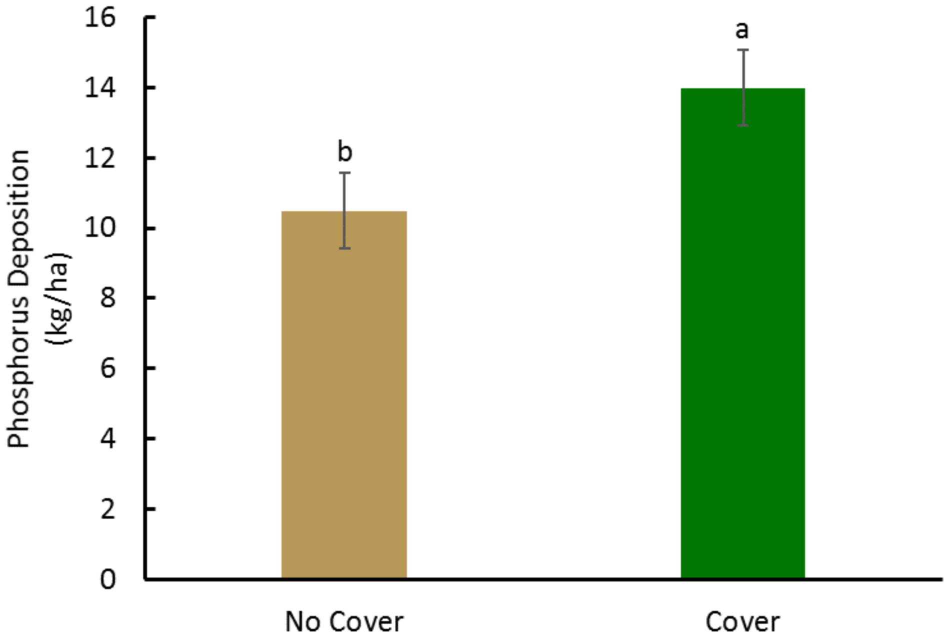


Figure 3.12. Main effect of cover on phosphorus deposition on the soil surface for the 2016 cropping year. Different letters indicate differences between treatments at *p<0.05.*

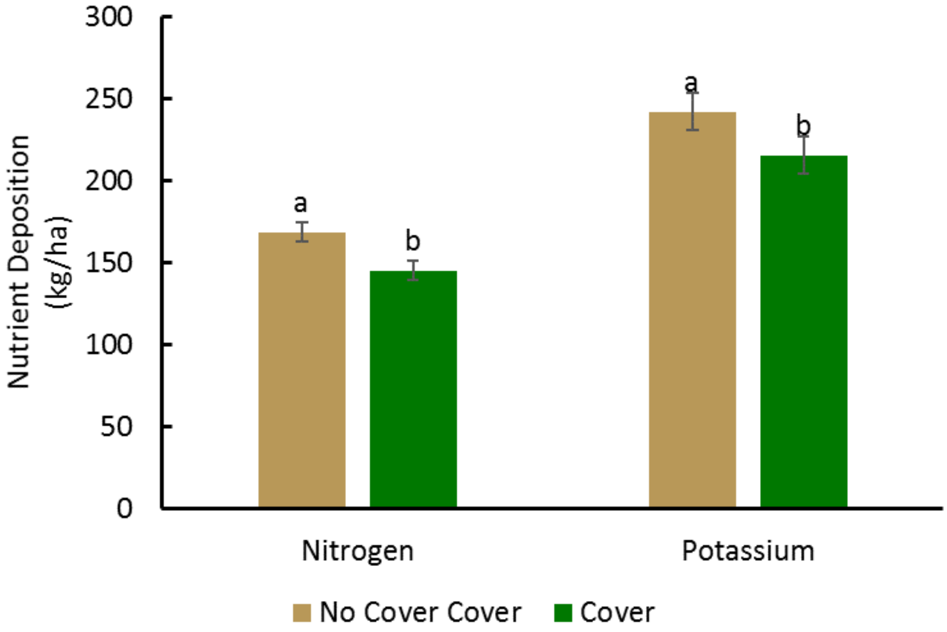


Figure 3.13. Impact of cover on nitrogen and potassium deposition on the soil surface for the 2017 cropping year. Different letters indicate differences between treatments at *p<0.05.*

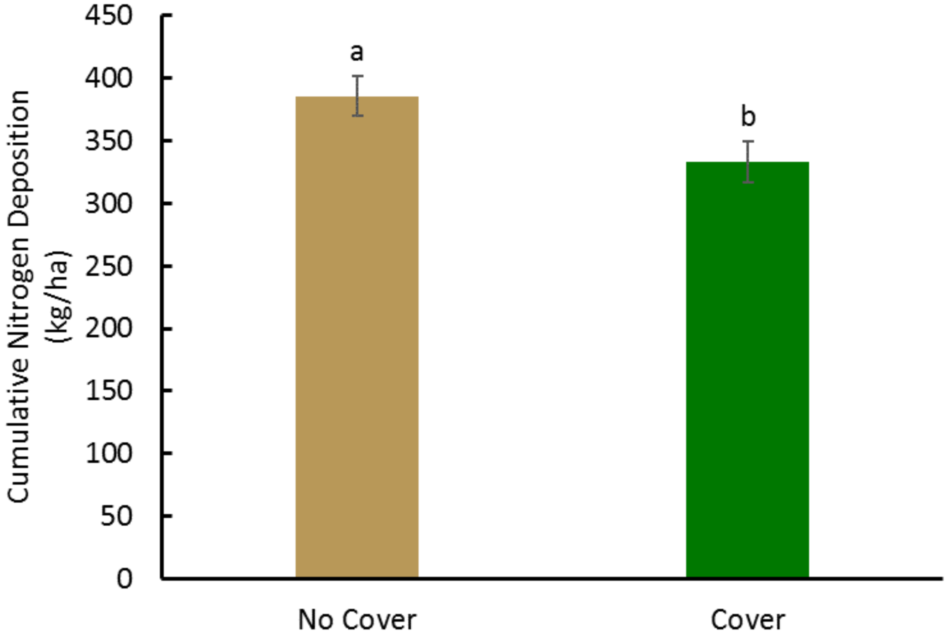


Figure 3.14. Main effect of cover on cumulative nitrogen deposition on the soil surface across 2015, 2016, and 2017 cropping years. Letters indicate differences between treatments at *p<0.05.*

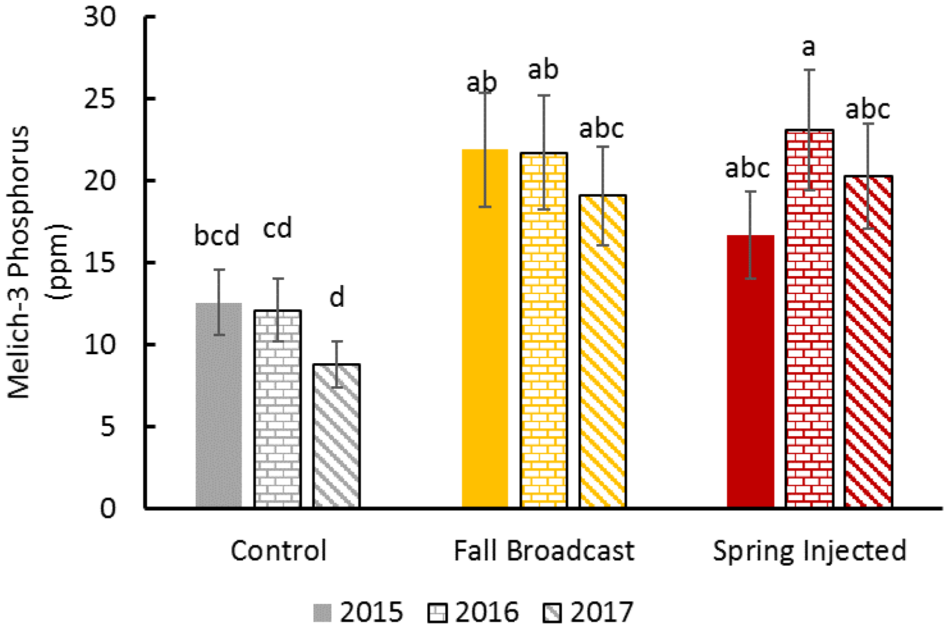


Figure 3.15. Fertilizer management practice by year interaction for Melich-3 phosphorus soil test levels. Letters indicate differences between treatments at *p<0.05*.

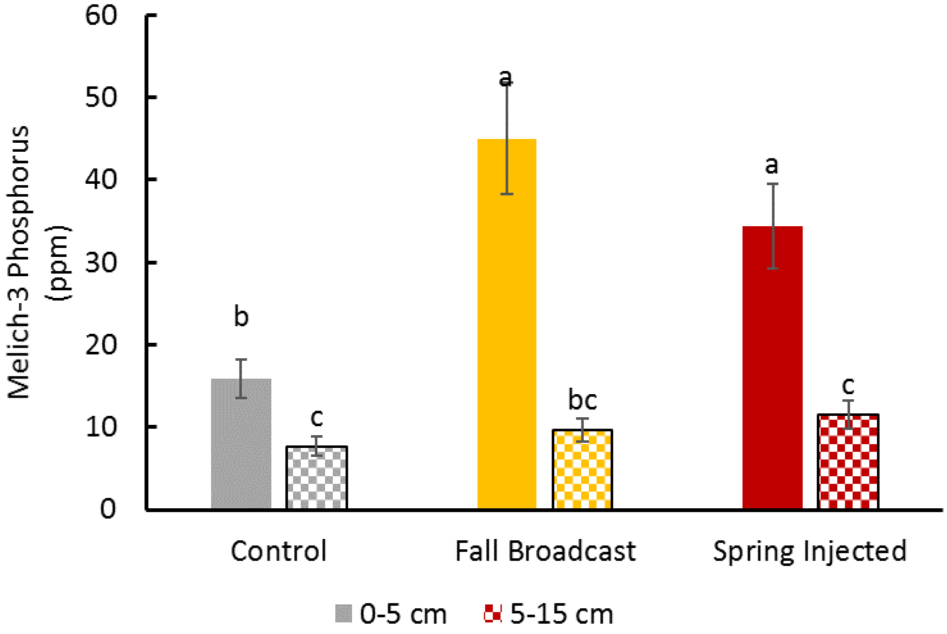


Figure 3.16. Fertilizer management practice by depth interaction for Melich-3 phosphorus soil test levels. Letters indicate differences between treatments at *p<0.05*.

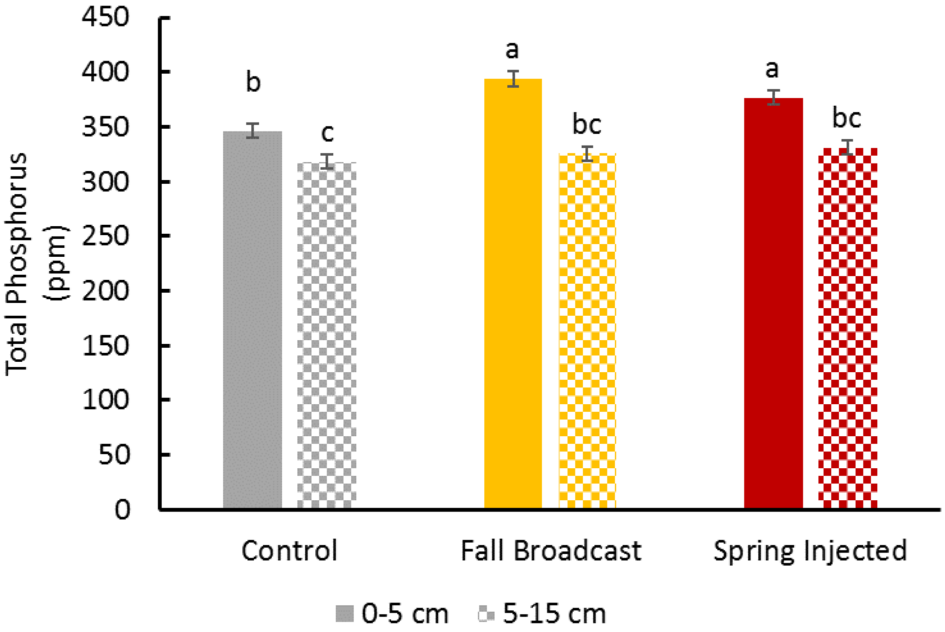


Figure 3.17. Fertilizer management practice by depth interaction for total phosphorus concentration of the soil at the Kansas Agricultural Watershed field laboratory. Letters indicated differences between treatments at *p<0.05*.

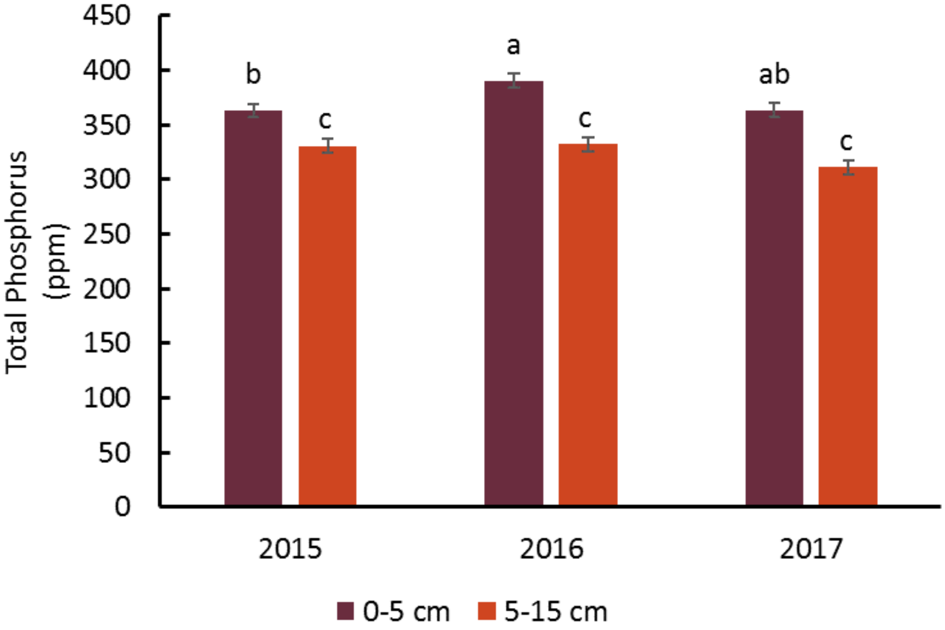


Figure 3.18. Year by depth interaction for total phosphorus concentration of the soil at the Kansas Agricultural Watershed field laboratory. Letters indicate differences between treatments at *p<0.05*.

