

The relationship of precipitation intensity, cover crops, and P management on hydrograph characteristics and water quality

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Abstract

An increased frequency of intense precipitation events will impact flood potential, soil erosion, and nutrient loss from agricultural lands. Current management practices include the application of cover crops to reduce sediment loss and increase infiltration, thereby reducing surface runoff. However, the effects of cover crops and phosphorous (P) fertilizer management on water quality and runoff characteristics need to be examined to understand how these practices will perform in an environment with more frequent intense precipitation events. The objective of this study was to analyze the change in water quality and surface runoff under a range of naturally occurring precipitation intensities with the application of cover crops and P fertilizer.

Runoff and water quality data were collected from the Kansas Agricultural Watershed (KAW) field laboratory in Ashland Bottoms, KS from 2015-2022 from a corn-soybean cropping rotation with edge-of-field runoff monitoring. The KAW field lab had 18 0.5-ha plots arranged in a 2x3 factorial randomized complete block design with two levels of cover (winter annual cover crops and no cover) and three levels of P fertilizer application replicated 3 times. This study used data from only two levels of P fertilization, control (CN) and spring injected P fertilizer (SI), both without cover crop (NC) and with cover crop (CC). For the SI treatments, ammonium polyphosphate (10-34-0) was subsurface applied at spring planting at a rate of 61 kg P₂O₅ ha⁻¹ from 2015 to 2019 with a slight decrease in rate to 55 kg kg P₂O₅ ha⁻¹ from 2020 to 2022. The CN plots did not receive P fertilizer. Real-time precipitation events were monitored for runoff and samples were collected and analyzed for total suspended sediment, total P, and dissolved reactive P concentrations. Mass losses of runoff, total suspended sediment, total P, and dissolved reactive P were normalized based on precipitation depth to isolate the effects of precipitation

intensity. Depth measurements taken inside the flume during the runoff event were paired with precipitation data to identify the point of runoff initiation, peak flow, and runoff termination. A multiple regression analysis was completed using SAS proc glimmix (version 9.4; Cary, NC) to test if treatment effects on response variables would change under increasing precipitation intensities.

The runoff ratio increased with increasing precipitation intensity for the SI-CC and the CN-NC treatments, with the greatest effect on the CN-NC treatment. Total suspended sediment load and total P load per unit of precipitation both increased with increasing precipitation intensity, with the greatest increase also occurring in the CN-NC treatment. Precipitation intensity had no effect on dissolved reactive P loss per unit of precipitation (DRP_p) for the treatments receiving P fertilizer, whereas DRP_p increased with increasing precipitation intensity for treatments not receiving P fertilizer. The time to runoff initiation and time to peak flow uniformly decreased with increasing precipitation intensity for all treatments. While not always significant, times to initiation and peak flow were longest in the SI-CC treatment. The time of concentration decreased for all treatments with increasing precipitation intensity. Cover crops significantly increased the time of concentration in the CN plots and significantly decreased the time of concentration in the SI plots. Peak flow increased with increasing precipitation intensity for all treatments. Cover crops and P fertilizer decreased the peak flow when compared to the CN-NC treatment with the SI-CC treatment having the smallest peak flow.

Cover crops alone were shown to reduce sediment loss, total P loss, peak flow and the runoff ratio under intense precipitation. For most of these variables the addition of P fertilizer further reduces the losses except for total P loss. Under the most intense storms in this dataset plots treated with P fertilizer showed no difference in total P loss than the CN-NC treatment

which was the treatment most sensitive to precipitation intensities. Dissolved reactive P was also the greatest with P fertilizer application at all intensities. Implementing these conservation management decisions should be weighed against what losses would most likely occur on the land and what local climate modeling predicts for the area. An increase in precipitation intensity is likely to occur with climate change, these management practices have shown to continue to work as a conservation effort.

Table of Contents

List of Figures	viii
List of Tables	x
Acknowledgements	xii
Chapter 1 - Introduction.....	1
Hydrological Budget and Surface Runoff	2
Impacts of Flooding, Sedimentation and Eutrophication.....	4
Soil Erosion and Sedimentation.....	5
Nutrient Loss.....	6
Climate Change.....	7
Cover Crops and Best Management Practices	9
Cover Crops	9
Conservation Practices	11
Objectives	14
Chapter 2 - Methods and Materials.....	15
Site Description.....	15
Treatment Description	15
Runoff Events, Sample and Flow Collection.....	16
Precipitation	16
Runoff Events	17
Runoff Sample Collection and Processing	18
Calculated Hydrograph Components	19
Water Quality	19
Biomass Sample Collection and Processing	20
Statistical Analysis.....	21
Chapter 3 - Results and Discussion	28
Runoff Ratio	28
Water Quality.....	31
Total Suspended Sediment Load.....	31
Dissolved Reactive Phosphorus Load.....	33

Total Phosphorus Load	36
Hydrograph characteristics	37
Time of Concentration	37
Time to Runoff Initiation	39
Time to Peak Flow	40
Peak Flow.....	41
Chapter 4 - Conclusion	57
References.....	60
Appendix A -.....	70
Appendix B -.....	72
Appendix C -.....	73

List of Figures

Figure 1 Map of the Kansas Agricultural Watershed (KAW) in Ashland Bottoms, KS.....	25
Figure 2 An image of a 0.45 m H-flume and sampling tube located at the plot outlets at the KAW	26
Figure 3 Example hydrograph from plot 306 on September 3, 2021 with diagramed response variables time to peak, time to initiation of runoff, and time of concentration	27
Figure 4. Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and the runoff ratio for a no-till corn-soybean production system (CN=no P fertilizer; SI=spring-injected P fertilizer; NC=no cover crop; CC=with winter cover crop).48	
Figure 5 Least squares means of annual above-ground biomass returned to the soil surface (i.e., residue) for the cover crop by year interaction (averaged across P fertilizer treatments). Letters above bars denote significant differences between treatments within a given year ($p < 0.05$). Odd years were planted corn and even years were planted soybean.	49
Figure 6. Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and total suspended solid load ($\text{kg ha}^{-1} \text{ mm}^{-1}$) in a no-till corn-soybean production system (CN=no P fertilizer; SI=spring-injected P fertilizer; NC=no cover crops; CC=with winter cover crops).	50
Figure 7 Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and the dissolved reactive phosphorus load ($\text{g ha}^{-1} \text{ mm}^{-1}$) in a no-till corn-soybean production system (CN=no P fertilizer; SI=spring-injected P fertilizer; NC=n	51
Figure 8 Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and the total phosphorus load ($\text{g ha}^{-1} \text{ mm}^{-1}$) in a no-till corn-soybean production system (CN=no P fertilizer; SI=spring-injected P fertilizer; NC=no cover crops.....	52
Figure 9 Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and time of concentration in a no-till corn-soybean production system (CN=no P fertilizer; SI=spring injected P fertilizer; NC=no cover crops; CC=with winter c	53
Figure 10 Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and time to runoff initiation (min) in a no-till corn-soybean production system (CN=no P fertilizer; SI=spring injected P fertilizer; NC=no cover crops; CC=with winter cover crops).....	54

Figure 11 Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and time to peak flow (min) in a no-till corn-soybean production system (CN=no P fertilizer; SI=spring injected P fertilizer; NC=no cover crops; CC=with winter cover crops)	55
Figure 12 Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and peak flow (L s ⁻¹) in a no-till corn-soybean production system. 12a is the regression using square-root transformed data. 12b is the same data back transformed.....	56
Appendix Figure B.1 Regression of maximum 30-minute precipitation intensity and the average site precipitation (mm) ($p<0.001$).	72

List of Tables

Table 1 Table of KAW planting and fertilizer application by crop year	23
Table 2. Runoff-producing precipitation events included in the final dataset with the runoff sample collection date, precipitation start date and time, precipitation duration, average site precipitation, the maximum 30-minute precipitation intensity	43
Table 3. Distribution of runoff-producing precipitation events by month with the maximum, minimum, and average 30-min maximum intensities (mm hr ⁻¹), precipitation (mm), and runoff (L s ⁻¹).....	44
Table 4. ANOVA with p-values of P fertilizer application (fert), winter cover crop (cover), precipitation intensity (max_p30) and their interactions on runoff ratio, total suspended solids load, total P load, dissolved reactive P load, time of concentration, time to initiation of runoff, time to peak flow, and peak flow (p<0.05).....	45
Table 5. Slope estimates (log-scale) from multiple regression analysis of precipitation intensity effects on runoff ratio [†] , total suspended solids, dissolved reactive phosphorus, and total phosphorus loss in surface runoff as affected by cover crop and P fertilizer treatments. Asterisks indicate if the slopes are significantly different from 0 at p<0.05 (*), p<0.01 (**), and p<0.001(***).....	45
Table 6. ANOVA with p-values of P fertilizer application (fert), winter cover crop (cover), precipitation intensity (max_p30) and their interactions on dissolved reactive P, time to initiation of runoff, time to peak flow, time of concentration, and peak flow (p<0.05) using a reduced model with 'X' denoting interactions not significant in the full model.	46
Table 7. Difference of slope estimates from multiple regression and analysis precipitation intensity effects on runoff ratio, total suspended solids load, and total phosphorous load for the four cover crop and P fertilizer treatments. Asterisks indicate if the slopes are significantly different from each other at p<0.05 (*), p<0.01 (**), and p<0.001(***).....	46
Table 8. Slope estimates (log-scale) from multiple regression and analysis of precipitation intensity effects on time of concentration, time to initiation of runoff, time to peak, and peak flow*. Asterisks indicate if the slopes are significantly different from 0 at p<0.05 (*), p<0.01 (**), and p<0.001(***).....	46

Table 9. LS-Means of time to initiation of runoff, time to peak flow and time of concentration (min) (log scale) for the significant fertilizer by cover interaction. Means with the same letter are not significantly different ($p < 0.05$).....	47
Appendix Table A.1. Table of herbicide applications to the Kansas Agricultural Watershed.....	70
Appendix Table C.C.1. ANOVA table of p-values for effects of fertilizer (fert), cover, and crop year (year) and their interactions for biomass produced over the 8 years of the study. P-values < 0.05 are significant	73
Appendix Table C.2 LS-Means of total biomass (kg ha^{-1}) from corn, soybean, and cover (excluding grain) for each year of the study. Letters indicate a significant difference in values with a p-value of < 0.05 . Uppercase letters reflect the significance of the main effect and lowercase letters reflect the significance of the year*cover interaction.....	73

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Chapter 1 - Introduction

The investigation of management practices for farmers under changing climate conditions is a serious research priority for agronomists. Observed precipitation data show positive trends in precipitation intensity, (Alexander et al., 2006; Flanagan & Mahmood, 2021; Ojima et al., 2021; Rahmani & Harrington Jr., 2018). Extreme precipitation events are increasing in frequency over most of the U.S. with the Midwest having a 42% increase in the number of storms in the 99th percentile relative to 1901 (USGCRP, 2018). The effects of increased precipitation intensity on conservation practice performance are unknown, thereby creating substantial concerns regarding future agronomic impacts on soil conservation and water quality.

Precipitation amount and intensity are drivers in the production of surface runoff. Surface runoff can cause flooding issues and also carries sediment and nutrients that can have detrimental effects on downstream aquatic ecosystems, leading to sedimentation and eutrophication (Correll, 1998; Dodds & Smith, 2016; Ramos et al., 2024). Increased precipitation extremes will likely increase the total runoff volume and thereby increase the chance for downstream flooding. Flooding can cause problems for both agricultural and urban land use. For instance, the flooding that occurred in 2008 across the midwestern U.S. caused \$14.8 billion (CPI-adjusted to 2024) in damages across seven states (NOAA NCEI, 2025). Damages included major crop losses with Iowa losing 8% and 9% of its soybean and corn acres, respectively. Sedimentation of reservoirs reduces storage capacity for freshwater. Solutions to this problem involve costly operations to remove the sediment, which can then create new problems downstream (Annandale et al., 2016). Eutrophication of waterbodies leads to deadly algal blooms that can impact humans as well as the fresh and saltwater species. These additional nutrients increase algal production that blocks sunlight from reaching benthic plant species, thereby interrupting photosynthesis and reducing

oxygen in the environment (i.e., hypoxia; Sharpley et al., 1993; Yasarer & Sturm, 2016). This reduction leads to fish kills, which not only bring disease, but also negative impacts on the fishing and recreation industries.

Cover crops are a commonly promoted conservation practice to reduce soil erosion, increase infiltration and improve soil health (Blanco-Canqui et al., 2013; Folorunso et al., 1992; Siller et al., 2016). However, it is not well understood whether cover crops will continue to provide these benefits under more intense precipitation conditions. Therefore, we desperately need information to help us understand cover crop effects on soil erosion and water quality under intense precipitation conditions to better prepare farmers and water managers for the changing climate of the future.

Hydrological Budget and Surface Runoff

Surface runoff can be described as a function of an area's initial abstraction, soil retention capacity, and the depth of precipitation that occurs, with the initial abstraction being the sum of the possible losses through interception, infiltration, evaporation, and surface storage. For surface runoff to occur, the depth of precipitation must be greater than the initial abstraction and the soil's infiltration capacity. This water has the potential to transport soil, nutrients, pesticides, and disease downstream and into other waterbodies. A combination of meteorological, soil, vegetation, and topographic factors affect the intensity and amount of runoff. By using a hydrological budget surface runoff can be estimated after taking surface and subsurface conditions into account. Factors on the surface of the land include interception by crop residue, or structures, transpiration by vegetation, surface storage and its evaporation, and infiltration into the soil profile. Subsurface factors may also be used when investigating groundwater recharge and stream flows from large basins. Subsurface factors include interflow, percolation, and

subsurface storage. These factors are affected by soil type, growing season, topography, land use, soil profile depth and climate. A hydrological budget equation may be modified based on the scale of the area of interest and time. Some factors may become negligible at shorter timescales such as evapotranspiration during a runoff event. An example equation of a hydrological budget on the surface may look like the following:

$$Pc - R - E_{surface} - I = \Delta S_{surface}$$

Where Pc is the precipitation depth, R is the surface runoff, $E_{surface}$ is the evaporation from surface storage, and I is the water infiltrating into the soil profile. By subtracting these amounts from Pc the change in storage on the surface can be calculated. The subsurface equation begins with the water from I that is added to the soil profile:

$$I - E_{soil} - T - Pr = \Delta S_{soil}$$

Where E_{soil} is the evaporation from soil, T is amount of water that vegetation transpires, and Pr is the water that percolates below the root zone and into groundwater recharge. This calculates the change in storage in the soil profile. These equations can be combined to solve for surface runoff as a function of precipitation, storage, percolation, evaporation, and transpiration:

$$Pc - (\Delta S_{surface} + \Delta S_{soil}) - Pr - E_{surface} - E_{soil} - T = R$$

This water budget can be further simplified for an individual precipitation and runoff event if we assume that evaporation and transpiration terms are negligible relative to the other terms during the short time period of rainfall and active surface runoff in an edge-of-field runoff event.

$$Pc - (\Delta S_{surface} + \Delta S_{soil}) - Pr = R$$

Runoff amount and intensity are often described with a hydrograph, or a graphical depiction of watershed discharge over time. Hydrographs are useful for designing water control structures as part of civil engineering and urban planning. The components of interest to this

research include the time to initiation of runoff, peak-flow discharge, and time of concentration. Agronomic practices have the potential to alter multiple components at once. For example, terraces reduce peak flow and increase the time to initiation of runoff by dividing the slope of the land, slowing down the water, and allowing more time for infiltration (Deng et al., 2021), thus, reducing the erosive force of the runoff. Alterations in these components have implications for erosion and flood management.

Impacts of Flooding, Sedimentation and Eutrophication

Flooding occurs either when water from a river or stream overflows onto land (i.e., fluvial flooding) or when the precipitation exceeds the land's absorption capacity (i.e., pluvial flooding). Reservoirs are often constructed to reduce downstream fluvial flooding by storing the excess water. Sediment loss from fluvial flooding can impact reservoirs by reducing the storage capacity as sediment washes in and settles on the bottom. Furthermore, this diminished storage capacity can increase the risk of overtopping or when the water level in a reservoir rises above the dam wall and lead to dam failure (Lee & You, 2013). Sedimentation estimations for reservoirs are difficult to conduct and are not always accurate. The effect of sedimentation leading to dam failure is also nonlinear with some reservoirs being more sensitive to its effects than others (Lee & You, 2013). This uncertainty only increases the need to stop sediment from entering the reservoir in the first place. A diminished storage capacity impacts the water supply used for other services such as supplying water to municipalities, agricultural irrigation, and generating renewable energy (Yasarer & Sturm, 2016). The water quality of the reservoir is also an important factor and if affected can lead to events like the harmful algal bloom in Toledo, OH in 2014 that left the residents unable to use or ingest their tap water for three days (Castle, 2019).

Containing sediment and nutrients that are transported via surface runoff is key to preventing these kinds of incidents.

