DEVELOPMENT OF SENSOR-BASED NITROGEN RECOMMENDATION ALGORITHMS FOR CEREAL CROPS

by

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B.A., Kansas State University, 2008
B.S., Kansas State University, 2010

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agronomy
College of Agriculture

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Abstract

Nitrogen (N) management is one of the most recognizable components of farming both within and outside the world of agriculture. Interest over the past decade has greatly increased in improving N management systems in corn (*Zea mays*) and winter wheat (*Triticum aestivum*) to have high NUE, high yield, and be environmentally sustainable.

Nine winter wheat experiments were conducted across seven locations from 2011 through 2013. The objectives of this study were to evaluate the impacts of fall-winter, Feekes 4, Feekes 7, and Feekes 9 N applications on winter wheat grain yield, grain protein, and total grain N uptake. Nitrogen treatments were applied as single or split applications in the fall-winter, and top-dressed in the spring at Feekes 4, Feekes 7, and Feekes 9 with applied N rates ranging from 0 to 134 kg ha^{-1}. Results indicate that Feekes 7 and 9 N applications provide more optimal combinations of grain yield, grain protein levels, and fertilizer N recovered in the grain when compared to comparable rates of N applied in the fall-winter or at Feekes 4.

Winter wheat N management studies from 2006 through 2013 were utilized to develop sensor-based N recommendation algorithms for winter wheat in Kansas. Algorithm RosieKat v.2.6 was designed for multiple N application strategies and utilized N reference strips for establishing N response potential. Algorithm NRS v1.5 addressed single top-dress N applications and does not require a N reference strip. In 2013, field validations of both algorithms were conducted at eight locations across Kansas. Results show algorithm RK v2.6 consistently provided highly efficient N recommendations for improving NUE, while achieving high grain yield and grain protein. Without the use of the N reference strip, NRS v1.5 performed statistically equal to the KSU soil test N recommendation in regards to grain yield but with lower applied N rates.

Six corn N fertigation experiments were conducted at KSU irrigated experiment fields from 2012 through 2014 to evaluate the previously developed KSU sensor-based N recommendation algorithm in corn N fertigation systems. Results indicate that the current KSU corn algorithm was effective at achieving high yields, but has the tendency to overestimate N requirements. To optimize sensor-based N recommendations for N fertigation systems, algorithms must be specifically designed for these systems to take advantage of their full capabilities, thus allowing implementation of high NUE N management systems.

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I also wish to say thank you to all my fellow graduate students Andrew Tucker, Matthew Wyckoff, Jason Matz, Timothy Foster, Nick Ward, Josh Stamper, and Holly Weber. These guys made working 16 hour days a good time. We would always take the time to scout fields and "Play Agronomist" which was challenging, but we worked together to make each other the best agronomists we could be. We established life long friendships, and even though our graduate studies are complete, we still maintain close ties and "Play Agronomist".

Dedication

This is dedicated to my wife, Miranda, our two daughters, Amira and Rosalie, and of course, my bulldog Betty. It's been a long journey to get here, but I would not change it. There was a time when I would say I made more mistakes than right choices. Looking back now, it was those "mistakes" that took me down the right path. It was your patience, encouragement, and dedication that made all we have achieved possible. My girls would always bring me coffee and food during the late nights, and Betty would always be at my side as I worked to develop new algorithms. This Ph.D. goes beside my name but it is an achievement that belongs to all of us. Amira and Rosalie, through determination and the support of those close to you, you can achieve anything. Never believe in the word "impossible."

Chapter 1 - Nitrogen in Agriculture: A Review of Literature

Discovering Nitrogen

Nitrogen (N), one of 115 known elements on earth, number seven on the periodic table for its atomic number, is the giver of life on this planet. The existence of N was first discovered and published by Scottish Botanist Daniel Rutherford in 1772 when he removed oxygen and carbon dioxide from air and isolated N_2, an inert gaseous form of N. Further research on N resulted in N_2 being called "burnt air" since N_2 remains after oxygen is used in the combustion process for fire. In 1786, scientist Antoine Laurent de Lavoisier termed N as "azote", which translates to "lifeless" (Britannica, 2015). Laurent's reasoning for calling N "lifeless" revolved around the fact that humans do not breath N, they breathe oxygen, and therefore N cannot support life. However, Antoine Laurent's unknowing reference to N to being lifeless could not be further from the truth. The production of many proteins in plants, humans, and all manner of life on earth are dependent upon N. Scharf (2015) states, "Many nitrogen-containing molecules are so crucial that death results if just one of them is absent or prevented from working". Therefore, it is more appropriate to say, "Without N, the earth would be lifeless".

Harnessing Nitrogen for Agriculture through Science

Nitrogen is one of 14 essential mineral nutrients required for plant growth. Of the three primary macronutrients (N, phosphorus (P), and potassium (K)), N is used in the largest quantity for most cereal crops. For this reason, N is often considered the most yield-limiting factor in agriculture, with the exception of water. Although N is abundant in the earth's atmosphere, plant-available forms of N are not. There are four commonly found forms of N on earth's surface:

1. N_2 (gas)
2. Organic N (proteins, amino acids, etc)
3. Nitrate (Inorganic N), plant available form
4. Ammonium (Inorganic N), plant available form

Ultimately the next question is, "How much N is actually plant-available?" considering only the N in the earth's soil surface and atmosphere, not including the mantle. Approximately 78% is found in the atmosphere as N_2 gas. The remaining 22% is found in the soil as organic and inorganic N. Considering only soil N, 97% is in the organic form, only leaving 3% in the plant-available inorganic form (IPNI, 2006; Scharf, 2015). Now we must ask, "What role does N_2 gas have and how is it harnessed? Who brings this form of N to the soil for plants? What is the purpose of organic N?"

The Nitrogen Cycle

N_2 gas in the atmosphere serves as our reservoir of N waiting to be utilized for building life and is the primary source for soil N (Stevenson, 1982). The first to discover and harness N_2 gas from the atmosphere was not human by a long shot. Bacteria discovered in fossils that date nearly 3.465 billion years old possessed the heterocyst-like structures necessary to fix N_2 gas and convert it to organic N similarly to our modern day cyanobacteria (Schopf, 1993; Postgate, 1998). This chemical conversion of N_2 gas to organic N is termed "Nitrogen Fixation". Nitrogen-fixing bacteria built the bridge for transferring N from the huge N reservoir in the atmosphere to the soil in the form of organic N. Nearly one billion years ago, symbiotic relationships between N-fixing bacteria and some higher eukaryotic life forms such as plants, fungi, and algae began to form (Barns and Nierzwicki-Bauer, 1997). Thus, these N-fixing bacteria converted N_2 gas and provided N to the plant in exchange for other photosynthates, further facilitating the rapid expansion of life on earth.

However, for the plant life that could not form symbiotic relationships with N-fixing bacteria, reliance on ammonium and nitrate forms of N remained. With potentially 3.465 billion years of N fixation occurring and filling the soil with a large organic pool of N, the next conversion necessary was the conversion of organic to inorganic N. This particular process is more straightforward and only requires death. Death and decomposition of free N-fixing bacteria, plant residue, and of all forms of life resulted in the build-up of soil organic matter. Other types of microorganisms called "decomposers" facilitate the decomposition of organic matter in the soil and change organic N into inorganic N. This process is referred as "Nitrogen Mineralization", the next bridge to transfer organic N to plant-available inorganic N. During N mineralization, organic N is first converted to ammonium by the process called "ammonification", and then ammonium is later oxidized to nitrate by "nitrification" (Stevenson, 1982).

With a stream of N feeding into the inorganic pool, plants and other microorganisms are free to utilize inorganic N, and this process is termed "assimilation" for plants and "immobilization" for microorganisms. With enough inorganic N available, plants and microorganisms will be able to live their full life cycle, reproduce, then die and allow the organic N to be converted back to inorganic N through mineralization for reuse (Bartholomew, 1965).

With the N reservoir in the atmosphere constantly utilized as an N source for the soil, there needs to be a means of protecting the N pool in the atmosphere. Nitrate that reaches water-saturated soils or water bodies such as the ocean will be subjected to a process called "denitrification" by heterotrophic bacteria. Denitrification results in the stepwise conversion of inorganic nitrate through a series of intermediate products such as NO_2, NO, and N_20 to the gaseous N_2 form, which then returns to the atmosphere to replenish the N pool in the atmosphere.

This overall process is known as "The Nitrogen Cycle" and is one of nature's marvels and that reflects a self-sustaining N fertilization system for plants and microorganisms in the soil. When earth was inhabited with low human populations, the natural N cycle provided enough fertilization of inorganic N to feed the world. However, as time progressed and human populations grew, it became necessary to increase N fertilization to plants in order to produce enough food to support the escalating human population.

Industrializing Nitrogen Fixation for Agriculture

In the early 1900's, it became clear that humans needed to harness N_2 gas by developing a form of N fixation in order to create N fertilizers to increase food production to support the expanding 1.6 billion people on earth. By 1910, a German chemist, Fritz Haber, developed a method to synthesize ammonia from N_2-N and hydrogen. In 1931, Carl Bosch refined the process for large-scale production. The Haber-Bosch process resulted in industrial production of N fertilizers (Britannica. 2015). How critical was the industrialization of N fixation to human life? According to Vaclav Smil (2001), 40% of the current human population would not be alive today if N fixation process such as Haber-Bosch were not discovered for making N fertilizers. Figure 1-1 shows the current state of the N cycle including the human N fixations.

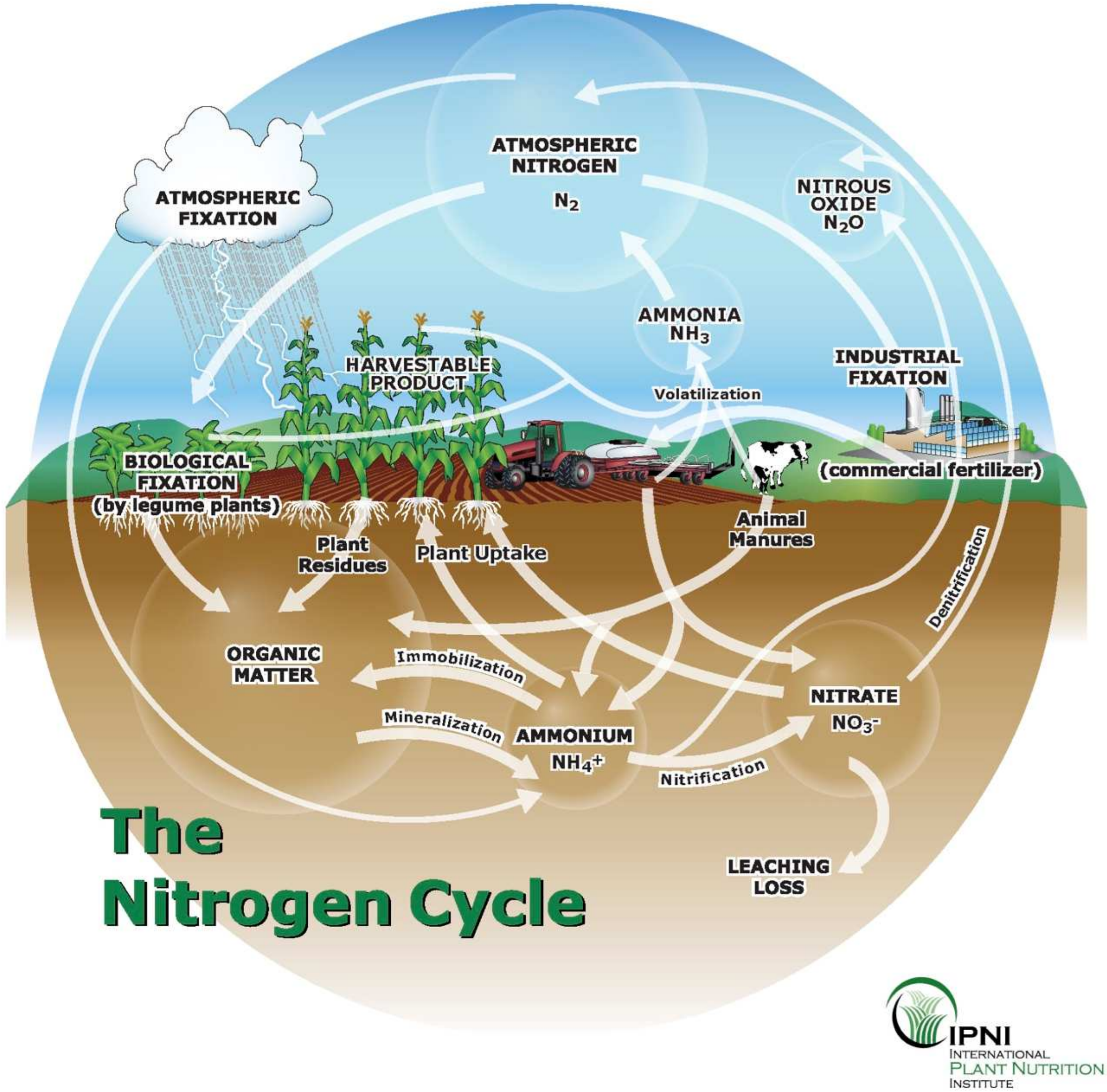

Figure 1-1 The Nitrogen Cycle, (IPNI, 2013)

Environmental Impacts of Nitrogen Fertilization

The industrialization of N fixation revolutionized production agriculture and greatly increased food production to support our current 7.125 billion people on earth. According to Johnson (2000), over the past couple of decades, no other applied nutrient has increased grain yield more dramatically than N. In the process of increasing grain yield through increasing applied N rates, agriculture introduced large fluxes of N into ecosystems away from the crop field, having detrimental impacts. There are many pathways for N losses from agricultural systems to reach other environmental systems. Gaseous plant emissions of ammonia, denitrification, surface runoff, ammonia volatilization, and NO_3 leaching (Raun and Johnson, 1999) (Figure 1-1), are all N loss pathways that can lead to an increased load of biologically reactive N in the environment (Cassman et al., 2002).

N management practices such pre-plant N applications can have poor synchrony between soil N supply and crop demand (Raun and Johnson, 1999; Cassman et al., 2002; Fageria and Baligar, 2005), thus having much greater potential for low Nitrogen Use Efficiency (NUE) and greater N loss. These types of N management practices in cereal crops have caused NO_3 to be the most commonly found contaminate in surface and ground waters in this region (CAST, 1999; Steinheimer et al., 1998; Schilling, 2002). The recorded amounts of biologically-reactive N that are streaming in from the Corn Belt into the Gulf of Mexico by the Mississippi river has greatly increased over the past century (Turner and Rabalais, 1991). According to Rabalais (2002), this issue has been the primary factor contributing to the oxygen depletion and formation of hypoxic zones in the coastal waters in the Gulf of Mexico.

An immediate response for mitigating the current impacts of N fertilization on the environment is to reduce total applied N rates, which in turn would reduce overall N load entering the environment. However, changes in N rate applied with no regard to when and how the N is applied will result in a direct reduction in crop yield, and the intended reductions in N load transported to the environment may not be fully achieved. N fertilizer needs to be managed efficiently in order to maximize yield and profit per acre in addition to minimizing environmental impact (Feinerman et al. 1990).

Nitrogen Use Efficiency

Nitrogen Use Efficiency is a term that has been developed to assess the effectiveness of N management systems in crop production. It is often a term shrouded by confusion because of the many different definitions used to describe NUE. How one defines NUE usually depends upon what data they have available to assess NUE. For a true assessment of NUE, as described by Moll et al. (1982) and Hawkesford (2012), two components are necessary:

1. Nitrogen Uptake Efficiency (NUpE)
    a. Defined as kg of N taken up by the plant divided by the kg N available in the soil including applied N
2. Nitrogen Utilization Efficiency (NUtE)
    a. Defined as kg of grain produced divided by total kg of N in plant and grain

By multiplying N uptake efficiency by N utilization efficiency, overall NUE of the plant can be derived to evaluate the plants ability to recover N from the soil and utilize it in the plant to generate yield (Figure 1-2).

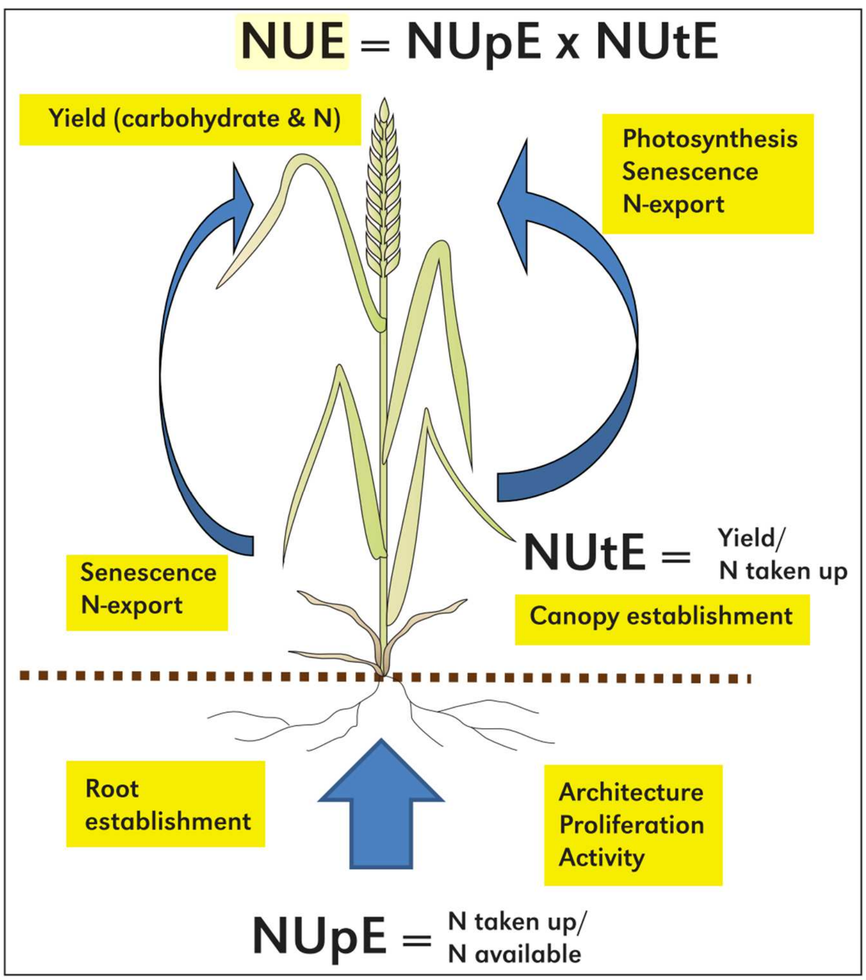

Figure 1-2 Nitrogen Use Efficiency (Hawkesford, 2012)

An additional method for calculated NUE described by Varvel and Peterson (1990) focused on the effects of N fertilizer applications. This method is defined as N Fertilizer Recovery Efficiency (FRE), and involves subtracting the total N uptake in the plant grown in an unfertilized control plot (totNup Control Plot) from the total N uptake in the plant from an N fertilized plot (TotNup N Fert Plot), then dividing this difference by the rate of fertilizer N applied.

N Fertilizer Recovery Efficiency = $\frac{TotNup\ N\ Fert\ Plot - Tot\ Nup\ Control\ Plot}{Total\ N\ Rate\ Applied}$

Because obtaining total plant N uptake is required for calculating NUE and FRE, it is rarely used in soil fertility research. Instead, a method called Partial Factor Productivity (PFP) is used to give insight on the NUE of an N management system. PFP as described by Hawkesford (2012) is simply Mg of grain yield divided by kg of fertilizer N applied in a given area. It is more commonly applied as kg fertilizer N applied divided by Mg of grain yield in American crop production and will be applied this way for the remainder of this writing. PFP can be calculated by any crop production operation for assessing the impacts of their N management system on potential NUE. Effectively, a lower PFP is more desirable and is indicative of a greater NUE-N management practice. However, an issue with PFP is that soil-available N is not usually included in the calculation. Therefore, the true effect of N fertilizer applications may be masked in regions like Kansas where NO_3 can accumulate in the soil over years due to low precipitation.

Partial Factor Productivity = $\frac{Grain\ Yield\ (Mg\ ha^{-1})}{(kg\ ha^{-1})\ N\ Applied}$

According to Raun and Johnson (1999) NUE defined by N fertilizer recovery is estimated to be 33% for cereal crop production. With such low NUE worldwide, it is clear that improvements in N management need to be made or detrimental environmental impacts will continue. There are numerous N management practices that have been developed for improving NUE: slow-release N fertilizers, precision N rate calculations, nitrification inhibitors, applying N at the time of peak N uptake, proper placement, and split applications (Cole et al., 1997; Dalal et al., 2003; Robertson, 2004; Paustian et al., 2004; Monteny et al., 2006). The big question is, "How do N management practices improve NUE?"

Addressing N Loss Mechanisms for Improving NUE

Specific N management practices and/or N fertilizer products are often designed to combat a specific N loss mechanism in order to improve NUE. There are three N loss mechanisms (denitrification, leaching, ammonia volatilization) and one N tie up mechanism (immobilization) that are most commonly addressed:

1. Denitrification: N loss
    a. This is the stepwise conversion of NO_3 to N_2 gas
        i. Environmental issue: creating greenhouse gas if stepwise conversion stops at N_20 (Figure 1-1). Often referred to as incomplete denitrification
        ii. Agronomic issue: if too much of applied N denitrifies and crop demand is not met, yield reductions will result
    b. Favorable conditions for denitrification involve low available O_2 that can be caused by compaction, poor drainage, flooding, and anaerobic conditions (Schepers and Raun, 2008). More commonly found on crop fields with heavy textured soils with patterns of heavy rainfall.
        i. Critical N management practices to mitigate denitrification
            1. N source as NH_4 form
                a. NH_4 is not subject to denitrification
                b. Nitrification inhibitors
                    i. Products designed to prevent nitrification (the conversion of NH_4 to NO_3) for period of time. Protection time is greatly dependent upon specific product and environment
            2. N application timing
                a. Apply N when conditions for denitrification are not optimal, therefore reducing denitrification losses.

i. Side-dress N applications, apply N when plant is actively taking up N and reduce probability of subjecting N to wet periods

2. Leaching: N loss
    a. Leaching is the movement of soluble material from one soil zone to another via water movement in the profile.
    b. NO_3 is a negatively charged anion. Since soil colloids are usually negatively charge, NO_3 is mobile in the soil solution and is free to move with water and potentially leach out of the root zone (Figure 1-1)
        i. Environmental issue: Excessive levels of NO_3 leaches into ground water that serves as a drinking water resource
        ii. Agronomic issue: High amounts of NO_3 leaches out of the root zone and not enough N remains to meet crop demand, resulting in yield reductions
    c. Leaching commonly occurs in crop fields with coarse texture soils with high infiltration and percolation rates and patterns for frequent and/or high rainfall events (Mulla and Strock, 2008). Such conditions promote water movement through the soil profile, and moves NO_3 out of the root zone
        i. Critical N management practices for mitigating leaching
            1. N Source as NH_4 form
                a. NH_4 is not as vulnerable to leaching
                    i. NH_4 is positively charged and as attraction to negatively charged soil colloids which helps reduce NH_4 movement with water
                b. Nitrification inhibitors
                    i. Products designed to prevent nitrification (the conversion of NH_4 to NO_3) for period of time. Protection time is greatly dependent upon specific product and environment
            2. N application timing

        i. Apply N during the growing season when crop is actively taking up N
        ii. "Spoon-feeding", low rates of N applied at stages of high N uptake by the plant. Meets crop demand for N and yield is maximized. Removes NO_3 from the soil solution quickly to minimize leaching losses

3. Ammonia Volatilization: N loss
    a. The transfer of N as ammonia gas from the soil, plant, animal, or N fertilizers to the atmosphere (Figure 1-1)
        i. Environmental issue: Greenhouse gas
        ii. Agronomic issue: High volatilization losses of N lead to crop N demand not being satisfied, resulting in yield reductions
    b. Associated with urea containing fertilizers that are surface applied to soils with high pH and moist surface conditions. If urea fertilizer is not dissolved and moved into the soil profile by precipitation, active water evaporation of the surface moisture will serve as a major carrier for ammonia volatilization. Ammonia volatilization losses for surface applied urea products have been reported to be as high as 40% (Fowler and Brydon, 1989).
        i. Critical N management practices to mitigate ammonia volatilization
            1. N placement
                a. Incorporating urea products into the soil will greatly reduce ammonia volatilization and is probably the single best practice for this purpose
4. Immobilization: N Tie Up
    a. As previously described, immobilization is the conversion of inorganic N to organic N in microbial or plant tissue
        i. Immobilization is not an N loss mechanism; it is the natural process of living organisms such as microbes and plants utilizing N

to complete their lifecycle. Once their life cycle is complete and they decompose, mineralization will occur and inorganic N will be released into the soil solution for reuse by microbes and plants. Some N must be provided and sustained in the soil to maintain healthy soil ecosystems

ii. Environmental issue: Dependent upon rate and time of mineralization

1. If mineralized, N is released when N uptake by the crop is not occurring, it will be subject to nitrification-denitrification, and leaching losses.

iii. Agronomic issue: Too much N is immobilized and not available for plant uptake during peak demand, resulting in yield reductions

b. High levels of immobilization are most common in cropping systems with high residue levels that have C:N ratios greater than 55:1, i.e. winter wheat (*Triticum aestivum*) and corn (*Zea mays*). The microbial population requires additional inorganic N for the decomposition of high C:N ratio residues. Surface applications of N fertilizers in no-till systems high C:N ratio residues can experience as much as 21% N tie up through immobilization, nearly double that was experienced by conventional tilled systems (Rice and Smith, 1984).

i. Critical N management practices for minimizing excessive immobilization

1. N Placement

a. Subsurface application or surface banding of N to minimize contact with residue (Mengel, et al., 1982)

Each source of N loss or tie up mechanism can contribute to lower NUE, but can be directly addressed with the appropriate N management practice, however, rarely is N subjected to only one mechanism of N loss. Therefore, optimizing NUE requires a dynamic management system that changes for specific growing conditions and mitigates multiple N loss/tie up mechanisms.

The 4-R's N Management System

"Right Product, Right Rate, Right Time, and Right Place". These are the fundamental components of the 4-R N management system (Roberts, 2007). Alone, each component can address a specific N loss mechanism as discussed in the previous section. However, the 4-R approach focuses on the integration of all of these components to make site-specific N management systems. Therefore, the choice of N fertilizer source, when it is applied, how much is applied, and where it is applied, will greatly depend upon the crop, cropping system, and its growing environment. This dynamic site-specific approach optimizes N management for any given crop in any given environment, thus maximizing N utilization by the crop, which will in turn increase grain yield and reduce environmental impact. The 4-R concept is fundamentally sound but can be difficult to implement. Knowing when and how much N to apply in sync with N demand of the crop is difficult to determine. Therefore, producers and consultants need tools to help them assess crop N status in order to properly implement the 4-R approach to N management.

Active Optical Sensors as Nitrogen Status Tools

Active optical sensors (AOS) as defined Holland et al. (2012) "are specialized instruments that irradiate a target with radiation and measure that which is scattered back to the sensor's integral photo-detector". More familiar optical sensors to the general populous are passive sensors such as cameras, which require sunlight to illuminate the target. With such passive optical sensors, irradiance values can vary with solar zenith angle, sensor position relative to altitude and field of view (Fitzgerald, 2010; Holland et al., 2012). Because AOS has a light source to illuminate the target, it is not influenced by changing sun and sky conditions (Fitzgerald, 2010; Erdle et al., 2011; Holland et al., 2012). Therefore, AOS is a consistently reliable technology for gathering spectral data.

How can optical sensors be used for assessing N status in plants? Like humans, optical sensors can see in the visible spectrum between 400 and 700 nm, but also see in the Near-infrared (NIR) spectrum between 700 and 2500 nm (Chappelle et al., 1992; Erdle et al., 2011). There exists a strong linear relationship between chlorophyll and leaf N content (Lamb et al., 2002) and we can use the visible spectrum to assess leaf chlorophyll content (Gausman, 1974, 1977; Slaton et al., 2001; Campbell, 2002). Now with an assessment of leaf chlorophyll, we need information on how many leaves are there, and NIR can be used to obtain an approximation of biomass (Campbell, 2002).

Thus, an AOS presents the opportunity to obtain data in regards to a plant's photosynthetic capacity and biomass, quickly and reliably throughout the growing season. Currently there are many AOS on the market but the most well-known on-the-go sensors available are Crop Circle® (Holland Scientific Inc., Lincoln, Nebraska) and Greenseeker® (Trimble Navigation, Ag Division, Westminster, CO). Most AOS are two-channel sensors, and therefore can only detect two wavelengths of a specified bandwidth. The two most commonly used wavelengths on AOS are Red (650-690 nm) and NIR (760-900 nm), as these two spectral ranges can be considered effective for evaluating N status (Thenkabail et al., 2002). Red light is specifically chosen because it is highly absorbed by chlorophyll a and b and improves contrast between the soil background and plant (Elvidge and Chen, 1995; Blackburn, 1998; 1999; Hatfield et al., 2008).

Once reflectance data in the visible and NIR spectrum are obtained, most AOS will calculate a vegetation index for the simplification of the spectral data and to hone in on a specific characteristic. For two channels sensors, the most commonly calculated vegetation index is the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973; Fitzgerald, 2010). NDVI has been used effectively for estimating crop yield, leaf area index, and biomass (Raun et al., 2001; Thenkabail et al., 2002; Pinter et al., 2003; Raun et al. 2005; Prasad et al., 2007), therefore NDVI is very applicable for addressing N status. However, NDVI will lose sensitivity once the crop leaf area index (LAI) is greater than 2 and is known as saturation (Gitelson et al., 1996; Myneni et al., 1997). Because of the saturation issue with NDVI in high LAI situations, it will have limited effectiveness for evaluating N status in crops like corn at later growth stages (Holland et al., 2012).

Nitrogen Recommendation Algorithms

Advancements in optical sensor technology have presented opportunities to collect in-season data on crop health that can be utilized for creating sustainable N management solutions. In order for spectral data provided by optical sensors to be useful, algorithms have to be generated to provide agronomic interpretations.

Dr. William Raun from Oklahoma State University and his collaborators were one of the first to develop algorithms for AOS for in-season on-the-go N management of winter wheat

(Raun et. al. 2002). Further development of optical sensor-based N recommendation algorithms for winter wheat has progressively continued at Oklahoma State University with additional algorithm releases in 2005 (Raun et al., 2005). Additional work by Solie and his collaborators at OSU resulted in the construction of a generalized algorithm that is designed for use in both corn and winter wheat (Solie et al., 2012). OSU continues to be an advocate of sensor-based N management of winter wheat and can be considered one of the leaders of this movement.

Additional algorithm designs that are very robust in nature have been created by Kyle Holland of Holland Scientific and James Schepers USDA ARS, who is now retired. An issue with algorithm design is they often become sensor specific and can be difficult to apply to other areas where data have not been collected. Holland and Schepers (2010) released an algorithm design for corn that was very robust for many reasons such as: can be readily used with a variety of AOSs ranging from on-the-go sensors to the traditional handheld chlorophyll meter, be applied throughout the growing season, and can be readily calibrated through user inputs. These attributes make it easy to use across a wide range of locations and environmental conditions. This type of modular design paved the way for a robust generalized algorithm approach that can be applied to numerous crops and greatly extend algorithm life expectancy.

Summarizing Review

The industrialization of N fixation has given humans the ability to greatly increase crop production and to support a larger population on limited agricultural resources. After nearly a century of N fertilization, impacts of poor N management on the environment are reaching levels of major concern. It is clear NUE of N management practices must be improved in order to create environmentally sustainable cropping operations.

Although many options exist for improving NUE in crop production, optical sensor technology presents an opportunity to accurately evaluate N status and provide N recommendations based on the individual crop needs at that moment. Therefore, optical sensor technology could be effectively used to determine when and how much N should be applied throughout the growing season, syncing N applications with crop demand and improving NUE.

Balancing the Human Element in the N Cycle

The N cycle is a very complex system that has perfected itself over billions of years for the purpose of providing life to this planet. Like cyanobacteria, humans have developed the ability for N fixation out of need to build and sustain their population through increased agricultural food production, and therefore are now a permanent component of the N cycle. Optimizing NUE in agriculture is essential for humans to become a harmonious element in Earth's N cycle and maintain its balance. However, this leaves us with important questions, "What is the optimal NUE and does it vary by environment? Is too high of NUE just as detrimental as low NUE?" Low NUE has led to excess algae bloom in the Gulf of Mexico, giving excess life to a few species which in turn has led to the death of entire ecosystems. If 100% NUE is achieved, we promote only the life of the crop and starve the microbial populations and other forms of life in the soil, which can only lead to their death. This will result in the reduction of soil productivity and the degradation of its ecosystems.

At the time this writing, no definitive information exists for determining the optimal NUE for a given environment, we only know NUE needs to be improved. The past century was marked by the creation of industrialized agriculture that brought us to the 7.125 billion people today. Will this century brandish the creation of sustainable agriculture for the 9 billion people of tomorrow?

Throughout the chapters in this dissertation, there is one common goal of research, which is to improve the synchrony between crop N demand and the timing of N applications by melding agronomics with advanced optical sensor technology. If N management was synchronized with crop N demand, producers will be able to increase grain yield, NUE, and reduce total N inputs in production agriculture, thus moving one step closer to sustainable agriculture.

References

Bartholomew, W. V. (1965). Mineralization and Immobilization of Nitrogen in the Decomposition of Plant and Animal Residues. *Soil Nitrogen* (285-306). Madison, WI: American Society of Agronomy

Barns, S.M., and S.A. Nierzwicki-Bauer. (1997). Microbial diversity in ocean, surface and subsurface environments. p. 34–79. In J.F. Banfield and K.H. Nealson (ed.) *Geomicrobiology: What can we learn from layered microbial communities? Reviews in mineralogy*. Washington, DC: Mineral. Soc. of Am.

Blackburn, G.A., (1998). Spectral indices for estimating photosynthetic pigment concentrations: A test using senescent tree leaves. *International Journal of Remote Sensing*, 19(4):657-675.

Blackburn, G.A., (1999). Relationships between spectral reflectance and pigment concentrations in stacks of deciduous broadleaves. *Remote Sensing of Environment*, 70(2):224-237.

Cassman, K.G., A. Dobermann, and D.T. Walters, (2002). Agroecosystems, nitrogen-use efficiency, and nitrogen management. *AMBIO* 31:132-140.

Downing, J., B. Darst, T. Franci, T. Jordan, S. Nixon, G. Randall, M. Ribaudo, J. Baker, R. Diaz, T. Prato, N. Rabalais, R. Zimmerman. (1999). *Gulf of Mexico hypoxia: Land and sea interactions.* CAST Task Force Report No. 134. Council for Agricultural Science and Technology, Ames, IA.