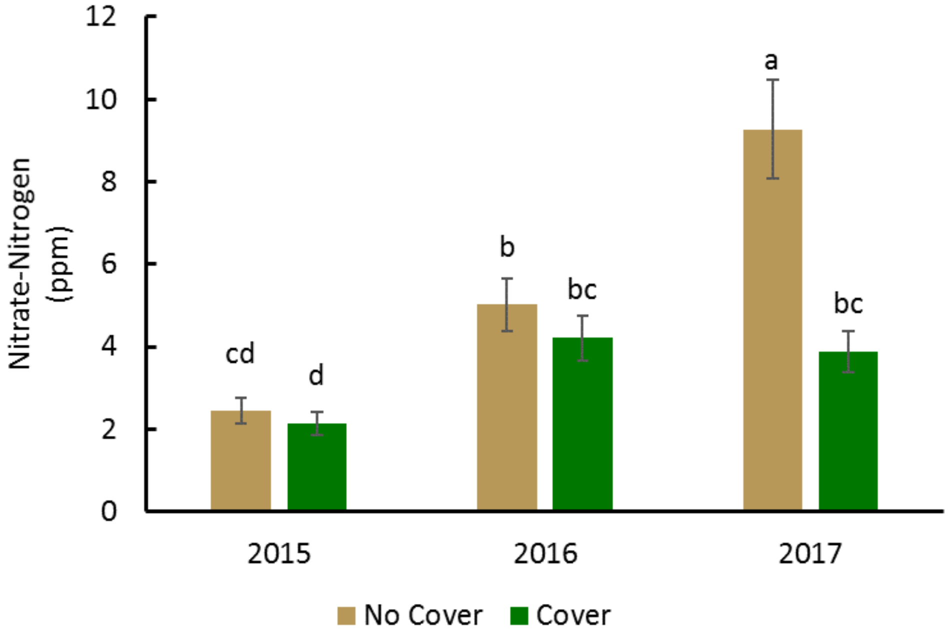


Figure 3.19. Cover by year interaction for nitrate-nitrogen concentration of the soil at the Kansas Agricultural Watershed field laboratory. Letters indicate differences between treatments at *$p<0.05$*.

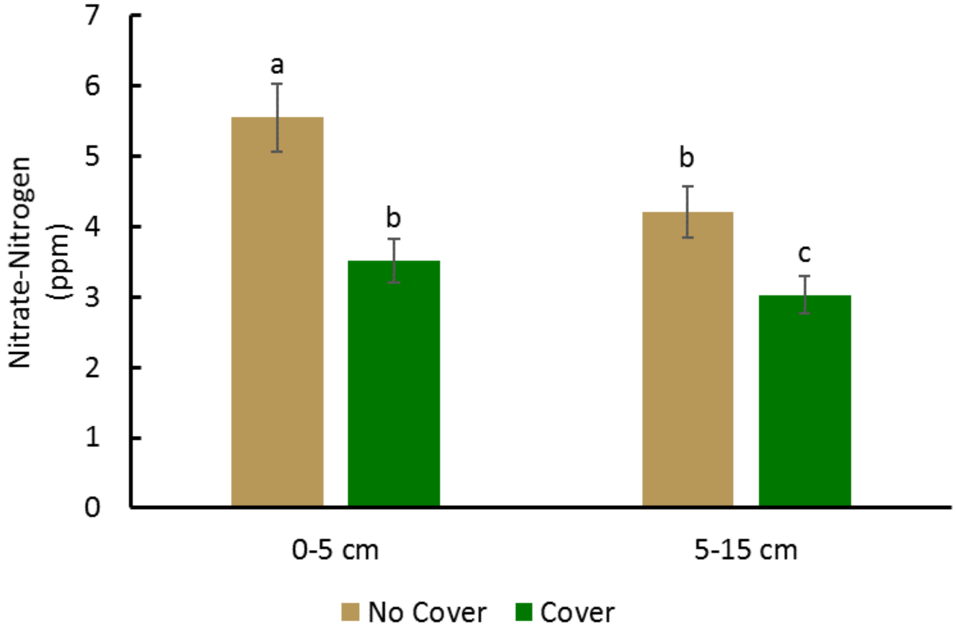


Figure 3.20. Cover by depth interaction for nitrate-nitrogen concentration of the soil at the Kansas Agricultural Watershed field laboratory. Letters indicate differences between treatments at *$p<0.05$*.

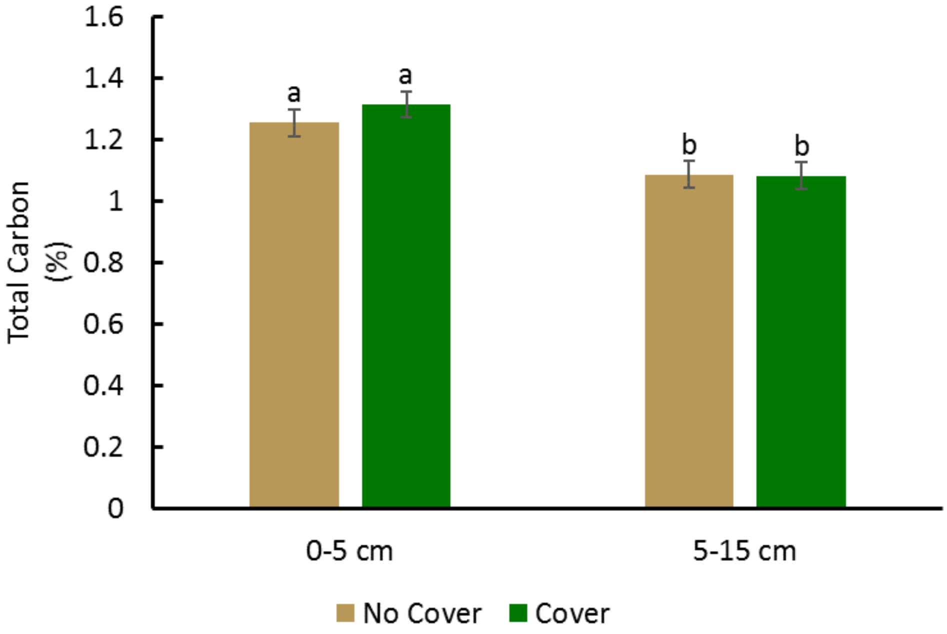


Figure 3.21. Cover by depth interaction for soil test levels of total carbon. Data is averaged over all fertilizer treatments. Letters indicate differences between treatments at *p<0.05*.

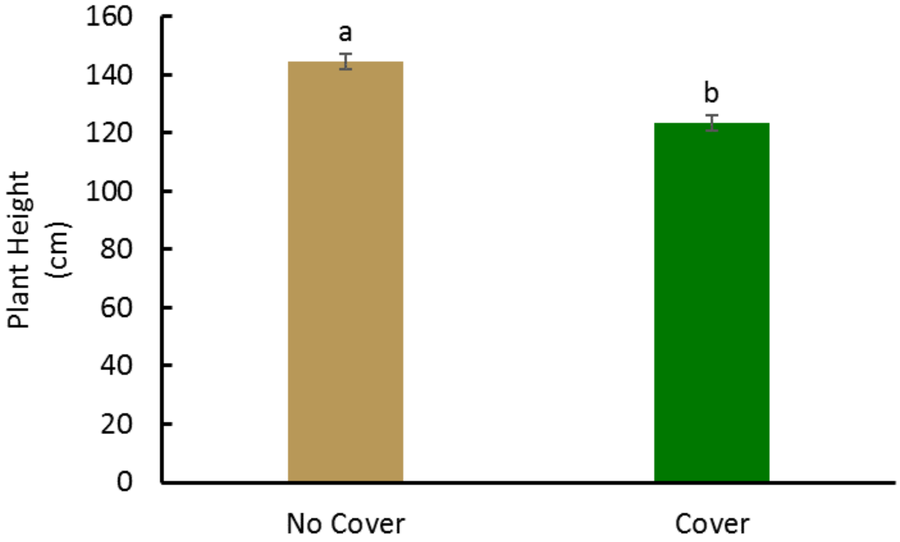


Figure 3.22. Effect of cover on corn plant height measured on 06/26/2017 in the 2017 cropping year. Height is averaged over all fertilizer treatments. Letters indicate differences between treatments at *p<0.05*.

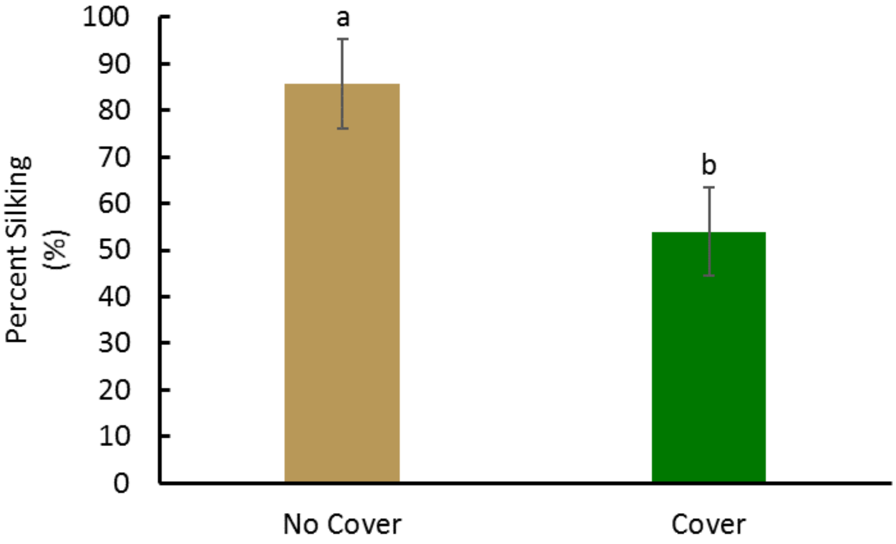


Figure 3.23. Effect of cover on percent silking of corn plants on 07/06/2017 during the 2017 cropping year. Data is averaged over all fertilizer treatments. Letters indicate differences between treatments at *p<0.05*.

Chapter 4 - Species and termination method effects on phosphorus loss from plant tissue

Introduction

The use of cover crops has shown to benefit soils by reducing erosion, increasing water infiltration, and aiding in weed suppression (Dabney et al., 2001). In addition, the use of cover crops is also an often cited as a best management practice (BMP) to help reduce potential nutrient loss during normally fallow periods (De Baets et al., 2011). However, throughout the cover crop’s growth, large amounts of phosphorus (P) can be accumulated in the plant’s tissue creating a potential source of P loss (Liu et al., 2014a). While this aboveground sink of P can possibly serve as a source of P loss, the uptake of P by cover crops can potentially reduce P loss if the accumulated P remains preserved within the plant’s tissue (Liu et al., 2014a).

After cover crop termination, during the decomposition process, accumulated nutrients in plant tissue will be recycled into the soil (Buchanan & King, 1991). Phosphorus released during plant decomposition can experience several fates within the agricultural system: remain readily available to plants, immobilized into organic P, precipitated as P minerals, undergo sorption, lost via leaching, or taken up by plants (Maltais-Landry & Frossard, 2015; Pierzynski et al., 2005). The release of P from cover crop tissue is vital for cover crops to positively affect P cycling back into the soil (Damon et al., 2014). However, Noack et al. (2012) found large variance in inorganic-P concentration of crop biomass across species suggesting that species selection plays a key role in P cycling.

Many cover crop species have low frost tolerances and are therefore susceptible to damage from exposure to freezing temperatures (Sturite et al, 2007). Frost tolerance is variable across cover crop species and different species have shown to have varying levels of leachable P from cover crop biomass after exposure to freezing (Liu et al., 2014a). When developing a cover crop management plan with the goal of controlling P loss, it is important to carefully select which cover crop species to be used.

A true cover crop is terminated before planting the subsequent cash crop (Hartwig & Ammon, 2002). Wayman et al. (2014) classify crop termination into three categories: natural, mechanical, and chemical. Cover crop termination by exposure to freezing conditions can be considered a natural termination method. Practices such as tillage, mowing, or crimping are considered mechanical termination methods while the application of herbicide is considered chemical termination (Wayman et al. 2014).

Several studies have shown that exposure of plant tissue to freezing conditions enhances levels of P loss from the plant tissue compared to plant tissue that was not exposed to freezing conditions (Miller et al., 1994; Bechmann et al., 2005; Liu et al., 2013, 2014a, 2014b). In these studies researchers used both greenhouse and field-grown crop tissue to examine the impact of freeze-thaw cycles on nutrient loss from crop tissue. Miller et al. (1994), Bechmann et al. (2005), and Liu et al. (2013, 2014a, 2014b) each found that cover crop species can directly impact the quantity of P released from plant tissue after exposure to freezing conditions. While the impact of freezing and cover crop species selection on P loss from crop tissue is clear, what remains unclear is the effect of mechanical and chemical termination on potential P loss from cover crop tissue. In addition, these studies do not address potential changes in P loss from cover crop tissue over time.

The objectives of this study are to quantify the effects of cover crop species, termination method, and time after termination on P uptake, water-extractable P (WEP) concentration in cover crop biomass, and the fraction of total P in biomass that is water soluble. In addition, the study looks to determine how management practice (i.e. species and termination method selection) effect the ratio of WEP concentration to total P concentration of cover crop biomass. Overall, this study aims to determine new agricultural BMPs to help reduce potential P loss in surface runoff.

Materials and Methods

This research was conducted at the Kansas State University greenhouse facility located in Manhattan, Kansas. The methods outlined below were used to conduct two greenhouse trials. The first occured from December 13, 2016-March 2, 2017, and the second occured from October 30, 2017-December 20, 2017. Findings from the first trial are not presented in this chapter because microbial growth occurred in the extracted samples between the extraction time and the analysis time (approximately 15 days). To ensure microbial growth did not affect the chemical analysis or experimental results, a second greenhouse trial was conducted where extract samples were analyzed within 24-hours after extraction. Results from the first greenhouse trial are presented in Appendix C.

Experimental Design

This study evaluated the effect of nine cover crop management strategies (treatments) on WEP from crop biomass. Treatments were structured in a 3x3x3 complete factorial arranged in a randomized complete block design with six replicates. Three levels of cover crops were used: brassica (*Brassica napus* var. *Winfred*), grass (*X Triticosecale; Triticum x Secale* var. *Trical),* and legume (*Trifolium incarnatum* L.). Three levels of termination method were: natural (freezing), mechanical (clipping), and chemical (herbicide). Finally, three levels of time after termination were: 1 day after termination (DAT), 7 DAT, and 14 DAT.

Greenhouse Cultivation

This study was conducted using field soil collected from the Kansas Agricultural Watershed (KAW) field laboratory located near Manhattan, KS. Soil was collected from the top 0-15 cm and is classified as a Smolan silty clay loam (fine, smectitic, mesic Pachic Argiustoll). A total of 15.4 ft^3 of soil was collected. Soil was then blended with 1.4 ft^3 sand and 5.0 ft^3 peat-based Miracle-Gro® Potting Media to aid with aeration, drainage, and nutrient supply. The Micarle-Gro® Potting Media contained Osmocote (N-P_2O_5-K_2O: 0.21-0.11-0.16) slow-release chemical fertilizer and provided approximately 275 mg/pot, 144 mg/pot, and 210 mg/pot of N, P_2O_5, and K_2O, respectively.