Soil Erosion and Sedimentation

Soil erosion is one consequence of surface runoff. As rain impacts the soil surface, soil particles may detach and be transported with the runoff. Certain soil characteristics aid in the resistance of erosion from runoff. In general, soils with high soil organic matter, large water stable aggregates, and a low bulk density are more resistant to water erosion than those with less soil organic matter, smaller water stable aggregates, and a high bulk density (Zhang et al., 2007). This is typically achieved by no-till management compared to conventional tillage management. No-till systems leave crop residue on the soil surface increasing the cover provided to the soil. This cover reduces or inhibits the impact of rain droplets on the soil, thereby decreasing particle detachment and transport. Low soil cover means the soil is vulnerable to the rain impact. The detachment and transportation of these particles results in sediment loss or surface crusting (Folorunso et al., 1992). These surface crusts are detrimental to crop growth and development, reducing water infiltration and emergence. Intense rainfall is the most likely to detach and transport soil particles.

It is well documented that increased precipitation intensity will increase soil erosion (Li & Fang, 2016; Nearing et al., 2004). Some studies have even shown that precipitation intensity is the primary driving factor affecting soil erosion (Tang et al., 2015), although it is generally accepted that precipitation amount is also an important factor that combines with intensity to affect soil erosion (Nearing et al., 2005, 2017). Almeida et al. (2021) investigated the relationship between rainfall intensity and duration on runoff volume and sediment loss under

normalized rainfall erosivity. They found that rainfall with a high intensity (67.4 mm h^{-1} , 75.0 mm h^{-1}) and short duration (48 min, 38 min) produced the highest sediment yield and runoff rates. The inverse of these rainfall treatments, low intensity (44.6 mm h^{-1}) and long duration (106 min) had the lowest sediment yield and runoff rates. However, with the differences in duration and the residue cover, the overall sediment yield was not found to be significantly different. Soil erosion removes valuable soil organic matter that would otherwise supply nutrients, improve soil structure, and hold water for crop use (Hudson, 1994). Crop productivity is generally thought to decrease with increased soil erosion, although this relationship hinges on several other factors such as water availability and root growth (Bakker et al., 2004).

Nutrient Loss

Nutrients are also lost in surface runoff. Fertilizers applied to crop fields are vulnerable to transport under certain conditions. Phosphorus (P) has multiple forms that can be lost easily in surface runoff. Phosphorus can be broadly grouped into two dynamic pools of solution-phase P and solid-phase P, which are maintained in an active equilibrium based on soil properties. Solid-phase P includes P that is incorporated in organic matter, adsorbed to mineral surfaces, or precipitated with a variety of cations present in the soil, such as aluminum (Al^{3+}), iron (Fe^{2+} , Fe^{3+}), and calcium (Ca^{2+} ; Islam et al., 2024). When P is absorbed by plant roots, this reduces the solution-phase P concentration and results in P being slowly released from the fixed, or solid-phase, pool to reestablish equilibrium. It is important to understand these differences because land use and soil type influences the form of P lost during runoff events. For example, tilled land is more susceptible to sediment loss, so when runoff events occur sediment-bound P is the dominant form lost (Sharpley et al., 1994). Once the soil is wetted by rain, P from applied

fertilizers and crop residue dissolves and may either be sorbed to soil particles or remain dissolved in the runoff (Sharpley et al., 1994).

Sediment-bound P is solid-phase P primarily composed of P sorbed to soil surfaces and P precipitated with metal cations, which can be transported to waterbodies where it provides P for algal blooms for an undetermined amount of time (Sharpley et al., 1994; Sondergaard et al., 2001). Sediment bound P is quantified as particulate P (PP), determined as the difference between the total phosphorus (TP) in the water and dissolved P (DP). Although the majority of PP is sediment-bound P, it will also include other forms of P such as particulate organic P or low-solubility mineral P that could be lost from animal manure or poultry litter.

Dissolved P is classified as the fraction of P that passes through a 0.45 μm filter. Dissolved reactive P (DRP) reacts with molybdenum creating a blue color that is measured using a colorimeter. This form mostly contains orthophosphate which is highly bioavailable. Dissolved unreactive P is the total DP minus DRP. Fields with high soil test phosphorus in surface soils are most susceptible producing high concentrations of DP as P desorbs from soil particles during rainfall or irrigation (Sharpley et al., 1993). Unlike PP, DP is immediately available for algal use. Both PP and DP are harmful to waterbodies in excess, creating conditions suitable for harmful algal blooms.

Climate Change

Global warming is altering multiple processes in the water cycle ultimately affecting the intensity of surface runoff (Lindsey & Dahlman, 2024). Precipitation amount and intensity seem to have an inverse relationship under climate models, where the average annual precipitation amount is decreasing as the intensity of the precipitation is increasing (Crimmins et al., 2023). Storm intensity is highly correlated with runoff intensity and will lead to more erosive runoff

(Almeida et al., 2021). Characterization of events with extreme precipitation intensities include both the intensity (mm hr^{-1}) and duration of the event (min). For example, an event with an intensity of 60 mm hr^{-1} and 5-min duration is not as extreme as an event with the same intensity but duration of 60 min, where the former would produce 5 mm of precipitation and the latter would produce 60 mm. Typical precipitation intensities for a geographic region are characterized with annual exceedance probabilities, or the probability of observing an event with a given intensity and duration on an annual basis. For example, in Manhattan, KS, a storm with an average intensity of 73 mm hr^{-1} and a 60-min duration will occur on average 4 times in 100 years, or it has a 4% chance (or probability of 0.04) of occurring each year (NOAA, 2017). A less intense storm of 35 mm hr^{-1} and 60-min duration would occur on average 100 times in 100 years, or the probability of that storm occurring in any given year is 1.0.

Flooding is predicted to increase because of these factors, which will have major economic effects (Crimmins et al., 2023). Soil moisture may suffer due to potential surface sealing from intense storms hindering subsequent precipitation from penetrating deeper into the soil profile (Flanagan et al., 1988). Shifts in precipitation type have been seen as more winter precipitation is falling as rain instead of snow (Cook et al., 2020). This change has decreased the amount of runoff in the spring and summer (AMJJAS) and increased runoff in fall and winter (ONDJFM) due to an overall warming of the Northern Hemisphere (Cook et al., 2020). All told, these shifts in precipitation characteristics have the potential to be extremely harmful to farmers and their communities. Management practices, such as cover crops, should be investigated for their effectiveness under these changing conditions to prepare for the reality that is a changing climate.

Cover Crops and Best Management Practices

Cover Crops

Cover crops, which are crops grown to improve soil health and as a forage but not for harvest, have a long history of being grown to improve soil productivity and to reduce sediment loss back to BC era cultures (Lal, 2015). The cyclic implementation and abandonment of cover crop use can be seen with leaps in agricultural technology. Improvements to farm implements, fertilizers, and genes of the crops themselves boosted productivity. However, some benefits could not be replaced as seen with the vast and harmful erosion of topsoil in the Dust Bowl of the U.S. during the late 1930s. While most benefits of cover crops are largely agreed upon across the literature there are still inconsistencies. Cover crop effects on infiltration, hydrological components, sediment loss, and nutrient loss have been studied using simulated and natural rainfall in greenhouse and field-scale trials. These different kinds of experiments give farmers and researchers a better understanding of how cover crops affect their environment.

Steele et al. (2012) researched the effects of winter cover crop on soil physical properties and organic matter and found that winter cover crops did increase infiltration rate when compared to a no cover control plot, however these results were not consistent throughout site locations and seasons. This inconsistency is prevalent throughout the literature (Blanco-Canqui et al., 2015). Steele et al. (2012) contributed this variability to the soil properties of the sites where the soil had less aggregate stability and was more susceptible to structural changes due to wetting and drying cycles. In soils that are more structurally sound, long term cover crop use increases soil macroaggregates. Rachman et al. (2003) conducted a study on the effects of long-term cropping systems on soil physical properties. The soil was a Mexico silt loam (fine, smectitic, mesic, Aeric Vertic Epiaqualfs) which is less sandy and has a higher clay content than

soils used in Steele et al., (2012). Rachman's long-term study resulted in an increase of aggregate stability from continuous corn or wheat when cropping systems switched to a corn-wheat-red clover rotation. They posited that the rotation had more canopy cover and more soil bonding material provided by the red clover cover crop. However, cover crop effects on different soil texture classes are limited and should be looked at critically in conjunction with other management practices.

Siller et al., (2016) primarily investigated soil erosion and nutrient runoff under different mulch and cover crop treatments. Rainfall simulations were conducted on the treatments at times during the growing season when runoff was likely to occur. The results from this study concerning runoff showed for three of the five simulations the monocrop corn silage with no-cover crop had the least amount of time before runoff occurred. This coincides with the monocrop no cover treatment having a greater amount of runoff under all rainfall simulations. The plots with the Kura clover as a living mulch generally had a longer time to initiation; however, these results were not always significant. Blanco-Canqui et al. (2013) investigated the effects of cover crops on soil properties after five years when put in previously fallow fields. Blanco-Canqui et al.'s study also utilized simulated rainfall to research any effects in runoff reduction. Total runoff was reduced in the winter triticale, spring pea, and spring triticale plots compared to the fallow control plots. Winter lentil showed no difference in runoff reduction. Runoff start time for winter triticale plots was longer by 24 minutes compared to fallow, spring triticale, and spring pea plots. Winter lentil runoff start time was not significantly different compared to either.

Carver et al., (2022) studied the effects of cover crops on multiple water quality parameters. The treatments consisted of three levels of phosphorus fertilizer applications

(control, fall broadcast, spring injected) and two levels of cover, with winter cover crop and no cover crop. Over a four-year period in a no-till corn-soybean rotation all cover crop treatments, regardless of fertilizer application, significantly reduced total suspended solid concentration in runoff and annual sediment load by 67% and 68% respectively compared to no cover crop treatments. Despite the reduction in sediment loss, TP loss in cover crop plots was not significantly different than no cover crop plots. However, DRP concentration and load were significantly higher at 69% and 63% respectively compared to no cover crop plots. Zhu et al. (1989) had similar results when cover crop treatments were compared to the no-cover control. Soil and $\text{NO}_3\text{-N}$ loss were highest for the no-cover control, concentrations of $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ were higher from plots with cover crops, however overall losses were reduced.

The effectiveness of cover crops as a conservation practice depends on the user's goals. These studies have highlighted the strengths and drawbacks to cover crop use which should continue to be studied to improve our preparedness for the climate conditions ahead.

Conservation Practices

The aims of conservation practices are to reduce the loss of sediment, nutrients, and water from agricultural land to mitigate any harmful effects that might occur to the broader environment. Nonpoint source pollution refers to losses of fertilizer, herbicides, and insecticides that come from agricultural fields and affect water quality. Pollution of this type is difficult to manage because of the absence of a single source. Conservation practices attempt to solve this kind of pollution and conserve the environment for future generations. A touchstone of conservation practices related to fertilizer management is referred to as the 4Rs. The 4Rs, right rate, source, timing, and placement are used to guide farmers on how to maximize yield and

minimize nutrient loss from fertilizers. Fertilizer management decisions are weighed against fertilizer price, labor cost, weather conditions, and the anticipated crop yield. Each component of the 4Rs contains a detailed management decision that will need to be considered heavily.

Determining the appropriate rate of P fertilizer application includes estimating the expected yield and the existing soil test P. Two approaches are the sufficiency approach and the build and maintain approach. Sufficiency management aims to optimize yield and the economic return for a single year. Build and maintain management builds up the soil test P to a certain range and then maintains that range to minimize the risk of P deficiency if for some reason P was not able to be applied that year (Ruiz Diaz, 2024).

The right source of P fertilizer depends on the existing P content of the soil, how the P is delivered to the plant, and what the cost and availability of the P fertilizer is to the farmer. For example, the choice between manure and commercial P fertilizer is one to consider. The precise P content of manure is less accurate than a commercial P fertilizer, but a farmer may choose manure if they have a readily available source that is cheaper compared to buying commercial. Manure is also high in organic P which needs to be mineralized into the inorganic form before being used by the plant. Commercial P fertilizer only has the inorganic form that is readily available to plants at the time of application.

The placement of P should also be considered. Subsurface banding or incorporation after surface placement is preferable if there are environmental concerns of P being lost due to surface runoff. Studies show a reduced risk of P loss in runoff if manure is incorporated via tillage or if P is subsurface applied (Sharpley & Moyer, 2000; Sharpley et al., 1994).

The right timing of P application can be the most difficult to control. While P is less mobile than nitrogen, the transport of P in a particulate, sediment-bound form, or in a dissolved

form is still a concern. Application of P well before storms with high erosivity is encouraged to avoid losses from erosion and surface runoff. The solubility of the P fertilizer source also matters. Inorganic sources are made to have a high or complete percentage of water solubility to dissolve P for plant uptake, while organic sources like manure have a lower percentage. This solubility may be detrimental if intense rainfall occurs directly after surface application. Shigaki et al. (2006) ran rainfall simulations on different organic and inorganic P sources that showed high concentrations of DRP and TP in surface runoff from the inorganic sources when rainfall was applied one day after application. Organic sources, like manure, had much lower concentrations because of the decreased water solubility.

Conservation management practices should not be utilized in a vacuum and are often best when used in combination. No-till practices generally reduce soil erosion by leaving crop residue undisturbed on the soil surface providing cover to reduce raindrop impact and maintain soil moisture (Rachman et al., 2003). No-till, subsurface placement, and timing the P application to avoid intense rainstorms are all practices that have been found to significantly reduce P loss to runoff (A. N. Sharpley et al., 1993). However, because P is not a mobile nutrient, P stratification occurs in no-till soils, with higher soil test P values found in the surface than in the subsurface layers (Sharpley et al., 1994). The higher concentration of P on the soil surface is sometimes more vulnerable to loss because it is not incorporated into the deeper subsoil with conventional tillage. In particular, the concentration of the dissolved form of P has been seen to increase.

Studies concerning how management practices will perform under climate change conditions are mostly based on numerical model simulations. Basche et al., (2016) modeled a maize-soybean rotation with winter cover crop using a 45 year simulation period to test how yields, soil erosion, soil carbon, and nitrous oxide emissions would change under management.

Both cover crop and no cover crop treatments decreased yield with soybean decreasing by 1.6% and maize by 2.7% due to a predicted increase in water stress. Soil erosion was reduced 11-29% in cover crop plots under 1%, 2% and 5% slopes. Additional research is needed to fully investigate the interaction between conservation fertilizer management and cover crops and what it would mean for a climate with more frequent intense precipitation.

Objectives

The objective of this study is to investigate how cover crops and P fertilizer use affected the relationships between precipitation intensity and runoff, sediment loss, and P loss. These interactions may change the understanding of how the current management practices will perform in a changing climate and how future research may address potential gaps in performance. This would benefit not only farmers, but also the broader population who are also affected by water pollution, flooding, and erosion.

Chapter 2 - Methods and Materials

Site Description

This study was conducted at the Kansas Agricultural Watershed (KAW) field laboratory in Ashland Bottoms, KS, which was established in 2014 as a site for a long-term field studies investigating effects of cover crops and phosphorus fertilizer management on surface water quality. Soils at the KAW field lab are mapped as Smolan silty clay loam (*Fine, smectitic, mesic Pachic Argiustoll*) with 6 to 8% slope. Prior to establishment, the cropping system was conventional till wheat (*Triticum aestivum* L.) - soybean (*Glycine max* (L.) Merr.) production. In the summer of 2014, the site was divided into 18 experimental units, or plots, approximately 0.5 ha in size and separated by berms and terraces such that surface runoff from each plot drained to a single point to facilitate monitoring of surface runoff volume and collection of runoff samples from each plot. The site was transitioned to a no-till corn (*Zea mays* L.) – soybean cropping system in spring of 2015 with corn in odd years and soybean in even years. The area has a humid continental climate with hot humid summers and cold, dry winters with an average annual precipitation of 830 mm with the greatest monthly precipitation in May and June.

Treatment Description

The treatments were arranged in a 2x3 factorial randomized complete block design with two levels of cover, cover (CC) and no cover (NC), and three P fertilizer treatments (Figure 1). During the 2015 to 2019 crop years, the P fertilizer treatments were fall broadcast (FB), spring injected (SI) and a control (CN), where FB received 61 kg P₂O₅ ha⁻¹ in fall (November through January) as diammonium phosphate (18-46-0) broadcast on the soil surface, SI received 61 kg P₂O₅ ha⁻¹ as ammonium polyphosphate (10-34-0) applied 5 cm below the seed and 5 cm to the

side of the seed at planting of the main crop, and CN did not have any P fertilizer applied. There was a change in P fertilizer management for the 2020, 2021, and 2022 cropping years, where the FB treatment changed to a drawdown (zero P fertilizer applied) and the P application rate for the SI treatment decreased slightly to 55 kg P₂O₅ ha⁻¹ (still applied as ammonium polyphosphate at planting). Because of the drastic change in P management for the FB treatment in 2020, this study only used data from the SI and CN treatments.

The cover crops used from 2014 to 2019 varied slightly from year to year depending on cropping sequence and soil and weather conditions at time of planting, consisting of a small grain mixed with rapeseed (*Brassica napus*). Small grains were either winter wheat (*Triticum aestivum*) or triticale (*Triticosecale*). In 2015, hairy vetch (*Vicia villosa*) was also added to the mix. Despite the mixed species planting, the cover crop biomass was primarily from the small grain, with very few rapeseed or hairy vetch plants surviving the winter. The cover crop used from 2020 to 2022 was only cereal rye (*Secale cereale*). A full table of management practices can be seen in Table 1 excluding herbicide applications which can be found in Appendix A, Table A.1.