Campbell, J.B., (2002). *Introduction to Remote Sensing*. New York, NY: The Guilford Press

Cole, C.V., J. Duxbury, J. Freney, O. Heinemeyer, K. Minami, A. Mosier, K. Paus- tian, N. Rosenberg, N. Sampson, D. Sauerbeck, and Q. Zhao. (1997). Global estimates of potential mitigation of greenhouse gas emissions by agriculture. *Nutr. Cycling Agroecosyst*. 49:221–228.

Dalal, R.C., W. Wang, G.P. Robertson, and W.J. Parton. (2003). Nitrous oxide emission from Australian agricultural lands and mitigation options: A review. *Aust. J. Soil Res*. 41:165–195.

Darst, B. C. (2006). *Soil Fertility Manual*. Norcross, GA: International Plant Nutrition Institute

Erdle, K., B. Mistele, and U. Schmidhalter. (2011). Comparison of active and passive spectral sensors in discriminating biomass parameters and nitrogen status in wheat cultivars. *Field Crops Research*, *124*(1), 74–84. http://doi.org/10.1016/j.fcr.2011.06.007

Elvidge, C.D., and Z. Chen, (1995). Comparison of broadband and narrow-band red and near-infrared vegetation indices, *Remote Sensing of Environment*, 54:38-48.

Fageria, N.K., and V.C. Baligar. (2005). Enhancing nitrogen use efficiency in crop plants, *Adv. Agron*. 88:97-185

Feinerman, E., E.K. Choi, and S.R. Johnson. (1990). Uncertainty and split nitrogen application in crop production. *Amer. J. Agr. Econ*. 72:975-984.

Fitzgerald, G. J. (2010). Characterizing vegetation indices derived from active and passive sensors. *International Journal of Remote Sensing*, *31*(16), 4335–4348. http://doi.org/10.1080/01431160903258217

Fowler, D. B., and J. Brydon. (1989). No-till winter wheat production on the Canadian prairies: Placement of urea and ammonium nitrate fertilizers. *Agronomy J. 81*:518-524.

Gausman, H. W. (1974). Leaf reflectance of near-infrared. *Photogrammetric Engineering & Remote Sensing*, 40(2):183-191.

Gausman, H. W. (1977). Reflectance of leaf components. *Remote Sens. Environ.* 6:1-9.

Gitelson, A. A., Y.J. Kaufman, and M.N. Merzlyak. (1996). Use of a green channel in remote sensing of global vegetation from EOS-MODIS. *Remote Sens. Environ*. 58:289-298.

Haber-Bosch process. In *Encyclopedia Britannica online*. (2014). Retrieved from http://www.britannica.com/EBchecked/topic/250771/Haber-Bosch-process

Hawkesford, M. (2012). The diversity of nitrogen use efficiency for wheat varieties and the potential for crop improvement. *Better Crops with Plant Food*, *96*(3), 10–12.

Hatfield, J.L., A.A. Gitelson, J.S. Schepers, and C.L. Walthall. (2008). Application of spectral remote sensing for agronomic decisions. *Agronomy J.* 100: S-117–S-131.

International Plant Nutrition Institute. *Generalized Nutrient Cycles*. (2013). Retrieved March 20, 2015, from http://www.ipni.net/article/IPNI-3326

Holland, K. H., and J.S. Schepers (2010). Derivation of a variable rate nitrogen application model for in-season fertilization of corn. *Agronomy J. 102*(5):1415-pages. http://doi.org/10.2134/agronj2010.0015

Holland, K. H., D.W. Lamb, and J.S. Schepers. (2012). Radiometry of proximal active optical sensors (AOS) for agricultural sensing. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *5*(6), 1793–1802. http://doi.org/10.1109/JSTARS.2012.2198049

Lamb, D.W., M. Steyn-Ross, P. Schaare, M.M. Hanna, W. Silvester, and A. Steyn-Ross, (2002). Estimating leaf nitrogen concentration in ryegrass (*Lolium* spp.) pasture using the chlorophyll red-edge: theoretical modeling and experimental observations. *Int. J. Remote Sens*. 23, 3619–3648.

Mengel, D. B., D. W. Nelson, and D. M. Huber. (1982). Placement of N fertilizers for no-till and conventional till corn. *Agronomy J. 74*:515-518.

Moll, R.H., E.J. Kamprath, and W.A. Jackson. (1982). Analysis and interpretation of factors which contribute to efficiency to nitrogen utilization. *Agronomy J*. 74:562-564.

Monteny, G. J., A. Bannink, and D. Chadwick. (2006). Greenhouse gas abatement strategies for animal husbandry. *Agric. Ecosyst. Environ*. 112:163–170.

Mulla, D. J., and J. S. Strock. (2008). Nitrogen Transport Processes in Soil. *Nitrogen in Agricultural Systems* (361-400). Madison, WI: ASA-CSSA-SSSA

Myneni, R. B., R. R. Nemani, and S. W. Running. (1997). Estimation of global leaf area index and absorbed PAR using radiative transfer models. *IEEE Trans. Geosci. Remote Sensing*. 33:1380-1393.

Paustian, K., B.A. Babcock, J. Hatfield, R. Lal, B.A. McCarl, S. McLaughlin, A. Mosier, C. Rice, G.P. Robertson, N.J. Rosenberg, C. Rosenzweig, W.H. Schlesinger, and D. Zilberman. (2004). *Agricultural mitigation of greenhouse gases: Science and policy options*. CAST Rep. R141. Council on Agricultural Science and Technology, Ames, IA.

Pinter, P.J., Hatfield, J.L., Schepers, J.S., Barnes, E.M., Moran, M.S., Daughtry, C.S.T., Upchurch, D.R., (2003). Remote sensing for crop management. *Photogramm. Eng. Remote Sens*. 69, 647–664.

Postgate, J. (1998). *Nitrogen fixation*. Cambridge Univ. Press, Cambridge, UK.

Prasad, B., Carver, B.F., Stone, M.L., Babar, M.A., Raun, W.R., & Klatt, A.R. (2007). Potential use of spectral reflectance indices as a selection tool for grain yield in winter wheat under Great Plains conditions. *Crop Science*. 47, 1426–1440.

Raun, W.R., and G.V. Johnson. (1999). Improving nitrogen use efficiency for cereal production. *Agronomy J*. 91:357-363.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, E.V. Lukina, W.E. Thomason, J.S. Schepers, (2001). In-season prediction of potential grain yield in winter wheat using canopy reflectance. *Agronomy J*. 93:131–138.

Raun, W. R., J. B. Solie, G. V. Johnson, Stone, M. L., Mullen, R. W., Freeman, K. W., Lukina, E. V. (2002). Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. *Agronomy J. 94*(4), 815–820. http://doi.org/10.2134/agronj2002.8150

Raun, W.R., J.B. Solie, M.L. Stone, K.L. Martin, K.W. Freeman, R.W. Mullen, H. Zhang, J.S. Schepers, and G.V. Johnson. (2005). Optical sensor based algorithm for crop nitrogen fertilization. *Commun. Soil Sci. Plant Anal.* 36:2759–2781. doi:10.1080/00103620500303988

Raun, W.R., J.B. Solie, K.L Martin, K.W. Freeman, M.L. Stone, G.V. Johnson, and R.W. Mullen. (2005). Growth stage, development, and spatial variability in corn evaluated using optical sensor readings. *Journal of Plant Nutrition* 28:173-182.

Rabalais, N.N. (2002). Nitrogen in aquatic ecosystems. *AMBIO* 31:102-112.

Rice, C. W., and M.S. Smith. (1984). Short-term immobilization of fertilizer nitrogen at the surface of no-till and plowed soils. *Soil Science Society of America J. 48*:295-297.

Robertson, G.P. (2004). Abatement of nitrous oxide, methane and other non- CO2 greenhouse gases: The need for a systems approach. p. 493–506. In C.B. Field and M.R. Raupach (ed.) *The global carbon cycle. Integrating humans, climate, and the natural world*. SCOPE 62, Island Press, Washington, DC.

Roberts, T. L. (2007). *Right product, right rate, right time and right place...the foundation of best management practices for fertilizer.* Retrieved from IPNI: http://www.ipni.net/ipniweb/portal.nsf/0/55C6FA392D96B89885257A8C0057EDAA/$FILE/Roberts_2007_4Rs.pdf

Rouse, J. W., R. H. Haas, J. A. Schell, and D. W. Deering (1973). Monitoring vegetation systems in the Great Plains with ERTS, *Third ERTS Symposium*, NASA SP-351 I, 309- 317.

Scharf, P. (2015). *Managing Nitrogen in Crop Production*. Madison, WI: American Society of Agronomy.

Schepers, J., and W. Raun. (2008). Nitrogen Management to Protect Water Resources. *Dl.sciencesocieties.org*, 911–945.

Schopf, J. W. (1993). Microfossils of the Early Archean Apex chert: New evidence of the antiquity of life. *Science* 260:640–646.

Schilling, K. E. (2002). Chemical transport from paired agricultural and restored prairie watersheds. *Journal of Environmental Quality*. 31:1184-1193.

Slaton, M. R., E. R. Hunt, and W.K.Smith. (2001). Estimating near-infrared leaf reflectance from leaf structural characteristics. *American Journal of Botany*, 88:278-284.

Smil, Vaclav. (2001). *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production*. Cambridge, MA and London: MIT Press.

Solie, J. B., A.D. Monroe, W. R. Raune, and M. L. Stone. (2012). Generalized algorithm for variable-rate nitrogen application in cereal grains. *Agronomy J. 104*(2):378-?. http://doi.org/10.2134/agronj2011.0249

Source nitrogen. In *Encyclopedia Britannica online*. (2014). Retrieved from http://www.britannica.com/EBchecked/topic/416180/nitrogen-N

Steinheimer, T.R., K.D. Scoggin, and L.A. Kramer. (1998). Agricultural chemical movement through a field size watershed in Iowa: Surface hydrology and nitrate losses in discharge. *Environmental Science & Technology* 32:1048-1052.

Stevenson, F.J. (1982).“Origin and Distribution of Nitrogen in the Soil” Nitrogen in Agricultural Soils. Madison, WI: ASA-CSSA-SSSA

Thenkabail, P. S., R. B. Smith, and E. D. Pauw. (2002). Evaluation of narrowband and broadband vegetation indices for determining optimal hyperspectral wavebands for agricultural crop characterization. *Photogrammetric Engineering and Remote Sensing*, *68*(6), 607–621. Retrieved from http://www.asprs.org/a/publications/pers/2002journal/june/2002_jun_607-621.pdf

Turner, R. E., and N. N. Rabalais. (1991). Changes in Mississippi River water-quality this century. *Bioscience* 41:140-147.

Varvel, G.E., and T.A. Peterson. (1990). Nitrogen fertilizer recovery by corn in monoculture and rotation systems. *Agronomy J*. 82:935–938.

Chapter 2 - Evaluation of Nitrogen Application Timing in Winter Wheat (*Triticum aestivum L.*)

Abstract

Nitrogen (N) management systems that utilize full N applications in the fall or winter on poorly drained or highly leachable soils with normal patterns of heavy precipitation in the spring have greater potential for low Nitrogen Use Efficiency (NUE). Low NUE has many implications for Kansas' wheat producers: increased fertilizer cost, lower profit per acre, and increased environmental impact. The objectives of this study were to evaluate the impacts of fall-winter, Feekes 4, 7, and 9 N applications on winter wheat grain yield, grain protein, and total grain N uptake. Nine field studies across seven locations from 2011 through 2013 were conducted. Nitrogen treatments were applied as single or split applications in the fall-winter, Feekes 4, Feekes 7, and Feekes 9 with applied N rates ranging from 0 to 134 kg ha^{-1}. Results indicate that Feekes 7 and Feekes 9 N applications provide more optimal combinations of grain yield and grain protein levels when compared to Feekes 4, particularly when high precipitation events in the early spring potentially lead to N loss. Results show that total applied N rates of greater than or equal to 134 kg N ha^{-1} generated grain yield response that was statistically equal across fall-winter, Feekes, 4, Feekes 7, and Feekes 9 applications. However, split N applications with 34 kg N ha^{-1} applied in the winter and an additional 100 kg N ha^{-1} applied at Feekes 9 produced statistically higher grain protein and total grain N uptake over fall and Feekes 4 treatments. Nitrogen management programs that incorporate Feekes 7 or Feekes 9 split N applications provide the wheat producer more time to assess precipitation outlook, N mineralization, and N loss. Therefore, N management programs can be better tailored for a specific field for a specific year and improve NUE and potentially enhance grain yield, which can reduce environmental impact and increase profits.

Introduction

Nitrogen management is an essential part of winter wheat production in Kansas. Nitrogen is the most frequent yield-limiting factor in the Great Plains, and therefore the most abundantly applied nutrient (Schlegel and Grant, 2006). However, NUE, the fraction of the fertilizer N applied which is taken up and used by the crop, has been relatively low throughout the world. Raun and Johnson (1999) estimate that only 33% of the total N fertilizer applied for cereal production in the world is actually removed in the grain. Low NUE has many implications for the Kansas wheat producer such as increased fertilizer cost, lower profits and increased environmental impact. Both farmers and environmentalists have become increasingly aware of the detrimental impact low NUE systems have on our economy and environment. Therefore, interest over the past decade has greatly increased in improving N management systems in winter wheat to have high NUE, high yield, and be environmentally sustainable.

A number of methods for improving NUE in winter wheat cropping systems exist today. Producers have access to a number of publications describing best management practices (BMP) for reducing N inputs without sacrificing profits (Roberts, 2007). "Right Time" is one of the fundamental pieces of the 4-R N management system and emphasizes the synchrony between crop N demand and the time of N applications is essential for improving NUE (Roberts, 2008). Timing of N applications in winter wheat can have very positive impacts on optimizing grain yield and NUE by aligning N applications with growth stages that establish the grain yield components and comprise the majority of active N uptake.

Winter wheat has four grain yield determining components that can be described in order of its lifecycle with the Feekes growth staging system (Miller, 1999). The first component is number of heads per plant, which is determined by seeding rate and tiller formation. Tillering occurs from Feekes 2 through 4 and N applications during these growth stages can have a positive impact on the number of tillers formed, thus generating more heads per plant and a larger grain yield potential. If N stress occurs during Feekes 2 through 4, tillering will be reduced and permanent grain yield loss may occur through a reduction in head numbers, which cannot be corrected with an N application after Feekes 4. The second component is the size of each head. The determination of head size and the maximum number of seeds per head occurs at Feekes 5. Preventing N stress at this growth stage will ensure potential head size and seed number is maximized and will increase potential grain yield capacity. Once Feekes 5 has passed head size will be fixed, and N applications intending to correct N deficiencies will not have an impact on head size, therefore again permanent reductions in grain yield capacity may occur. The third and fourth components are number of seeds per head and the size of each seed. Actual seed number and seed size is determined from Feekes 10 through 11. By maintaining N sufficiency during these growth stages, a greater number of seed will be set and filled if given good growing conditions.

With an understanding of when winter wheat determines its grain yield components, it is clear that preventing N stress during the Feekes growth stages previously described is important. However, we must also consider when winter wheat takes up most of its N in order to have the greatest impact on these grain yield components. According to Waldren and Flowerday (1979), winter wheat's N uptake is most rapid from tillering through booting stages, with 80% of the total accumulation occurring before grain fill. Therefore, winter wheat will acquire most of its N from Feekes 3 through Feekes 9, storing it in the stem and leaves for use during grain fill. This creates an ideal alignment between determination of yield components, N uptake, and potential applications of N. Although high rates of N could be applied pre-plant to address all the grain yield components, Cassman et al. (2002) determined that split applications of N during the growing season were more effective at increasing NUE when compared to single pre-plant applications. This is likely due to the potential for N loss, through various N loss mechanisms, if N remains in the soil for extended periods between application and uptake.

There is also an inverse relationship that exists between grain yield and grain protein levels, caused by the increase of carbohydrate content as grain yield increases, resulting in the dilution of protein in the grain (Hawkesford, 2012). Single pre-plant applications can support the generation of more tillers and increase head size but may not provide enough late-season N to support grain fill, therefore reducing grain protein. Optimal grain yield and grain protein can be obtained with N management strategies that maintain N sufficiency during the early growth stages to support tiller and head-size formation and incorporate late-season N applications to support grain fill (Wuest and Cassman, 1992; Cassman et al., 1992).

There are two traditional methods for timing of N fertilization of winter wheat in Kansas. The first is a full rate of N applied in the fall prior to planting. Concerns with N loss from this approach are highly dependent upon where in Kansas the producer is located. In western Kansas, if the N was subsurface applied, N loss is potentially low due to low annual rainfall (Figure 2-1). However, in eastern Kansas, potential for N loss from denitrification or leaching is much greater due to more frequent combinations of high rainfall and poorly drained or leachable soils (Figure 2-1)(NRCS, 2015). Therefore, it is not uncommon for wheat producers in eastern

Kansas to employ a common approach for timing of N fertilization by applying a small amount of starter N in the fall at seeding and then apply the balance of the N in the early spring at Feekes 3 and Feekes 4 to help reduce N losses through the fall and winter. Both of these systems have their merits, but may only support the first two yield components, tillering and headsize. In order to potentially optimize grain yield, grain protein, and NUE, additional considerations for N management systems that support early growth stages (tillering and headsize) and late-season growth stages (seed number and seed size) should be taken. The objective of this study was to evaluate the impact of single rate fall N applications and split rate Feekes 4, Feekes 7, Feekes 9 N applications on grain yield, grain protein, and total grain N uptake.

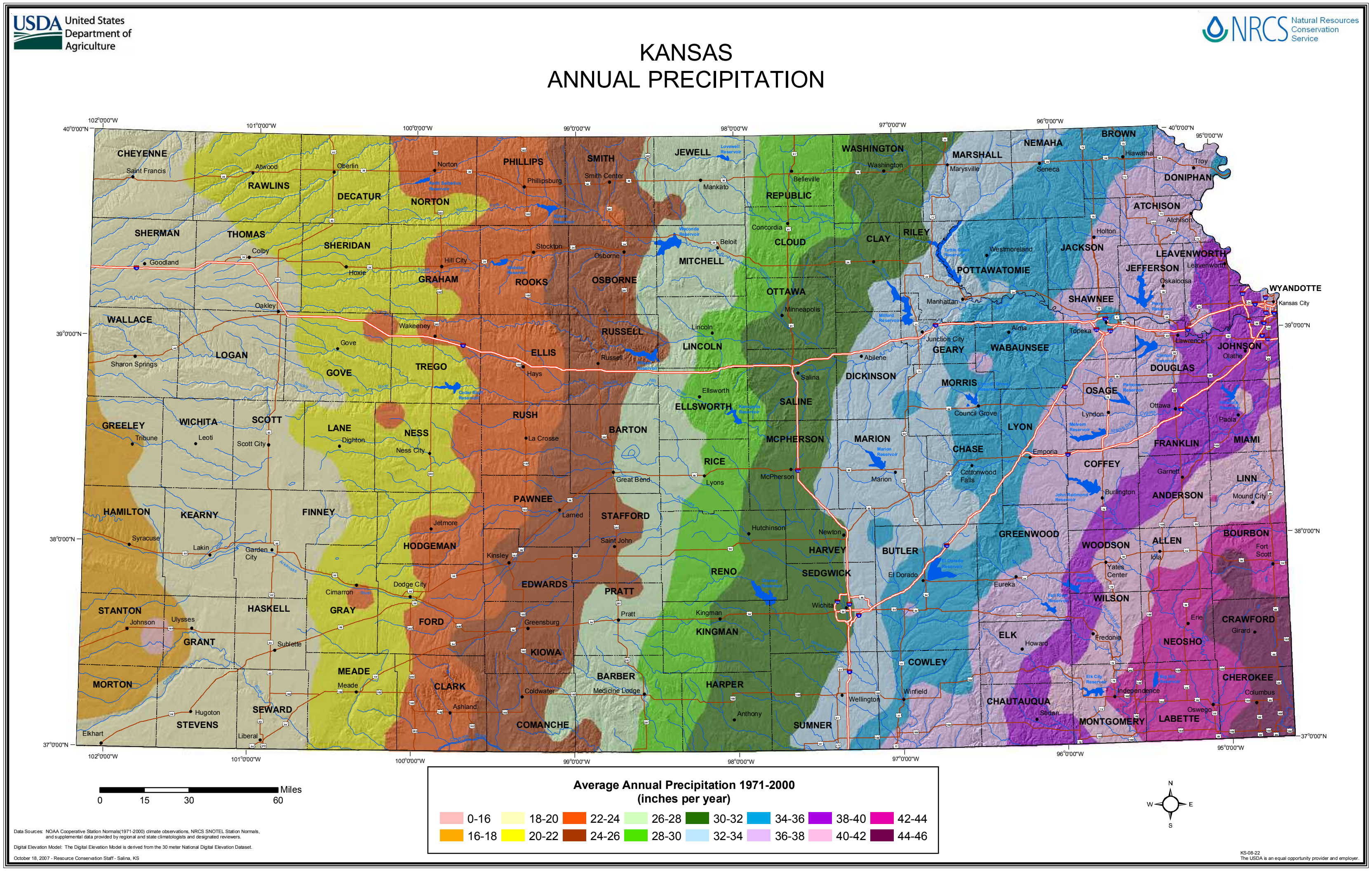

Figure 2-1 State of Kansas Cumulative Precipitation Gradient (NRCS, 2007)

Materials and Methods

Site Selection and Experimental Design

The study was conducted for two winter wheat crop years, from 2011-12 and 2012-13 in cooperation with Kansas producers and KSU Agronomy Experiment Fields for a total of nine site years. Sites were all located in eastern half of Kansas and sites were selected on the basis of soil, local weather patterns, and their potential grain yield and productivity. The Web Soil Survey (NRCS, 2015) was utilized to establish site soil texture and drainage class at each location.

Small plots (3x13 meters) were arranged at each location in a randomized complete block design with four replications. Treatment structure was two-way (N time x N split) fractional factorial design (Table 2.1). An N response curve with single rates of 0, 34, 67, 100, and 134 kg N ha^{-1} was applied during the fall or winter period to determine the magnitude of grain yield response to different rates of applied N at each location. Split applications had the initial application of N during the Fall/Winter and the remaining balance of N applied either at Feekes 4, 7, or 9 for a total N rate of 134 kg N ha^{-1}. All treatments were broadcast applied by hand with granular urea (46-0-0) as the N source.

Table 2.1 Timing, rate and total N applied to winter wheat on the 2012 and 2013 field locations in Kansas

Treatment	Fall/Winter	Feekes 4	Feekes 7	Feekes 9	Total N Applied
	kg N ha^{-1}				
1	0	0	0	0	0
2	34	0	0	0	34
3	67	0	0	0	67
4	100	0	0	0	100
5	134	0	0	0	134
6	34	100	0	0	134
7	67	67	0	0	134
8	100	34	0	0	134
9	34	0	100	0	134
10	67	0	67	0	134
11	100	0	34	0	134
12	34	0	0	100	134
13	67	0	0	67	134
14	100	0	0	34	134

Northeast Kansas

Manhattan (3 site-years)

The KSU Agronomy North Farm is located in Manhattan in northeast Kansas. Three different fields were utilized at this location with each field presenting different N response and N loss characteristics. Northeast Kansas presents weather patterns that can be considered a paradox in the state. It is not uncommon for northeast Kansas to receive high precipitation totals similar to that of southeast Kansas, the highest cumulative precipitation zone in Kansas, in one year and observe dry weather conditions similar to central or western Kansas in other years (KSU Mesonet, 2015). This presents challenges for designing optimal N management plans, and requires area producers to have more in-depth knowledge of the soil, N loss potential, and productivity characteristics of their soil and cropping system, in order to generate management plans that will be successful in all years.

An experiment was established in Field J3 for the 2011-2012 crop year and Field J3 is located on an upland, terraced soil position (39.207589° Lat, -96.591582° Long). The soil is classified as a Smolan silt loam with an abrupt increase in clay content within the first 15 cm of the soil surface (NRCS, 2015). This high clay subsoil results in the field having lower available water holding capacity, leaving the wheat crop vulnerable to drought stress under dry conditions. A particular area of concern is for precipitation to cease at the start of grain fill. Thus, Field J3 may have enough available water to support tillering and dense winter wheat stands with high biomass early in the season, but this may result in water stress and ultimately yield reductions under dry conditions if precipitation shuts off in late April and May. This field is representative of many upland areas in northeast Kansas that have the potential to generate good yields, but require careful management of winter wheat biomass for water conservation.

An experiment was also established in Field F for the 2011-2012 crop year. Field F is located in bottom ground position that contains alluvial soils that can flood when severe rainfall events occur (39.214623° Lat, -96.591262° Long). It is classified as a Kahola silt loam with a high available water holding capacity (NRCS, 2015) and is very productive. If frequent rainfall events in excess of 20-30 mm occur, the likelihood of denitrification and anaerobic conditions are very high. Therefore, this site has the potential to benefit greatly from N management programs that utilize split applications to reduce N loss potential, through denitrification, but is also very resilient to drought conditions. This field is very representative of crop fields that are considered consistently high performers for winter wheat across years.

An experiment was established in Field C for the 2012-2013 crop year. Field C is located in a bottom ground position that occasionally floods under severe rainfall events (39.212153° Lat, -96.598840° Long). It is also highly productive. This particular field is in a transitional position and has areas with characteristics of both fields J3 and F. Soils found in this field are the Ivan and Kennebec silt loam (NRCS, 2015). Soil characteristics dealing with N and available water holding capacity in the Ivan silt loam are very similar to field J3. Areas of the field located in Kennebec silt loam behave similarly to field F in regards to available water holding capacity and N characteristics. Plots were laid in this field with careful attention to soil type differences for the reasons mentioned. Blocks were established to ensure each block was in a uniform soil type. Blocks one and two consisted of Kennebec silt loam and did not have restrictive layers in the top 90 cm of the soil profile. Blocks three and four were in an Ivan silt loam with increasing clay content in the top 90 cm of the soil profile. Hard compaction layers were found within the first 15 cm of the soil profile, which result in an increased vulnerability to drought conditions. Field C is representative of fields with high soil variability that can dramatically impact productivity if not managed to a greater degree of detail.

Central Kansas

Gypsum

The Gypsum location was established for the 2011-2012 crop year with a collaborating Kansas producer. Historical yield records had shown this site to be productive and generated yields greater than 4 Mg ha^{-1} across years consistently. The study area consisted of a uniform Hord silt loam soil (NRCS, 2015)(38.704400° Lat, -97.4405073° Long). Overall N loss characteristics were low, but denitrification and anaerobic events could be observed under high rainfall events in depressional areas of the field where ponding would occur. This field is similar to Manhattan field F in the sense of being a consistent performer, but lacks the shallow water table, and is therefore more reliant on consistent rainfall events and a full soil profile of available water when entering grain fill if precipitation stops at this time. Because this location is in central Kansas, the common late-season weather pattern in this area is for precipitation to cease as grain filling begins. Therefore, additional considerations for managing high yields are required.

Solomon

The Solomon location was established for the 2012-2013 crop year on the same farm as the Gypsum location but was located approximately 16.5 km northeast of Gypsum (38.833269° Lat, -97.355152° Long). Historical yields records show consistency in generating yield levels in excess of 5 Mg ha^{-1}. The soil is classified as a Muir silt loam and was very uniform across the study area. The Muir silt loam is characterized by increasing clay content in the sub-soil (NRCS, 2015) and this was noted during initial soil sampling to confirm NRCS's report. This location has the potential for denitrification under severe rainfall events, however it was noted by the collaborating producer that at this location it is rare. The same issues concerning lack of precipitation during grain fill exist at this location as the Gypsum site. Therefore, this site also requires a management plan that can help mitigate potential late-season water stress.

Southeast Kansas

Pittsburg

The Pittsburg location was established for the 2012-2013 crop year with a collaborating Kansas wheat producer. The study area was uniform Parsons silt loam with the producer's reported yield history of 7 Mg ha^{-1} (37.3942278° Lat, -95.015905° Long). The Parsons silt loam soil is a classic "claypan" soil with dense Bt horizons 20 to 40 cm below the surface (NRCS, 2015). The typical patterns of high rainfall (KSU Mesonet, 2015) that are common in southeast Kansas provide ample moisture for generating very high yields. However, these high rainfall patterns and a soil profile that transitioned to heavy clay below 20-30 cm, produces an environment very conducive to high N loss by denitrification. This producer had a history of applying poultry litter to this field, with the last application being two years prior to this study. The producer also applies N rates pre-plant in excess of 134 kg ha^{-1} in the form of anhydrous ammonia. The collaborating farmer indicated that it was not uncommon for him to apply additional N during the growing season and have total applied N rates exceeding 224 kg ha^{-1}, not including N mineralized from the poultry litter. This field was representative of very high yielding production systems that compensate for potential N loss by utilizing N management strategies that result in excessive amounts of N. This system protects yield at the expense of NUE and the environment.

McCune

The McCune site was located within three kilometers of the Pittsburg location, and therefore experienced similar weather conditions during the 2012-2013 crop year (37.368732° Lat, -95.0947313° Long). The study area consisted of a uniform, poorly drained "claypan" Cherokee silt loam, with an abrupt change to clay 30 cm below the surface. Nitrogen loss potential from denitrification was very high and the producer historically applied N rates greater than 134 kg ha^{-1}. The collaborating producer indicated that his historical yields ranged from 6 to 7 Mg ha^{-1} if precipitation was not excessive, resulting in high N loss and high amounts of disease when utilizing his current management plan. This field did not have any applications of poultry litter on record.

Southcentral Kansas

Sterling

The Sterling location was established during the 2011-2012 crop year with a collaborating Kansas wheat producer. The study was located on highly variable Saltcreek and Naron fine sandy loams (NRCS, 2015)(38.153251° Lat, -98.289998° Long). This soil is conducive to high leaching losses of N and has a very low water holding capacity. Overall rainfall patterns for this area do not generate enough moisture to generate high yields (KSU Mesonet, 2015). A successful crop for this location is very dependent upon well-distributed rainfall and multiple topdressing of N to minimize leaching loss, with yield levels usually not exceeding 4.5 Mg ha^{-1}. This study location is representative of a field that requires a highly efficient N management strategy in order to generate profitable yield. However, due to a late freeze on April 8, 2012 (KSU Mesonet, 2015), the wheat was severely damaged and the study at this location was lost.

Partridge

The Partridge location was established in the 2012-2013 crop year in cooperation with the KSU Southcentral Experiment Field (37.961222° Lat, -98.123249° Long). The study was located on a uniform Taver loam that transitions to higher clay content below 60 cm in the soil profile (NRCS, 2015). Although not as conducive for N leaching losses as the Sterling location, N leaching was possible with high rainfall events. Overall yield productivity at this location is limited by late-season precipitation and water holding capacity and requires a well-designed management plan that controls early tillering and minimizes the overall biomass production of winter wheat to conserve soil moisture

Table 2.2 Site Soil Information and Management

Year	2012	2012	2012	2012	2013	2013	2013	2013	2013
Location	Manhattan Field J3	Sterling	Gypsum	Manhattan Field F	McCune	Pittsburg	Solomon	Manhattan Field C	Partridge
Latitude	39.207589°	38.153251°	38.704400°	39.214623°	37.368732°	37.394278°	38.833269°	39.212153°	37.961222°
Longitude	-96.591582°	-98.289998°	-97.445073°	-96.591262°	-95.047313°	-95.015905°	-97.355152°	-96.598840°	-98.123249°
Soil Series	Smolan Silt loam	Saltcreek and Naron fine sandy loams	Hord Silt loam	Kahola Silt loam	Cherokee Silt loam	Parson Silt loam	Muir silt loam	Ivan & Kennebec Silt loam	Taver Loam
Previous Crop	DC Soybeans	Failed Corn	Soybeans	Fallow	Failed Corn	Failed Corn	Soybeans	Soybeans	Fallow
Tillage Practice	No-Till	No-Till	No-Till	Conventional	Conventional	Conventional	No-Till	No-Till	Conventional
Drainage Class	Moderate	Well drained	Well drained	Well drained	Poorly drained	Poorly drained	Well drained	Well drained	Moderate
Available Water Storage (mm)	284	210	325	315	262	74	320	320	264

Cultural Practices

Key dates and cultural practices utilized for each location are summarized in Table 2.3. Locations in Manhattan were planted and maintained by the KSU soil fertility group. All locations were soil sampled to assess other nutrient needs beside N. Locations that required additional fertilization are discussed in the soil sampling section.

Winter wheat varieties utilized were representative for the area, with Everest as the dominant variety used if selected by the KSU soil fertility group. Producer cooperative fields utilized winter wheat varieties of their own choice for that season and were planted by their common methods. The typical method for planting winter wheat in Kansas is by drill. However, southeast Kansas producers commonly broadcast their wheat and utilize disc implements to mix in the wheat seed with the soil.

Starter N was applied at varying rates at each location (Table 2.3) as part of the farmer common practice with sources consisting of Mosaic MESZ (N-P-K-S-Zn, 10-18-0-10-1), mono ammonium phosphate (N-P-K, 11-23-0), and diammonium phosphate (N-P-K, 18-20-0).

Herbicide applications were made in the early spring as needed by the collaborating producers and KSU experiment stations and fungicides were applied at flag leaf formation.

Table 2.3 Key dates and cultural practices utilized at each location in 2012 and 2013

Year	2012	2012	2012	2012	2013	2013	2013	2013	2013
Location	Manhattan Field J3	Sterling	Gypsum	Manhattan Field F	McCune	Pittsburg	Solomon	Manhattan Field C	Partridge
Variety	Everest	.	Armour	Everest	Pioneer 25R30	Pioneer 25R78	Armour	Everest	Everest
Seeding Rate (kg ha^{-1})	112	.	112	112	101	101	112	112	101
Seeding Method	Drill	Drill	Drill	Drill	Broadcast/Disc	Broadcast/Disc	Drill	Drill	Drill
Starter N (kg ha^{-1})	10	0	13	10	0	0	26	20	30
Planting Date	11/1/11	.	10/6/11	10/8/12	10/16/12	10/9/12	10/17/12	10/19/12	10/11/12
Fall/Winter Treatments	1/20/12	1/19/12	1/26/12	1/20/12	11/20/12	11/20/12	12/19/12	11/2/12	10/11/12
Feekes 4 Treatments	3/26/12	3/20/12	3/20/12	3/7/12	2/19/13	2/19/13	3/19/13	3/29/13	3/19/13
Feekes 7 Treatments	4/5/12	.	3/30/12	3/26/12	4/15/13	4/15/13	4/25/13	4/25/13	4/22/13
Feekes 9 Treatments	4/11/12	.	4/6/12	4/6/12	5/6/13	5/6/13	5/10/13	5/6/13	5/10/13
Harvest Date	6/6/12	Freeze-Failed	6/8/12	6/6/12	7/2/13	7/2/13	7/1/13	7/3/13	7/1/13

Sampling Methods

Soil Sampling and Analysis

Soil sampling was conducted using a 2.54 cm diameter hand soil probe to a 90 cm depth throughout each field site to check for restrictive layers that may result in perched water tables and potentially affect the N loss potential of the given location. However, with the exception of 2013 Manhattan Field C Blocks three and four, all other locations utilized in 2012 and 2013 had well-maintained soils with no compaction layers found within the top 90 cm soil profile.