Plastic pots (3.7 L) were filled with the blended soil to within 2.5 cm of top edge. Once filled, pots received 500 mL of water and were allowed to equilibrate. Initial wetting of the blended soil was performed to help prevent channeling of water from occurring within the pot. After wetting, 15-25 seeds were placed on the surface of the blended soil. Seeds were then covered with approximately 2.5 cm of pre-wetted, blended soil. Once seeds were sown, pots were randomized and blocked across the greenhouse bench.

After emergence, seedlings were thinned to two plants per pot. Each pot contained two plants through the growth period. Pot moisture was monitored visually throughout the growth period. All plants were irrigated approximately every two days (based on visual soil moisture) with 200 mL of water. Plants were grown from October 30, 2017 through December 6, 2017.

In addition to natural light, supplemental artificial light was supplied for 16 hours during daytime (6:00 am-10:00 pm). Greenhouse temperature was regulated with forced air heat and set to 25°C from 6:00 am-10:00 pm and at 20°C from 10:00 pm-6:00 am.

Termination and Extraction

On December 6, 2017, all plants were terminated. Mechanical termination was performed by clipping the plant stalk at the soil surface. Clipped plant tissue was collected and placed on the pot surface. Chemical termination was performed via herbicide application using a Devries Manufacturing Research Track Sprayer. Full details of herbicide application can be seen in Table 4.1. Twenty-four hours after herbicide application, chemically terminated plants continued to be irrigated as needed to ensure plants where chemically terminated and not terminated from drought stress. The naturally terminated pots were removed from the greenhouse and placed in a walk-in freezer (-4°C) for 24-hours.

Water extractable phosphorus concentration in cover crop biomass was measured at 1, 7, and 14 DAT. Prior to extraction, cover crop biomass was stored in the greenhouse where plants had been grown. Greenhouse conditions were identical to growing conditions prior to termination.

At the given DAT, plants were transported from the greenhouse to the laboratory for processing and extraction. One of the two plants in each pot was randomly selected for water extraction while the second plant was used for determination of tissue moisture and total P concentration. A preliminary investigation determined that the moisture content and total P concentration of two plants grown in the same pot were highly correlated (Appendix D).

For the plant selected for water extraction, wet tissue weight was recorded and the crop biomass was placed into a 950 mL container with 300 mL of distilled deionized water. The container was sealed and placed on an end-to-end reciprocal shaker for at 180 oscillations per minute for one hour. After shaking, a 15-mL aliquot of extract was collected, filtered through 0.45 µm syringe filter and stored at 4 °C until analysis (<24 hours).

The wet weight of biomass from the second plant was recorded, placed in a paper bag, and dried at 60 °C to determine percent moisture and to be analyzed for total P. Dried tissue was weighed, ground with a ball mill, and analyzed for total P.

Chemical Analysis

Water-extractable phosphorus concentration of the extract was measured with a Lachat QuickChem 8500 Series II Automated Ion Analyzer using the “Orthophosphate in Waters” method (QuickChem Method 10-115-01-1-A). Extracts with P concentrations falling above the range of the standard curve (0-2 mg P/L) were diluted 10x with distilled deionized water using a Microlab 600 Series Autodiluter and re-analyzed.

Total P concentration of the plant tissue was determined by using sulfuric peroxide digestion as outlined by Linder & Harley (1942) and Thomas et al. (1967). Phosphorus concentrations in digest were measured using an inductively coupled plasma (ISP) spectrometer (Model 720-ES ICP Optical Emission Spectrometer).

Data Analysis

All data (WEP concentration, WEP release from crop tissue, total P concentration, total P uptake in crop tissue, and fraction of total P that is water extractable) were statistically analyzed in SAS version 9.4 using a PROC GLIMMIX procedure with analysis of variance to examine treatment effects. Water extractable phosphorus concentration is the mass of P extracted by the water divided by dry mass of tissue placed in the extraction vessel. Water extractable phosphorus release is the mass of P extracted by the water. Total P concentration is the quantity of P (mg) per kg of plant tissue. Total P uptake is the concentration of total P multiplied by the biomass. Fraction of total P that is water extractable is the ratio of WEP release to total P uptake.

Results

Statistical analysis of the data found main effects, two way (crop*method & method*DAT), and three way (crop*method*DAT) interactions (Table 4.2). For parameters where interactions were found, the main treatment effect will not be discussed.

Biomass

Cover crop species produced different amounts of biomass (Table 4.2). Brassica generated the greatest quantity of biomass during the growing period compared to both grass and legume (Figure 4.1). The brassica generated approximately 250% more biomass compared to the grass and over 570% more biomass compared to the legume.

Phosphorus Concentration, Release, and Uptake

Total P concentration in biomass was not influenced by any of the treatments or interactions (Table 4.2).Cover crop tissue contained between 3.2 and 3.4 g P/kg tissue regardless of species, termination method, or DAT (Figure 4.2). A main effect of crop species on total P uptake was observed with brassica taking up the greatest amount of total P compared to both grass and legume (Table 4.2 & Figure 4.3). Brassica took up nearly 250% more total P compared to grass and over 580% more total P compared to legume. Differences between grass and legume were not observed.

A main effect of crop species, termination method, and time after termination was found for WEP concentration (Table 4.2). Concentration of WEP in brassica crop tissue was 81% and 78% lower compared to grass and legume, respectively (Figure 4.4). Termination via freezing yielded greater levels of WEP compared to both clipping and herbicide (Figure 4.5). Plants terminated by freezing had 120% greater WEP tissue concentrations compared to those terminated by clipping and over 300% greater WEP concentrations compared to plants terminated by herbicide. As time after termination increased, WEP concentration also increased with both 7 DAT and 14 DAT having greater WEP concentrations compared to 1 DAT; however, no differences were found between 7 and 14 DAT (Figure 4.6).

A main effect of DAT and a crop species by termination method interaction were found for fraction of WEP compared to total P (Table 4.2). For time after termination, both 7 DAT and 14 DAT had a greater fraction of WEP compared to total P when compared to 1 DAT (Figure 4.7). Fractions of WEP compared to total P were two times and two and a half times greater for 7 DAT and 14 DAT, respectively, when compared to 1 DAT.

A crop species by termination method interaction was found for fraction of total P that was water-extractable (Table 4.2). Freezing increased the WEP fraction more for the grass and legume than for the brassica. In the grass and legume, the WEP:TP ratio in frozen tissue was greater than for tissue terminated by clipping or herbicide and there were no differences between clipping and herbicide (Figure 4.8). However, for brassica, the WEP:TP ratio of the frozen tissue was only greater than for the herbicide, yet similar to clipping. The WEP:TP ratio in tissue terminated by clipping and herbicide were also similar in brassica (Figure 4.8).

A crop species by termination method interaction, termination method by time after termination, and a crop species by termination method by time after termination interaction were all found for WEP release from crop tissue (Table 4.2). Termination method had a different effect on WEP release for each crop (Figure 4.9). Although freezing resulted in the greatest WEP release for all cover crops, it tended to have a greater impact on WEP release for grass and brassica, which both had greater WEP release than legume when freeze-terminated. Clipping had greater WEP release than herbicide for the grass, whereas the WEP release from clipping and herbicide termination were similar for brassica and legume. When examining termination method by time after termination, the later times after termination (7 and 14 DAT) had consistently greater WEP release compared to the 1 DAT within each termination method (Figure 4.10) Freezing crop tissue constantly resulted in the greatest release of WEP regardless of time after termination (Figure 4.10). In addition, at 1 DAT, clipped plants released less WEP compared to herbicide terminated plants, yet, at both 7 and 14 DAT, no differences between clipping and herbicide were observed.

There was a three-way interaction between crop species, termination method, and time after termination for WEP release (Table 4.2). Freezing resulted in consistently higher WEP release from brassica for 1, 7, and 14 DAT; however, this effect was not observed for grass (no difference at 14 DAT) or legume (no differences at 1 and 7 DAT) (Figure 4.11). Inconsistencies in WEP release from plants terminated by clipping and herbicide were found with clipping having greater WEP release compared to herbicide for the grass at 1 DAT, but the two termination methods resulted in similar WEP release from other crops and termination times (Figure 4.11). For both brassica and grass, clipping and herbicide consistently result in lower quantities of WEP release compared to freezing; however, for legume, differences in quantity of WEP release between time after termination are not observed until 14 DAT.

Discussion

Overall, there was no main effect of crop species on total P concentration of the crop tissue, but WEP concentration in the plant tissue varied significantly among crop species (Table 4.2). In addition, differences in quantities of WEP released and total P uptake by crop species were found. Differences in WEP release and total P uptake can primarily be explained by the differences in biomass produced by each crop species. For example, brassica had the lowest concentration of WEP; however, brassica produced much greater quantities of biomass compared to legume and grass. The increased biomass production of brassica resulted in brassica releasing a significant quantity of WEP on a per pot basis.

Upon examining the impact of freezing as a termination method, both grass and legume exhibit a dramatic increase in the fraction of WEP versus total P compared to other termination methods (Figure 4.8). When crop tissue is exposed to freezing conditions, ice can form within the plant cells causing expansion-induced lysis resulting in damage to the cell membrane (Thomashow, 1990). In addition, the chemical potential of ice is lower than liquid water, which ultimately results in the movement of unfrozen cell water from inside the cell to outside the cell (Thomashow, 1990). As cells are damaged by freezing, an increase in P leaching from plant tissue can occur (Øgaard, 2015). Several studies have found that exposing cover crop tissue to freeze-thaw cycles can increase the level of WEP released from crop tissue compared to tissue that was not exposed to freezing conditions (Liu et al., 2013, 2014; Millet et al., 1994; Sturite et al., 2007; Øgaard, 2015).

As previously mentioned, both grass and legume had a greater fraction of WEP after being terminated by freezing while brassica had the same fraction of WEP regardless of termination method (Figure 4.8). The difference in WEP fraction could suggest a difference in cold-tolerance between crop species. All three crops grown in this study are annuals and often annuals are considered less cold tolerant than perennials. In general, annual plants also exhibit higher growth rates compared to perennials and thus need larger quantities of P to promote cell division at the growing points (Primack, 1979). In a greenhouse study, Liu et al. (2013) found annual species to have greater P concentration in crop tissue compared to perennial species. The observed difference in WEP release and fraction of WEP compared to total P suggest that crop selection plays a key role in working to decrease losses of P from crop tissue.

It is important to note that plants used in this study were grown in the greenhouse and were not acclimated for the dramatic temperature change of being placed in the freezer at -4°C. Under natural conditions, ambient temperature changes are generally more gradual. Increased resistance to freezing tolerance, or climate acclimation, is triggered by exposure to low, non-freezing temperatures (Thomashow, 1990). Further studies examining the effect of termination method on WEP release from field-grown crops, which have been acclimated to winter conditions, are therefore needed.

Differences in time after termination were also observed with both 7 DAT and 14 DAT having greater WEP concentrations and fractions of WEP versus total P compared to 1 DAT (Table 4.2; Figure 4.6; Figure 4.7). Exact mechanisms behind the difference in WEP concentration and fraction of WEP at the later times after termination are not clear. However, findings from this study indicate that an increase in both WEP concentration and fraction of WEP versus total P occurs during the first week after termination. These findings suggest that terminating a cover crop during periods of heavy rainfall may possibly increase the risk of P loss in surface runoff. Therefore, it may be a best management practice (BMP) to help reduce the risk of P loss by terminating cover crops during periods of low rainfall so that P released from the cover crop tissue may enter and adsorb into the soil.

Conclusions

This study aimed to quantify the impacts of crop species, termination method, and time after termination on WEP and total P concentration and the release of WEP and total P from crop tissue. In conclusion, this study found that terminating plants by freezing increases WEP release and changes the fraction of WEP compared to total P. In addition, as time after termination increased from 1 DAT to 7 DAT, both concentration and fraction of WEP of crop tissue increased when averaged over crop species and termination method. These findings suggest that termination of cover crop should be timed to avoid potential surface runoff losses of WEP or to provide additional P to the main crop. In addition, findings from this study could allow producers to predict the quantity of WEP being released from cover crop tissue after cover crops are terminated based on the fraction of total P that is water-extractable and the quantity of biomass produced. These predicted values could then be used to help assess the risk of P loss from the field. Further research should be conducted and expanded to include additional cover crop species to help identify which species have the greatest potential of P release from crop tissue. Additional research assessing WEP release from cold acclimated plants that have been terminated by freezing would also provide greater insight into how crop selection can influence P release.

References

Bechmann, M.E., P.J.A. Kleinman, A.N. Sharpley and L.S. Saporito. 2005. Freeze-thaw effects on phosphorus loss in runoff from manured and catch-cropped soils. J. Environ. Qual. 34:2301-2309.

Buchanan, M. and L. King. 1993. Carbon and phosphorus losses from decomposing crop residues in no-till and conventional till agroecosystems. Agronomy Journal. 85:631-638.

Dabney, S., J. Delgado and D. Reeves. 2001. Using winter cover crops to improve soil and water quality. Commun. Soil Sci. Plant Anal. 32:1221-1250.

Damon, P.M., B. Bowden, T. Rose and Z. Rengel. 2014. Crop residue contributions to phosphorus pools in agricultural soils: A review. Soil Biology and Biochemistry 74:127-137.

De Baets, S., J. Poesen, J. Meersmans, and L. Serlet. 2011. Cover crops and their erosion reducing effects during concentrated flow erosion. Catena. 85:237–244.

Hartwig, N. and H. Ammon. 2002. 50th anniversary - invited article - cover crops and living mulches. Weed Sci. 50:688-699.

Liu, J., R. Khalaf, B. Ulen, and G. Bergkvist. 2013. Potential phosphorus release from catch crop shoots and roots after freezing-thawing. Plant Soil 371:543-557.

Liu, J., B. Ulen, G. Bergkvist, and H. Aronsson. 2014. Freezing-thawing effects on phosphorus leaching from catch crops. Nutrient Cycling Agroecosystems. 99:17-30.

Maltais-Landry, G. and E. Frossard. 2015. Similar phosphorus transfer from cover crop residues and water-soluble mineral fertilizer to soils and a subsequent crop. Plant Soil 393:193-205.

Miller, M., E. Beauchamp, and J. Lauzon. 1994. Leaching of nitrogen and phosphorus from the biomass of three cover crop species. J. Environ. Qual. 23:267-272.

Noack, S.R., M.J. McLaughlin, R.J. Smernik, T.M McBeath, R.D. Armstrong. 2012. Crop residue phosphorus: speciation and potential bio-availability. Plant Soil. 359-375.

Øgaard, A.F. 2015. Freezing and thawing effects on phosphorus release from grass and cover crop species. Acta Agriculturae Scandinavica Section B-Soil and Plant Science 65:529-536.

Pierzynski, G. M., R.W. McDowell, and T. Sims. 2005. Chemistry, cycling, and potential movement of inorganic phosphorus in soils. In J.T. Sims and A.N. Sharpley (Eds.), Phosphorus: Agriculture and the Environment. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Primack, R. 1979. Reproductive effort in annual and perennial species of plantago. Am. Nat. 114:51-62.

