EDGE OF FIELD ASSOCIATED NITRATE-N LOSS IN SOYBEAN-CORN ROTATION

by

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Dedicated to my grandparents.

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ABSTRACT

Across the United States corn-belt region substantial quantities of nitrogen (N) fertilizer are applied in both continuous corn (*Zea mays* L.) and corn grown in rotation with soybean [*Glycine max* (L.) Merr.]. When compared to continuous corn, corn grown in rotation with soybean typically receives less applied N fertilizer (typically 20-45 kg ha^{-1} less) than continuous corn due to expected carryover of N from biological N fixation (BNF) by soybean in the preceding year. However, when current N recommendations are followed in both systems, rotational corn has been shown to lose similar or, in some cases, greater amounts of N through subsurface tile lines than continuous corn although the reports in the literature have been inconsistent. In rain-fed systems a key limitation to many previous studies has been an insufficient number of site-years of data to fully characterize management effects across varied environments. Regardless, the development of better management practices to reduce nitrate leaching losses has largely remained focused on managing N applied to corn and soybean's role in degradation of surface water has been relatively understudied in tile drained agroecosystems. Therefore, the objectives of this study were to use a 23-yr data record to: (1) compare quantities and patterns of N loss in tile drainage water among a soybean-corn rotation fertilized with the recommended preplant N rate, a soybean-corn rotation fertilized with a N reduced rate applied as a sidedress, continuous corn fertilized with the recommended preplant N rate, and an unfertilized, restored prairie as a natural system control, (2) determine whether and when cumulative soybean-corn load losses in drainage water surpassed that of continuous corn, and (3) evaluate the current recommended N credits from the dual perspective of crop productivity and protection of water quality.

Established in 1992, the Purdue University Water Quality Field Station has continuously assessed field-scale N cycling and losses in tile drains and the N management of the five treatments

examined in this study have been maintained since 1995. Treatments were 135 kg N ha^{-1} applied in rotational corn as a sidedress at approximately V6 each year (CS-135), 157 kg N ha^{-1} applied preplant in rotational corn (CS-157), and 180 kg N ha^{-1} applied preplant in continuous corn (CC-180). All corn plots received 23 kg N ha^{-1} as starter at planting. A restored perennial prairie control with no fertilizer applied (Pgrass) was utilized to compare and discuss the implications of intensively fertilized annual row crops. The 23-yr data record includes N concentration in drainage water, drainflow volume, N load losses in drainflow, grain yield, tissue N concentrations at harvest and N amounts returned to soil in crop residues and removed in grain.

Analysis of variance found CS-157 resulted in significantly greater daily flow-proportional N concentrations (23-year mean 11.98 mg L^{-1}) when compared to all other cropping systems ($\leq$ 10.96 mg L^{-1}). No reportable significant differences occurred in mean annual drainage flow volume among the respective cropping systems. Annual N load loss was statistically similar among cropping systems, ranging between 9.88 to 12.32 kg N ha^{-1} yr^{-1}, and these were all significantly higher than the Pgrass control (1.70 kg N ha^{-1} yr^{-1}). When corn and soybean years in rotational systems were analyzed separately for leaching losses, CS-157 was significantly higher than CS-135 and CC-180 (14.70, 10.85 and 11.88 kg N ha^{-1}, respectively) whereas losses by SC-157 and SC-135 were similar averaging 12.26 and 12.13 kg N ha^{-1}, respectively. Nitrogen treatment did not impact either corn or soybean mean yields. We concluded that soybean BNF production may be a major driver in N load loss in rotational corn when compared to continuous corn and further reductions in load losses from rotational systems will require a focus on managing soybean-derived N. Lastly, future research should include monthly or seasonal assessment of N load losses to better target practices at vulnerable times of nutrient loss.

CHAPTER 1. REVIEW OF LITERATURE

1.1 Introduction to Corn-Soybean Agroecosystems in the United States

Corn (*Zea mays L.*) and soybean (*Glycine max* L.) are the two most common production crops in the United States accounting for 500 million tonnes of grain produced annually (FAO, 2017). Corn may be grown in rotation with soybeans, or continuously as monoculture. With the world population projected at more than 9.7 billion by 2050 it is crucial to create more sustainable solutions to feed this growing population (United Nations, 2015), while simultaneously diminishing food production's negative environmental effects (Godfray et al., 2010). Inorganic nitrogen (N) fertilizer use is one means of significantly increasing the amount of food produced on a decreasing land base (Kinzig and Socolow, 1994) and continuous corn monocultures in the US have typically relied on high rates of N fertilizer to maximize yields (Dumanski et al., 2006). However, over-application of inorganic N fertilizer has resulted in decreased N utilization efficiency (Cassman et al., 2002) and excess N not utilized by crops may be lost to the environment via atmospheric or water pathways, by means of nitrification-denitrification, ammonia volatilization, and leaching (Vitousek et al., 1997). Rotational systems benefit from biological nitrogen fixation (BNF) produced by legume species, such as soybeans, which reduces the need for external N inputs. In the US Midwest, fertilizer recommendations typically call for a rate reduction or soybean "credit" of 20 to 45 kg ha^{-1}.

Midwestern soils that are used for agricultural production have a seasonal high water table that must be drained via artificial tile drainage to create ideal soil conditions for productive cropping systems (Kladivko et al., 2004). This management practice is justified by having higher yielding crops in rain-fed areas compared to undrained soils. Consequently, artificial tile drainage systems have cumulatively increased the transport of nitrate (NO_3–N) concentrations to surface waters (David et al., 1997). Indiana, Illinois, Iowa, Ohio, and Minnesota are Midwestern states that all have extensive artificial drainage systems, and are responsible for approximately 46% of the NO_3–N load that ultimately reaches the Gulf of Mexico (Alexander et al. 2007; Robertson et al. 2009). Rabalais et al. (1996) found that from 1950 to 1996 N concentration and load has almost doubled in the Gulf of Mexico, due to intensive fertilizer applications to crops. Increased NO_3-N contamination creates hypoxic conditions in local watersheds and eventually in the Gulf of Mexico resulting in decreased aquatic species abundance and degraded drinking water quality (Rabalais et al., 1996). The primary focus of this study will be on N leaching from rotational and continuous corn systems grown on poorly drained soils with subsurface drainage enhancement.

The BNF production from soybean systems is one strategy to lower fertilizer N applications, and possibly reduce edge-of-field environmental losses. The BNF is the reduction of N_2 gas to NH_3 by means of microorganisms (Hardy and Burns, 1968). Nitrogenase is a multimeric enzyme containing iron, sulfide, and molybdenum and is the enzyme catalyzing this reaction (Hardy and Burns, 1968). Global estimates of annual BNF has been previously reported to range between 100 and 175 million tonnnes N (Delwiche, 1970; Burns and Hardy, 1975). The role of legumes, specifically soybeans, as an N source in agroecosystems has been drastically reduced after the introduction of the Haber-Bosch process which led to abundantly cheap inorganic N fertilizers (Peoples and Craswell, 1992). Soybeans remain an important protein source but, unlike corn, this crop does not yield well when grown in monoculture (Crookston et al. 1991); thus, optimizing N management for rotational corn remains important for the U.S. corn belt.

Crediting soybean BNF production as a partial N source maintains corn yield in rotational systems, when compared to continuous corn systems, but N loss remains highly variable and poorly understood (Drinkwater et al. 1998; Gregorich et al. 2001; Ross et al. 2008). Although corn grown in rotation with soybeans typically receives a reduced N rate when compared with continuous corn, rotational system N loss has yet to be fully characterized. Drinkwater et al. (1998) stated that fertilizer N use efficiency (NUE) is typically increased in rotational corn when compared to continuous corn, because less fertilizer N is applied in rotational corn while maintaining comparable yields with continuous corn. Moreover, the underlining cause for increased NUE in rotational corn due to soybean BNF is difficult to characterize because quantifying BNF contributions to the available N pool has shown to be rather difficult. Since there is little evidence to support if soil N availability or environmental growing conditions are most influential to BNF production (Schipanski et al., 2010).

Soybean aboveground biomass has shown relevance to the available N credit for the subsequent corn in rotational systems. A meta-analysis conducted by Salvagiotti et al. (2008) found that soybean above ground-biomass accumulated 400 kg N ha^{-1}, when average yield was 5 Mg ha^{-1}, and a corresponding grain N content range of 122-184 kg N ha^{-1}. This suggests that soybean production results in a net N gain in aboveground biomass, a significant portion of which will be returned to the soil in plant residues. This above ground biomass N eventually becomes plant available in soil after microbial processes mineralize the organic N.

Evaluating recommended N rates inclusive of any contributions of legumes to system level N balances is valuable for water quality improvement given, irrespective of its source, leached N is consequential to the environment. Ochsner et al. (2017) found similar N concentrations and loads in leachate from the soybean-corn rotation system as compared to continuous corn, even though the rotational system was fertilized with half of the applied N to the continuous system. They further suggested the plausible cause for their results stemmed from soybean BNF contributing to the available N pool similarly as fertilizer N. An important conclusion from this study was that soybean BNF may have a bigger role in N drainage loss under tile drained soils than previously suspected.

1.2 Role of Legumes in Rotational Systems

1.2.1 Introduction to Legumes in Agroecosystems

Corn and soybeans are two important economic cash crops in the United States, and management to reduce NO_3–N losses in these grain-based crops is becoming increasingly important. Kurtz et al. (1984) stated that one important management practice is to account for a soybean N credit to corn grown the following year which can reduce over application of fertilizer and NO_3–N loss, while maintaining high grain yield. The N credit is due to BNF production and high N content in plant residue which is typically returned to the soil resulting in a net credit to the available N pool for the following corn crop (Board et al., 2003; Kahlon et al., 2011). Vitosh et al. (1995) recommends a reduced N rate of 35 kg N ha^{-1} when corn is planted following soybeans in Indiana. Numerous methods have been employed in the past attempting to quantify the amount of N available from soybean to the subsequent corn crop. Each of the main methods are summarized in the following sections including the strengths and shortcomings for each method. The main purpose in providing these descriptions is to show how university recommended credits are derived from.

1.2.2 Mineralization (Buried Bag) Method

Soil organic matter (OM) mineralization rate can be measured via the buried bag technique, and is useful for interpreting *in situ* plant available N changes over time (Eno, 1960; Paschke et al., 1989). Gentry et al. (2001) utilized this technique in an Illinois, USA study to quantify soil N availability prior to soybean harvest through the winter fallow period and into the subsequent corn season. Soil samples were collected at 0-10 and 10-30 cm depth increments. Samples were placed into bags, incubated in the plot between specific sampling intervals, and measured for NO_3–N. Mineralization was calculated by adding the sum of each sample interval together to determine total N changes in soil. They found a cumulative mineralization rate of 112 kg N ha^{-1} in rotational systems, when soybean was the previous crop. Alternatively, a cumulative mineralization-rate of 92 kg N ha^{-1} in continuous corn was observed. These results support the idea that plant available N is greater in rotational soybean-corn systems as compared to continuous corn systems and suggest an N credit of about 20 kg N ha^{-1} .

The buried-bag method has several disadvantages, such as, disturbed soil may not present an accurate representation of natural processes (Urakawa et al. 2017). Urakawa et al. (2017) further stated that *in situ* experiments are year-around, labor intensive, and many replications are required to account for spatial variability. Khanna and Raison (2013) concluded that *in situ* buried bag mineralization measurements should be used as a tool to understand baseline changes in soil N rather than a method for interpreting and managing N cycles. Since the buried bag method only utilizes a small amount of material to interpret localized N changes within a year then it may be difficult to interpret results over multiple years or environments since the N cycle is so variable.

1.2.3 N_{15} Dilution Method

The N isotope (N_{15}) has long been used to understand N metabolism in plants (Schoenheimer et al., 1937; Zapata et al., 1987), and N_{15} dilution and enrichment research protocols have been developed to try to understand BNF contributions to soil and plant N status, soil-plant N cycling and efficiency of inorganic N fertilizer use. The N_{15} dilution method has been used to directly measure the amount of N a legume adds to the system (Salvagiotti et al. 2008), while enriched N_{15} tracers are used to determine where fertilizer is being partitioned within in the plant.

In terms of method limitations, labeled N_{15} fertilizer is a time-consuming and costly method for deriving N contributions from legume plants (Varvel and Wilhelm, 2003). This method requires nodulated and historically non-nodulated soybean varieties treated with N_{15} isotopes. More recently, an isolated soybean treatment was quantified through atmospheric N accumulation only with no other sources of N (*B* term; Figure 1.1) (Gelfand and Robertson, 2015). This method requires part of the study to be grown in a greenhouse to isolate *B* which represents the atmospheric fixation with no other sources of nutrients and may not account for natural field conditions. Indeed, the Gelfand and Robertson (2015) study in Michigan, USA, found a net negative N credit (-55 kg N ha^{-1}) from soybeans to subsequent crop when a partial N balance was calculated. Schipanski et al. (2010) commented that one of the challenges with this estimation is establishing a reference plant, since older cultivars are typically used to reference against modern cultivars. The challenge with this situation is older cultivars such as Williams 82 may not capture true comparisons when referenced to modern soybean cultivars because high yielding genetic selections have been made over time. Unkovich et al. (2008) stated that inconsistencies in labeled N^{15} call for multiple non-nodulating reference cultivars to be used since varieties respond differently.

$$\%\,\text{N from fixation} = 100*((\delta^{15}\text{N Non–Nod} - \delta^{15}\text{N}_2\ \text{–fixing})/(\delta^{15}\text{N Non–Nod}-B))$$

Figure 1.1. Calculation for N fixation (Schipanski et al., 2010), where $\delta_{15}N_{nomN}$ and $\delta_{15}N_{Nfix}$ are δ_{15}N values for nodulating and non-nodulating plants, respectively and *B* is the δ_{15}N value for soybean grown with atmospheric N only.

1.2.4 Ureide Plant Nitrogen Tracers

The ureide plant N tracer method measures excreted NO_3–N sap. The specific ureides that are measured in this technique are allantoin and allantoic acid (Pauferro et al., 2010). It can be colorimetrically analyzed making it simple to quantify (Davison and Seitzinger et al., 2006; Unkovich et al., 2008). For accurate assessment of BNF contribution to above ground biomass several samples are needed (Pauferro et al., 2010). This method may be used as a quick assessment for measuring N changes in soybean plants, but overall BNF quantification is limited, unless calibrated against the N_{15} dilution method. Although Pauferro et al. (2010) did not directly estimate BNF production using this method, they concluded that that the N_{15} natural abundance method was the best option. Additionally, it is noteworthy that Herridge (1982) concluded field-based studies utilizing the ureide method have proven difficult. Moreover, since field based studies which collect xylem zap are difficult the use of greenhouse studies for this specific method are ideal.

1.2.5 Acetylene Reduction Method

The acetylene reduction assay measures acetylene to ethylene reduction catalyzed by nitrogenase enzymes, which is assessed by gas chromatography (Hardy and Burns. 1968). The rate at which acetylene can be reduced to ethylene is presumed to be an index for N fixation rate (Stewart et al., 1967). It was previously used as a quick and inexpensive method for measuring nitrogenase changes in different treatments (Shearer and Kohl, 1986). They also stated that living tissue must be used for analysis which can be difficult for *in situ* studies because the time between plant collection and lab analysis could influence nitrogenase levels. Bergersen (1970) concluded that a calibrated relationship between acetylene reduction and N fixation indexes for every condition or environment that the assay will be used in is necessary for greater accuracy.

1.2.6 Soybean Nitrogen Credit to Corn Methods

The following sections discuss estimates of soybean BNF production to the subsequent corn crop in rotational systems. These yield-based methods are based upon N rates utilized to achieve maximum yield in rotational corn systems. Direct contributions of soybean BNF are not measured in these methods; rather they are estimated based on a yield response curve from multiple N fertilizer rates ranging from 0 kg N ha^{-1} to 234 kg N ha^{-1}.

1.2.7 Traditional Yield Response Curve Method

Quantifying soybeans credit to the available N pool began with a simple N rate by yield response curve, known at the traditional method, which is utilized by Extension specialists and field agronomists in the development of N recommendations (Nafziger et al., 2004). Shrader et al. (1966) first demonstrated the traditional method utilizing a y vs. x fertilizer response curve, where y is observed corn yield, and x is varying N rates typically starting at 0 N to a rate expected to exceed crop demand. The N credit estimate is determined by solving for x when y is equal to the nonfertilized corn crop yield. The traditional method was used into the mid 1980's for determining soybean N credits (Lory et al., 1995). This traditional method N estimate was the basis for most Land Grant University N Credits since it is a quick assessment not requiring many parameters (Oyer and Touchton, 1990; Smyth et al., 1991; Pare et al., 1993).

The traditional method has several disadvantages including that it assumes that continuous corn and rotational soybean-corn systems respond similarly to changes in the available N pool throughout the growing season (Shrader et al., 1966). Additionally, this method assumes rotational and continuous systems have the same maximum yield potential, but rotational systems typically yield higher (Nafziger et al., 2004). Moreover, Nafziger et al. (2004) further stated that this method does not provide economic justification because a single response curve will not encompass variability in responses over years or fields.

1.2.8 Difference Method

The difference method proposed by (Smith et al., 1987) utilizes a similar quadratic response curve as the traditional method. However, the difference in the economic N rates for continuous corn and rotational corn on separate response curves is the estimated N credit (Lory et al, 1995). The economic N rate can be defined as maximum yield achieved with the least amount of N fertilizer applied. They also stated that fertilizer and grain prices often fluctuate and may be included into the N credit estimation. Another notable factor between the traditional and difference method is that each system uses a response curve independent from each other. This means that rotational and continuous systems do not need to be defined by the same yield goal since this approach focuses on the difference in the quadratic curve plateaus between rotational corn and continuous corn.

A two-year study in Ontario, Canada suggested a soybean N credit of 50 kg N ha^{-1} and was determined using the difference method (Ding et al., 1998). Varvel and Wilhelm, (2003) also quantified a credit with the difference method using a quadratic yield response curve in rotational and continuous systems, and found a 65 kg N ha^{-1} credit to corn. They further determined through a twenty-year data set that N credits may be difficult to determine through soil analysis processes, and suggested that yield response curve approaches were best. Although, studies have previously identified that soil N cycle fluctuations are so vast that it is extremely difficult to credit based upon yield N rate trials (Brophy and Heichel, 1989; Ta et al., 1986). The difference method, much like the traditional method, is missing key components behind soybean N credits such as: quantity and qualities of C: N residue returned, mineralization, denitrification, N grain removal, and N mass in tile drainage.

1.2.9 Maximum Return to Nitrogen (MRTN)

Nafziger et al. (2004) developed a regional approach to determine optimal N rates to corn using a Maximum Return to N calculation (MRTN). The MRTN calculator is available online through Iowa State University (Sawyer and Nafziger, 2005). The MRTN tool builds upon the traditional and difference method by simply providing a range of most profitable N rates that are within a dollar of economic return to N (Sawyer, 2014). They determine the optimal N rates by utilizing N rate response trials and corresponding yield increase from N applications over a variety of environmental regions. This is one way to quickly assess field N budgets with yield and probability in mind, but underlying environmental impacts remain unaccounted for in this model.

1.2.10 Nitrogen mass balance

Nitrogen mass balance calculations are useful for determining N use efficiency and understanding N sources and sinks and overall N availability to crops (Gentry et al., 2009). Although, collecting measurements for all the sources and sink pathways has proven difficult due to changes in the N cycle, environment, and the amount of time needed to conduct such studies (Davison and Seitzinger, 2006). Mass balance systems have been used to determine specific negative environmental impacts agricultural N has on field scale, watershed, and regional land scales (Karlen et al., 1998; Jaynes and Karlen, 2008). Mass balance measurements are the ideal method for calculating N budgets since N inputs and outputs can be accounted for (Barry et al., 1993).

1.2.11 Soybean Nitrogen Credit to Corn

Table 1.1. University recommended N rates

University	Year	N Credit (kg. N/ha)	Source
Ohio State	2016	33	https://agcrops.osu.edu/newsletter/corn-newsletter/2015-16/what's-right-n-rate-corn-ohio
Purdue	2007	33	https://www.agry.purdue.edu/ext/forages/publications/ay9-32.htm
Penn State	2007	1 kg./bu soy yield	http://nmsp.cals.cornell.edu/publications/factsheets/factsheet30.pdf
Illinois	2017	MRTN	http://bulletin.ipm.illinois.edu/?p=3975
Wisconsin	N/A	45	http://corn.agronomy.wisc.edu/Management/pdfs/A3591.pdf
Kentucky	2007	28	http://www.uky.edu/Ag/CornSoy/cornsoy7_2.htm
Missouri	2006	33	https://extension2.missouri.edu/ipm1027
Iowa State	2017	MRTN	https://crops.extension.iastate.edu/cropnews/2017/08/nitrogen-considerations-dry-conditions-2017
Nebraska	2008	40-50	http://extensionpublications.unl.edu/assets/pdf/ec117.pdf
Minnesota	2013	22-445	https://www.extension.umn.edu/agriculture/nutrient-management/nitrogen/providing-proper-n-credit-for-legumes/
Cornell	2007	22-33	http://nmsp.cals.cornell.edu/publications/factsheets/factsheet30.pdf

The table outlined above summarizes the range of soybean N credits in current Land Grant University fertilizer recommendations. The scientific research behind these credits are generally not referenced in the recommendation bulletins posted on the university Extension websites. However, these credits are based on field trials and can therefore be assumed that they utilize the traditional or difference method. Additionally, as previously demonstrated it is challenging to accurately determine N credits since these baseline recommendations are targeted for yield goals (Bundy et al., 1993) and not environmental concerns or objectives.

The ideal goal is to reduce NO_3–N drainage load while simultaneously maintaining yield. Mass-balance approaches are the only method which includes drainage loss when figuring the optimal N rate for corn following soybean. The traditional yield response curve and its modifications base credits off of corn grain yield and the corn N rate. The soil N cycle which is a major component of N credits is excluded in this methodology. Persistent high NO_3–N loads in drainage rotational systems suggest a need to reevaluate these N credits. More specifically, are we crediting the right amount of N to corn or can reducing fertilizer inputs even further reduce NO_3–N loss while maintaining yield?

1.3 Nitrate Nitrogen Leachability, form of N, and Drainage N Mass

1.3.1 Tillage and No-till

Controllable factors in drainage N loss may help reduce edge-of-field N losses. Several of the more prominent practices are highlighted to introduce their relative role in drainage N loss. Tillage has long been practiced across the corn-belt for simultaneously achieving critical management goals including weed control and warmer spring seedbeds to enable earlier planting Bharati et al., 1986). However, when residue incorporation occurs microorganisms take advantage of the easily decomposable organic material, specifically soybean residue (Sarrantonio and Scott, 1998).

Soybean plant residue mineralization rates are roughly 1.5 times greater than corn due to its lower C to N ratio (Burkart et al., 2005). Rapidly mineralized organic N to NO_3–N has shown the capability to leach when plant uptake is not available during the fallow period (Drinkwater et al., 2000). Given low C: N ratios, soybean residue can decompose relatively quickly even when not mechanically incorporated (Burkart et al., 2005; Rice and Smith, 1984); thus, it is relevant to acknowledge that minimizing tillage may only alleviate when N loss occurs and not total N was lost.

Alternatively, no-tillage (NT) systems has been recognized for having better soil structure, water holding capacity, and resilience to intense equipment traffic. NT has numerous benefits, but the main persuasive arguments are higher soil organic matter content, better vegetative growth, and increased fertilizer-use efficiency (Francis and Knight, 1993; Wells, 1984). Although NT seems like an ideal strategy, Di and Cameron (2002) stated that high N loss rates under NT systems can occur. Moreover, high N loss be explained by larger more continuous pores creating channels for water flow. In conclusion, tillage and no-tillage have their strengths and weaknesses, but it has been observed that tillage itself does not seem to be an important driver of either crop yield or drainage N losses (Zhao et al., 2016).

1.3.2 N Application Source, Timing, and Inhibitors

Randall and Iragavarapu (1997) stated the N rate and timing of application were the most important controllable management factors that alter NO_3–N losses in agricultural systems. Applying more N than what is required for crop growth increases NO_3–N leaching potential. Moreover, N loss risk increases as the time from application to plant uptake increases, which is held true for residual soil N as well (Frye et al., 1985; Magdoff, 1991; Karlan et al., 1998). Randall and Iragavarapu (1997) found that NO_3–N losses were reduced by 36% when fall N applications were abandoned, and N fertilizer use efficiency increased 20% by utilizing only spring N applications. The greatest challenge with N applications is timing so that N availability is matching temporal patterns of crop demand and edge-of-field NO_3–N loss is minimized (Cambardella et al., 1999; Dinnes et al., 2002).

One method previously investigated for manipulating N availability was the use of nitrification inhibitors. These inhibitors slow down the conversion of NH_4^+ to NO_3, which was previously thought to reduce NO_3–N loss (Timmons, 1984). However, studies have indicated that the use of inhibitors and their effectiveness is influenced by soil type, environmental conditions, and inhibitor type (Pain et al. 1994; Williamson et al. 1998). Randall and Vetsch (2005) found that a nitrification inhibitor reduced NO_3–N loss up to 14% in a 6-year Minnesota, USA study. It is also noteworthy that the additional cost of inhibitors may discourage their use by producers seeking to maximize profit if the additional cost of N fertilizer does not offset the cost of inhibitors.

1.3.3 Precipitation, Temperature, and Soil Type

Uncontrollable factors in production agriculture are often accounted for in analyzing N drainage mass since they can affect NO_3–N transport to ground water. Zhao et al. (2016) concluded from a meta-analysis that soil texture and precipitation tended to impact drainage N loss regardless of management practice. Temperature can also influence N drainage loss because prolonged warmer temperatures can dry out the soil surface causing cracks or channels. If N fertilizer is broadcast on the surface under dry conditions it can be flushed by following rain events, by-passing micro pores (Di and Cameron, 2002). They also stated, that ground water or tile depth influences NO_3–N leaching since having more-or-less soil above tile lines influences the amount of time to transport.