A single composite soil sample consisting of 15 cores was taken at both 0-15 and 0-60 cm depth, across each study area prior to planting and fertilization. The 0-15 cm samples were analyzed for soil pH, organic matter by Walkley Black, Mehlich-3 phosphorus, and NH_4AC exchangeable potassium. The 0-60 cm samples were analyzed for nitrate-N, chloride, and sulfate-sulfur. Soil nutrient analysis data are summarized in Table 2.4. All samples were analyzed by the KSU Soil Testing Laboratory using procedures recommended by NCERA-13 (Denning et al., 2011). Additional fertilization for nutrients other than N was applied as per the KSU soil test analysis recommendations. The 2012 Gypsum location soil nutrient analysis showed a 12 mg kg^{-1} Mehlich-3 P test (Table 2.4). Therefore the 2012 Gypsum location received 90 kg ha^{-1} P_2O_5 in the form of Mosaic MESZ (10-40-0-10-1) by the collaborating producer, and Triple Superphosphate (0-46-0) by KSU soil fertility research crew at-planting to ensure adequate P. No other locations received fertilizer supplementations other than N. No visual deficiencies of other nutrients were observed.

Table 2.4 2012 and 2013 Soil Nutrient Analysis Across Locations

Year	2012	2012	2012	2012	2013	2013	2013	2013	2013
Location	Manhattan Field J3	Sterling	Gypsum	Manhattan Field F	McCune	Pittsburg	Solomon	Manhattan Field C	Partridge
Soil pH	5.5	6.2	6.9	6.9	5.9	4.6	5.9	6.9	6.0
Soil 0-15 cm O.M. g kg^{-1}	25.0	14.0	26.0	21.0	18.0	19.0	26.0	24.0	16.0
Soil 0-15 cm Mehlich-3 P mg kg^{-1}	21.5	37.3	12.0	48.7	21.8	23.5	33.8	43.8	51.0
Soil 0-15 cm K mg kg^{-1}	312.0	257.0	205.0	287.0	130.0	140.0	133.0	401.0	309.0
Soil 0-60 cm NO_3-N kg N ha^{-1}	24.0	13.0	13.7	96.8	93.5	220.1	45.9	10.5	70.2
Soil 0-60 cm Cl mg kg^{-1}	2.0	2.3	7.4	13.0	23.3	20.6	3.3	4.0	1.4
Soil 0-60 cm SO_4-S mg kg^{-1}	6.7	2.6	6.5	6.7	4.0	9.5	7.3	5.7	4.0

Precipitation Data

Precipitation data were collected from each site every crop year using the closest location available on the KSU Mesonet. Data were collected prior to planting through grain harvest and daily sums for precipitation were tabulated into specific groups pertaining to winter wheat's current yield determining physiological stages (Table 2.5) for that period.

Table 2.5 Precipitation Summary Groups by Yield Determining Periods

Yield Determining Periods	2012	2013
Preplant	August-September	August-September
Fall Tillering and Stand Establishment	October-November	October-November
Spring Tillering	December-February	December-March
Growth and Development	March-April	April-May
Grainfill	May	June

These yield factor physiological growth stages can be addressed in the Feekes scale (Miller, 1999) as follows:

1. Preplant addresses adequate precipitation for germination and development of uniform wheat stands under Feekes 1
2. Fall tillering and stand establishment consists of Feekes 2 and 3
3. Spring tillering and spring green up is the mark for Feekes 4
4. Growth and development
    a. Feekes 5, head size determination
    b. Feekes 6 through 7, rapid stem elongation, spike expansion, and flag leaf formation
    c. Feekes 8 and 9, Flag leaf formation
    d. Feekes 10, boot and flowering period
5. Grain Fill
    a. Feekes 11, grain development and ripening

Grain Harvest

All experiment sites were machine harvested with a plot combine from an area of 1.5 meters by 12 meters. The grain from the harvested area was placed into a sack, weighed, and a subsample taken for analysis. The subsamples were then analyzed for moisture and test weight using a moisture meter. Grain yield was adjusted to 125 g kg^{-1} moisture. Grain samples were submitted to the KSU Soil Testing Lab for analysis to obtain grain N concentrations for calculating total grain N uptake (Eq. 2.1) and grain protein (Eq. 2.2). Analysis of grain N was performed using a sulfuric acid peroxide digestion (Denning, 2011).

$$Total\ Grain\ N\ Uptake\ (kg\ N\ ha^{-1}) =$$
$$\left(Grain\ Yield\ \frac{Mg}{ha}\ x\ \frac{1000\ kg}{Mg}\right) x\ (Grain\ N\,\frac{g}{kg}\ x\ \frac{kg}{1000\ g}) \qquad \text{[Eq. 2.1]}$$

$$Grain\ Protein\ (g\ kg^{-1}) = \ Grain\ N\ (g\ kg^{-1})\ x\ 6.25 \qquad \text{[Eq. 2.2]}$$

Statistical Analysis

Statistical Model

A generalized linear mixed effects model was utilized to model grain yield, grain protein, and total grain N uptake data for interpretation. "Treatment" is representative of the two-way treatment structure of N timing and N rate split ratio that is analyzed as a one-way treatment structure. Precipitation summary groups as shown in Table 2.5 were treated as random effects to account for the year to year variability of precipitation throughout the growing season. Location, blocks within location, and block by treatment within location were also treated as random effects.

Statistical and Graphing Software

Statistical analysis of the data was conducted with SAS 9.3 (SAS Institute, 2011) utilizing UNIVARIATE and GLIMMIX procedures. Tables and graphical representations of the dataset were created with EXCEL (Microsoft, 2013)

Analysis of Data

Normality of the response variable grain yield was assessed using the UNIVARIATE PROCEDURE with the NORMAL and HISTOGRAM NORMAL options. Assessment of normality was conducted across sites with the exception of Pittsburg location. The Pittsburg location was removed due to severe lodging conditions. Table 2.6 summarizes the assessment of normality and suggests that the normal distribution does not fit the data perfectly. However, Figure 2-2 shows the histogram distribution of grain yield data with a high percentage of observations between 2.7 and 3.3 Mg ha^{-1}. This is not surprising; these yield ranges can be considered around the average for the state that is usually a result of lack of precipitation during grain fill. The normal distribution provided acceptable approximations of confidence intervals and across the quartile range and therefore was utilized for data analysis.

Table 2.6 Assessment of Normality for Grain Yield across Sites

Test	Statistic		Pvalue
Shapiro-Wilk	0.97	Pr<W	<0.0001
Kilmogorox-Smirnov	0.11	Pr>D	>0.01
Cramer-von Mises	0.91	Pr>W-Sq	>0.005
Anderson-Darling	5.01	Pr>A-Sq	>0.005

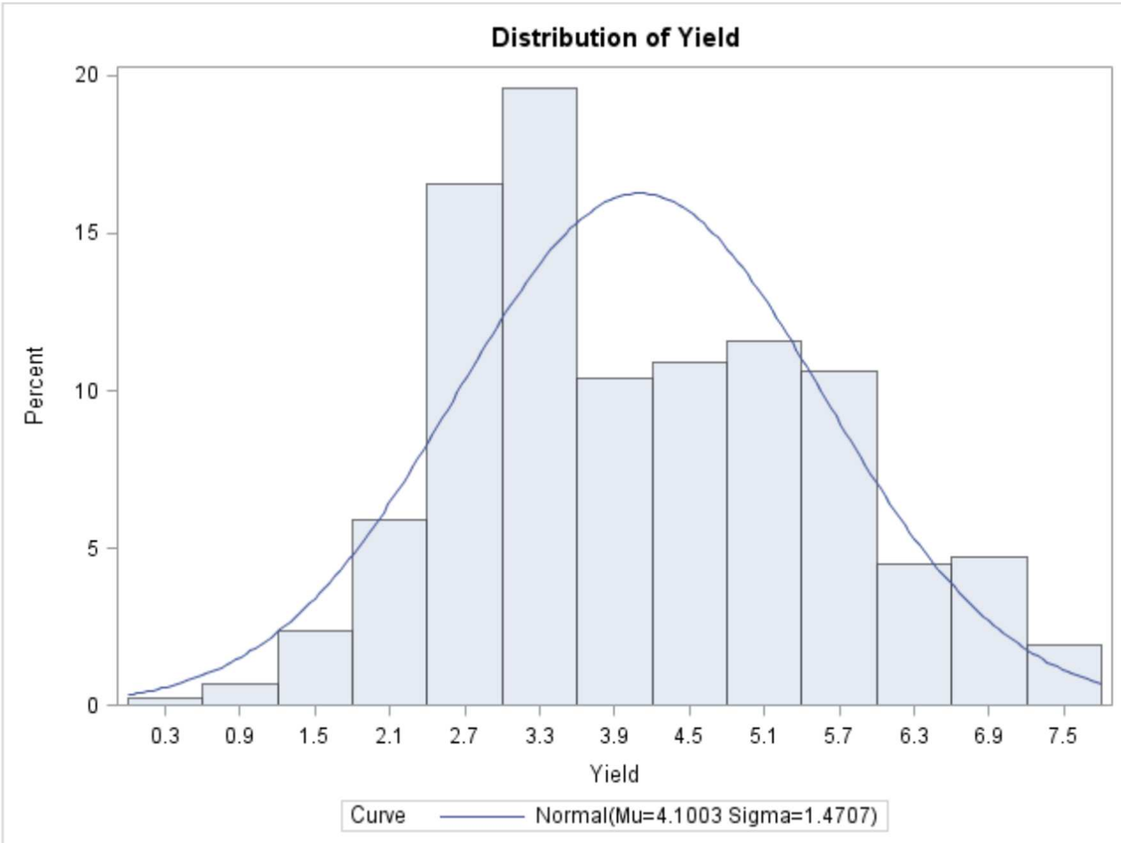

Figure 2-2 Histogram Distribution of Grain Yield (Mg ha^{-1}) across Sites

Hypothesis Testing

The GLIMMIX PROCEDURE was utilized with the Kenward-Rodgers denominator degrees of freedom method and Fisher's Protected LSD adjustment for testing hypotheses relevant to the objectives of this study. Alpha level was set to 0.1 for individual site analysis and 0.05 for pooled across site analysis.

Results and Discussion

By Year and Location

2012 Weather Conditions and Potential Impact on Grain Yield Components

2011-2012 locations received ample precipitation in fall and winter coupled with mild temperatures during the winter to provide adequate of moisture and heat units to tiller through most of the winter season (Figure 2-3). Heat units never fully dropped for a long dormancy period and show that warm conditions came early as the wheat entered spring tillering. This resulted in winter wheat looking exceptional at the start of spring and misleading local wheat producers into believing 2012 would be an exceptional wheat year. However, precipitation and heat units decreased as growth and development stages began (Figure 2-3). This resulted in potential reductions in head size due to water stress and continued tiller abortion from winter growth that could not be supported due to potential inadequate precipitation. Precipitation continued to decrease as the wheat entered grain fill and generated drought conditions, further increasing the potential for yield loss (Figure 2-3).

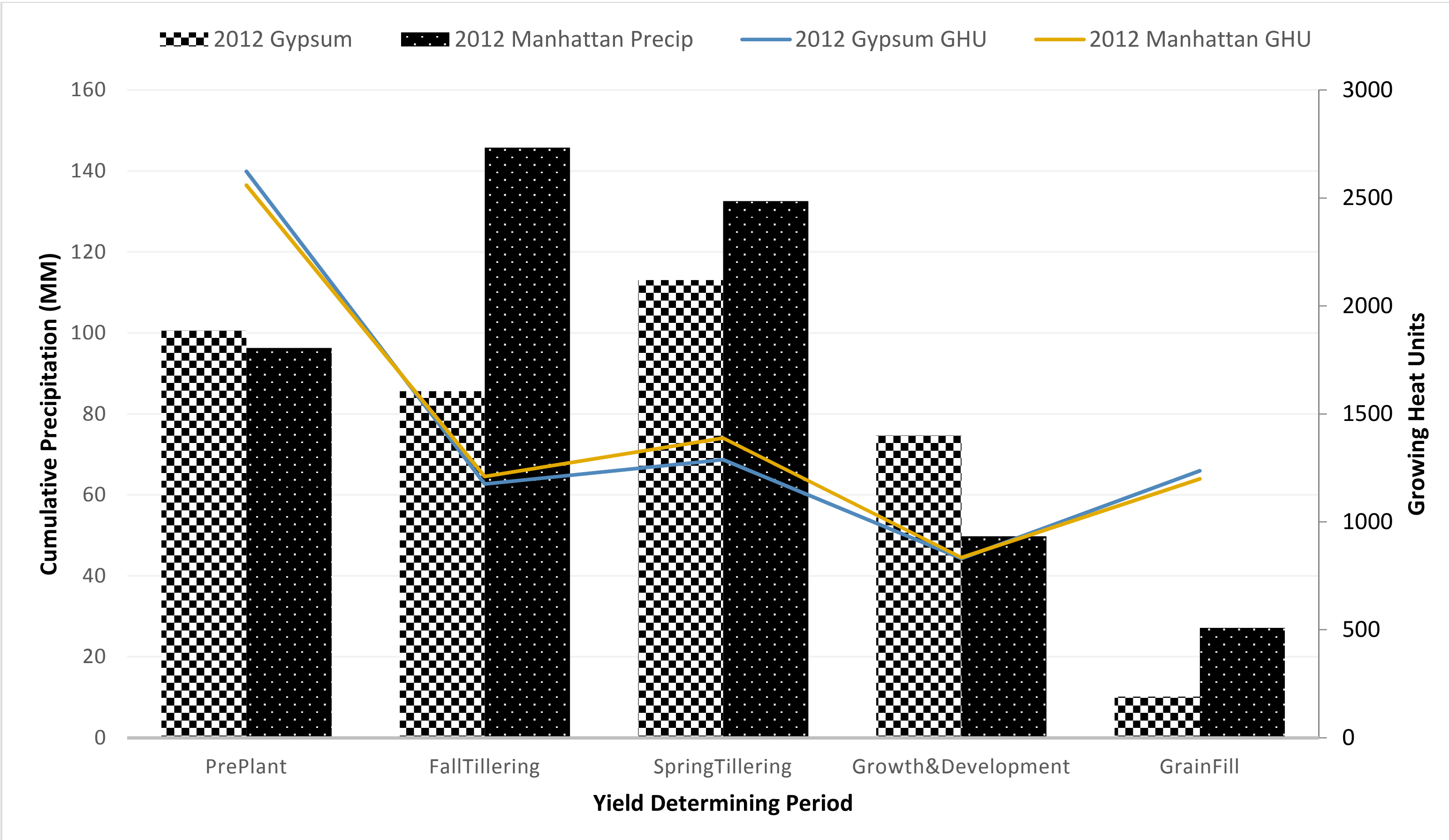

Figure 2-3 2012 Locations' Cumulative Precipitation and Growing Heat Units by Yield Determining Period

2012 Manhattan Field F Analysis

The Manhattan Field F location was the most productive out of all the 2012 locations. The control No N applied treatment averaged 3.82 Mg ha^{-1} grain yield due to the high levels of residual profile nitrate (Table 2.4), high water holding capacity (Table 2.2), and potential N mineralization. Limited grain yield response to applied N was observed. Overall grain yield limitations were likely due to high density of stems as a result of good early season growth and low precipitation during grain fill (Figure 2-3). Despite the application of fungicide, disease pressure was high in plots where the majority of N was applied in the fall or at Feekes 4. Figure 2-4 shows that only one precipitation event greater than 35 mm took place over the winter after N applications, and N loss potential for the winter treatments were low. Therefore, Feekes 4 treatments did not provide a statistical advantage over fall treatments concerning grain yield, protein, and total grain N uptake (Table 2.7).

Feekes 9 split treatment with fall 34 kg/Feekes 9 100 kg had numerically higher grain yield and protein over Feekes 4 treatments and had the statistically highest total grain N uptake (Table 2.7). Feekes 9 split treatments with a fall 34 kg/Feekes 9 100 kg and fall 67 kg/Feekes9 67 kg provided the best balance of grain yield, protein, and total grain N uptake (Table 2.7).

Table 2.7 2012 Manhattan Field F Summary Statistics for Grain Yield, Grain Protein, and Total Grain Nitrogen Uptake

Starter N	Fall/Winter	Feekes 4	Feekes 7	Feekes 9	Total N	Grain Yield	GY LSD Group	Grain Protein	GP LSD Group	Total Grain N Uptake	TotGNUP LSD Group
N Application Rate kg N ha^{-1}						Mg ha^{-1}		g kg^{-1}		kg N ha^{-1}	
10	0	0	0	0	10	3.82	BCDE	137	BCDE	82	DEF
10	34	0	0	0	44	4.22	ABC	129	E	84	DEF
10	67	0	0	0	77	3.14	DE	146	ABC	72	F
10	100	0	0	0	110	3.06	E	150	ABC	72	F
10	134	0	0	0	144	4.03	ABCD	143	ABCD	92	CDE
10	34	100	0	0	144	3.99	ABCD	142	ABCD	90	CDE
10	67	67	0	0	144	4.41	AB	134	CDE	94	CD
10	100	34	0	0	144	4.13	ABC	128	E	82	DEF
10	34	0	100	0	144	4.51	AB	142	ABCD	102	ABC
10	67	0	67	0	144	3.28	CDE	149	AB	78	EF
10	100	0	34	0	144	4.78	A	127	E	95	CD
10	34	0	0	100	144	4.86	A	150	A	117	A
10	67	0	0	67	144	4.92	A	143	ABCD	113	AB
10	100	0	0	34	144	4.78	A	132	DE	101	BC
SE						0.44		5.66		7.23	
F Value						2.60		2.62		4.56	
Treatment Pr > F						0.01		0.01		< 0.00	
Fisher's LSD Alpha = 0.1						0.94		12.11		15.36	

NS = Not significant

Treatments with same letter are not statisitcally different at 0.1 alpha

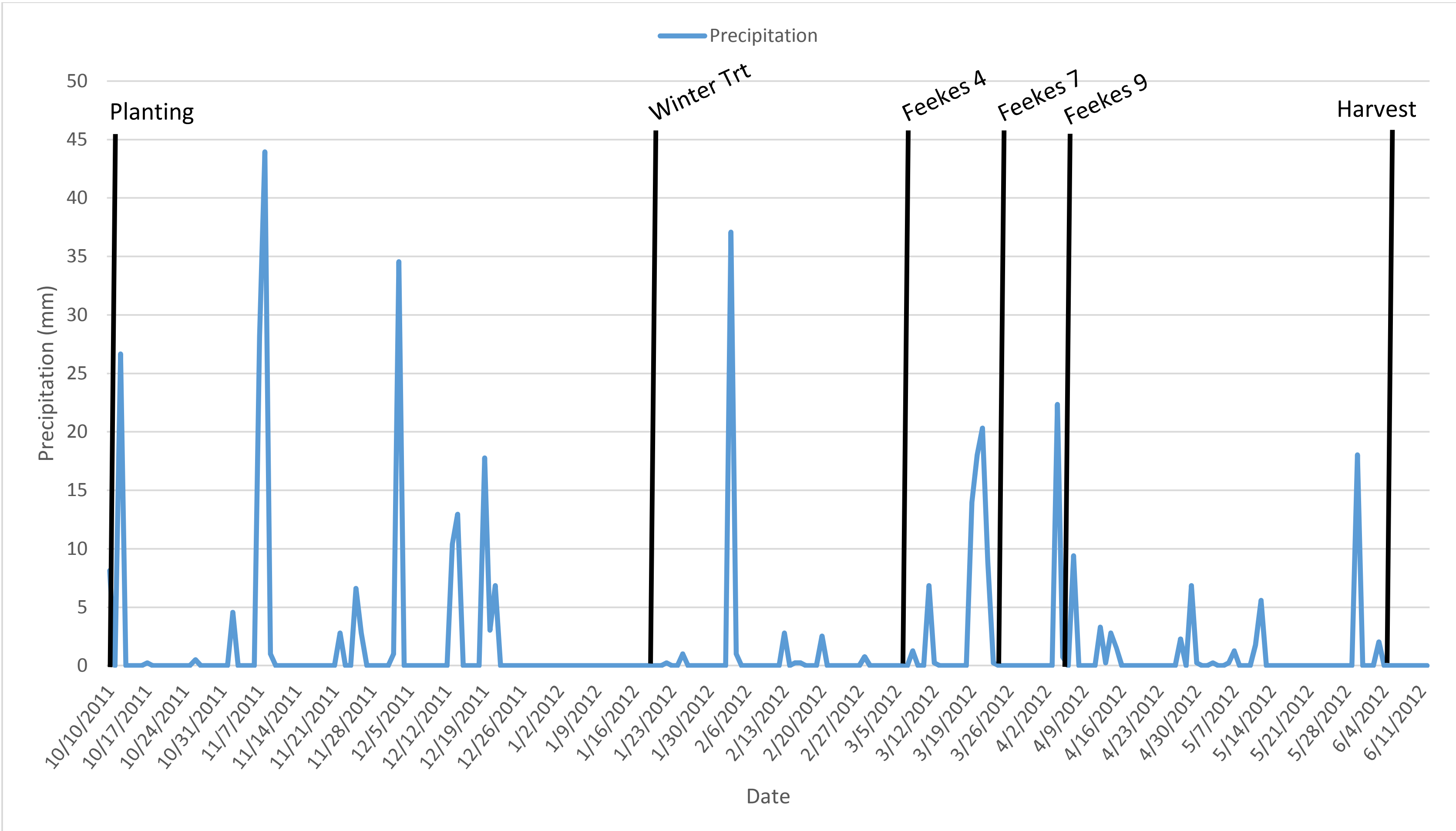

Figure 2-4 2012 Manhattan Field F Precipitation and Key Treatment Dates

2012 Manhattan Field J3 Analysis

Field J3, upland terraced ground with heavier clay content, presented increased risk for water stress that was met with periods of drought conditions, which limited overall production of grain yield (Table 2.8). Figure 2-5 shows there was limited precipitation during February and early March of 2012, which may have limited spring tiller formation. In addition, limited precipitation was observed from Mid-April through May of 2012, thus potentially having a detrimental impact on grain fill and further limiting overall grain yield potential.

Feekes 9 treatments received two three-millimeter precipitation events shortly application, which may have induced volatilization losses of N (Figure 2-5). However, the Feekes 9 treatments produced statistically equivalent grain yield, protein, and total N uptake compared to Feekes 4 treatments (Table 2.8). If volatilization occurred, it was not great enough to reduce grain yield compared to all other N rates greater than 100 kg N ha^{-1} (Table 2.8). Although some N response was observed at this location, the main grain yield-limiting factor was soil-available water during the 2011-2012 winter wheat crop-year.

Table 2.8 2012 Manhattan Field J3 Summary Statistics for Grain Yield, Grain Protein, and Total Grain Nitrogen Uptake

Starter N	Fall/Winter	Feekes 4	Feekes 7	Feekes 9	Total N	Grain Yield	GY LSD Group	Grain Protein	GP LSD Group	Total Grain N Uptake	TotGNUP LSD Group
N Application Rate kg N ha^{-1}						Mg ha^{-1}		g kg^{-1}		kg N ha^{-1}	
10	0	0	0	0	10	1.54	E	117	D	29	G
10	34	0	0	0	44	2.38	D	119	CD	45	F
10	67	0	0	0	77	2.53	BCD	124	C	50	EF
10	100	0	0	0	110	2.71	ABCD	133	B	57	CDE
10	134	0	0	0	144	2.86	AB	144	A	66	AB
10	34	100	0	0	144	3.08	A	145	A	72	A
10	67	67	0	0	144	2.69	ABCD	145	A	62	BCD
10	100	34	0	0	144	2.91	AB	145	A	67	AB
10	34	0	100	0	144	2.81	ABC	145	A	65	ABC
10	67	0	67	0	144	3.05	A	143	A	70	AB
10	100	0	34	0	144	2.42	CD	145	A	56	DE
10	34	0	0	100	144	2.69	ABCD	147	A	63	ABCD
10	67	0	0	67	144	2.72	ABCD	145	A	63	BCD
10	100	0	0	34	144	2.81	ABC	145	A	65	ABC
SE						0.21		3.55		4.10	
F Value						4.90		20.88		9.61	
Treatment Pr > F						< 0.00		< 0.00		< 0.00	
Fisher's LSD Alpha = 0.1						0.41		5.62		8.78	

NS = Not significant

Treatments with same letter are not statisitcally different at 0.1 alpha

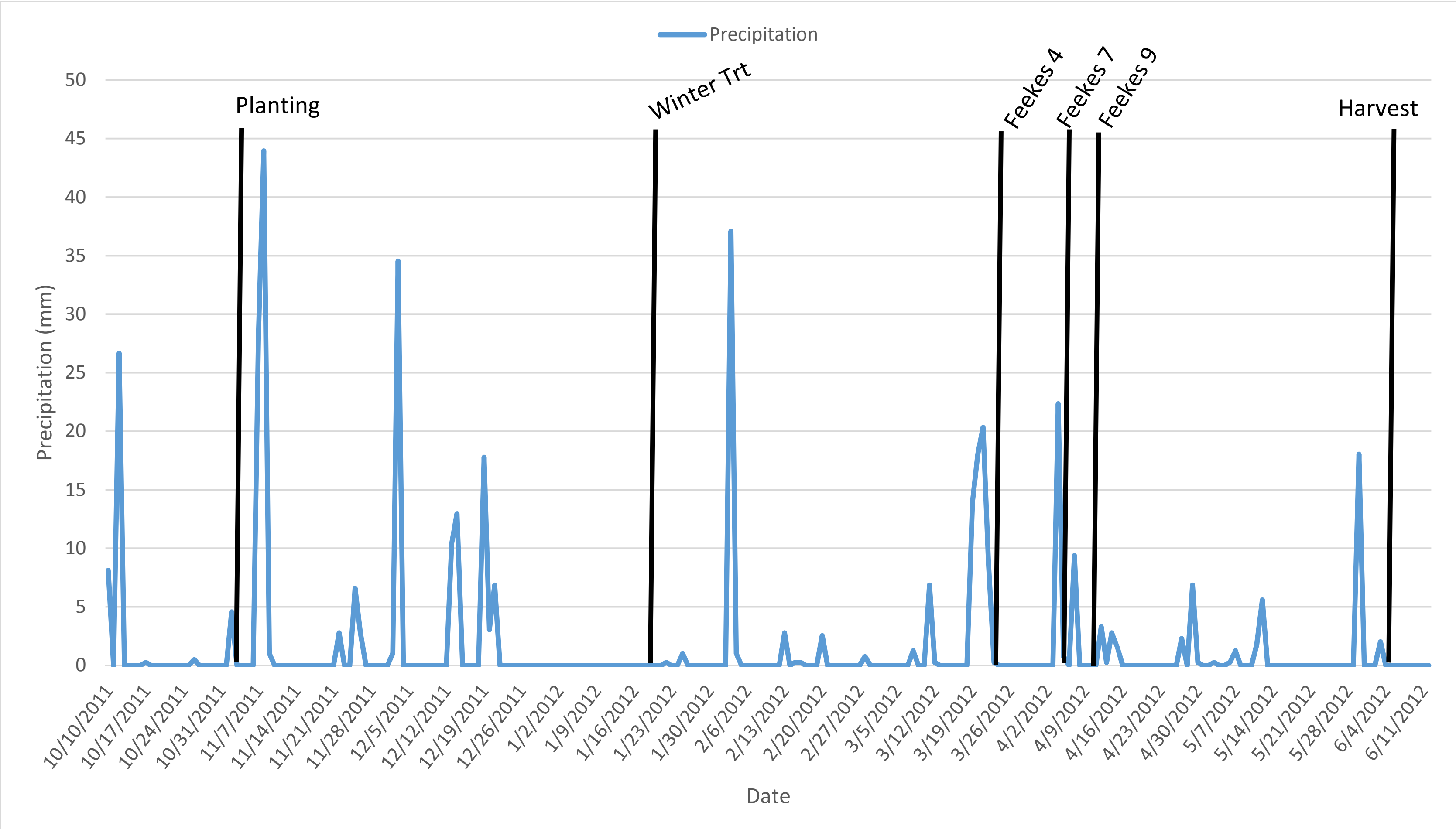

Figure 2-5 2012 Manhattan Field J3 Precipitation and Key Treatment Dates

2012 Gypsum Analysis

Gypsum generated much lower than expected yields (all <3.46 Mg ha-1) compared with collaborating producer's long-term field yield averages ranging from 4 to 4.5 Mg ha^{-1} (Table 2.9). The lack of precipitation from mid-April through May of 2012 (Figure 2-6) resulted in a grain yield cap and limited statistical response of grain yield to the timing of N applications was observed (Table 2.9). Additional considerations for reductions in overall grain yield could be attributed to potential N loss. Figure 2-6 shows precipitation events greater than 25 mm occurred after each Feekes 4, 7, and 9 treatments. The plots were located in bottom position ground with depression areas, which had observed pooling after each one these events, which may have led to denitrification losses of N.

Additionally, high levels of early season growth were observed over the fall and winter months, which may have been a contributor to the late-season water stress that resulted in overall grain yield reductions. Weed, insect, and disease pressure were low and not likely a contributor to the overall reduced grain yield. Feekes 7 split treatment with fall 34 kg/Feekes 7 100 kg provided the best balance of grain yield, protein, and the numerically highest total grain N uptake.

Table 2.9 2012 Gypsum Summary Statistics for Grain Yield, Grain Protein, and Total Grain Nitrogen Uptake

Starter N	Fall/Winter	Feekes 4	Feekes 7	Feekes 9	Total N	Grain Yield	GY LSD Group	Grain Protein	GP LSD Group	Total Grain N Uptake	TotGNUP LSD Group
N Application Rate kg N ha^{-1}						Mg ha^{-1}		g kg^{-1}		kg N ha^{-1}	
13	0	0	0	0	13	0.84	F	144	BCD	19	G
13	34	0	0	0	47	2.16	E	126	F	43	F
13	67	0	0	0	80	2.52	DE	137	CDE	55	E
13	100	0	0	0	113	3.12	ABC	134	EF	67	CD
13	134	0	0	0	147	2.92	BCD	140	CDE	65	D
13	34	100	0	0	147	3.19	ABC	145	BC	74	ABC
13	67	67	0	0	147	3.31	AB	145	BCD	76	AB
13	100	34	0	0	147	3.32	AB	139	CDE	74	ABCD
13	34	0	100	0	147	3.29	AB	152	B	80	A
13	67	0	67	0	147	3.12	ABC	142	CDE	70	BCD
13	100	0	34	0	147	3.29	AB	141	CDE	74	ABC
13	34	0	0	100	147	2.82	CD	163	A	73	ABCD
13	67	0	0	67	147	3.15	ABC	153	B	77	AB
13	100	0	0	34	147	3.46	A	136	DE	75	AB
SE						0.20		3.84		3.76	
F Value						13.30		6.31		22.98	
Treatment Pr > F						< 0.00		< 0.00		< 0.00	
Fisher's LSD Alpha = 0.1						0.45		8.60		8.32	

NS = Not significant

Treatments with same letter are not statisitcally different at 0.1 alpha

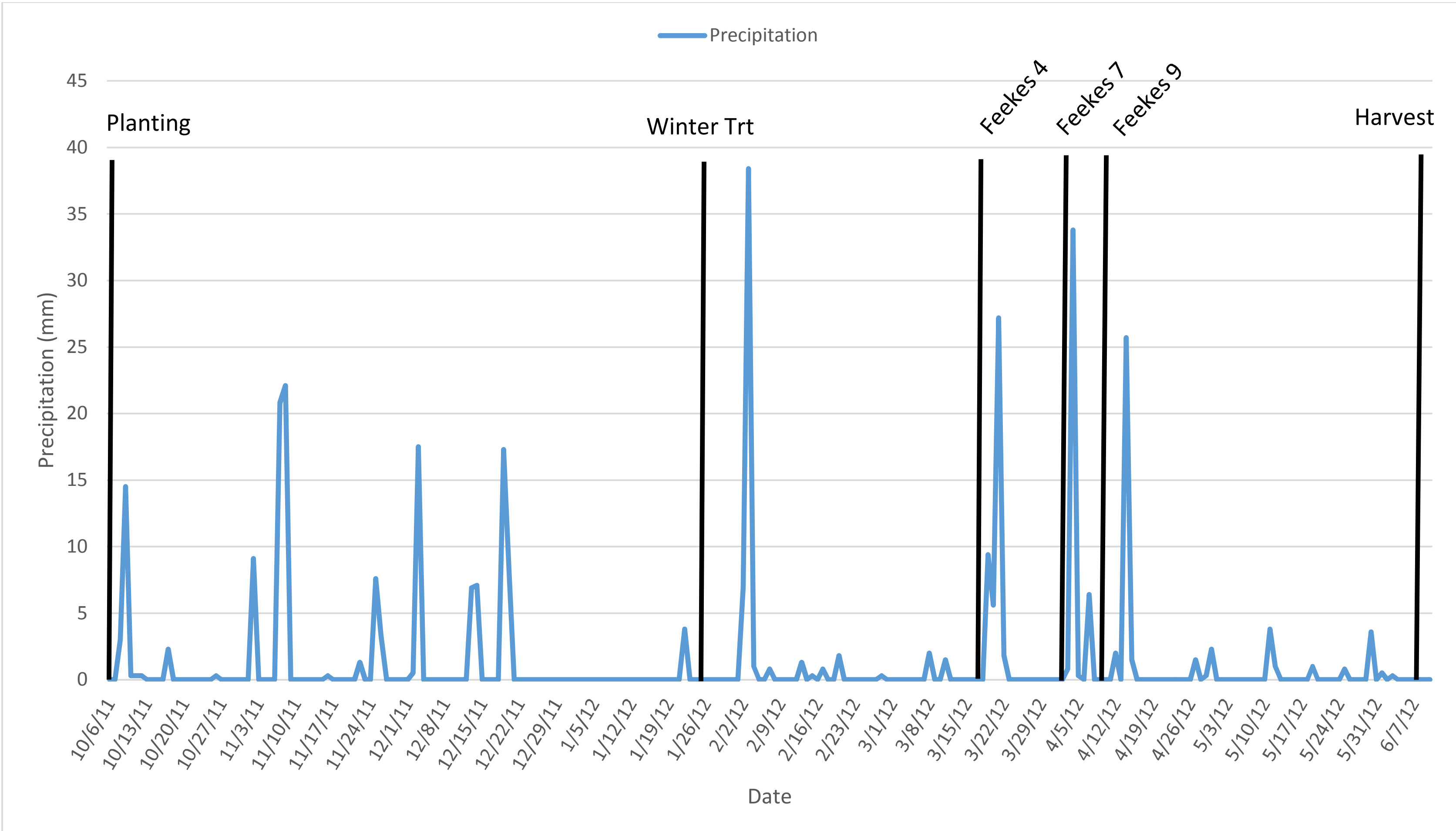

Figure 2-6 2012 Gypsum Precipitation and Key Treatment Dates

2013 Weather Conditions and Potential Impact on Grain Yield Components

2012-2013 was the opposite of 2011-2012 in terms of weather and productivity. Ample precipitation was observed for germinating uniform wheat stands (Figure 2-7). However, precipitation dramatically decreased for the fall tillering period resulting in the Manhattan and Solomon locations having limited fall tiller formation. Local winter wheat producer outlook on wheat conditions were low with considerations for killing their wheat crop in favor of then planting grain sorghum. The spring tillering period received adequate precipitation for generating additional tillers, but had lower cumulative heat units when compared to 2012 during this period, thus providing an environment very conducive for spring tiller production (Figure 2-7). An important difference between 2012 and 2013 during this period was that 2013 had four months for spring tillering as compared to only three months with 2012 (Table 2.5). This can be attributed to the cooler temperatures and reduced winter wheat growth over the fall and winter, which in combination with lower plant water requirements and overall water use. The growth and development period in 2013 was met with considerable precipitation at all locations with continued low heat units (Figure 2-7). This helped reduce the potential water stress and potentially maximize head size. The 2013 winter wheat crop entered grain filling period with the soil profile full of moisture and received some precipitation through this period (Figure 2-7).