Sturite, I., T.M. Henriksen and T.A. Breland. 2007. Winter losses of nitrogen and phosphorus from Italian ryegrass, meadow fescue and white clover in a northern temperate climate. Agric. Ecosyst. Environ. 120:280-290.

Thomashow, M.F.1990. Plant cold acclimation: freezing tolerance genes and regulatory mechanisms. Annu. Rev. Plant Physiol. Plant Mol. Biol. 50:571–99.

Wayman, S., C. Cogger, C. Benedict, I. Burke, D. Collins, and A. Bary. 2015. The influence of cover crop variety, termination timing and termination method on mulch, weed cover and soil nitrate in reduced-tillage organic systems. Renewable Agriculture and Food Systems. 30:450-460.

Table 4.1. Greenhouse operations and extractions timeline. Brassica (B), legume (L), grass (G), clipping (C), freezing (F), herbicide (H), days after termination (DAT), water-extractable phosphorus (WEP), ammonium sulfate (AMS).

Date	Activity	B-C	G-C	L-C	B-F	G-F	L-F	B-H	G-H	L-H	Notes
10/30/2017	Seeds planted	YES	YES	YES	YES	YES	YES	YES	YES	YES	
12/6/2017	Mechanical Termination	YES	YES	YES	NO	NO	NO	NO	NO	NO	Plants were cut at soil surface
12/6/2017	Chemical Termination	NO	NO	NO	NO	NO	NO	Glyphosate (3.5 L ha^{-1}); 2,4-D LV6 (0.87 L ha^{-1}); AMS	Glyphosate (3.5 L ha^{-1}); 2,4-D LV6 (0.87 L ha^{-1}); AMS	Glyphosate (3.5 L ha^{-1}); 2,4-D LV6 (0.87 L ha^{-1}); AMS	Nozzle: TeeJet 8002E
12/6/2017	Freeze Termination	NO	NO	NO	24hours at -4°C	24hours at -4°C	24hours at -4°C	NO	NO	NO	Entire pot placed in walk-in freezer
12/7/2017	1 DAT WEP Extraction	YES	YES	YES	YES	YES	YES	YES	YES	YES	Lab temperature: 26°C
12/8/2017	1 DAT WEP Analysis	YES	YES	YES	YES	YES	YES	YES	YES	YES	
12/13/2017	7 DAT WEP Extraction & Analysis	YES	YES	YES	YES	YES	YES	YES	YES	YES	Lab temperature: 26°C
12/20/2017	14 DAT WEP Extraction & Analysis	YES	YES	YES	YES	YES	YES	YES	YES	YES	Lab temperature: 26°C

Table 4.2. Probabilities (p-values) for ANOVA F-test on the effects of cover crop species (crop), method of termination (method), time after termination (DAT), and their interactions on crop biomass, water-extractable phosphorus (WEP) concentration in tissue, WEP mass, total phosphorus (Total P) concentration in tissue, total P uptake by cover crops, and the ratio between WEP and total P in crop tissue (WEP:Total P).

	Biomass	WEP Concentration	WEP Release	Total P Concentration	Total P Uptake	WEP:Total P
Crop	<0.001	<0.001	<0.001	0.285	<0.001	<0.001
Method	0.790	<0.001	<0.001	0.729	0.742	<0.001
DAT	0.738	<0.001	<0.001	0.278	0.820	<0.001
Crop*Method	0.930	0.070	<0.001	0.117	0.849	0.016
Crop*DAT	0.790	0.189	0.157	0.740	0.817	0.144
Method*DAT	0.457	0.13	0.005	0.082	0.404	0.073
Crop*Method*DAT	0.251	0.299	0.049	0.576	0.476	0.332

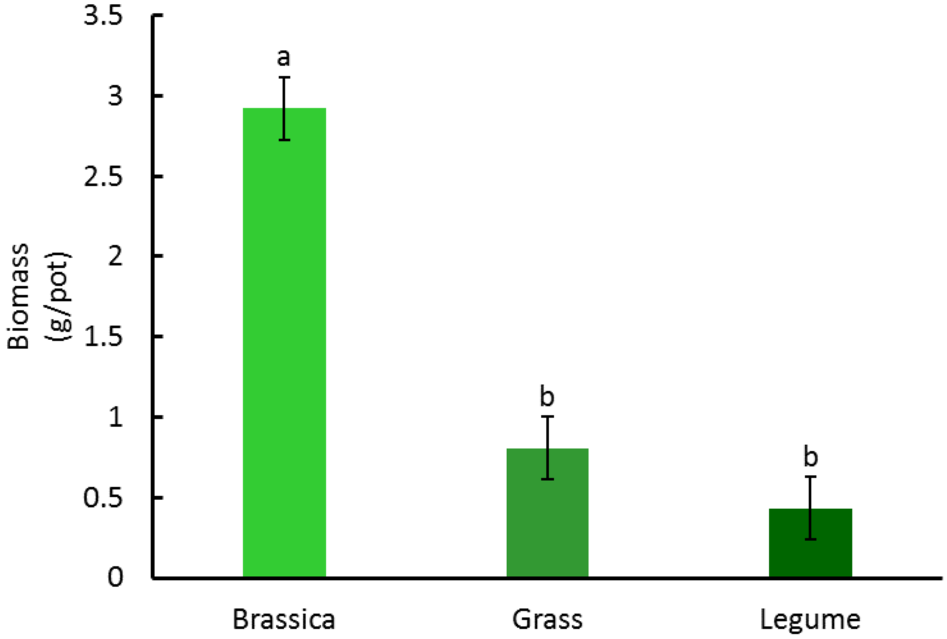


Figure 4.1. Average biomass generated per pot on a cover crop species basis (data averaged over termination method and time after termination). Letters indicate significant difference between treatments at *p<0.05*.

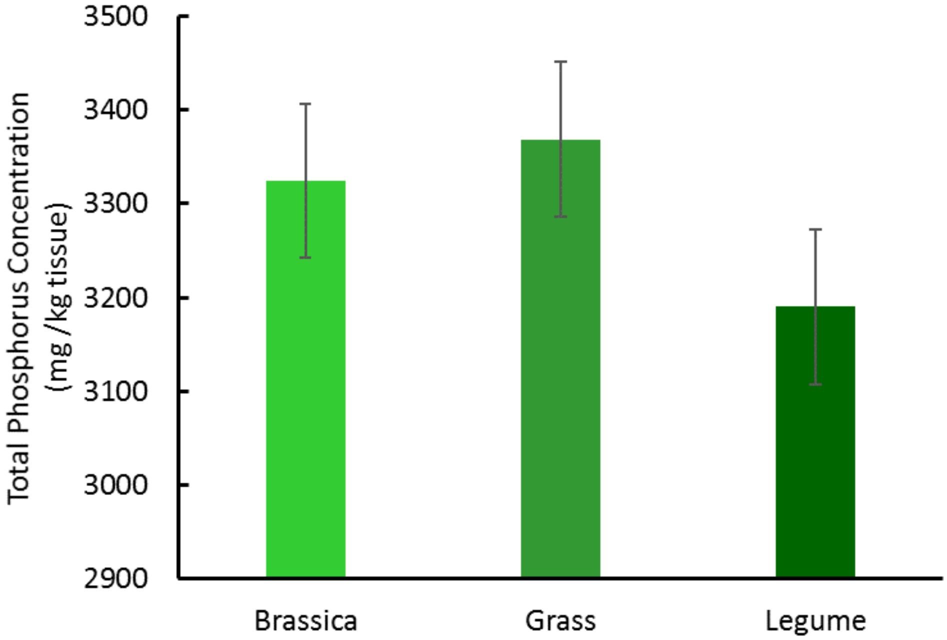


Figure 4.2. Effect of cover crop species on total phosphorus concentration of crop biomass (data averaged over termination method and time after termination).

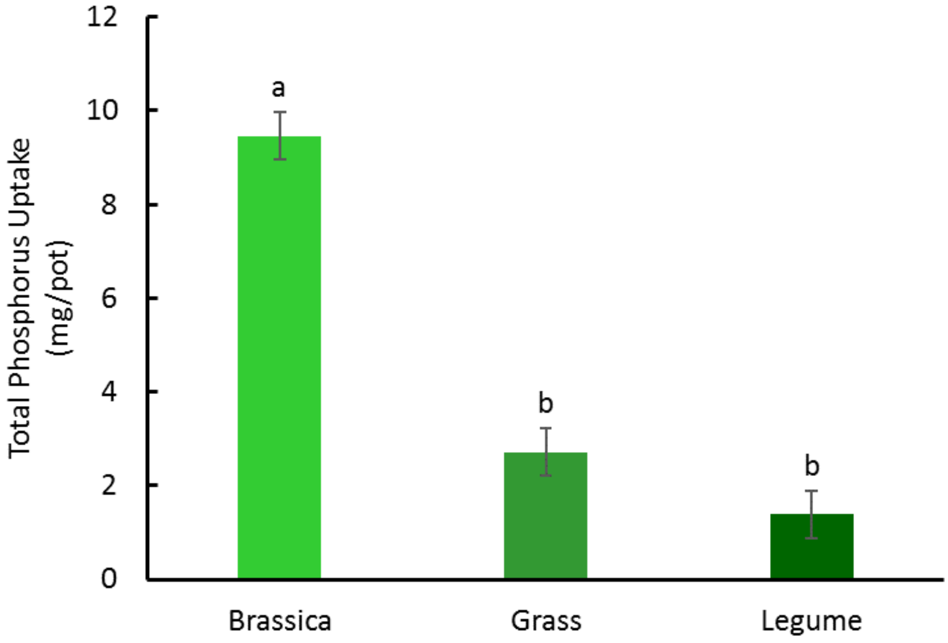


Figure 4.3. Main effect of cover crop species on total phosphorus uptake in crop tissue (data averaged over termination method and time after termination). Different letters indicate differences between treatments at *p<0.05*.

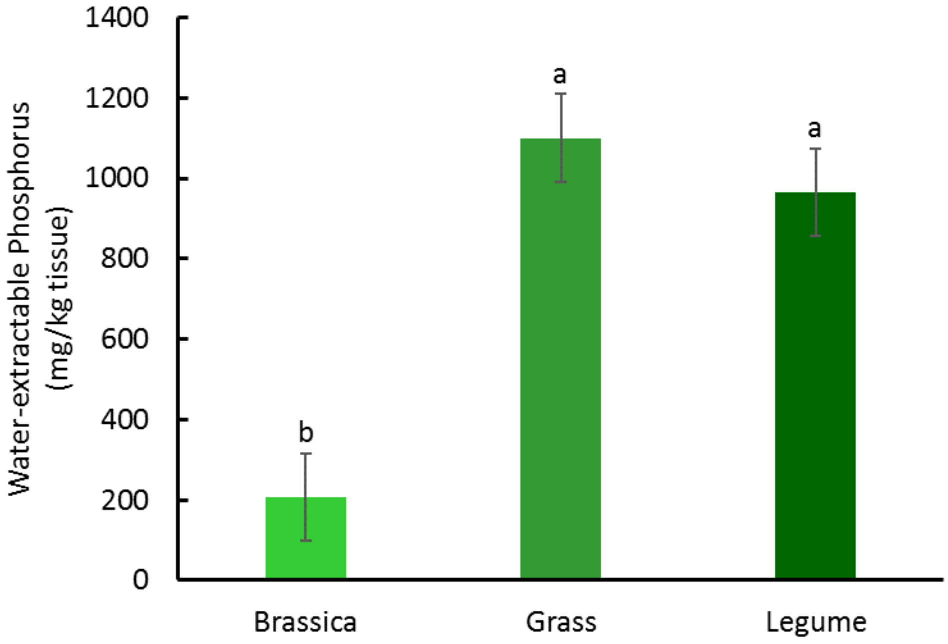


Figure 4.4. Effect of cover crop species on water-extractable phosphorus concentration of crop biomass (data averaged over termination method and time after termination). Letters indicate significant difference between treatments at *p<0.05*.

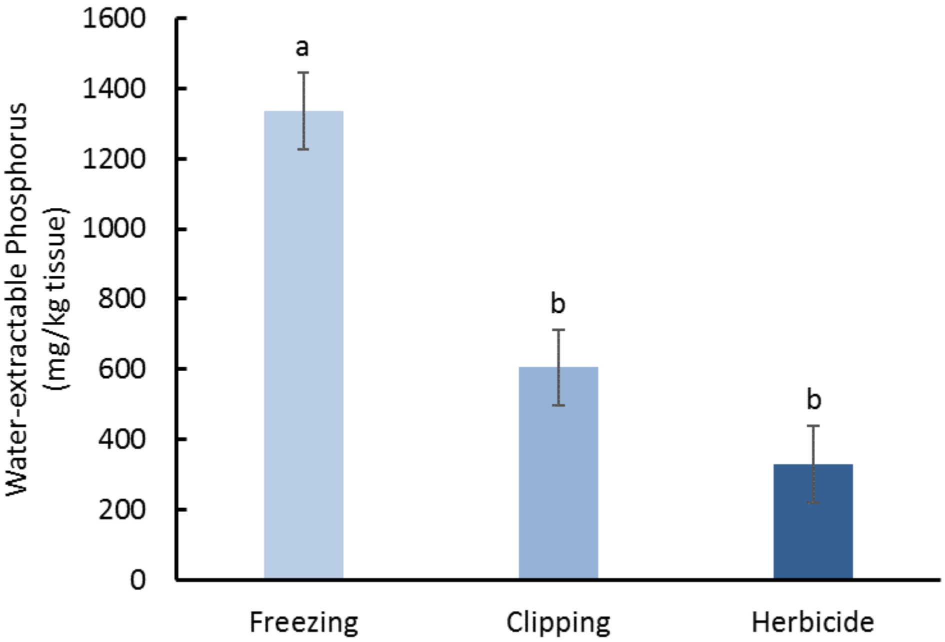


Figure 4.5. Effect of termination method on water-extractable phosphorus concentration of crop biomass (data averaged over species and termination times). Different letters indicate differences between treatments at *p<0.05*.

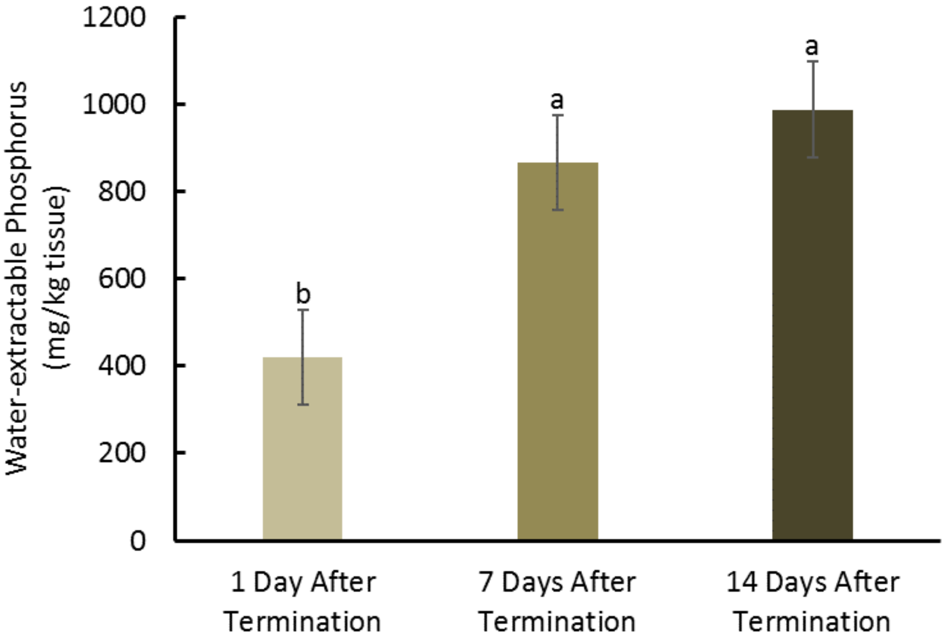


Figure 4.6. Effect of time after termination on water-extractable phosphorus concentration of crop biomass (data averaged over species and termination method). Different letters indicate differences between treatments at *p<0.05*.