Runoff Events, Sample and Flow Collection

Precipitation

One-minute precipitation was recorded at the outlets of plots 104, 105, 303, and 304 (Figure 1) using Texas Electronics TE 525 tipping bucket rain gauges during months of the year where there was no snowfall (typically March through November). Winter precipitation was recorded at the Ashland Bottoms Kansas Mesonet station, approximately 1000 m from the research site (Kansas Mesonet, 2025). Manual rain gauges were mounted alongside the tipping

buckets as a check of the total rainfall. Precipitation associated with each runoff event included all precipitation that occurred during the period of active runoff and all continuous precipitation occurring prior to the start of runoff; where continuous precipitation was defined as at least 0.25 mm of precipitation occurring in a 60-min period. The precipitation intensity for this study was defined as the maximum precipitation intensity (mm/hr) in a 30-min period for each runoff-producing precipitation event. This dataset used a 30-min rolling sum of the 1-min precipitation data to calculate the maximum amount that fell in a 30-minute period.

Runoff Events

Each of the 18 plots were fitted with a 0.45 m H-flume. They were also fitted with aluminum flume wings to guide runoff into the H-flume approach. Slightly below the H-flume's outlet, a sampling tube approximately 1.2 m in length was secured in a gutter made from half of a PVC tube. The end of the PVC tube included a cap with two holes drilled in it to slowly drain the runoff that was to be sampled (Figure 2). At a slightly elevated position from the H-flume was an accompanying hut or enclosed metal box that contained an ISCO 6700 or 6712 Auto Sampler with an attached 730 Bubbler Module. One-minute gauge-height measurements were recorded by the 730 Bubbler Modules continuously including when no precipitation was occurring.

A center-weighted 7-minute rolling average was applied to gauge-height measurements to smooth any irregular measurements due to environmental factors such as wind or instrument inaccuracy. The equation used in Bos (1989) was used to convert gauge-height to water flow (Q) for a 0.45 m H-flume.

Equation 1: Conversion of depth to flow

$$\log Q = 0.0238 + 2.5473 \log h_a + 0.2540[\log h_a]^2$$

Where Q is flow (L s^{-1}) and h_a is the water depth in the flume (m). The flow was multiplied by 60 to convert to L min^{-1} and the one-minute measurements were summed to compute total runoff volume (L) from when gauge-height was above the enable level (0.015 m) which indicated active runoff. Sediment or residue that moved into the flume during the runoff event was cleared afterwards.

Runoff Sample Collection and Processing

A 200-mL sample was collected for every 1 mm of runoff that exited the flumes. Runoff sample collection was terminated once the water depth in the flume fell below the 0.015-m threshold. Samples were collected in a single 10 L carboy inside of the auto-sampler creating a single flow-weighted composite sample for the event. Samples were removed from the auto-samplers within 24 hours of collection and submitted to Kansas State University's Soil Testing Laboratory. Total P was determined by digesting a 1 to 10 ml sample at 120°C for 60 minutes with a potassium persulfate reagent followed by analysis by the molybdate-blue colorimetric procedure with an Alpkem Rapid Flow Analyzer (Nelson, 1987). Dissolved reactive phosphorus (DRP) was determined by passing the sample through a $0.45\ \mu\text{m}$ filter and then analyzing the filtrate by the molybdate-blue colorimetric procedure with an Alpkem Rapid Flow Analyzer. Total suspended sediment (TSS) was determined gravimetrically by vacuum filtration of a 50 to 100 mL aliquot through a pre-dried $0.45\ \mu\text{m}$ filter (Csuros, 1997).

Calculated Hydrograph Components

The time to runoff initiation was calculated as the difference in minutes between the time of the start of rainfall minus the time when the water depth in the flume reached 0.015 m. Time to peak was calculated in minutes from when rainfall was initiated to when runoff reached its peak flow (i.e., the maximum Q value). Peak flow was determined as the maximum discharge in $L\ m^{-1}$. Time of concentration was calculated by subtracting the time when the precipitation intensity dropped below $3\ mm\ hr^{-1}$ from the time when runoff ended (i.e. when the depth of water in the flume fell below 0.015m). Figure 3 shows an example hydrograph with the start and end times of these components.

Water Quality

Water quality components were converted from concentration units ($ug\ L^{-1}$, $mg\ L^{-1}$) to load units ($g\ ha^{-1}$, $kg\ ha^{-1}$). Because there was a significant regression relationship between precipitation amount and intensity (Figure B.1; Appendix B), load data were normalized by dividing the load by the precipitation depth that fell during the event, for final units of $kg\ ha^{-1}\ mm^{-1}$ precipitation or $g\ ha^{-1}\ mm^{-1}$ precipitation to isolate the effect of precipitation intensity. Those water quality components, TSS, DRP, and TP per unit of precipitation, will be referred to as TSS_p , DRP_p , and TP_p respectively. Runoff depth was calculated by converting the depth in meters to flow ($L\ s^{-1}$), then to volume in millimeters, which was then divided by the plot area to account for the varying plot sizes at the KAW, resulting in runoff depth in millimeters. The runoff ratio was then calculated using the converted runoff depth by the precipitation depth for the event.

Biomass Sample Collection and Processing

Above-ground biomass production was determined at three georeferenced points within each plot for the cover crop and main crop each year. All plant samples were cut as close to the soil surface as possible while avoiding root biomass collection. Cover crop biomass was collected from 3.05 m of two rows (1.16 m^2) at each point immediately prior to termination. Samples were dried at 60°C for at least 72 hours and weighed. For soybean, above ground biomass (including seeds and pods) was collected from 1 m of two rows (1.52 m^2) at the late R6 or early R7 growth stage when the most biomass was present before the lower leaves dropped. Biomass was dried at 60°C for at least 72 hours and weighed. Soybean grain yield was determined at full maturity by harvesting three, 20 to 70-m x 2-row subplot areas within each main plot with a Gleaner E III combine (AGCO Corp., Duluth, GA). For corn, ears were harvested from every plant in two 9.14-m rows (13.9 m^2) after which ten plants (without ears) were harvested at random from within the two rows where ears were harvested. Stalks were weighed in the field for an initial wet weight before being fed into a chipper to shred stalks and leaves. A subsample of the shredded biomass was collected, weighed, dried at 60°C for at least 72 hours, and weighed dry to obtain a moisture content. After shelling corn, cobs were weighed and a subsample was dried to determine moisture. All biomass is reported on a dry-weight basis. Corn and soybean biomass does not include the grain because it was harvested not left behind as residue, however cob weight was included.

Statistical Analysis

Runoff, precipitation, and water quality data were compiled into a final dataset. SAS proc glimmix (version 9.4; Cary, NC) was used to perform multiple regression analysis on all components to test if there was a change in the response variable as the precipitation intensity increased. Visual inspection of residual plots was used to determine if the data met assumptions of normality. Data for which residuals were not normally distributed were transformed with the $\log_{10}$ transformation (TSS_p , DRP_p , TP_p , time to initiation of runoff, time to peak flow, and time of concentration) or the square root transformation (peak flow rate and runoff ratio). The initial model used fertilizer (fert), cover, and the maximum 30-minute precipitation intensity (max_p30) and their interaction to test the response of the dependent variables. If higher-order interactions were insignificant ($p > 0.05$) to the response variable a second model was used without those interactions. Both models had the unique identifier of the event (ID) nested in the repetition (rep) of the experiment as well as ID being a random variable. This was to account for the rain event being “applied” to all reps, but that each event was not a distinct treatment, but a random natural event that changed every application. Contrast and estimate statements were used to test if the slope of the response variable was significantly different between treatments and to test if it was significantly different from zero ($p < 0.05$). LS-Means with the pdiff option was used to identify the mean of the response variable at specific precipitation intensities and determine if the means were significantly different ($p < 0.05$). Data were plotted with SAS using proc sgplot, where the 95% confidence limits for the linear predictors were indicated with a shaded region around each regression line. Results for log-transformed response variables were back transformed and plotted on a log-scale axis. Results for square root transformed variables were plotted in both transformed and back-transformed units. SAS proc glimmix was also used to

produce an ANOVA using a model that tested interactions between fertilizer treatment, cover crop use, and year. Rep and year were used as random variables.

Table 1 Table of KAW planting and fertilizer application by crop year

Crop Year	Field Operation	Date (M/D/Y)
2015	Lime application (7900 kg ha ⁻¹)	11/6/14
	Tillage (disking)	11/7/2014, 11/13/2014
	Cover crop planting of <i>Triticum</i> L., (135 kg ha ⁻¹) <i>Vicia villosa</i> , (6 kg ha ⁻¹) <i>Brassica napus</i> (9 kg ha ⁻¹)	11/13/14
	DAP application (83 kg P ₂ O ₅ to FB plots)	1/12/15- 1/13/15
	<i>Zea mays</i> L. planting (26,000 seeds/ac)	4/14/15
	APP application (81.6 kg P ₂ O ₅ ha ⁻¹ to SI plots)	4/14/15
	UAN application (157.9 kg N ha ⁻¹ to CN, 132.6 kg N ha ⁻¹ to SI, 124.4 kg N ha ⁻¹ to FB)	4/14/15 -4/15/15
	Combine harvest	9/18/15 - 9/21/15
2016	Cover crop planting <i>Triticum</i> L. (145 kg ha ⁻¹)	9/22/15
	DAP application (52.1 kg P ₂ O ₅ ha ⁻¹ to FB reps 2 and 3, 77.8 kg P ₂ O ₅ ha ⁻¹ to FB rep 1 due to machine error)	11/13/15
	Cover crop terminated	5/6/16
	<i>Glycine max.</i> planting 321,098 seeds ha ⁻¹	6/6/16
	APP application (56.3 kg P ₂ O ₅ ha ⁻¹ to FB 79.9 kg P ₂ O ₅ ha ⁻¹ to SI)	6/6/16
	Combine harvest	10/19/16
2017	Cover crop planting <i>Tritosecale</i> Wittmack (56 kg ha ⁻¹), <i>Vicia villosa</i> at (5.6 kg ha ⁻¹)	10/19/16 -10/20/16
	DAP application (63.8 kg P ₂ O ₅ ha ⁻¹ to FB plots)	12/2/16
	<i>Zea mays</i> L. planting 64,247 seeds ha ⁻¹	4/24/17
	UAN application (177 kg N ha ⁻¹ to CN plots, 153 kg N ha ⁻¹ to SI plots, 149 kg N ha ⁻¹ to FB plots)	4/24/17-4/26/17
	APP application (59.5 kg P ₂ O ₅ ha ⁻¹ to SI plots)	4/24/17
	Cover crop terminated	4/27/17
	UAN application (44.8 kg N ha ⁻¹ to all plots)	6/12/17
	Combine harvest	9/20/17
2018	Cover crop planting <i>Tritosecale</i> Wittmack (56 kg ha ⁻¹) <i>Vicia villosa</i> (5.6 kg ha ⁻¹)	9/21/17
	DAP applied (61 kg P ₂ O ₅ ha ⁻¹ to FB plots)	11/28/17
	<i>Glycine max.</i> planting 321,098 seeds ha ⁻¹	5/9/18
	APP application (55 lb P ₂ O ₅ ha ⁻¹ to SI plots)	5/9/18
	Cover crop terminated	5/10/18
	Combine harvest	11/1/18
2019	Cover crop planting <i>Triticum</i> L. (56 kg ha ⁻¹) <i>Vicia villosa</i> (5.6 kg ha ⁻¹)	11/1/18-11/2/18
	DAP application (59.5 kg P ₂ O ₅ ha ⁻¹ to FB)	12/21/18
	UAN application (153 kg N ha ⁻¹ -FB, 160 kg N ha ⁻¹ -SI, 176.3 kg N ha ⁻¹ to CN)	4/24/19
	Cover crops terminated	4/26/19
	<i>Zea mays</i> L. planting 64,247 seeds ha ⁻¹	4/25/19-4/26/19
	Combine harvest	9/18/19
2020	Cover crop planting <i>Secale cereale</i> L. (59 kg ha ⁻¹)	9/27/19
	<i>Glycine max.</i> planting 345,947 seeds ha ⁻¹	5/18/20-5/19/20
	APP application (38.9 kg P ₂ O ₅ ha ⁻¹ to SI)	5/18/20-5/19/20
	Cover crop terminated	7/4/20
	Combine harvest	10/12/20

Crop Year	Field Operation	Date (M/D/Y)
2021	Cover crop planting <i>Secale cereale</i> L. (61 kg ha ⁻¹)	10/13/20
	Cover crop terminated	4/13/21
	UAN application (142.5 kg N ha ⁻¹ to FB, 142.5 kg N ha ⁻¹ to SI, 160 kg N ha ⁻¹ to CN)	4/22/21
	<i>Zea mays</i> L. planting 64,247 seeds ha ⁻¹	4/26/2021, 4/29/2021
	APP application (71 kg P ₂ O ₅ ha ⁻¹ to SI)	4/26/2021, 4/29/2021
	Combine harvest	9/16/21-9/17/21
2022	Cover crop planting <i>Secale cereale</i> L. 74 kg ha ⁻¹)	9/24/21-9/25/21
	Cover crop terminated	5/20/22
	<i>Glycine max.</i> planting 345,947 seeds ha ⁻¹	6/15/22
	APP and UAN application (54.1 kg P ₂ O ₅ ha ⁻¹ to SI)	6/15/22
	Combine harvest	10/20/22

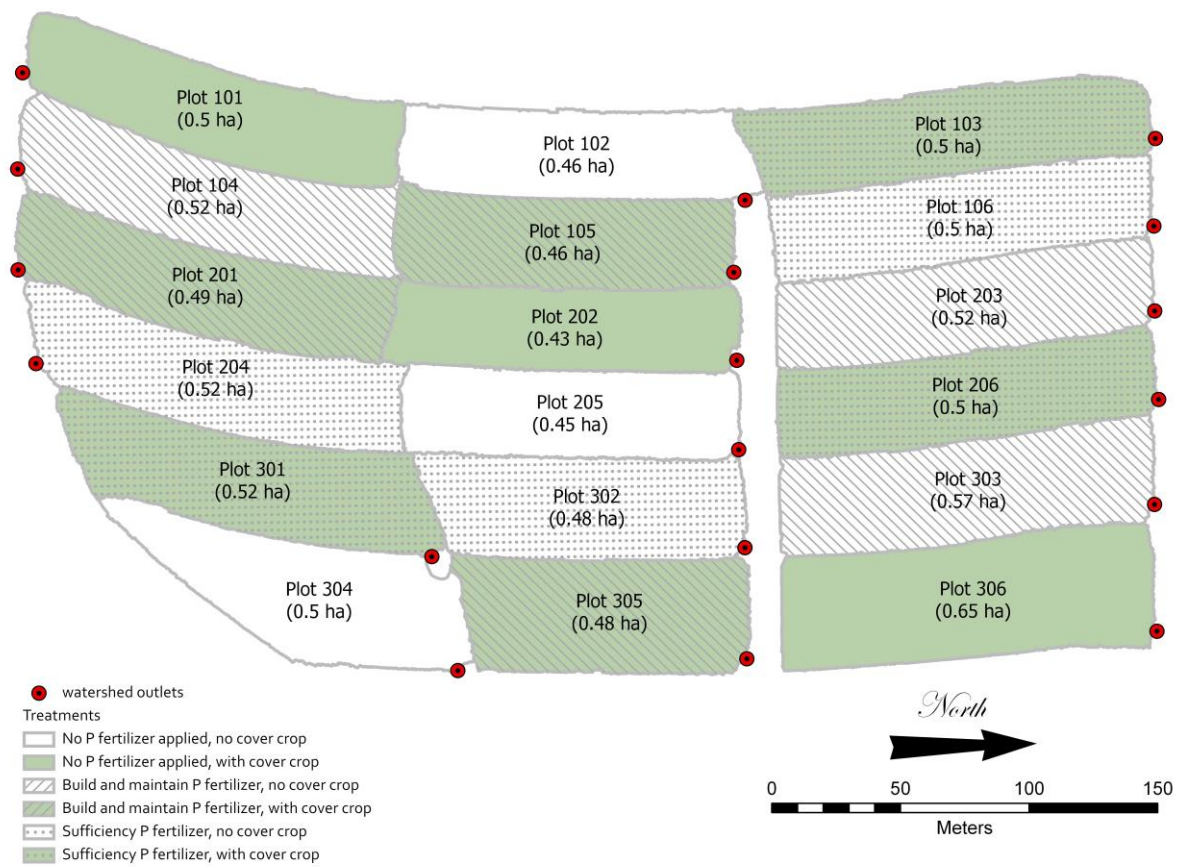


Figure 1 Map of the Kansas Agricultural Watershed (KAW) in Ashland Bottoms, KS.