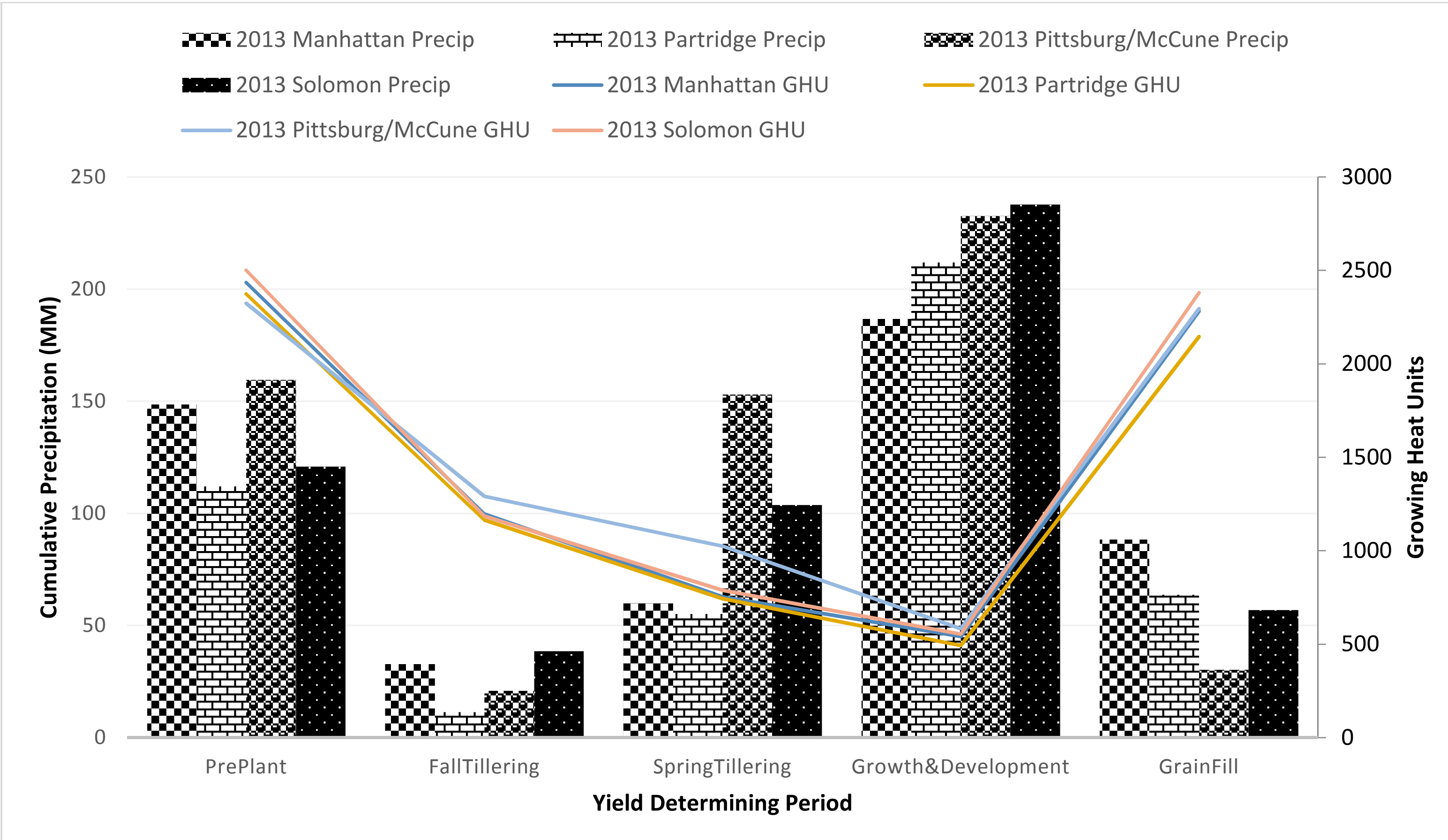

Figure 2-7 2013 Locations' Cumulative Precipitation and Growing Heat Units by Yield Determining Periods

2013 Partridge Analysis

Overall N response to applied N was low at Partridge. No statistical grain yield response to applied N was observed (Table 2.10). This was likely due to three primary reasons. First, the high residual N in the soil profile at 70 kg ha^{-1} (Table 2.4); second, low precipitation during tillering and stand establishment period (Figure 2-7); third, the inadequate weed control of cheat (*Bromus secalinus*) may have reduced available water, which may have led to reductions in winter wheat grain yield capacity. Therefore with overall yield components reduced, the high residual profile nitrate provided enough N to achieve the winter wheat's maximum grain yield (Table 2.10).

Frequent precipitation events occurred during April 2013 and one 78 mm precipitation event in May (Figure 2-8) greatly increased the potential for nitrate leaching losses in the Taver loam soil. This would have had a larger effect on fall and Feekes 4 treatments as they were subjected to all of the precipitation events in April and May. Grain protein content was very high across all treatments except for Feekes 9, but Feekes 9 treatments had a trending increase in grain yields (Table 2.10).

Table 2.10 2013 Partridge Summary Statistics for Grain Yield, Grain Protein, and Total Grain Nitrogen Uptake

Starter N	Fall/Winter	Feekes 4	Feekes 7	Feekes 9	Total N	Grain Yield	GY LSD Group	Grain Protein	GP LSD Group	Total Grain N Uptake	TotGNUP LSD Group
N Application Rate kg N ha^{-1}						Mg ha^{-1}		g kg^{-1}		kg N ha^{-1}	
30	0	0	0	0	30	3.18	NS	120	H	61	F
30	34	0	0	0	64	3.26	NS	124	H	64	F
30	67	0	0	0	97	3.59	NS	141	G	80	CDE
30	100	0	0	0	130	3.17	NS	153	DEF	77	E
30	134	0	0	0	164	3.04	NS	167	ABC	81	BCDE
30	34	100	0	0	164	3.33	NS	162	ABCD	86	ABCD
30	67	67	0	0	164	3.05	NS	164	ABCD	80	DE
30	100	34	0	0	164	3.15	NS	157	CDEF	79	DE
30	34	0	100	0	164	3.35	NS	168	AB	89	A
30	67	0	67	0	164	3.46	NS	155	DEF	85	ABCDE
30	100	0	34	0	164	2.99	NS	170	A	81	ABCDE
30	34	0	0	100	164	3.73	NS	147	EFG	88	ABC
30	67	0	0	67	164	3.58	NS	146	FG	83	ABCDE
30	100	0	0	34	164	3.52	NS	158	BCDE	89	AB
SE						0.20		7.92		3.42	
F Value						1.58		10.51		6.22	
Treatment Pr > F						0.13		< 0.00		< 0.00	
Fisher's LSD Alpha = 0.1						NS		11.34		7.97	

NS = Not significant

Treatments with same letter are not statisitcally different at 0.1 alpha

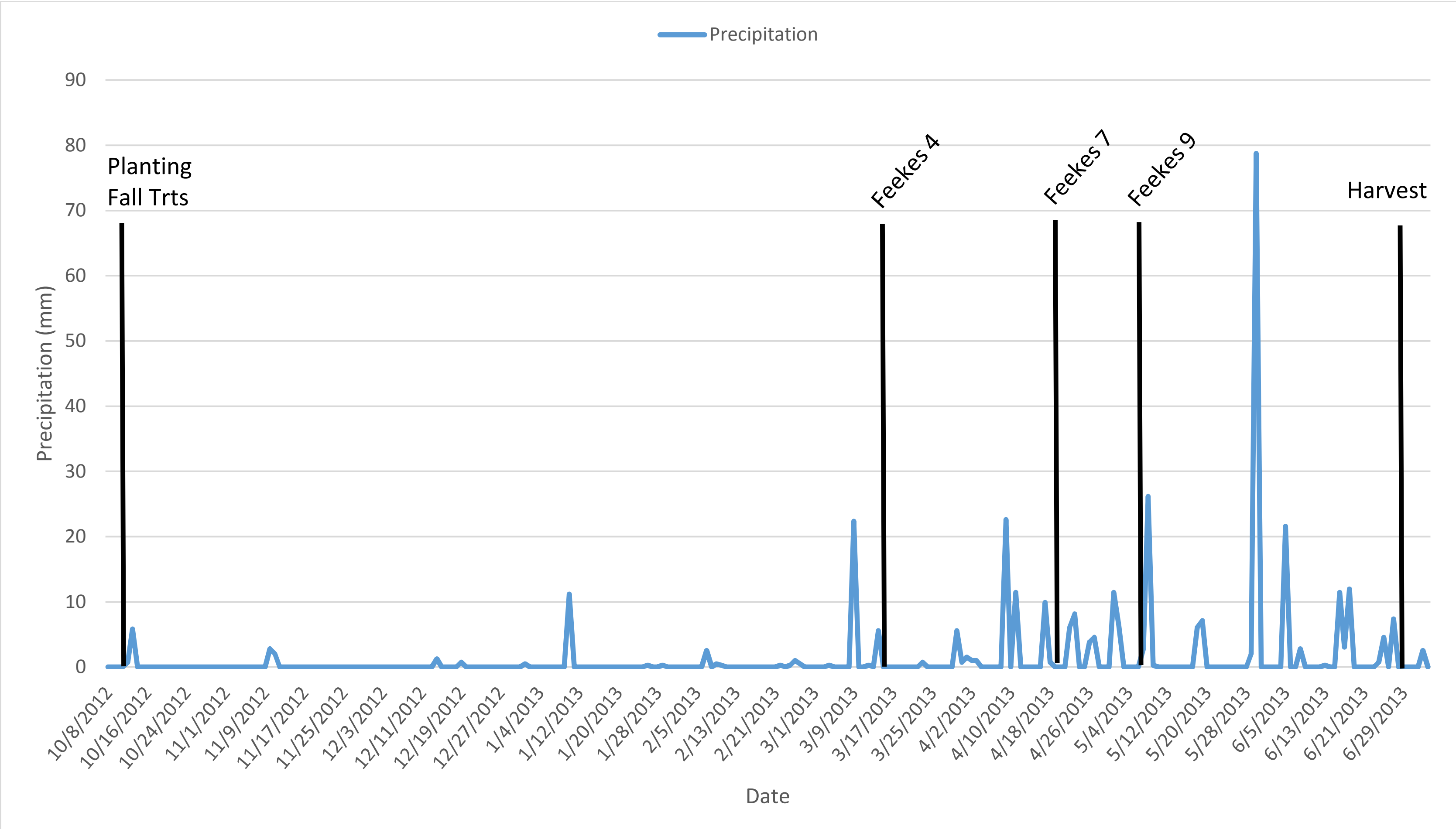

Figure 2-8 2013 Partridge Precipitation and Key Treatment Dates with Fall Treatments being Applied at Planting

2013 Manhattan Field C

The winter wheat crop at Manhattan Field C entered the spring season with limited growth, but was able to generate adequate spring growth for producing high grain yield (Table 2.11). Frequent precipitation events occurred mid-March and through harvest (Figure 2-9), which presented good spring tillering conditions to facilitate good spring growth. Potential for N loss was low, and no disease or insect pressure was observed. Limited statistical differences in grain yield and protein were observed across fall and Feekes 4, Feekes 7, or Feekes 9 treatments, which received the 134 kg N ha^{-1} rate (Table 2.11). However, Feekes 9 treatments provided the best balance of grain yield, protein, and the numerically highest total grain N uptake.

Table 2.11 2013 Manhattan Field C Summary Statistics for Grain Yield, Grain Protein, and Total Grain Nitrogen Uptake

Starter N	Fall/Winter	Feekes 4	Feekes 7	Feekes 9	Total N	Grain Yield	GY LSD Group	Grain Protein	GP LSD Group	Total Grain N Uptake	TotGNUP LSD Group
N Application Rate kg N ha^{-1}						Mg ha^{-1}		g kg^{-1}		kg N ha^{-1}	
20	0	0	0	0	20	2.74	F	106	FG	45	G
20	34	0	0	0	54	3.86	E	103	G	64	F
20	67	0	0	0	87	4.37	D	109	FG	76	E
20	100	0	0	0	120	4.71	BCD	113	EF	85	DE
20	134	0	0	0	154	4.97	AB	127	BCD	99	ABC
20	34	100	0	0	154	4.61	BCD	122	CD	89	CD
20	67	67	0	0	154	4.86	ABC	126	BCD	98	ABC
20	100	34	0	0	154	4.70	BCD	129	ABC	96	BC
20	34	0	100	0	154	4.73	BCD	128	BC	96	BC
20	67	0	67	0	154	4.57	CD	123	CD	89	CD
20	100	0	34	0	154	5.20	A	118	DE	98	ABC
20	34	0	0	100	154	4.88	ABC	135	AB	104	AB
20	67	0	0	67	154	4.92	ABC	136	A	107	A
20	100	0	0	34	154	4.90	ABC	129	ABC	100	AB
SE						0.35		6.45		5.75	
F Value						15.50		8.03		14.78	
Treatment Pr > F						< 0.00		< 0.00		< 0.00	
Fisher's LSD Alpha = 0.1						0.37		8.73		10.53	

NS = Not significant

Treatments with same letter are not statisitcally different at 0.1 alpha

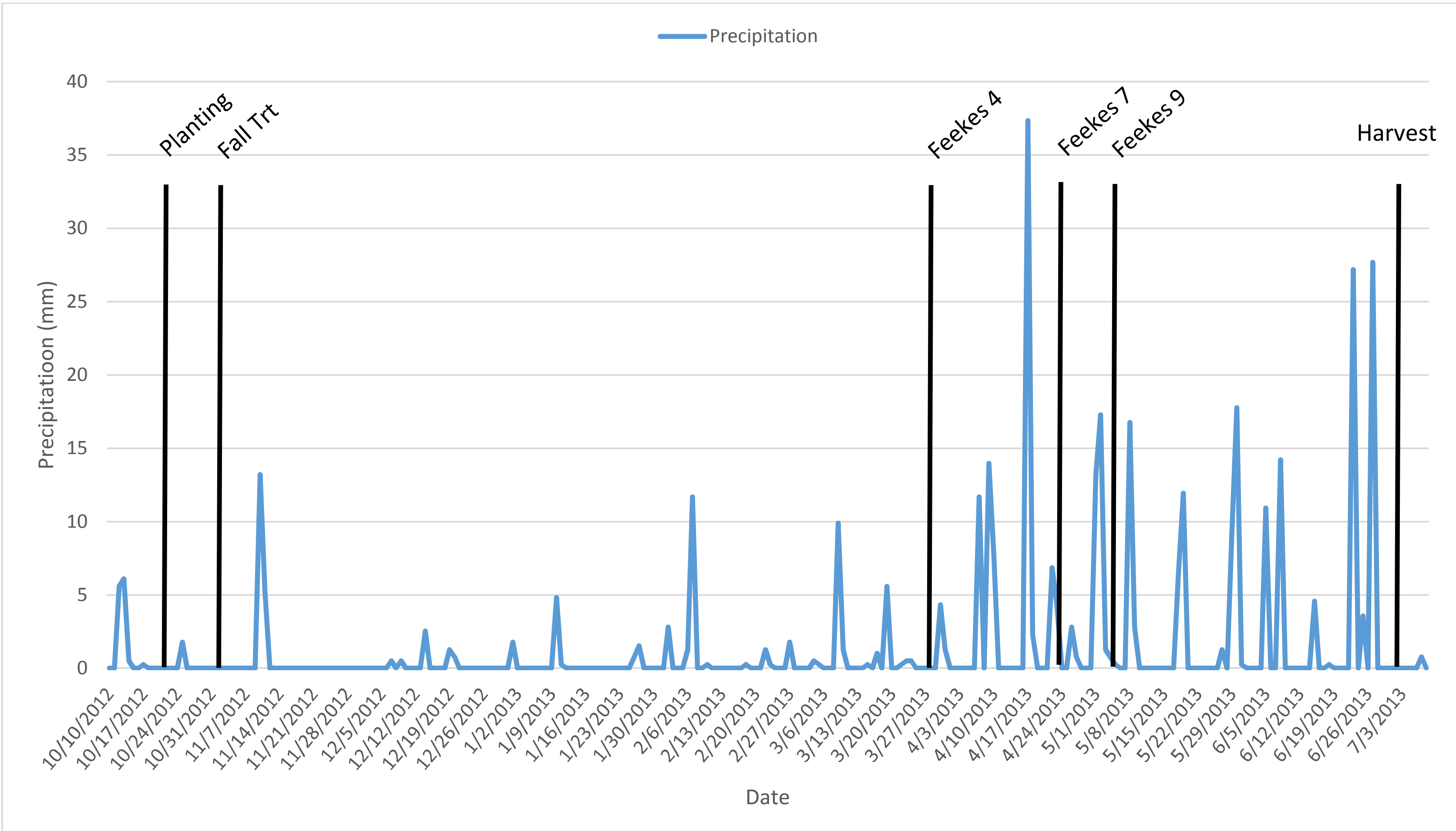

Figure 2-9 2013 Manhattan Field C Precipitation and Key Treatment Dates

2013 Solomon Analysis

Field conditions in the early spring were almost identical to those at Manhattan Field C. Limited winter wheat growth was observed over the fall and winter months and substantial spring growth would be needed to generate high grain yield. Adequate precipitation was received in February through mid-March to facilitate good tillering and early spring growth (Figure 2-10). Frequent precipitation events occurred in April together with a 70 mm event in May that provided soil moisture to facilitate good conditions for grain fill. However, these events also raised the potential for denitrification losses at this site.

Excellent grain yield response to applied N was observed with grain yields exceeding 5 Mg ha^{-1} with total applied N rates greater than 90 kg N ha^{-1} (Table 2.12). Fall-applied N applications and those at Feekes 4 produced good grain yields exceeding 5 Mg ha^{-1} (Table 2.12). However, where large amounts of N such as 100 kg ha^{-1} applied at Feekes 7 or greater than 67 kg ha^{-1} applied at Feekes 9, grain yields were significantly higher (Table 2.12). This was likely due to the significant precipitation in April and May, which may have created conditions for denitrification loss from N applied prior to this wet period (Figure 2-10)

Grain protein levels in general were low at this site (Table 2.12). This supports observations of Cassman (1992) and Hawksford (2012) that high grain yield in winter wheat systems produces high levels of carbohydrates that result in the dilution of grain protein. The Feekes 9 split N treatments of fall 34 kg/Feekes 9 100 kg and fall 67 kg/Feekes 9 67 kg applied most of its N after the frequent precipitation events in April therefore avoiding potential denitrification losses (Figure 2-10). Fall 34 kg/Feekes 9 100 kg and fall 67 kg/Feekes 9 67 kg generated the highest grain yield, protein, and grain N uptake (Table 2.12).

Table 2.12 2013 Solomon Summary Statistics for Grain Yield, Grain Protein, and Total Grain Nitrogen Uptake

Starter N	Fall/Winter	Feekes 4	Feekes 7	Feekes 9	Total N	Grain Yield	GY LSD Group	Grain Protein	GP LSD Group	Total Grain N Uptake	TotGNUP LSD Group
N Application Rate kg N ha^{-1}						Mg ha^{-1}		g kg^{-1}		kg N ha^{-1}	
26	0	0	0	0	26	3.67	G	90	FG	53	G
26	34	0	0	0	60	4.05	F	84	H	55	G
26	67	0	0	0	93	5.02	E	87	GH	70	F
26	100	0	0	0	126	5.38	D	90	FG	78	E
26	134	0	0	0	160	5.58	CD	95	EF	84	CDE
26	34	100	0	0	160	5.50	CD	102	C	90	BCD
26	67	67	0	0	160	5.38	D	96	DE	83	DE
26	100	34	0	0	160	5.55	CD	97	DE	86	CD
26	34	0	100	0	160	5.80	BC	102	C	95	B
26	67	0	67	0	160	5.68	CD	100	CD	91	BC
26	100	0	34	0	160	5.49	CD	95	DEF	83	CDE
26	34	0	0	100	160	6.11	AB	119	A	117	A
26	67	0	0	67	160	6.37	A	109	B	111	A
26	100	0	0	34	160	5.76	CD	97	CDE	90	BCD
SE						0.15		2.18		3.16	
F Value						25.53		17.24		31.32	
Treatment Pr > F						< 0.00		< 0.00		< 0.00	
Fisher's LSD Alpha = 0.1						0.34		5.17		7.53	

NS = Not significant

Treatments with same letter are not statisitcally different at 0.1 alpha

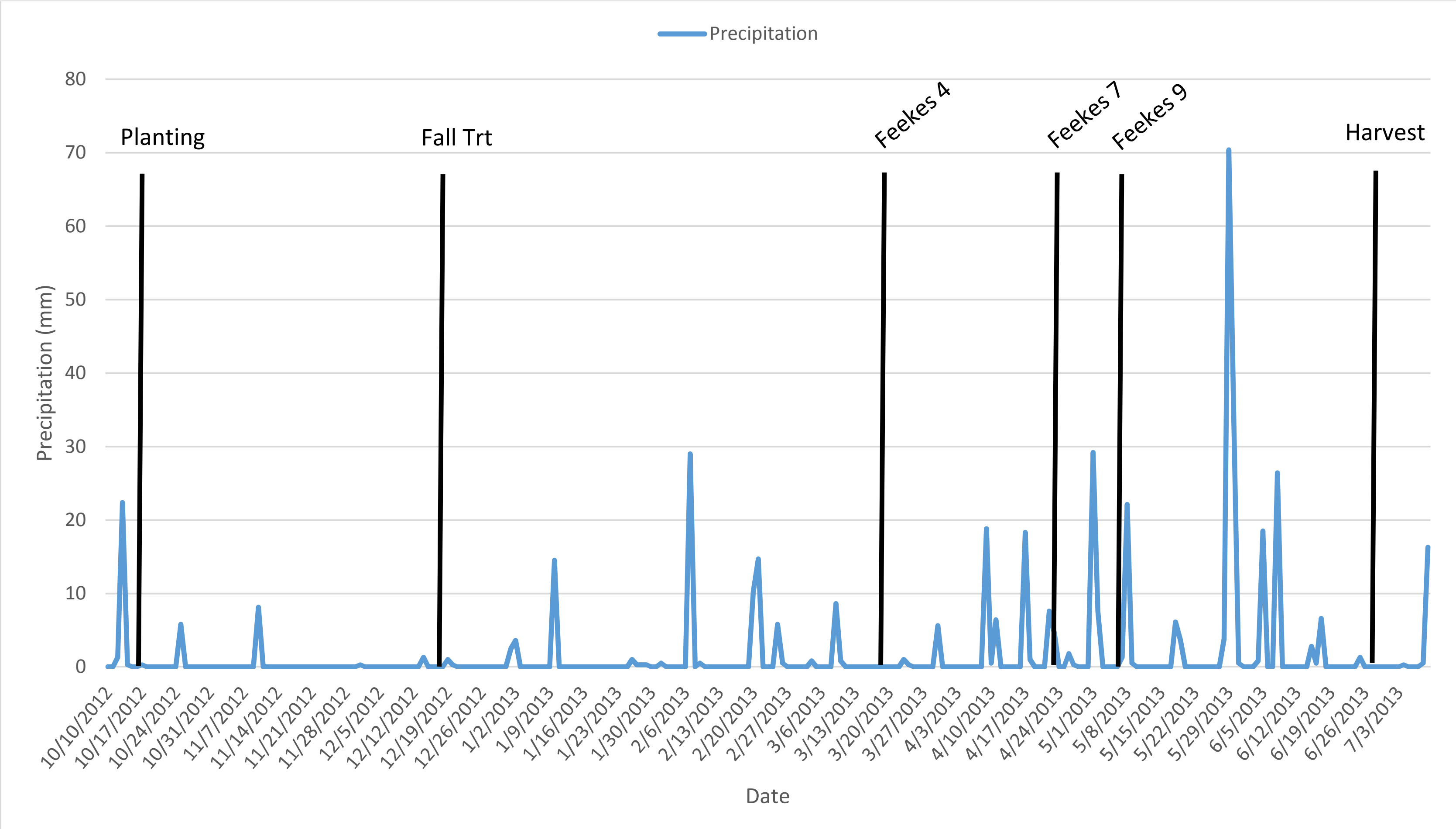

Figure 2-10 2013 Solomon Precipitation and Key Dates

2013 McCune Analysis

The McCune site produced excellent grain yield across all treatments and significant grain yield response to applied N was observed (Table 2.13). Frequent precipitation events occurred from February through May, with the intensity of these events increasing in April and May (Figure 2-11). These patterns of precipitation events increased the potential for denitrification in the claypan soils at this site. Results show that Feekes 9 treatments had a statistical decrease in grain yield compared to Feekes 4 and 7 treatments. This could be attributed to potential denitrification losses earlier in the growing season and the Feekes 9 application in May was not soon enough to prevent grain yield reductions from N stress. Although not statistically different from Feekes 4 treatments, the Feekes 7 treatments of fall 34 kg/Feekes 7 100 kg and fall 67 kg/Feekes 7 67 kg had a trending increase in grain yield (Table 2.13). Feekes 7 treatment 34 kg/Feekes 7 100 kg provided the best balance of grain yield, protein, and total grain N uptake (Table 2.13)

Table 2.13 2013 McCune Summary Statistics for Grain Yield, Grain Protein, and Total Grain Nitrogen Uptake

Starter N	Fall/Winter	Feekes 4	Feekes 7	Feekes 9	Total N	Grain Yield	GY LSD Group	Grain Protein	GP LSD Group	Total Grain N Uptake	TotGNUP LSD Group
N Application Rate kg N ha^{-1}						Mg ha^{-1}		g kg^{-1}		kg N ha^{-1}	
0	0	0	0	0	0	4.34	E	88	H	62	F
0	34	0	0	0	34	5.17	D	92	GH	76	EF
0	67	0	0	0	67	5.61	CD	92	GH	83	DE
0	100	0	0	0	100	6.96	AB	103	DEF	115	ABC
0	134	0	0	0	134	6.42	BC	95	FGH	98	CD
0	34	100	0	0	134	6.78	AB	114	ABC	125	AB
0	67	67	0	0	134	7.05	AB	111	BCD	125	AB
0	100	34	0	0	134	6.94	AB	106	CDE	117	ABC
0	34	0	100	0	134	7.36	A	114	ABC	135	A
0	67	0	67	0	134	7.11	AB	100	EFG	114	ABC
0	100	0	34	0	134	6.76	AB	103	DEF	112	BC
0	34	0	0	100	134	5.92	CD	122	A	116	ABC
0	67	0	0	67	134	5.85	CD	117	AB	109	BC
0	100	0	0	34	134	5.60	CD	111	BCD	100	CD
SE						0.34		4.88		8.87	
F Value						6.54		6.90		5.36	
Treatment Pr > F						< 0.00		< 0.00		< 0.00	
Fisher's LSD Alpha = 0.1						0.82		9.50		21.12	

NS = Not significant

Treatments with same letter are not statisitcally different at 0.1 alpha

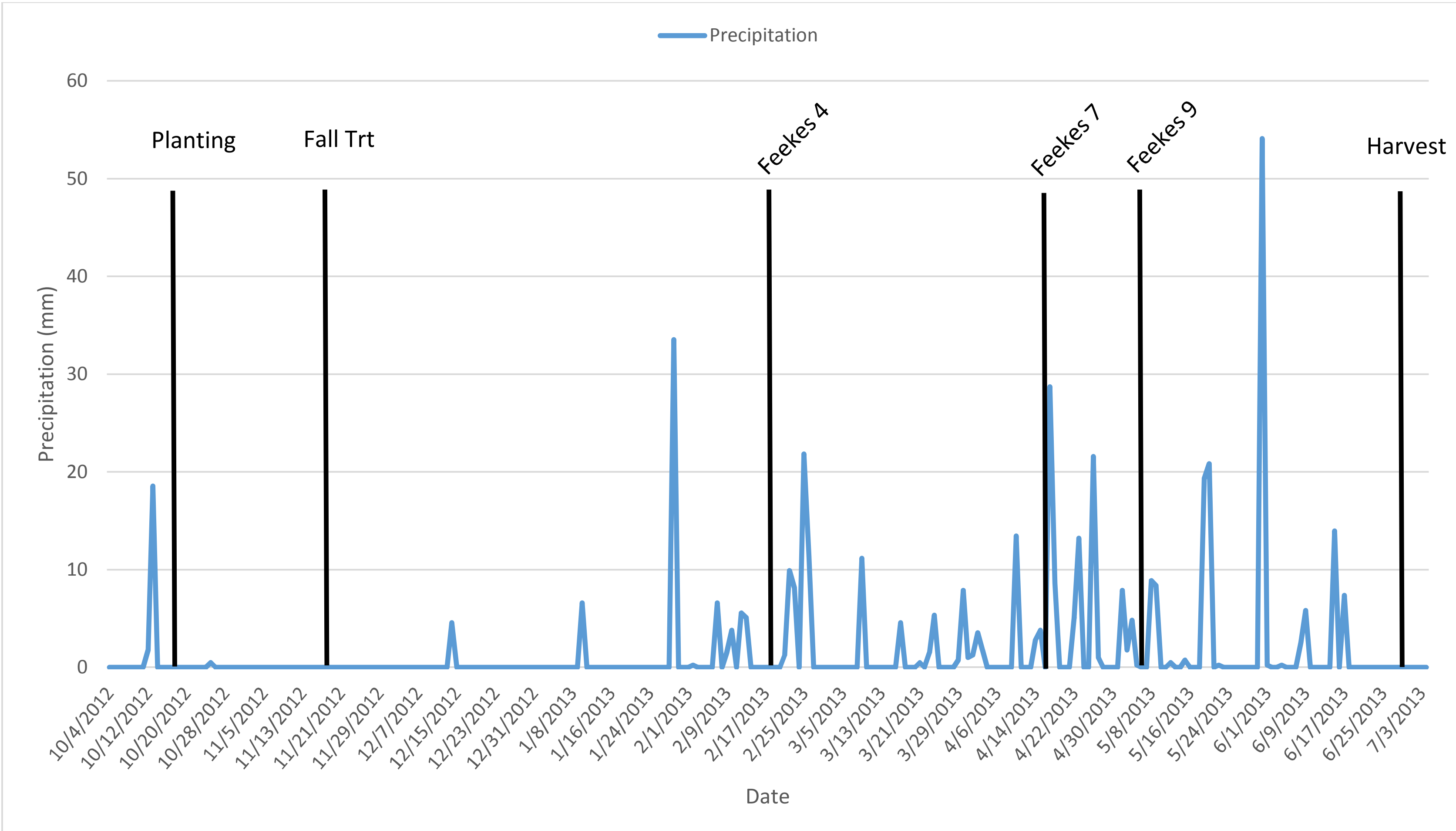

Figure 2-11 2013 McCune Precipitation and Key Treatment Dates

2013 Pittsburg Analysis

The field site at Pittsburg began the winter wheat season with over 220 kg N ha^{-1} of residual nitrate in the soil profile (Table 2.4) and that was also coupled with potential N mineralization from poultry litter that was applied in 2011. This created an extremely N rich environment and generated very high levels of early season growth. A significant negative response to applied N was observed on all treatments with the no applied N control achieving the highest grain yield 3.80 Mg ha^{-1} (Table 2.14). The fertilizer N applied induced lodging conditions and resulted in severe yield reductions. In this situation the best N management plan would have been to not apply N.

The cooperating producer did not soil test or use any other technology on the surrounding field for determining N status. With his standard practice of applying 170 kg N ha^{-1} prior to planting, he experienced similar reductions to grain yield that was observed in this experiment. It is important to note that the most severe grain yield reductions occurred where N fertilizer was applied in the fall or early spring. Delaying top-dressing until Feekes 9 may have reduced the excess vegetative growth and minimized the grain yield reductions (Table 2.14).

This demonstrates the need for winter wheat growers in Kansas to utilize tools to measure soil N supplies when possible to avoid similar situations of extreme losses in profits due to grain yield reductions and costs of N fertilizer that was not needed.