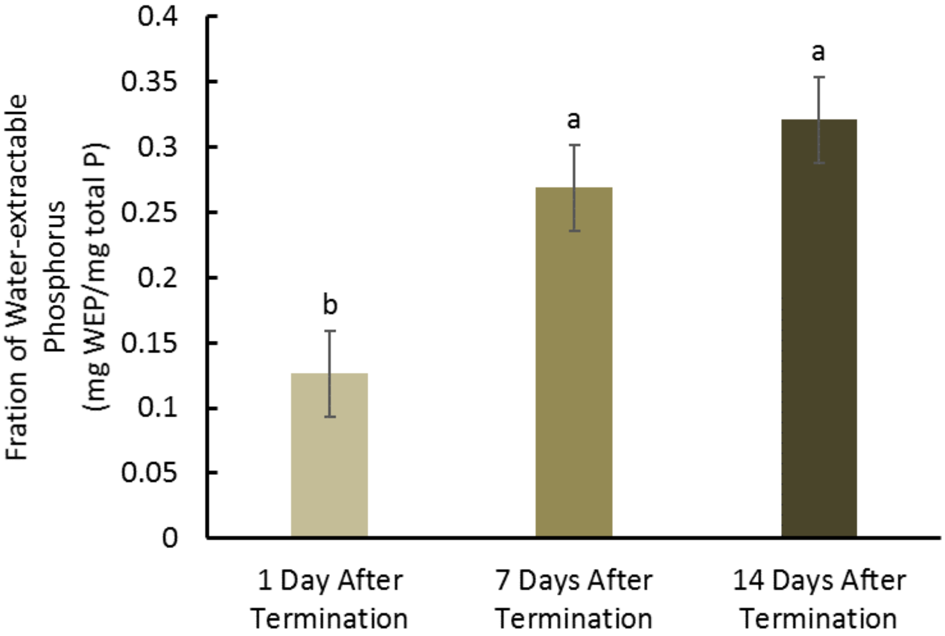


Figure 4.7. Impact of time after termination on fraction of water-extractable phosphorus to total phosphorus in crop biomass (data averaged over species and termination method). Letters indicate significant difference between treatments at *p<0.05*.

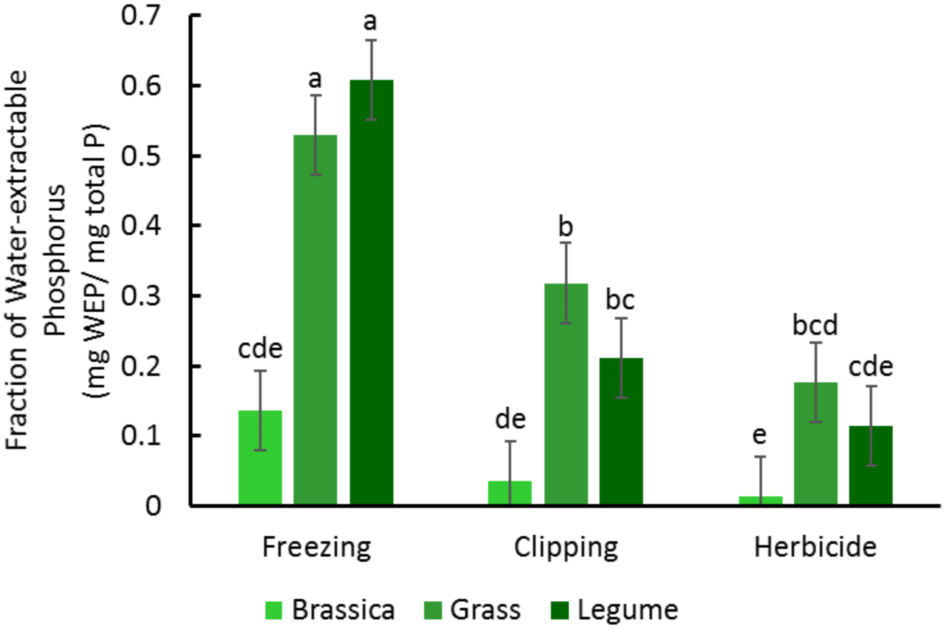


Figure 4.8. Effect of cover crop species and termination method on the water-extractable phosphorus fraction of total phosphorus in cover crop biomass (data averaged over time after termination time). Letters indicate significant difference between treatments at *p<0.05*.

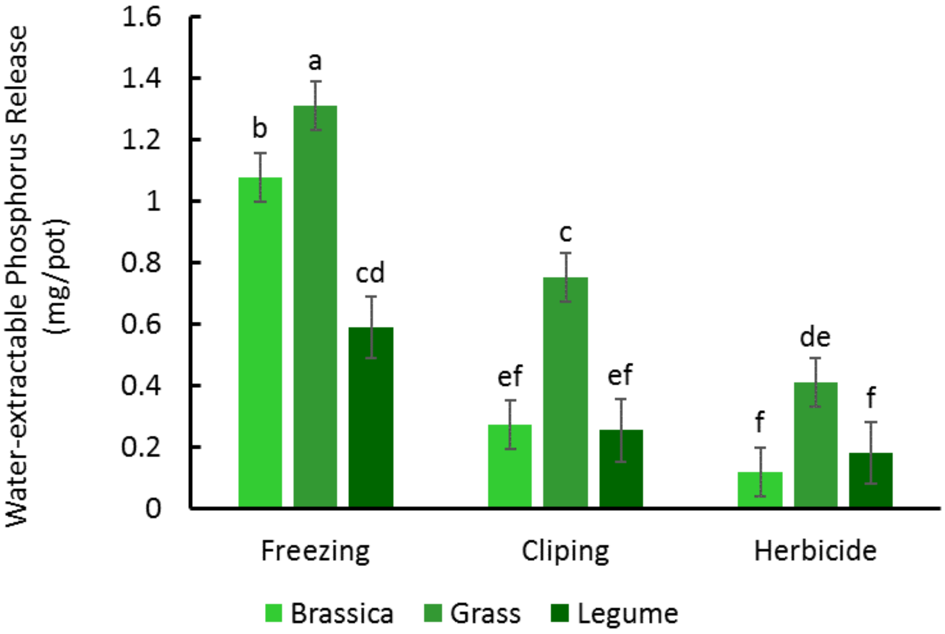


Figure 4.9. Effect of cover crop species and termination method on water-extractable phosphorus release from crop tissue (data averaged over time after termination). Different letters indicate significant difference between treatments at *p<0.05*.

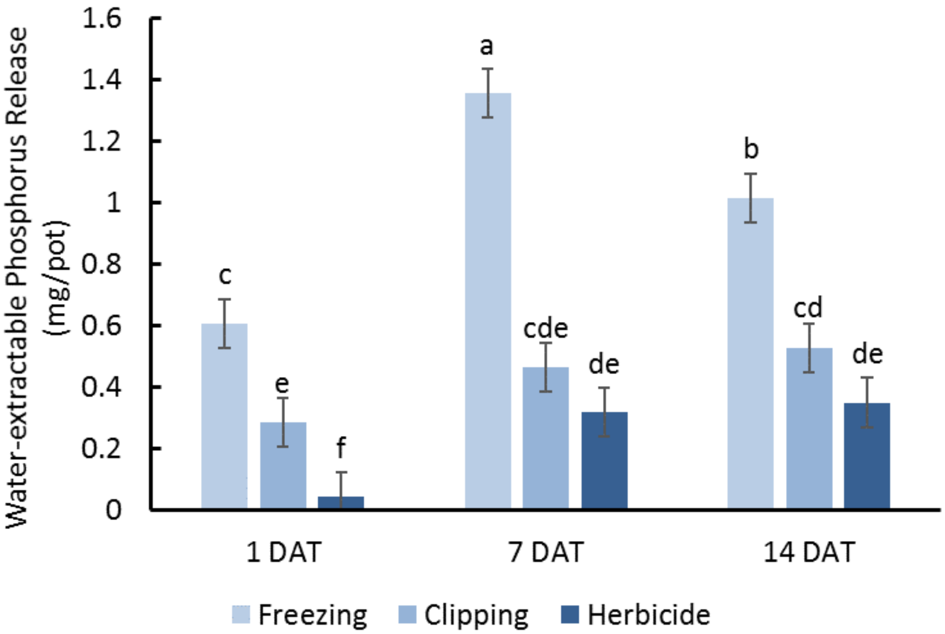


Figure 4.10. Effect of Time after termination and termination method on water-extractable phosphorus release from crop tissue (data averaged over species). Different letters indicate significant difference between treatments at p<0.05.

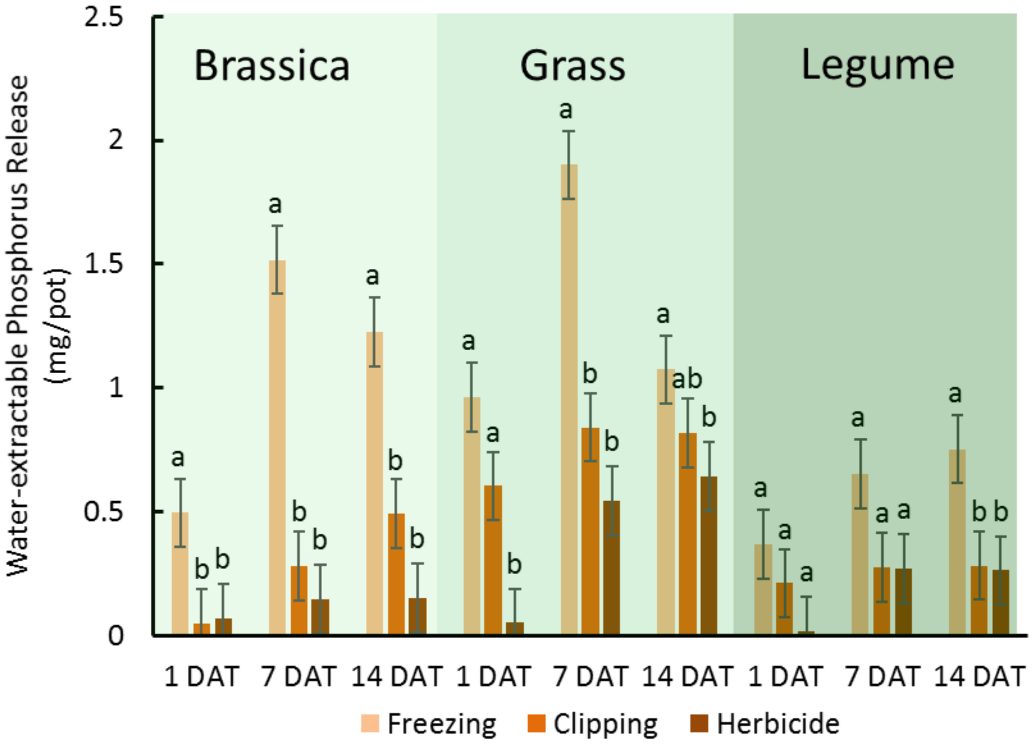
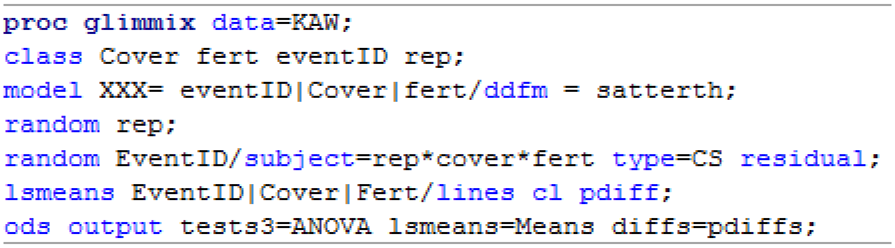


Figure 4.11. Effect of cover crop species, termination method, and time after termination on water-extractable phosphorus release from crop tissue. 1 day after termination (1), 7 days after termination (7), 14 days after termination (14). Different letters indicate significant difference between treatments within groups at *$p<0.05$*.

Appendix A – Runoff water analysis SAS code

The following SAS code was used to analyze all data covered in Chapter 2. Cover represents cover crop treatment (no cover crop and with cover crop). Fert represents fertilizer treatment (control, fall broadcast, and spring injected). EventID represents the date runoff was collected. Rep represents which block the runoff sample was collected from. XXX represents the variable of interest.



```
proc glimmix data=KAW;
class Cover fert eventID rep;
model XXX= eventID|Cover|fert/ddfm = satterth;
random rep;
random EventID/subject=rep*cover*fert type=CS residual;
lsmeans EventID|Cover|Fert/lines cl pdiff;
ods output tests3=ANOVA lsmeans=Means diffs=pdiffs;
```

Appendix B – Means Tables for Nutrient Cycling and Soil Test Data

Table B.1. LSD table for 2016 cropping year. No cover (NC), cover crop (CC) standard error (SE), control application of phosphorus (P) fertilizer (CN), fall broadcast application of P fertilizer (FB), spring injected application of P fertilizer (SI), nitrogen (N), potassium (K).