Figure 2 An image of a 0.45 m H-flume and sampling tube located at the plot outlets at the KAW

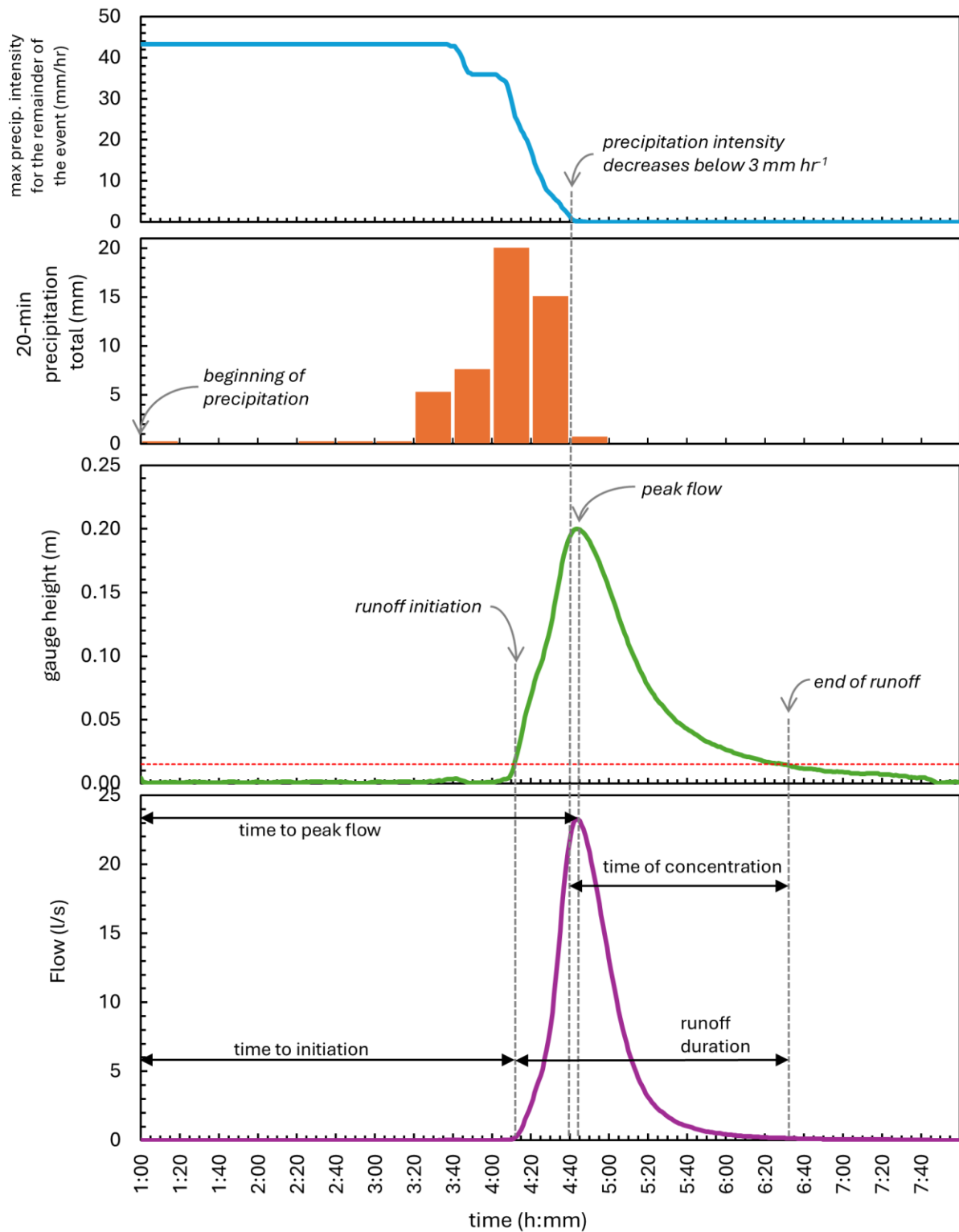


Figure 3 Example hydrograph from plot 306 on September 3, 2021 with diagramed response variables time to peak, time to initiation of runoff, and time of concentration

Chapter 3 - Results and Discussion

From 2015 to 2022 there were 121 recorded precipitation events that produced runoff samples. Precipitation events that produced an average of less than 2 mm of runoff were removed. Events that were missing data for all three replicates of a treatment were also removed from the dataset. Missing data were most often due to missing water quality analysis resulting from low flow, equipment malfunction, or sedimentation that resulted in biased sample collection. This left the final dataset with 71 runoff-producing precipitation events (Table 2). The distribution of events throughout the calendar year showed an increase in events from spring (March and April) to the summer (May through August) and a decrease going into the fall and winter (September through December) (Table 3). Of the 71 events, nineteen occurred in May, which was the most followed by July and August. Over the eight years of the study the most intense storm occurred in August and had a 30-min maximum precipitation intensity of 48.91 mm hr⁻¹ which is consistent with a 10% exceedance probability as reported by NOAA for the Manhattan, KS area (NOAA, 2017). The runoff-producing storm with the lowest 30-min maximum precipitation intensity (2.88 mm hr⁻¹) occurred in March.

Runoff Ratio

The runoff ratio is the volume of runoff divided by the precipitation depth of the rain event. A lower runoff ratio indicates that a greater proportion of precipitation has infiltrated into the soil surface than it has exited the plot as surface runoff. Phosphorus fertilizer application with cover crop use affected the relationship between the runoff ratio and precipitation intensity (Table 4). The runoff ratio increased with increasing precipitation intensity for the SI-CC and the CN-NC treatment (Figure 4). The CN-CC and SI-NC treatment had slopes not significantly

different from zero (Table 5). In the NC treatments the application of P fertilizer reduced the slope of the line to zero whereas in the CC treatments P fertilizer application increased the slope. Runoff ratios in the SI-CC treatment for intensities less than 32 mm hr⁻¹ were significantly less than for the CN-CC treatment. Runoff ratios for intensities greater than 32 mm hr⁻¹ had no significant difference. The reverse occurred for the NC treatments where at intensities less than 22 mm hr⁻¹ the SI-NC treatment had significantly greater runoff ratios than the CN-NC treatment. From 24 mm hr⁻¹ to 30 mm hr⁻¹ there is no significant difference between the ratios in the two treatments, whereas the CN-NC treatment had significantly greater runoff ratios than all other treatments for intensities greater than 32 mm hr⁻¹.

Total annual biomass returned to the soil surface (i.e., sum of cover crop biomass and crop residue) was affected by the main effect of fertilizer and cover and a significant year by cover interaction (Appendix C.1). The CN treatments produced 12% less biomass than the SI treatments averaged over the 7 years (Appendix C.2), thus resulting in a greater proportion of bare soil. This may have increased evaporation but decreased surface soil water content, which could have decreased runoff in the low intensity precipitation events. However, the bare soil would be more prone to surface crusting caused by raindrop splash at high intensity precipitation events (D. C. Flanagan et al., 1988; Folorunso et al., 1993), thus greatly increasing runoff ratio with increasing precipitation intensity.

The cover crop treatments increased biomass returned to the soil surface by 14%, averaged across all years of the study, but the effect was much greater during years with soybean production, where the cover crop increased surface biomass as much as 63% in 2020 (Figure 5). Use of a cover crop can shade soils, decrease evaporation, and increase surface soil moisture, thereby increasing runoff ratio at lower precipitation intensities, yet the added residue will

protect the soil from raindrop energy in the high intensity events (Jin et al., 2009), thus explaining the contrasting effects of precipitation intensity on runoff for the CN-NC and CN-CC treatments. Alternatively, no-till fields have been found to have increased soil water repellency compared to conventionally tilled fields (Blanco-Canqui, 2011; P. D. Hallett et al., 2001). Soil water repellency is the resistance to wetting due to hydrophobic films on the soil particles that come from fungi, soil microbes and plant matter (P. D. Hallett & Young, 1999). Hallett and Young's 2001 study reported soil water repellency (referred to as subcritical water repellency in the study) index values for conventionally tilled, no-till, and pasture fields and found a strong link between management and soil water repellency index. Pikul et al. (2009) also linked soil health parameters like soil organic matter, soil organic carbon, nitrogen, glomalin, and basidiomycetes fungi with decreased aggregate wettability in no-till fields. No-till fields had an abundance of a wax type carbon compounds that are hydrophobic. Previous studies at the KAW found a significant increase in surface (0-5 cm) soil organic carbon in the CC plots compared to the NC (Stahl, 2023). Further studies on how soil water repellency affects surface runoff are still needed, but this could be why at low intensities the CN-CC treatment had greater surface runoff.

Similarly, the greater biomass produced by corn and soybean from P fertilization can also protect soils from raindrop energy during high intensity precipitation events, maintaining less runoff in the SI-NC treatment relative to CN-NC. The combined effects of cover crop and P fertilization in the SI-CC treatment increased cover crop growth, which could decrease soil moisture, improve soil physical properties (Stahl, 2023), and protect the soil surface, thus reducing runoff at both low and moderate rainfall intensities relative to either use of P fertilizer or cover crops alone. The maximum runoff volume (78.8 mm) and the maximum precipitation amount (107.5 mm) of the dataset was from a storm in May with an intensity of 30.14 mm hr⁻¹.

This storm occurred in late May (5/24/2020) which was four days after the experiment had been planted with soybeans (5/19/2020). This storm also had the highest runoff ratio at 0.73. The most intense storm that occurred in August had a lower runoff ratio (0.69) and produced less runoff 57.19 mm. It occurred on 8/30/2019 which was eighteen days before the corn was harvested (9/18/2019). This highlights the importance of biomass for runoff reduction when comparing similar storms at different times of the year.

Overall, these data suggest that the use of cover crop with P fertilization would result in the most consistently reduced runoff across the spectrum of rainfall intensities observed in this study.

Water Quality

Total Suspended Sediment Load

The total suspended sediment load per unit of precipitation (TSS_p) had a significant three-way interaction between precipitation intensity, fertilizer, and cover (Table 4). The TSS_p increased with increasing precipitation intensity for all treatments (Figure 6). The CN-NC treatment had the greatest change in TSS_p compared to all other treatments (Table 5 and 7).

The application of P fertilizer decreased the slope of TSS_p in the NC treatments but had no effect on the slope for the CC treatments (Table 5). Although P fertilizer reduced the slope, the TSS_p was greater at low intensities in the SI-NC treatment than in the CN-NC treatment. At moderate intensities there was no significant difference between the two treatments. Once intensities were greater than 32 mm hr^{-1} the TSS_p in the CN-NC treatment was greater than the SI-NC treatment. Crop residue acts as a shield to the soil decreasing detachment from raindrop

impact (Folorunso et al., 1992). The SI treatments had significantly more biomass than the CN which would also increase the crop residue left after harvest.

The application of cover crops decreased the slope in the CN treatments but had no effect on the slope of the SI treatments. However, cover crops did reduce TSS_p in the SI treatments for the entire range of intensities. Cover crops build soil structure with root biomass that increases soil aggregation and shear strength therefore increasing durability to raindrop impact (Rachman et al., 2003). At the KAW, Stahl (2023) found a main effect of cover on the mean weight diameter of soil aggregates with an increase from CC to NC plots. Greater mean weight diameters are an indication of greater structural stability in the soil which results in more resistance to erosion. Like for the runoff ratio, the possibility of water repellency from soil organic carbon, would make aggregates even more resistant to raindrop impact reducing sediment loss.

These data suggest that TSS_p is most consistently reduced with the application of P fertilizer and cover crops even under intense precipitation. This result agrees with previous studies that have found that high rainfall intensities and low cover result in higher sediment loss (Jin et al., 2009; Ramos et al., 2019; Siller et al., 2016). Biomass data from the study also supports this with the CC treatments having significantly more biomass than the NC treatments in three out of the eight years, with the other five years having no significant difference (Figure 5). This is highlighted when paired with the runoff ratio results that show the SI-NC and SI-CC treatment having similar runoff ratios at high intensities (Figure 4), but different amounts of sediment loss.

Dissolved Reactive Phosphorus Load

Dissolved reactive P loss per unit of precipitation (DRP_p) was affected by the 2-way interaction between phosphorus fertilizer and precipitation intensity but not affected by any other higher order interactions (precipitation intensity by cover, or precipitation intensity by cover by P fertilizer) (Table 4). Therefore, these higher order non-significant effects were dropped from the model and data were analyzed with a reduced model (Table 6). Increasing precipitation intensity significantly increased DRP_p loss in runoff from CN treatments but did not affect DRP_p losses from the SI treatments. In the CN treatments, the DRP_p loss increased on average over 150% from the least intense precipitation event (2.9 mm hr^{-1}) to the most intense precipitation event (48.9 mm hr^{-1}) (Figure 7). The DRP_p losses from SI treatments were greater overall until intensities of 42 mm hr^{-1} were reached where SI-NC and CN-CC losses were not significantly different. Cover crops did not significantly change the relationship between DRP_p loss and precipitation intensity, but did significantly increase overall DRP_p loss at every intensity compared to the NC treatments. Cover crops have been shown to increase DRP load particularly in freeze-thaw conditions that release P from cell tissues (Carver et al., 2020; Liu et al., 2014, 2019). Cover crops are often recommended as a best management practice to reduce erosion, weed pressure, and nutrient loss. However, cover crops may be sources of phosphorus (P) to runoff water after termination. Two greenhouse trials were conducted to determine the effects of cover crop species, termination method, and time after termination on water-extractable P (WEP) release from crop biomass. Treatments were structured in a $3 \times 3 \times 3$ factorial and arranged in a randomized complete block design with six replicates. Treatments included three cover crop species (triticale [$\times$ Triticosecale; *Triticum* $\times$ *Secale* ‘Trical’], rapeseed [*Brassica napus* L. ‘Winfred’], and crimson clover [*Trifolium incarnatum* L.]); three termination methods (clipping,

freezing, and herbicide); and three WEP extraction times (1, 7, and 14 d after termination). Rapeseed consistently resulted in the least WEP when exposed to the same method of termination and at the same extraction time as the other species. For both trials, terminating crop tissue via freezing increased concentrations of WEP compared with other termination methods. The WEP release from cover crop tissue increased as the time after extraction increased, but the effect was greater for herbicide- and freeze-terminated cover crops and less for clipping-terminated cover crops. Future studies on WEP release from cover crops should pay close attention to the effects of extraction timing. Producers may be able to reduce P loss from cover crop tissue by selecting cover crop species with low WEP and minimizing the amount of biomass exposed to freezing conditions (Carver et al., 2020; Liu et al., 2014, 2019). It is suggested that catch crops be grown to reduce phosphorus (P) losses. However, after exposure to freezing–thawing cycles (FTCs), catch crop material can become a source of P losses to waters in moderately cold climates. This study screened potential P leaching from intact plant material of eight catch crop species: chicory (*Cichorium intybus* L.), cocksfoot (*Dactylis glomerata* L.), perennial ryegrass (*Lolium perenne* L.), red clover (*Trifolium pratense* L.), phacelia (*Phacelia tanacetifolia* L.), white mustard (*Sinapis alba* L.), oilseed radish (*Raphanussativus* L. *oleiformis*) and white radish (*R. longipinnatus*). The catch crops were grown in six field experiments on clay soils, where soil lysimeters (0.25 m deep) with intact crops were extracted in autumn and used for leaching experiments before and after seven FTCs in the laboratory. The eight catch crops did not reduce P leaching before FTCs. After FTCs, leachate total-P concentrations from ryegrass, oilseed radish and red clover lysimeters were significantly ($p = 0.0022$) higher than those from the other species and the control without a catch crop. FTCs significantly ($p = 0.0064$) altered total-P concentration and the proportions of different forms of P. There was a significant increase

in total-P concentration in leachate from ryegrass ($p = 0.0008$) and oilseed radish ($p = 0.02$). Thus the potential risk of P leaching from ryegrass and oilseed radish material after FTCs must be considered, since they are commonly grown as nitrogen catch crops in the Nordic countries. Moreover, the roots of the tested catch crops contained 7–86 % total-P, which is important when evaluating P leaching (Liu et al., 2014). The use of cover crops and crop residues is a common strategy to mitigate sediment and nutrient losses from land to water. In cold climates, elevated dissolved P losses can occur associated with freeze–thaw of plant materials. Here, we review the impacts of cover crops and crop residues on dissolved P and total P loss in cold climates across ~41 studies, exploring linkages between water-extractable P (WEP) in plant materials and P loss in surface runoff and subsurface drainage. Water-extractable P concentrations are influenced by plant type and freezing regimes. For example, WEP was greater in brassica cover crops than in non-brassicacaeae, and increased with repeated freeze–thaw cycles. However, total P losses in surface runoff and subsurface drainage from cropped fields under cold climates were much lower than plant WEP, owing to retention of 45 to >99% of released P by soil. In cold climatic regions, cover crops and crop residues generally prevented soil erosion and loss of particle-bound P during nongrowing seasons in erodible landscapes but tended to elevate dissolved P loss in nonerodable soils. Their impact on total P loss was inconsistent across studies and complicated by soil, climate, and management factors. More research is needed to understand interactions between these factors and plant type that influence P loss, and to improve the assessment of crop contributions to P loss in field settings in cold climates. Further, tradeoffs between P loss and the control of sediment loss and N leaching by plants should be acknowledged. Core Ideas Winter crop covers reduce soil erosion but may enhance dissolved P loss under cold climates. In cold climates, FTCs increase dissolved P release from plants and soils. Plant water-extractable P

varies with crop species, hardness, and freeze regimes. Phosphorus losses in runoff and leaching are complicated by soil, hydrology, and management. Assessment of crop impacts on P loss should consider tradeoffs and future climates (Carver et al., 2020; Liu et al., 2014, 2019). However, the studied effects of cover crops on DRP_p loss are inconsistent with some studies reporting insignificant effects (Aboelnour et al., 2025; Kleinman et al., 2022).