Table 2.14 2013 Pittsburg Summary Statistics for Grain Yield, Grain Protein, and Total Grain Nitrogen Uptake

Starter N	Fall/Winter	Feekes 4	Feekes 7	Feekes 9	Total N	Grain Yield	GY LSD Group	Grain Protein	GP LSD Group	Total Grain N Uptake	TotGNUP LSD Group
N Application Rate kg N ha^{-1}						Mg ha^{-1}		g kg^{-1}		kg N ha^{-1}	
0	0	0	0	0	0	3.80	A	122	NS	73	A
0	34	0	0	0	34	1.54	BCDE	132	NS	30	BCDEF
0	67	0	0	0	67	2.18	ABCD	126	NS	44	ABCDE
0	100	0	0	0	100	0.00	E	0	NS	0	F
0	134	0	0	0	134	0.70	DE	141	NS	15	EF
0	34	100	0	0	134	1.12	CDE	145	NS	26	DEF
0	67	67	0	0	134	0.95	CDE	130	NS	20	DEF
0	100	34	0	0	134	3.03	AB	136	NS	66	ABC
0	34	0	100	0	134	1.29	BCDE	136	NS	28	CDEF
0	67	0	67	0	134	2.15	ABCD	129	NS	44	ABCDE
0	100	0	34	0	134	1.03	CDE	129	NS	22	DEF
0	34	0	0	100	134	2.61	ABC	141	NS	58	ABCD
0	67	0	0	67	134	3.00	AB	144	NS	68	AB
0	100	0	0	34	134	0.99	CDE	150	NS	23	DEF
SE						0.84		33.40		18.17	
F Value						2.03		1.16		1.90	
Treatment Pr > F						0.04		0.35		0.06	
Fisher's LSD Alpha = 0.1						1.80		NS		38.67	

NS = Not significant

Treatments with same letter are not statisitcally different at 0.1 alpha

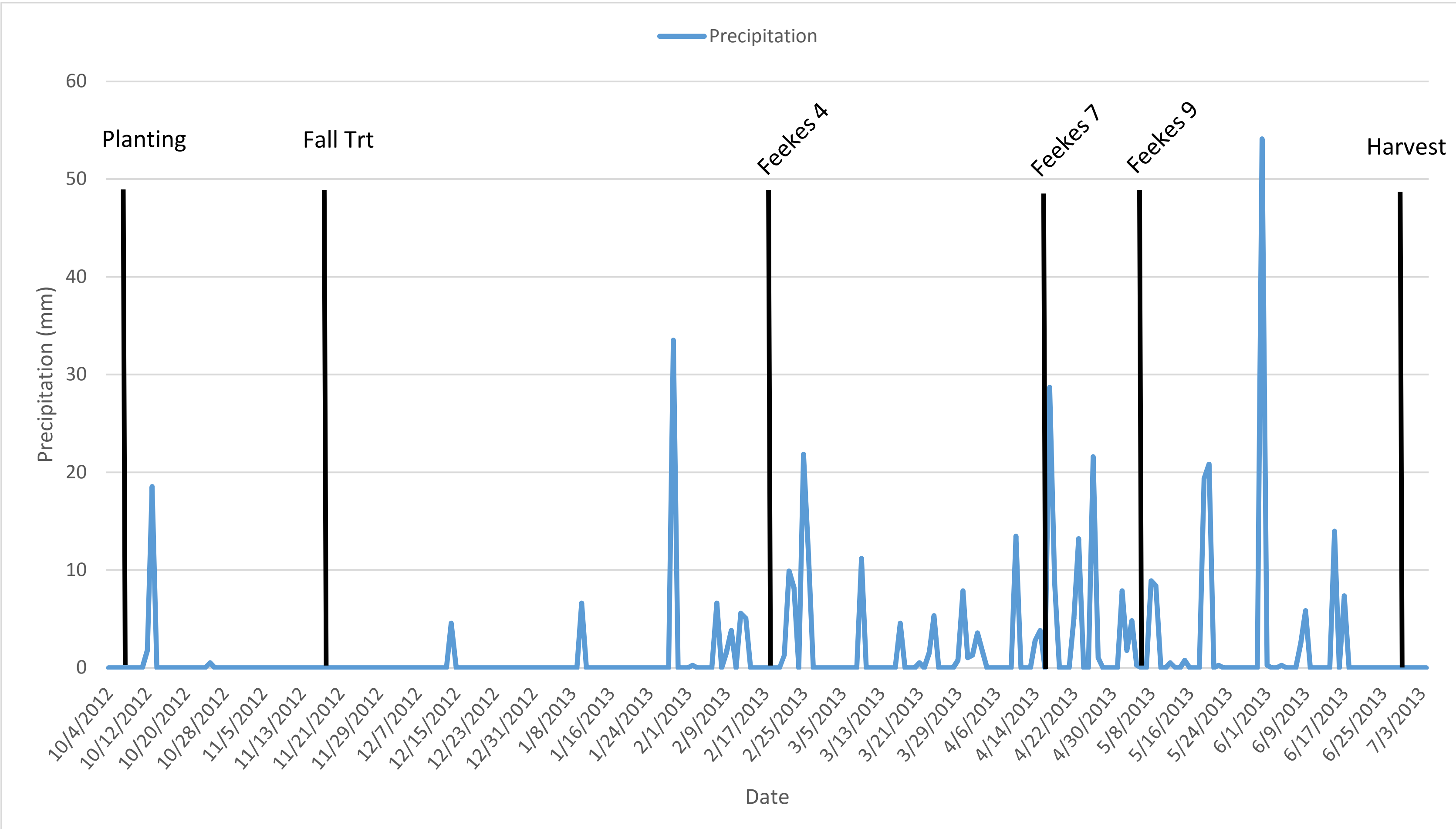

Figure 2-12 2013 Pittsburg Precipitation and Key Treatment Dates

Pooled analysis of Crop Response to N Application Timing

Pooled analysis was conducted by combining data from all sites with the exception of Pittsburg due to severe lodging of the winter wheat when fertilized. Pooled results show that with an average starter fertilizer rate of 16 kg N ha^{-1} and an additional 134 kg N ha^{-1} for a total applied N rate of 150 kg N ha^{-1}, grain yield response is statistically equal across fall, Feekes 4, Feekes 7, and Feekes 9 applications (Table 2.15). Feekes 9 treatment fall 34 kg/Feekes 9 100 kg had a higher grain protein response, and greater total grain N uptake as compared to fall and Feekes 4 treatments (Table 2.15). These results indicates that N fertilization at Feekes 7 or Feekes 9 will not result in a yield penalty if the appropriate amount of N is applied in the fall, and has the potential to produce higher grain protein and total grain N uptake over fall and Feekes 4 N applications.

The pooled results also show that the grain protein and grain N uptake were significantly higher when the majority of the top-dressed N was applied at Feekes 7 or Feekes 9, rather than fall, winter, or Feekes 4 (Table 2.15). This suggests a potential for being able to produce higher grain yield with lower N rates applied by utilizing split application systems that include later season applications at Feekes 7 or Feekes 9. Thus enhancing system NUE and producer profits through lower costs, and reducing potential negative environmental impacts through the loss of excess fertilization.

Table 2.15 2012 and 2013 Combined Summary Statistics for Grain Yield, Grain Protein, and Total Grain Nitrogen Uptake Across Seven Locations, Pittsburg Location Excluded

Starter N	Fall/Winter	Feekes 4	Feekes 7	Feekes 9	Total N	Grain Yield	GY LSD Group	Grain Protein	GP LSD Group	Total Grain N Uptake	TotGNUP LSD Group
N Application Rate kg N ha^{-1}						Mg ha^{-1}		g kg^{-1}		kg N ha^{-1}	
16	0	0	0	0	16	2.70	D	116	EF	40	H
16	34	0	0	0	50	3.41	C	112	F	51	G
16	67	0	0	0	83	3.65	C	121	E	59	F
16	100	0	0	0	116	3.98	B	127	D	68	E
16	134	0	0	0	150	4.08	AB	131	CD	73	DE
16	34	100	0	0	150	4.18	AB	135	BC	79	BCD
16	67	67	0	0	150	4.22	AB	133	BC	78	CD
16	100	34	0	0	150	4.21	AB	130	CD	75	D
16	34	0	100	0	150	4.37	A	137	AB	84	ABC
16	67	0	67	0	150	4.15	AB	132	CD	75	DE
16	100	0	34	0	150	4.24	AB	130	CD	75	D
16	34	0	0	100	150	4.25	AB	142	A	86	A
16	67	0	0	67	150	4.32	A	137	AB	84	AB
16	100	0	0	34	150	4.23	AB	131	CD	78	BCD
SE						0.67		9.32		7.67	
F Value						15.56		20.22		33.41	
Treatment Pr > F						< 0.00		< 0.00		< 0.00	
Fisher's LSD Alpha = 0.05						0.32		5.08		6.42	

NS = Not significant

Treatments with same letter are not statisitcally different at 0.05 alpha

Conclusions

Analysis of the effects of N application timing strongly supports that N management systems that spread N applications throughout the vegetative growth of winter wheat can provide grain yields equivalent or greater than traditional all pre-plant or Feekes 4 N management systems, while increasing grain protein and total grain N uptake, thus improving NUE. This results from better synchronization of N applications with crop N demand and minimizes the potential for N loss and potentially reduced profits to producers. Nitrogen management programs that incorporate later spring Feekes 7 or 9 split N applications allow farmers more time to assess changes in grain yield potential and N fertilizer needs that might result from precipitation events, crop water stress, N mineralization or N loss. Therefore, N management programs can be better tailored for a specific field for a specific year and improve NUE and potentially enhance grain yield, which can reduce environmental impact and increase profits.

References:

Cassman, K.G., D.C. Bryant, A.E. Fulton, and L.F. Jackson. (1992). Nitrogen supply effects on partitioning of dry matter and nitrogen to grain of irrigated wheat. *Crop Sci*. 32:1252–1258.

Denning, J., Eliason, R., Goos, R. J., Hoskins, B., Nathan, M. V, and Wolf, A. (2011). *Recommended Chemical Soil Test Procedures for the North Central Region*, *221*(221), 75.

Hawkesford, M. (2012). The diversity of nitrogen use efficiency for wheat varieties and the potential for crop improvement. *Better Crops with Plant Food*, *96*(3), 10–12.

Knowles, T.C., B.W. Hipp, P.S. Graff, and D.S. Marshall. (1994). Timing and rate of topdress nitrogen for rainfed winter wheat. *J.Prod.Agric.* Vol. 7, no.2.1994.

KSU Mesonet. (2015). Available at: http://mesonet.k-state.edu

Microsoft. (2013). Microsoft Excel computer software. Redmond, Washington: Microsoft.

Miller, B. T. D. (1999). *Growth Stages of Wheat*. Texas Ag. Ext. Service, (SCS-1999-16), 4p. Retrieved from http://baylor-agrilife-org.wpengine.netdna-cdn.com/files/2011/06/growthstagesofwheat_11.pdf

Raun, W.R., and G.V. Johnson. (1999). Improving nitrogen use efficiency for cereal production. *Agronomy J.* 91:357–363.

Roberts, T. L. (2007). *Right product, right rate, right time and right place...the foundation of best management practices for fertilizer.* Retrieved from IPNI: http://www.ipni.net/ipniweb/portal.nsf/0/55C6FA392D96B89885257A8C0057EDAA/$FILE/Roberts_2007_4Rs.pdf

Roberts, T. L. (2008). Improving Nutrient Use Efficiency. *Turkish Journal of Agriculture & Forestry*. *32*:177–182.

Schlegel, A.J., and C.A. Grant. *Soil Fertility. Dryland Agriculture*, 2nd ed. (2006). Madison, WI: ASA-CSSA-SSSA

SAS Institute. (2011). Release 9.3 ed. SAS Inst., Cary, NC.

NRCS Resource Conservation Staff, Natural Resources Conservation Service, United States Department of Agriculture. (2007). Available online at http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_032018.pdf

NRCS Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. (2015). *Web Soil Survey*. Available online at http://websoilsurvey.nrcs.usda.gov/

Waldren, R.P., and A.D. Flowerday. (1979). Growth stages and distribution of dry matter, N, P, and K in winter wheat. *Agronomy J.* 71:391-397.

Wuest, S. B., and Cassman, K. G. (1992). Fertilizer-Nitrogen Use Efficiency of Irrigated Wheat: II. Partitioning Efficiency of Preplant versus Late-Season Application. *Agronomy J.* 84:689-694.

Waldren, R.P., and A.D. Flowerday. (1979). Growth stages and distribution of dry matter, N, P, and K in winter wheat. *Agronomy J.* 71:391-397.

Wuest, S. B., & Cassman, K. G. (1992). Fertilizer-Nitrogen Use Efficiency of Irrigated Wheat: II. Partitioning Efficiency of Preplant versus Late-Season Application. *Agronomy J*. 84:689-694.

Chapter 3 - Using Optical Sensor Technology to Manage Nitrogen in Winter Wheat (*Triticum aestivum L.*)

Abstract

Meeting the conflicting goals of both high yields and limited environmental impact of nitrogen (N) fertilization makes N management one of the most challenging components of crop production. Nitrogen management is a complex issue, and solutions we create to improve our agricultural practices must mitigate N loss from soils, reduce environmental impact, improve grain yield, and increase profit. The objective of this study was to develop sensor-based N recommendation algorithms for state-wide use in Kansas that can be used at multiple growth stages of winter wheat for use in single and multiple N application systems without extensive requirements for algorithm input parameters. Data collected from winter wheat N management studies conducted from 2006 through 2012 were utilized to develop optical sensor-based N recommendation algorithms for winter wheat in Kansas. Two different algorithms were developed to address intensive N management systems; one that would make multiple N applications throughout the season (Algorithm RK v2.6) and the traditional top-dress at Feekes 4 N management system (Algorithm NRS v1.5). Algorithm RK v.2.6 utilized the traditional approach of integrating an N reference strip and basing N recommendations on the observed difference between the N reference strip and target area. Algorithm NRS v1.5 removed the requirement of the N reference strip and utilized a growth response index to determine if additional N is needed. Field validations of both algorithms were conducted at eight locations across Kansas in 2013 to provide multiple environments with different histories of field productivity. Highly efficient N recommendations were provided by algorithm RK v2.6, while protecting yield in response to N loss events. Because of its multiple N application strategy, RK v2.6 is very conducive for crop monitoring and optimizing N application timings for improving Nitrogen Use Efficiency (NUE), while achieving high grain yield and protein. Positive results during field validation were provided by algorithm NRS v1.5. Without the use of the N reference strip, NRS v1.5 consistently performed equal to or better than the KSU soil test N recommendation. NRS v1.5 can accurately assess the status of the wheat crop at Feekes 4 and determine if additional N is necessary, or if ample N is present for optimizing grain yield and the NUE of single top-dress N management systems.

Introduction

Meeting the conflicting goals of both high yields and limited environmental impact of nitrogen (N) fertilization makes N management one of most challenging components of crop production. Inside the world of agriculture, N fertilizer is one of the highest yearly input costs for wheat farmers. Hence, wheat producers want to find ways to optimize their N management practices to reduce N fertilizer costs, maintain high grain yields, and therefore increase profit per acre. Outside the world of agriculture, N management practices that have low Nitrogen Use Efficiency (NUE) are making headlines for contributing to adverse environmental impacts on water resources and aquatic ecosystems. For example, excessive nitrate-N levels in ground water can potentially cause methoemoglobinemia, which can be fatal to infants (Comly, 1945). Ecosystem concerns can vary, but the most commonly known is when excess N and other nutrient runoff leads to increased algae blooms, which have been implicated in the cause of the hypoxic zone in the Gulf of Mexico (Rabalais et al. 1996, 1998).

What is important to recognize is that both production agriculture and the environmental sector want the same things: sustainable management of our agricultural systems that is both economically profitable and environmentally sustainable, therefore benefiting the entire world. The difference between these two groups lies in the priorities and subsequent means for achieving these goals. Agricultural research into N management revolves around multiyear experiments that test a variety of different management strategies under different weather and soil environments to determine which strategies generate the best combination of NUE and grain yield. Therefore, the reduction of environmental impacts becomes a byproduct of this work and overall grain yield is increased, or not reduced. Environmental research on N determines the impact of N concentration levels in air and water on ecosystems and its resources and will advise if N concentration levels should be reduced to match the load the environmental system can handle. If N concentrations are too high, it is a natural conclusion that N inputs in agriculture should be reduced to reduce N load to the environmental system. However, overall reductions in N rate with no regard to NUE will result in overall yield reductions. If the current 6.5 billion people in the world and the 9 billion expected by 2050 are to be fed, the removal of N fertilizer from agriculture is not possible (Cassman et al., 2003). However, if N is managed to increase NUE to enhance crop use and reduce loss, overall N inputs could be reduced and potentially both environmental and crop needs could be met.

In addition, research indicates that mandating a reduction in N fertilizer application rates does not result in automatic reductions of N losses due to the observed poor relationship between N fertilizer applied by farmers and N uptake efficiency by the plant (Cassman et al., 2002; Goulding et al., 2000). Nitrogen management is a complex issue and solutions we create to improve our agricultural practices must mitigate N loss, reduce environmental impact, improve grain yield, and increase profit. It is a large order to create solutions that can accomplish all of the above. However, the stakes are equally high:

1. Increase crop production by 2050 or humans will experience widespread famine.
2. Reduce environmental impact or we devastate the world we live in.

Agriculture is up to the task for generating the world's food supply in a manner that is environmentally sustainable. However, producers and agronomists need tools to assist them in optimizing N management systems for specific crops in their specific growing environment. Advancements in active optical sensors (AOSs) technology have presented opportunities to collect in-season data on crop health that can be utilized for creating sustainable N management solutions.

Active optical sensors as defined Holland et al. (2012) "are specialized instruments that irradiate a target with radiation and measure that which is scattered back to the sensor's integral photo-detector". More familiar optical sensors to the general populous are passive sensors such as cameras, which require sunlight to illuminate the target. With such passive optical sensors, irradiance values can vary with solar zenith angle, sensor position relative to altitude and field of view (Fitzgerald, 2010; Holland et al., 2012). Because an AOS has a light source to illuminate the target, it is not influenced by changing sun and sky conditions (Fitzgerald, 2010; Erdle et al., 2011; Holland et al., 2012). Therefore, an AOS is a consistently reliable technology for gathering spectral data.

Most AOSs are two-channel sensors, and therefore can only detect two wavelengths of a specified bandwidth. The two most commonly used wavelengths on AOSs are Red (650-690 nm) and NIR (760-900 nm), as these two spectral ranges can be considered effective for evaluating N status (Thenkabail et al., 2002). Red light is specifically chosen because it is highly absorbed by chlorophyll a and b and improves contrast between the soil background and plant (Elvidge and Chen, 1995; Blackburn, 1998; 1999; Hatfield et al., 2008). NIR light is chosen because it interacts with the spongy mesophyll within the plant tissue and reflects back to the optical sensor. Therefore if more plant material is present, more NIR light will be reflected.

Once reflectance data in the visible and NIR spectrum are obtained, the AOSs will calculate a vegetation index for the simplification of the spectral data and to hone in on a specific characteristic. For two-channel sensors, the most commonly calculated vegetation index is the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973; Fitzgerald, 2010). NDVI has been used effectively for estimating crop yield, leaf area index, and biomass (Raun et al., 2001; Thenkabail et al., 2002; Pinter et al., 2003; Raun et al. 2005; Prasad et al., 2007). Phillips et al. (2004) have determined that NDVI has a strong relationship with winter wheat tiller density and could be used to assist in N fertilization of winter wheat. Therefore NDVI can be used as an index for determining biomass (tillers) and is very applicable for addressing the N status of winter wheat. However, in order for NDVI data provided by optical sensors to be useful, algorithms have to be generated to provide agronomic interpretations.

Raun et al. (2002) were one of the first groups to develop algorithms for AOSs for in-season on-the-go N management of winter wheat. Further development of optical sensor-based N recommendation algorithms for winter wheat has progressively continued at Oklahoma State University with additional algorithm releases in 2005 (Raun et al., 2005). Additional work by Solie et al. (2012) resulted in the construction of a generalized algorithm that is designed for use in both corn and winter wheat.

Additional algorithm designs that are very robust in nature were created by Kyle Holland of Holland Scientific and James Schepers USDA ARS, who is now retired. An issue with algorithm design is that they often become sensor-specific and can be difficult to apply to other areas where data have not been collected. Holland and Schepers (2010) released an algorithm design for corn that is very robust for many reasons such as: can be readily used with a variety of active optical sensors ranging from on-the-go sensors to the traditional handheld chlorophyll meter; be applied throughout the growing season; and can be readily calibrated through user inputs. These attributes make it easily utilizable across a wide range of locations and environmental conditions. This type of adaptable design paved the way for a robust generalized algorithm approach that can be applied to numerous crops and greatly extend algorithm life expectancy.

Robust and specific are two objectives for algorithm design that are difficult to achieve together when developing N recommendation algorithms. Essentially, the more robust and generalized the design, the less site specific and crop specific it will be. However, if an algorithm is developed to be very specific in nature, it will only be applicable for specific equipment, crops, and environments, thus requiring the generation of a large database with multiple environments, across multiple years, by crop, in order to be applied across a large range of areas. Therefore, the developer must decide the appropriate combination of robustness and specifics to meet their intended application.

As a land grant university, Kansas State University has a mission to provide effective N management tools to Kansas' wheat farmers. Not only does the development of the algorithms enhance crop yield and producer profits but it also provides equal value to the general public in minimizing any adverse effects of winter wheat N fertilization on the environment. The objective of this study was to develop sensor-based N recommendation algorithms for state-wide use in Kansas that can be used at multiple growth stages of winter wheat for use in single and multiple N application systems without extensive requirements for algorithm input parameters.

Materials and Methods

Data Source and Data Selection Criteria for Algorithm Components

Winter wheat N management studies from 2006 to 2012 conducted at sites located throughout the state of Kansas were utilized for the development of these algorithms. Each of these studies shared common features in their treatment and measurement protocols:

1. Soil sampled for profile nitrate-N
2. N response curve
3. Feekes 4 topdress N application
4. Feekes 7 and Feekes 9 N applications
    a. Only on some of the studies
5. Active Optical Sensor spectral readings

N source for each study varied depending on the treatment protocol, but consisted of anhydrous ammonia (82-0-0), urea (46-0-0), and UAN (28-0-0) solutions. The complete dataset with site location and relevant information is in appendix B. The data from each experiment were utilized for the purpose of developing components to implement N recommendation algorithms. SAS 9.3 (SAS Institute, 2011) was used for creating selection criteria and sub setting the dataset for use in each algorithm component. The SAS codes utilized are provided with an explanation of data removal if warranted (Appendix C). Nonlinear regression was conducted and plotted in R using the easynls package (Arnhold, 2014; R project, 2015).

Algorithm Inputs and Outputs

Description of Algorithm Inputs

Nitrogen Reference Strip

The N reference strip is nothing more than a very high rate of N applied to an area of field. The N reference strip then can be considered an N sufficient area, thus allowing the rest of the wheat to be compared to it for determining relative N sufficiency. Most algorithms require the use of an N reference in order to function and provide recommendations. Therefore, these types of algorithms are nothing more than difference engines whose performance rise and falls with the integrity of the N reference strip. Three common issues with the N Reference strip are:

1. No difference observed between the N reference and target area due to water stress in the fall or early spring
    a. Algorithms designed to be a difference engine with the N reference would recommend no N, which has high probability of being incorrect during the early spring, Feekes 4, when N is commonly applied
2. N loss occurs, resulting in the N reference being N deficient
3. Disease or water stress compromises the N reference, thus making the algorithm less effective or not useable.
4. N reference is put in an area of the field and the rest of the field is assumed to be similar in soil conditions
    a. Most fields are rarely completely uniform to where this approach would be valid. N reference strips would need to be placed in each zone of variability within the field. Failure to do so will reduce the algorithms effectiveness.

Although the N reference strip can provide useful information, it is a serious point of potential algorithm failure and its shortcoming should be considered. Two different approaches for algorithm development will be presented, one requires an N reference strip and the other does not.

Field Grain Yield Productivity History

This parameter provides the algorithm with the user's assessment of normal productivity levels and serves as a means for calibrating algorithms for the specific area it is being used. Soil and weather play important roles in regulating the potential grain yield that can be produced. Although we cannot predict the long-term weather, we can assess the usual patterns a given area receives. With yield monitors and farm management software becoming commonplace, analyzing field productivity across years at a fine spatial resolution within a given field has become feasible for consultants and producers to do. With these types of data, the algorithm can calibrate itself and generate recommendations for specific areas within a field, across fields within a farm, and across the state of Kansas if the algorithm is designed to do so. This parameter serves as a cap to prevent N fertilization for grain yields that are rarely obtained at a given area of a field.

Red Normalized Difference Vegetation Index of N Reference and Bulk Field

Red NDVI (Eq. 3.1) (Rouse et. al. 1973) is acquired from the N Reference strip and/or bulk field using AOSs. This would include handheld sensor units, vehicle-mounted units for on-the-go variable rate applications, units for small-unmanned aerial systems (sUAS), and manned aircraft. Red NDVI provides an approximate status of health of the wheat plant mostly directed at biomass and photosynthetic activity. With Red NDVI, additional indices can be calculated to assess plant N status.

$$Red\ NDVI = \frac{(NIR-RED)}{(NIR+RED)} \qquad [Eq.\ 3.1]$$

Feekes Growth Stage

The Feekes growth staging system as described in the Texas A&M extension publication "Growth Stages of Wheat" (Miller, 1999) is used to determine what stage in its life cycle the wheat is at when spectral readings are being obtained. Identification of the Feekes growth stage allows the algorithm to change internal data sources to determine what grain yield components are currently being determined and how it should address them in order to optimize grain yield and NUE.

There are four primary grain yield components of winter wheat: number of heads, head size or potential seeds per head, seeds set per head, and seed weight or size. Each of these can be influenced by N status of the plant at a specific growth stage. Some of the growth stages used in the algorithms and the grain yield components related to them are:

Feekes 2-4: Tiller formation determines total heads per plant, N applications after Feekes 4 will not generate additional tillers

Feekes 5: Head size determination, N applications after Feekes 5 will not increase head size

Feekes 6-7: Rapid stem elongation and increased N uptake, N stress at this stage can cause tiller abortion

Feekes 8-9: Last point for effective N applications to increase seeds per head, through enhanced seed set, seed size, and grain protein

Adjustment in N Fertilizer Rate for Expected NUE: Nitrogen Recovery Efficiency

The concept of nitrogen recovery efficiency (NRE) is a common point of confusion for producers and consultants. Often Nitrogen Recovery Efficiency and Nitrogen Use Efficiency are used interchangeably, but the users expressed meaning is the same: "If I apply X amount of N, how much is taken up by the plant?" (Eq. 3.2). NRE is an attempt to adjust the N recommendation provided by the algorithm for the expected recovery of N by the crop at that location. NRE varies greatly throughout Kansas since there is dramatic change in observed weather and soil as one travels from eastern to western Kansas. NRE is specific to the interaction of the plant, soil, weather, and N management practice. For example, due to the poorly drained claypan soils and heavy rainfall patterns observed in southeast Kansas, NRE for pre-plant subsurface N applications will struggle to achieve 40%, while the same N management strategy in northwest Kansas would easily achieve 60%. The most effective use of NRE for any algorithm is to provide some idea of the usual N loss characteristics observed in the specific field it is being utilized in. However, it is uncommon for consultants and producers to have this type of data, and therefore it is necessary for land-grant universities to provide this information to the finest scale possible. The algorithms use NRE to determine if the user can provide additional information on N loss potential. Changes in the NRE parameter will result in an overall increase or decrease in N recommendations at the users discretion. The default standard for NRE is 50% for the state of Kansas.

$$NRE = \frac{50\ kg\ of\ N\ Fertilizer\ taken\ up\ by\ the\ Plant}{100\ kg\ of\ N\ Fertilizer\ Applied} = 0.50 \quad \text{[Eq. 3.2]}$$

Description of Algorithm Outputs

Grain Yield Potential by Growth Stage

Red NDVI collected from the N Reference strip and the unfertilized bulk field area is used to determine the grain yield potential from the N sufficient area and will be termed YP_{Nfert} and YP_{unfert}. The users input for Feekes growth stage will determine which dataset is applied for determining YP_{Nfert} and YP_{unfert}. In order to compensate for potential user error in judging growth stages, Feekes 4-5, 6-7, and 8-9 have been grouped together for determining YP_{fert} and YP_{unfert}. Determination of YP_{fert} and YP_{unfert} with Red NDVI is shown in Figures 3-1 through 3-6 and summarized in Table 3.1.

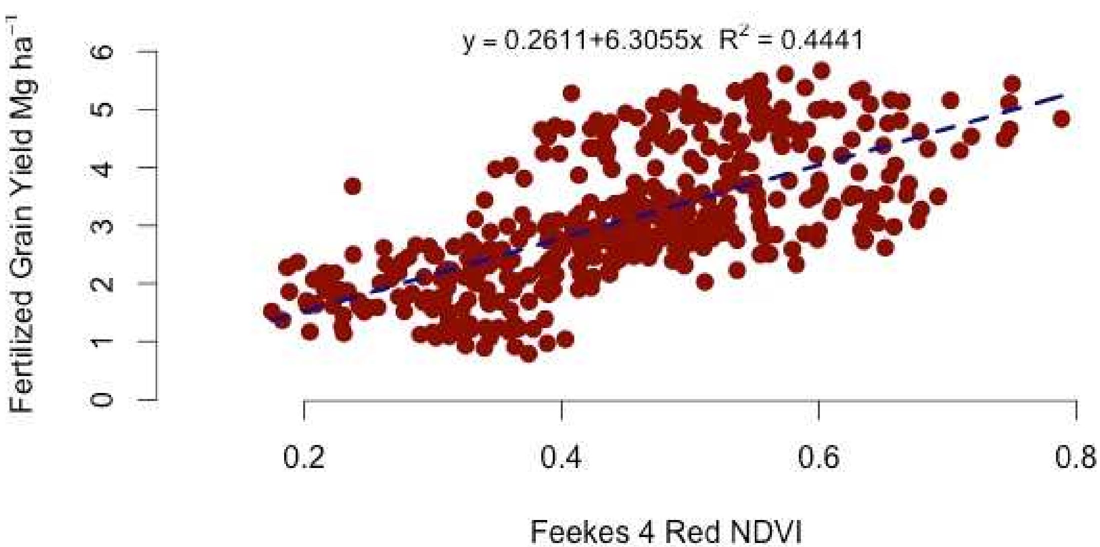

Figure 3-1 Determination of YP_{fert} at Feekes 4 with Red NDVI

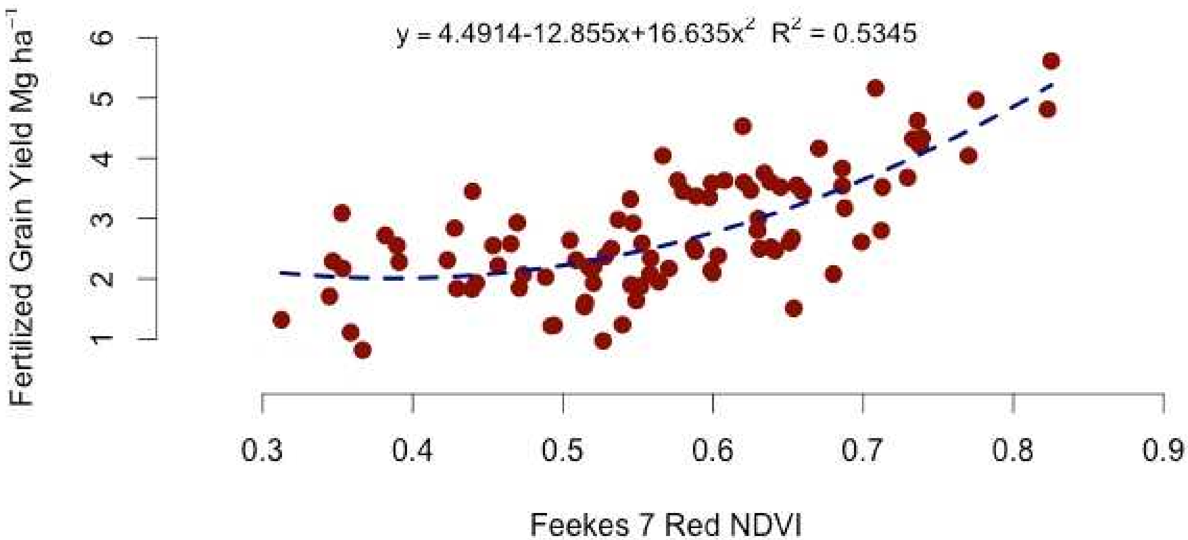

Figure 3-2 Determination of YP_{fert} at Feekes 7 with Red NDVI

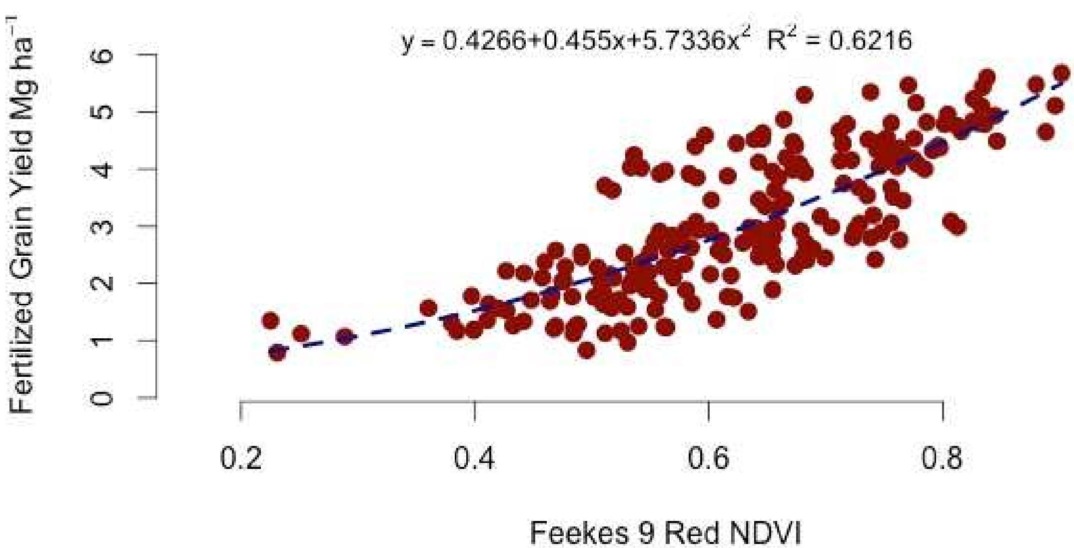

Figure 3-3 Determination of YP_{fert} at Feekes 9 with Red NDVI

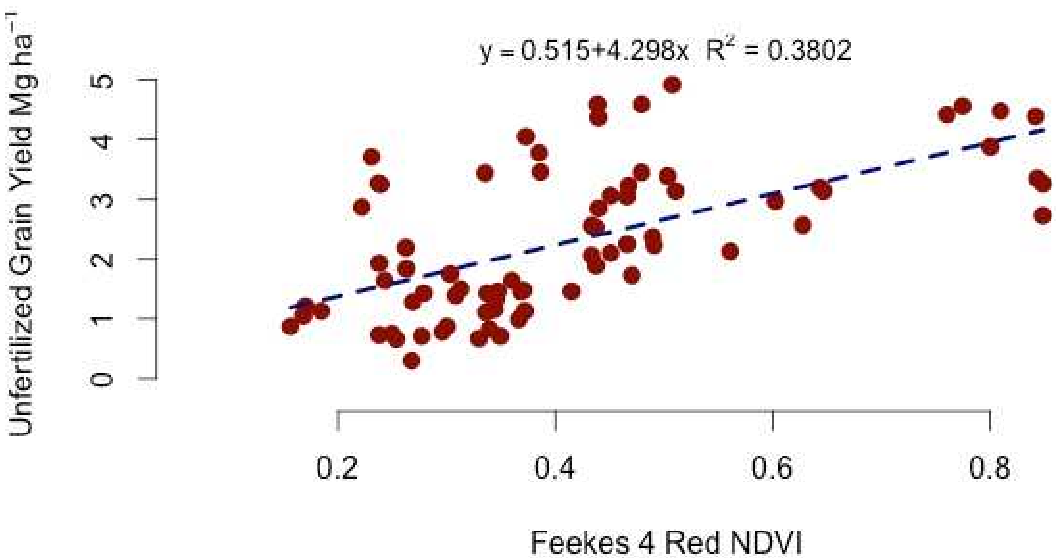

Figure 3-4 Determination of YP_{unfert} at Feekes 4 with Red NDVI

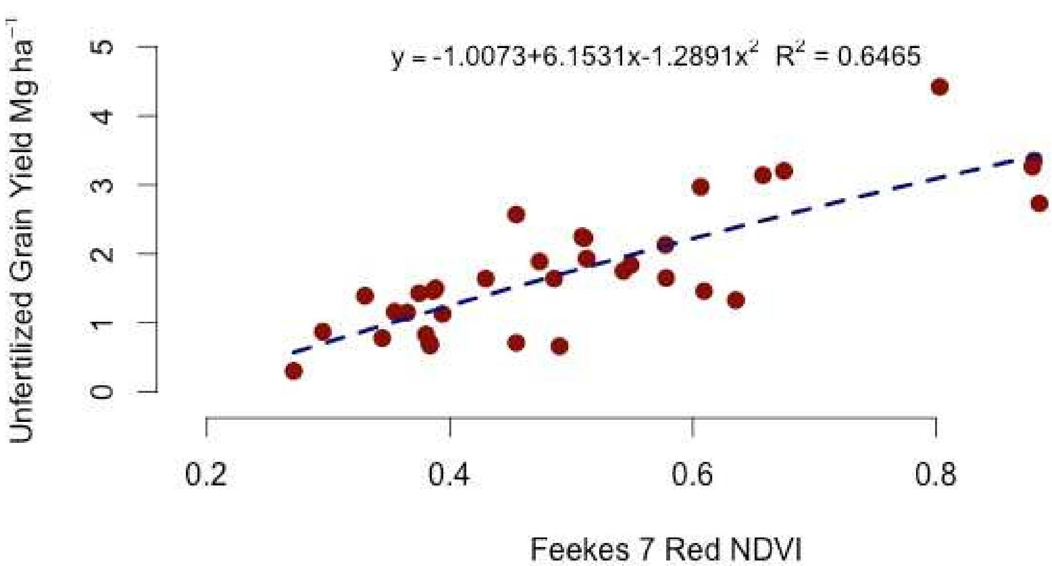

Figure 3-5 Determination of YP_{unfert} at Feekes 7 with Red NDVI

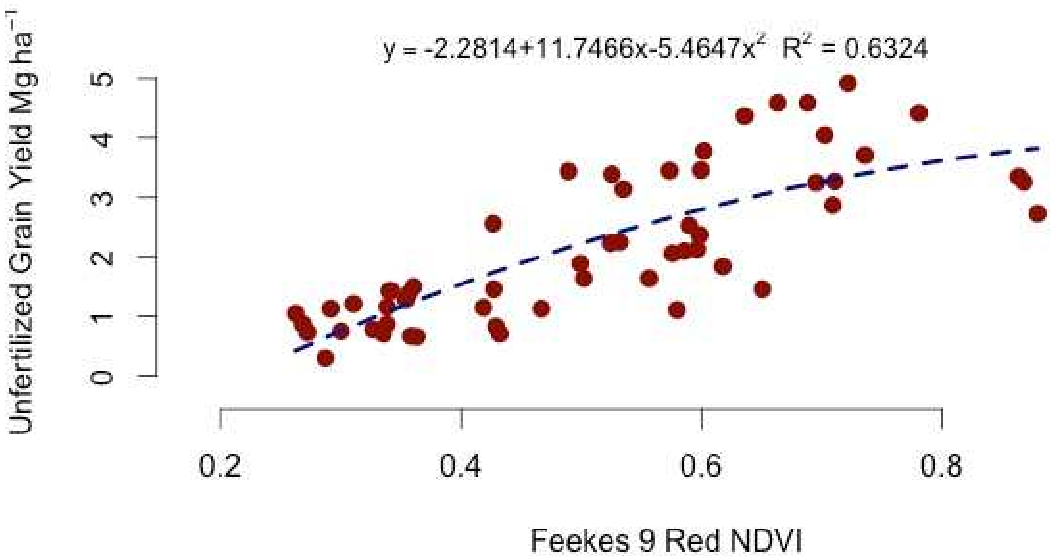

Figure 3-6 Determination of YP_{unfert} at Feekes 9 with Red NDVI

The Response Index and Recoverable Yield

The Response Index is the quantified Red NDVI difference between the N reference Red NDVI and bulk field Red NDVI and is described in equation 3.3. The algorithm calculates the Response Index once the user has put in all the user inputs and provides a measure of observed N stress. A Response Index of 1.0 indicates that the winter wheat is N sufficient at that point in time. However, as the Response Index increases above 1.0, N stress is occurring.