				Uptake			Removal			Deposition		
	Yield	Soybean Biomass	Cover Crop Biomass	N	P	K	N	P	K	N	P	K
						kg/ha						
NC	4160	12435		401	30	193	257	21	72	152	10	123
CC	4188	12462		385	31	197	261	22	74	139	14	144
p-value	0.833	0.961		0.493	0.572	0.662	0.628	0.443	0.410	0.370	0.042	0.011
SE	130.18	537.23		19.65	1.78	8.51	8.91	0.75	2.38	13.76	1.53	7.00
LSD	290.04	1170.62		44	4	19	20	2	5	31	3	15
CN	3918	11828	1367	372	27	184	243	18	66	138	11	126
FB	4393	12940	2424	418	34	204	275	23	78	161	14	138
SI	4212	12576	1679	389	32	199	260	22	74	138	12	135
p-value	0.040	0.265	0.272	0.294	0.020	0.180	0.042	0.001	0.005	0.326	0.455	0.401
SE	159.81	657.97	420.60	22.64	2.19	10.42	10.92	0.92	2.92	16.85	1.88	8.57
LSD	356.06	1433.72	1167.59	50	5	23	24	2	6	38	4	19
NC-CN	3846	12761		377	25	181	238	18	63	144	10	120
CC-CN	3990	11834		367	28	187	247	19	68	132	12	133
NC-FB	4464	12431		423	33	198	276	23	77	166	11	121
CC-FB	4323	1182		412	35	209	274	23	78	156	16	155
NC-SI	4171	12721		403	32	201	256	22	74	147	10	127
CC-SI	4253	13120		376	31	196	263	22	75	130	14	143
p-value	0.656	0.8864		0.941	0.649	0.754	0.867	0.701	0.731	0.981	0.730	0.470
SE	226.00	930.51		39.22	3.09	14.73	15.14	1.31	4.13	23.83	2.65	12.12
LSD	503.53	2027.58		87	7	32	34	3	9	53	6	26

Table B.2. LSD table for 2017 cropping year. No cover (NC), cover crop (CC) standard error (SE), control application of phosphorus (P) fertilizer (CN), fall broadcast application of P fertilizer (FB), spring injected application of P fertilizer (SI), nitrogen (N), potassium (K)

					Uptake			Removal			Deposition		
	Yield	Corn Stalk Biomass	Corn Cob Biomass	Cover Crop Biomass	N	P	K	N	P	K	N	P	K
							kg/ha						
NC	7700	10971	991		253	43	260	85	17	18	169	26	242
CC	5600	15288	730		188	34	193	66	14	15	145	27	215

p-value	0.002	<0.001	0.005		<0.001	0.020	<0.001	0.002	0.014	0.008	0.013	0.718	0.032
SE	496.330	712.56	72.137		10.282	3.108	11.598	4.410	1.063	0.922	8.045	2.430	10.685
LSD	1105.82	1587.58	160.72		22.40	6.92	25.84	9.83	2.37	2.05	17.53	5.41	23.81
CN	6000	12539	803	1367	205	30	214	66	12	14	148	21	215
FB	7000	13662	897	2424	227	43	234	79	17	17	163	31	242
SI	7000	13188	881	1679	230	42	231	81	17	17	159	28	230
p-value	0.183	0.462	0.546	0.008	0.149	0.015	0.365	0.046	0.007	0.015	0.321	0.017	0.164
SE	607.880	872.70	88.349	167.790	12.593	3.806	14.205	5.401	1.302	1.130	9.854	2.976	13.087
LSD	1354.36	1944.38	196.84	465.79	27.44	8.48	31.65	12.03	2.90	2.52	21.47	6.63	29.16
NC-CN	7100	14707	909		233	32	246	76	14	15	157	18	230
CC-CN	4800	10371	698		178	29	183	57	11	12	140	23	199
NC-FB	8000	15886	1074		264	48	270	88	19	19	175	29	250
CC-FB	6000	11438	720		190	38	199	69	15	15	151	32	233
NC-SI	8000	15271	990		263	48	263	89	18	18	174	30	245
CC-SI	6000	11105	771		196	35	198	73	15	16	145	25	214
p-value	0.954	0.987	0.671		0.770	0.419	0.958	0.947	0.744	0.498	0.838	0.310	0.818
SE	859.670	1234.19	124.940		17.809	5.382	16.381	7.638	1.842	1.598	13.935	4.208	18.507
LSD	1915.34	2749.78	278.37		38.81	11.99	36.50	17.02	4.10	3.56	30.36	9.38	41.23

Table B.3. LSD table for soil test data at Kansas Agricultural Watershed field laboratory. Melich-3 Phosphorus (M3P), Nitrate-nitrogen (NO3), Potassium (K), total phosphorus (TP), total carbon (TC), no cover crop (NC), cover crop (CC), control application of phosphorus fertilizer (CN), fall broadcast (FB), spring injected (SI), standard error (SE), least significant difference (LSD).

	pH	M3P*	NO3*	K	TP	TC
				ppm		
NC	6.7	2.9	1.6	356.0	350.6	1.2
CC	6.8	2.8	1.2	345.1	346.3	1.2
p-value	0.163	0.288	0.003	0.242	0.519	0.431
SE	0.042	0.101	0.099	8.816	6.541	0.034
LSD	0.1	0.2	0.2	19.2	13.7	0.1
CN	6.8	2.4	1.5	350.1	332.1	1.2
FB	6.7	3.0	1.3	345.2	359.6	1.2
SI	6.7	3.0	1.3	356.3	353.8	1.2
p-value	0.158	<0.001	0.571	0.604	0.012	0.630
SE	0.051	0.123	0.121	10.797	8.041	0.042
LSD	0.1	0.3	0.3	23.5	17.5	0.1
2015	6.7	2.8	0.8	344.0	346.8	1.2
2016	6.8	2.9	1.5	372.9	361.2	1.2
2017	6.6	2.7	1.8	334.7	337.4	1.2
p-value	<0.001	0.041	<0.001	<0.001	0.012	0.315
SE	0.027	0.716	0.118	5.320	7.314	0.011
LSD	0.1	1.5	0.2	10.6	15.1	0.02

0-5 cm	6.9	3.4	1.5	408.7	372.2	1.3
5-15 cm	6.5	2.2	1.3	292.4	324.7	1.1
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
SE	0.022	0.058	0.029	4.341	3.813	0.009
LSD	0.04	0.1	0.1	8.7	7.7	0.02
NC-CN	6.7	2.5	1.7	353.1	329.3	1.2
CC-CN	6.8	2.3	1.2	347.1	334.9	1.1
NC-FB	6.7	3.2	1.6	351.8	358.2	1.2
CC-FB	6.7	2.9	1.1	338.6	361.0	1.2
NC-SI	6.7	3.0	1.5	362.9	364.5	1.2
CC-SI	6.8	3.0	1.2	349.6	343.1	1.2
p-value	0.658	0.551	0.752	0.928	0.222	0.318
SE	0.072	0.174	0.172	15.269	11.334	0.059
LSD	0.2	0.4	0.4	33.3	24.7	0.1
CN-2015	6.7	2.5	0.9	336.8	330.2	1.1
CN-2016	6.9	2.5	1.5	383.8	341.3	1.2
CN-2017	6.7	2.2	2.0	329.7	324.7	1.2
FB-2015	6.7	3.1	0.9	339.6	355.3	1.2
FB-2016	6.8	3.1	1.5	362.7	370.9	1.2
FB-2017	6.6	2.9	1.7	333.4	352.6	1.2
SI-2015	6.7	2.8	0.7	355.5	355.0	1.2
SI-2016	6.7	3.1	1.6	372.2	371.4	1.2
SI-2017	6.7	3.0	1.7	341.2	334.8	1.2
p-value	0.182	0.048	0.473	0.133	0.769	0.325
SE	0.043	0.159	0.207	13.159	13.084	0.045
LSD	0.1	0.3	0.4	27.1	26.5	0.1
NC-2015	6.7	2.8	0.9	343.1	353.5	1.2
NC-2016	6.8	3.0	1.6	382.8	366.6	1.2
NC-2017	6.6	2.8	2.2	341.9	331.9	1.2
CC-2015	6.7	2.8	0.8	344.8	340.2	1.2
CC-2016	6.8	2.8	1.4	363.0	355.9	1.2
CC-2017	6.7	2.6	1.4	327.6	342.9	1.2
p-value	0.027	0.319	0.007	0.117	0.212	0.598
SE	0.038	0.130	0.169	10.745	10.684	0.037
LSD	0.1	0.3	0.3	22.1	21.7	0.1
CN:0-5	7.0	2.8	1.6	405.8	346.2	1.3
CN:5-15	6.6	2.0	1.3	294.4	317.9	1.1
FB:0-5	6.9	3.8	1.5	407.8	393.8	1.3
FB:5-15	6.5	2.3	1.2	282.7	325.4	1.1

SI:0-5	6.9	3.5	1.4	412.6	376.6	1.3
SI:5-15	6.5	2.4	1.3	299.9	330.9	1.1
p-value	0.651	<0.001	0.380	0.371	<0.001	0.805
SE	0.058	0.142	0.126	12.036	9.275	0.043
LSD	0.1	0.3	0.3	25.3	19.3	0.1
NC:0-5	6.9	3.4	1.3	405.2	374.4	1.3
NC:5-15	6.5	2.3	1.1	285.0	326.9	1.1
CC:0-5	7.0	3.3	1.7	412.2	370.1	1.3
CC:5-15	6.5	2.2	1.4	299.7	322.5	1.1
p-value	0.089	0.948	0.035	0.381	0.993	<0.001
SE	0.047	0.115	0.103	9.828	7.574	0.035
LSD	0.2	0.2	20.6	15.3	0.1	0.077
2015:0-5	6.9	3.3	0.8	392.9	363.0	1.3
2015:5-15	6.5	2.3	0.8	295.1	330.7	1.1
2016:0-5	7.0	3.5	1.8	444.5	390.3	1.3
2016:5-15	6.6	2.3	1.3	301.3	332.2	1.1
2017:0-5	6.8	3.3	1.9	388.8	363.4	1.3
2017:5-15	6.5	2.1	1.7	280.6	311.4	1.1
p-value	0.054	0.156	<0.001	<0.001	0.023	0.119
SE	0.038	0.101	0.123	7.521	8.678	0.016
LSD	0.1	0.2	0.3	15.0	17.5	0.03
NC-CN-2015	6.7	2.5	1.0	327.1	328.1	1.2
NC-CN-2016	6.9	2.6	1.7	392.9	343.2	1.2
NC-CN-2017	6.6	2.3	2.4	339.3	316.4	1.2
NC-FB-2015	6.7	3.2	1.0	339.7	362.2	1.2
NC-FB-2016	6.8	3.2	1.5	375.3	371.9	1.2
NC-FB-2017	6.5	3.1	2.2	340.5	340.5	1.2
NC-SI-2015	6.7	2.7	0.8	362.6	370.0	1.2
NC-SI-2016	6.7	3.2	1.5	380.3	384.5	1.2
NC-SI-2016	6.6	2.9	1.2	346.0	338.8	1.2
CC-CN-2015	6.8	2.6	0.7	346.4	332.2	1.1
CC-CN-2016	6.9	2.4	1.3	374.8	339.4	1.2
CC-CN-2017	6.7	2.0	1.7	320.1	333.0	1.1
CC-FB-2015	6.6	3.0	0.8	339.6	348.4	1.2
CC-FB-2016	6.8	3.0	1.5	350.1	369.9	1.2
CC-FB-2017	6.7	2.8	1.2	326.2	364.6	1.2
CC-SI-2015	6.7	2.9	0.6	348.4	339.9	1.2
CC-SI-2016	6.8	3.0	1.6	364.1	358.3	1.2
CC-SI-2017	6.8	3.1	2.1	336.3	330.9	1.3
p-value	0.222	0.740	0.642	0.527	0.963	0.263

SE	0.065	0.223	0.292	18.611	18.504	0.063
LSD	0.1	0.5	0.6	38.3	37.5	0.1

NC-CN:0-5	6.9	2.8	1.8	411.5	340.1	1.3
NC-CN:5-15	6.6	2.1	1.5	294.7	318.5	1.1
NC-FB:0-5	6.8	4.0	1.7	413.2	396.5	1.3
NC-FB:5-15	6.5	2.4	1.4	290.4	319.9	1.1
NC-SI:0-5	6.9	3.5	1.6	412.0	386.5	1.2
NC-SI:5-15	6.5	2.5	1.4	313.9	342.4	1.1
CC-CN:0-5	7.0	2.7	1.3	400.0	352.4	1.3
CC-CN:5-15	6.6	2.0	1.2	294.1	317.4	1.0
CC-FB:0-5	6.9	3.7	1.3	402.3	391.1	1.3
CC-FB:5-15	6.5	2.2	1.0	275.0	330.8	1.1
CC-SI:0-5	7.0	3.6	1.2	413.3	366.7	1.4
CC-SI:5-15	6.5	2.4	1.1	285.9	319.4	1.1
p-value	0.942	0.501	0.616	0.171	0.284	0.051
SE	0.082	0.201	0.179	17.022	12.272	0.061
LSD	0.2	0.4	0.4	35.8	24.5	0.1

NC-2015:0-5	6.9	3.3	0.9	388.3	370.3	1.3
NC-2015:5-15	6.5	2.3	0.8	298.0	336.6	1.1
NC-2016:0-5	7.0	3.6	1.8	452.3	397.6	1.2
NC-2016:5-15	6.6	2.4	1.4	313.4	335.5	1.1
NC-2017:0-5	6.7	3.4	2.4	396.1	355.2	1.3
NC-2017:5-15	6.4	2.2	2.1	287.7	308.6	1.1
CC-2015:0-5	6.9	3.3	0.8	397.4	355.6	1.3
CC-2015:5-15	6.5	2.4	0.8	292.2	324.7	1.1
CC-2016:0-5	7.1	3.5	1.7	436.6	383.0	1.3
CC-2016:5-15	6.6	2.1	1.2	289.3	328.8	1.1
CC-2017:0-5	6.9	3.2	1.3	381.6	371.6	1.3
CC-2017:5-15	6.5	2.1	1.4	273.6	314.1	1.1
p-value	0.537	0.714	0.091	0.771	0.582	0.347
SE	0.054	0.164	0.176	13.117	13.118	0.039
LSD	0.1	0.3	0.4	26.4	27.3	0.1

CN-2015:0-5	6.9	2.9	0.9	382.8	341.0	1.3
CN-2015:5-15	6.6	2.2	0.8	290.7	319.4	1.0
CN-2016:0-5	7.1	2.8	1.7	452.6	355.5	1.3
CN-2016:5-15	6.7	2.1	1.3	315.1	327.2	1.1
CN-2017:0-5	6.8	2.6	2.1	381.9	342.2	1.3
CN-2015:5-15	6.5	1.8	2.0	277.4	307.2	1.0
FB-2015:0-5	6.8	3.8	0.9	388.7	382.8	1.3
FB-2015:5-15	6.5	2.4	0.8	290.6	327.8	1.1

FB-2016:0-5	7.0	3.9	1.8	441.4	409.8	1.3
FB-2016:5-15	6.5	2.2	1.3	283.9	332.0	1.1
FB-2017:0-5	6.8	3.7	1.8	393.1	388.9	1.3
FB-2017:5-15	6.4	2.2	1.5	273.6	316.3	1.1
SI-2015:0-5	7.0	3.3	0.7	407.1	365.1	1.3
SI-2015:5-15	6.5	2.4	0.7	303.9	344.9	1.1
SI-2016:0-5	7.0	3.8	1.8	439.4	405.5	1.3
SI-2016:5-15	6.5	2.5	1.4	304.9	337.4	1.1
SI-2017:0-5	6.8	3.5	1.7	391.4	359.2	1.3
SI-2017:5-15	6.5	2.5	1.6	290.9	310.5	1.1
p-value	0.807	0.750	0.817	0.848	0.506	0.209
SE	0.065	0.201	0.215	16.065	15.383	0.048
LSD	0.1	0.4	0.4	32.3	30.8	0.1