Sediment-bound P is often the dominant form of P lost in systems that have high rates of erosion (Sharpley et al., 1993; Alewell et al., 2020), but in no-till systems where erosion and sediment loss are reduced, dissolved P may be the dominant form lost if dissolved P is unable to sorb to sediment particles in runoff (Sharpley et al., 1993). This is also seen in tile drainage systems where DRP loads can be even higher compared to surface runoff loads (Bodrud-Doza et al., 2025).

Total Phosphorus Load

Phosphorus fertilizer and cover crop use significantly affected the relationship between the precipitation intensity and total phosphorus loss per unit of precipitation (TP_p) loss (Table 4, Figure 8). Increasing precipitation intensity only increased the total P load for the CN-NC treatment. Although there were positive relationships between precipitation intensity and P loss for the other treatments, their slopes were not significantly different than zero (Table 5).

The application of P fertilizer to NC plots decreased the slope for the relationship between TP loss and precipitation intensity. At intensities less than 38 mm hr^{-1} the CN-NC treatment had less TP loss. When intensities were greater than or equal to 38 mm hr^{-1} the CN-NC and SI-NC treatments had no significant difference in TP loss. The strong effect of precipitation intensity on TP_p loss in the CN-NC treatment may be due to the precipitation intensity effects on runoff (Figure 4) and sediment loss (Figure 6) for this same treatment. Greater runoff could

result in greater dissolved P losses and greater sediment loss could result in greater sediment-bound P loss. However, because dissolved P loss is least in the CN-NC treatment (Figure 7), it is more likely that this effect is due to increased particulate P loss with the eroded sediments. The sediment-bound form of P is often the dominant form lost. An increase in sediment loss in the CN-NC treatment could then potentially lead to a total P loss equal to that in the SI-NC treatment. The application of P fertilizer to CC plots did not significantly change the relationship between TP loss and precipitation intensity, where the SI-CC and CN-CC treatments have no significant difference in slope (Table 7).

Cover crop use did not affect the slope in the SI treatments, but significantly decreased the slope in the CN treatments. This could be attributed to the additional biomass that is produced from cover crops that would aid in the protection of the soil surface from erosion as seen in Figure 5, where either P fertilizer addition or cover crop use would increase biomass production and residue coverage on the soil surface (Appendix C).

Hydrograph characteristics

Time of Concentration

The time of concentration did not have any significant interactions between the treatments and the precipitation intensity (Table 4) but did have a significant interaction between the fertilizer and cover treatments. Because of the lack of higher order interactions, a reduced model was used (Table 6). Because there were no interactions with the change in precipitation intensity, the treatment effects on time of concentration was the same for all precipitation intensities. However, the fertilizer*cover interaction is significant. The time of concentration has critical importance when assessing flood-control measures. It is defined as the time taken for

water to travel from the most hydrologically remote location in a watershed to the outlet. The CN-NC treatment had the shortest time of concentration (Figure 9, Table 9). This short time of concentration in the CN-NC treatment could be because of the relative lack of surface cover which slows down runoff (Dabney, 1998). A shorter time of concentration could be due to less overall runoff (thus less time needed for runoff to occur) or a greater runoff speed. We hypothesized that the decreased time of concentration for the CN-NC treatment is a result of the greater runoff velocity. This is shown in the runoff ratio of the CN-NC treatment which was similar to SI-CC at low precipitation intensities but had a shorter time of concentration. These results show that the application of cover crops greatly increases the time of concentration in the CN plots. In the SI plots the application of cover crops decreased the time of concentration. The SI-NC treatment had a significantly longer time of concentration than the SI-CC treatment. However, this shorter time of concentration in the SI-CC treatments when compared with the runoff ratio values in Figure 4, indicates that the shorter time of concentration may be a result of less water being lost to runoff in the SI-CC treatments until intensities reach 38 mm hr^{-1} when there is no significant difference in runoff ratio. The time of concentration for CN-CC and SI-NC was not significantly different from each other.

The application of P fertilizer to the CC treatments reduced the time of concentration. The same trend is seen when comparing the time of concentration and runoff ratio (Figure 4) of the SI-CC treatments, where the SI-CC treatment had a lower runoff ratio than the CN-CC treatment until intensities were greater than or equal to 32 mm hr^{-1} when runoff ratios are not significantly different. Therefore, the effect of P fertilizer on runoff duration in the cover crop treatments may be a result of less runoff occurring at lower precipitation intensities.

Time to Runoff Initiation

There were not any significant interactions between P fertilizer or cover crops with precipitation intensity (Table 4). Therefore, we removed the higher order non-significant interactions and analyzed the data with a reduced model (Table 6). Time to initiation of runoff decreased consistently across all treatments with increasing precipitation intensity (Figure 10; Table 8). Other studies have also found a negative correlation between precipitation intensity and time to initiation of runoff (Zhang et al., 2019). The lack of interaction between precipitation intensity and other model components indicates that the effects of precipitation intensity on the time to runoff initiation were not affected by cover crop use or P fertilizer application.

There is a significant two-way interaction between P fertilizer and cover crop indicating that these treatments are affecting the time to runoff initiation independent of the precipitation intensity (Table 6). The addition of P fertilizer and cover crops significantly increased the time to initiation at all precipitation intensities (Table 9). The SI-CC treatment consistently had the longest time to initiation. When compared with the time to concentration (Figure 9) and runoff ratio (Figure 4) the SI-CC treatment is the slowest to initiate runoff, with the second shortest time of concentration and the least amount of runoff. Simulated rainfall studies have shown that above ground biomass and below ground root systems work in tandem to delay runoff initiation through the growth stages of wheat (*Triticum aestivum* L.) and alfalfa (*Medicago sativa* L.) (Lin et al., 2019; Yao et al., 2023). Once the wheat reached the heading stage in Lin et al, (2019), it significantly increased the time to runoff initiation from the bare ground and stubble phases. The average time to runoff initiation from the bare, wheat, and stubble ground had no significant difference at the 60 mm hr⁻¹ intensity, but the wheat and stubble ground are significantly different than the bare ground at the highest intensity (120 mm hr⁻¹). Zhang et al, (2019) also

showed that increased vegetation will delay or, with certain land uses, eliminate runoff. This delay in the runoff initiation means that surface flow has more time to absorb into the soil profile and has implications for reduced downstream flooding.

Time to Peak Flow

Only the main effects of cover and precipitation intensity significantly affected the time to peak flow (Table 4). Therefore, the data were analyzed with a reduced model that eliminated the higher order interactions with peak flow (Table 6). Time to peak runoff decreased equally for all treatments as precipitation intensity increased (Figure 11). The CN-NC treatment had the shortest time to peak runoff across all intensities. The two cover crop treatments had no significant difference in their mean times to peak flow while the two no cover treatments did (Table 9). The SI-NC treatment had a longer time to peak flow than the CN-NC treatment. The addition of biomass seemed to increase the time to peak flow with CN-NC having had the shortest time, SI-NC with the second shortest time, and the CN-CC and SI-CC treatments having the same times.

Comparing the two NC treatments and their times to initiation, the SI-NC treatment had the shorter time to initiation of runoff, but as the runoff flowed through the plots the time to peak was delayed due to the additional biomass. These results in combination with the runoff ratio (Figure 4) and the time of concentration (Figure 9) add to the conclusion that the CN-NC treatment lost more water faster than the SI-NC treatment and that the speed of the runoff increased as it traveled to the plot outlet especially once precipitation intensities increased.

There was no significant difference in the time to peak flow between the two CC treatments. The SI-CC treatment did have a significantly longer time to runoff initiation than the

CN-CC treatment (Table 9) while the CN-CC mean duration was the longest along with the SI-NC treatment (Table 9). Mean times of all the treatments compared to the runoff ratio results indicate that the SI-CC treatment loses the least amount of water to runoff, likely because of an increased infiltration rate, the CN-CC treatment initially had less water absorbed than the SI-CC treatment but had a slowed runoff velocity due to the biomass amount. The SI-NC treatment on average has the shortest time to initiation of runoff, but like the CN-CC treatment, has enough biomass to reduce the velocity of the runoff to increase the time to peak and have an overall longer time of concentration. The CN-NC treatment had the fastest runoff with a short time to initiation, peak and duration that loses a great portion of water to runoff once precipitation intensities increase past a certain point (Figure 4).

Peak Flow

The three-way interaction between P fertilizer use, cover crop use, and precipitation intensity was not significant (Table 4). We therefore removed that interaction from the model and analyzed the data with a reduced model (Table 6). Both cover crop use and P fertilizer application affected the relationship between precipitation intensity and peak flow (Table 4). There was a positive relationship between peak flow and precipitation intensity for all treatments (Figure 12a and b). In general, both P fertilizer and cover crop use decreased the slope for the relationship between peak flow and fertilizer use, but the effects of cover crop were greater than those of P fertilizer use. The greatest slope was for the CN-NC treatment, slopes for SI-NC and CN-CC were not different, and the slope for SI-CC was the least ($p < 0.001$). A reduction in peak flow can be seen on land with increased amounts of vegetation in rainfall simulations and natural rainfall experiments (Fu et al., 2020; Montaldo et al., 2020).

The results from the runoff ratio, time to initiation, time to peak flow, and duration solidify the conclusion that the SI-CC treatment produced the slowest moving runoff with the least erosive force and the least amount of water lost to runoff. Even as precipitation intensities increase and the runoff ratio increased to be not significantly different than the SI-NC or CN-CC treatment, the peak flow of the SI-CC for those intensities is reduced producing less erosive force on the sediment (Figure 4).

The effectiveness of cover crops at the catchment scale may not garner the same results. A study by Zhu (2016) evaluates the effectiveness of conservation practices that included terraces, contoured earth banks, and the planting of grasses, shrubs, and trees. He found that storms with an exceedance probability of greater than 5% had a reduction in peak runoff from conservation practices compared to without. Storms with an exceedance probability of 5% or less showed no difference in peak flow between the conservation watershed and the control.

Table 2. Runoff-producing precipitation events included in the final dataset with the runoff sample collection date, precipitation start date and time, precipitation duration, average site precipitation, the maximum 30-minute precipitation intensity

Sample collection date	Precipitation start date and time	Precipitation Duration (min)	Average Site Precipitation (mm)	Maximum 30-minute precipitation intensity (mm hr ⁻¹)	Average Runoff (mm)
12/1/2015	11/26/2015 7:21	806	42.38	4.78	6.21
12/15/2015	12/12/2015 23:44	1268	57.16	8.34	22.35
4/25/2016	4/24/2016 20:19	135	52.35	31.78	19.25
4/27/2016	4/26/2016 15:28	613	74.71	28.74	41.89
5/25/2016	5/24/2016 23:13	521	14.22	6.76	2.53
5/26/2016	5/25/2016 20:04	177	15.80	9.79	4.85
5/27/2016	5/26/2016 14:22	793	62.15	17.92	36.32
7/12/2016	7/12/2016 3:17	122	26.25	22.31	1.12
7/13/2016	7/13/2016 8:31	81	24.29	23.23	11.13
8/20/2016	8/19/2016 17:18	213	46.50	37.52	2.68
8/25/2016	8/25/2016 6:00	123	37.45	25.19	8.34
8/26/2016	8/26/2016 4:29	408	26.72	15.63	11.62
8/27/2016	8/27/2016 3:51	263	8.75	8.57	1.19
9/14/2016	9/14/2016 1:19	509	14.35	3.97	2.27
10/11/2016	10/11/2016 7:23	291	14.77	7.81	2.51
3/31/2017	3/28/2017 23:34	2060	63.78	5.26	23.91
4/3/2017	4/3/2017 2:36	263	17.50	4.75	5.17
4/6/2017	4/4/2017 14:23	838	31.75	5.00	13.26
5/20/2017	5/19/2017 13:26	799	16.69	10.02	5.75
8/7/2017	8/5/2017 20:39	171	41.83	36.77	21.16
8/11/2017	8/11/2017 0:31	132	22.30	12.48	3.14
10/8/2017	10/6/2017 21:29	403	37.40	17.00	2.14
10/16/2017	10/14/2017 11:42	324	31.16	16.26	7.34
8/24/2018	8/23/2018 4:44	434	44.95	18.54	15.86
9/3/2018	9/3/2018 0:18	919	74.77	13.94	24.82
9/6/2018	9/5/2018 2:15	692	21.20	9.11	7.57
10/6/2018	10/5/2018 23:59	1312	43.71	13.11	2.70
10/10/2018	10/7/2018 2:54	3653	70.98	9.22	19.97
5/7/2019	5/6/2019 17:25	869	43.43	21.73	19.48
5/8/2019	5/7/2019 15:35	900	80.08	14.58	49.88
5/9/2019	5/8/2019 17:50	186	14.33	5.68	5.21
5/13/2019	5/12/2019 0:12	155	16.01	5.39	3.13
5/19/2019	5/18/2019 3:41	1629	54.92	12.28	19.98
5/22/2019	5/20/2019 12:31	1965	49.02	4.75	20.64
5/27/2019	5/25/2019 21:00	1897	26.95	13.07	5.12
6/24/2019	6/22/2019 18:54	818	80.41	22.88	42.92
7/5/2019	7/4/2019 3:17	347	48.75	14.32	3.93
8/16/2019	8/15/2019 19:32	217	44.61	24.29	19.24
8/26/2019	8/25/2019 0:16	404	49.22	14.71	19.39
8/30/2019	8/30/2019 0:16	249	82.12	48.91	57.19
10/5/2019	10/4/2019 10:46	1384	32.42	7.08	15.12
4/25/2020	4/24/2020 10:51	603	30.63	9.94	6.66
5/4/2020	5/4/2020 7:11	230	33.25	25.97	11.80
5/25/2020	5/24/2020 21:10	692	107.52	30.14	78.84
5/27/2020	5/25/2020 23:08	1443	36.99	6.43	17.44
6/4/2020	6/4/2020 1:02	301	20.97	20.72	4.69
6/27/2020	6/27/2020 2:25	657	32.08	16.25	5.49
7/9/2020	7/9/2020 2:02	276	37.69	23.04	1.94
7/15/2020	7/15/2020 3:39	370	36.54	24.79	3.64
7/20/2020	7/20/2020 6:18	231	33.97	28.40	12.14
7/21/2020	7/20/2020 22:39	575	29.25	16.25	13.59
7/30/2020	7/29/2020 14:00	165	59.41	31.17	38.90
7/31/2020	7/30/2020 18:17	232	22.36	14.28	13.67

Sample collection date	Precipitation start date and time	Precipitation Duration (min)	Average Site Precipitation (mm)	Maximum 30-minute precipitation intensity (mm hr ⁻¹)	Average Runoff (mm)
11/25/2020	11/25/2020 1:18	358	22.00	4.50	4.34
5/17/2021	5/16/2021 2:53	798	85.73	25.83	41.98
7/16/2021	7/15/2021 0:36	601	97.96	27.37	33.85
9/3/2021	9/3/2021 1:11	217	49.64	31.13	7.06
10/28/2021	10/27/2021 17:01	1082	13.14	7.39	2.89
11/11/2021	11/10/2021 12:05	341	28.63	8.79	5.09
3/24/2022	3/21/2022 14:39	3446	39.56	2.88	2.45
5/6/2022	5/5/2022 15:14	994	24.19	6.52	10.48
5/18/2022	5/17/2022 20:41	317	28.13	23.88	3.39
5/26/2022	5/25/2022 8:21	1366	35.50	3.25	9.62
5/31/2022	5/30/2022 23:18	527	57.91	23.36	26.34
6/8/2022	6/7/2022 23:42	287	15.15	11.40	2.78
6/13/2022	6/11/2022 19:24	210	30.16	16.72	17.19
6/22/2022	6/21/2022 20:36	347	34.21	26.58	10.28
6/23/2022	6/23/2022 8:11	391	20.75	7.09	9.23
6/24/2022	6/23/2022 21:04	809	20.82	10.93	12.63
7/2/2022	7/1/2022 18:10	1065	73.20	11.53	35.25
7/25/2022	7/25/2022 0:00	579	69.07	12.36	16.21

Table 3. Distribution of runoff-producing precipitation events by month with the maximum, minimum, and average 30-min maximum intensities (mm hr⁻¹), precipitation (mm), and runoff (L s⁻¹).