1.3.4 Previous Corn-Soybean Rotation Nitrogen Leaching Studies

Quantifying NO_3–N concentrations and loads in tile drainage has previously been successful in identifying problematic agricultural production practices and their direct influences to ground water quality (Baker and Johnson, 1981; Randall and Goss, 2008). To accurately assess

NO_3–N concentrations and loads, drainage lysimeter studies have been identified as one of the top methods for characterizing N losses. Since lysimeters contain an isolated measured area, the leachate collected can determine the quantity of NO_3–N being lost from a cropping system. If there is a known volume of water flowing through the soil profile. NO_3–N is an anion that does not absorb to soil particles, thus it moves freely through the soil profile with water (Bergstrom and Johansson, 1991; Owens et al. 2000). Purdue University Water Quality Field Station in West Lafayette, Indiana serves a pivotal role in assessing NO_3–N drainage from varying cropping systems (Hernandez-Ramirez et al., 2011), since few locations around the world possess its capabilities.

1.3.5 Previous Quantities of N Concentrations and Load Lost

Previous lysimeter research has compared rotational soybean-corn to continuous corn, and concluded a rotational phase may have a significant effect on N concentrations (Goldstein et al., 1998; Dinnes et al., 2002; Christianson et al., 2015). Logan et al. (1994) showed in a four-year study that NO_3–N concentrations from the soybean phase can be just as high as the corn phase when analyzed separately. They concluded that applied fertilizer in the corn phase was carried over into the soybean phase. Alternatively, in a Minnesota study results were similar for NO_3–N concentrations were 28 mg L^{-1} for continuous corn, and 23 mg L^{-1} for soybean-corn rotations (Randall et al., 1997). Numerous studies have reported that annual row crop's NO_3–N concentrations in drainage flow exceed the drinking water standard 10 mg L^{-1} (Owens et al., 2000; Randall et al., 1997; Cambardella et., 1999).

NO_3–N load enables us to derive how much mass is lost over time. A previous study conducted at Purdue's Water Quality Field Station reported a five-year cumulative mean NO_3–N load for soybean-corn rotations to be 57 kg ha^{-1}, and 30 kg ha^{-1} for continuous corn (Long et. al., 2015). A six-year study in Minnesota reported N loads to be identical in continuous corn and rotational soybean-corn under spring applied fertilizer with 85 kg N ha^{-1} being lost (Randall et al., 2005). Ambiguities among a variety of shorter studies provides inconclusive interpretation of the net N load that is being lost. Additionally, the underlying cause of rotational systems showing substantial N losses remains to be identified.

1.3.6 Peak Concentration and Load Occurrence

Kladivko et al. (2004) found in a 15-year study that NO_3–N load was greatest from November to March when there are no plants actively taking up nutrients. They further stated that NO_3–N concentrations were highest during the growing season, from April to October, but were not significantly different by month. This is likely caused by plant nutrient and water uptake which reduces the chance of NO_3–N being leached (Bakhsh et al., 2002; Amon-Armah et al., 2013). Load loss tends to be more important than concentrations, because researchers typically care about total N lost from comparable systems rather than N amount in collected samples (Baker and Laflen, 1983).

1.3.7 Shorter Study Limitations

Long-term drainage studies comparing rotational to continuous corn are sparse in existing literature. Randall et al. (2008) compiled a list of previous studies and their resulting NO_3–N load lost. The longest study reported was 11-years for continuous corn, and 8-years for rotational corn with the more common trend being 3-5 year studies. Longer term studies which encompasses wet and dry years are needed for deeper understanding of treatment variability (Christianson and

Harmel, 2015). Kladivko et al. (2004) reported that greater than 10-year studies would be sufficient for NO_3–N load assessment to encompass seasonal variability, and statistical power.

1.3.8 Comparing seasonal treatment means has shown no sig. diffs.

The MANAGE data base (Christianson and Harmel, 2015), found no significant NO_3–N load difference in rotational corn compared to continuous corn from 91 peer reviewed papers. However, the MANAGE data base combined field-scale studies only and does not include lysimeter research. Christianson and Harmel (2015) reported no significant difference among drainage load response to N rate, even at greater than 250 kg N ha^{-1} applied fertilizer to corn. Moreover, this may mean that drainage N load loss may not be capable of reduction, regardless of current N rates to corn. It should also be known that this data base would often aggregate similar N rate groups together for analysis since uniform experimental design among all the studies did not occur in the meta-analysis which may elevate variability. Thus, true comparisons of N rate to drainage N load may not be possible in their study because individual aims or objectives for each study encompassed in their meta-analysis are different.

Alternative studies outside of the MANAGE data base have suggested that high fertilizer N applications to corn increased NO_3–N load (Randall and Iragavarapu, 1997). Although it was previously stated that N rate does not significantly affect N load (Christianson and Harmel, 2015). The tri-state fertilizer recommendations through the late 1990's was 220 kg N ha^{-1} for continuous corn. Current N recommendations are 160 kg N ha^{-1} for continuous corn and there is no significant difference in NO_3–N load lost (Christianson and Harmel, 2015). Thus, the need for side-by-side comparison of continuous and rotational systems to identify the cause of N load loss, more specifically, interpretation of soybeans role is needed.

Christianson and Harmel (2015) found significant differences in drainage load, and corresponding precipitation for studies that encompassed the capability to monitor full year patterns compared to studies that retired equipment due to winter conditions. This ultimately means that sites not encompassing full-year analysis may not accurately represent N loss drainage patterns.

1.3.9 Justification and Rationale

Several assumptions have been discussed in the previous literature explaining why high NO_3–N loss occurs in the soybean phase of rotational systems. Klocke et al. (1999), stated that high N loss in soybean years can be attributed to high levels of residual N from the previous corn crop. Castellano et al. (2016) stated that soil organic matter (SOM) may be the cause for excess drainage given soybean has a lower C:N ratio and its residue is more readily decomposable releasing N faster than corn residue. Dinnes et al. (2002) stated that higher C:N ratio of corn residue becomes immobilized and then released later as the C:N ratio aligns with SOM which may also significantly contribute to soybean drainage N load.

The major assumptions describing N loss in rotational systems has been associated with the corn phase. Previous literature has identified that the N load in a soybean phase can be just as high as the corn phase (Randall and Vetsch, 2005). This suggests soybean BNF production is a significant contributor to the similar N loss. Previous literature has reported no significant differences in rotational versus continuous systems when analyzed by year (Logan et al., 1994; Zhu and Fox, 2003; Strock et al., 2004; Jaynes et al.,1999; Qi et al., 2011). These studies did not assess cumulative treatment N loads over time, rather they analyze average N load over the number of study years which may mask long-term trends.

Christianson and Harmel (2015) concluded from 1300 drainage studies in the MANAGE database that studies that treated soybean-corn rotations as a single system were lacking. Christianson and Harmel (2015) also stated previous studies have found no significant differences when corn phase N load was compared to a soybean phase N load in rotational systems. Randall et al. (2003) stated that long-term drainage studies are critical to elevate statistical power which would overcome the strong effect precipitation has on drainage flow.

1.4 Hypothesis and Objectives

The overall goal of this study is to better understand rotational soybean-corn systems effects on NO_3–N lost through artificial drainage systems in the Eastern Corn Belt. Existing research suggests that spring-applied fertilizer to the corn increases NO_3–N leaching through the root zone into tile drainage water during the fallow period from November to April. However, current literature suggest that decomposition of soybean residue may also be an important contributor to N load losses via tile drains. The contributions of soybean N to the N status of a subsequent corn crop have long been recognized in regional fertilizer recommendations that typically call for a reduced rate when compared to corn grown continuously without rotation. Our hypothesis is that cumulative NO_3– N concentrations and loads in tile drainage drain flow will be greater in a soybean-corn rotation than in a continuous corn system when both are managed according to current university recommendations due to inaccurate accounting for soybean N contribution; this inaccuracy results in over applications of fertilizer to the following corn crop. The rationale for this study is to address the N credit from soybeans to corn in assessing existing recommendations for the suitability for both yield and environmental goals. Underestimating soybean N contribution to the available N pool after residue mineralization may have a significant impact on edge-of-field loss associated with NO_3–N leaching.

Objectives:

1.) Compare quantities and patterns of N loss in tile drainage water among a soybean-corn rotation fertilized with the recommended preplant N rate, a soybean-corn rotation fertilized with a N reduced rate applied as a sidedress, continuous corn fertilized with the recommended preplant N rate, and an unfertilized, restored prairie as a natural system control.

2.) Determine whether and when cumulative soybean-corn load losses in drainage water surpassed that of continuous corn.

3.) Evaluate the current recommended N credits from the dual perspective of crop productivity and protection of water quality.

CHAPTER 2. EDGE-OF-FIELD ASSOCIATED NITRATE-N LOSS IN A SOYBEAN-CORN ROTATION, AS COMPARED TO CONTINUOUS CORN

2.1 Introduction

Modern production agriculture is currently a balance between producing higher yielding crops than previously achieved and limiting excess nitrogen (N), as well as other nutrients from escaping the root zone. Across the corn-belt, excess N is lost through subsurface tile drainage lines and preferential flow pathways via leaching (Dinnes et al., 2002). In our study, two different rotational soybean-corn N rates, a continuous corn N rate, and a prairie control were analyzed to better understand long-term impacts of reduced N rates on N concentrations, flow, and drainage load. Moreover, we sought to understand if grain yield could be maintained in rotational cropping systems when recommendations increase the N being credited from soybean N returned to soil, and thus, reduced rates of fertilizer N applications. Given producers will often attempt to minimize risk of having insufficient yields by applying N in excess of than what is traditionally recommended by land grant universities (Vetsch et al., 2019), it is important to summarize long-term datasets and report findings.

2.2 Materials and Methods

2.2.1 Experimental Site

This study used data collected from 1995 to 2017 at Purdue's Water Quality Field Station (WQFS), an experimental field research facility located at the Agronomy Center for Research and Education (ACRE), West Lafayette, IN (40°29'55" N; 86° 59' 53" W). The soils at the WQFS are primarily a Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquolls) with an area of Raub silt loam (fine-silty, mixed, superactive, mesic Aquic Argiudolls; (profile descriptions can be found in the appendix) with slopes 0-2%. Annual mean rainfall for the study period ranged between 734 mm to 1250 mm (Table 2.4). Annual mean temperature ranged between 9 °C to 13 °C during the same period as precipitation (Table 2.5). Both temperature and precipitation were reported from data gathered by https://iclimate.org, at the ACRE weather station.

2.2.2 Facility Design and Treatments

The WQFS was established in 1992 with forty-eight plots in four blocks, with twelve treatments per block arranged in a randomized block design. Individual treatment plot dimensions are 9.1 m by 48.7 plot area of 436 m^2; treatment plots and the facility in general are highly instrumented for measurement and monitoring of water, C and N cycles (details described below). Each plot is bordered by a grass berm to minimize lateral flow of any surface runoff and consequent cross-treatment contamination. Given the rapid evolution of crop and soil management technology, the general philosophy pursued at the WQFS is one of "adaptive management." Thus, hybrids and varieties of the crops grown have continually evolved, using commercial germplasm that have been improved for the local environment and proven in the region during the preceding season(s). Additionally, since inception, some treatments have been changed significantly (e.g. crop species and N managements) to address emerging research questions. However, a subset of treatments has been maintained since 1995 with only the adaptive changes in management and are the focus of this study. The specific treatments used in this research include a restored native prairie and three corn-based cropping systems where N management adheres to University fertilizer recommendations (Vitosh et al., 1995).

Table 2.1. Complete listing of all treatments at the Water Quality Field Station including the crop species and major N management details. Highlighted treatments (nos. 1, 6 – 9, and 12) were used in this study; their abbreviations are given parenthetically.

Trt.	Plot/Tile No.	Prior management (1995-2006/2007)	Current Management (2007/2008-2017)	Tillage
1 (Pgrass)	1,17,36,42	Mixed Prairie (annual burn) w/ 0 kg N ha^{-1}	Mixed prairie (residue removed)	No
2	11,22,32,43	179 kg. N ha^{-1} Corn-Soybean Rotation	Miscanthus × giganteus (2008)	Yes-No
3	12,23,30,46	200 kg. N ha^{-1} Continuous corn	160 lb. N Continuous No-till corn with residue removal	Yes-No
4	10,18,26,44	179 kg. N ha^{-1} Corn-Soybean Rotation	Upland Switchgrass (2007)	Yes-No
5	6,16,29,39	157 kg. N ha^{-1} Continuous corn	Corn/Kura Clover (2017)	Yes-No
6 (CS-157)	5,13,35,40	157 kg. N ha^{-1} Corn-Soybean Rotation	Continued	Yes
7 (SC-157)	8,20,27,47	157 kg. N ha^{-1} Corn-Soybean Rotation	Continued	Yes
8 (CS-135)	2,14,33,45	135 kg. N ha^{-1} Corn-Soybean Rotation	Continued	Yes
9 (SC-157)	9,19,34,48	135 kg. N ha^{-1} Corn-Soybean Rotation	Continued	Yes
10	4,15,25,37	Spring manure Continuous corn	Corn-Soybean No N	Yes
11	7,24,28,38	Fall manure continuous corn	Continuous Corn No N	Yes
12 (CC-180)	3,21,31,41	180 kg. N Continuous corn	Continued	Yes

2.2.3 Treatment Management

The cropping systems and their N management include continuous corn (CC) and two annual corn-soybean rotations with both species present in every study year (designated CS and SC to distinguish between plots initially planted to corn and soybean, respectively, in 1995). In the first rotational treatment, corn received a preplant N application of 157 kg N ha^{-1} (CS-157) and, in the second rotational treatment, corn received an N application of 135 kg N ha^{-1} (CS-135) applied in a sidedress application; (treatments 6 and 8, Table 2.1). Soybean years in the corn-soybean rotations (SC-157 and SC-135, respectively, treatments 7 and 9, Table 2.1) received no N applications. The continuous corn was fertilized with 180 kg ha^{-1} preplant (CC-180, treatment 12, Table 2.1). The N source was 28% urea ammonium nitrate (UAN) solution injected approximately 0.1 m below the soil surface. Additionally, all annual corn crops received 23 kg ha^{-1} of 19-17-0 starter fertilizer [19% (w/w) N and 17% (w/w P_2O_5] at planting, injected 5 cm to the side of the seed and 5 cm deep.

Planting dates for corn ranged from April 25th to June 5th with seeding rates increasing from an average of <72,000 seeds ha^{-1} prior to 2008 to >81,000 seeds ha^{-1} thereafter (12 rows per plot planted with a 6-row planter). Soybean planting typically occurred after corn with planting dates ranging from May 1st to June 17th with a slight reduction in seeding rates over the duration of the study (518,920 to 444,790 seeds ha^{-1}; drill seeded in 0.2-m rows). Range in harvest dates are September 20th to October 30th and September 29th to November 15th for soybean and corn, respectively. Detailed annual planting, harvest, and fertilization (corn only) dates and seeding rates are given in Tables 2.2 and 2.3 for soybean and corn, respectively.

The restored prairie plots are intended to serve as an experimental control representing natural habitat restoration against which agricultural systems may be compared for productivity, nutrient cycles and edge-of-field nutrient losses. Plots were hand seeded in 1992 with a tall-grass prairie mixture of big bluestem (*Andropogan girardii*), indiangrass (*Sorghastrum nutans*), and native forbs. Since establishment, the prairie system has evolved to be dominated (>90% species representation) by big bluestem (Burks, 2013). Until 2006, prairie plots were regularly burned in spring (April or May) to mimic natural burns (e.g. lightning strikes) that control species composition and succession. Since 2007, prairie biomass has been removed by a mechanical harvester, typically in October/November, as a biomass crop for cellulosic ethanol (harvest dates not shown). These plots have not received any N fertilizer.

All WQFS corn-soybean systems used in this study were tilled (dates given in Tables 2.2 and 2.3). Weather permitting, annual corn and soybean plots were chisel plowed in the fall and then disked and/or field cultivated in the spring prior to planting.

2.2.4 Soil Sample Collection and Processing

Composite (9 cores) soil samples were collected with hand probes from each treatment replication at 0-20 cm in depth. Soil sample collection was initiated in the fall of 1993 and continued annually or biennially as time, weather, and recourses permitted; included here are data from approximately 5-year incriminates from 1996 to 2015 and again in the concluding year of this study (2017). Samples were air dried for approximately 2 weeks and then ground to pass a 2-mm sieve. A subsample was packaged and sent to A&L Great Lakes Laboratories, Inc. (Fort Wayne, Indiana, http://www.algreatlakes.com). Soil samples sent to A&L were analyzed for organic matter, available phosphorus (P), exchangeable potassium (K), magnesium (Mg), calcium (Ca), soil pH, and cation exchange capacity (CEC). Protocols for these routine fertility assays generally followed the regional recommendations (North Central Regional Research Publication No. 221, 1998) with a major procedural change occurring after the 2000 sampling when A&L switched from a Bray P1 extraction with colorimetric analysis for P to a Mehlich 3 extraction with analysis by inductively couple plasma spectrometry (ICP, Chalmers and Handley, 2006). Concomitantly, the protocol for basic cations was changed from a neutral 1 M ammonium acetate extractant analyzed with flame spectrophotometry to the Mehlich 3/ ICP procedure. Additionally, soil from the last 6-years (2012-2017) of this study were analyzed for total N concentrations using a flash combustion elemental analyzer (Flash EA 1112 Series, Thermo Fisher Scientific, The Netherlands) following methods proposed by Nelson and Sommers (1996).

2.2.5 Stand Assessment, Residue Collection, Processing and Analysis

During the growing season, the establishment populations were recorded each year on an individual plot basis at V6 (corn) and V5 (soybeans). Corn populations were determined by counting all plants within 5.3 m of two neighboring rows at three random locations in each plot. Soybean populations were estimated by placing a 1-m-diameter ring at three random locations within a plot and counting the number of soybean plants. Three counts per plot were averaged for the plot-level population estimate.

To assess the quantities of stover biomass that are returned to soil at harvest (all aboveground residues except grain) and its N content, 10 random whole plant samples were collected at physiological maturity from each corn and soybean treatment plot. Corn plants were selected from rows immediately adjacent to the inner 6 rows that are reserved for yield determination with a plot combine (e.g. rows 2, 3, 10, and 11). Soybean plants were collected in the same manner as corn, but were collected from the outside the inner 5.5 m wide harvest strip running the length of the plot that is reserved for yield determination. Plants were hand cut just above the soil surface. Corn ears were separated from the plant and air dried for 3 to 5 days and shelled using a hand-sheller (McCormick Deering, International Harvester, Rock Island, IL). Stover samples were brought back to the lab where they were weighed, oven dried at 60°C, reweighed, ground, and then analyzed for tissue N concentrations using a flash combustion elemental analyzer (Flash EA 1112 Series, Thermo Fisher Scientific, The Netherlands; Nelson and Sommers, 1996). Nitrogen concentrations were multiplied by estimated population count averages for each plot to determine total N content.

2.2.6 Grain Harvest and Analysis

Grain was collected at physiological maturity and the inner 6 (of 12) rows of each corn plot were harvested and individually weighed using a Parker weigh wagon. The inner 5.5 m of each soybean plot were harvested and weighed in the same manner as corn. A subsample of grain from each soybean and corn plot was collected at harvest and measured for moisture using a Dickey John GAC 3000 meter (Dickey John Corp., Aurora, IL), and combine yields were adjusted to 15.5% and 13% moisture content for corn and soybean, respectively. Additionally, the same grain subsamples from each plot were analyzed for quality and protein using near-infrared spectrometry in most years (Infratec 1229 NIRS, Dresden, Germany). Grain subsamples were oven dried for 3 to 4 days at 60 °C, were weighed, then ground using a food processor and analyzed. Analyzed protein measurements were used to estimate standard N concentrations in years where direct N analysis was not completed using protein-to-N conversion factors, 6.25 for corn and 5.7 for soybeans (Jones, 1931). Long et. al. (2015) found that protein-estimated N concentrations were not significantly different from A&L analyzed N concentrations.

Table 2.2. Soybean cultivars, seeding rates and dates of major field operation in plots planted to soybean during a specific experimental year.

Year	Variety†	Planting Rate (seeds ha-1)	Data of Major Field Operations			
			Planting Date	Harvest Date	Tillage	Fertilizer N Application
1995	A3730	NRℑ	June 9	Oct 2	Disk (6/7) Chisel (10/9)	None
1996	NR	NR	June 17	Oct 28	Disk (6/6) Chisel (11/12)	None
1997	NR	518,920	May 17	Oct 11	Disk (4/25) Chisel (11/13)	None
1998	P93645	518,920	May 22	Oct 10	Disk (5/20) Chisel (11/12)	None
1999	B302RR	494,210	May 29	Oct 14	Disk (5/18) Chisel (11/1)	None
2000	P93B45	NR	May 26	Oct 20	Disk (5/16) Chisel (10/27)	None
2001	A3201RR	469,500	May 1	Oct 30	Disk (4/30) Chisel (11/21)	None
2002	B323	469,500	June 6	Oct 15	Disk (6/4) Chisel (11/8)	None
2003	93B67	469,500	May 24	Oct 8	Disk (4/16) Chisel (10/31)	None
2004	B323	469,500	May 19	Oct 5	Disk (4/20) Chisel (10/25)	None
2005	B5737	447,251	May 5	Oct 10	Disk (4/19) Chisel (10/18)	None
2006	NR	NR	NR	Oct 1	Disk (5/8) Chisel (11/28)	None
2007	P93M11	444,790	May 7	Sept 20	Disk (NR) Chisel (10/5)	None
2008	B354	444,790	May 30	Oct 23	Disk (4/24) Chisel (NR)	None
2009	B364	447,260	May 24	Oct 20	Disk (5/22) Chisel (NR)	None
2010	BR325	447,251	May 26	Oct 19	Disk (4/2) Chisel (10/25)	None
2011	P93Y51	444,790	June 6	Oct 17	Disk (5/13) Chisel (11/22)	None
2012	P93Y15	444,790	May 4	Oct 11	Disk (4/10) Chisel (11/16)	None
2013	P93Y40	444,790	May 17	Nov 11	Disk (5/17) Chisel (12/6)	None
2014	A62431	444,790	May 27	Oct 9	Disk (4/23) Chisel (11/14)	None
2015	P93Y60	444,790	May 25	Oct 14	Disk (5/6) Chisel (11/5)	None
2016	P34T07	444,790	May23	Oct 14	Disk (5/20) Chisel (11/15)	None
2017	P34T07	444,790	May 31	Oct 19	Disk (5/18) Chisel (11/29)	None

†A, B, and P indicate seed sourced from Asgrow, Becks, and Pioneer seed companies, respectively.

ℑ NR corresponds to no record.

Table 2.3. Corn hybrids, seeding rates and dates of major field operation in plots planted to corn during a specific experimental year.

Year	Hybrid†	Planting Rate (seeds ha^{-1})	Date of Major Field Operations			
			Planting Date	Harvest Date	Tillage	Fertilizer N Application
1995	P3525	NRℑ	June 6	Oct 10	Disk (6/7) Chisel (10/18)	Preplant (NR) Starter (6/6)
1996	3489	67,510	June 6	Oct 26	Disk (NR) Chisel (11/12)	Preplant (NR) Starter (6/6)
1997	P3491	73,142	April 30	Oct 15	Disk (4/25) Chisel (11/15)	Preplant (4/26) Starter (4/30)
1998	P34G81	75,615	May 21	Oct 10	Disk (5/20) Chisel (11/12)	Preplant (5/18) Starter (5/21)
1999	P34G81	66,718	May 29	Oct 14	Disk (5/22) Chisel (11/1)	Preplant (5/21) Starter (5/29)
2000	P34G81	76,600	May 24	Oct 19	Disk (5/16) Chisel (11/1)	Preplant (5/8) Starter (5/24)
2001	P34G81	73,142	May 2	Oct 29	Disk (4/30) Chisel (11/9)	Preplant (4/20) Starter (5/2)
2002	B5737CL	70,177	June 4	Oct 15	Disk (6/4) Chisel (11/8)	Preplant (6/1) Starter (6/4)
2003	B5737CL	73,142	April 28	Oct 22	Disk (4/16) Chisel (10/31)	Preplant (4/14) Starter (4/28)
2004	B5737CL	70,177	May 5	Oct 5	Disk (4/20) Chisel (10/22)	Preplant (4/19) Starter (5/5)
2005	B5737	73,142	May 5	Oct 13	Disk (4/19) Chisel (10/18)	Preplant (4/5) Starter (5/5)
2006	A715RR	70,176	May 9	Nov 2	Disk (5/8) Chisel (11/28)	Preplant (4/21) Starter (5/9)
2007	P34A20RR	70,176	May 15	Nov 5	Disk (NR) Chisel (NR)	Preplant (5/14) Starter (5/15)
2008	P34P87RR	73,142	May 29	Nov 3	Disk (NR) Chisel (NR)	Preplant (5/27) Starter (5/29)
2009	B6733	84,755	May 24	Oct 20	Disk (5/22) Chisel (NR)	Preplant (5/21) Starter (5/24)
2010	B5435HXR	79,072	May 26	Oct 11	Disk (4/16) Chisel (11/4)	Preplant (5/25) Starter (5/26)
2011	B5716	84,755	June 3	Oct 28	Disk (5/13) Chisel (11/22)	Preplant (5/13) Starter (6/3)
2012	P5552	78,332	April 25	Oct 2	Disk (4/10) Chisel (11/16)	Preplant (4/18) Starter (4/25)
2013	P1018	81,545	May 20	Nov 15	Disk (5/20) Chisel (12/6)	Preplant (5/18) Starter (5/20)
2014	DKC65-63	81,545	May 28	Nov 10	Disk (5/13) Chisel (11/22)	Preplant (5/27) Starter (5/28)
2015	B5131	81,545	May 25	Oct 14	Disk (5/13) Chisel (11/22)	Preplant (5/6) Starter (5/25)
2016	B5337	81,545	May 23	Sept 29	Disk (5/20) Chisel (11/15)	Preplant (5/20) Starter (5/23)
2017	DKC65-63	81,545	May 30	Oct 19	Disk (5/18) Chisel (11/29)	Preplant (5/30) Starter (5/30)

†A, B, DK, and P indicate seed sourced from Asgrow, Becks, Dekalb and Pioneer seed companies.