$$Response\ Index\ = \frac{Specific\ Growth\ Stage\ N\ Reference\ Strip\ Red\ NDVI}{Specific\ Growth\ Stage\ Bulk\ Red\ NDVI} \quad \text{[Eq. 3.3]}$$

Recoverable yield is a measure of how much grain yield can be recovered at a given level of N stress as indicated by the Response Index, by applying N at a specific Feekes growth stage (Eq. 3.4). Recoverable yield attempts to provide the user with an estimation of how much potential yield loss is occurring from the observed N deficiency, and if the application of N fertilizer can fully or partially correct the problem. The recoverable yield concept prevents the N fertilization for grain yield that cannot be recovered, thus adding to NUE and reducing environmental impact from N applications that likely would not be utilized, and have little positive impacts on grain yield or quality. The relationship between the Response Index and percent recoverable yield at Feekes 4, 7, and 9 is presented in Figures 3-7, 3-8, and 3-9. Summary of equations are shown in Table 3.1.

$$Recoverable\ Yield\ (\%) = \frac{Specific\ Growth\ Stage\ N\ Application\ Grain\ Yield}{Specific\ Growth\ Stage\ Highest\ Yielding\ N\ Reference} \qquad \text{[Eq. 3.4]}$$

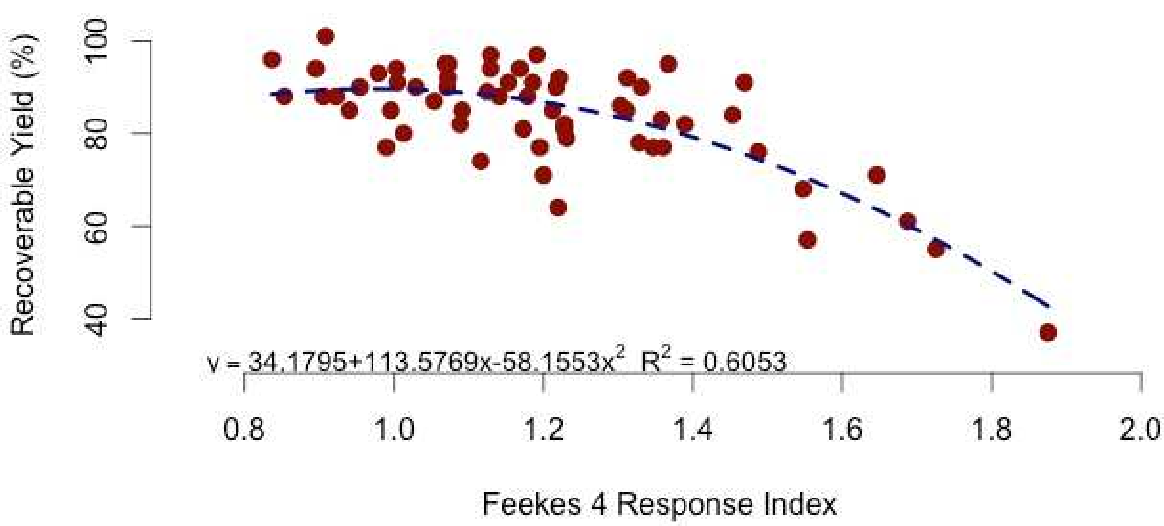

Figure 3-7 Portion of N Reference Grain Yield to be Recovered with N Application at Feekes 4

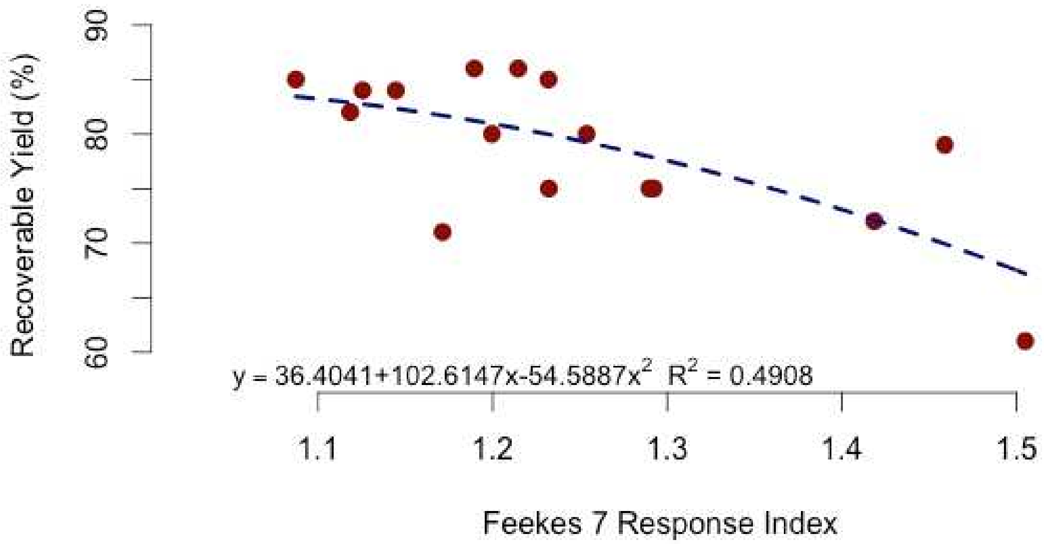

Figure 3-8 Portion of N Reference Grain Yield to be Recovered with N Application at Feekes 7

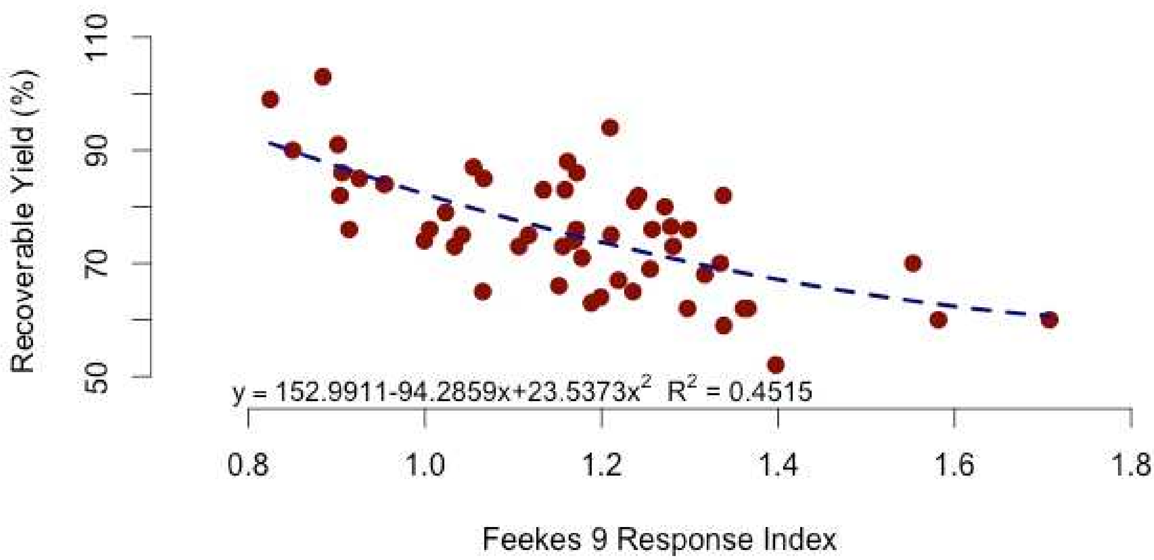

Figure 3-9 Portion of N Reference Grain Yield to be Recovered with N Application at Feekes 9

Feekes 4 Biomass Response Index and Potential Feekes 9 Red NDVI

The Feekes 4 to Feekes 9 biomass response index (BRI?) is designed to assess the potential biomass response to applied N at Feekes 4. The biomass response index is determined by utilizing experimental data that received high rates of N at Feekes 4 and had Red NDVI measurements made at both Feekes 4 and Feekes 9. The difference in Red NDVI from Feekes 4 to 9 is quantified using equation 3.5. An index value is created that gives an estimate of potential growth response based on the Feekes 4 Red NDVI (Figure 3-10). This relationship allows the algorithm to determine how much biomass as measured by Red NDVI can be produced by Feekes 9 when an N application is made at Feekes 4 (Figure 3-10). The biomass response index eliminates the requirement of the N reference strip and uses the producer's input of grain yield productivity to reduce the potential for over fertilization. This index can be calibrated at the field level or by management zones; however, well-calibrated yield maps, to the finest spatial resolution, will optimize this function's use with on-the-go systems since it will capture finer details of historical soil by weather effects on grain yield and productivity. If variable-rate N applications were available to the producer or consultant, it would be recommended to have the grain yield history of the field feed into the algorithms productivity parameter (yield potential), thus allowing the algorithm to calibrate to the finest detail the historical grain yield maps provide. Because this index is designed to assume spring tillering is possible, it can only be used at late Feekes 3 and Feekes 4. Once the wheat advances in development to Feekes 5 and tiller formation is complete, this index is no longer applicable.

$$Biomass\ Response\ Index = \frac{N\ Treatment\ Feekes\ 4\ Red\ NDVI}{N\ Treatment\ Feekes\ 9\ Red\ NDVI} \quad \text{[Eq. 3.5]}$$

Once the Biomass Response Index (BRI) is determined the algorithm will automatically calculate the Potential Feekes 9 Red NDVI (P Fks Red NDVI) (Eq. 3.6) to determine the Feekes 9 YP_{fert} (Figure 3-3; Table 3.1).

$$Potential\ Feekes\ 9\ Red\ NDVI = Feekes\ 4\ Bulk\ Red\ NDVI * BRI \quad \text{[Eq. 3.6]}$$

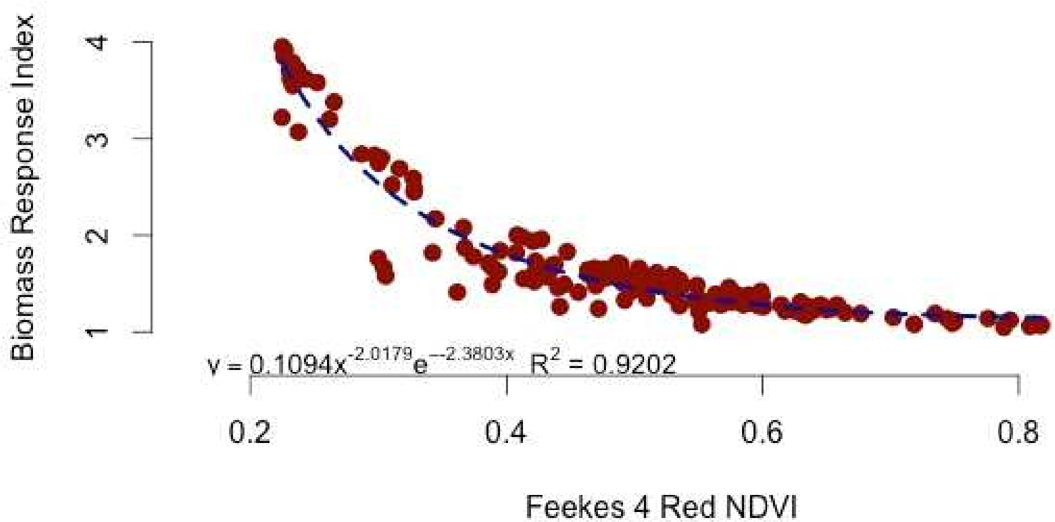

Figure 3-10 Potential Feekes 9 Biomass Response to Feekes 4 N Application

Production Efficiency

Production Efficiency provides a measure of N requirement per Mg of grain yield (Eq. 3.7). Figure 3-11 shows the relationship between unfertilized grain yield and its Production Efficiency when it is fertilized, as grain yield increases the N fertilizer requirement per unit of grain yield decreases. This reflects the normal increase in harvest index and other internal plant efficiencies associated with healthy, high yielding crops. Production Efficiency encompasses the overall NUE of the cropping system including the plant's internal NUE and its ability to recover N from the soil (NRE).

The trendline shown in Figure 3-11 is assumed to represent the Production Efficiency of winter wheat with a 50% NRE. The user is allowed to make adjustments to NRE based on their perception of N loss characteristics for their field. Therefore the algorithm will calculate Production Efficiency then calculate the adjusted NRE to be utilized for determining N requirements per Mg of grain yield (Table 3.1).

$$Production\ Efficiency = \frac{kg\ N\ applied\ ha^{-1}}{Grain\ Yield\ Mg\ ha^{-1}} \quad [3.7]$$

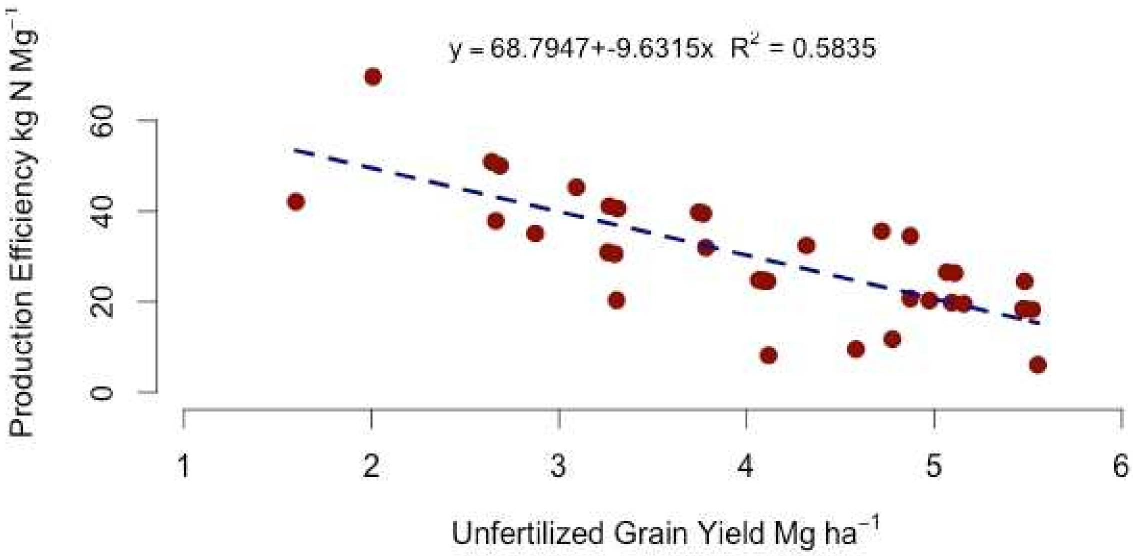

Figure 3-11 Determination of Production Efficiency from YP_{unfert}

Table 3.1 Summary of Algorithm Inputs and Output Equations

Feekes Growth Stage	Input	Output	Equation	Figure
4 and 5	Nref Red NDVI	YP_{fert}	YP_{fert} = 0.2611+6.3055(Nref Red NDVI)	3-1
4 and 5	Bulk Red NDVI	YP_{unfert}	YP_{unfert} = 0.515+4.298(Bulk Red NDVI)	3-4
6 and 7	Nref Red NDVI	YP_{fert}	YP_{fert} = 4.4914-12.855(Nref Red NDVI)+16.635(Nref Red NDVI)^2	3-2
6 and 7	Bulk Red NDVI	YP_{unfert}	YP_{unfert} = -01.0073+6.1531(Bulk Red NDVI)-1.2891(Bulk Red NDVI)^2	3-5
8 and 9	Nref Red NDVI	YP_{fert}	YP_{fert} = 0.4266+0.455(Nref Red NDVI)+5.7336(Nref Red NDVI)^2	3-3
8 and 9	Bulk Red NDVI	YP_{unfert}	YP_{unfert} = -2.2814+11.7466(Bulk Red NDVI)-5.4647(Red NDVI)^2	3-6
3 through 9	NA	Response Index	Response Index = Nref Red NDVI/Bulk Red NDVI	NA
4 and 5	NA	RY Fks 45	RYfks45 = 0.3516+1.1194(ResponseIndex)-0.5748(ResponseIndex)^2	3-7
6 and 7	NA	RY Fks 67	RYfks67 = 0.3663+1.0262(ResponseIndex)-0.5471(ResponseIndex)^2	3-8
8 and 9	NA	RY Fks 89	RYfks89 = 1.5386-0.957(ResponseIndex)+0.2412(ResponseIndex)^2	3-9
3 and 4	Bulk Red NDVI	BRI	BRI = 0.1094(Bulk Red NDVI)$^{-2.0179}$e$^{-2.3803(Bulk Red NDVI)}$	3-10
3 and 4	NA	P Fks 9 Red NDVI	P Fks 9 Red NDVI = Bulk Red NDVI * BRI	NA
3 through 9	NA	Production Efficiency	Production Efficiency = 68.7947+-9.6315(YP_{unfert})	3-11
3 through 9	NRE	NRE adj. Production Efficiency	NRE adj. Production Efficiency = (PE*0.5)/NRE	NA
3 through 9	Field Yield Prod.	$Yield_{cap}$	$Yield_{cap}$ = if(RY > Field Yield Prod., Field Yield Prod, RY)	NA
3 through 9	NA	$Yield_{Diff}$	$Yield_{Diff}$ = $Yield_{cap}$ - YP_{unfert}	NA

NA = Not Applicable

Optical Sensor-Based Nitrogen Recommendation Algorithms

Intensive Nitrogen Management Algorithm "RosieKat" v2.6

Algorithm RK v2.6 was designed for wheat growers that want to optimize grain yield, grain protein, and reduce total applied N rates by making multiple N applications during the growing season, specifically targeting growth stages Feekes 4 through 9. Multiple N application strategies have the greatest potential of synchronizing N applications with the N demand of winter wheat. The difficulty is determining exactly when to apply N and how much. Algorithm RK v2.6 was designed to help determine the appropriate time and rate for N applications by comparing Red NDVI data collected from the bulk field throughout the growing season with an area of the field where a high rate of N was applied and is considered "N sufficient," or better known as a N reference strip. At the beginning of spring (Feekes 4), if no differences in Red NDVI are observed, N would not be applied. Even if wheat vegetative growth levels were obviously low, the RK v2.6 could abstain from making an N recommendation because a second N application later in the growing season would be made, thus allowing more time for potential N mineralization and N deficiencies to form so an accurate assessment of N needs could be made. This algorithm was designed to be simplistic and not have heavy requirements for data input and continued internal component development (Eq. 3.8; Table 3.2). Therefore, it is easier for a producer or consultant to use the RK v2.6 as a foundation to build his or her own version with on-farm data. This algorithm can be easily programmed into customizable precision agriculture software or even Microsoft Excel (Figure 3-12). The basic process used in making this N recommendation is summarized in equation 3.8 with order of implementation summarized in Table 3.2.

$$Algorithm\ RK\ v2.6\ N\ Recommendation\ kg\ N\ ha^{-1} = Yield_{Diff} * NRE\ adj.Production\ Efficiency \qquad [Eq.\ 3.8]$$

Table 3.2 Algorithm RKv2.6 Inputs and Outputs for Generating an N Recommendation

Step	Feekes Growth Stage	Input	Output	Equation	Figure
1	4 and 5	Nref Red NDVI	YP_{fert}	YP_{fert} = 0.2611+6.3055(Nref Red NDVI)	3-1
1	4 and 5	Bulk Red NDVI	YP_{unfert}	YP_{unfert} = 0.515+4.298(Bulk Red NDVI)	3-4
1	6 and 7	Nref Red NDVI	YP_{fert}	YP_{fert} = 4.4914-12.855(Nref Red NDVI)+16.635(Nref Red NDVI)^2	3-2
1	6 and 7	Bulk Red NDVI	YP_{unfert}	YP_{unfert} = -01.0073+6.1531(Bulk Red NDVI)-1.2891(Bulk Red NDVI)^2	3-5
1	8 and 9	Nref Red NDVI	YP_{fert}	YP_{fert} = 0.4266+0.455(Nref Red NDVI)+5.7336(Nref Red NDVI)^2	3-3
1	8 and 9	Bulk Red NDVI	YP_{unfert}	YP_{unfert} = -2.2814+11.7466(Bulk Red NDVI)-5.4647(Red NDVI)^2	3-6
2	3 through 9	NA	Response Index	Response Index = Nref Red NDVI/Bulk Red NDVI	NA
3	4 and 5	NA	RY Fks 45	RYfks45 = 0.3516+1.1194(ResponseIndex)-0.5748(ResponseIndex)^2	3-7
3	6 and 7	NA	RY Fks 67	RYfks67 = 0.3663+1.0262(ResponseIndex)-0.5471(ResponseIndex)^2	3-8
3	8 and 9	NA	RY Fks 89	RYfks89 = 1.5386-0.957(ResponseIndex)+0.2412(ResponseIndex)^2	3-9
4	3 through 9	NA	Production Efficiency	Production Efficiency = 68.7947+-9.6315(YP_{unfert})	3-11
5	3 through 9	NRE	NRE adj. Production Efficiency	NRE adj. Production Efficiency = (PE*0.5)/NRE	NA
6	3 through 9	Field Yield Prod.	$Yield_{cap}$	$Yield_{cap}$ = if(RY > Field Yield Prod., Field Yield Prod, RY)	NA
7	3 through 9	NA	$Yield_{Diff}$	$Yield_{Diff}$ = $Yield_{cap}$ - YP_{unfert}	NA
8	4 through 9	NA	N Recommendation	N Recommendation = YP_{Diff}*NRE adj. Production Efficiency	NA

NA = Not Applicable

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Intensive Management
Multiple Application N Rate Algorithm for Winter Wheat

Inputs	
Current Crop Growth Stage (Feekes Stage 4, 5, 6, 7, 8, or 9)	4
Yield Potential for this field or area, bushels/acre	60
Normal Nitrogen Use Efficiency for this area (see examples)	50%
Average RED NDVI Value from the Reference Strip Area	0.450
Average RED NDVI Value from the Bulk Field or Target Area	0.350
Outputs	
Current Yield Potential of Reference Strip bushels/acre	41
Response Index (Reference NDVI/Field or Target NDVI)	1.29
Recoverable Yield	84%
Yield Potential Without Additional N Fertilization, bushels/acre	29
Yield Potential with Additional N Fertilization, bushels/acre	39
lbs N per bushel of Yield	**2.18**
Sensor Based N Recommendation, adjusted for NUE, lbs. N/acre	**43**

Figure 3-12 Algorithm RK v2.6 Current Version (2015) in MS Excel

Feekes 4 N Management Algorithm "No Reference Strip" v1.5

Algorithm NRS v1.5 was designed for single top-dress N applications at early spring green-up (Late Feekes 3-Feekes 4). NRS v1.5 replaces an earlier KSU Feekes 4 single N application algorithm released in 2009 that was developed and utilized the N reference strip approach. The majority of wheat producers in Kansas utilize a single top-dress approach, in part because their current operation does not afford the time necessary for more intensive N management, or they believe that intensive management would be of no benefit to them. Therefore, these winter wheat producers need an accurate N recommendation in the early spring that is efficient, addresses growth necessary to achieve desired yield, and also adds a level of insurance against N loss events. Algorithms that are completely based on an N reference strip may not be a good fit. NRS v1.5 removes the necessity of an N reference strip and can function without one. NRS v1.5 assesses the potential growth response to applied N at Feekes 4. Then, it estimates the vegetative growth needed at the time of flag leaf formation for a given yield productivity level to make an N recommendation (Eq. 3.9; Table 3.3). This algorithm can be easily programmed into customizable precision agriculture software or even Microsoft Excel (Figure 3-13). The basic process used in making this N recommendation is summarized in equation 3.8 with order of implementation summarized in Table 3.3.

$$Algorithm\ NRS\ v1.5\ N\ Recommendation\ kg\ N\ ha^{-1} = Yield_{Diff} * NRE\ adj. Production\ Efficiency \quad [Eq.\ 3.9]$$

Table 3.3 Algorithm NRS v1.5 Inputs and Outputs for Generating an N Recommendation

Step	Feekes Growth Stage	Input	Output	Equation	Figure
1	3 and 4	Bulk Red NDVI	YP_{unfert}	YP_{unfert} = 0.515+4.298(Bulk Red NDVI)	3-4
2	3 and 4	Bulk Red NDVI	BRI	BRI = 0.1094(Bulk Red NDVI)$^{-2.0179}$e$^{-2.3803(\text{Bulk Red NDVI})}$	3-10
3	3 and 4	NA	P Fks 9 Red NDVI	P Fks 9 Red NDVI = Bulk Red NDVI * BRI	NA
4	3 and 4	NA	YP_{fert}	YP_{fert} = 0.4266+0.455(P Fks 9 Red NDVI)+5.7336(P Fks 9 Red NDVI)^2	3-3
5	3 and 4	NA	Production Efficiency	Production Efficiency = 68.7947+-9.6315(YP_{unfert})	3-11
6	3 and 4	NRE	NRE adj. Production Efficiency	NRE adj. Production Efficiency = (PE*0.5)/NRE	NA
7	3 and 4	Field Yield Prod.	$Yield_{cap}$	$Yield_{cap}$ = if(YP_{fert} > Field Yield Prod., Field Yield Prod, YP_{fert})	NA
8	3 and 4	NA	$Yield_{Diff}$	$Yield_{Diff}$ = $Yield_{cap}$ - YP_{unfert}	NA
9	3 and 4	NA	N Recommendation	N Recommendation = YP_{Diff}*NRE adj. Production Efficiency	NA

NA = Not Applicable

KANSAS STATE UNIVERSITY	**Creators:** Antonio Ray Asebedo | ara4747@ksu.edu Dr. David Mengel | dmengel@ksu.edu
Single Application **Sensor Based N Rate Algorithm for Winter Wheat Feekes 4**	
Inputs	
Yield Potential for this field or area, bushels/acre	60
Average RED NDVI Value from the Reference Strip Area	0.450
Average RED NDVI Value from the Bulk Field or Target Area	0.350
Normal Nitrogen Use Efficiency for this area (see examples)	50%
Outputs	
Current Yield Potential of Reference Strip bushels/acre	71
Yield Potential Without Additional N Fertilization, bushels/acre	23
Obtainable Yield Potential with Additional Fertilizer,	80
Final Yield to Fertilize For after selection	37
lbs N per bushel Adjusted for Field NUE	2.34
Sensor Based N Recommendation, adjusted for NUE, pounds N/acre	**87**

Figure 3-13 Algorithm NRS v1.5 Current Version (2015) in MS Excel

Validation Study Site Selection and Experimental Design

Field trials for evaluating algorithm performance were established in 2012-2013 in cooperation with Kansas' wheat producers and KSU Agronomy Experiment Field staff. Sites were selected on the basis of exploring different soils, local weather patterns, and their potential productivity. The Web Soil Survey (NRCS, 2015) was utilized to establish site soil texture and drainage class.

Both replicated and un-replicated field sites were established around KS. Small plots 3 meters by 12 meters were arranged at each location in a randomized complete block design with two or four replications. A total of four replicated trials were located at Manhattan (2 sites), McCune, and Solomon, KS. Protocol for the replicated trials consisted of eight treatments, which included five individual rates from an N response curve of 0, 34, 67, 101, and 134 kg N ha^{-1}, and three N rates based on Algorithm RK v2.6, Algorithm NRS v1.5, and KSU soil test N recommendation for winter wheat (Eq. 3.10). Nitrogen treatments were broadcast applied by hand with granular urea (46-0-0) as the N source. Cultural practices and key treatment dates for replicated trials are summarized in Table 3.4. The KSU soil test N recommendation for winter wheat in Kansas utilizes data from soil organic matter and residual soil nitrate in the 60 cm soil profile (Eq. 3.10). Default values of 11 kg ha^{-1} per 20 g kg^{-1} soil organic matter and 34 kg NO_3-N soil test N are used if soil test information is not available.

$$KSU\ Soil\ Testing\ N\ Rec\ for\ winter\ wheat\ = (Yield\ Goal\ (kg\ ha^{-1})\ x\ 0.043\ kg\ N\ kg^{-1}\ of\ Grain\ Yield) - (Organic\ Matter\ (g\ kg^{-1}) x\ 1.12) - \ Soil\ Profile\ Nitrate\ (kg\ ha^{-1}) - manure\ credits - additional\ \ credits \qquad [Eq.\ 3.10]$$

Table 3.4 Cultural Practices for Replicated Locations in 2013

Location	McCune	Solomon	Manhattan Site 1	Manhattan Site 2
Latitude	37.368732°	38.833269°	39.211738°	39.212591°
Longitude	-95.047313°	-97.355152°	-96.598641°	-96.599366°
Soil Series	Cherokee Silt loam	Muir Silt loam	Kennebec silt loam	Ivan silt loam
Drainage Class	Poorly Drained	Well Drained	Well Drained	Mod. Well Drained
Previous Crop	Failed Corn	Soybeans	Soybeans	Soybeans
Tillage Practice	Conventional	No-Till	No-Till	No-Till
Variety	Pioneer 25R30	Armour	Everest	Everest
Seeding Rate kg ha^{-1}	101	112	112	112
Seeding Method	Broadcast/Disc	Drill	Drill	Drill
Starter N kg ha^{-1}	0	26	20	20
Planting Date	10/16/12	10/17/12	10/19/12	10/19/12
Fall/Winter Treatments	11/20/12	12/19/12	11/2/12	11/2/12
Feekes 4 Treatments	2/19/13	3/19/13	3/29/13	3/29/13
Feekes 7 Treatments	4/15/13	4/25/13	4/25/13	4/25/13
Feekes 9 Treatments	5/6/13	5/10/13	5/6/13	5/6/13
Harvest Date	7/2/13	7/1/13	7/3/13	7/3/13

Un-replicated trials were located at Lawrence (3 sites) and Galena (2 sites), KS and were established during the spring of 2013 based on producer calls and requests. Space for these trials within a given field was generally limited, as majority of the fields were already fully fertilized at the time of trial establishment. Background information regarding cooperating farmer operations specifically dealing with seeding rates, variety selection, and soil information will not be disclosed by producer request. Un-replicated trials consisted of five treatments if enough space was available, which included an N reference strip, producer normal N rate, no N applied control plots, and N applications based on output from algorithms RK v2.6 and NRS v1.5. Nitrogen treatments were broadcast applied by hand with granular urea (46-0-0) as the N source. Cultural practices and key treatment dates for un-replicated trials are summarized in Table 3.5.