	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Number of events	0.0	0.0	2.0	5.0	19.0	8.0	12.0	10.0	4.0	7.0	3.0	1.0
Max. Intensity	0.0	0.0	5.3	31.8	30.1	26.6	31.2	48.9	31.1	17.0	8.8	8.3
Min. Intensity	0.0	0.0	2.9	4.8	3.3	7.1	11.5	8.6	4.0	7.1	4.5	8.3
Average Intensity	0.0	0.0	4.1	16.0	14.1	16.6	20.8	24.3	14.5	11.1	6.0	8.3
Max. Precipitation	0.0	0.0	63.8	74.7	107.5	80.4	98.0	82.1	74.8	71.0	42.4	57.2
Min. Precipitation	0.0	0.0	39.6	17.5	14.2	15.2	22.4	8.8	14.4	13.1	22.0	57.2
Avg. Precipitation	0.0	0.0	51.7	41.4	42.3	31.8	46.6	40.4	40.0	34.8	31.0	57.2
Max. Runoff	0.0	0.0	23.9	41.9	78.8	42.9	38.9	57.2	24.8	20.0	6.2	22.4
Min. Runoff	0.0	0.0	2.5	5.2	2.5	2.8	1.1	1.2	2.3	2.1	4.3	22.4
Avg. Runoff	0.0	0.0	13.2	17.2	19.6	13.2	15.4	16.0	10.4	7.5	5.2	22.4

Table 4. ANOVA with p-values of P fertilizer application (fert), winter cover crop (cover), precipitation intensity (max_p30) and their interactions on runoff ratio, total suspended solids load, total P load, dissolved reactive P load, time of concentration, time to initiation of runoff, time to peak flow, and peak flow ($p < 0.05$).

Effect	Runoff Ratio	Total Suspended Solids [†]	Total P [†]	Dissolved Reactive P [†]	Time of Concentration	Time to Initiation of Runoff	Time to Peak Flow	Peak Flow
fert	0.6691	0.2000	<.0001	<.0001	<.0001	0.1791	0.0802	0.4857
cover	0.0015	<.0001	<.0001	<.0001	<.0001	0.0002	0.0002	0.5694
fert*cover	<.0001	<.0001	<.0001	0.0005	<.0001	0.0421	0.0725	<.0001
max_p30	0.0086	0.0002	0.0091	0.0727	<.0001	<.0001	<.0001	<.0001
max_p30*fert	0.0733	0.0007	0.0037	0.0213	0.2610	0.1499	0.6024	0.0008
max_p30*cover	<.0001	<.0001	0.0003	0.4229	0.1822	0.6405	0.6931	<.0001
max_p30*fert*cover	<.0001	0.0006	0.0002	0.0553	0.4636	0.846	0.3619	0.0527

[†]Variables are normalized by precipitation amount

Table 5. Slope estimates (log-scale) from multiple regression analysis of precipitation intensity effects on runoff ratio[†], total suspended solids, dissolved reactive phosphorus, and total phosphorus loss in surface runoff as affected by cover crop and P fertilizer treatments. Asterisks indicate if the slopes are significantly different from 0 at $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***).

Treatments	Runoff Ratio	Total Suspended Solids	Dissolved Reactive Phosphorus	Total Phosphorus
CN-CC	0.0004	0.0098*	0.0088**	0.0032
CN-NC	0.0070***	0.0297***	0.0088**	0.0170***
SI-CC	0.0035*	0.0099*	0.0026	0.0048
SI-NC	0.0020	0.0142*	0.0026	0.0046

[†]Runoff ratio is on a square root scale

Table 6. ANOVA with p-values of P fertilizer application (fert), winter cover crop (cover), precipitation intensity (max_p30) and their interactions on dissolved reactive P, time to initiation of runoff, time to peak flow, time of concentration, and peak flow (p<0.05) using a reduced model with ‘X’ denoting interactions not significant in the full model.

Effect	Dissolved Reactive P	Time to Initiation of Runoff	Time to Peak Flow	Time of Concentration	Peak Flow
fert	<.0001	0.8304	0.0127	<.0001	0.4857
cover	<.0001	<.0001	<.0001	<.0001	0.5694
fert*cover	0.0005	<.0001	0.0501	<.0001	<.0001
max_p30	0.0727	<.0001	<.0001	<.0001	<.0001
max_p30*fert	0.0213	X	X	X	0.0008
max_p30*cover	X	X	X	X	<.0001
max_p30*fert*cover	X	X	X	X	X

Table 7. Difference of slope estimates from multiple regression and analysis precipitation intensity effects on runoff ratio, total suspended solids load, and total phosphorous load for the four cover crop and P fertilizer treatments. Asterisks indicate if the slopes are significantly different from each other at p<0.05 (*), p<0.01 (**), and p<0.001(***).

Treatments	Runoff Ratio	Total Suspended Solids	Total Phosphorus
CN-CC=SI-CC	-0.0031***	-0.0001	-0.0017
CN-NC=SI-NC	0.0050***	0.0156***	0.0124***
CN-CC=CN-NC	-0.0066***	-0.0199***	-0.0138***
SI-CC=SI-NC	0.0015	-0.0042	0.0003
CN-NC=SI-CC	0.0035***	0.0198***	0.0122***
CN-CC=SI-NC	-0.0016*	-0.0043	-0.0014

Table 8. Slope estimates (log-scale) from multiple regression and analysis of precipitation intensity effects on time of concentration, time to initiation of runoff, time to peak, and peak flow*. Asterisks indicate if the slopes are significantly different from 0 at p<0.05 (*), p<0.01 (**), and p<0.001(***).

Treatments	Time of Concentration	Time to Runoff Initiation	Time to Peak	Peak Flow (effect of P fertilizer)	Peak Flow (effect of cover)
CN-CC	-0.01497***	-0.02006***	-0.02025***	0.1563***	0.1349***
CN-NC	-0.01497***	-0.02006***	-0.02025***	0.1563***	0.1600***
SI-CC	-0.01497***	-0.02006***	-0.02025***	0.1386***	0.1349***
SI-NC	-0.01497***	-0.02006***	-0.02025***	0.1386***	0.1600***

*Peak flow is on a square root scale

Table 9. LS-Means of time to initiation of runoff, time to peak flow and time of concentration (min) (log scale) for the significant fertilizer by cover interaction. Means with the same letter are not significantly different ($p < 0.05$).

Fertilizer	Cover	Time to Initiation of Runoff	Time to Peak Flow	Time of Concentration
SI	CC	1.9877 A	2.2849 A	2.1860 B
CN	CC	1.9519 B	2.2825 A	2.2497 A
CN	NC	1.9321 B	2.2388 C	2.0202 C
SI	NC	1.8926 C	2.2588 B	2.2351 A

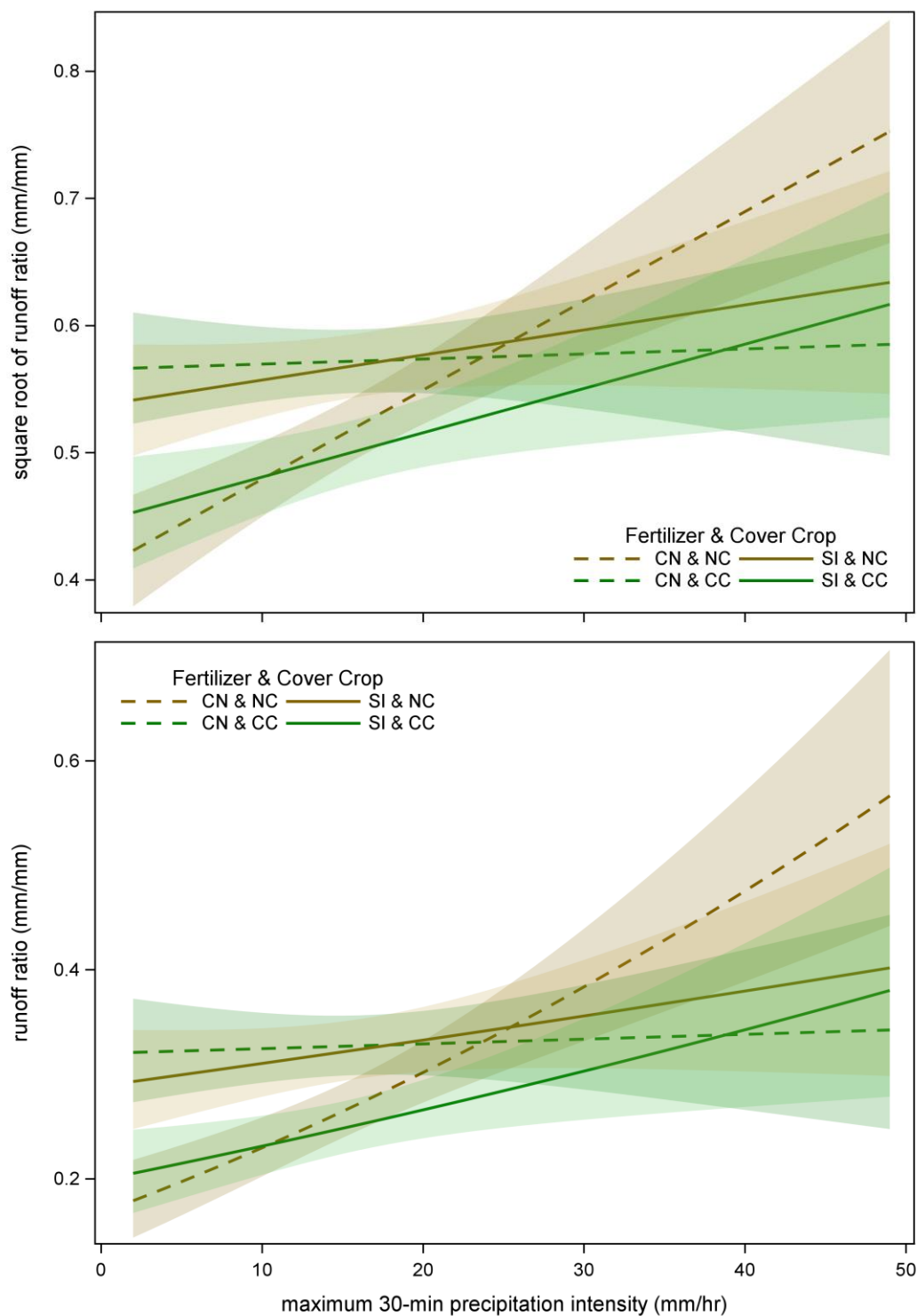


Figure 4. Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and the runoff ratio for a no-till corn-soybean production system (CN=no P fertilizer; SI=spring-injected P fertilizer; NC=no cover crop; CC=with winter cover crop).

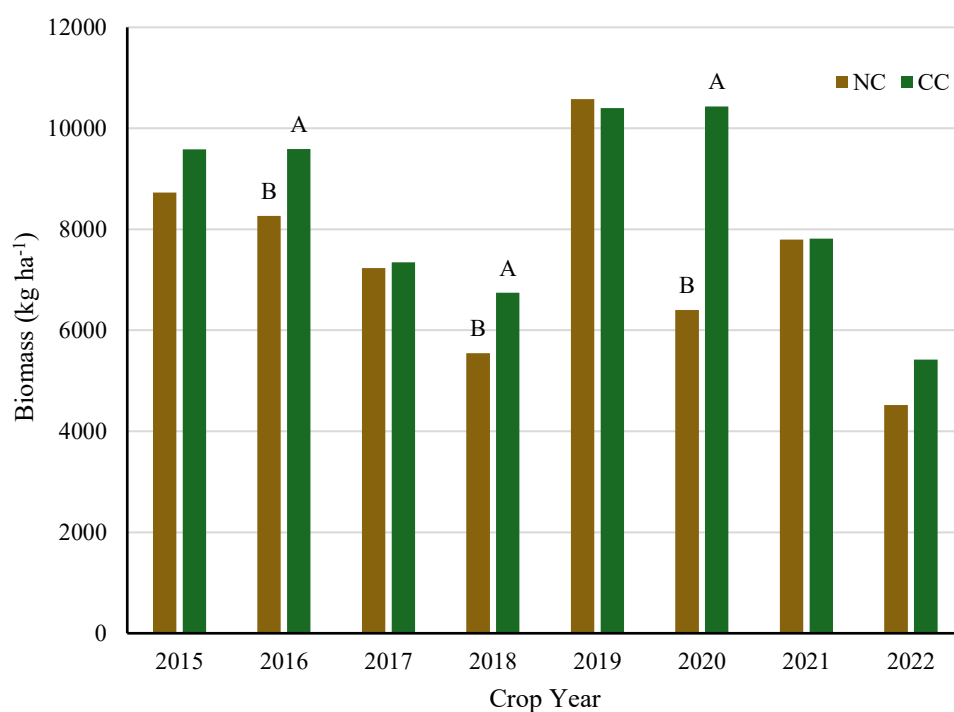


Figure 5 Least squares means of annual above-ground biomass returned to the soil surface (i.e., residue) for the cover crop by year interaction (averaged across P fertilizer treatments). Letters above bars denote significant differences between treatments within a given year ($p < 0.05$). Odd years were planted corn and even years were planted soybean.

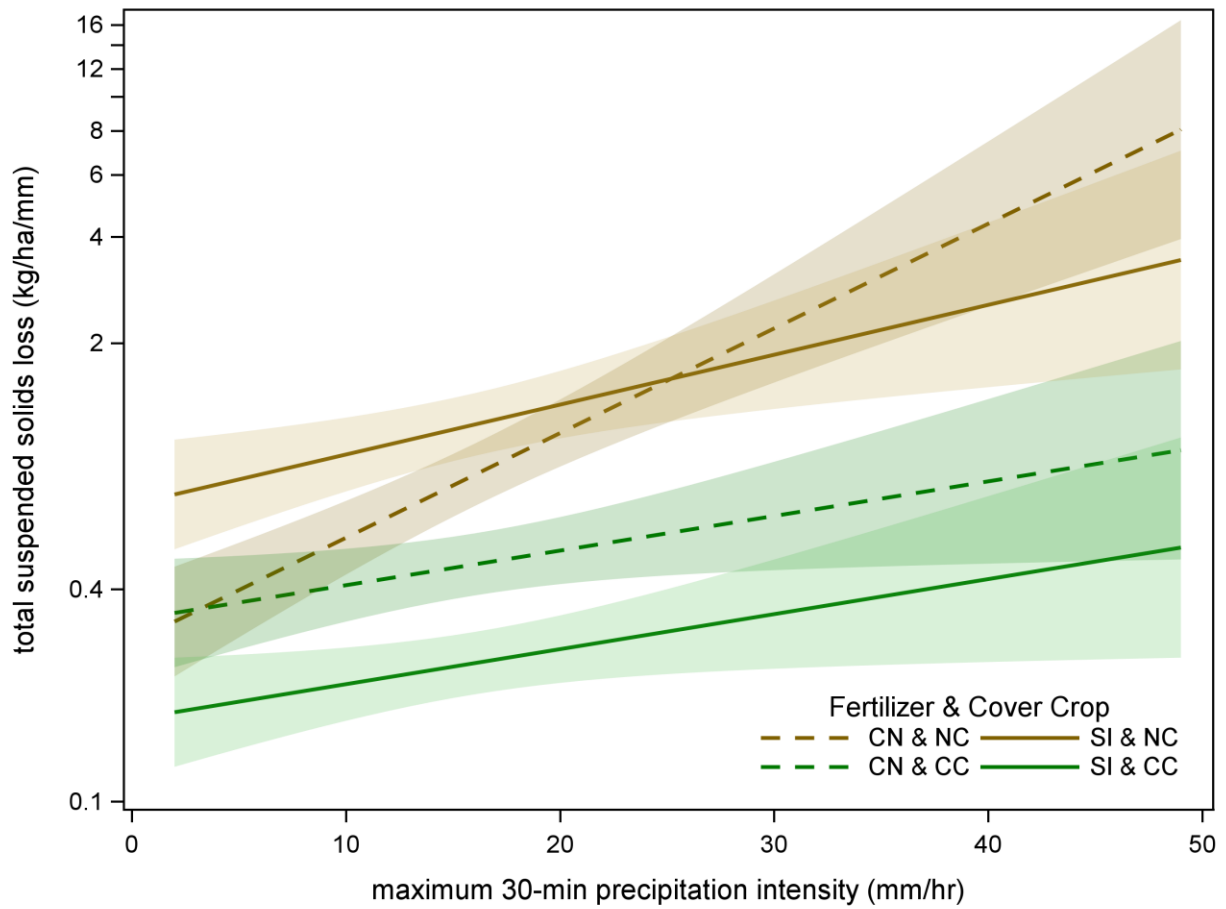


Figure 6. Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and total suspended solid load ($\text{kg ha}^{-1} \text{mm}^{-1}$) in a no-till corn-soybean production system (CN=no P fertilizer; SI=spring-injected P fertilizer; NC=no cover crops; CC=with winter cover crops).