NC-CN-2015:0-5	6.9	2.8	1.1	369.4	337.4	1.2
NC-CN-2015:5-15	6.5	2.2	1.0	284.8	318.9	1.1
NC-FB-2015:0-5	6.9	3.9	1.0	388.1	398.6	1.2
NC-FB-2015:5-15	6.5	2.4	0.9	291.2	325.8	1.1
NC-SI-2515:0-5	6.9	3.2	0.7	407.2	374.9	1.3
NC-SI-2015:5-15	6.5	2.3	0.6	317.9	365.1	1.1
CC-CN-2015:0-5	7.0	2.9	0.7	396.1	344.5	1.3
CC-CN-2015:5-15	6.6	2.2	0.6	296.7	319.8	1.0
CC-FB-2015:0-5	6.8	3.6	0.8	389.3	367.0	1.3
CC-FB-2015:5-15	6.5	2.4	0.8	289.9	329.7	1.1
CC-SI-2015:0-5	7.0	3.3	0.8	406.9	355.3	1.3
CC-SI-2015:5-15	6.5	2.5	0.9	290.0	324.6	1.1
NC-CN-2016:0-5	7.2	3.0	1.9	469.0	354.3	1.3
NC-CN-2016:5-15	6.7	2.2	1.4	316.8	332.2	1.1
NC-FB-2016:0-5	7.0	4.0	1.8	452.8	416.6	1.3
NC-FB-2016:5-15	6.6	2.4	1.3	297.9	327.2	1.1
NC-SI-2016:0-5	6.9	3.8	1.8	435.1	421.9	1.2
NC-SI-2016:5-15	6.5	2.7	1.5	325.4	347.2	1.1
CC-CN-2016:0-5	7.1	2.7	1.5	436.1	356.6	1.3
CC-CN-2016:5-15	6.7	2.1	1.1	313.4	322.2	1.1
CC-FB-2016:0-5	7.1	3.8	1.8	430.1	403.0	1.3
CC-FB-2016:5-15	6.5	2.1	1.2	270.0	336.7	1.1
CC-SI-2016:0-5	7.1	3.8	1.7	443.7	389.2	1.3
CC-SI-2016:5-15	6.5	2.3	1.3	284.4	327.5	1.1
NC-CN-2017:0-5	6.7	2.7	2.5	396.0	328.5	1.3
NC-CN-2017:5-15	6.6	1.9	2.3	282.6	304.3	1.1
NC-FB-2017:0-5	6.7	3.9	2.3	398.8	374.4	1.3
NC-FB-2017:5-15	6.4	2.3	2.0	282.2	306.7	1.1
NC-SI-2017:0-5	6.7	3.5	2.3	393.6	362.7	1.3

NC-SI-2017:5-15	6.4	2.4	2.0	298.4	314.9	1.1
CC-CN-2017:0-5	7.0	2.4	1.6	367.9	355.9	1.2
CC-CN-2017:5-15	6.5	1.6	1.7	272.3	310.2	1.0
CC-FB-2017:0-5	6.9	3.5	1.2	387.4	403.3	1.4
CC-FB-2017:5-15	6.5	2.1	1.1	265.0	325.9	1.1
CC-SI-2017:0-5	6.9	3.6	1.2	389.3	355.6	1.4
CC-SI-2017:5-15	6.6	2.5	1.3	283.3	306.2	1.2
p-value	0.140	0.962	0.557	0.709	0.680	0.639
SE	0.111	0.284	0.305	22.719	21.754	0.069
LSD	0.2	0.6	0.6	45.7	43.5	0.1

*: all data for both M3P and NO3 are depicted as natural logarithm transformed means

Appendix C – Greenhouse study data

Prior to conducting the study outlined in Chapter 4, an initial study was run using the same treatments and methodology as previously stated in Chapter 4. The initial greenhouse study was conducted at the Kansas State University Greenhouse Facilities located in Manhattan, KS and occurred from December 13, 2016-March 2, 2017. Results from the initial study and second round study are presented below.

Table C.1. LSD table for first round greenhouse trial. Total phosphorus (TP), concentration (concn), water-extractable phosphorus (WEP), fraction of total phosphorus that is water-extractable (WEP:TP), cover crop species (crop), method of termination (method), time after termination (DAT).

Effect	Treatment	Biomass	TP concn.	TP uptake	WEP concn.	WEP release	WEP:TP
		g/pot	mg/kg	g/pot	mg/kg	mg/pot	mg/mg
Crop	Brassica	4	3493	53	500	0.5	0.15
	Grass	3	4848	16	1051	1.1	0.22
	Legume	1	3109	20	908	0.9	0.24
	p-value	<0.001	<0.001	0.461	0.002	<0.001	<0.001
	SE	0.29	116.87	32.58	157.39	0.25	0.03
	LSD	0.58	231	64	311	0.5	0.05
Method	Clipping	3	3831	49	579	1.4	0.14
	Freezing	3	3913	15	1198	2.7	0.31
	Herbicide	3	3707	24	681	1.4	0.15
	p-value	0.695	0.21	0.55	<0.001	<0.001	<0.001
	SE	0.29	116.87	32.58	157.39	0.25	0.03
	LSD	0.58	231	64	311	0.5	0.05
DAT	1	3	4021	12	670	1.2	0.14
	7	20	3713	66	761	1.9	0.20
	14	3	3716	10	1027	2.3	0.27
	p-value	0.500	0.012	0.159	0.066	<0.001	<0.001
	SE	0.29	116.87	32.58	157.39	0.25	0.03
	LSD	0.58	231	64	311	0.5	0.05

Table C.2. LSD table for two-way interactions in first round greenhouse trial. Total phosphorus (TP), concentration (concn), water-extractable phosphorus (WEP), fraction of total phosphorus that is water-extractable (WEP:TP), cover crop species (crop), method of termination (method), time after termination (DAT).

Effect	Crop	Method	DAT	Biomass	TP concn.	TP uptake	WEP concn.	WEP release	WEP:TP
				g/pot	g/kg	g/pot	g/kg	g/pot	g/g
Crop*Method	Brassica	Clipping		5	3559	129	228	1.2	0.07
	Brassica	Freezing		4	3447	13	925	3.0	0.27
	Brassica	Herbicide		5	3474	16	346	1.7	0.11
	Grass	Clipping		3	4980	16	791	2.4	0.16
	Grass	Freezing		3	5166	18	1585	4.4	0.32
	Grass	Herbicide		3	4399	13	776	2.0	0.18
	Legume	Clipping		1	2954	2	717	0.6	0.21
	Legume	Freezing		1	3126	12	1084	0.6	0.35
	Legume	Herbicide		1	3248	44	922	0.5	0.16
	p-value			0.392	0.007	0.305	0.551	<0.001	0.683
	SE			0.51	202.43	56.42	272.61	0.42	0.05
	LSD			1	400	111	539	0.8	0.09
Crop*DAT	Brassica		1	4	3580	14	265	1.0	0.08
	Brassica		7	5	3476	129	435	2.0	0.13
	Brassica		14	5	3424	15	800	2.8	0.23
	Grass		1	4	5084	20	660	2.0	0.13
	Grass		7	3	4679	14	1106	3.3	0.24
	Grass		14	3	4782	13	1386	3.6	0.29
	Legume		1	1	3399	3	1087	0.6	0.20
	Legume		7	1	2985	54	742	0.5	0.23
	Legume		14	1	2944	2	895	0.6	0.30
	p-value			0.098	0.739	0.582	0.127	0.017	0.747
	SE			0.51	202.43	56.42	272.61	0.42	0.05
	LSD			1	400	111	539	0.8	0.09
Method*DAT		Clipping	1	3	3937	12	439	0.75	0.12
		Clipping	7	3	3894	125	606	1.63	0.12
		Clipping	14	3	3663	10	691	1.76	0.19
		Freezing	1	3	4127	14	966	2.17	0.25
		Freezing	7		3653	20	1062	2.74	0.29
		Freezing	14	2	3959	10	1566	3.22	0.40
		Herbicide	1	3	3999	10	606	0.73	0.04
		Herbicide	7	3	3593	52	615	1.46	0.19
		Herbicide	14	3	3529	11	823	2.03	0.23
	p-value			0.527	0.297	0.649	0.783	0.938	0.243

Effect	Crop	Method	DAT	Biomass	TP concn.	TP uptake	WEP concn.	WEP release	WEP:TP
				g/pot	g/kg	g/pot	g/kg	g/pot	g/g
	SE			0.51	202.43	56.42	272.61	0.42	0.05
	LSD			1	400	111	539	0.8	0.09

Table C.3. LSD table for three-way interactions in first round greenhouse study. Total phosphorus (TP), concentration (concn), water-extractable phosphorus (WEP), fraction of total phosphorus that is water-extractable (WEP:TP), cover crop species (crop), method of termination (method), time after termination (DAT).

Effect	Crop	Method	DAT	Biomass	TP concn.	TP uptake	WEP concn.	WEP release	WEP:TP
				g/pot	g/kg	g/pot	g/kg	g/pot	g/g
Crop*Method*DAT	Brassica	Clipping	1	5	3655	17	57	0.2	0.02
	Brassica	Clipping	7	6	3628	357	180	1.5	0.05
	Brassica	Clipping	14	4	3395	13	447	1.7	0.13
	Brassica	Freezing	1	4	3477	13	509	1.8	0.15
	Brassica	Freezing	7	4	3315	14	820	3.4	0.26
	Brassica	Freezing	14	4	3548	12	1448	3.9	0.39
	Brassica	Herbicide	1	3	3608	12	228	1.1	0.07
	Brassica	Herbicide	7	5	3483	16	305	1.2	0.10
	Brassica	Herbicide	14	6	3330	21	505	2.8	0.15
	Grass	Clipping	1	3	4853	16	467	1.2	0.10
	Grass	Clipping	7	3	4995	17	859	2.8	0.17
	Grass	Clipping	14	3	5092	16	1047	3.2	0.21
	Grass	Freezing	1	4	5778	28	1330	4.2	0.25
	Grass	Freezing	7	3	4637	13	1593	4.2	0.35
	Grass	Freezing	14	3	5082	14	1832	5.0	0.36
	Grass	Herbicide	1	4	4620	17	183	0.6	0.04
	Grass	Herbicide	7	3	4405	13	866	2.8	0.20
	Grass	Herbicide	14	2	4173	9	1279	2.7	0.31
	Legume	Clipping	1	1	3302	3	793	0.9	0.25
	Legume	Clipping	7	1	3058	2	779	0.6	0.14
	Legume	Clipping	14	1	2502	1	580	0.4	0.25
	Legume	Freezing	1	1	3125	2	1061	0.5	0.35
	Legume	Freezing	7	2	3008	33	774	0.7	0.28
	Legume	Freezing	14	1	3246	2	1417	0.8	0.44
	Legume	Herbicide	1	1	3770	3	1407	0.5	0.01
	Legume	Herbicide	7	1	2890	128	673	0.4	0.26
	Legume	Herbicide	14	1	3083	2	686	0.6	0.22
	p-value			0.136	0.191	0.303	0.848	0.445	0.243
	SE			0.885	350.61	97.73	472.18	0.74	0.08
	LSD			2	693	193	933	1.5	0.16

Table C.4. LSD table for main effect of treatment for 2nd round greenhouse trial. Total phosphorus (TP), concentration (concn), water-extractable phosphorus (WEP), fraction of total phosphorus that is water-extractable (WEP:TP), cover crop species (crop), method of termination (method), time after termination (DAT).

Effect	Treatment	Biomass g/pot	TP concn. mg/kg	TP uptake g/pot	WEP concn. mg/kg	WEP release mg/pot	WEP:TP mg/mg
Crop	Brassica	2.9	3324	9.5	207	0.5	0.06
	Grass	0.8	3369	2.7	1100	0.8	0.34
	Legume	0.4	3190	1.4	965	0.3	0.31
	p-value	<0.001	0.285	<0.001	<0.001	<0.001	<0.001
	SE	0.278	116.724	0.708	154.077	0.065	0.046
	LSD	0.5	231	1.4	304	0.1	0.09
Method	Clipping	1.28	3339.07	4.22	605.34	0.43	0.19
	Freezing	1.47	3298.15	4.75	1336.51	0.99	0.43
	Herbicide	1.41	3246.30	4.58	330.29	0.24	0.10
	p-value	0.791	0.73	0.74	<0.001	<0.001	<0.001
	SE	0.278	116.724	0.708	154.077	0.065	0.046
	LSD	0.5	231	1.4	304	0.1	0.09
DAT	1	1.3	3299	4.3	419	0.3	0.13
	7	1.4	3386	4.5	865	0.7	0.27
	4	1.5	3198	4.7	988	0.6	0.32
	p-value	0.738	0.28	0.82	<0.001	<0.001	<0.001
	SE	0.278	116.724	0.708	154.077	0.065	0.046
	LSD	0.5	231	1.4	304	0.1	0.09

Table C.5. LSD table for two-way interactions in 2nd round greenhouse trial. Total phosphorus (TP), concentration (concn), water-extractable phosphorus (WEP), fraction of total phosphorus that is water-extractable (WEP:TP), cover crop species (crop), method of termination (method), time after termination (DAT).

Effect	Crop	Method	DAT	Biomass	TP concn.	TP uptake	WEP concn.	WEP release	WEP:TP
				g/pot	g/kg	g/pot	g/kg	g/pot	g/g
Crop*Method	Brassica	Clipping		3	3250	9	110	0.3	0.04
	Brassica	Freezing		3	3502	10	464	1.1	0.14
	Brassica	Herbicide		3	3222	9	46	0.1	0.01
	Grass	Clipping		1	3313	3	993	0.8	0.32
	Grass	Freezing		1	3407	3	1711	1.3	0.53
	Grass	Herbicide		1	3386	3	596	0.4	0.18
	Legume	Clipping		0	3454	1	712	0.3	0.21
	Legume	Freezing		0	2986	1	1835	0.6	0.61
	Legume	Herbicide		1	3131	2	349	0.2	0.12
	p-value			0.930	0.117	0.849	0.07	0.002	0.016
	SE			0.481	202.171	1.226	266.870	0.113	0.080
	LSD			1.0	399	2.4	527	0.2	0.16
Crop*DAT	Brassica		1	2.7	3271	8.7	98	0.2	0.03
	Brassica		7	2.8	3359	9.3	282	0.6	0.09
	Brassica		14	3.3	3343	10.4	240	0.6	0.07
	Grass		1	0.8	3349	2.8	684	0.5	0.20
	Grass		7	0.8	3538	2.8	1346	1.1	0.40
	Grass		14	0.8	3219	2.6	1270	0.8	0.42
	Legume		1	0.4	3278	1.3	475	0.2	0.15
	Legume		7	0.5	3261	1.6	968	0.4	0.32
	Legume		14	0.4	3033	1.2	1453	0.4	0.47
	p-value			0.790	0.740	0.817	0.189	0.157	0.144
	SE			0.481	202.171	1.226	266.870	0.113	0.080
	LSD			1.0	399	2.4	527	0.2	0.16
Method*DAT		Clipping	1	1.3	3386	4.2	518	0.3	0.16
		Clipping	7	1.3	3336	4.1	635	0.5	0.19
		Clipping	14	1.3	3296	4.3	663	0.5	0.22
		Freezing	1	1.3	3468	4.7	695	0.6	0.21
		Freezing	7	1.2	3233	3.9	1514	1.4	0.49
		Freezing	14	2.0	3193	5.7	1800	1.0	0.57
		Herbicide	1	1.3	3044	3.9	45	0.0	0.02
		Herbicide	7	1.6	3588	5.6	447	0.3	0.12
		Herbicide	14	1.3	3106	4.2	500	0.4	0.17
	p-value			0.457	0.082	0.404	0.132	0.005	0.073

Effect	Crop	Method	DAT	Biomass	TP concn.	TP uptake	WEP concn.	WEP release	WEP:TP
				g/pot	g/kg	g/pot	g/kg	g/pot	g/g
	SE			0.481	202.171	1.226	266.870	0.113	0.080
	LSD			1.0	399	2.4	527	0.2	0.16

Table C.6. LSD table for three-way interactions in 2nd round greenhouse trial. Total phosphorus (TP), concentration (concn), water-extractable phosphorus (WEP), fraction of total phosphorus that is water-extractable (WEP:TP), cover crop species (crop), method of termination (method), time after termination (DAT).