ℑ NR corresponds to no record.

2.2.7 Water Sample Collection and Analyses

Each WQFS treatment plot contains a centrally located, large, in-ground drainage lysimeter which is constructed as a bottomless bentonite lined box that collects water from a known hydrologically isolated area of the soil (10.8 x 24.4 m). A pair of tile drains (0.1 m diameter), buried at 0.9 m, span the length of each of plot. The collection tiles are only perforated within the drainage lysimeter and drain the area within each lysimeter into instrumentation huts where calibrated tipping buckets quantify drain flow volumes for each lysimeter. Companion tiles were installed next to the collection tiles to minimize the seepage of water and nutrients from outside the lysimeter area into the lysimeter area. The companion tiles also ensure similar soil moisture conditions throughout the entire plot; together, the collection and companion tiles simulate a tile drain spacing of 10 m

This study used CR 10 Data loggers (Campbell Scientific, Logan, UT) to record hourly tip counts, and data were obtained from the Purdue University Research Repository (PURR) Water Quality Field Station project (https://purr.purdue.edu). Hourly tip counts for each plot were summed into daily totals and then multiplied by calibrated tipping bucket volumes to calculate daily water flow. Calibrated tipping bucket volumes were manually measured with graduated cylinders by determining the volume of water necessary to tip each bucket.

Adjacent to each tipping bucket was a 20 L catch bucket equipped with a slotted top to catch a flow-proportional drainage water subsample (ca. 10 mL/two tips); these subsamples were manually collected and documented from each bucket for each day that flow occurred at approximately 1200 hrs. Each sample was directly labeled on the bottle and documented on a record sheet then frozen at 4°C until analyzed. The water samples were filtered (Whatman #2, ~8 μm, Maidstone, UK) and analyzed for NO_3 –N concentrations. Samples were analyzed colorimetrically according to EPA method NO_3 –N (EPA-114-A Rev.6), using a Lachet QuickChem AE Automated Flow Injection Ion Analyzer (1995-1998), Lachet QuickChem 8000 Flow Injection Analyzer (1998-2006), and AQ2 Discrete Seal Analyzer (2007-2017) (Seal Analytical, Southampton, Hampshire, United Kingdom).

2.2.8 Missing Water Data Estimation and Data Calculations

Occasionally NO_3–N concentration and/or flow volume data were missing. Concentration data loss typically resulted from extreme flooding due to excessive rainfall events or when personnel were unavailable to manually retrieve samples on a select few days. Nitrate N concentration data were gap-filled using a decision rule that if flow occurred and a concentration value was not observed than the closest concentration value within four days before or after that flow volume was utilized. If a missing concentration was in between two flow volumes with observed concentrations than those observed concentrations were averaged to estimate the missing concentration. Less than 10% of all concentration values were estimated using this gap-fill decision rule. If only reported NO_3 –N concentrations were utilized it would substantially underestimate total N load from each treatment, making our decision rule justifiable. In general, it was also observed that N concentrations from a given tile were similar within the four-day timeframe justifying this decision rule.

Loss of flow volume data loss typically resulted from tipping bucket sensor malfunction, short-term flooding events, and data logger failure. Flow data were not gap filled as unlike concentration values, flow data is rainfall dependent difficult to predict the antecedent and subsequent flow values. However, manual archived field logs were referenced to differentiate when the tiles were true 0 flow versus when data loggers were offline or flooded. The field logs suggest that less than 1% of data total were not true 0's. Gap-filled concentrations were only utilized in calculating N load to accurately determine total N lost. Observed NO_3–N concentration and N flow values were used to analyze these specific variables.

2.2.9 Statistical Analyses

Univariate descriptive statistics were calculated for daily drain flow, N concentration, and drainage N load for each tile line replication using SAS JMP. The univariate statistics were used to summarize tile-to-tile variation and to determine tile functionality throughout the study and if certain tiles needed to be omitted from further analysis. Due to widespread data logger failure, calculated N loads from 2007-2008 and 2015 were omitted from this study. Analysis of variance (ANOVA) was used to determine differences in cropping system means and the interaction between year and cropping system using restricted maximum likelihood estimates from the lme4 package in R. Tukey’s Honest Significant Difference (HSD) were used post-hoc to determine specific cropping system differences. Cropping system and year were treated as fixed factors in the mixed model and replication was used as a random factor to account for random variation from each plot. The variables assessed in the model were: daily N concentrations in water, annual mean subsurface drainage flow, annual mean subsurface drainage load, grain yield, grain N concentration and content, and plant grain N concentration and content. A log flux-flow relationship was determined by regressing log transformed annual subsurface drainage load and annual drainage flow to understand the per unit change of N loss among the cropping systems. Regression relationships were evaluated for their coefficient of determination (R_2 values) and for slopes differing from unity indicating concentrations differing from flow volumes. Piecewise regression was used to determine the correlation between cropping system and N load loss over time. Two different slopes were visually detected and the segmented package in R was employed to specify where the break occurred for changing slopes. All tests, excluding descriptive statistics, were conducted in R (R Core Team, 2017) using the lme4 package (Bates et al., 2015), and ggplot2 (Wickham, 2016) for graphical interpretation.

2.2.10 Calculations

The following equations were used to estimate system parameters of interest:

Nitrate Load Loss (kg ha$_{-1}$) =Nitrate Concentration (mg)/L*Flow (L)/ha *1 kg/1,000,000 mg

Yield-Scaled N Losses (kg/Mg =Nitrate N Load (kg)/ Grain Yield (Mg)

Cumulative Load Loss = sum (Annual rep 1+rep2+rep 3+rep 4)/4 + all previous years

Grain N Content =Grain N Concentration*Grain Yield

Stover N Content =Stover N Concentration*Plant Population

2.3 Results

2.3.1 Weather and Climate

Outside of management practices, precipitation and temperature are strong drivers in both crop yield and N loss through tile lines. Monthly and annual mean precipitation values were reported over the entire data record (Table 2.4). Average Indiana rainfall for this 23-year dataset was 1032 mm (http://www.iclimate.org), and multiple years in this study have experienced annual totals either above or below the reported average. In 2012, a minimal 736 mm of rainfall occurred, while in 2017, a maximum 1250 mm of rainfall was reported. When analyzed by month, mean precipitation was 83 mm, February had a minimal 51 mm of precipitation when compared to other monthly means. In contrast, June had 125 mm mean monthly precipitation which was greater than all other months. In Indiana, June and July are typically months when crop water demand is crucial. In June, the years 1995, 2005, 2006, 2007, and 2012 had 47, 51, 56, 73, and 19 mm of precipitation respectively. July also contained notable low precipitation values in years 1997, 2007, 2011, and 2012 which were 47, 60, 60, and 30 mm of precipitation, respectively.

Yearly average temperature across all months ranged from 9 to 13 °C. July (23°C) and August (23°C) had the highest mean monthly temperature when averaged across all 23-years of this dataset (Table 2.5). January had an average monthly temperature low of -3 °C when compared to all other months. Typically, in Indiana, USA temperatures reach at or below freezing in December of each year and last until March of the subsequent year.

Table 2.4. Monthly mean precipitation for all 23 years at the WQFS field site. Data sourced from https://ag.purdue.edu/indiana-state-climate/.

	Year																							
	---- Monthly Mean Precipitation (mm) ----																							
Month	**95**	**96**	**97**	**98**	**99**	**00**	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**Month Avg.**
Jan	51	49	52	22	77	50	70	53	16	57	152	63	86	61	15	17	19	87	111	47	52	29	111	56
Feb	11	34	32	28	95	64	82	48	14	24	69	26	47	136	65	27	79	26	61	120	29	34	19	51
Mar	71	53	90	147	28	60	8	87	23	92	29	103	119	70	86	85	62	49	23	78	60	130	109	72
Apr	87	87	42	104	150	31	62	127	89	63	53	93	97	58	159	71	209	27	160	56	56	66	108	89
May	247	202	112	174	99	100	127	125	152	122	45	130	95	158	123	128	187	69	77	81	88	43	175	124
Jun	47	138	145	307	95	87	99	107	77	252	51	56	73	119	146	245	186	19	105	77	198	119	135	125
Jul	48	82	47	97	63	211	169	79	187	77	117	157	60	97	78	129	60	30	68	77	116	128	200	103
Aug	131	34	67	72	83	44	68	66	134	99	52	155	148	61	107	45	119	162	44	169	27	154	123	94
Sep	12	83	22	25	79	38	46	46	217	13	123	57	52	108	14	48	101	86	89	128	77	81	50	69
Oct	96	37	37	89	35	37	227	38	34	73	54	95	100	45	154	22	57	83	37	99	24	32	68	68
Nov	49	101	45	74	27	84	68	29	76	130	43	123	135	31	68	102	122	13	53	34	53	135	125	77
Dec	39	34	37	19	42	36	56	26	83	50	37	76	99	148	83	44	82	80	135	59	208	58	20	67
Year Sum	895	940	734	1163	853	848	1026	836	1109	1055	828	1138	1114	1096	1102	967	1288	736	967	1031	993	1015	1250	83

Table 2.5. Monthly mean air temperature for all 23 years of this data set. Data sourced from https://ag.purdue.edu/indiana-state-climate/.

	Year																							
	---------- Monthly Mean Temperature (°C) ----------																							
Month	**95**	**96**	**97**	**98**	**99**	**00**	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**Month Avg.**
Jan	-3	-5	-6	0	-3	-3	-3	1	-6	-4	-2	3	-1	-3	-7	-6	-5	0	-3	-6	-3	0	0	-3
Feb	-1	-1	1	4	2	2	0	0	-3	-1	1	0	-7	-3	0	-4	-1	1	0	-8	-3	-2	1	-1
Mar	6	1	5	4	3	7	2	2	5	6	3	5	8	3	6	6	5	12	0	0	-2	7	5	4
Apr	10	8	8	11	11	10	14	11	12	12	12	13	10	10	10	14	11	12	9	8	10	8	11	11
May	15	15	13	19	18	17	17	14	16	18	16	16	20	14	17	18	16	20	16	15	15	14	14	16
Jun	22	21	21	21	22	21	21	23	19	20	23	21	23	22	23	23	22	21	21	22	21	22	20	22
Jul	24	22	23	23	25	22	24	26	23	22	24	24	22	23	21	24	27	27	23	22	22	23	23	23
Aug	26	23	21	23	21	23	23	23	23	20	24	23	25	22	21	25	24	23	21	21	23	24	23	23
Sep	17	18	18	22	18	18	18	21	17	20	21	17	21	19	19	19	17	18	21	20	21	22	20	19
Oct	12	12	12	13	12	14	11	11	12	12	13	10	15	12	9	13	12	11	13	14	15	19	20	13
Nov	1	1	3	6	8	3	9	4	7	7	6	6	5	4	7	5	7	4	5	4	10	11	8	6
Dec	-2	-1	0	1	-0	-8	1	0	0	0	-3	2	-1	-3	-2	-5	1	3	-3	0	4	0	3	0
Year Avg.	10	9	10	12	11	10	11	11	10	11	11	12	11	10	10	11	11	13	10	10	11	12	12	

2.3.2 General Fertility

Fall soil N samples have been collected after plant harvest since 2012; samples were analyzed for total N content (Table 2.6), and only the last six years of this study were reported due to data availability. Across cropping systems, continuous corn with 180 kg N ha^{-1} applied fertilizer (CC-180) had the highest overall mean soil N content of 1.98 g kg^{-1}. The prairie grass (Pgrass) control, which had 0 kg N ha^{-1} applied had the second highest soil N content of 1.90 g kg^{-1}. The four-rotational soybean-corn rotations (135 kg N ha^{-1} applied sidedress and 157 kg N ha^{-1} applied preplant) soil N content ranged between 1.72 and 1.88 g kg^{-1}. Between year means for Pgrass ranged from 1.75 to 1.99 g kg^{-1}, CS-157 was 1.68 to 1.84 g kg^{-1}, SC-157 was 1.79 to 1.95 g kg^{-1}, CS-135 was 1.56 to 2.05 g kg^{-1}, SC-135 was 1.74 to 1.90 g kg^{-1}, and CC-180 ranged between 1.85 to 2.08 g kg^{-1}. Presenting the standard error alongside of cropping systems means allowed for quick interpretation of fall soil N differences which did not occur in this instance because standard error estimates overlapped with cropping system means.

Routine soil fertility data were reported in approximately five-year intervals beginning in 1996 through 2017 (Table 2.7). Reported values include organic matter percentage, relative potassium, phosphorus, magnesium, calcium, soil pH, and Cation Exchange Capacity (CEC). These assessments are presented to showcase baseline soil conditions at the Water Quality Field Station (WQFS). In 2005 soil test data switched from a colorimetric analysis of Bray P1 extract to a Mehlich-3 extractant assessed with inductivity coupled plasma spectroscopy. Across all cropping systems and years, organic matter percentage ranged from 3.7 to 5.0. Phosphorus ranged from 16.0 to 42.8 mg kg^{-1}, potassium ranged from 86.3 to 174.5 mg kg^{-1}, magnesium ranged from 572.5 to 846.3 mg kg^{-1}, calcium ranged from 2212.5 to 3565 mg kg^{-1}, soil pH ranged between 6.1 to 6.8, and CEC ranged between 17.9 to 29 meg 100g-1. All reported parameters would be considered in the maintenance regime, rather than build up, or draw down according to Vitosh et al. (1995).

Table 2.6. Soil N concentrations collected in the fall. The 0-20 cm cores were taken from 9 random locations from within each plot. Data shown are mean ± standard error across 4 replications. Background shading represents soybean years in rotational systems.

	Cropping System†					
Year	Pgrass	CS 157	SC 157	CS 135	SC 135	CC 180
	----------------------------Fall Soil N g kg^{-1}-------------------------------					
2012	1.92±0.12	1.84±0.14	1.95±0.19	1.72±0.15	1.90±0.20	2.01±0.16
2013	1.98±0.13	1.78±0.16	1.91±0.18	1.67±0.14	1.88±0.19	2.00±0.18
2014	1.85±0.08	1.73±0.15	1.86±0.17	1.67±0.14	1.84±0.18	2.02±0.19
2015	1.75±0.11	1.68±0.15	1.79±0.22	1.56±0.14	1.74±0.14	1.85±0.17
2016	1.91±0.17	1.82±0.21	1.91±0.22	2.04±0.15	1.88±0.19	2.08±0.22
2017	1.99±0.13	1.75±0.19	1.87±0.21	1.64±0.15	1.78±0.17	1.97±0.19
Trt Ave.	1.90±0.21	1.77±0.18	1.88±0.19	1.72±0.16	1.83±0.19	1.98±0.17

† Cropping systems abbreviated as: Prgass, perennial prairie grass; CS 157, tilled corn-soybean rotation corn planted first with 157 kg ha-1 N applied preplant; SC 157, tilled soybean-corn rotation soybean planted first with 157 kg ha-1 N applied preplant; CS 135, tilled corn-soybean rotation corn planted first with 135 kg ha-1 N applied sidedress; SC 135, tilled soybean-corn rotation soybean planted first with 135 kg ha-1 N applied sidedress; CC 180, tilled continuous corn with 180 kg ha-1 N applied preplant.

Table 2.7. Soil test results. The 0-20 cm cores were taken from 9 random locations from within each plot. Data shown are the mean ± standard error across 4 replications

Year	Cropping System λ	O.M. %†	P, mg kg^{-1}	K, mg kg^{-1}	Mg, mg kg^{-1}	Ca, mg kg^{-1}	Soil pH	CEC§ meg/100g
1996	Pgrass	4.3 ± 0.2	19 ± 3	157 ± 7	628 ± 24	2213 ± 121	6.6 ±0.1	17.9 ± 1.0
2000	Pgrass	4.8 ± 0.2	19 ± 8	104 ± 12	573 ± 40	2463 ± 196	6.6 ± 0.1	19.0 ± 1.7
2005	Pgrass	4.5 ± 0.2	32 ± 8	135 ± 12	746 ± 44	3274 ± 248	6.6 ± 0.1	24.6 ± 1.6
2010	Pgrass	5.2 ± 0.3	26 ± 7	1745 ± 7	666 ± 52	3241 ± 195	6.6 ± 0.2	23.9 ± 1.5
2015	Pgrass	5.0 ± 0.3	26 ± 10	148 ± 8	747 ± 33	3221 ± 240	6.6 ± 0.1	25.6 ± 1.8
2017	Pgrass	5.0 ± 0.2	26 ± 5	163 ± 3	736 ± 17	3172 ± 128	6.7 ± 0.1	26.0 ± 1.1
1996	CS 157	4.2 ± 0.2	26 ± 4	154 ± 4	656 ± 19	2238 ±143	6.6 ±0.1	18.2 ± 0.9
2000	CS 157	4.3 ± 0.2	31 ± 6	112 ± 9	567 ± 18	2438 ± 80	6.5 ± 0.1	19.7 ± 0.8
2005	CS 157	3.8 ± 0.3	38 ± 5	107 ± 12	790 ± 42	3434 ± 90	6.3 ± 0.2	27.5 ± 1.2
2010	CS 157	4.2 ± 0.3	23 ± 6	138 ± 8	674 ± 12	3233 ± 119	6.4 ± 0.1	25.1 ± 1.7
2015	CS 157	4.4 ± 0.2	26 ± 5	118 ± 3	735 ± 17	3003 ± 128	6.7 ± 0.1	25.7 ± 1.1
2017	CS 157	4.2 ± 0.4	25 ± 8	139 ± 5	739 ± 55	3136 ± 217	6.7 ± 0.1	26.1 ± 1.8
1996	SC 157	4.6 ± 0.4	19 ± 5	147 ± 6	701 ± 36	2438 ± 131	6.6 ± 0.1	19.7 ± 1.4
2000	SC 157	5.0 ± 0.5	31 ± 10	123 ±15	670 ± 64	2763 ± 213	6.6 ± 0.2	21.8 ± 2.0
2005	SC 157	4.4 ± 0.3	32 ± 5	124 ± 9	845 ± 71	2693 ± 220	6.6 ± 0.1	28.0 ± 2.0
2010	SC 157	4.5 ± 0.4	22 ± 6	152 ± 7	741 ± 52	3521 ± 226	6.5 ± 0.1	26.9 ± 1.9
2015	SC 157	4.6 ± 0.4	23 ± 8	139 ± 5	846 ± 55	3421 ± 217	6.7 ± 0.1	28.4 ± 1.8
2017	SC 157	4.5 ± 0.5	21 ± 5	158 ± 9	829 ± 35	3565 ± 194	6.7 ± 0.1	29.0 ± 1.6

Table 2.7 Continued

Year	Cropping System	O.M. %	P, mg kg^{-1}	K, mg kg^{-1}	Mg, mg kg^{-1}	Ca, mg kg^{-1}	Soil pH	CEC meg/100g
1996	CS 135	4.0 ± 0.4	21 ± 4	151 ± 4	681 ± 20	2237 ± 70	6.8 ± 0.2	17.9 ± 1.0
2000	CS 135	4.2 ± 0.5	25 ± 5	86 ± 4	606 ± 54	2488 ± 92	6.8 ± 0.2	18.6 ± 1.5
2005	CS 135	3.7 ± 0.4	28 ± 3	113 ± 6	810 ± 58	3336 ± 205	6.7 ± 0.2	24.9 ± 1.3
2010	CS 135	4.0 ± 0.4	19 ± 5	151 ± 8	766 ± 40	3528 ± 199	6.7 ± 0.1	26.2 ± 2.1
2015	CS 135	4.1 ± 0.5	17 ± 5	135 ± 9	847 ± 35	3394 ± 212	6.8 ± 0.1	26.5 ± 1.6
2017	CS 135	4.0 ± 0.3	16 ± 2	149 ± 2	776 ± 40	3254 ± 194	7.0 ± 2.0	25.8 ± 1.1
1996	SC 135	4.4 ± 0.4	22 ± 2	158 ± 16	688 ± 37	2363 ±133	6.6 ± 0.1	19.1 ± 0.7
2000	SC 135	4.6 ± 0.4	27 ± 4	117 ± 11	631 ± 38	2725 ± 159	6.8 ± 0.1	20.4 ± 1.2
2005	SC 135	3.7 ± 0.4	31 ± 4	122 ± 7	814 ± 54	3525 ± 170	6.8 ± 0.2	26.4 ± 1.8
2010	SC 135	4.4 ± 0.3	24 ± 3	149 ± 9	728 ± 35	3471 ± 127	6.6 ± 0.1	25.7 ± 1.4
2015	SC 135	4.5 ± 0.3	28 ± 3	135 ± 2	800 ± 40	3492 ± 111	6.7 ± 2.0	27.5 ± 1.1
2017	SC 135	4.3 ± 0.4	23 ± 8	155 ± 10	791 ± 42	3388 ± 233	6.6 ± 1.9	27.3 ± 2.3
1996	CC 180	4.6 ± 0.4	30 ± 6	158 ± 11	676 ± 31	2463 ± 176	6.4 ± 0.1	20.1 ± 1.6
2000	CC 180	4.9 ± 0.3	34 ± 10	112 ± 18	579 ± 47	2550 ± 228	6.7 ± 0.2	19.3 ± 1.5
2005	CC 180	4.2 ± 0.4	43 ± 6	149 ± 8	762 ± 48	3413 ± 227	6.1 ± 0.3	28.3 ± 1.8
2010	CC 180	4.4 ± 0.3	29 ± 9	157 ± 5	671 ± 38	3353 ± 149	6.3 ± 1.9	26.1 ± 1.9
2015	CC 180	4.8 ± 0.4	32 ± 8	142 ± 10	741 ± 42	3112 ± 233	6.6 ± 1.9	28.5 ± 2.3
2017	CC 180	4.7 ± 0.3	30 ± 8	159 ± 9	709 ± 17	3165 ± 95	6.6 ± 0.1	27.2 ± 1.4

† Organic matter percentage

§ Cation Exchange Capacity

λ Cropping systems abbreviated as: Prgass, perennial prairie grass; CS 157, tilled corn-soybean rotation corn planted first with 157 kg ha^{-1} N applied preplant; SC 157, tilled soybean-corn rotation soybean planted first with 157 kg ha^{-1} N applied preplant; CS 135, tilled corn-soybean rotation corn planted first with 135 kg ha^{-1} N applied sidedress; SC 135, tilled soybean-corn rotation soybean planted first with 135 kg ha^{-1} N applied sidedress; N applied sidedress; CC 180, tilled continuous corn with 180 kg ha^{-1} N applied preplant.

2.3.3 Nitrate-N Concentrations in Drainage Flow

Univariate descriptive statistics for nitrate-N concentrations in 24-hour flow proportional samples were reported to illustrate variability among replicates (Table 2.8). Analyzing concentration data by replication allows for an understanding of tile behavior and diagnosing possible tile failure. The restored prairie replications (Pgrass) skewness and kurtosis were highest among all other treatment replications, which means more outliers relative to the mean were observed. All treatments were positively skewed with the greatest positive skew in the Pgrass plot; positive skewness is expected in water quality data.

With no fertilizer N applied to the plots since planting in 1995, univariate statistics also revealed that the Pgrass control contained the lowest replicate means of 0.95 to 2.85 mg L^{-1} (Table 2.8). The annual cropping systems had the following concentration ranges with no fertilizer N applied to soybeans in rotation with corn: CS-157 was 10.80 to 13.82 mg L^{-1}, SC-157 was 7.56 to 11.27 mg L^{-1}, CS-135 was 7.44 to 9.90 mg L^{-1}, SC-135 was 6.72 to 11.45 mg L^{-1}, and CC-180 was 10.34 to 12.82 mg L^{-1}.

Tile-to-tile variation in drain flow duration and volume was prominent at this study site influencing the number of days' samples were collected from each treatment plot (discussed below). Across all study years and replicates the restored Pgrass ranged from 91 to 642 days of sample capture. In the annual cropping systems, CS-157 ranged from 122 to 610 days, SC-157 ranged from 242 to 1067 days, CS-135 ranged from 215 to 1028 days, SC-135 ranged from 322 to 1037 days, and CC-180 ranged from 232 to 696 days. Ideally an equal number of samples would be collected from each replicate, but variation in each tiles behavior best describes our results (Table 2.8).

Nitrate-N concentrations in drain flow of cropping system varied from year-to-year in this study (Table 2.9). The restored prairie control had consistently low means ranging from 1.38 mg

L^{-1} in 2014 to 3.17 mg L^{-1} in 2000. CS-157 ranged from 6.29 mg L^{-1} in 2016 to 38.06 mg L^{-1} in 1996, SC-157 ranged from 5.17 mg L^{-1} in 2011 to 13.78 mg L^{-1} in 1997, CS-135 ranged from 4.52 mg L^{-1} in 2014 to 30.28 mg L^{-1} in 1996, SC-135 ranged from 5.85 mg L^{-1} in 2011 to 14.64 mg L^{-1} in 1997, and CC-180 ranged from 5.20 mg L^{-1} in 2005 to 26.25 mg L^{-1} in 1996. Additionally, annual means averaged across all treatments including Pgrass ranged from a minimum of 6.22 mg L^{-1} in 2009 to a maximum of 15.89 mg L^{-1} in 2006.

Analysis of variance (ANOVA) detected a significant difference amongst cropping system flow proportional N concentration means ($p \leq 0.001$, Figure 2.1). Furthermore, post-hoc Tukey-Kramer identified CS-157 as having a significantly different ($p \leq 0.05$) mean (11.98 mg L^{-1}) from all other cropping systems. The CC-180 cropping system had the second highest numeric mean value (10.96 mg L^{-1}) and this was also significantly different from all other cropping systems. The SC-157, CS-135, and SC-135 cropping systems all had statistically similar means. Pgrass had a significantly lower mean value 2.18 mg L^{-1}. The annual mean concentration tended to decrease over time, most notably around 2003 (Table 2.9).