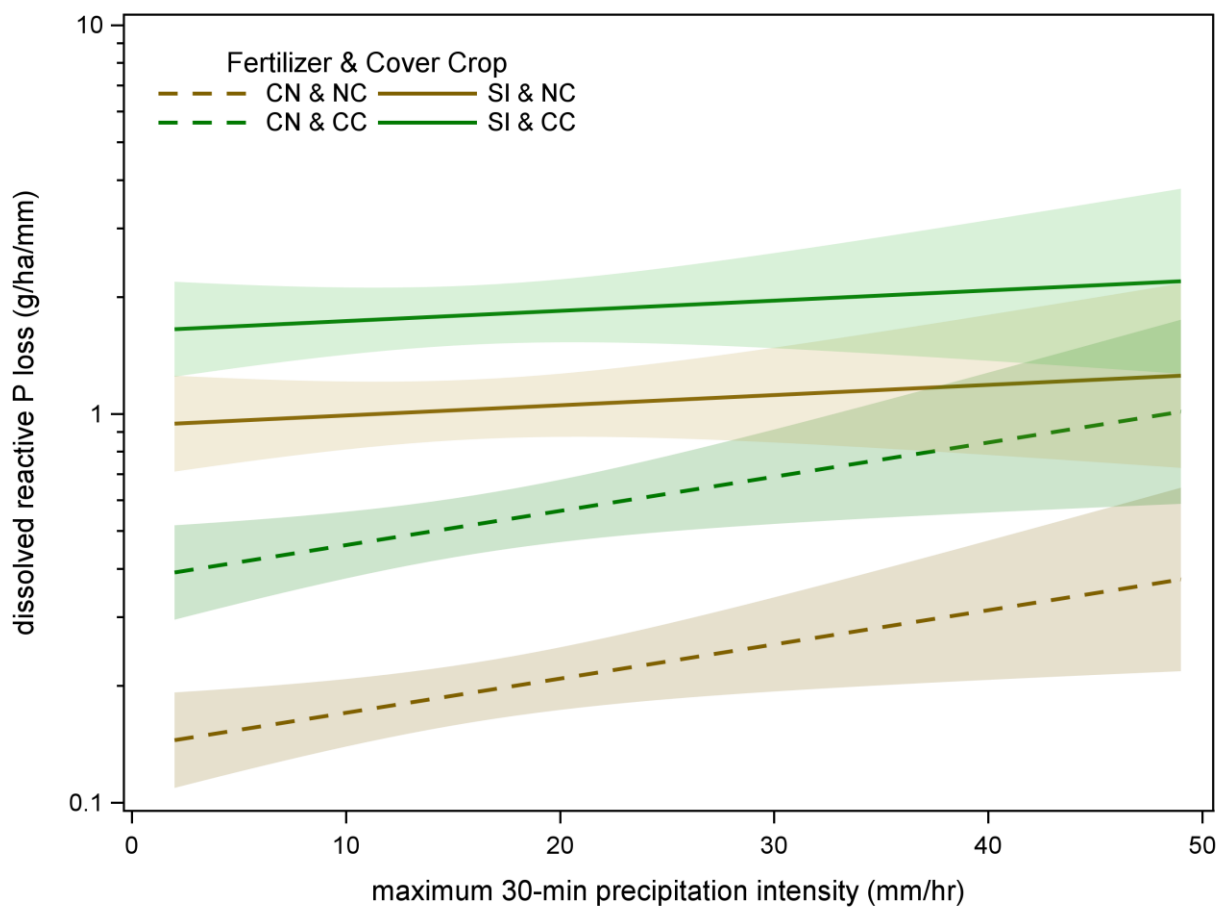


Figure 7 Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and the dissolved reactive phosphorus load ($\text{g ha}^{-1} \text{ mm}^{-1}$) in a no-till corn-soybean production system (CN=no P fertilizer; SI=spring-injected P fertilizer; NC=n

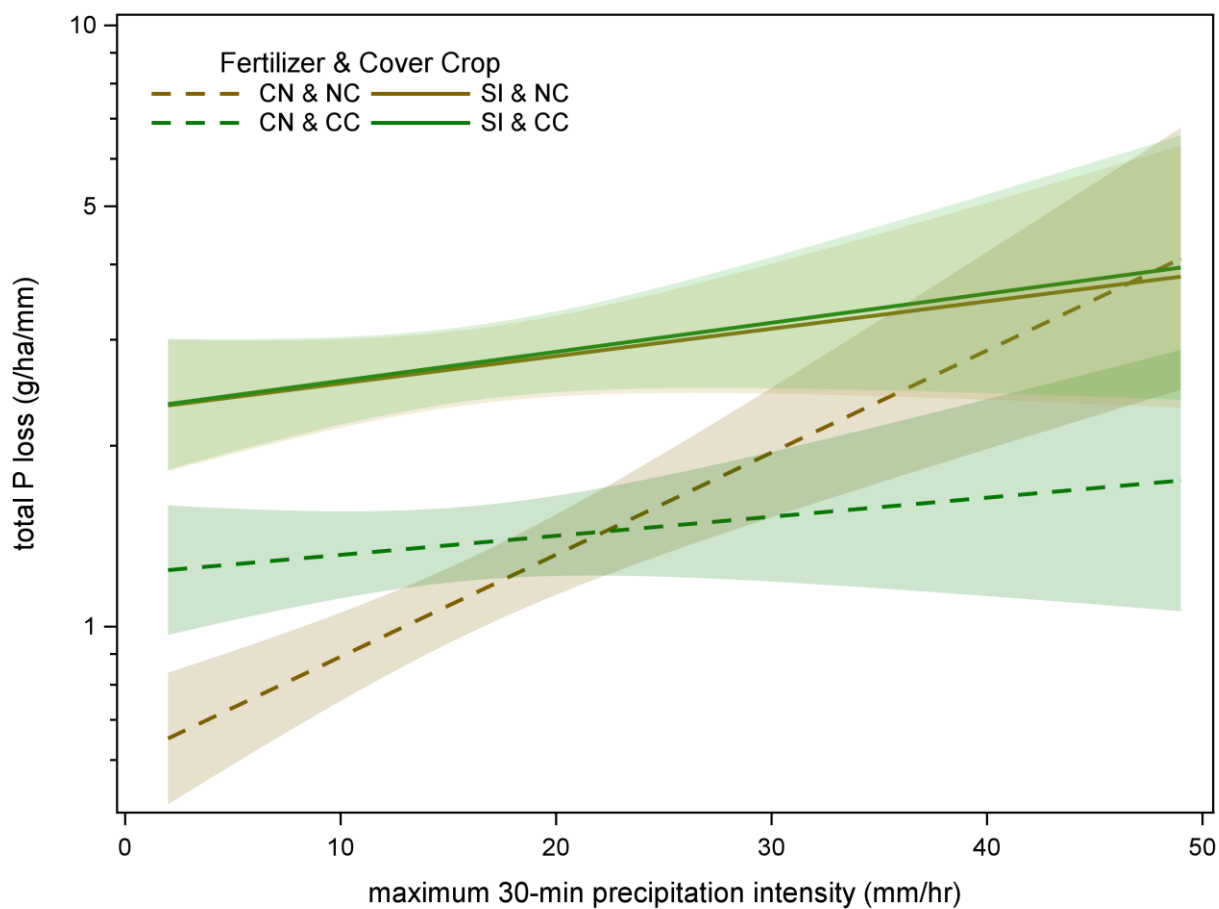


Figure 8 Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and the total phosphorus load ($\text{g ha}^{-1} \text{ mm}^{-1}$) in a no-till corn-soybean production system (CN=no P fertilizer; SI=spring-injected P fertilizer; NC=no cover crops)

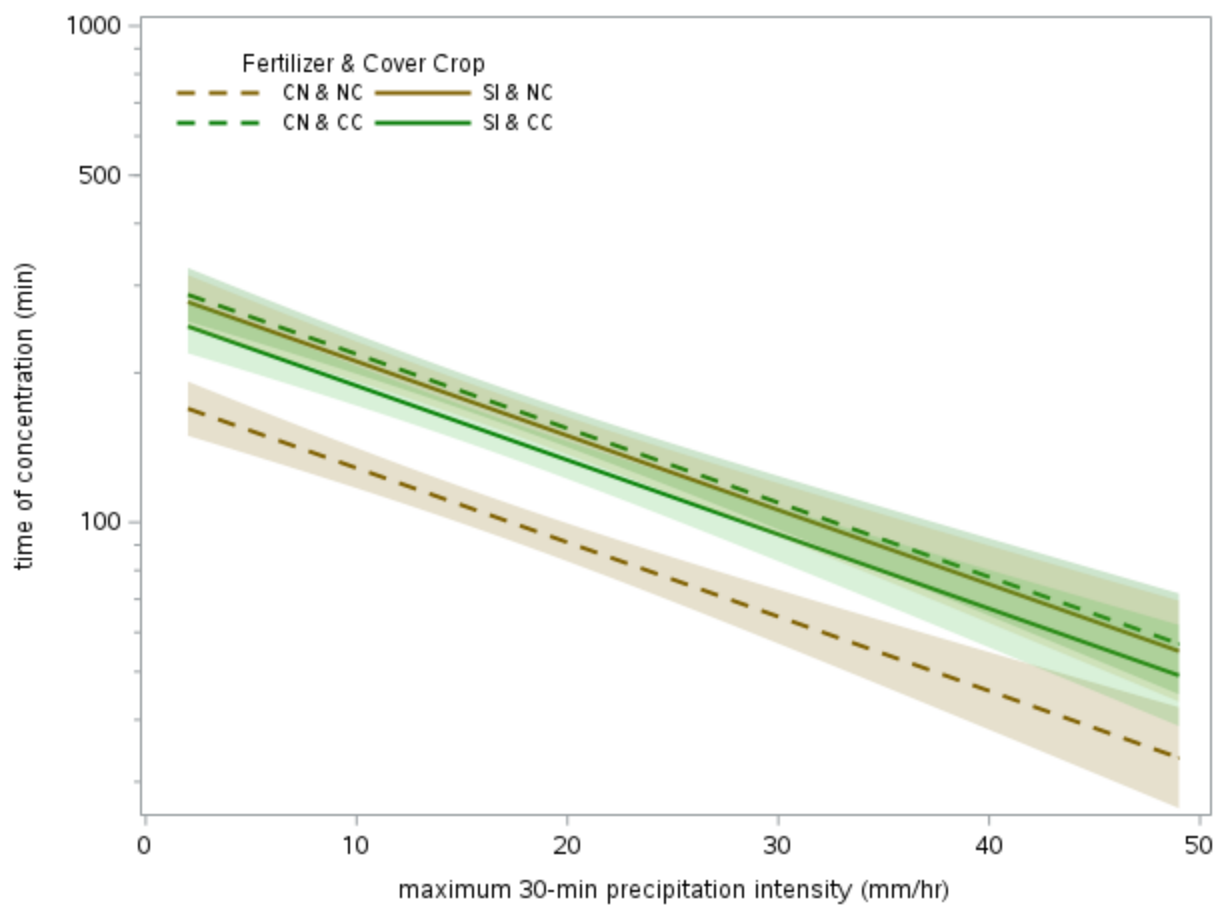


Figure 9 Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and time of concentration in a no-till corn-soybean production system (CN=no P fertilizer; SI=spring injected P fertilizer; NC=no cover crops; CC=with winter c

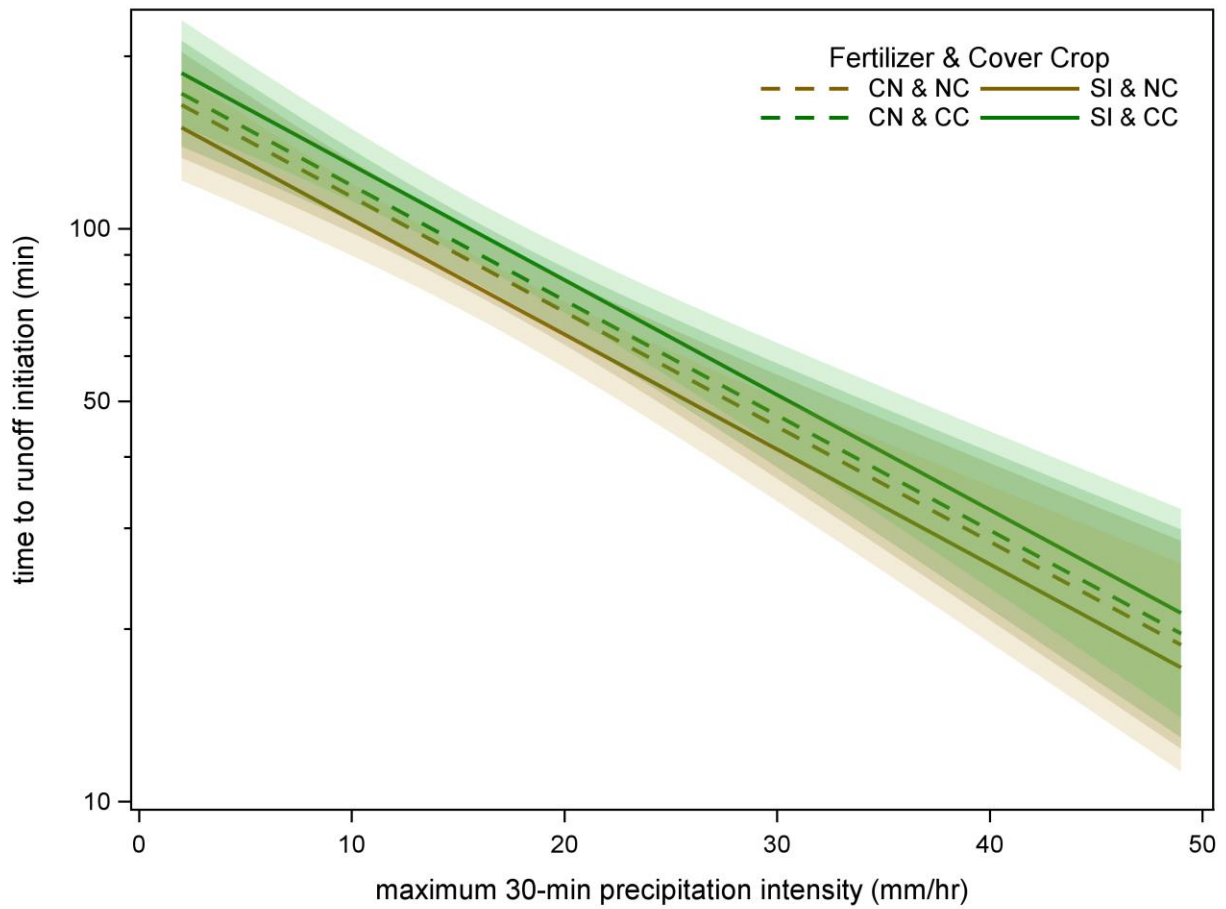


Figure 10 Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and time to runoff initiation (min) in a no-till corn-soybean production system (CN=no P fertilizer; SI=spring injected P fertilizer; NC=no cover crops; CC=with winter cover crops)

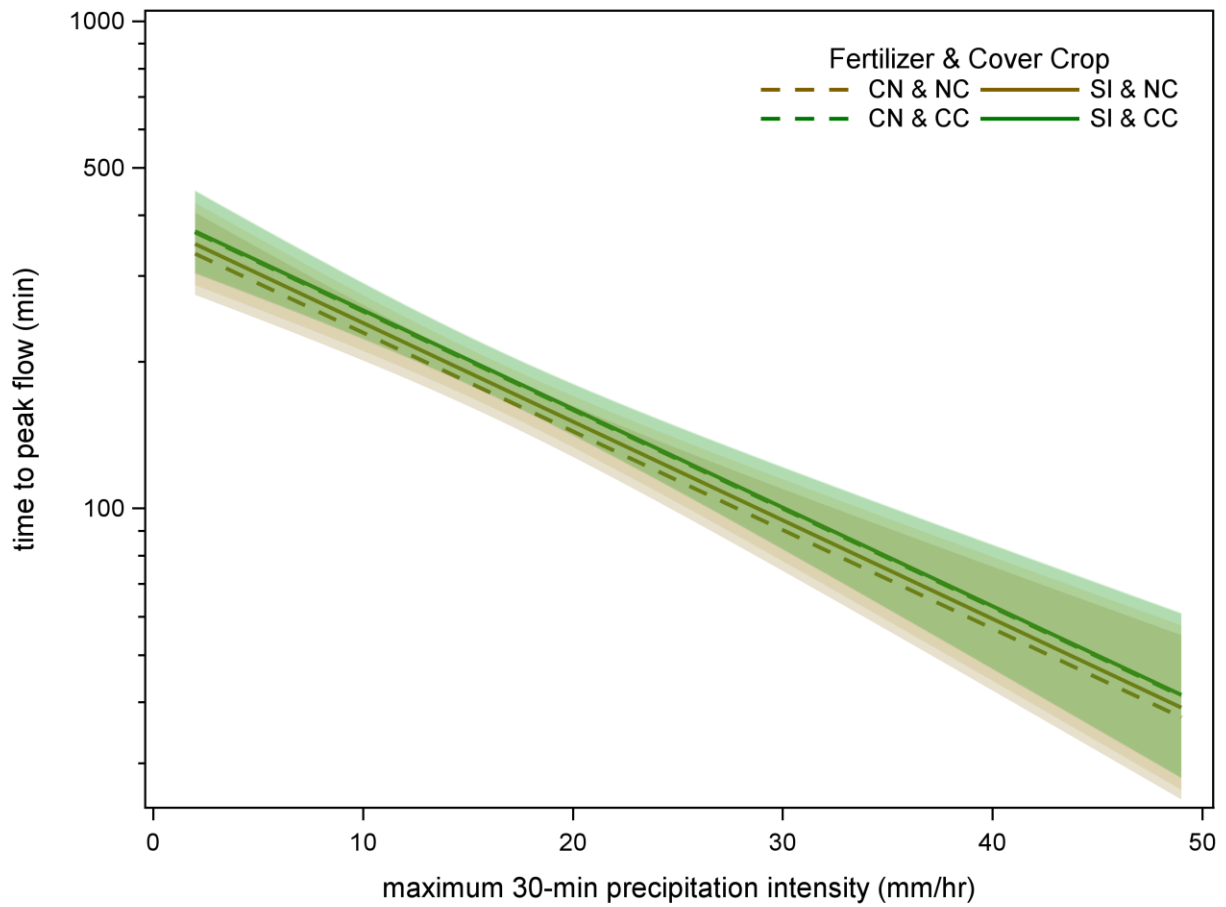


Figure 11 Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and time to peak flow (min) in a no-till corn-soybean production system (CN=no P fertilizer; SI=spring injected P fertilizer; NC=no cover crops; CC=with winter cover crops)