Effect	Crop	Method	DAT	Biomass	TP concn.	TP uptake	WEP concn.	WEP release	WEP:TP
				g/pot	g/kg	g/pot	g/kg	g/pot	g/g
Crop*Method*DAT	Brassica	Clipping	1	2.8	3120	8.9	17	0.0	0.01
	Brassica	Clipping	7	2.6	3178	8.4	124	0.3	0.04
	Brassica	Clipping	14	2.5	3452	8.7	191	0.5	0.06
	Brassica	Freezing	1	2.4	3822	9.4	252	0.5	0.07
	Brassica	Freezing	7	2.2	3448	7.7	674	1.5	0.20
	Brassica	Freezing	14	5.0	3235	13.9	467	1.2	0.14
	Brassica	Herbicide	1	2.8	2872	7.9	27	0.1	0.01
	Brassica	Herbicide	7	3.5	3450	11.7	47	0.1	0.01
	Brassica	Herbicide	14	2.5	3343	8.6	63	0.1	0.02
	Grass	Clipping	1	0.7	3373	2.4	884	0.6	0.29
	Grass	Clipping	7	0.8	3322	2.7	1037	0.8	0.32
	Grass	Clipping	14	0.9	3245	3.0	1059	0.8	0.35
	Grass	Freezing	1	0.9	3577	3.2	1108	1.0	0.30
	Grass	Freezing	7	0.9	3372	2.8	2165	1.9	0.68
	Grass	Freezing	14	0.6	3272	2.1	1858	1.1	0.60
	Grass	Herbicide	1	0.8	3098	2.6	61	0.0	0.02
	Grass	Herbicide	7	0.8	3920	2.9	835	0.5	0.21
	Grass	Herbicide	14	0.9	3140	2.7	891	0.6	0.30
	Legume	Clipping	1	0.4	3663	1.3	653	0.2	0.17
	Legume	Clipping	7	0.4	3507	1.4	743	0.3	0.22
	Legume	Clipping	14	0.4	3192	1.2	740	0.3	0.24
	Legume	Freezing	1	0.5	3007	1.5	726	0.4	0.25
	Legume	Freezing	7	0.4	2880	1.1	1703	0.7	0.59
	Legume	Freezing	14	0.3	3072	1.0	3075	0.8	0.98
	Legume	Herbicide	1	0.3	3163	1.1	46	0.0	0.02
	Legume	Herbicide	7	0.7	3395	2.3	457	0.3	0.14
	Legume	Herbicide	14	0.5	2835	1.4	544	0.3	0.19
	p-value			0.251	0.576	0.476	0.299	0.049	0.332
	SE			0.834	350.171	2.124	462.232	0.195	0.139
	LSD			1.6	692	4.2	913	0.4	0.27

Appendix D – Greenhouse methods validation study

A methods validation study was conducted in the Kansas State University Greenhouse Facility to determine if moisture content and total phosphorus concentration of two plants grown in the same pot were correlated. This study was conducted using the same growing conditions and materials as outlined in Chapter 4 with the exception that multiple termination methods and time after termination were not used. Three species of cover crops were grown: brassica (*Brassica napus* var. *Winfred*), grass (*X Triticosecale; Triticum x Secale* var. *Trical),* and legume (*Trifolium incarnatum* L.). Seeds were sown in 3.7-L plastic pots containing the same soil mixture outlined in Chapter 4. Pots were randomized and blocked across the greenhouse bench and a total of 10 replicates of each species was used. Each pot contained two plants (plant A and plant B) of the same species. Plants were grown for approximately 6 weeks. After 6 weeks, plants were clipped at soil level, wet tissue weight recorded, and placed in a 60 °C forced air oven. After drying, percent moisture of the plant tissue was recorded. Plants were then ground using a Wiley Mill and submitted to the Kansas State University Testing Lab for total phosphorus analysis. Results from this validation study are listed below.

Table D.1. LSD for greenhouse methods validation study.

Effect	Treatment	Moisture	Total Phosphorus
		%	%
Plant Selection	A	78.38	0.42
	B	78.90	0.41
	p-value	0.659	0.690
	SE	1.185	0.019
	LSD	2.680	0.042
Crop	Brassica	79.21	0.31
	Grass	81.85	0.56
	Legume	74.86	0.37

	p-value	<0.001	<0.001
	SE	1.324	0.022
	LSD	2.995	0.049
Crop*Plant Selection	Brassica-A	79.80	0.30
	Brassica-B	78.62	0.31
	Grass-A	81.32	0.59
	Grass-B	82.39	0.54
	Legume-A	74.02	0.36
	Legume-B	75.70	0.38
	p-value	0.584	0.404
	SE	1.674	0.029
	LSD	3.786	0.066

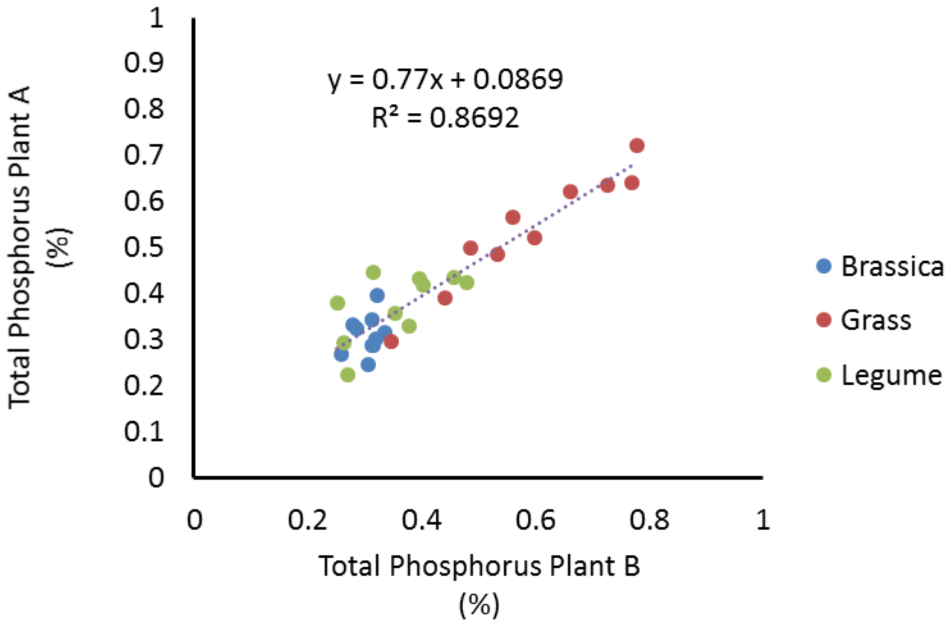


Figure D.1. Linear regression for total phosphorus concentration (%) in cover crop biomass.

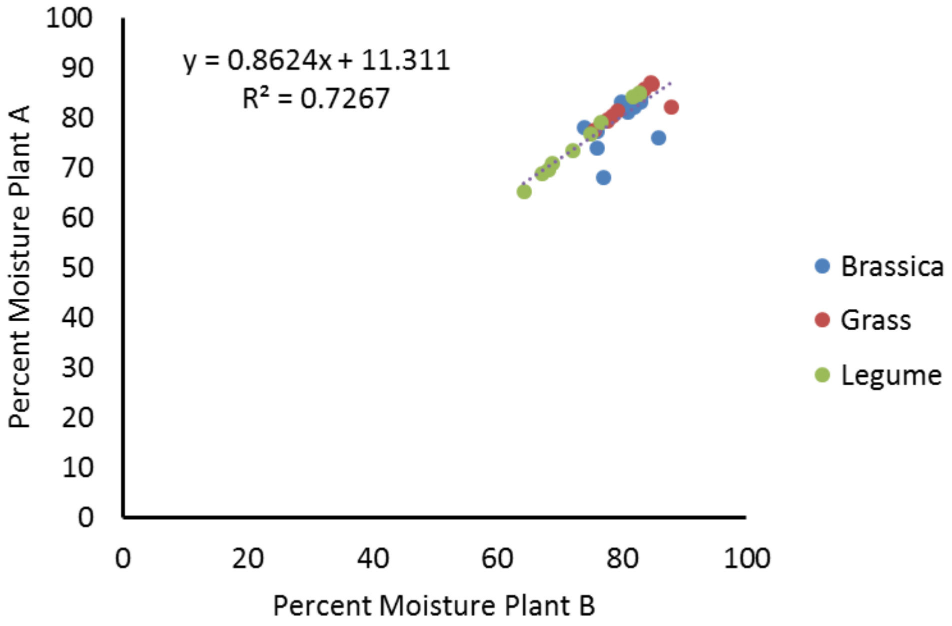


Figure D.2. Linear regression for percent moisture in cover crop biomass.

Appendix E - Extractable levels of ammonia and nitrate from cover crop tissue

As part of the chemical analysis run in Chapter 4, the levels of extractable ammonia and nitrate from crop tissue were measured. However, due to equipment error, the 1 day after termination (DAT) analysis for nitrate was not performed correctly. This error was not noted until after the 1 DAT samples had been discarded; therefore, statistical analysis was only performed on the 7 DAT and 14 DAT samples.

Table E.1. ANOVA table for analysis of ammonia and nitrate release from extracted crop biomass. Analysis only includes 7 and 14 days after termination due to inconsistencies in the 1 day after termination chemical analysis process. Cover crop species (crop), method of termination (method), days after termination (DAT), ammonia (NH_3), nitrate (NO_3^-).

	NH_3	NO_3^-
Crop	<0.001	<0.001
Method	<0.001	0.001
DAT	0.055	0.929
Crop*Method	<0.001	0.006
Crop*DAT	0.215	0.432
Method*DAT	0.195	0.745
Crop*Method*DAT	0.402	0.656

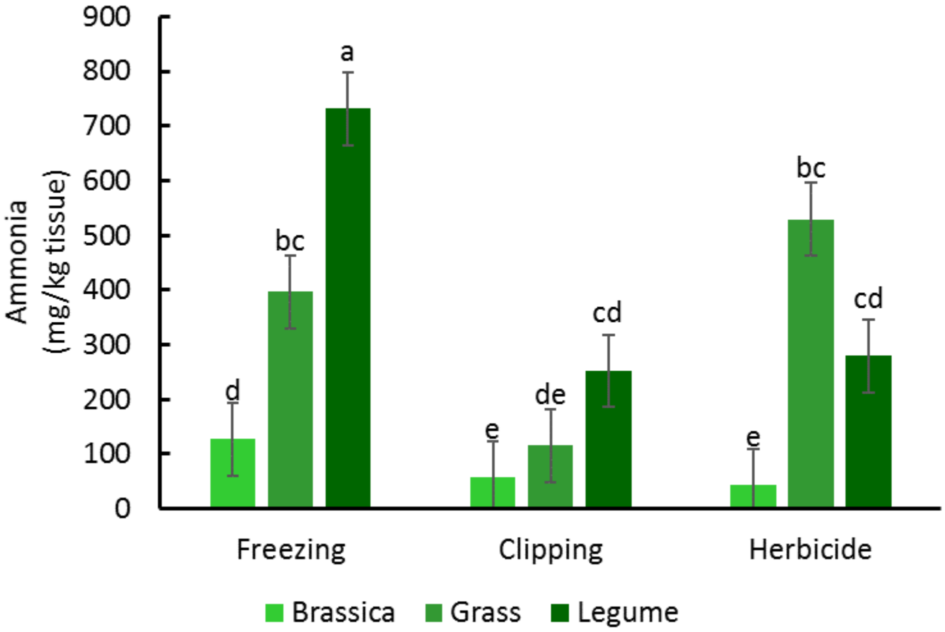


Figure E.1. Effect of cover crop species and termination method on ammonia concentration of crop tissue. Letters represent differences between treatments at *p<0.05*.

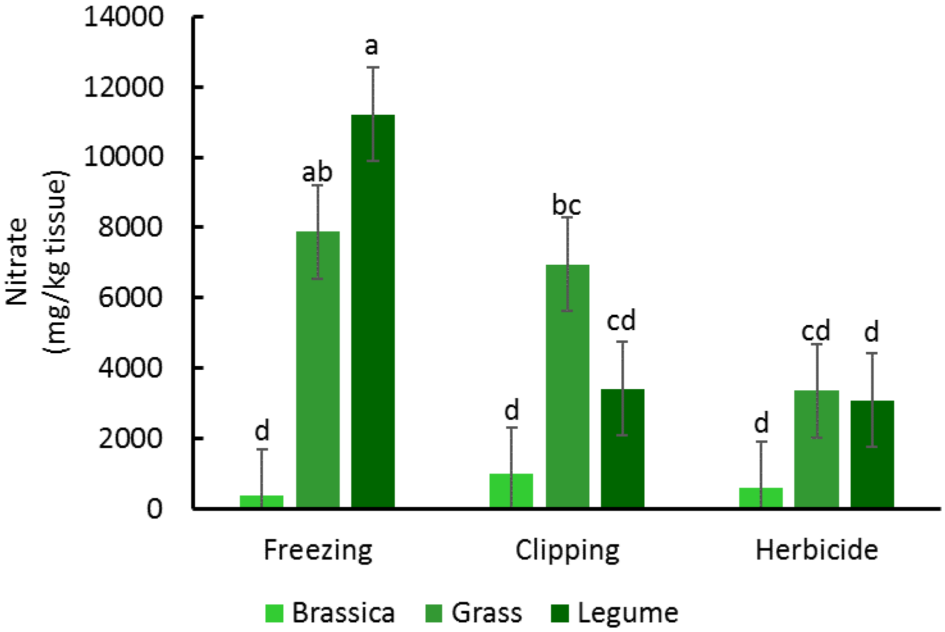


Figure E.2. Effect of cover crop species and termination method on nitrate concentration of crop tissue. Different letters indicate differences between treatments at *p<0.05*.