Table 3.5 Cultural Practices for Un-replicated Locations on KS producer fields in 2013

Location	Lawrence Site 1	Lawrence Site 2	Lawrence Site 3	Galena Site 1	Galena Site 2
Soil Type	Silt loam	Silt loam	Silt loam	Silt loam	Silt loam
Previous Crop	Failed Corn	Failed Corn	Failed Corn	Soybeans	Soybeans
Tillage Practice	Conventional	Conventional	Conventional	Conventional	Conventional
Seeding Method	Drill	Drill	Drill	Drill	Drill
Starter N kg ha^{-1}	0	0	0	0	0
Fall/Winter Treatments	2/6/13	2/6/13	2/6/13	.	.
Feekes 4 Treatments	3/15/13	3/15/13	3/15/13	3/20/13	3/20/13
Feekes 7 Treatments	4/27/13	4/27/13	4/27/13	.	.
Feekes 9 Treatments	5/9/13	5/9/13	5/9/13	.	.
Harvest Date	6/30/13	6/30/13	6/30/13	7/2/13	7/2/13

Soil Sampling and Analysis Methods

Single composite soil samples at both 0-15 and 0-60 cm depth consisting of 15 cores each were collected at each of the four replicated locations prior to planting and fertilization. The 0-15 cm surface samples were analyzed for soil pH, soil organic matter by Walkley Black, Mehlich-3 extractable phosphorus, and NH_4AC exchangeable potassium. The 0-60 cm profile samples were analyzed for nitrate-N, chloride, and sulfate-sulfur. All samples were analyzed by the KSU Soil Testing Laboratory using procedures recommended by NCERA-13 (Denning et al., 2011). Soil nutrient analysis for the replicated locations are summarized in Table 3.6.

Table 3.6 Soil Nutrient Analysis for Replicated Locations in 2013

Location	McCune	Solomon	Manhattan Site 1	Manhattan Site 2
Soil pH	5.9	5.9	7.2	6.6
Soil 0-15 cm O.M. g kg^{-1}	18.0	26.0	24.0	23.0
Soil 0-15 cm Mehlich-3 P mg kg^{-1}	22.0	34.0	64.0	24.0
Soil 0-15 cm K mg kg^{-1}	130.0	133.0	425.0	378.0
Soil 0-60 cm NO_3-N kg N ha^{-1}	83.5	44.1	13.9	5.1
Soil 0-60 cm Cl mg kg^{-1}	23.3	3.3	4.7	3.4
Soil 0-60 cm SO_4-S mg kg^{-1}	4.0	7.3	5.1	6.2

A single soil sample composite consisting of 15 cores at a depth of 0-30 cm were taken at each of the un-replicated sites at Lawrence and to 0-60 cm depth at the two Galena sites. The un-replicated site soil samples were analyzed for nitrate-N only by the KSU Soil Testing Laboratory using procedures recommended by NCERA-13 (Denning et al., 2011). The results are presented in Table 3.7.

Table 3.7 Soil Nitrate-N Analysis for Un-replicated Locations in 2013

Year	2013	2013	2013	2013	2013
Location	Lawrence Site 1	Lawrence Site 2	Lawrence Site 3	Galena Site 1	Galena Site 2
Soil 0-30 cm NO_3-N kg N ha^{-1}	22.7	61.2	18.3	.	.
Soil 0-60 cm NO_3-N kg N ha^{-1}	.	.	.	29.5	8.6

The Greenseeker (Trimble Navigation, Ag Division, Westminster, CO) optical sensor was used at a walking speed of one meter per second at a height approximately one meter above the canopy. The Greenseeker utilizes two channels set for 656 nm (RED) and 774 nm (NIR). Canopy reflectance data were used to calculate the Red Normalized Difference Vegetation Index (Rouse et al., 1973) and were averaged within each individual plot.

All experimental sites were machine harvested with a plot combine and an area of 1.5 meters by 12 meters was used to estimate grain yield. The grain from the harvested area was placed into a sack, weighed, and a subsample taken for analysis of grain moisture and test weight using a moisture meter (Dickey John 2100 GAC). Grain yield was adjusted to 125 g kg^{-1} moisture. Grain samples were submitted to the KSU Soil Testing Lab for analysis using a sulfuric acid-peroxide digestion to obtain grain N concentration (Denning et al., 2011). Total grain N uptake and grain protein were calculated using equations 3.11 and 3.12 respectively.

$$Total\ Grain\ N\ Uptake\ (kg\ N\ ha^{-1}) = \left(Grain\ Yield\ \frac{Mg}{ha}\ x\ \frac{1000\ kg}{Mg}\right) x\ (Grain\ N \frac{g}{kg}\ x\ \frac{kg}{1000\ g}) \qquad \text{[Eq. 3.11]}$$

$$Grain\ Protein\ (g\ kg^{-1}) = Grain\ N\ (g\ kg^{-1})\ x\ 6.25 \qquad \text{[Eq. 3.12]}$$

An approximation of NUE was made by estimating fertilizer N recovery in the grain using equation 3.13. It is important to note that the target of this NUE calculation is the percent recovery of "top-dress applied N fertilizer" in the grain. Starter fertilizer N applied to all the treatments at a constant rate was considered a control function much like residual NO_3-N measured by soil test or mineralized N from organic matter or crop residue.

$$NUE\ by\ Fertilizer\ N\ Recovery = \frac{Treatment\ Total\ Grain\ N\ Uptake\ (kg\ N\ ha^{-1}) - Control\ Total\ Grain\ N\ Uptake\ (kg\ N\ ha^{-1})}{Total\ Top\text{-}dress\ N\ Applied\ (kg\ N\ ha^{-1})} \quad \text{[Eq. 3.13]}$$

Statistical Analysis on Algorithm Validation Trials

A generalized linear mixed effects model was utilized to model grain yield data for interpretation. Nitrogen treatments were treated as fixed effects and location, block within location, and block by N treatment within location were treated as random effects. Replicated trials were analyzed by site and pooled across sites with the GLIMMIX PROCEDURE with the Kenward-Rodgers denominator degrees of freedom method and Fisher's LSD adjustment for testing hypotheses relevant to the objectives of this study and with by-site analysis using an alpha = 0.1 and 0.05 alpha for pooled analysis (SAS Institute, 2011). Un-replicated trials were not statistically analyzed and were used only to observe grain yield differences between the algorithms and the cooperating producer's standard N practice. Tables and bar graphs of the dataset were created with EXCEL (Microsoft, 2013).

Validation Trials Results and Discussion

Replicated Trials

Evaluation by Location

Manhattan Site 1

2013 Manhattan Site 1 was on a Kennebec silt loam that was in a bottom ground position with usual productivity of 4 to 5 Mg ha^{-1} grain yields (Table 3.4). Table 3.8 shows that the fall applied N rate treatments significantly increased grain yield up to a rate of 121 kg N ha^{-1}, with an additional trending increase in grain yield at 154 kg N ha^{-1} achieving 5.47 Mg ha^{-1}. However, initial outlook for making high grain yield at the start of spring was low. Very little vegetative growth had occurred over the fall and at the start of spring, no visible color or growth differences between the bulk field and the N reference strip (Treatment 5) could be found. This can be explained by the lack of precipitation during the fall and winter leading to very dry conditions during fall and early spring tillering (Figure 3-15). Therefore additional spring tillering was needed to generate a high grain yield. Figure 3-15 shows that after the Feekes 4 treatments had been applied, frequent precipitation events occurred, creating conditions conducive for spring tiller formation, allowing for 5 Mg ha^{-1} grain yield to be achieved across all treatments that received more than 100 kg total applied N ha^{-1} (Table 3.8).

For input parameters at Feekes 4, both algorithms and the KSU soil test N recommendation had their yield productivity measures set to 4 Mg ha^{-1} and NRE was set to the default 50%. Even though RK v2.6 requires an N Reference strip, because of its multiple N application strategy, the lack of visible differences between the N reference and bulk area was assumed not to be an issue because RK v2.6 assumes additional sensor readings will be obtained later in the growing season. RK v2.6 recommended a modest N rate of 37 kg N ha^{-1} at Feekes 4 to ensure early season yield components (head number, head size) would not be restricted (Table 3.8). Grain yield performance for RK v2.6 was not as good as NRS v1.5 or the KSU soil test N recommendation (Table 3.8). The potential cause of this yield lag may have been the increased variability in stand quality in the RK v2.6 plots. Thick piles of soybean residue were found randomly throughout the plot area that led to poor winter wheat emergence in those areas therefore leading to potential reductions in grain yield. Another issue may have been inadequate N application at Feekes 4 to stimulate enough new tillers and create adequate head size and seed numbers per head.

Although the performances of RK v2.6, NRS v1.5, and the KSU soil test N recommendation were similar across grain yield, grain protein, total grain N uptake, and NUE, their actual applied N rates were different (Table 3.8). Both RK v2.6 and NRS v1.5 applied 30 kg less N per hectare than the KSU soil test N Recommendation. Utilizing Figure 3-14, the optimum N rate for achieving the 95% agronomic optimum grain yield, considered a standard for establishing N recommendations in Kansas, at this site was 110 kg N ha^{-1} and therefore both RK v2.6 and NRS v1.5 were effective at determining the optimum N rate for this site. However, the design of RK v2.6 may have led to a delay in application and slightly reduced grain yield.

Table 3.8 2013 Manhattan Site 1 Summary Statistics on Grain Yield, Grain Protein, Total Grain N Uptake, and NUE by Fertilizer Recovery

Treatment	Starter	Fall	Feekes 4	Feekes 7	Feekes 9	Total Applied N	Grain Yield	GY LSD Group	Grain Protein	GP LSD Group	Total Grain N Uptake	TotGNup LSD Group	NUE as Recovery	NUE LSD Group
				kg N ha^{-1}			Mg ha^{-1}		g kg^{-1}		kg N ha^{-1}		%	
1	20	0	0	0	0	20	3.28	E	95	NS	50	E	NA	NA
2	20	34	0	0	0	54	4.54	D	104	NS	76	D	76	A
3	20	67	0	0	0	87	4.81	CD	109	NS	84	CD	51	B
4	20	101	0	0	0	121	5.14	ABC	105	NS	86	BCD	36	B
5	20	134	0	0	0	154	5.47	A	116	NS	101	AB	38	B
NRS v1.5	20	0	89	0	0	109	5.31	AB	109	NS	92	ABC	47	B
RK v2.6	20	0	37	40	15	111	4.97	BCD	115	NS	92	ABCD	49	B
Soil Test Rec.	20	0	123	0	0	143	5.27	AB	124	NS	104	A	44	B
SE							0.16		7.24		6.11		6.10	
F Value							18.15		2.01		8.26		5.27	
Treatment Pr >F							< 0.00		0.19		< 0.00		0.03	
Fisher's LSD Alpha = 0.1							0.91		NS		15.82		16.00	

NA = Not Applicable NS =Not Significant Groups with same letter are not significantly different, alpha = 0.1

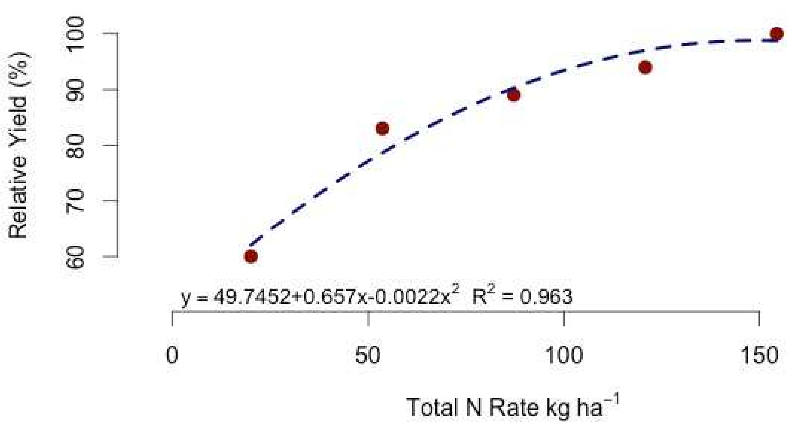

Figure 3-14 2013 Manhattan Fall Nitrogen Rate Treatments for Determining Optimum Nitrogen Rate

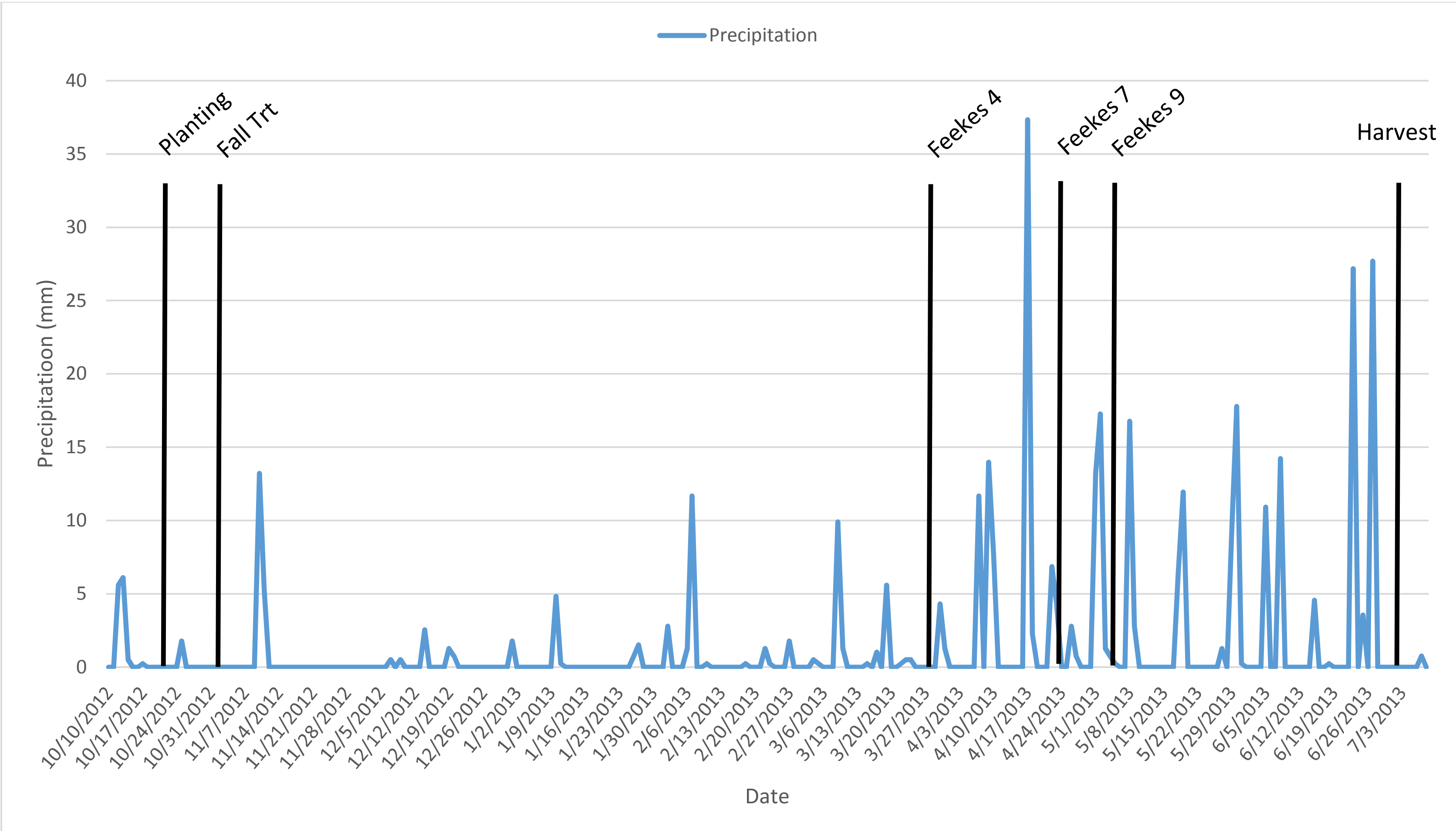

Figure 3-15 2013 Manhattan Site 1 Precipitation and Key Treatment Dates

Manhattan Site 2

Manhattan Site 2 was located on upland terraced ground in an Ivan silt loam soil that was prone to drought stress (Table 3.4). Overall grain yield productivity at this site was historically low to moderate yields, with maximum achieved grain yields reported at 4 Mg ha^{-1}. Yield productivity was set to 4 Mg ha^{-1} for RK v2.6, NRS v1.5, and the KSU soil test N recommendation. NRE was set to the default 50%. The confounding issues with water stress early and excess late-season precipitation potentially leading to N loss may have impacted grain yield, grain protein, and NUE (Figure 3-17; Table 3.4). Table 3.9 shows that NRS v1.5, RK v2.6, and the KSU soil test N recommendation had statistically equal performance in regards to grain yield, though NRS v1.5 recommended 20 kg N ha^{-1} less. However, RK v2.6 had statistically higher grain protein compared to NRS v1.5 and the KSU soil test N recommendation (Table 3.9). The 95% agronomic optimum N rate determined by Figure 3-16 was 111 kg N ha^{-1}. NRS v1.5 applied 10 kg over the fall optimum, and RK v2.6 and the KSU soil test N recommendation applied 30 kg N over the fall optimum (Table 3.9).

It is interesting to note that both algorithms and the KSU soil test N recommendation all had significantly lower grain yield when compared to fall-applied 121 kg N ha^{-1} (Table 3.9). Figure 3-17 shows that precipitation events throughout the fall and winter were low and therefore potential for N loss from fall-applied N was also low. However, the low precipitation during the fall limited fall tillering and early spring formation and therefore required additional spring tillering to generate higher grain yield (Figure 3-17). In addition, a five mm precipitation event occurred after the Feekes 4 applications made from both algorithms and the KSU soil test N recommendation (Figure 3-17). This event would have not been adequate to move the fertilizer into the toot zone, but would likely have initiated urea hydrolysis on the soil surface. Ten days passed before an additional 12 mm precipitation event occurred that would have incorporated the Feekes 4 treatments into the soil (Figure 3-17). This may have led to volatilization losses and the late incorporation of the Feekes 4 N applications. Thus the promotion of tillering during Feekes 4 and maximizing head size at Feekes 5 with an N application may have been missed. This could have led to the overall reductions in grain yield observed with RK v2.6, NRS v1.5, and the KSU soil test N rec when compared to the fall applied N treatments (Table 3.9).

A series of precipitation events totaling approximately 65 mm occurred between Feekes 4 N applications and Feekes 7 N applications (Figure 3-17). This may have resulted in some denitrification of NO_3-N which was present in the soil at that time. By delaying the majority of the N applications until Feekes 7 and Feekes 9, RK v2.6 would have avoided this potential N loss period. The grain yields observed with RK v2.6 and the potential avoidance of late-season N loss may explain the higher grain protein, total N uptake, and NUE when compared to NRS v1.5 and the KSU soil test N recommendation (Table 3.9).

Table 3.9 2013 Manhattan Site 2 Summary Statistics on Grain Yield, Grain Protein, Total Grain N Uptake, and NUE by Fertilizer Recovery

Treatment	Starter	Fall	Feekes 4	Feekes 7	Feekes 9	Total Applied N	Grain Yield	GY LSD Group	Grain Protein	GP LSD Group	Total Grain N Uptake	TotGNup LSD Group	NUE as Recovery	NUE LSD Group
				kg N ha^{-1}			Mg ha^{-1}		g kg^{-1}		kg N ha^{-1}		%	
1	20	0	0	0	0	20	2.19	D	116	CD	41	E	NA	NA
2	20	34	0	0	0	54	3.18	C	102	E	52	D	34	NS
3	20	67	0	0	0	87	3.94	B	109	DE	69	C	42	NS
4	20	101	0	0	0	121	4.28	A	121	C	83	B	42	NS
5	20	134	0	0	0	154	4.46	A	137	AB	98	A	43	NS
NRS v1.5	20	0	100	0	0	120	3.94	B	111	D	70	C	29	NS
RK v2.6	20	0	33	49	40	142	3.79	B	139	A	84	B	36	NS
Soil Test Rec.	20	0	123	0	0	143	3.80	B	130	B	79	B	31	NS
SE							0.15		3.61		2.51		3.50	
F Value							45.72		19.78		54.13		2.90	
Treatment Pr >F							< 0.00		< 0.00		< 0.00		0.11	
Fisher's LSD Alpha = 0.1							0.62		8.12		6.59		NS	

NA = Not Applicable NS =Not Significant Groups with same letter are not significantly different, alpha = 0.1

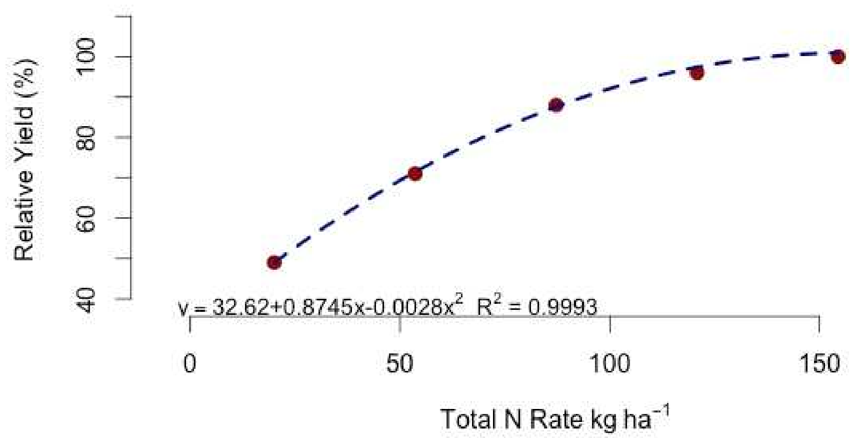

Figure 3-16 2013 Manhattan Site 2 Fall Nitrogen Rate Treatments for Determining Optimum Nitrogen Rate

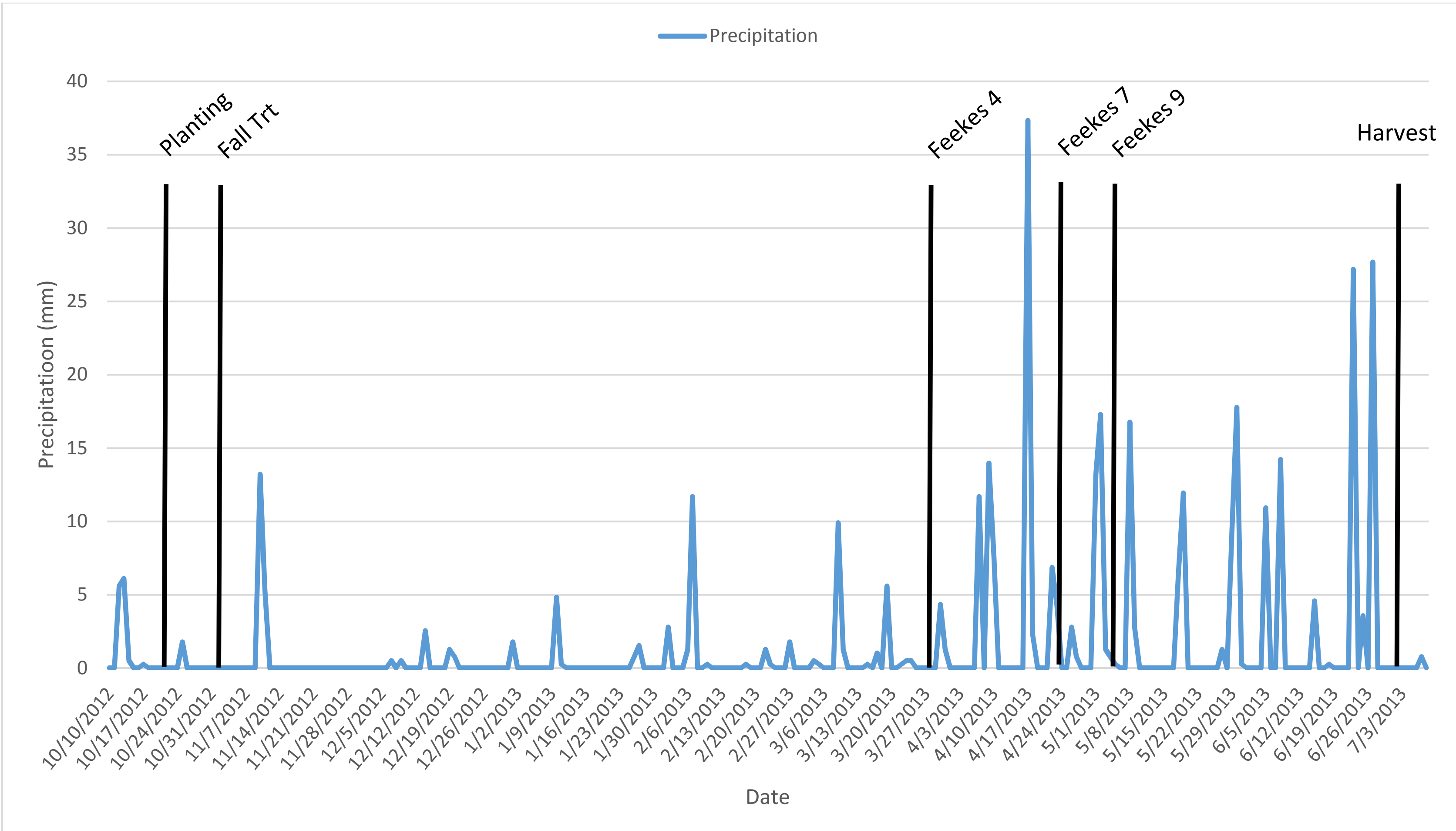

Figure 3-17 2013 Manhattan Site 2 Precipitation and Key Treatment Dates

McCune

The McCune site was located on a Cherokee silt loam, a “claypan” soil, that was very poorly drained (Table 3.4). High frequency and/or high precipitation events would potentially result in N losses from denitrification at this site. This location entered the spring with adequate early season growth. The producer’s highest productivity for this field was 7 Mg ha^{-1} if disease could be kept under control. However, historical yield productivity for this field was not disclosed before the initial Feekes 4 treatments. Therefore, NRS v1.5 and the soil test N recommendation grain yield parameter were set to 4 Mg ha^{-1}. Because RK v2.6 has the multiple N application strategy, the yield parameter was increased to 6 Mg ha^{-1} for Feekes 7 and 9 evaluation and N recommendations. Figure 3-18 shows that the optimum N rate for this site was 100 kg N ha^{-1} based on the fall applied N rates (Table 3.10). However, the frequent precipitation observed from February through June likely created significant N loss from denitrification that would have severely affected the fall applied N (Figure 3-19). Table 3.10 shows that with significant N present in the soil from the failed 2012 corn crop RK v2.6 readily achieved grain yields over 6 Mg ha^{-1} and was statistically equal to the highest yielding fall treatment. RK v2.6 performance at McCune optimized grain yield, protein, and significantly improved NUE (Table 3.10). The multiple N application strategy of RK v2.6 allowed it to properly address N loss events that took place just prior to Feekes 7 and 9, thus recovering grain yield with only 44 kg N ha^{-1} applied (Table 3.10) (Figure 3-19).

NRS v1.5 performed exactly the way it was told based on the yield parameter input. With the directive to maintain a minimum grain yield of 4 Mg ha^{-1}, NRS v1.5 determined no additional N was needed and over 5 Mg ha^{-1} was achieved, but was statistically lower yielding than the KSU soil test N recommendation and RK v2.6 (Table 3.10). However, if the historical grain yield data had been available, the yield productivity parameter would have been set to 6 Mg ha^{-1}. Red NDVI levels of NRS v1.5 test plots ranged from 0.62 to 0.75 and based on a yield productivity parameter of 6 Mg ha^{-1}, NRS v1.5 would have made an N recommendation of 46 kg N ha^{-1}. That is the equivalent N recommendation of the soil N recommendation applied at Feekes 4, which achieved over 6 Mg ha^{-1} (Table 3.10). Therefore, it is very likely NRS v1.5 would have achieved equal yield to RK v2.6 and the soil test N recommendation if the yield productivity parameter were set accordingly. This stresses the importance of utilizing historical yield data to properly set the yield productivity parameter for NRS v1.5 as this parameter will not allow the fertilization of grain yield potential that exceeds this input.

The KSU soil test N recommendation performed well at this site, showing that the use of a fall profile soil test is a valuable tool, even in areas of Kansas with high denitrification loss potential and high precipitation. If the collaborating producer elected to use the KSU N recommendation without the soil test utilizing the default values, the resulting N recommendation for the low 4 Mg ha^{-1} yield level would have been 103 kg N ha^{-1}. Which would have been equal to the optimum fall applied N rate but nearly 60 kg more than a similarly yielding spring applied soil test N recommendation or intensive sensor-based N recommendation.

Table 3.10 2013 McCune Summary Statistics on Grain Yield, Grain Protein, Total Grain N Uptake, and NUE by Fertilizer Recovery

Treatment	Starter	Fall	Feekes 4	Feekes 7	Feekes 9	Total Applied N	Grain Yield	GY LSD Group	Grain Protein	GP LSD Group	Total Grain N Uptake	TotGNup LSD Group	NUE as Recovery	NUE LSD Group
				kg N ha^{-1}			Mg ha^{-1}		g kg^{-1}		kg N ha^{-1}		%	
1	0	0	0	0	0	0	4.22	E	88	C	60	D	NA	NA
2	0	34	0	0	0	34	5.03	DE	92	C	74	CD	43	B
3	0	67	0	0	0	67	5.46	BCD	92	C	81	BC	31	B
4	0	101	0	0	0	101	6.73	A	104	A	112	A	51	B
5	0	134	0	0	0	134	6.24	ABC	95	ABC	95	AB	26	B
NRS v1.5	0	0	0	0	0	0	5.32	CD	93	BC	80	BC	100	A
RK v2.6	0	0	0	27	17	44	6.26	AB	103	AB	103	A	117	A
Soil Test Rec.	0	0	47	0	0	47	6.29	AB	103	AB	104	A	93	A
SE							0.39		4.31		8.48		20.00	
F Value							4.68		2.01		4.39		4.79	
Treatment Pr >F							< 0.00		0.01		< 0.00		< 0.00	
Fisher's LSD Alpha = 0.1							1.81		10.42		20.53		41.00	

NA = Not Applicable NS =Not Significant Groups with same letter are not significantly different, alpha = 0.1

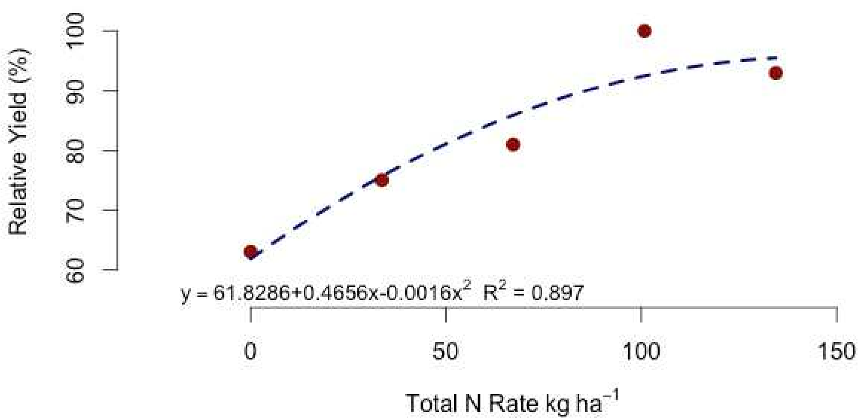

Figure 3-18 2013 McCune Fall Nitrogen Rate Treatments for Determining Optimum Nitrogen Rate

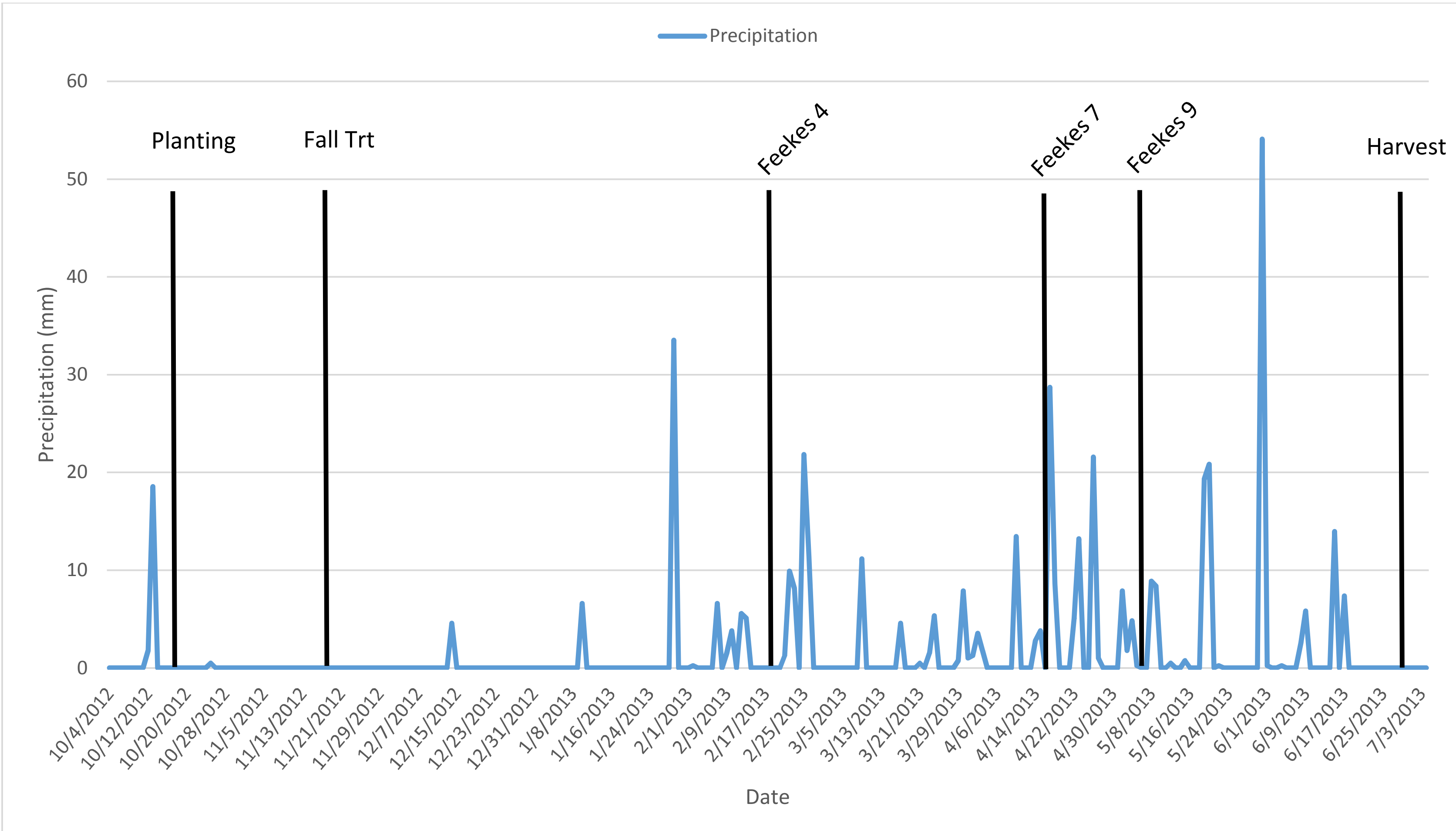

Figure 3-19 2013 McCune Precipitation and Key Treatment Dates

Solomon

The Solomon location was located in a bottom ground position on a Muir silt loam (Table 3.4). Producer historical yields had shown this location to be very productive with 4 to 5 Mg ha^{-1} being consistently achieved. Therefore, the yield productivity parameters were set to 4 Mg ha^{-1} and 50% for NRE. Like the other locations, the Solomon site entered the spring with limited early season growth and no visible difference in growth and color between the bulk field and N reference strip. This was likely due to the lack of precipitation during the fall (Figure 3-21)

Table 3.11 shows that a significant grain yield response was observed across the fall applied N rates up to 127 kg N ha^{-1}. Figure 3-20 shows that the 95% agronomic optimum N rate would have been 125 kg N ha^{-1} based upon the fall applied N rates. However, Figure 3-21 shows that frequent precipitation events occurred through April with one 70 mm precipitation event in May. These events likely induced denitrification losses that would have reduced the effectiveness of the fall and Feekes 4 N applications (Table 3.11). Algorithm RK v2.6 showed a clear advantage at this location by splitting N application timing and utilizing a later N application (Table 3.11). Although the total applied N rate was near identical to NRS v1.5 and the KSU soil test N recommendation, the split N application system used with RK v2.6 produced statistically higher grain yield, grain protein, total grain N uptake, and NUE (Table 3.11). RK v2.6 effectively optimized grain yield, protein, and NUE with 10 kg N ha^{-1} less applied N than the fall applied optimum N rate.