Table 2.8. Univariate descriptive statistics for daily NO_3^- N concentrations. Values presented represents means across all days where concentrations were greater than 0.01 mg L^{-1}. Cropping systems abbreviated as: Prgass, perennial prairie grass; CS 157, tilled corn-soybean rotation corn planted first with 157 kg ha^{-1} N applied preplant; SC 157, tilled soybean-corn rotation soybean planted first with 157 kg ha^{-1} N applied preplant; CS 135, tilled corn-soybean rotation corn planted first with 135 kg ha^{-1} N applied sidedress; SC 135, tilled soybean-corn rotation soybean planted first with 135 kg ha^{-1} N applied sidedress; N applied sidedress; CC 180, tilled continuous corn with 180 kg ha^{-1} N applied preplant.

Cropping System	N Rate kg ha^{-1}	Rep	N Days	Mean	Standard Error	Standard Deviation	Min.	Lower Quartile	Median	Upper Quartile	Max	Skewness	Kurtosis
				--mg L^{-1}--									
Pgrass	0	1	488	2.47	0.11	2.48	0.01	1.03	1.81	3.60	37.85	6.86	87.03
Pgrass	0	2	467	0.95	0.08	1.72	0.01	0.24	0.42	0.96	22.56	7.14	70.96
Pgrass	0	3	642	2.85	0.12	3.27	0.01	0.98	1.86	3.36	32.37	3.51	18.69
Pgrass	0	4	91	2.33	0.27	2.63	0.01	0.85	1.37	2.94	16.25	2.68	9.31
CS-157	157	1	497	10.80	0.39	8.75	0.01	5.66	8.18	12.87	51.3	2.34	6.51
CS-157	157	2	122	12.92	0.80	8.86	0.01	8.16	12.36	18.11	46.52	0.96	2.48
CS-157	157	3	432	13.82	0.50	10.50	0.01	7.65	10.83	16.76	79.06	2.54	8.51
CS-157	157	4	610	11.43	0.39	9.68	0.01	5.56	8.57	13.72	81.72	2.52	9.14
SC-157	157	1	603	11.11	0.25	6.24	0.01	7.59	10.40	13.10	68.82	2.78	16.61
SC-157	157	2	242	10.68	0.42	6.61	0.01	6.26	9.42	14.00	44.72	1.83	5.92
SC-157	157	3	589	11.27	0.29	7.17	0.01	6.40	9.14	14.72	48.19	1.50	3.18
SC-157	157	4	1067	7.56	0.15	4.98	0.01	4.40	6.27	9.40	41.62	2.16	7.45
CS-135	135	1	215	7.44	0.30	4.40	0.01	5.01	7.30	8.88	33.59	2.29	10.31
CS-135	135	2	336	9.90	0.31	5.68	0.01	5.49	8.32	11.22	34.05	1.73	4.38
CS-135	135	3	1028	9.48	0.23	7.55	0.01	5.21	7.72	11.96	60.56	2.77	10.57
CS-135	135	4	897	9.24	0.22	6.60	0.01	5.52	7.63	11.23	45.36	2.30	7.07
SC-135	135	1	322	11.45	0.29	5.22	0.01	7.93	11.25	14.14	41.87	0.95	3.75
SC-135	135	2	352	9.39	0.24	4.68	0.01	6.54	8.67	11.71	29.93	1.21	3.45
SC-135	135	3	1037	8.41	0.15	4.83	0.01	5.43	7.09	10.26	44.59	1.70	5.67
SC-135	135	4	386	6.72	0.24	4.90	0.01	3.62	5.34	8.55	41.75	2.62	11.41
CC-180	180	1	340	10.34	0.47	8.67	0.01	4.10	7.33	14.79	49.25	1.70	3.78
CC-180	180	2	277	10.55	0.52	8.78	0.01	4.15	7.97	14.55	49.8	1.33	1.61
CC-180	180	3	696	10.79	0.29	7.70	0.01	5.52	8.43	13.67	55.38	1.51	3.09
CC-180	180	4	232	12.82	0.70	10.74	0.01	5.28	9.15	17.53	51.28	1.39	1.68

Table 2.9. Mean and standard error of daily flow proportional nitrate concentrations from 1995 to 2017 for each of the six cropping systems. Different letters represent statistical treatment differences accord to Tukey HSD post hoc analysis ($p \leq 0.05$). Background shading represents soybean years in the rotation system.

Year	Pgrass λ	CS 157	SC 157	CS 135	SC 135	CC 180	Annual mean
	-------------	-------------	-------------	mg L^{-1}	-------------	-------------	-------------
1995	2.10±0.3	15.50±0.3	9.89±0.3	12.76±0.3	9.89±0.4	12.34±0.2	10.37±0.2 bc
1996	2.47±0.3	38.06±1.7	12.45±0.5	30.28±1.3	12.61±0.8	26.25±1.2	19.69±0.6 a
1997	2.85±0.5	16.82±0.8	13.78±0.3	12.33±0.4	14.64±0.5	18.38±0.7	13.47±0.3 ab
1998	2.74±0.5	14.20±0.7	12.64±0.3	10.74±0.4	11.52±0.4	16.06±1.1	11.44±0.3 bc
1999	1.99±0.1	9.43±0.3	11.40±0.6	10.14±0.3	11.71±0.3	5.87±0.2	8.51±0.2 c
2000	3.17±0.3	14.64±0.7	14.79±0.7	12.69±0.6	9.78±0.5	14.29±0.8	11.27±0.3 bc
2001	2.27±0.2	9.52±0.4	8.40±0.2	8.54±0.4	6.94±0.2	6.73±0.4	7.03±0.1 c
2002	1.27±0.1	8.03±0.1	9.83±0.2	6.94±0.1	7.79±0.2	6.30±0.2	7.19±0.1 c
2003	1.43±0.3	17.37±1.4	7.37±1.8	8.23±2.7	7.04±1.3	15.54±1.5	10.46±0.8 bc
2004	2.41±0.9	7.59±0.7	7.92±0.9	7.29±0.5	6.46±0.6	9.01±1.5	6.89±0.3 c
2005	1.43±0.3	9.07±.9	5.49±0.5	8.09±0.5	4.72±0.3	5.20±0.4	5.71±0.3 c
2006	3.39±0.7	20.51±1.1	14.84±1.1	20.35±1.1	13.10±0.8	21.94±1.8	15.89±0.7 ab
2007	1.44±0.4	11.01±0.8	8.54±0.3	6.72±0.3	9.04±0.4	7.77±0.7	7.41±0.3 c
2008	1.44±0.4	6.73±0.6	11.58±1.4	6.01±0.3	7.27±0.4	6.71±0.9	7.39±0.4 c
2009	2.59±0.2	9.12±0.6	5.62±0.2	7.46±0.3	5.96±0.2	6.15±0.6	6.22±0.1 c
2010	1.86±0.2	6.34±0.2	13.05±1.3	6.29±0.1	10.39±0.7	7.56±1.0	7.39±0.3 c
2011	2.08±0.3	10.75±1.1	5.17±0.1	9.44±0.4	5.85±0.3	4.08±0.3	6.44±0.2 c
2012	2.07±03	6.36±0.7	8.29±1.1	8.69±0.4	7.84±0.8	8.11±1.3	7.06±0.4 c
2013	1.62±0.3	8.95±0.8	11.69±0.6	5.96±0.2	10.27±0.4	14.24±0.7	8.67±0.3 c
2014	1.38±0.3	4.48±0.3	11.78±0.7	4.52±0.3	7.27±0.6	10.07±1.0	6.92±0.3 c
2015	2.95±1.2	11.68±2.0	9.60±0.9	7.03±1.1	6.86±0.9	13.68±2.2	8.45±0.6 c
2016	2.13±0.4	6.29±0.4	8.30±0.4	6.34±0.3	7.80±0.4	8.16±0.7	6.86±0.2 c
2017	1.41±0.2	11.68±1.4	6.64±0.3	9.09±0.6	7.38±0.5	11.94±0.9	7.78±0.3 c
Trt. Ave.	2.18±0.1 d	11.98±0.2 a	9.60±0.1 c	9.17±0.1 c	8.74±0.1 c	10.96±0.2 b	

λ Cropping systems abbreviated as: Prgass, perennial prairie grass; CS 157, tilled corn-soybean rotation corn planted first with 157 kg ha^{-1} N applied preplant; SC 157, tilled soybean-corn rotation soybean planted first with 157 kg ha^{-1} N applied preplant; CS 135, tilled corn-soybean rotation corn planted first with 135 kg ha^{-1} N applied sidedress; SC 135, tilled soybean-corn rotation soybean planted first with 135 kg ha^{-1} N applied sidedress; N applied sidedress; CC 180, tilled continuous corn with 180 kg ha^{-1} N applied preplant.

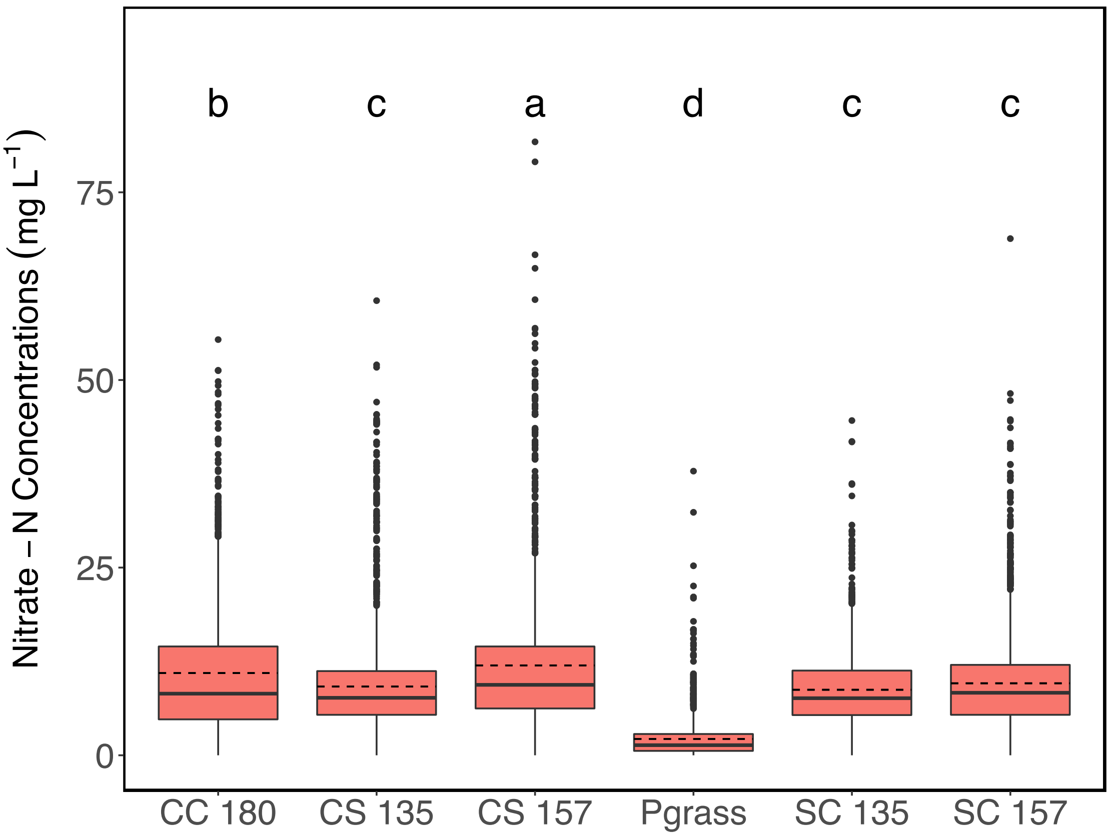

Figure 2.1. Nitrate-N Concentrations showing variability among treatments in 24-hour flow proportional samples collected from 1995-2017. Continuous corn abbreviated as CC, corn-soybean abbreviated as CS with corn planted first in the rotation, and soybean-corn abbreviated as SC with soybean planted first in the rotation. The number behind each treatment identifier corresponds to N rate applied (kg ha^{-1}). Individual points represent outliers, box represents 25th and 75th IQR, solid line is the median, and dashed line is the mean. Letters denote significant (p<0.05) differences among treatments means using the Tukey HSD post-hoc test.

2.3.4 Subsurface Drainage Flow

Univariate descriptive statistics of drain flow (Table 2.10), show daily variability amongst treatment replications. The number of days that flow occurred across all 23-years of data was highly variable across replications. The Pgrass treatment ranged from 271 to 985 days of flow, CS-157 ranged from 352 to 957 days of flow, SC-157 ranged from 627 to 1432 days, CS-135 ranged from 547 to 1301 days, SC-135 was 561 to 1187 days, and CC-180 ranged between 416 and 1317 days. Within a treatment, replicate daily flow volumes were highly variable as were the number of days' flow day occurred. The Pgrass replicate means were between 10946 and 41241 L day^{-1} ha^{-1}, CS-157 ranged between 20130 and 41670 L day^{-1} ha^{-1}, SC-157 ranged between 23994 and 31120 L day^{-1} ha^{-1}, CS-135 was between 21709 and 29300 L day^{-1} ha^{-1}, CS-135 ranged between 24324 and 43937 L day^{-1} ha^{-1}, and CC-180 ranges were 25847 and 54995 L day^{-1} ha^{-1}.

Over the duration of this study, drainage flow was found to be not significantly different among cropping systems (Figure 2.2). Numerically, CS-157 possessed the lowest yearly mean of all treatments, which was 1023508 L year^{-1} ha^{-1}. In contrast, SC-157 had the highest, although not significantly different, reported mean (1624705 L year^{-1} ha^{-1}), while the other four treatments had very similar flow means, ranging between 1103710 and 1257270 L year^{-1} ha^{-1}.

Subsurface drainage flow is a function of precipitation and in 2012 when 736.1 mm of rainfall occurred, approximately 5% of that was lost through tile lines, whereas in 2017 when 1249.5 mm of rainfall occurred (Table 2.11) approximately 12% of the annual rainfall was lost through tile lines. At the beginning of this study when higher N concentrations were observed (1995-2002, Table 2.9), a range of 14 to 31% of the precipitation that occurred was lost through tile lines. Although a water balance was not calculated for each cropping system or crop there tended to be more drainage flow in soybean wet years when precipitation was above normal for the region when compared to corn wet years (i.e. 2003, 2011, 2017).

Table 2.10. Univariate descriptive statistics for daily subsurface drainage flow L day^{-1} ha^{-1}. Values presented represents days where flow values were greater than 0.01 L. Cropping systems utilized abbreviated as: Prgass, perennial prairie grass; CS 157, tilled corn-soybean rotation corn planted first with 157 kg ha^{-1} N applied preplant; SC 157, tilled soybean-corn rotation soybean planted first with 157 kg ha^{-1} N applied preplant; CS 135, tilled corn-soybean rotation corn planted first with 135 kg ha^{-1} N applied sidedress; SC 135, tilled soybean-corn rotation soybean planted first with 135 kg ha^{-1} N applied sidedress; N applied sidedress; CC 180, tilled continuous corn with 180 kg ha^{-1} N applied preplant.

Cropping System	N rate kg ha^{-1}	Rep	N Days	Mean	Standard Error	Standard Deviation	Min	Lower Quartile	Median	Upper Quartile	Max	Skewness	Kurtosis
				-----	-----	-----	-----	----- L $day^{-1}ha^{-1}$ -----	-----	-----	-----	-----	-----
Pgrass	0	1	757	41241	2418	66541	45	486	12429	54447	595647	3.1	13.5
Pgrass	0	2	681	33389	2200	57421	42	90	4763	40696	351889	2.4	5.9
Pgrass	0	3	985	31341	1683	52842	55	389	7065	39250	571654	3.1	15.7
Pgrass	0	4	271	10946	1543	25404	52	56	113	13240	260854	5.1	39.5
CS-157	157	1	652	41670	2991	76380	65	131	6947	50593	769908	3.4	18.4
CS-157	157	2	352	20914	2407	45167	44	47	1006	21832	365335	3.9	19.5
CS-157	157	3	643	29054	2069	52465	62	248	6659	30559	598800	38	25.1
CS-157	157	4	957	20130	1357	42000	39	175	2109	16230	375102	3.3	13.7
SC-157	157	1	1374	26200	1476	54730	44	399	5144	20289	491688	3.6	15.6
SC-157	157	2	627	23944	2235	55984	46	49	393	15492	455480	3.8	18.7
SC-157	157	3	840	24164	1682	48771	46	111	1980	24340	465449	3.3	14.6
SC-157	157	4	1432	31120	1387	52519	44	2546	10390	32880	470333	3.1	11.9
CS-135	135	1	547	29300	2722	63669	45	57	1948	25558	546865	3.8	19.4
CS-135	135	2	553	24958	1997	46964	42	44	1704	27348	331991	2.7	8.3
CS-135	135	3	1301	21709	1091	39354	56	1020	6434	22424	431191	3.5	17.4
CS-135	135	4	1246	25979	1298	45831	40	368	6691	27328	416929	2.9	11.0
SC-135	135	1	682	27373	1987	51897	49	163	4293	29550	463783	3.2	14.5
SC-135	135	2	589	34041	2759	66981	44	51	2267	36462	596436	3.1	13.5
SC-135	135	3	1187	24324	1294	44594	54	1024	6340	24712	475332	3.3	16.2
SC-135	135	4	561	43937	3109	73640	42	199	7933	61501	656793	2.8	11.8
CC-180	180	1	416	54595	2390	25272	50	115	9694	52830	458853	15.3	261.3
CC-180	180	2	555	28664	2642	62241	44	60	214	27067	586049	3.6	18.5
CC-180	180	3	1317	30690	1581	57397	52	1793	8756	29555	647574	3.6	19.3
CC-180	180	4	468	25847	2374	51373	47	118	1665	29570	483597	3.4	17.4

Table 2.11. Mean subsurface drainage flow from 1995 to 2017 for each of the six cropping systems. Background shading represents soybean years in the rotation system.

Year	Pgrass	CS 157	SC 157	CS 135	SC 135	CC 180	Annual mean	Annual Precip.
	------------------------------------- L water $yr^{-1}ha^{-1}$ --------------------------------							mm
1995	1121245	970720	1852747	1032823	1623954	1219001	1303415	895
1996	1956858	1494909	2596059	1703476	1975328	2042634	1961544	940
1997	1757462	2017183	1973750	1983359	1705726	2408364	1974308	734
1998	2238189	1793958	2674777	2025860	2381175	2457471	2261906	1163
1999	3236434	2567880	2505784	2695655	2649408	2405174	2676723	853
2000	1635317	965088	1630973	1556271	1141844	1366436	1382655	848
2001	3313685	1652925	2416885	1778511	1893889	2037656	2182259	1026
2002	1548900	2088739	3237004	2733084	2708520	1994078	2385055	836
2003	1475040	1378000	2177834	1534924	1830811	1253112	1608288	1109
2004	904680	784548	1655613	1339571	1279067	804765	1128041	1055
2005	916780	474739	1970379	1361117	1481764	1030082	1205811	828
2006	273211	435479	689472	561871	553642	387983	483610	1138
2007	299174	136772	260117	111461	314316	1361940	413964	1114
2008	83541	256203	327197	101698	324160	665029	292972	1096
2009	882992	701417	2363420	1279812	593782	698630	1086676	1102
2010	443835	692738	818123	1178771	1056045	606514	799338	967
2011	820542	1385606	2513129	2129928	2163948	1721941	1789183	1288
2012	308087	352826	501060	446312	426212	368501	400500	736
2013	494298	605820	771854	1001756	765815	710681	725038	967
2014	402138	1000094	1204464	1736875	1181342	1052247	1096194	1031
2015	260778	491736	397855	438700	584734	626233	466673	993
2016	229588	327964	651529	1563789	525370	229363	587934	1015
2017	782559	965322	2178201	1559172	1711575	1469286	1444353	1250
Trt. Ave.	1103710 ns†	1023508 ns	1624705 ns	1384991 ns	1342280 ns	1257270 ns		

† ns corresponds to not significant

λ Cropping systems abbreviated as: Prgass, perennial prairie grass; CS 157, tilled corn-soybean rotation corn planted first with 157 kg ha^{-1} N applied preplant; SC 157, tilled soybean-corn rotation soybean planted first with 157 kg ha^{-1} N applied preplant; CS 135, tilled corn-soybean rotation corn planted first with 135 kg ha^{-1} N applied sidedress; SC 135, tilled soybean-corn rotation soybean planted first with 135 kg ha^{-1} N applied sidedress; N applied sidedress; CC 180, tilled continuous corn with 180 kg ha^{-1} N applied preplant.

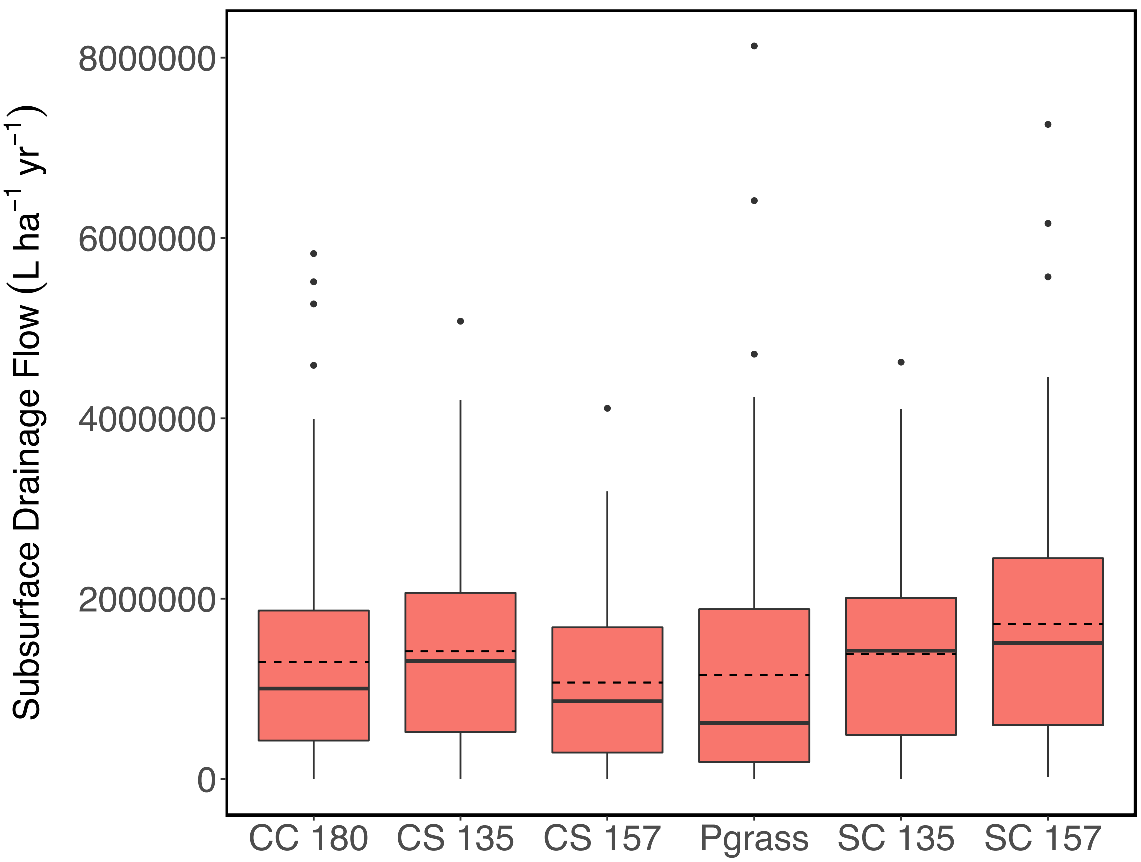

Figure 2.2. Subsurface drainage flow showing variability among treatments from 1995-2017. Continuous corn abbreviated as CC, corn-soybean abbreviated as CS with corn planted first in the rotation, and soybean-corn abbreviated as SC with soybean planted first in the rotation. The number behind each treatment identifier corresponds to N rate applied (kg ha^{-1}). Individual points represent yearly outliers, box represents 25th and 75th IQR, solid line is the median, and dashed line is the mean.

2.3.5 Nitrate-N Subsurface Drainage Load

Analysis of drainage NO_3-N load found all replicates were strongly positively skewed with the Pgrass cropping system containing some of the highest skewed values (Table 2.12). The Pgrass system also contained some of the highest kurtosis values. As for nitrate concentration data, positive skewness and kurtosis is very common in NO_3-N load data as the number of days' samples occurred and the volume drainage flow is variable among cropping systems replicates. Positively skewed data may be attributed to occasional extreme drainage events outside of the norm.

The number of days that N load was captured (Table 2.12) is the direct product of N concentration data multiplied by flow data. As described in the methodology, daily concentrations were matched to daily flow, and a decision rule was employed to gap-fill missing concentrations (see methods). Over all study years, the Pgrass cropping system had between 84 and 834 days of usable NO_3-N load data, CS-157 ranged between 145 and 869 days, SC-157 ranged between 340 and 1368 days, CS-135 had days between 275 and 1241, SC-135 ranged between 400 and 1072 days, and CC-180 ranged between 309 and 1117 days. Across all treatment means, the minimum value extracted from the descriptive statistics was 1103 mg day^{-1} in the Pgrass cropping system and a maximum value of 18145 mg day^{-1} in the CC-180 cropping system.

Across years, subsurface NO_3-N loads averaged across years were significantly different ($p \leq 0.001$, Table 2.13). Across treatments, the highest recorded drainage load was in 1996 when 26.49 kg ha^{-1} of NO_3-N was lost through tile lines. In 2012, 3.14 kg ha^{-1} of NO_3-N was lost through tile lines which was the lowest reported annual mean in the study. The annual mean across all years was 10.56 kg ha^{-1} of NO_3-N. Year-to-year variation was prominent in a data record this large, however, when mean NO_3-N load was regressed against annual precipitation there was little to no correlation (data now shown).