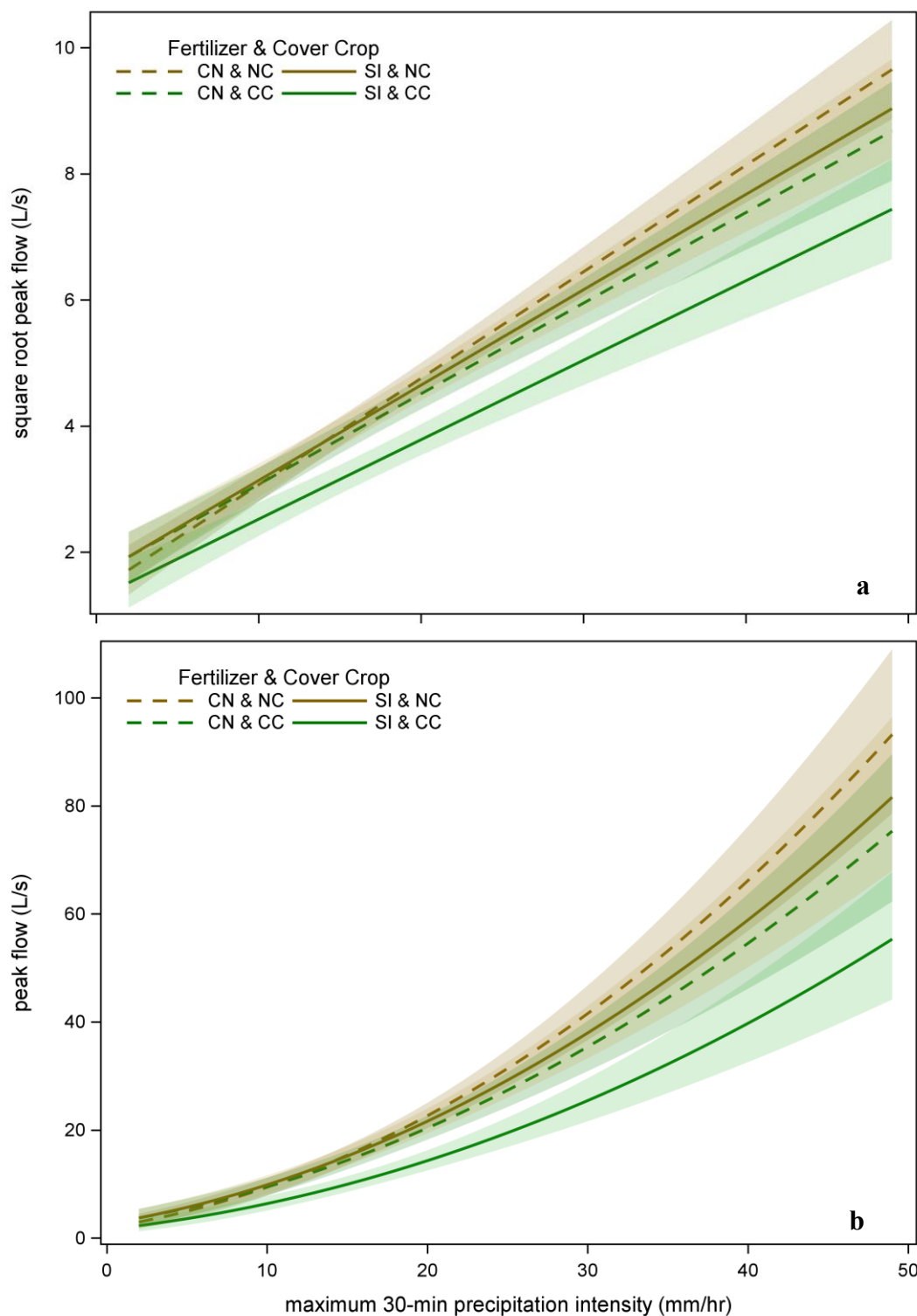


Figure 12 Effect of P fertilizer and cover crop use on the relationship between precipitation intensity and peak flow ($L s^{-1}$) in a no-till corn-soybean production system. 12a is the regression using square-root transformed data. 12b is the same data back transformed

Chapter 4 - Conclusion

The purpose of this study was to investigate the relationships between water quality components and hydrograph characteristics with precipitation intensity under P management strategies and cover crops. This was done to predict what the responses would be in order to prepare for a climate with more frequent intense storms. Using multiple regression analysis, this study was able to identify multiple variables that had a higher order interaction between P fertilizer, cover crops, and precipitation intensity.

The CN-NC treatment was the most sensitive to a change in precipitation intensity for the runoff ratio, TSS_p , TP_p , and peak flow. Decreased biomass production from a lack of P fertilizer and no cover crop application reduced infiltration and exposed more bare ground to raindrop impact. At low intensities this interaction sometimes resulted in lesser overall losses than other treatments but had the greatest losses once moderate to high intensities were reached. These sensitive relationships to precipitation intensity highlight the need for a management intervention to reduce losses.

The application of P fertilizer increased the amount of P lost for both TP_p and DRP_p . Total P was mostly lost in the particulate form which with the great amount of sediment loss in the CN-NC treatment resulted in an insignificant difference in load between the CN-NC treatment and those that received P fertilizer at high intensities. The DRP_p slope was reduced by P fertilizer application but ultimately had more DRP lost than the control. Cover crops had no effect on the relationship between DRP_p and precipitation intensity but did increase the load from NC to CC treatments. It is clear that the dissolved form of P was the dominant form lost from the CC treatments when comparing the TSS_p , TP_p , and DRP_p (Figures 4, 5 and 6). Dissolved reactive P is still a concern to watersheds as it is the most readily available form for algae and should not

be ignored in favor of reducing other losses. Deciding whether to apply cover crops knowing that they increase DRP loss but reduce particulate P loss could come down to whether the land is more vulnerable to sediment loss or large volumes of surface runoff. Having both cover crops and P fertilizer resulted in some of the least losses (runoff ratio, peak flow, TSS_p) but the largest losses for total P and DRP. Applying P fertilizer using the 4Rs may also decrease P loss. This study only used data from plots using a subsurface spring-injected build and maintain management and a zero P control treatment. Reducing the rate of P fertilizer to a sufficiency management may decrease these losses.

High precipitation intensities have the potential to produce runoff with high erosivity that increases losses in water from the soil profile, sediment, and nutrients. Time to runoff initiation, time to peak flow, and time of concentration all increased in this study due to cover crops and P fertilizer use, which slowed down runoff compared to the CN-NC treatment. This could be due to the increased time that water has with the soil surface allowing for increased infiltration. Further research should be undertaken at larger scales to fully understand the effectiveness of the treatments. This study also did not have access to infiltration rate or soil moisture measurements which would identify any differences in the responses in wet and dry conditions. The time to initiation of runoff and time to peak flow variables did not have a significant interaction with precipitation intensity meaning that the treatment effects were not affected by precipitation intensity.

This study has concluded that cover crops and P fertilizer application have the potential to reduce sediment losses and increase the resiliency of the soil by increasing biomass to improve infiltration and soil structure. Current conservation practices will continue to mitigate some losses while exacerbating others. As climate change progresses, its local effects will be

dependent on the management strategies implemented. Careful considerations to the tradeoffs of cover crops and P applications must be taken in order to maintain and/or improve the environment.

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https://hdsc.nws.noaa.gov/pfds/pfds_map_cont.html?bkmrk=ks

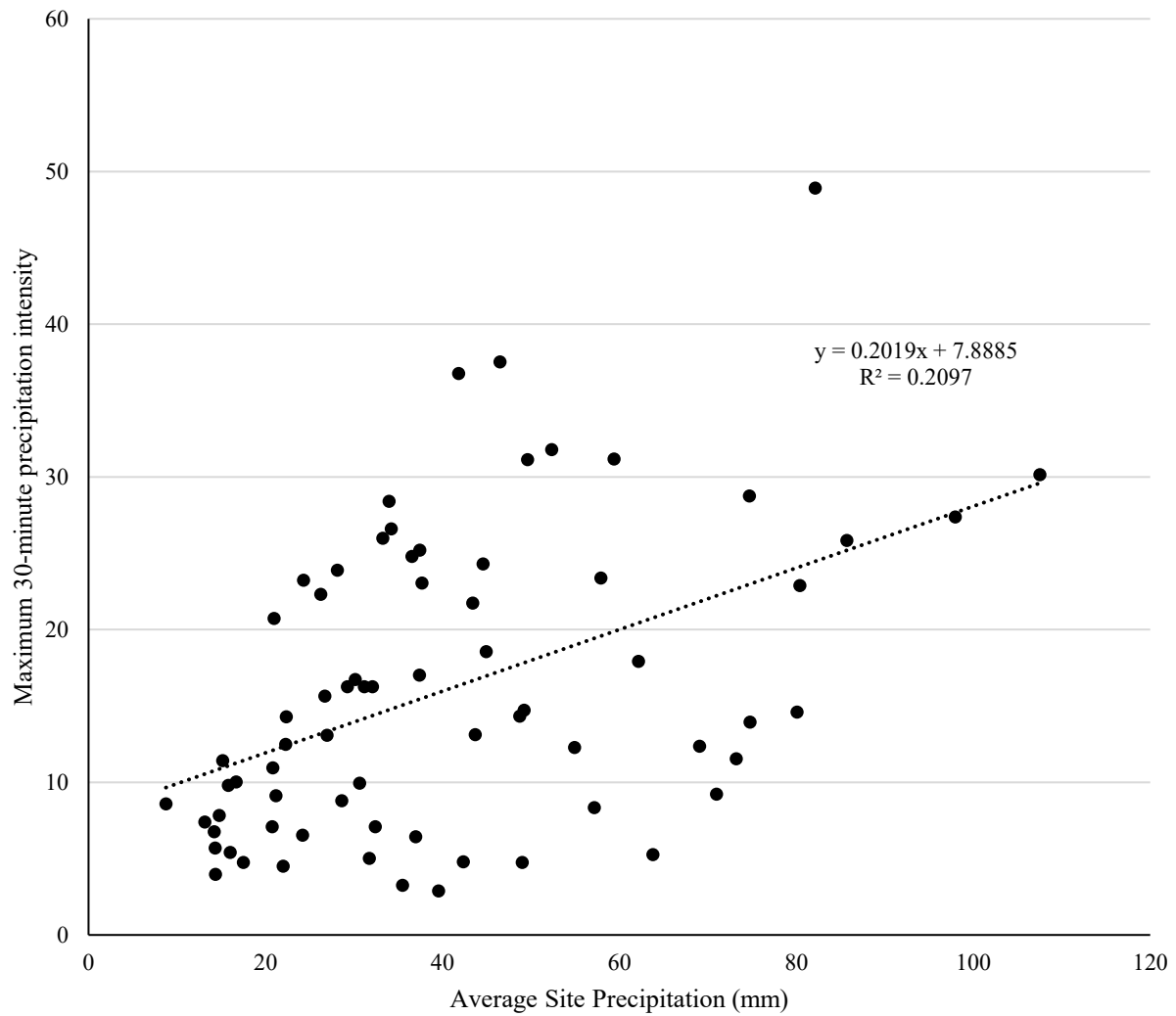
Appendix A -

Appendix Table A.1. Table of herbicide applications to the Kansas Agricultural Watershed

Crop Year	Herbicide Application	Date (M/D/YYYY)
2015	Post emergence: Visor II.2 L ha ⁻¹ , Duall II Mag 1.05 L ha ⁻¹ , Calisto 469 mL ha ⁻¹ , Glyphosate 4.2 L ha ⁻¹	4/16/2015
	Status 1.5 g L ⁻¹ , Glyphosate 3.4 L ha ⁻¹	6/16/2015
2016	Pre-emergent/CC termination: NC plots- Glyphosate 3.4 L ha ⁻¹ , Sterling Blue 560 g ha ⁻¹ , 2,4-D LV6 840 mL ha ⁻¹ ; CC plots - Sterling Blue 560 g ha ⁻¹ , 2,4-D 840 mL ha ⁻¹	4/12/2016
	CC plots: Glyphosate 3.4 L ha ⁻¹ , Fierce 263 mL ha ⁻¹	6/6/2016
	NC plots: Glyphosate 3.4 L ha ⁻¹ , Cobra 87.5 g ha ⁻¹	6/29/2016
2017	NC- plots: Atrazine 1.12 kg ha ⁻¹ , Dicamba 280 g ha ⁻¹ , 2,4-D LV6 840 g ha ⁻¹ , Glyphosate 2.2 L ha ⁻¹ , AMS (rate not recorded)	3/8/2017
	CC termination/ Pre-plant: AMS 640 g ha ⁻¹ , Lumax 7 L ha ⁻¹ , 2,4-D 840 g ha ⁻¹ , Glyphosate 2.2 L ha ⁻¹	4/27/2017
2018	Pre-plant NC plots: Sterling Blue 560 g ha ⁻¹ , 2,4-D LV6 770 mL ha ⁻¹ , Glyphosate 2.2 L ha ⁻¹	4/10/2018
	CC termination/ pre-emergent: Glyphosate 3.4 L ha ⁻¹ , Fierce 263 mL ha ⁻¹ , AMS 224 g ha ⁻¹	5/10/2018
	Post-emergent: Liberty 3 L ha ⁻¹ , clethodium 1.1 L ha ⁻¹ , crop oil 2.8 L ha ⁻¹ , AMS 3.4 kg ha ⁻¹	6/22/2018
2019	CC termination/ pre-plant: Glyphosate 3.4 L ha ⁻¹ , 2,4-D 840 mL ha ⁻¹ , Dicamba 420 mL ha ⁻¹ , Atrazine 4L 3.4 L ha ⁻¹ , Explorer 378 mL ha ⁻¹ , Brawl 1.8 L ha ⁻¹ , AMS 224 g ha ⁻¹	4/26/2019
2020	Dicamba 280 mL ha ⁻¹ and MCPA 560 g ha ⁻¹	11/19/2019
	CC termination/ pre-plant: Glyphosate 4.5 L ha ⁻¹ , Liberty 3 L ha ⁻¹ , Fierce 263 mL ha ⁻¹	5/19/2020
	Post-emergence: NC plots- Liberty 3 L ha ⁻¹ , Volunteer 560 mL ha ⁻¹	6/24/2020
	Post-emergence: CC plots- Liberty 3 L ha ⁻¹ , Volunteer 560 mL ha ⁻¹	7/4/2020
2021	CC termination- Glyphosate 3.4 L ha ⁻¹ , 2,4-D 840 g ha ⁻¹ , Dicamba 420 mL ha ⁻¹	4/13/2021
	Post-emergence: Atrazine 4L 3.4 L ha ⁻¹ , Explorer 378 g ha ⁻¹ , Brawl II 1.8 L ha ⁻¹ , Glyphosate 3.4 L ha ⁻¹	5/13/2021

Crop Year	Herbicide Application	Date (M/D/YYYY)
2022	CC termination: Glyphosate 3.4 L ha ⁻¹ , 2,4-D 840 g ha ⁻¹	5/20/2022
2022	Post-emergence: Glyphosate 1.7 L ha ⁻¹ , 2,4-D 1.1 L ha ⁻¹ , BroadAx 2.2 L ha ⁻¹	6/16/2022
	Post emergence: Enlist One 2.2 L ha ⁻¹ , Interline 2.2 L ha ⁻¹ , AMS 1.7-3.4 kg ha ⁻¹	7/13/2022

Appendix B -



Appendix Figure B.1 Regression of maximum 30-minute precipitation intensity and the average site precipitation (mm) ($p < 0.001$).

Appendix C -

Appendix Table C.1. ANOVA table of p-values for effects of fertilizer (fert), cover, and crop year (year) and their interactions for biomass produced over the 8 years of the study. P-values <0.05 are significant

Effect	Pr > F
fert	0.0009
cover	0.0005
fert*cover	0.2379
year	<.0001
year*fert	0.2608
year*cover	<.0001
year*fert*cover	0.4153

Appendix Table C.2 LS-Means of total biomass (kg ha^{-1}) from corn, soybean, and cover (excluding grain) for each year of the study. Letters indicate a significant difference in values with a p-value of <0.05. Uppercase letters reflect the significance of the main effect and lowercase letters reflect the significance of the year*cover interaction.

Fertilizer	Cover	2015	2016	2017	2018	2019	2020	2021	2022	Mean
CN		9043	8581	6873	5847	9636	7398	7307	4608	7412 B
SI		9271	9273	7704	6441	11344	9436	8305	5331	8388 A
	NC	8729 bc	8264 cd	7232 ef	5547 g	10581 a	6404 fg	7795 cde	4523 h	7384 B
	CC	9585 ab	9590 ab	7346d ef	6741 f	10400 a	10430 a	7817 cde	5417 gh	8416 A
	Mean	9157 B	8927 BC	7289 D	6144 E	10491 A	8417 C	7806 D	4970 F	