There were significant ($p \leq 0.05$) cropping system mean differences in mean annual NO_3-N loads in drainage load (Figure 2.3). The Pgrass (1.70 kg ha^{-1}) control had the significantly lowest mean among all treatments. The SC-135 was not significantly different from the Pgrass cropping system. Across all years, CS-135 (10.52 kg ha^{-1}) and SC-135 (9.88 kg ha^{-1}) had lowest mean NO_3-N load losses, but values from these treatments were not significantly different from those of CS-157 (11.80 kg ha^{-1}), SC-157 (12.32 kg ha^{-1}) and CC-180 (11.46 kg ha^{-1}, Figure 2.3).

Partitioning the annual load loss data by crop found differences in load losses that were not apparent in the cropping system comparison. Nitrogen load loss from rotational corn 157 kg ha^{-1} was significantly ($p \leq 0.05$) greater than rotational corn receiving 135 kg ha^{-1} and continuous corn 180 kg ha^{-1}, and rotational corn 135 kg ha^{-1} and continuous corn 180 kg ha^{-1} were not significantly different from each other in their load losses (Figure 2.4). Soybean in rotation with corn was analyzed separately from corn and no significant differences in load losses occurred between Soybean 135 kg ha^{-1} and Soybean 157 kg ha^{-1} (Figure 2.5).

Regression analysis was utilized to describe the relationship between NO_3-N load and flow data (Figure 2.6). Based upon adjusted R^2 values, SC-135 had the overall strongest relationship with an $R^2 = 0.82$. The Pgrass cropping system had the weakest relationship between NO_3-N load and flow although the relationship was significant with flow explaining 67% of the variation in flux. The CC-180 had a relationship described by an $R^2 = 0.76$, CS-135 had an $R^2 = 0.69$, CS-157 had an $R^2 = 0.82$, and SC-157 had an $R^2 = 0.69$. The equations describing the relationships for each cropping system can be found on Figure 2.6. The slope of the relationship ranged from 0.932 for treatment SC-157 to 1.14 for CS-157 and in all cases, were not significantly different from each other or 1.

When cumulative subsurface NO_3-N load was calculated over all study years CS-157 and SC-157 had the numerically highest total N lost with means of 272 kg ha^{-1} and 284 kg ha^{-1} respectively (Figure 2.7). The CC-180 treatment lost 263.65 kg ha^{-1} which was between the five cropping systems. CS-135 (242.16 kg ha^{-1}) and SC-135 (227.31 kg ha^{-1}) had the lowest cumulative NO_3-N amounts lost through tile lines when compared to other three annual row crop systems. The Pgrass treatment lost 38.96 kg ha^{-1} of NO_3-N which was substantially lower then all intensively fertilized cropping systems. A piecewise regression model fit to all treatment data calculated two different slopes (Figure 2.7), and found that regression 1 (years 1995 to 2002) had an adjusted R^2 = 0.88 ($p \leq 0.001$), and regression 2 (years 2003-2017) had an adjusted R^2 = 0.97 ($p \leq 0.001$). Slopes of these regression values were 6.81 (regression 1) and 3.04 (regression 2) kg ha^{-1} yr^{-1}. This model was fit to describe the slopes of the two lines across all treatments including Pgrass.

Table 2.12. Univariate descriptive statistics for subsurface daily nitrate drainage load. Values presented represents days where flow values were greater than 0.01 L. Cropping systems abbreviated as: Prgass, perennial prairie grass; CS 157, tilled corn-soybean rotation corn planted first with 157 kg ha^{-1} N applied preplant; SC 157, tilled soybean-corn rotation soybean planted first with 157 kg ha^{-1} N applied preplant; CS 135, tilled corn-soybean rotation corn planted first with 135 kg ha^{-1} N applied sidedress; SC 135, tilled soybean-corn rotation soybean planted first with 135 kg ha^{-1} N applied sidedress; N applied sidedress; CC 180, tilled continuous corn with 180 kg ha^{-1} N applied preplant.

Cropping System	N Rate kg ha^{-1}	Rep	N Days	Mean	Standard Error	Standard Deviation	Min.	Lower Quartile	Median	Upper Quartile	Max	Skewness	Kurtosis
					-- mg NO3-N day^{-1} $plot^{-1}$ --								
Pgrass	0	1	513	3183	238	5188	1	195	1394	4524	56816	4.4	31.1
Pgrass	0	2	435	1103	304	6095	1	9	104	633	108340	14.4	244.3
Pgrass	0	3	834	2289	197	357	1	77	614	2630	60172	6.1	53.5
Pgrass	0	4	84	1343	357	3004	1	4	222	1586	21259	4.7	28.1
CS-157	157	1	594	16496	1551	29990	2	74	3701	21877	211411	3.3	14.3
CS-157	157	2	145	11960	1948	23857	5	37	1716	15645	184988	3.9	20.1
CS-157	157	3	599	15901	1338	26424	1	845	4977	19122	212061	3.1	13.6
CS-157	157	4	869	7850	712	18013	5	116	944	6706	169973	4.5	27.1
SC-157	157	1	1049	9096	715	19857	10	600	2023	6823	275715	5.5	50.1
SC-157	157	2	340	6940	804	13088	1	21	419	7675	100099	2.9	12.2
SC-157	157	3	751	10905	1073	23375	1	57	1595	11309	245848	5.0	36.3
SC-157	157	4	1368	8693	626	16809	2	679	2452	8271	199282	4.5	32.2
CS-135	135	1	275	8198	977	15635	2	27	1335	8525	111547	3.2	13.7
CS-135	135	2	411	7148	822	13563	3	19	806	9805	128880	4.0	26.3
CS-135	135	3	1213	9005	635	16928	2	638	2750	10580	229605	5.6	53.2
CS-135	135	4	1241	9813	784	19778	2	435	2870	10052	215503	4.9	33.3
SC-135	135	1	473	10522	942	19477	7	242	2154	12576	144085	3.3	14.1
SC-135	135	2	400	11300	1162	20335	2	31	2001	14497	166792	3.2	14.1
SC-135	135	3	1072	7566	490	13047	3	401	2122	8461	118572	3.1	13.1
SC-135	135	4	461	9323	1050	18171	2	90	1679	11524	166902	4.0	23.4
CC-180	180	1	368	18145	2472	34881	1	230	6513	22890	294910	4.7	29.7
CC-180	180	2	374	12397	1423	22102	2	37	1454	15646	140834	2.7	9.5
CC-180	180	3	1117	10026	658	19155	2	687	2761	9565	169832	3.8	19.0
CC-180	180	4	309	11400	1231	20456	4	83	2512	12863	168078	3.3	15.7

Table 2.13. Mean subsurface nitrate load from 1995 to 2017 for each of the six cropping systems. Different letters represent statistical differences accord to Tukey HSD post hoc analysis ($p \leq 0.05$). Background shading represents soybean years in the rotation system.

Year	Pgrass λ	CS 157	SC 157	CS 135	SC 135	CC 180	Annual mean
	----------------------------------- kg NO3-N $ha^{-1}yr^{-1}$ ---						
1995	2.26 c	14.40 b	17.56 a	13.75 b	16.15 a	18.00 a†	13.69 A δ
1996	3.30 c	36.84 a	22.78 b	38.81 a	18.10 b	39.08 a	26.49 A
1997	2.23 c	15.84 b	12.73 b	11.72 b	12.43 b	21.71 a	12.78 AB
1998	3.41 d	18.48 c	27.53 a	17.47 c	22.63 b	21.59 b	18.52 A
1999	4.78 d	25.82 b	30.89 a	26.56 b	30.93 a	14.86 c	22.31 A
2000	5.08 d	16.14 b	27.80 a	12.70 c	11.50 c	23.47 a	16.12 A
2001	6.58 c	14.21 b	19.08 a	12.68 b	14.35 b	14.52 b	13.57 A
2002	1.34 d	16.36 b	24.62 a	15.26 b	17.95 b	12.34 c	14.65 A
2003	1.31 d	25.59 a	4.79 b	2.85 c	5.09 b	20.19 a	9.97 B
2004	1.80 c	6.14 b	11.06 a	9.37 a	5.56 b	4.75 b	6.45 B
2005	1.02 c	8.26 b	10.55 a	9.32 a	6.67 b	11.21 a	7.84 B
2006	1.11 c	9.38 a	9.33 a	8.15 a	6.05 b	8.07 a	6.97 B
2007	NA†	NA	NA	NA	NA	NA	NA
2008	NA	NA	NA	NA	NA	NA	NA
2009	2.49 d	9.51 b	14.12 a	12.35 a	4.21 c	6.58 c	8.21 B
2010	0.32 d	6.13 b	7.88 b	6.60 b	10.43 a	4.57 c	5.99 B
2011	1.03 d	16.72 a	11.52 b	19.67 a	11.57 b	7.68 c	11.37 AB
2012	0.28 c	3.09 b	3.73 b	4.14 ab	3.05 b	4.52 a	3.14 B
2013	0.21 c	6.65 b	7.16 b	6.47 b	7.19 b	11.35 a	6.51B
2014	0.07 d	4.05 c	12.49 a	8.06 b	7.25 b	9.73 b	6.94 B
2015	0.26 d	7.28 a	1.57 c	2.87 b	3.02 b	4.75 b	3.29 B
2016	NA	NA	NA	NA	NA	NA	NA
2017	0.30 c	10.72 a	6.22 b	3.39 b	13.22 a	4.69 b	6.41 B
Trt. Ave.	1.70 B	11.80 A	12.32 A	10.52 A	9.88 AB	11.46 A	10.56
Cumulative Total	38.96	271.59	283.50	242.16	227.31	263.65	

†NA corresponds to not available, data was removed a priori due to limited data and excluded from analysis.

λ Cropping systems utilized abbreviated as: Prgass, perennial prairie grass; CS 157, tilled corn-soybean rotation corn planted first with 157 kg ha^{-1} N applied preplant; SC 157, tilled soybean-corn rotation soybean planted first with 157 kg ha^{-1} N applied preplant; CS 135, tilled corn-soybean rotation corn planted first with 135 kg ha^{-1} N applied sidedress; SC 135, tilled soybean-corn rotation soybean planted first with 135 kg ha^{-1} N applied sidedress; N applied sidedress; CC 180, tilled continuous corn with 180 kg ha^{-1} N applied preplant.

δ Lower case letters represent treatments differences among years. Upper case letters represent differences across years inclusive of all treatments.

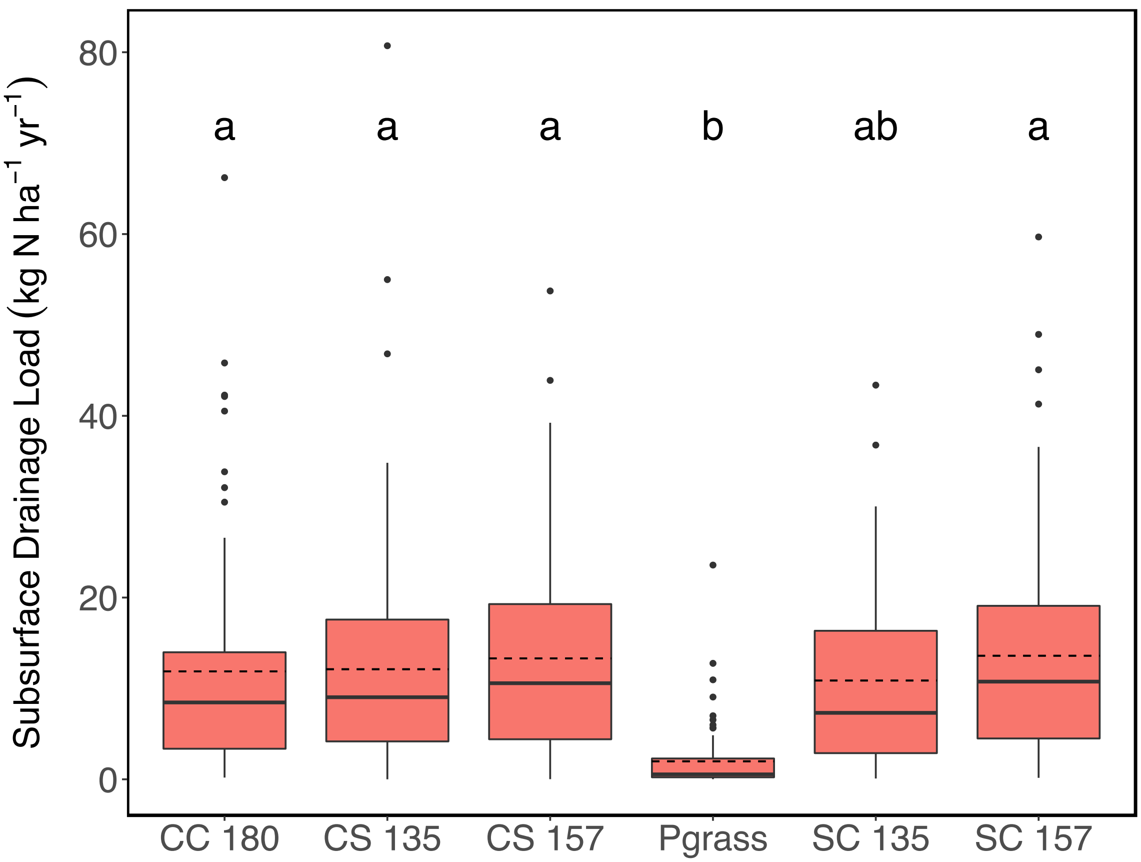

Figure 2.3. Subsurface drainage load showing variability among treatments from 1995-2017. Continuous corn abbreviated as CC, corn-soybean abbreviated as CS with corn planted first in the rotation, and soybean-corn abbreviated as SC with soybean planted first in the rotation. The number behind each treatment identifier corresponds to N rate applied (kg ha^{-1}). Individual points represent yearly outliers, box represents 25^{th} and 75^{th} IQR, solid line is the median, and dashed line is the mean. Letters denote significant (p<0.05) differences among treatments means using the Tukey HSD post-hoc test.

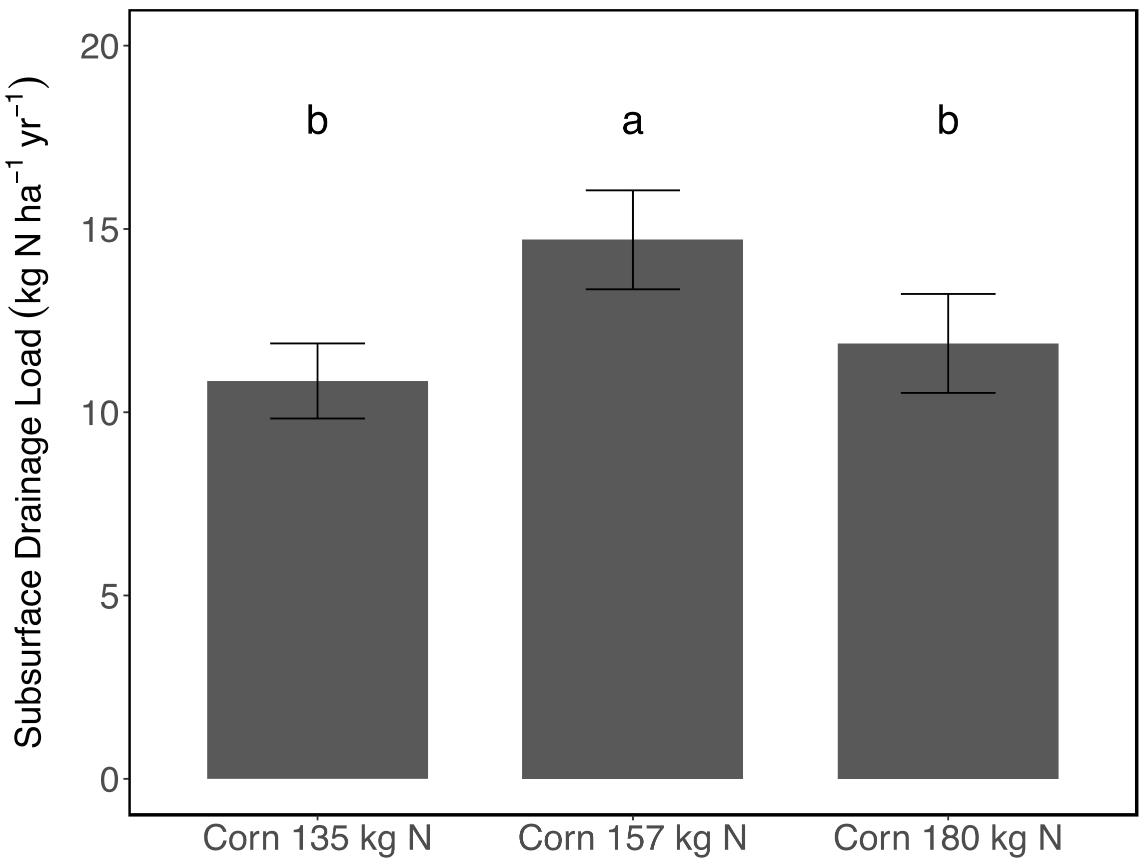

Figure 2.4. Mean ± standard error subsurface drainage load for corn by nitrogen rate. Annual treatment sums were used to compute the grand 23-year mean. Letters denote significant (p<0.05) differences among treatments means using the Tukey HSD post-hoc test.

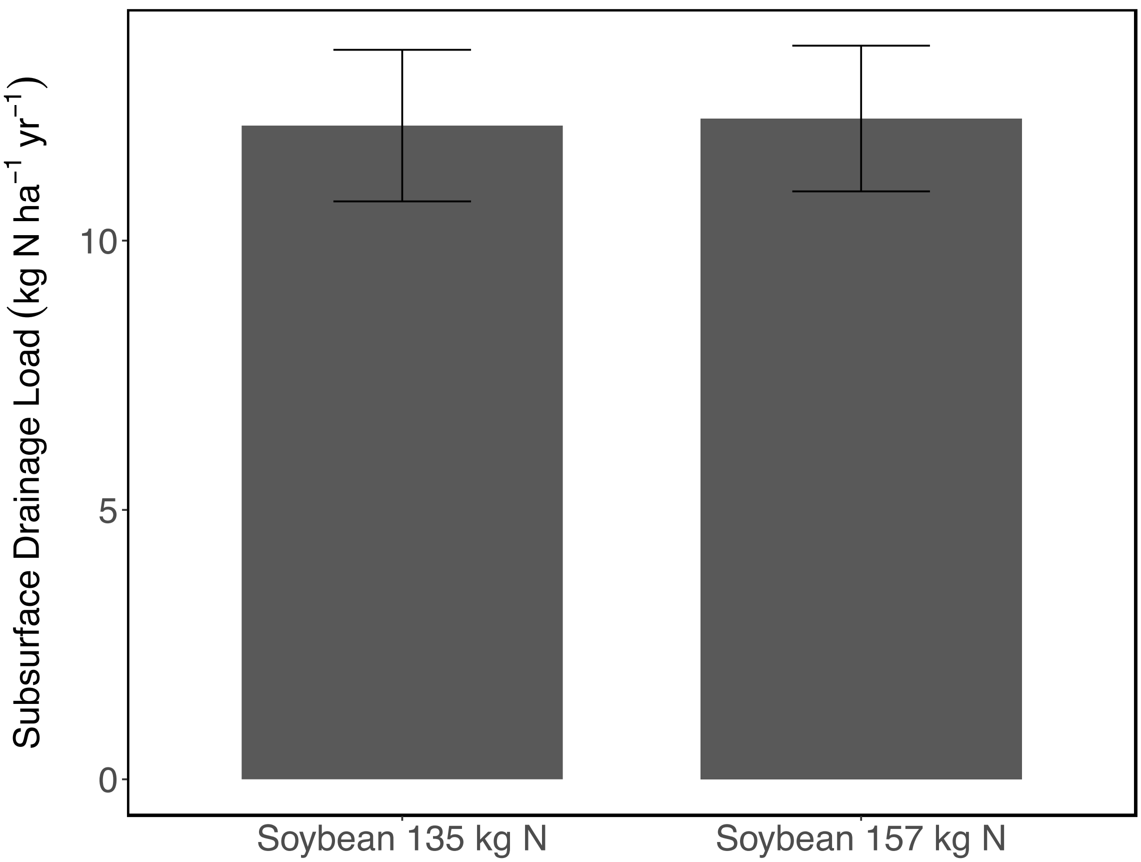

Figure 2.5. Mean ± standard error subsurface drainage load for soybean by corn nitrogen rate, no N was applied in soybeans years. Annual treatment sums were used to compute the grand 23-year mean. Treatments were not significantly different.

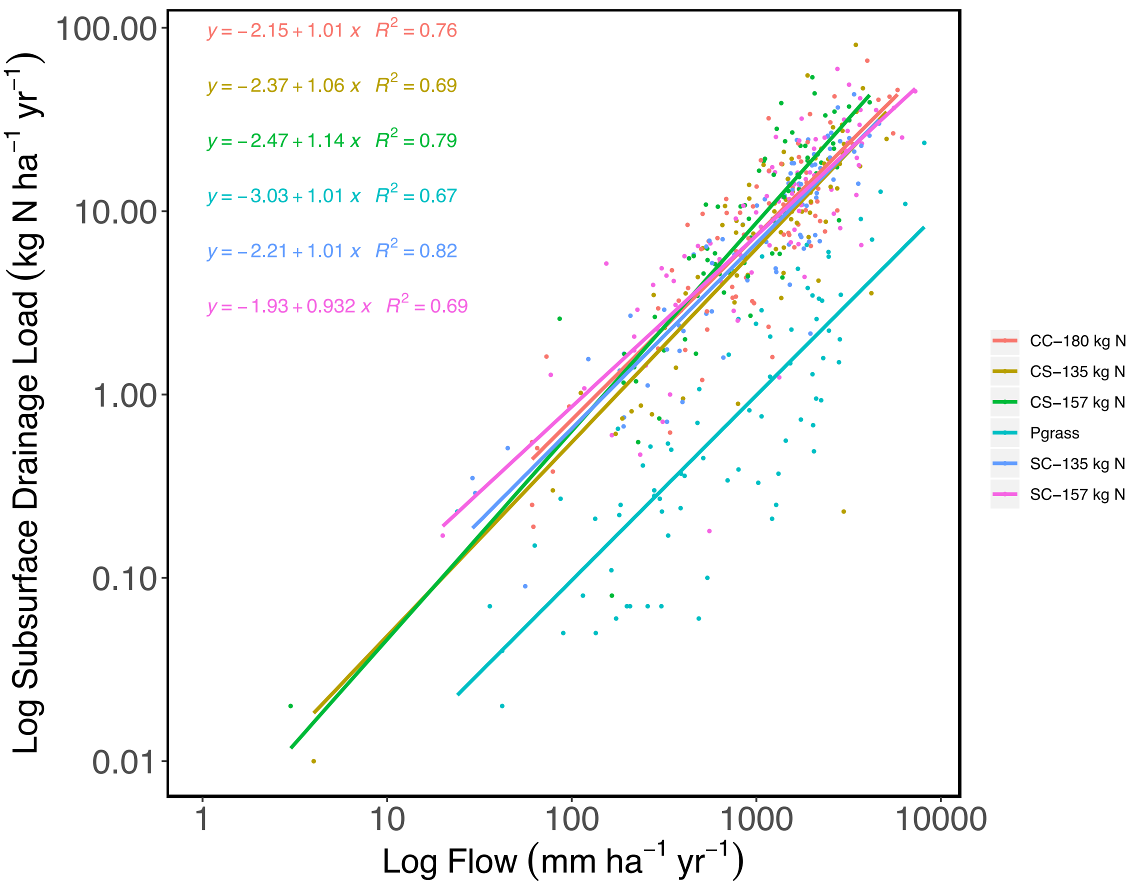

Figure 2.6. Mean annual N load as a function of flow for all 23 years of the study. Data was log transformed and then back-transformed for data visualization. Solid regression lines correspond to each treatment in the study and are identified by color. Continuous corn abbreviated as CC, corn-soybean abbreviated as CS with corn planted first in the rotation, and soybean-corn abbreviated as SC with soybean planted first in the rotation. The number behind each treatment identifier corresponds to N rate applied (kg ha-1).

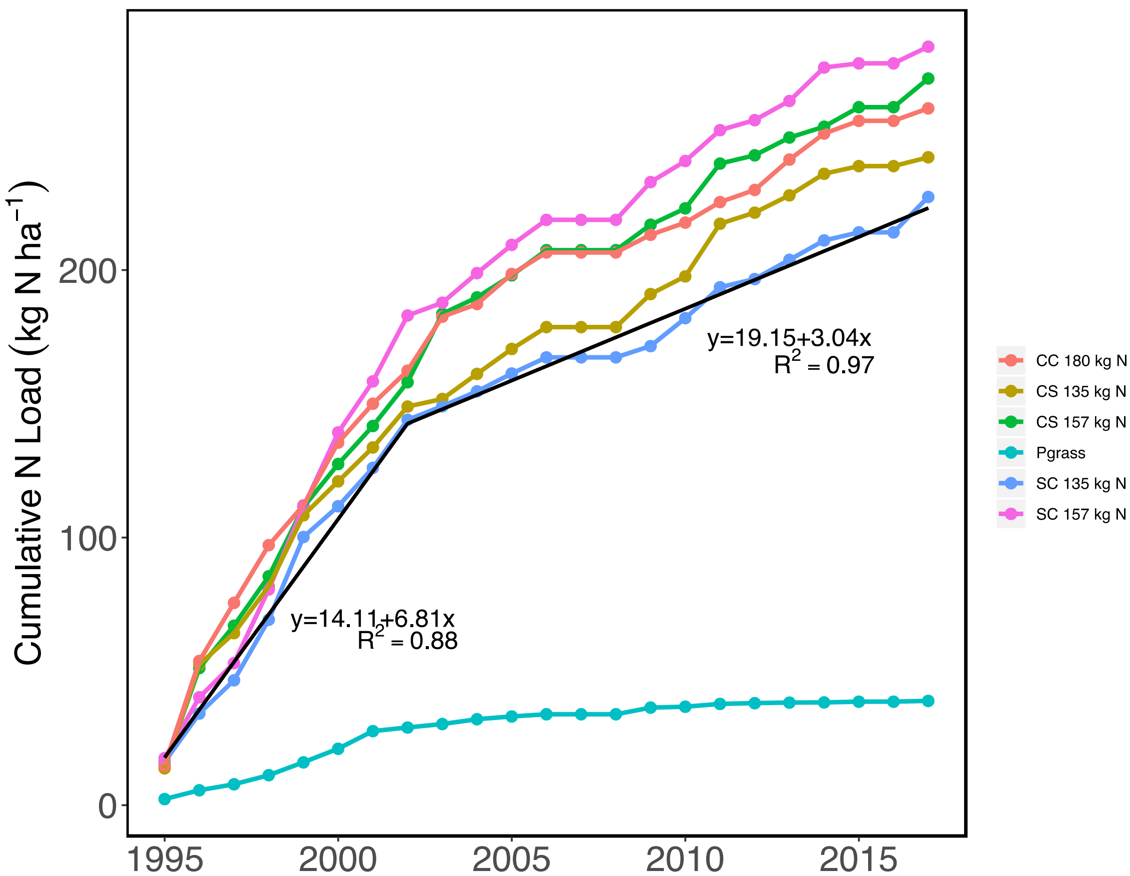

Figure 2.7. Mean cumulative annual N load for each treatment identified by color. Black line signifies regression line for two different slopes using data from all treatmetns. Continuous corn abbreviated as CC, corn-soybean abbreviated as CS with corn planted first in the rotation, and soybean-corn abbreviated as SC with soybean planted first in the rotation. The number behind each treatment identifier corresponds to N rate applied (kg ha-1).

2.3.6 Grain Yield and Yield-Scaled N Losses

Across all years there were no significant differences in grain yield among corn treatments or between the two soybean treatments, regardless of N application rate in this study (Table 2.14). All corn treatments were reported at 15.5% moisture content, and soybeans were reported at 13%. Treatment identifiers as designated below correspond to which crop was planted first at the beginning of this study (i.e. C1 corresponds to corn first and C2 corresponds to corn planted second following soybean). Corn yields (Figure 2.8), were analyzed separately from soybean yields and 23-year average yields are as follows: C1-135 yielded 8.81 Mg ha^{-1}, C1-157 yielded 9.48 Mg ha^{-1}, C2-135 yielded 9.70 Mg ha^{-1}, C2-157 yielded 9.40 Mg ha^{-1}, CC1-180 yielded 8.75 Mg ha^{-1}, and CC2-180 yielded 8.99 Mg ha^{-1}. Soybean yields (Figure 2.9), had the following yields: S1-135 yielded 3.12 Mg ha^{-1}, S1-157 yielded 3.04 Mg ha^{-1}, S2-135 yielded 3.57 Mg ha^{-1}, and S2-157 yielded 3.46 Mg ha^{-1}.

Year-to-year yields may be found on Table 2.15, and grey background shading denotes soybean years in rotation with corn. Across all years, CS-157 had a grain yield range of 6.67 to 11.82 Mg ha^{-1} for corn, and a range between 2.20 and 4.86 Mg ha^{-1} for soybeans. SC-157 grain yields for corn ranged between 6.00 and 11.57 Mg ha^{-1}, soybean yields had a range between 1.10 and 3.74 Mg ha^{-1}. CS-135 corn yield ranged between 4.66 and 12.26 Mg ha^{-1}, while soybeans in that cropping system ranged between 2.22 and 5.87 Mg ha^{-1}. SC-135 corn yields were between 6.49 and 12.73 Mg ha^{-1} across all years, and soybeans yield range was between 1.28 and 3.74 Mg ha^{-1}. CC-180 yields ranged between 4.79 and 12.45 Mg ha^{-1}.

Yield-scaled N losses are calculated by dividing N load losses (kg) by grain yield (Mg) to compare cropping system efficiencies (Figure 2.10). Although no significant differences occurred it was observed that the rotational systems tended to have markedly yield-scaled N losses when compared to continuous corn. The higher means in soybean-corn rotations can be attributed to lower grain yields in soybeans while maintaining similar magnitudes of N losses across all treatments. It was also observed that the rotational cropping systems had more outliers when compared to continuous corn (Figure 2.10).

Table 2.14. Mean grain yield among treatments. Corn and soybeans were analyzed separately. Yield values are reported at 15.5% moisture content for corn, and 13% for soybeans.

Crop	Trt λ	N Rate kg ha^{-1}	Mean	Mean Sum	Standard Error (annual mean)
			-------------Grain Yield Mg ha^{-1}------------		
Soybean	6	157	3.46 a†	152	0.12
Corn	6	157	9.48 A	455	0.25
Soybean	7	157	3.04 a	146	0.11
Corn	7	157	9.40 A	413	0.32
Soybean	8	135	3.57 a	155	0.21
Corn	8	135	8.81 A	423	0.33
Soybean	9	135	3.12 a	150	0.11
Corn	9	135	9.70 A	427	0.33
Corn	12-1	180	8.75 A	420	0.29
Corn	12-2	180	8.99 A	395	0.29

†Soybean and corn grain yield was analyzed separately. Values followed by the same capitalized or lower case letters are not significantly different (p>0.05).

λ Cropping systems utilized abbreviated as: Prgass, perennial prairie grass; CS 157, tilled corn-soybean rotation corn planted first with 157 kg ha^{-1} N applied preplant; SC 157, tilled soybean-corn rotation soybean planted first with 157 kg ha^{-1} N applied preplant; CS 135, tilled corn-soybean rotation corn planted first with 135 kg ha^{-1} N applied sidedress; SC 135, tilled soybean-corn rotation soybean planted first with 135 kg ha^{-1} N applied sidedress; N applied sidedress; CC 180, tilled continuous corn with 180 kg ha^{-1} N applied preplant.

Table 2.15. Annual mean grain yield for each of the six cropping systems. Different letters represent statistical differences accord to Tukey HSD post hoc analysis ($p \leq 0.05$). Background shading represents soybean years in the rotation system. Yield values are reported at 15.5% moisture content for corn, and 13% for soybeans.

Year	CS 157	SC 157	CS 135	SC 135	CC 180
	---------------------Grain Yield Mg ha^{-1}---------------------				
1995	6.67±2.3	3.26±0.6	6.57±4.5	3.26±1.2	6.14±1.8
1996	3.08±2.1	6.00±3.7	2.86±1.2	6.52±5.1	6.81±1.1
1997	9.77±3.8	3.12±0.7	7.65±6.7	3.24±1.7	9.47±2.1
1998	3.33±0.9	9.06±7.2	3.15±2.1	9.06±6.2	9.94±2.5
1999	7.58±5.5	1.10±0.4	4.66±1.4	1.28±0.5	8.38±3.3
2000	3.13±1.7	7.68±2.1	3.13±1.9	7.87±4.1	7.71±4.8
2001	9.67±5.2	3.42±1.6	9.59±4.4	3.45±0.9	7.39±3.9
2002	4.12±1.0	10.26±1.3	5.87±1.7	10.27±2.5	9.51±1.1
2003	10.55±2.6	3.51±1.5	7.97±2.4	3.35±1.7	9.28±2.6
2004	3.70±1.2	8.77±1.6	3.49±1.1	9.50±2.1	8.85±1.6
2005	10.43±5.9	3.43±1.1	9.89±2.1	3.37±1.5	9.84±1.8
2006	3.54±1.2	11.37±1.7	3.27±1.3	11.72±1.9	11.17±1.9
2007	10.39±4.6	2.85±0.9	10.14±2.4	3.10±1.1	9.69±1.7
2008	3.91±1.5	11.57±3.2	3.69±1.1	12.73±3.3	10.02±3.5
2009	9.77±4.1	2.81±2.2	9.33±3.1	3.34±1.3	7.63±2.2
2010	3.59±0.9	10.27±5.3	3.32±0.6	10.14±4.7	8.79±3.5
2011	7.41±3.6	2.19±1.1	7.38±3.8	2.12±1.7	7.4± 1.9
2012	2.20±0.7	6.92±3.5	2.22±0.4	6.49±1.4	4.79±2.2
2013	11.82±3.1	3.73±0.9	12.26±2.9	3.74±1.7	12.45±3.2
2014	3.54±2.5	10.55±3.5	3.56±0.9	11.24±4.9	10.37±2.1
2015	8.79±1.4	3.30±1.1	8.72±4.5	3.38±0.8	6.31±2.3
2016	4.86±1.7	10.92±3.7	4.68±2.7	11.14±3.3	10.89±1.8
2017	10.9±5.2	3.74±0.6	11.50±2.7	3.83±1.2	11.00±3.1
Trt. Ave.	6.64 ±1.5	6.08 ±2.4	6.30 ±2.1	6.27 ±1.7	8.86 ±1.3

λ Cropping systems utilized abbreviated as: Prgass, perennial prairie grass; CS 157, tilled corn-soybean rotation corn planted first with 157 kg ha$_{-1}$ N applied preplant; SC 157, tilled soybean-corn rotation soybean planted first with 157 kg ha$_{-1}$ N applied preplant; CS 135, tilled corn-soybean rotation corn planted first with 135 kg ha$_{-1}$ N applied sidedress; SC 135, tilled soybean-corn rotation soybean planted first with 135 kg ha$_{-1}$ N applied sidedress; N applied sidedress; CC 180, tilled continuous corn with 180 kg ha$_{-1}$ N applied preplant.

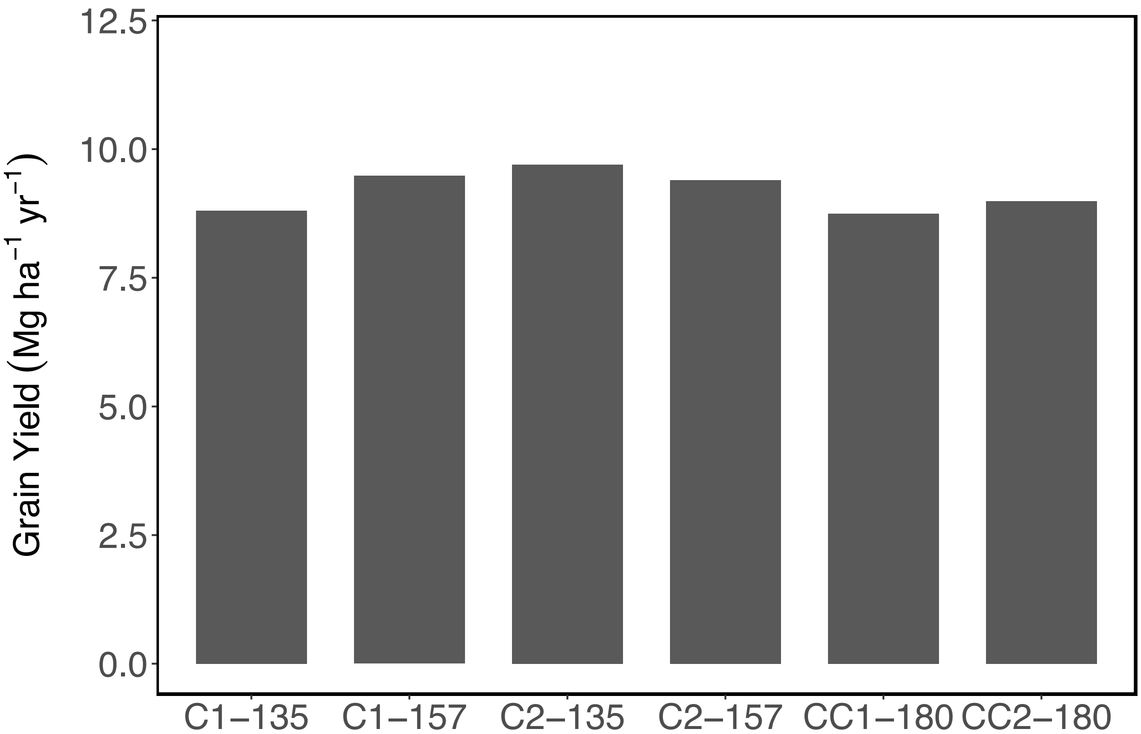

Figure 2.8. Mean grain yield showing corn only. Continuous corn abbreviated as CC1(odd years), Continuous corn abbreviated as CC2 (even years), corn abbreviated as C1 with corn planted first in the rotation, and corn abbreviated as C2 with corn planted first in the rotation. The number behind each treatment identifier corresponds to N rate applied (kg ha-1). Yield values are reported at 15.5% moisture content for corn. Treatments were not significantly different.

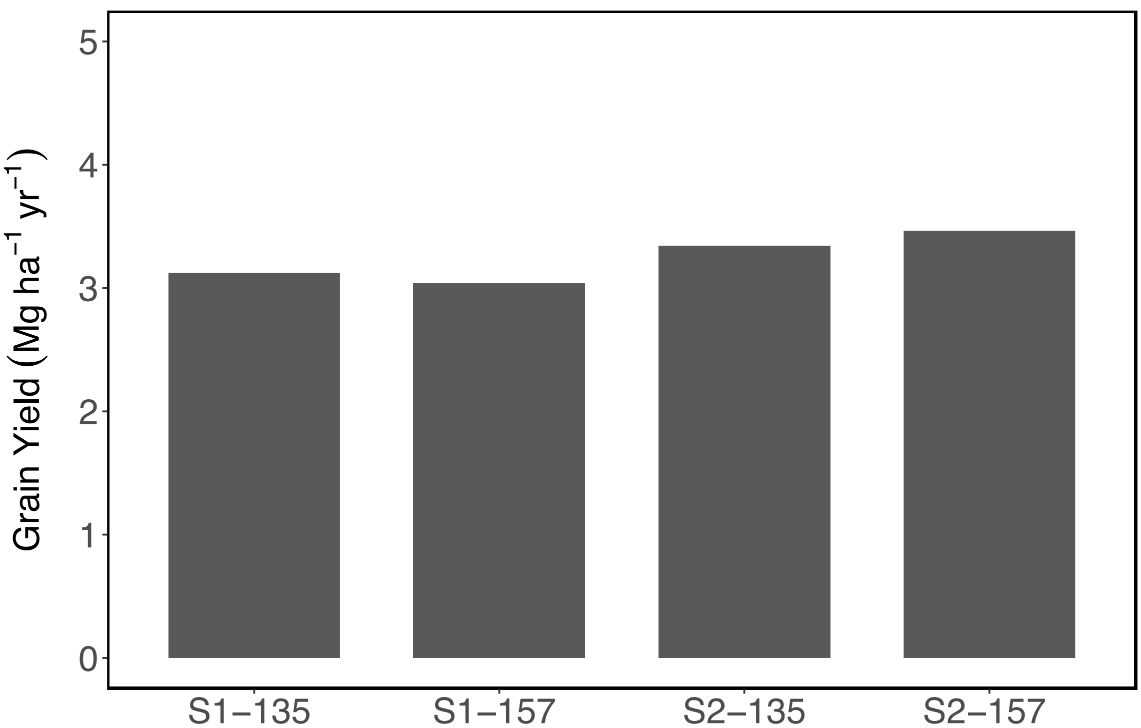

Figure 2.9.Mean grain yield showing soybean only. Soybean abbreviated as S2 with soybean planted second in the rotation, and soybean abbreviated as S1 with soybean planted first in the rotation. The number behind each treatment identifier corresponds to N rate applied to corn (kg ha_{-1}), no N was applied in soybean years. Yield values are reported at 13% moisture for soybeans. Treatments were not significantly different.

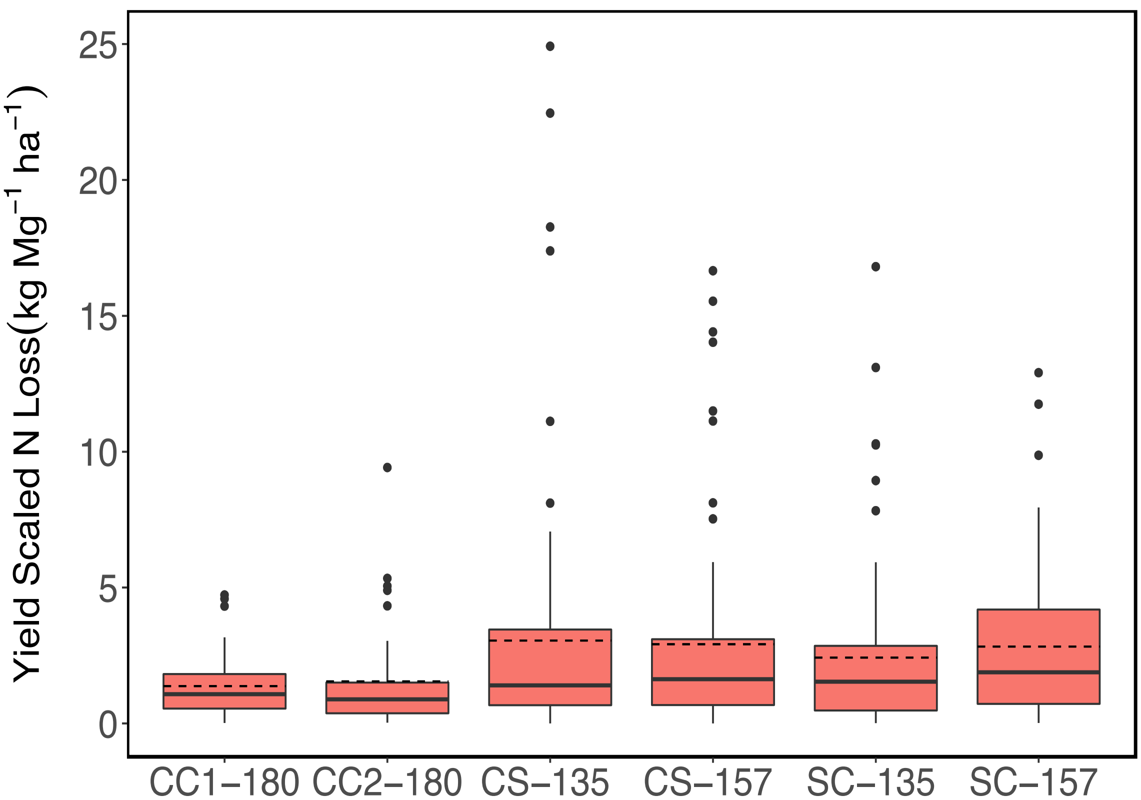

Figure 2.10. Yield-scaled N loss variability among treatments from 1995-2017. Continuous corn abbreviated as CC, corn-soybean abbreviated as CS with corn planted first in the rotation, and soybean-corn abbreviated as SC with soybean planted first in the rotation. The number behind each treatment identifier corresponds to N rate applied (kg ha^{-1}). Individual points represent yearly outliers, box represents 25^{th} and 75^{th} IQR, solid line is the median, and dashed line is the mean. Yield values are reported at 15.5% moisture content for corn, and 13% for soybeans. Treatments were not significantly different.

2.3.7 Stover N Concentration and Content

Significant cropping system by year interactions ($p \leq 0.001$) in stover N concentrations occurred, when soybean and corn crops were analyzed separately (Table 2.16). The N concentrations in the stover of rotational soybean in each respective cropping system had the following ranges across all 23-years of data: CS-157 N concentration ranged from 7.85 to 27.79 g kg^{-1}, SC-157 ranged from 9.72 to 30.65 g kg^{-1}, CS-135, 11.90 to 28.54 g kg^{-1}, and SC-135, 9.50 to 28.21 g kg^{-1}(Table 2.16). Corn treatments varied greatly in stover N concentration from year-to-year as is expected with a wide variety of growing conditions within a 23-year data set (Table 2.16). The CS-157, ranged from 4.8 to 9.85 g kg^{-1}, SC-157, 6.60 to 18.10 g kg^{-1}, CS-135, 5.30 to 8.80 g kg^{-1}, SC-135, 6.75 to 17.24 g kg^{-1}, and CC-180 5.11 to 18.01 g kg^{-1}.

On average, the corn stover residue, typically returned to soil, did not differ among corn treatments (Figure 2.11). The C1-157, C2-157, C1-135, C2-135, and CC-180 treatments returned 72, 77, 77, 83, and 74 kg N ha^{-1}, respectively. Soybean residue N returned to soil was analyzed separately from corn and quantities of N in soybean residues were almost two-fold that of corn residue (Figure 2.12). Soybeans average tissue N mass returned to soil was also not significantly affected by the N rate applied to the preceding corn crop; annual values ranged from 155 to 185 kg ha^{-1}.

Table 2.16. Annual mean ± standard error N concentrations in dry matter for each of the six cropping systems. Corn and soybean treatments were not significantly different. Background shading represents soybean years in the rotation system.

Year	CS 157 λ	SC 157	CS 135	SC 135	CC 180
	----------------------------Stover N g kg^{-1}	------------------------------			
1995	NR†	NR	NR	NR	NR
1996	NR	NR	NR	NR	NR
1997	7.85±0.63	9.72±0.64	5.80±0.42	9.56±0.44	6.70±0.23
1998	15.45±1.0	8.90±0.70	13.00±0.87	9.73±0.30	7.88±0.77
1999	9.85±0.26	11.53±0.89	8.80±0.21	9.50±0.46	9.48±0.34
2000	11.25±0.32	8.58±0.58	11.90±0.80	8.93±0.46	9.68±0.29
2001	8.83±0.50	NR	8.25±0.66	NR	9.15±0.82
2002	NR	8.20±0.72	NR	7.85±0.17	7.90±0.34
2003	7.28±0.57	NR	5.80±0.34	NR	6.23±0.41
2004	NR	6.38±0.34	NR	7.10±0.65	6.38±0.23
2005	7.93±0.26	NR	7.18±0.29	NR	6.80±0.45
2006	NR	7.35±0.60	NR	7.48±0.19	7.80±0.35
2007	NR	NR	NR	NR	NR
2008	NR	6.60±0.35	NR	6.75±0.50	5.78±0.24
2009	7.90±0.46	NR	8.48±0.58	NR	7.35±0.36
2010	NR	8.15±0.26	NR	8.90±0.20	7.85±0.27
2011	7.1±0.26	18.99±0.83	7.1±0.25	17.14±1.39	6.3±0.25
2012	23.95±1.67	18.1±0.22	24.81±1.00	17.2±0.21	18.0±0.33
2013	5.0±0.31	26.93±1.52	5.3±0.31	27.74±0.76	5.4±0.89
2014	27.79±0.71	16.6±0.22	28.44±0.67	16.4±0.14	16.2±0.07
2015	4.8±0.17	30.65±0.79	5.3±0.31	28.21±1.42	5.1±0.27
2016	27.73±0.50	9.9±0.08	28.54±1.95	10.1±0.16	9.7±0.18
2017	8.55±0.55	24.80±0.99	8.40±0.46	26.10±0.88	8.50±0.47
Corn Ave.	7.55±0.42 b	9.91±0.67 a	7.06±0.51 b	10.12±0.71a	8.42±0.44 b
Soy Ave.	21.21±0.85	22.63±1.01	21.32±0.99	21.8±0.88	

†NR corresponds to no record.

λ Cropping systems utilized abbreviated as: Prgass, perennial prairie grass; CS 157, tilled corn-soybean rotation corn planted first with 157 kg ha^{-1} N applied preplant; SC 157, tilled soybean-corn rotation soybean planted first with 157 kg ha^{-1} N applied preplant; CS 135, tilled corn-soybean rotation corn planted first with 135 kg ha^{-1} N applied sidedress; SC 135, tilled soybean-corn rotation soybean planted first with 135 kg ha^{-1} N applied sidedress; N applied sidedress; CC 180, tilled continuous corn with 180 kg ha^{-1} N applied preplant.

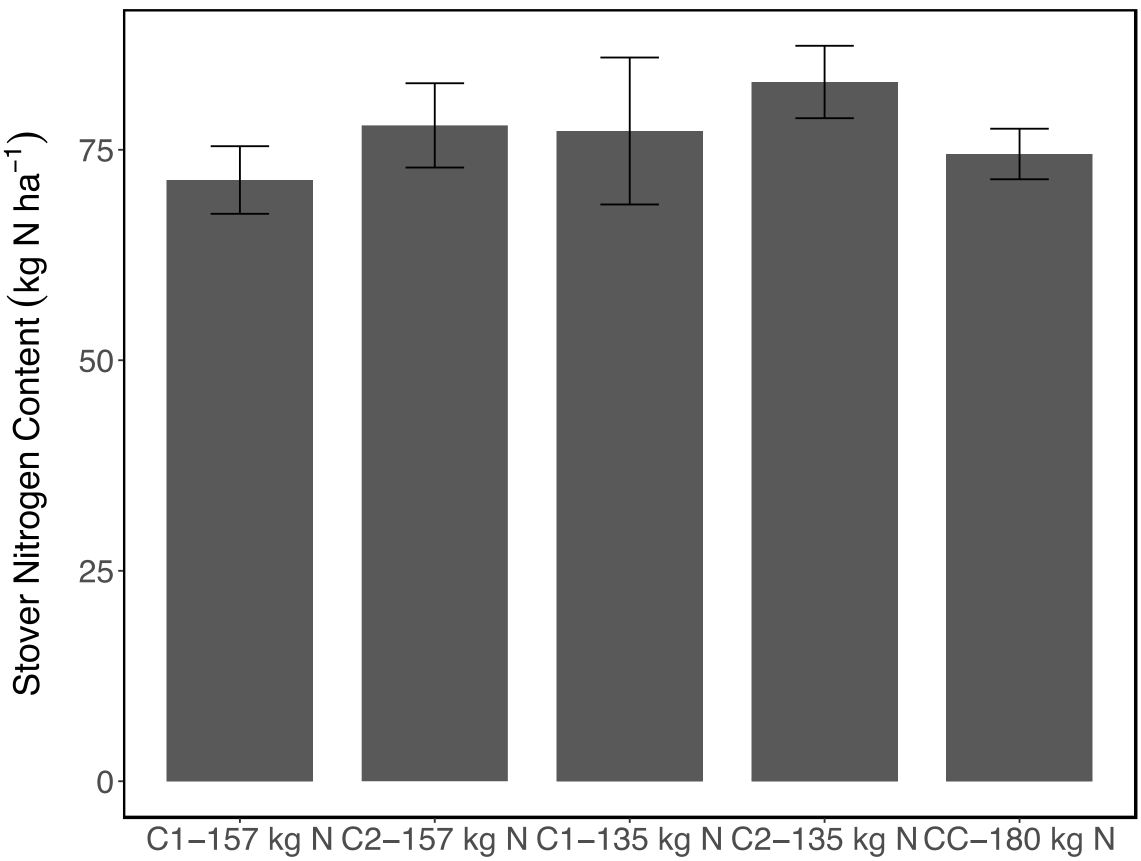

Figure 2.11.Mean ± standard error stover showing corn only. Continuous corn abbreviated as CC-180, corn-soybean abbreviated as C1 with corn planted first in the rotation, and soybean-corn abbreviated as C2 with corn planted first in the rotation. The number behind each treatment identifier corresponds to N rate applied (kg ha^{-1}). Treatments were not significantly different.

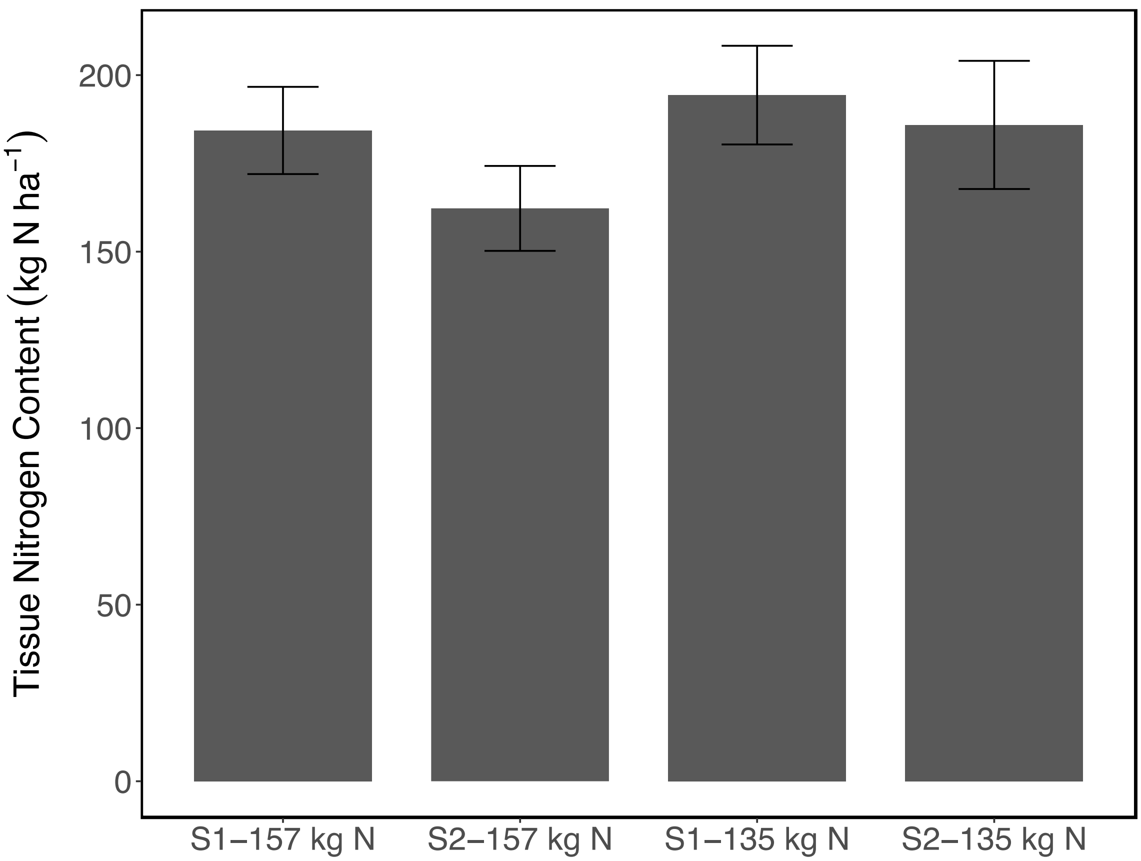

Figure 2.12.Mean ± standard error tissue N content showing soybean only. Corn-soybean abbreviated as S2 with soybean planted second in the rotation, and soybean-corn abbreviated as S1 with soybean planted first in the rotation. The number behind each treatment identifier corresponds to N rate applied (kg ha-1), no N was applied in soybean years.

2.3.8 Grain N Concentration and Content

Mean soybean N concentrations in the grain were not significantly different among annual cropping systems (Table 2.17). Soybeans grain N concentrations were approximately five-fold greater than that of corn grain N, regardless of treatment. Soybeans had a maximum 66.45 g N kg^{-1}, and a minimum of 53.26 g N kg^{-1} (Table 2.17). The highest average soybean grain N concentration across years was from CS-157 (61.98 g kg^{-1}), while the lowest average came from SC-157 (60.24 g kg^{-1}). Mean corn N concentrations in the grain (Table 2.17) were not significantly different among cropping systems. Corn had a maximum 14.28 g N kg^{-1}, and a minimum of 10.30 g N kg^{-1}. The highest average corn grain N concentration was from CC-180 (12.73 g kg^{-1}) while the lowest came from CS-135 (11.87 g kg^{-1}). Although not significantly different from each other the CC-180 tended to have the highest yearly mean grain N concentration when compared to rotational corn.

When grain N mass was calculated by multiplying grain N concentrations by dry grain yield there were significant differences by cropping system ($p \leq 0.001$). Post-hoc analysis concluded that C1-135 (91 kg ha^{-1}) had the lowest significant mean ($p \leq 0.05$), which was significantly lower than (Figure 2.14), C1-157 (102 kg ha^{-1}), C2-157 (104 kg ha^{-1}), C2-135 (1078 kg ha^{-1}), and CC-180 (97 kg ha^{-1}). Only C1-135 was significantly different, the other cropping system treatments were statistically similar with each other. Soybean grain N mass had significantly different cropping system means ($p \leq 0.0001$, Figure 2.13). The S1-135 cropping system mean was 159 kg ha^{-1}, and S1-157 cropping system mean was 154 kg ha^{-1} both cropping systems were not significantly different from each other ($p \leq 0.05$). However, S2-135 (198 kg ha^{-1}), and S2-157 (188 kg ha^{-1}) were significantly higher than the previously stated cropping systems, but were not significantly different from each other.

Table 2.17. Annual mean ± standard error N concentrations in grain for each of the six cropping systems. Corn and soybeans were not significantly different. Background shading represents soybean years in the rotation system.

Year	CS 157	SC 157	CS 135	SC 135	CC 180
	---------------------------Grain N g kg^{-1}				-------------------------------
1995	NR†	NR	NR	NR	NR
1996	NR	NR	NR	NR	NR
1997	NR	NR	NR	NR	NR
1998	66.38±0.45	NR	66.05±0.71	NR	NR
1999	13.50±0.27	62.58±0.47	13.58±0.26	61.05±0.21	13.48±0.36
2000	62.85±0.13	12.63±0.08	62.60±0.91	13.25±0.18	13.50±0.66
2001	13.43±0.17	65.05±0.32	13.05±0.39	64.83±0.39	14.30±0.62
2002	64.30±0.47	14.68±0.08	65.15±0.52	14.23±0.43	14.73±0.52
2003	13.53±0.42	NR	10.58±0.51	NR	13.15±0.73
2004	NR	10.30±0.68	NR	11.23±0.19	11.13±0.31
2005	13.98±0.49	62.93±0.46	12.88±0.77	62.45±1.61	14.28±0.53
2006	64.30±0.39	12.85±0.41	65.03±0.34	12.10±0.47	13.70±0.90
2007	13.70±0.40	62.23±0.65	12.88±0.11	63.18±0.57	14.23±0.52
2008	66.45±0.36	12.65±0.72	66.23±0.25	14.15±0.12	13.10±0.36
2009	10.43±0.30	61.85±0.43	10.70±0.52	62.20±0.39	10.60±0.51
2010	59.48±0.56	12.53±0.14	58.85±0.62	12.28±0.30	12.15±0.38
2011	12.55±0.38	59.55±0.99	12.25±0.19	61.60±0.12	11.95±0.27
2012	58.00±1.54	12.43±0.45	56.45±0.43	12.20±0.49	13.28±0.47
2013	12.02±0.36	55.78±0.60	11.32±0.17	55.04±0.71	11.96±0.29
2014	55.83±0.46	11.87±0.49	55.62±0.68	11.71±0.13	12.33±0.36
2015	10.58±0.46	55.67±0.17	10.70±0.30	53.26±2.86	10.34±0.50
2016	60.31±0.57	12.58±0.39	61.04±1.32	12.33±0.63	12.52±0.53
2017	10.74±0.26	56.94±1.32	10.80±0.48	56.39±1.23	11.22±0.36
Soy Ave.	61.98 ±0.69	60.24±0.62	61.88±0.74	60.44±0.88	-
Corn Ave.	12.44±0.32	12.50±0.42	11.87±0.57	12.60±0.40	12.73±0.43

†NR corresponds to no record.

λ Cropping systems utilized abbreviated as: Prgass, perennial prairie grass; CS 157, tilled corn-soybean rotation corn planted first with 157 kg ha-1 N applied preplant; SC 157, tilled soybean-corn rotation soybean planted first with 157 kg ha-1 N applied preplant; CS 135, tilled corn-soybean rotation corn planted first with 135 kg ha-1 N applied sidedress; SC 135, tilled soybean-corn rotation soybean planted first with 135 kg ha-1 N applied sidedress; N applied sidedress; CC 180, tilled continuous corn with 180 kg ha-1 N applied preplant.

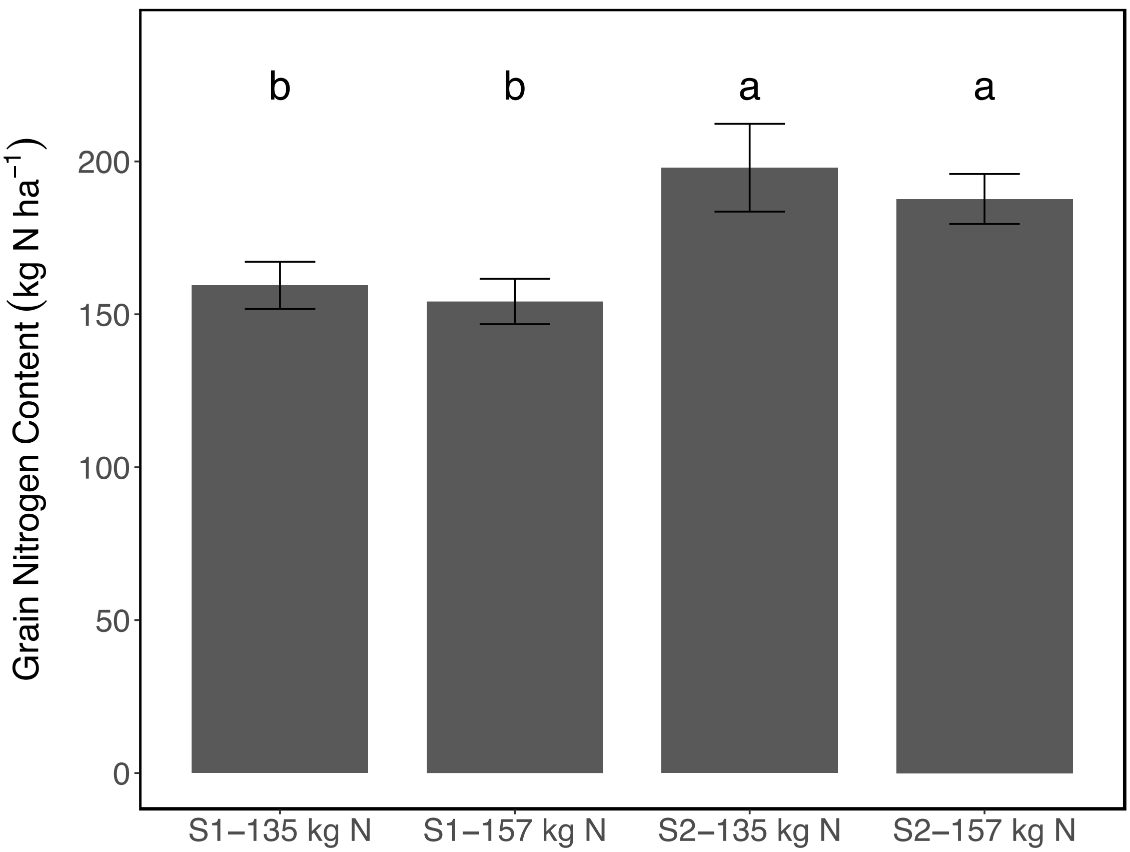

Figure 2.13.Mean grain N content showing soybean only. Corn-soybean abbreviated as S2 with soybean planted second in the rotation, and soybean-corn abbreviated as S1 with soybean planted first in the rotation. The number behind each treatment identifier corresponds to N rate applied (kg ha-1), no N was applied in soybean years. Letters denote significant (*p*<0.05) differences among treatments means using the Tukey HSD post-hoc test.

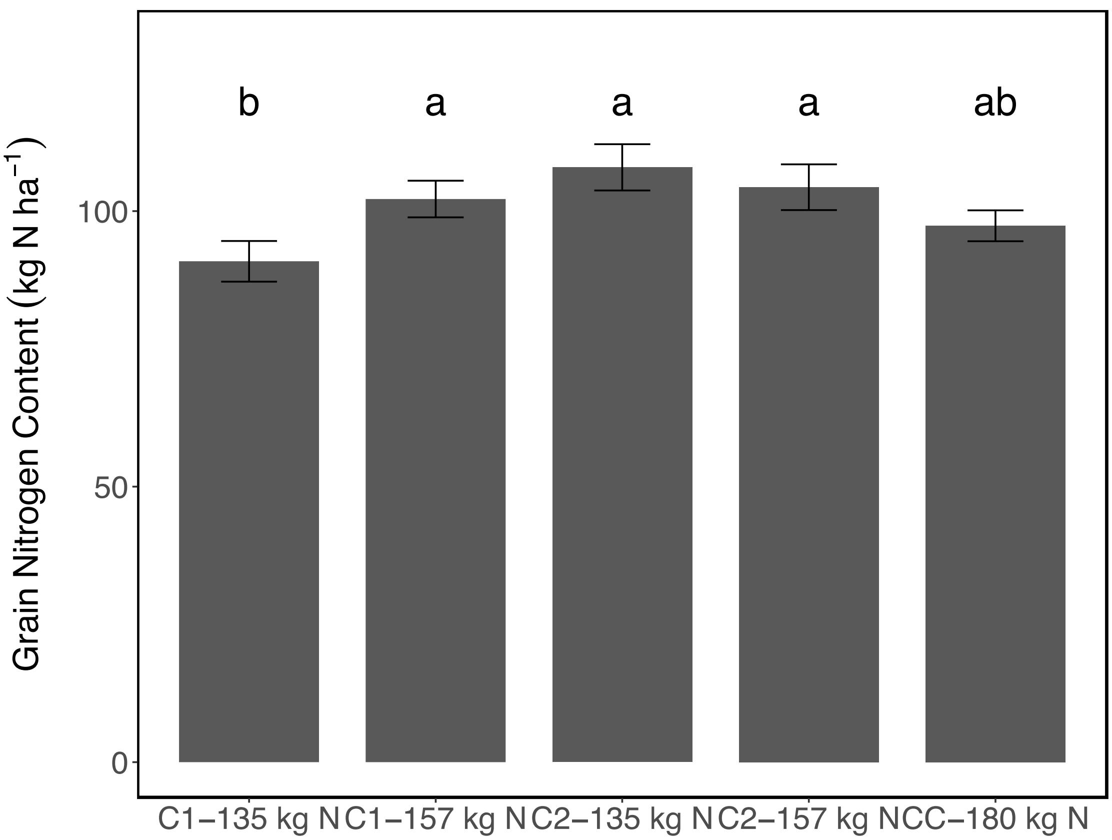

Figure 2.14. Mean grain N content showing corn only. Continuous corn abbreviated as CC-180, corn-soybean abbreviated as C1 with corn planted first in the rotation, and soybean-corn abbreviated as C2 with corn planted first in the rotation. The number behind each treatment identifier corresponds to N rate applied (kg ha_{-1}). Letters denote significant (p<0.05) differences among treatments means using the Tukey HSD post-hoc test.

2.3.9 Partial Mass Nitrogen Balance

A partial mass N balance was put together from the previously discussed parameters (Table 2.18). The estimated N balance suggests that a range of 40 to 95 kg N ha^{-1} may be left in the soil profile following either soybeans or corn. The estimated amount of N available after corn was found to range from 41 to 95 kg N ha^{-1}.

Table 2.18. Nitrogen mass balance calculated by subtracting N parameters outgoing the system from N parameters being input to the system. Note soybean BNF was not directly measured in our study, rather it was estimated.

		Nitrogen Mass Balance						
		----------kg ha^{-1}----------						
Cropping System λ	Crop	N Fertilizer Input	N Fertilizer Starter	Estimated BNF†	N Returned to Soil via Plant Material γ	N Removed in Grain	N Lost through Tile Drainage	Estimated N Balance
CS-157	Corn	157	23	0	72	102	14	64
	Soybean	0	0	250	155	188	13	49
SC-157	Corn	157	23	0	77	104	15	61
	Soybean	0	0	250	175	154	12	84
CS-135	Corn	135	23	0	77	91	12	55
	Soybean	0	0	250	177	198	12	40
SC-135	Corn	135	23	0	83	107	10	41
	Soybean	0	0	250	185	159	12	79
CC-180	Corn	180	23	0	74	97	11	95

† Estimated biological N fixation from university calculations (Ciampitti and Salvagiotti, 2018), actual BNF was not directly measured in this study.

λ Cropping systems utilized abbreviated as: Prgass, perennial prairie grass; CS 157, tilled corn-soybean rotation corn planted first with 157 kg ha^{-1} N applied preplant; SC 157, tilled soybean-corn rotation soybean planted first with 157 kg ha^{-1} N applied preplant; CS 135, tilled corn-soybean rotation corn planted first with 135 kg ha^{-1} N applied sidedress; SC 135, tilled soybean-corn rotation soybean planted first with 135 kg ha^{-1} N applied sidedress; N applied sidedress; CC 180, tilled continuous corn with 180 kg ha^{-1} N applied preplant.

γ N returned to soil via plant material was not included in the partial mass balance calculations.

2.4 Discussion

The overarching goal for our study was to determine if nitrogen (N) load loss in drainflow would be reduced in soybean-corn cropping systems as compared to continuous corn when N applications were reduced below currently recommended rotational corn rates (< 180 kg N ha^{-1}: by Vitosh et al., 1995). Our study included many of the same cropping treatments that have been previously examined (Hernandez-Ramirez et al., 2011a; Ruark et al., 2009) but these earlier studies examined only a 6-year subset of the data. This study included all available site-years of the treatments that have remained consistent since Water Quality Field Station (WQFS) establishment. The annual N load losses in drainflow observed in this 23-year data set are highly comparable to Hernandez-Ramirez et al. (2011a) in terms of no significant differences among cropping systems. However, the 23-year means in our study tended to be lower than the 6-year means reported in Hernandez-Ramirez et al. (2011a), and their means were reportedly 30% greater than ours. The annual N load results in our study were also similar to other studies in that significant differences among treatments with applied N fertilizer < 180 kg N ha^{-1} did not occur, which was also found in Illinois and Iowa, USA (Helmers et al., 2012; Jaynes, 2015; Pittelkow et al. 2017). However, Pittelkow et al., (2017) found that N rate effected N load lost in drainage flow if N is applied in excess of 180 kg N ha^{-1}, specifically- the probability of more N being lost is greater when comparing N rates as high as 234 kg N ha^{-1}. Pittelkow et al. (2017) also observed reduced N load losses when the majority of N was applied in the spring closer to crop demand when compared to fall N applications when using similar N rates as the ones utilized in our study.

No significant differences in cumulative N load among cropping systems were found when was analyzed across all years (Figure 2.7). However, the corn-soybean rotations with greater N applied (CS-157) tended to have greater but not significantly different cumulative means when compared to continuous corn (CC-180) and CS-135 tended to have lower load losses than both CS-157 and CC-180. In the greater context of this study, cumulative N load loss totals were relatively minor when compared to cumulative N fertilizer applications which occurred on each treatment for 23-years. On average, 8% of the applied N was lost through subsurface drainage across all crops and years in this study when N load lost in drainage flow was divided by fertilizer N applications, meaning that the other 92% was either recovered by crops, removed in grain, or maintained in soil. Ladha et al., (2005) reported that 63% of fertilizer N is recovered by maize globally and since we did not directly calculate fertilizer use efficiency in this study we would hypothesize we recovered more than that. Interestingly, our cumulative N load loss (Figure 2.7) demonstrated two different slope patterns over time. For the first seven years of this study (1995-2002) our data had a slope approximately greater than 50% greater than the slope for the subsequent years from 2003 to 2017. Annual flow tended to decline over time during these two periods (Appendix). Additionally, in 2001 a 6-inch lateral tile was installed on the west side of the field site which may have reduced drainage flow volumes by limiting lateral flow movement from outside the study area to inside. Seeing as this is the first long-term evaluation of the field-site since establishment more exploration into the cause of this relationship will need to be examined further.

When soybean and corn N load losses were separated by their representative N application rates a few interesting results were observed, which have not been reported in previous literature. The annual N load losses in the soybean phase of the two rotational systems were not significantly different in our study (Figure 2.5), indicating that previous corn crop's N rate made no impact on the amount of N lost in the soybean phase of a rotational system. Also, when corn phase was analyzed separately from soybean by N rate, the CS-157 treatment had the significantly highest N load loss, when compared to CC-180 which had approximately 23 kg ha^{-1} more N applied annually, and the CS-135 (Figure 2.4). Indeed, N load losses in CC-180 were not significantly different from load losses in the corn years of CS-135. This relationship is relevant because the highest applied N rate occurred in the CC-180, which had a lower mean cropping system N load loss than the CS-157, and this suggests that soybean biological nitrogen fixation (BNF) may be a major contributor to N load loss but primarily manifested in the corn year. Also, not only are the quantities of N returned to soil by soybean residue greater than the N returns with corn stover but the C:N ratios are substantially lower and mineralization of residues are expected to be faster according to Moser, (2016). Moser (2016) conducted a study and stated that corn N application carryover may not be occurring based upon soil N quantification in which they measured soil N changes throughout the growing season and found decreasing amounts residual N, meaning that N was lost throughout the growing season leading up to and directly after harvest in the same season. Scott (2015) studied N carryover from corn into the subsequent soybean year across various locations in Indiana, USA and found no significant N rate effect to soil N. They further concluded that any N not taken up by corn crop demand was susceptible to leaching and more than likely lost through the fallow period before soybean planting. Thus, soybean residue following harvest may also contribute to N load losses.

The analysis of variance (ANOVA) results from our study (Table 2.13) showed that N load was highly variable from year-to-year, a result similar to previous analyses of WQFS data (Hernandez-Ramirez et al., 2011a; Ruark et al., 2009). Year-to-year variability has been attributed to precipitation occurrence and amount (e.g. Vetsch et al., 2019). Although an in-depth analysis of N load by growing season and fallow period was beyond the scope of this study, when N load was plotted as a function of each day of year by cropping system for a preliminary visual analysis data within years' (time series not shown) it was evident that peak N load loss occurred typically after emergence when preplant or starter fertilizer begins to leach through the soil profile, and directly after crop senescence when crop demand for N ceases. This preliminary visualization of the data suggests that N fertilizer carryover from the previous corn crop to the subsequent soybean crop may occur, but not in quantities that may reflect N rate differences which has been discussed as the source of N losses in the soybean year (Pittelkow et al., 2017).

Flow-proportional N concentration means tended to be greater when more N was applied to rotational corn and CS-157 had a significantly higher mean than all other treatments (Figure 2.1). Vetsch et al. (2019) reported that N rate did not significantly increase mean N concentrations in drainage water when comparing rates <180 kg N ha^{-1} which is contrary to our results. It is relevant to note that their study included similar N rates as ours, but they also included N stabilizers, and fall/spring applications. Also, Vetsch et al. (2019) had four site-years in comparison to the 23 site-years in this study. Additionally, Randall and Mulla (2001) and Dinnes et al. (2002) both analyzed N concentrations in a soybean/corn rotations grown on soils described as high in organic matter and remarked that N mineralization, when accompanied by excessive N applications can lead to large quantities of mineral N in the soil solution that is readily susceptible to leaching. Vetsch et al. (2019) did not report their soil test data, but our soil organic matter generally ranged between 3.8 to 5.2% which would arguably be described as high organic matter soils. Organic matter, soil type, and climatic regime (Indiana vs. Minnesota) may best describe the differences that occurred in our study when compared to the study conducted by Vetsch et al. (2019), in which they found higher concentration means than what was reported in our study, but not significantly different N concentrations using comparatively similar N rates as ours (<180 kg N ha^{-1}).

Gast et al. (1978), Lawlor et al. (2008), Helmers et al. (2012), and Qi et al. (2012) all agree that N losses in drainflow are minimized when N rate is reduced below 234 kg N ha^{-1}. However, even at low N fertilizer rates (e.g. 157 kg ha^{-1}) seldom do these reduced load losses occur in conjunction with N concentrations below the drinking water standard (Christianson and Harmel, 2015). Helmers et al. (2012) utilized N rates ranging from 0 to 234 kg N ha^{-1} and Lawlor et al. (2008) had N rates ranging from 0 to 168 kg N ha^{-1}, whereas our study had N rates between 135 and 180 kg N ha^{-1}, plus 23 kg N ha^{-1} applied as starter at planting. Helmers et al., (2012) four-year mean N concentrations in drainflow when fertilizer was applied at 112 and 168 kg N ha^{-1} applied fertilizer rate in rotational corn were 11.5 and 11.8 mg L^{-1}, respectively. Our study contradicted this finding as in three out of five cropping systems had mean N concentrations below the USEPA standard of 10 mg L^{-1}. The two cropping systems with mean drainflow N concentrations greater than the drinking water standard of 10 mg L^{-1} were from CS-157 and CC-180 which had the most amount of N applied to our plots annually (Figure 2.1). Regardless, given that soil is highly variable and precipitation is an uncontrollable factor, our data suggests that there may be a relative floor to the amount of N that can be recovered by the crop, i.e. N rate management will only reduce edge-of-field associated N losses so far which was also concluded by Pittelkow et al. (2017). Pittelkow et al. (2017) further concluded that reducing spring applied corn N rates to approximately 156 kg N ha^{-1} provided sufficient yield when compared to a fall applied N rate of 234 kg N ha^{-1}. Study differences among previous literature reports for N concentrations in drainflow frequently occur. This is noteworthy because it demonstrates the value in long-term data sets that encompass a wide variety of growing conditions and precipitation amounts to accurately describe N rate management within cropping system studies.

No significant drainage flow differences occurred among the rotational soybean-corn systems, continuous corn system, and the prairie control (Figure 2.2), a finding similar-to previous work at this research site (Hernandez-Ramirez et al., 2011a; Ruark et al., 2009). In addition, Vetsch et al. (2019), found no significant drainage flow differences among N treatments in corn, but did produce a significant drainage flow treatment response in one soybean year from their 4-year study. However, it should be noted that these differences may have been due to annual precipitation within that given year, not a treatment effect, as noted by Vetsch et al. (2019). Likewise in a meta-analysis conducted by Christianson and Harmel (2015a); they concluded that studying corn-soybean rotations as a single system is necessary given no significant flow differences occurred when crops were analyzed separately. It is also relevant to note, in our study that tile-to-tile drainage flow variation was prominent across all cropping system replicates, and each tile showcases different behavior which has been documented by another research site (Pittelhow et al., 2017).

In their 40 site-year, meta-analysis of tile drainage studies, Christianson and Harmel, (2015a) found annual drainage flow volumes increased with increased amounts of annual precipitation. However, we did not find a relationship between drainflow volumes and annual precipitation (Appendix). It is important to note Christianson and Harmel (2015a) reported that N load increases when annual precipitation is above 850 mm and N application rates to corn are above ~150 kg ha^{-1}. Given our N rates were based on current recommendations or were greater than this 150 kg N ha^{-1} threshold, a more granular analysis of our data by season or event may be needed to uncover direct effects of precipitation on drainflow and, thus, load loss. It is interesting to note; however, a majority of our annual rainfall totals were greater than the 850 mm rule of thumb identified by Christianson and Harmel (2015a) (Table 2.4). Finally, Christianson and

Harmel (2015a) synthesized their data from a database constructed from true field site research designs not inclusive of lysimeters, and synthesis would often group similar N rates together, an analytical strategy to synthesize various study designs such as: varied tile spacing's, N rates, climatic regimes, and environments. In contrast, our research was synthesized from the same research site using treatments that were fixed from year-to-year so less variation may exist in our study compared to the study conducted by Christianson and Harmel (2015a).

Our analysis signified N concentration dilution did not occur in years with higher flow volumes when a log flux-flow regression was performed by treatment (Figure 2.6). This finding agrees with previous research at this field site when similar treatments were utilized over a shorter duration of time (Long, 2015). Long (2015) found slopes in their 5-year study for CC-180, CS-135, and SC-135 to be 0.65, 1.15, 0.80, respectively. Our study used these same treatments over 23-years and found slopes to be 1.01, 1.06, and 1.01 for CC-180, CS-135, and SC-135, respectively. In our study, slopes were found not be different from nor each other. In the Long (2015) study, CC-180 was found to be significantly lower than CS-135 and SC-135. The noted differences in our flux-flow analysis from the same field-site may be attributed to a larger sample size which fully characterized the relationship over a greater number of site-years.

Helmers et al. (2012) and Pittelkow et al. (2017) both agreed that greater corn yield was not achieved by applying excessive amounts of N (>200 kg N ha^{-1}). Pittelkow et al. (2017) had spring and fall N applications as high as 234 kg N ha^{-1} in a soybean-corn rotation. While our study did not include a N rate that high we did achieve similar grain yield in rotational corn when comparing preplant vs. sidedress applied fertilizer (Table 2.14). Christianson and Harmel (2015a) concluded that grain yield was equivalent when N was applied > 2 months (168 kg N ha^{-1}) before planting and when N was applied pre-plant < 2 months (200 kg N ha^{-1}) before planting. Moreover, Christianson and Harmel (2015a) also concluded that grain yield for pre-plant <2 months (200 kg N ha^{-1}) was significantly greater than N applied at planting (152 kg N ha^{-1}) and when side dressed (160 kg N ha^{-1}). In our study, mean corn grain yields were not significantly different among treatments, meaning that neither N application rate nor timing influenced cropping system grain yield. Our lack of response in grain yields to N application management is not a surprise considering the highly productive Drummer and Raub soil series that dominate the experimental site which more than likely provides ample amounts of plant available N. Jaynes (2015) demonstrated in an Iowa, USA study that when current recommended N rates (~180 kg ha^{-1}) were utilized, grain yield was statistically equivalent or in some cases greater in comparison to higher N rates or even fall applied nitrogen. Vetsch et al. (2019) concluded that N concentrations and loads may be reduced in situations where N fertilizer is applied to soybean-corn cropping systems at the recommended spring rate (134 kg N ha^{-1}), and grain yield was reportedly similar to a fall application rate of 180 kg N ha^{-1}. In short, numerous studies agree that applying N in season, especially closer to the time of peak crop N demand, at reduced rates may sufficiently reduce environmental impacts while maintaining sufficient yield.

The previous corn's N rate had no statistical influence on the subsequent soybean yield. Vetsch et al. (2019) also found no rotational soybean yield response to previous corn crop N management. In their study, N rate, application timing, and nitrapyrin N stabilizer were studied in rotational soybean-corn. Ciampitti and Salvagiotti (2018) found that soybean fixed a maximum of 372 kg N ha^{-1} which is added to the soil system. Seeing how soybean can fix their own N it not surprising that soybean grain yield was not significantly different among treatments.

Yield-scaled N losses were one way to determine cropping system efficiency, and were grouped as so (Figure 2.10). The ANOVA found insignificant differences in yield-scaled N load losses. However, rotational systems tended to contain higher yield-scaled N loss means when compared to continuous corn. The rotational systems were greater due to lower soybean grain yields when compared to corn grain yields, but both soybeans and corn contained similar N loss loads through tile lines. Vetsch et al. (2019) calculated yield-scaled N load losses and found one significant difference in one year among four total years when data were analyzed between years. However, similar to our results, no significant differences occurred among treatments. Vetsch et al. (2019) further concluded that in their study precipitation amount and timing was the plausible explanation for one significant yield-scaled N load year.

Creating a complete mass N balance in this study was not possible as we did not measure BNF production by soybean. However, utilizing an N rate (CS-135) currently below the recommended rotational N rate for Indiana (CS-157) it was observed that no additional grain yield was observed when compared. This suggests that the additional applied N fertilizer in rotational systems was not necessary to achieve sufficient grain yield when averaged across 23-years. Although CS-157 was applied as preplant and CS-135 was applied as sidedress it was noticed that the two treatments were typically applied within a few weeks from each other meaning they could be coupled to designate an N rate effect for annual load losses (Table 2.3). Given that N load losses in drainage for CS-157 was statistically greater than CS-135 when corn was analyzed separately from soybean it is evident that too much N was applied in CS-157 (Figure 2.4). Additionally, our analysis of grain N concentrations in corn (Table 2.17) demonstrated no significant differences among treatments regardless of N rate. However, a study conducted by Brouder et al., (2000) reported grain N concentration critical values for induced N deficiency in corn and based upon the grain N concentrations in our study the CS-135 treatment was nearing N deficiency. In conclusion, tailoring N rate recommendations to satisfy both yield and water quality goals are difficult regardless of methodology (Morris et al., 2017). Thus, our current N recommendations are sufficient and reducing them further may not reduce edge-of-field associated N load losses. Given our highly productive soils at WQFS it is recommend that producers implement N rate yield trials on their specific fields to determine if yield is not sacrificed when adhering to N fertilizer rates below the current standard.

2.5 Summary and Conclusions

Objective 1 of this study was to compare the quantities and qualities of N load loss in two rotational corn N rate systems with continuous corn, and a restored prairie. Soybean-corn rotations demonstrated that they are just as much of an environmental concern as continuous corn when existing N management recommendations are followed. Nitrogen fertilizer applications occurred every other year in these rotational systems and they had comparatively similar N loads as continuous corn which had 200 kg N ha^{-1} applied. In this study, 23-year mean N load losses were not significantly different among the annual cropping systems, but they were all significantly higher than in the restored prairie control. Having the prairie control allowed for us to demonstrate the impact that intensively fertilized annual row crops have on edge-of-field associated N load losses since the annual row crops were approximately 12-fold greater than the prairie control.

Objective 2 of this study was to determine when cummulative soybean-corn N drainage mass may surpass that of continuous corn over time. Although no significant differences occurred between cropping systems for cumulative N load losses the CS-157 treatments tended to have a greater impact on cumulative load loss when compared to continuous corn. An argument could be made that soybean BNF carryover is driving this finding, but it would be pure speculation until additional analysis can be conducted.

Objective 3 was to evaluate the current recommended N credits from the dual perspective of crop productivity and protection of water quality. We observed no significant grain yield differences regardless of N rate in both corn and soybeans. Additionally, 23-year mean N load loss results were not significantly different from each other. These two results suggest that more in-depth research is critical for understanding soybean's role in supplementing N to the subsequent corn crop- specifically, evaluate when the most N is being lost within the soybean phase of rotational systems.

Outside of N rate management, producers should consider; cover cropping highly erodible land, around surface tile risers, and along drainage ditches which may reduce the movement of nutrients to edge-of-field. Additionally, installing controlled drainage to impede water movement during vulnerable times (e.g. during the fallow period) may mitigate nutrient losses to water. Lastly, producer utilization of variable rate technology and the 4R's (right rate, right timing, right source, right place) coupled with routine soil fertility testing would help place essential nutrients where they are needed.

A few limitations occurred in this study. Data loggers would temporarily fail creating gaps in the flow data. Flow data was calculated from tipping bucket sensors, but a small portion of the data record was lost and no attempt to gap fill the missing flow volumes was made. Ultimately, this means that even in a data record this large we may be underestimating true N load losses across each cropping system. Additionally, N concentration data was gap filled when no N concentration subsample was collected, but N loss evidently occurred, by matching concentration values to flow values within a 4-day window with no reported concentration to ensure a representative N load for each treatment. Observed concentration values are preferred to gap filled, but unfortunately grab samples were not occasionally taken and/or data may have been lost during lab analysis. Lastly, our data was collected across multiple site-years, but only one site location was utilized in this study. Additional field sites may possess different soil types, climatic regimes, and water table depths which may affect our results. It would be difficult to replicate and manage any additional field sites in detail like WQFS without dedicated personnel.

2.6 Future Considerations

Within years there are some notable precipitation patterns which raises concern for increased drainage flow. For example, in 2001 there was 227 mm of precipitation which occurred in October which is generally outside of crop demand. Additionally, 2007, 2016, and 2017 had on average 135, 135, and 125 mm of precipitation in November respectively. These high precipitation months may have carried substantial amounts of N through the soil profile. Alternatively, 1999, 2002, and 2012 experienced lower than normal mean November precipitation values of 27, 29, and 13 mm respectively, which may have left substantial residual N in the soil profile. Although, precipitation was found not to be a major driver of N load loss on an annual basis these observations should be investigated further in more granular fashion. Additionally, mean monthly temperature values were reported in November for 2001, 2015, and 2016 which would prolong biological activity in soil meaning the conversion of N was still actively occurring. Lower monthly mean reported temperature values for 1995, 1996, and 2002 would slow biological activity, which in return, would slow the conversion of organic N to inorganic N meaning that more N may not have been converted to a leachable form. Aggregating similar precipitation and temperature conditions within year as covariate data may enhance our understanding of when peak N load losses occur leading to better management practices to mitigate N load losses.

Lastly, future research with this data record should investigate seasonal time-series trends, the specific behavior of corn and soybeans after large drainage events, and responses during drought periods. Aggregating wet versus dry years for each crop within their respective system, and conducting ANOVA statistics would supplement our understanding of how crops respond to varying growing conditions.

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APPENDIX

Soil Description 1

Location: Purdue Agronomy Research Station, Water Quality Field Station.

Tipton till plain physiographic region, S ½, E ½, SW ¼, NW ¼, Sec 28, T24N, R5W.

Landform, depression Soil Delineation, Drummer Soils

Soil series of Pedon, description fits Drummer

Soil Classification, fine-silty, mixed, mesic Typic Endoaquoll, Drainage Class, poorly drained

A1- 0 to 5 cm; black (10YR 2/1) silty clay loam; moderate fine and medium granular structure; firm; many fine and medium roots; clear smooth boundary.

A2- 5 to 12 cm; black (10YR 2/1) silty clay loam; moderate medium and thick platy structure; firm; many fine and medium roots; clear smooth boundary.

A3- 12 to 29 cm; (10YR 2/1) silty clay loam; moderate fine and medium sub-angular blocky structure; firm; many fine and medium roots; gradual wavy boundary.

A4-29 to 42 cm; very dark gray (10YR 3/1) silty clay loam; moderate medium sub-angular blocky structure; firm; many fine and medium roots; gradual wavy boundary.

Bg1-42 to 51 cm; dark grayish brown (2.5Y 4/2) silty clay loam; few medium distinct light yellowish brown (2.5Y 6/4) mottles; moderate medium sub-angular blocky structure; firm; few fine roots; common fine and medium pores; thin continuous dark grayish brown (2.5Y 4/2) clay films on face of peds; many thin continuous black (10YR 2/1) organic coatings on faces of peds and on surfaces of root channels; gradual wavy boundary.

Bg2-51 to 70 cm; grayish brown (2.5Y 5/2) silty clay loam; few medium distinct olive yellow (2.5Y 6/6) mottles; moderate medium prismatic structure parting to moderate medium sub-angular blocky; firm; few fine roots; common fine and medium pores; thin continuous very dark grayish brown (10 YR 3/2) clay films on faces of peds; many thin continuous black (10YR 2/1) organic coatings on faces of peds and on surfaces of root channels; gradual wavy boundary.

Bg3- 70 to 82 cm; grayish brown (2.5Y 5/2) silty clay loam; common medium prominent brownish yellow (10YR 6/8) mottles; weak medium prismatic structure parting to moderate sub-angular blocky; firm; many black (10YR 2/1) organic coatings on surface of root channels

2Bg4-82 to 113 cm; grayish brown (2.5Y 5/2) clay loam; many medium prominent brownish yellow (10YR 6/8) mottles; moderate medium sub-angular blocky structure; firm; patchy grayish brown (2.5Y 5/2) clay films on surfaces of peds; many black (10YR 2/1) organic coatings on surface of root channels; thin continuous carbonate coatings on faces of peds.

2C-113 to 147 cm; light olive brown (2.5Y 5/4) loam and clay loam; common medium distinct gray (2.5Y 6/1) mottles; massive structure; strongly effervescent.

Soil Description 2:

Location: Purdue Agronomy Research Station, Water Quality Field Station.

Tipton till plain physiographic region, S ½, E ½, SW ¼, NW ¼, Sec 28, T24N, R5W.

Landform, swell, Soil Delineation, Raub-Brenton Complex 0 to 1 percent slope

Soil series, more like Throckmorton soil with a mollic epipedon

Soil Classification, fine-silty, mixed, mesic Typic Argiudoll, Drainage Class, well drained

A1-0 to 8 cm; black (10YR 2/1) silty clay loam; weak fine granular structure; firm; many fine and medium roots; clear and smooth boundary.

A2-8 to 20 cm; black (10YR 2/1) silty clay loam; weak medium platy structure; firm; many fine and medium roots; clear smooth boundary.

A3-20 to 37 cm; dark brown (10YR 3/3) silty clay loam; few medium faint dark yellowish brown (10YR 4/4) mottles; moderate medium sub-angular blocky structures; firm; many fine and medium roots; thin patchy black (10YR 2/1) clay films on faces of peds; gradual wavy boundary.

Bt1-37 to 60 cm; dark yellowish brown (10YR 4/4) silty clay loam; common medium distinct brownish yellow (10YR 6/6) mottles; moderate medium sub-angular blocky structure; firm; many fine roots; thin continuous light olive brown (2.5Y 5/4) clay films on faces of peds; thin continuous black (10YR 2/1) organic coatings on surfaces of root channels; gradual wavy boundary.

Bt2-60-84 cm; dark yellowish brown (10YR 4/4) silty clay loam; common medium distinct brownish yellow (10YR 6/6) mottles; moderate medium sub-angular blocky structure; firm thin continuous dark grayish brown (10YR 4/2) clay films on faces of peds; gradual wavy boundary.

2Bt3-84 to 104 cm; brown (10YR 5/3) clay loam; common medium prominent brownish yellow (10YR 6/8), and common fine faint grayish brown (10YR 5/2) mottles; weak medium sub-angular black structure; firm; few fine black (10YR 2/1) manganese accumulations; continuous carbonate coatings on faces of peds; gradual wavy boundary.

2C-104 to 180 cm; light olive brown (2.5Y 5/4) loam; common medium distinct brownish yellow (10YR 6/6), and common medium distinct gray (2.5Y 5/1) mottles; massive structure; continuous carbonate coatings on faces of fractures; gradual wavy boundary; strongly effervescent.

Regression Analysis: MeanFlow versus Precip

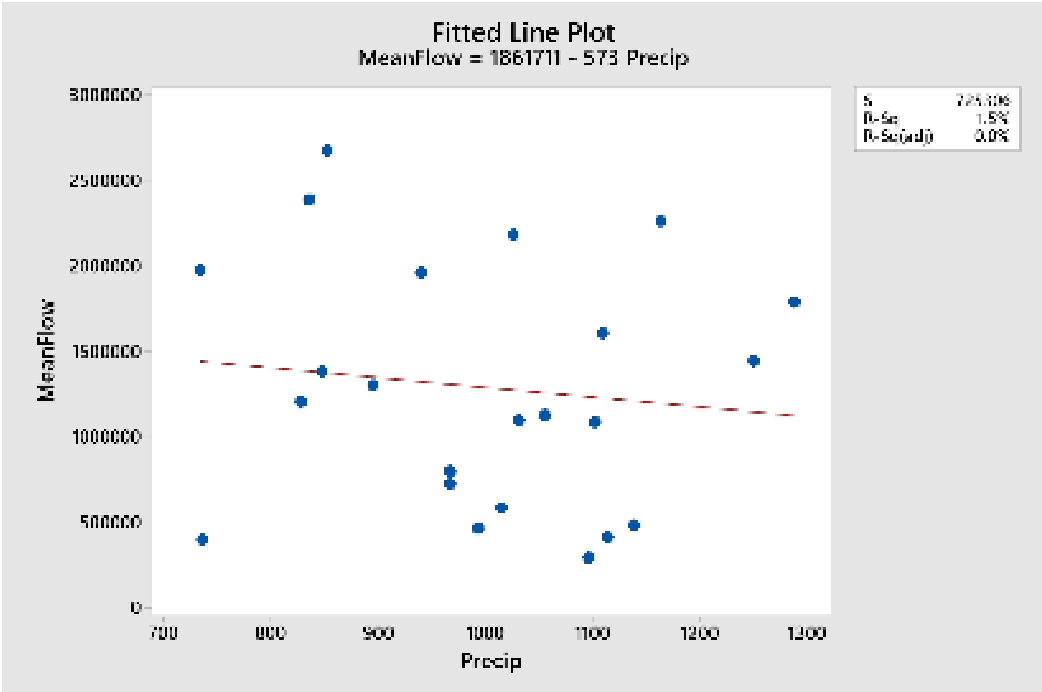
The regression equation is
MeanFlow = 1861711 - 573 Precip

Model Summary

S	R-sq	R-sq(adj)
725306	1.46%	0.00%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1.63640E+11	1.63640E+11	0.31	0.583
Error	21	1.10474E+13	5.26069E+11		
Total	22	1.12111E+13			



Regression Analysis: MeanLoad versus Precip

The regression equation is

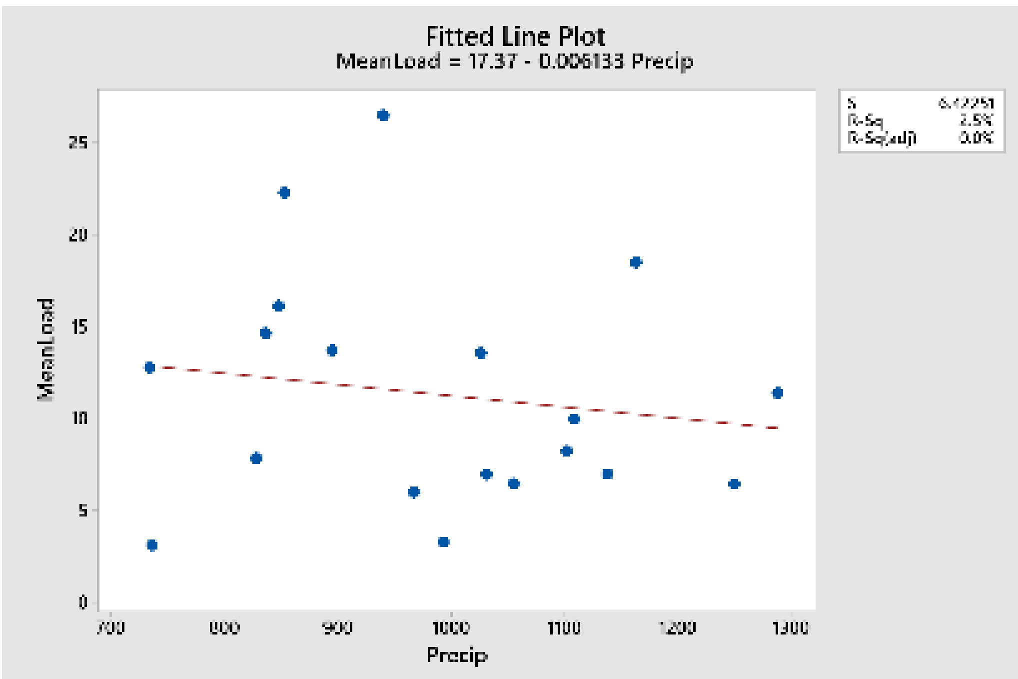
MeanLoad = 17.37 - 0.006133 Precip

Model Summary

S	R-sq	R-sq(adj)
6.42251	2.48%	0.00%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	17.798	17.7975	0.43	0.520
Error	17	701.226	41.2486		
Total	18	719.023			



Regression Analysis: MeanLoad versus MeanFlow

The regression equation is

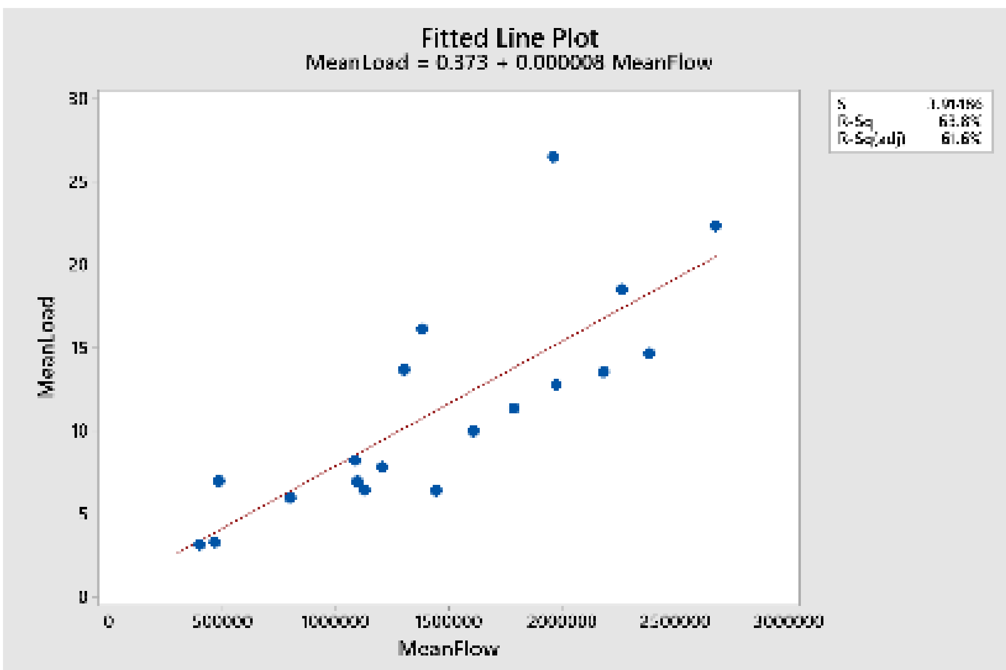
MeanLoad = 0.373 + 0.000008 MeanFlow

Model Summary

S	R-sq	R-sq(adj)
3.91486	63.76%	61.63%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	458.479	458.479	29.91	0.000
Error	17	260.544	15.326		
Total	18	719.023			



Regression Analysis: MeanFlow versus year

The regression equation is

MeanFlow = 1.34E+08 - 66176 year

Model Summary

S	R-sq	R-sq(adj)
568176	39.53%	36.65%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	4.43180E+12	4.43180E+12	13.73	0.001
Error	21	6.77929E+12	3.22823E+11		
Total	22	1.12111E+13