Table 3.11 2013 Solomon Summary Statistics on Grain Yield, Grain Protein, Total Grain N Uptake, and NUE by Fertilizer Recovery

Treatment	Starter	Fall	Feekes 4	Feekes 7	Feekes 9	Total Applied N	Grain Yield	GY LSD Group	Grain Protein	GP LSD Group	Total Grain N Uptake	TotGNup LSD Group	NUE as Recovery	NUE LSD Group
			kg N ha^{-1}				Mg ha^{-1}		g kg^{-1}		kg N ha^{-1}		%	
1	26	0	0	0	0	26	3.54	D	90	BC	51	E	NA	NA
2	26	34	0	0	0	60	3.91	D	84	D	53	E	5	C
3	26	67	0	0	0	93	4.83	C	87	CD	67	D	24	B
4	26	101	0	0	0	127	5.17	ABC	90	BC	75	BC	24	B
5	26	134	0	0	0	160	5.32	AB	95	AB	80	B	22	B
NRS v1.5	26	0	79	0	0	105	4.90	C	87	CD	69	CD	22	B
RK v2.6	26	0	6	53	27	112	5.57	A	99	A	88	A	45	A
Soil Test Rec.	26	0	82	0	0	108	5.03	BC	90	C	72	CD	26	B
SE							0.17		1.91		3.03		6.40	
F Value							17.54		6.00		17.65		4.37	
Treatment Pr >F							< 0.00		< 0.00		< 0.00		< 0.00	
Fisher's LSD Alpha = 0.1							0.78		8.95		7.34		13.60	

NA = Not Applicable NS =Not Significant Groups with same letter are not significantly different, alpha = 0.1

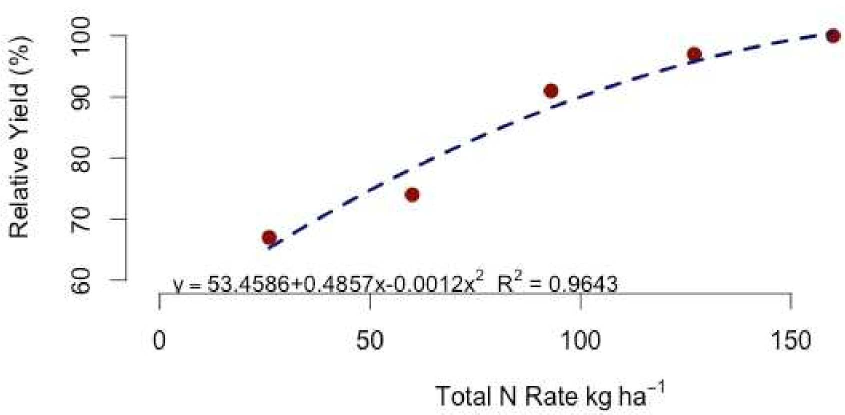

Figure 3-20 2013 Solomon Fall Nitrogen Rate Treatments for Determining Optimum Nitrogen Rate

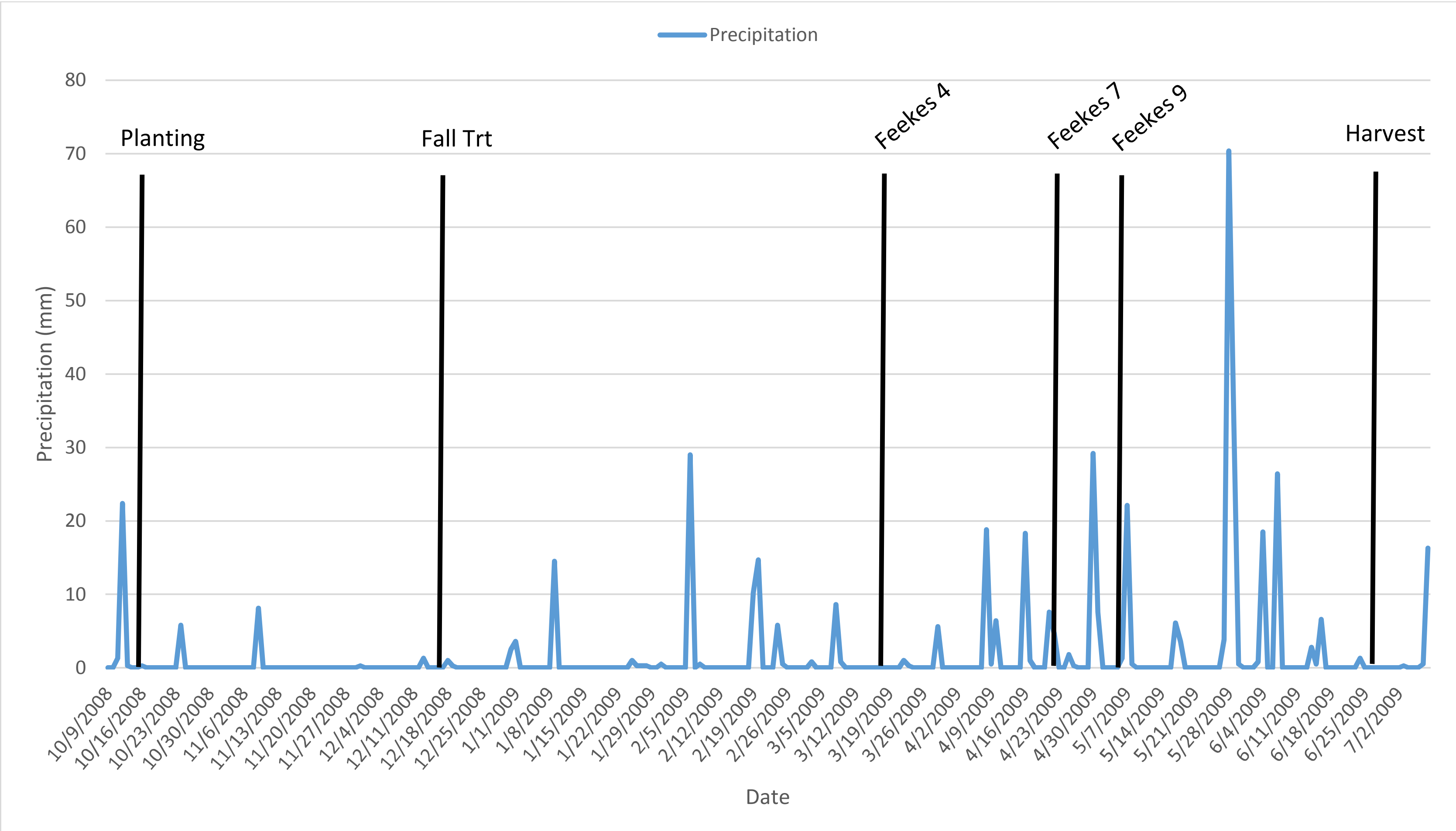

Figure 3-21 2013 Solomon Precipitation and Key Treatment Dates

Across Location Analysis of Algorithm Performance, Pooled Results

Table 3.12 presents the pooled results for grain yield, grain protein, total grain N uptake, and NUE. Overall grain yield response to applied N response was very positive to fall applied N, forming a plateau at 119.64 kg N ha^{-1} (Figure 3-22). The optimum N rate based upon the fall applied N rates was 110 kg N ha^{-1}). Grain protein response to fall-applied N continued to increase to 169 kg N ha^{-1} (Table 3.12).

The KSU soil test N recommendation was able to achieve grain yield and grain protein in the highest statistical groups (Table 3.12), and applied the optimum N rate with a trending increase in NUE over the fall applied N treatments (Table 3.12). Therefore, soil test-based N recommendations still provide very valid recommendations, and their use should still be encouraged. The agronomically-sound performance of the soil test N recommendations provided a good standard for evaluating the performance of algorithms RK v2.6 and NRS v1.5.

Algorithm NRS v1.5 was designed with the primary goal of generating high grain yield and high NUE in Feekes 4 single top-dress N management systems. Therefore, NRS v1.5 N recommendations would only be for generating grain yield, and would not prioritize fertilizing for grain protein. Table 3.12 shows that NRS v1.5 applied 30 kg N ha^{-1} less than RK v2.6 and the KSU soil test N recommendation but produced grain yield significantly lower than RK v2.6, and achieved NUE equal to the KSU soil test N recommendation. However, with the overall reduced N rates of NRS v1.5, grain protein concentrations were statistically lower than RK v2.6 and the KSU soil test N recommendation (Table 3.12).

Algorithm RK v2.6 was designed for optimizing both grain yield and grain protein by incorporating an intensive N management strategy that would potentially make multiple N applications based on crop N requirements. Intensive N management has many agronomic advantages over a single early spring top-dress approach that must be noted.

1. Allows producer more time to assess current year's weather conditions and determine if it is a favorable crop year
2. Allows producer to respond to potential N loss events
    a. Increased N rates don't need to be applied to protect grain yield, potentially improving NUE
    b. N recommendations following N loss event only fertilizes for recoverable grain yield, potentially improving grain yield

3. Partitioning efficiency of winter wheat is better with late season N applications
    a. Applied N will be more effectively utilized for grain production, potentially improving NUE
4. N recovery of applied N is greater in the late season (Feekes 7-9)
    a. Well-developed root structures and active N uptake, better syncing N applied with crop demand, potentially improving NUE

RK v2.6 achieved grain yield and protein in the statistically highest group but with a NUE of 61%, which was significantly greater than all other treatments (Table 3.12). This increase in NUE while producing high grain yield and protein is potentially due to the better synchronization of N applications with crop N demand and when the crop determines its yield components.

Table 3.12 2013 Across Replicated Trials Analysis, 4 Locations

Treatment	N Timing	Total N Rate	Grain Yield	GY LSD Group	Grain Protein	GP LSD Group	Total Grain N Uptake	TotGNup LSD Group	NUE as Recovery	NUE LSD Group
		kg N ha^{-1}	Mg ha^{-1}		g kg^{-1}		kg N ha^{-1}		%	
1	Fall	24	3.34	D	98	D	52	D	NA	NA
2	Fall	57	4.11	C	97	D	64	C	34	BC
3	Fall	91	4.73	B	100	D	75	B	34	BC
4	Fall	133	5.38	A	106	BC	91	A	38	BC
5	Fall	169	5.35	A	109	AB	92	A	29	C
NRS v1.5	Fks 4	77	4.79	B	100	CD	77	B	53	AB
RK v2.6	Fks 4-9	110	5.24	A	113	A	93	A	68	A
Soil Test Rec.	Fks 4	111	5.13	AB	110	AB	89	A	52	AB
SE			0.43		7.08		5.80		12.10	
F Value			22.91		9.24		20.31		3.35	
Treatment Pr >F			< 0.00		< 0.00		< 0.00		< 0.00	
Fisher's LSD Alpha = 0.05			0.42		5.73		9.40		21.68	

NA = Not Applicable NS =Not Significant Groups with same letter are not significantly different, alpha = 0.05

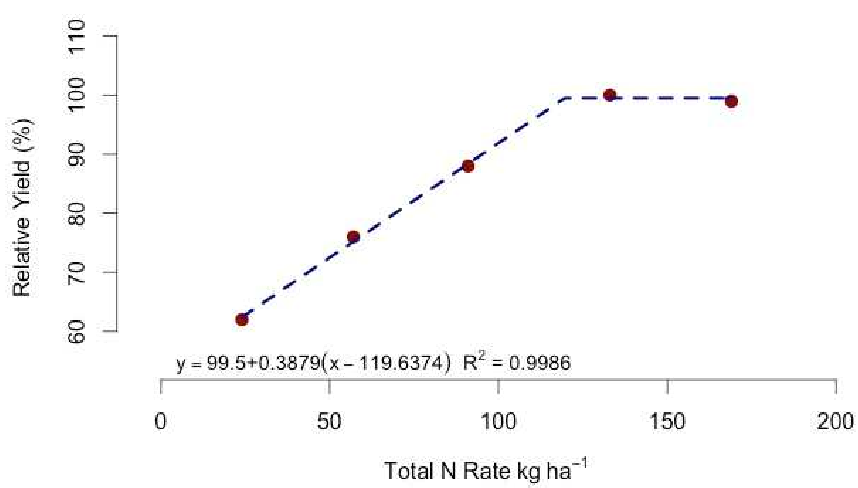

Figure 3-22 2013 Across Replicated Trials with Four Locations, Fall Nitrogen Rate Treatments for Determining Optimum Nitrogen Rate

Un-replicated Trials

By Site Evaluation

Galena Site 1 and 2

Galena 1 was an un-replicated trial in southeast Kansas. Only algorithm NRS v1.5 was tested at this site due to producer request. The producer owns a variable rate spray rig that is equipped with AOS technology and was not impressed with the performance of the algorithms preprogramed into the system controller. In addition, the producer wanted to move away from using N reference strips due to logistic issues and previous experience with N reference strip failures caused by excessive biomass making microclimates conducive for disease. The producer traditionally fertilized for 5 Mg ha^{-1}grain yields. However, disease usually limits overall yield production.

NRS v1.5 yield productivity parameter was set to 4.5 Mg ha^{-1} with an NRE of 50% as requested by the producer. NRS v1.5 was able to achieve this yield with 40 kg N ha^{-1} (Table 3.13). The producer's normal practice achieved his 5 Mg ha^{-1} yield goal but utilized 101 kg N ha^{-1}. The N Reference strip experienced a number of diseases with powdery mildew becoming the most prevalent during grain fill which resulted in a reduction in grain yield (Table 3.13).

Galena Site 2 (Table 3.13) was in collaboration with the same producer with Galena Site 1. Conditions for Site 2 were the same as site 1. Results at Galena site 2 were nearly identical as Galena site 1 with the exception of the N reference strip not becoming compromised by disease. Algorithm NRS v1.5 achieved the 4.5 Mg ha^{-1} grain yield with 40 kg N ha^{-1}. The N reference achieved the highest grain yield with 134 kg N ha^{-1}.

Table 3.13 Galena Site 1 and 2 Grain Yield Response to N Application

Site	Treatment	Fall	Feekes 4	Feekes 7	Feekes 9	Total Applied	Grain Yield
		N Rate kg N ha^{-1}					Mg ha^{-1}
Galena 1	NRS v1.5	0	40	0	0	40	4.37
Galena 1	N Reference	0	134	0	0	134	4.24
Galena 1	Producer Rate	0	101	0	0	101	5.16
Galena 1	Flat rate	0	34	0	0	34	4.70
Galena 2	NRS v1.5	0	36	0	0	36	4.35
Galena 2	N Reference	0	134	0	0	134	5.69
Galena 2	Producer Rate	0	101	0	0	101	5.17
Galena 2	Flat Rate	0	34	0	0	34	4.41

Lawrence Site 1, 2, and 3

Lawrence 1 was established in collaboration with an area consultant. Fall and early spring growth was high since the wheat was following a failed corn crop and high profile nitrate-N levels were present (Table 3.7). Yield parameters were set to 5 Mg ha^{-1} at the request of the consultant with an NRE of 50%. Algorithms RK v2.6 and NRS v1.5 easily attained 5 Mg ha^{-1} with 19 kg N ha^{-1} (Table 3.14). Because algorithm NRS v1.5 assumes a single top-dress N management system, the evaluation of early spring growth determined that some N should be applied for yield protection against N loss to insure 5 Mg ha^{-1} is achieved (Table 3.14). RK v2.6 did not apply any N at Feekes 4 and applied 19 kg N ha^{-1} at Feekes 9 with a very positive increase in grain yield (Table 3.14)

Lawrence Site 2 was established in collaboration with the same consultant as Lawrence site 1, but on a different farm. Lawrence Site 2 was following failed corn, and therefore high levels of residual nitrate-N were expected (Table 3.7). However, this field experienced issues with spotty stands due to complications when planting. The consultant questioned if grain yields of 3 Mg ha^{-1} were achievable, and the producer considered tilling the field and planting grain sorghum (*Sorghum bicolor*). However, after conversations with the consultant, insisting the wheat crop can still produce very respectable yields, the field was kept in wheat and the trial was continued. Yield productivity parameter was set to 4 Mg ha^{-1} with an NRE of 50%. Table 3.14 shows that algorithm RK v2.6 and NRS v1.5 achieved grain yields above 5 Mg ha^{-1} with less than 50 kg N ha^{-1} applied (Table 3.14). Most of these treatments had very similar spotty stands and yields maxed out at 5.6 Mg ha^{-1} (Table 3.14). However, an additional plot was established for RK v2.6 where the stand condition was excellent and achieved over 6.2 Mg ha^{-1} without the need of additional N (Table 3.14).

Lawrence Site 3 was established in collaboration with the same consultant as the other Lawrence Sites, but on a different farm. The winter wheat was following a corn crop that achieved moderate yields and had high levels of fall growth. However, winter wheat color was visibly becoming yellow at Feekes 4 and easily distinguishable from the N reference strip. Yield productivity parameter was set to 5 Mg ha^{-1} with an NRE of 50%. Algorithms RK v2.6 and NRS v1.5 exceeded 5 Mg ha^{-1} with less than 50 kg N ha^{-1} applied (Table 3.14). Algorithm RK v2.6 was applied to two plots, one with a fairly uniform stand, and a plot with a patchy stand. 5 Mg ha^{-1} input was achieved in both RK v2.6 plots but overall yield was reduced when compared to NRS v1.5 because of issues with stand quality (Table 3.14).

Table 3.14 Lawrence Site 1, 2, and 3 Grain Yield Response to N Application

Site	Treatment	Fall	Feekes 4	Feekes 7	Feekes 9	Total Applied	Grain Yield
		N Rate kg N ha^{-1}					Mg ha^{-1}
Lawrence 1	RK v2.6	0	19	0	0	19	6.73
Lawrence 1	RK v2.6	0	19	0	0	19	6.59
Lawrence 1	NRS v1.5	0	26	0	0	26	5.36
Lawrence 1	Control	0	0	0	0	0	5.45
Lawrence 1	N Reference	134	34	0	0	168	4.53
Lawrence 2	RK v2.6	0	0	0	0	0	6.24
Lawrence 2	RK v2.6	0	46	0	0	46	5.57
Lawrence 2	NRS v1.5	0	26	0	0	26	5.39
Lawrence 2	Control	0	0	0	0	0	5.43
Lawrence 2	N Reference	134	0	0	0	134	5.57
Lawrence 3	RK v2.6	0	24	0	0	24	5.33
Lawrence 3	RK v2.5	0	20	0	0	20	5.99
Lawrence 3	NRS v1.5	0	47	0	0	47	6.14
Lawrence 3	Control	0	0	0	0	0	5.59
Lawrence 3	N Reference	134	0	0	0	134	6.11

Conclusions and Discussion

The KSU soil test N recommendation system for winter wheat has proved itself to still be a very valid approach that works very well for achieving high grain yield with high NUE. The problem of making an N recommendation with the current KSU N recommendation formula using the default soil organic matter and profile NO3-N values is the likely hood of over application N and less than satisfactory NUE. The use of soil testing for N recommendations should still be strongly encouraged.

Algorithm RK v2.6 performed very well across the field validation trials. It consistently provided highly efficient N recommendations while protecting yield in response to N loss events. Because of its multiple N application strategy, RK v2.6 is very conducive for crop monitoring and optimizing N application timings for lower applied N rates while achieving high grain yield and protein. In addition, the multiple N application strategy of RK v2.6 utilized more conservative N rates with Feekes 4 applications, and does not become overly concerned when no visible differences with the N reference strip are observed. However, if no differences in NDVI exist between the N reference strip and bulk field and tiller numbers are low, RK v2.6 will not recommend an N application. This may reduce spring tiller formation and limit overall grain yield capacity; therefore this characteristic in RK v2.6 is should be changed to better support early season grain yield components.

A suggested reformulation of RK v2.6 would be to disconnect its functions from the N reference and incorporate components similar to NRS v1.5 that address early-season grain yield components and are more capable of calibrating for specific fields while maintaining its multiple N application strategy for supporting late-season grain yield components. This would present an opportunity to generate a new intensive algorithm that can inform consultants if the opportunity exists to go for higher yield and provide risk assessment of potential N applications, thus optimizing grain yield, protein, profits, and NUE specifically for conditions of the current crop year.

Algorithm NRS v1.5 provided very positive results in regards to grain yield and NUE. Without the use of the N reference strip, NRS v1.5's performance in regards to grain yield was statistically equal to the soil test-based N recommendation and algorithm RK v2.6. Although RK v2.6 has the advantage of a multiple N application strategy, NRS v1.5 can accurately assess early spring growth and determine how much N needs to be applied to achieve the yield productivity put in by the user, if possible. Hence, NRS v1.5 can better assess the status of the wheat crop and determine if additional N is necessary early, or if enough N is present for achieving the yield productivity parameter inputs. Simply put, NRS v1.5 is a more advanced design that better incorporates agronomics than RK v2.6, thus it will perform more consistently when addressing Feekes 4 N management.

Both algorithms, RK v2.6 and NRS v1.5, were effective at achieving their intended goals. RK v2.6 focused on optimizing grain yield and protein concurrently with NUE with a multiple N application strategy. NRS v1.5 was only concerned with optimizing grain yield with the highest NUE possible from an early spring single top-dress approach. In that regard, both algorithms were very successful from the 2013 validation trials.

References:

Arnhold, E. (2014). easynls: Easy nonlinear model. R package version 4.0. http://CRAN.R-project.org/package=easynls

Blackburn, G.A., (1998). Spectral indices for estimating photosynthetic pigment concentrations: A test using senescent tree leaves. *International Journal of Remote Sensing*, 19(4):657-675.

Blackburn, G.A., (1999). Relationships between spectral reflectance and pigment concentrations in stacks of deciduous broadleaves. *Remote Sensing of Environment*, 70(2):224-237.

Cassman, K.G., A.D. Dobermann, and D.T. Walters. (2002). Agroecosystems, N- use efficiency, and N management. *Ambio* 31:132–140.

Cassman, K.G., A.D. Dobermann, D.T. Walters, and H. Yang. 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. *Ann. Rev. Environ. Resour.* 28:315–358.

Comly, H.H. (1945) Cyanosis in infants caused by nitrates in well water. *JAMA* 129(2), 112–116.

Denning, J., Eliason, R., Goos, R. J., Hoskins, B., Nathan, M. V, & Wolf, A. (2011). *Recommended Chemical Soil Test Procedures for the North Central Region*, *221*(221), 75.

Elvidge, C.D., and Z. Chen, (1995). Comparison of broadband and narrow-band red and near-infrared vegetation indices, *Remote Sensing of Environment*, 54:38-48.

Erdle, K., B. Mistele, and U. Schmidhalter. (2011). Comparison of active and passive spectral sensors in discriminating biomass parameters and nitrogen status in wheat cultivars. *Field Crops Research*, *124*(1), 74–84. http://doi.org/10.1016/j.fcr.2011.06.007

Fitzgerald, G. J. (2010). Characterizing vegetation indices derived from active and passive sensors. *International Journal of Remote Sensing*, *31*(16), 4335–4348. http://doi.org/10.1080/01431160903258217

Goulding, K.W.T., P.R. Poulton, C.P. Webster, and M.T. Howe. (2000). Nitrogen leaching from the Broadbalk Wheat Experiment, Rothamsted, UK, as influenced by fertilizer and manure inputs and weather. *Soil Use Manage*. 16:244–250.

Hatfield, J.L., A.A. Gitelson, J.S. Schepers, and C.L. Walthall. (2008). Application of spectral remote sensing for agronomic decisions. *Agronomy J*. 100: S-117–S-131.

Hawkesford, M. (2012). The diversity of nitrogen use efficiency for wheat varieties and the potential for crop improvement. *Better Crops with Plant Food*, *96*(3), 10–12.

Holland, K. H., and J. S. Schepers. (2010). Derivation of a Variable Rate Nitrogen Application Model for In-Season Fertilization of Corn. *Agronomy J. 102*(5), 1415.

Holland, K. H., D.W. Lamb, and J.S. Schepers. (2012). Radiometry of proximal active optical sensors (AOS) for agricultural sensing. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *5*(6), 1793–1802. http://doi.org/10.1109/JSTARS.2012.2198049

Microsoft. (2013). Microsoft Excel computer software. Redomond, Washington: Microsoft.

Miller, B. T. D. (1999). *Growth Stages of Wheat*. Texas Ag. Ext. Service, (SCS-1999-16), 4p. Retrieved from http://baylor-agrilife-org.wpengine.netdna-cdn.com/files/2011/06/growthstagesofwheat_11.pdf

NRCS Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. (2015). *Web Soil Survey*. Available online at http://websoilsurvey.nrcs.usda.gov/

Pinter, P.J., Hatfield, J.L., Schepers, J.S., Barnes, E.M., Moran, M.S., Daughtry, C.S.T., Upchurch, D.R., (2003). Remote sensing for crop management. *Photogramm. Eng. Remote Sens*. 69, 647–664.

Phillips, S. B., D. A. Keahey, J. G. Warren, and G. L.v Mullins. (2004). Estimating winter wheat tiller density using spectral reflectance sensors for early-spring, variable-rate nitrogen applications. *Agronomy J. 96*(3), 591–600.

Prasad, B., Carver, B.F., Stone, M.L., Babar, M.A., Raun, W.R., & Klatt, A.R. (2007). Potential use of spectral reflectance indices as a selection tool for grain yield in winter wheat under Great Plains conditions. *Crop Science*. 47, 1426–1440.

Rabalais, N.N., R.E. Turner, Q. Dortch, W.J. Wiseman, Jr., and B.K. Sen Gupta. (1996). Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. *Estuaries* 19:366–407.

Rabalais, N.N., R.E. Turner, W.J. Wiseman, and Q. Dortch. (1998). Consequences of the 1993 Mississippi River flood in the Gulf of Mexico. *Regulated Rivers Res. Manage*. 14:161–177.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, E.V. Lukina, W.E. Thomason, J.S. Schepers, (2001). In-season prediction of potential grain yield in winter wheat using canopy reflectance. *Agronomy J*. 93:131–138.

Raun, W. R., J. B. Solie, G. V. Johnson, M. L. Stone, R. W. Mullen, K. W. Freeman, E. V. Lukina. (2002). Improving Nitrogen Use Efficiency in Cereal Grain Production with Optical Sensing and Variable Rate Application. *Agronomy J. 94*(4), 815–820.

Raun, W.R., J.B. Solie, M.L. Stone, K.L. Martin, K.W. Freeman, R.W. Mullen, H. Zhang, J.S. Schepers, and G.V. Johnson. (2005). Optical sensor based algorithm for crop nitrogen fertilization. *Commun. Soil Sci. Plant Anal*. 36:2759–2781. doi:10.1080/00103620500303988

R Core Team (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Rouse, J. W., R. H. Haas, J. A. Schell, and D. W. Deering (1973). Monitoring vegetation systems in the Great Plains with ERTS, *Third ERTS Symposium*, NASA SP-351 I, 309- 317.

SAS Institute. (2011). Release 9.3 ed. SAS Inst., Cary, NC.

Schlegel, A.J., C.A. Grant. (2006). Chapter Six. *Dryland Agriculture*, 2nd ed., Agronomy Monograph no.23.2006.

Solie, J. B., A. D. Monroe, W. R. Raun, and M. L. Stone. (2012). Generalized Algorithm for Variable-Rate Nitrogen Application in Cereal Grains. *Agronomy J. 104*(2), 37

Thenkabail, P. S., R. B. Smith, and E. D. Pauw. (2002). Evaluation of narrowband and broadband vegetation indices for determining optimal hyperspectral wavebands for agricultural crop characterization. *Photogrammetric Engineering and Remote Sensing*, *68*(6), 607–621. Retrieved from http://www.asprs.org/a/publications/pers/2002journal/june/2002_jun_607-621.pdf

Chapter 4 - Evaluation of Nitrogen Management Strategies and Potential for Fertigation Applications Utilizing Remote Sensing in Corn (*Zea mays*)

Abstract

Nitrogen use efficiency (NUE) in high-yield irrigated corn (*Zea mays*) production systems has many economic and environmental implications. The increasing conversion of flood irrigated land in Kansas to center pivot sprinkler irrigation systems presents the opportunity to develop automated systems for advanced N management through fertigation that can potentially increase N utilization, reduce environmental impact, and increase profit per acre. The purpose of this study was to evaluate single pre-plant, split, and sensor-based N management practices under irrigation on two different soil textural classes and evaluate previously developed KSU sensor-based N recommendation algorithm. Three N rates were applied pre-plant, pre-plant/V-4, and pre-plant/sensor on coarse and medium texture soils at Scandia and Rossville, KS from 2012 through 2014 for three corn crop years. Results indicate split applications of N provide the ability to reduce overall N rates and still achieve high grain yield because N applications have better synchronization with corn N demand. Application of 45 kg N ha^{-1} prior to planting and an additional 122 kg N ha^{-1} applied based on the sensor N recommendation during the growing season, was able to achieve grain yields equal to 243 kg N ha^{-1} pre-plant application, but with 54 kg N ha-1 less. . The overall performance of the sensors and the KSU corn N recommendation algorithm was effective at achieving high corn yields, but has the tendency to overestimate corn N requirements if too much N is applied prior to planting.

Introduction

Nitrogen is a critical nutrient for increasing grain yield in corn. According to Johnson (2000), over the past two decades no other applied nutrient has increased grain yield more dramatically than N. Corn producers realized long ago the potential for improving yield through N applications, and therefore it was a logical decision to increase the total rates of applied N as part of their current pre-plant N management practice to achieve higher grain yields.

Many producers in the region rely on pre-plant applications of granular urea or anhydrous ammonia fertilizer as the primary N source in irrigated corn production systems. Pre-plant N management applications are utilized in production agriculture for their logistical efficiency and can be considered common practice in Kansas corn production.

These types of N management practices for corn have caused NO_3 to be the most commonly found contaminate in surface and ground waters in this region (CAST, 1999; Steinheimer et al., 1998; Schilling, 2002). The recorded amount of biologically-reactive N that is streaming in from the Corn Belt states into the Gulf of Mexico by the Mississippi River has greatly increased over the past century (Turner and Rabalais, 1991). According to Rabalais (2002), this issue has been the primary factor contributing to the oxygen depletion and formation of hypoxic zones in the coastal waters in the Gulf of Mexico.

Nitrogen management practices such pre-plant N applications can have poor synchrony between soil N supply and crop demand (Raun and Johnson, 1999; Cassman et al., 2002; Fageria and Baligar, 2005), thus having much greater potential for low NUE and greater N loss.
There are many pathways for N losses from agricultural systems to reach the environment. Plant emissions of ammonia, denitrification, surface runoff, ammonia volatilization, and NO_3 leaching (Raun and Johnson, 1999), are all N loss pathways that can lead to an increased load of biologically-reactive N in the environment (Cassman et al., 2002).

An immediate response for mitigating the current impacts of N fertilization on the environment is to reduce total applied N, which in turn would reduce overall N load entering the environment. However, changes in N rate applied with no regard to when and how the N is applied, will result in a direct reduction in corn grain yield, and the intended reductions in N load transported to the environment may not be fully achieved. Nitrogen fertilizer needs to be managed efficiently in order to maximize yield and profit per acre in addition to minimizing environmental impact (Feinerman et al. 1990).

There are numerous N management practices that are available for improving NUE such as slow-release N fertilizers, precision N rate calculations, nitrification inhibitors, applying N at the time of peak N uptake by the crop, proper placement, and split applications (Cole et al., 1997; Dalal et al., 2003; Robertson, 2004; Paustian et al., 2004; Monteny et al., 2006) The application of N during important yield-determining stages of corn growth with reduced amounts throughout the growing season has great potential for improving NUE. This method is often referred as “spoon-feeding” and has the advantage of applying the right rate of N at the right time thus applying N on an “as needed” basis for enhanced NUE (Olson and Kurtz, 1982;

Schepers et al., 1995). Although these types of N applications are not practical for dryland production, irrigation systems such as sprinkler and subsurface drip are choice platforms for season-long N management.

With the fertigation capabilities of sprinkler and subsurface drip irrigated corn systems, multiple N applications throughout the growing season are feasible. However, as Schepers et al. (1995) states, "knowing when and how much fertilizer N to apply during the growing season is essential to implement this N management strategy". Numerous efforts have been made over the past two decades to develop tools to provide in-season measurements for scheduling fertigation of N. The hand-held chlorophyll meter as demonstrated by Blackmer and Schepers (1995) could be used for determining N sufficiency and fertigation scheduling. However, collecting sufficient data with the chlorophyll meter for whole-field management was very difficult (Schepers et al., 1995). Developments in remote sensing technology have made it possible to provide season-long monitoring of N status with on-the-go optical sensors. Sripada et al. (2005) demonstrated that remotely-sensed NearInfrared (NIR) radiance could be used to estimate economic optimum N rates through corn growth stage VT. Solari et al. (2010) have shown that active optical sensors (AOSs) can effectively assess N status of corn at V11 and V15 growth stages. Tucker and Mengel (2010) developed two KSU sensor-based N recommendation algorithms for based on the premise that AOSs can assess N status and corn will respond to mid and late-season N applications. Each algorithm was specific to a set of corn growth stages, with the first algorithm targeting V8 to V10, while the second algorithm targeted V16 to R1. Although the current KSU sensor-based N recommendation algorithms are not designed for multiple N applications, they are growth stage specific and can provide a good foundation for building sensor-based N recommendation algorithms for multiple N applications in fertigation systems.

AOSs combined with fertigation systems present the possibility for assessing soil and weather interactions and their effects on plant-available N based on crop spectral response. Therefore, sensor-based fertigation systems have the potential to provide accurate recommendations for when, where, and how much N to apply throughout the growing season.

The purpose of this study was to evaluate single pre-plant, split, and sensor-based N management practices under irrigation on two different soil textural classes and evaluate previously developed KSU sensor-based N recommendation algorithm.

Materials and Methods

Site Selection and Experimental Design

The study was initiated in 2012 and conducted through the 2014 crop year in cooperation with a Kansas producer and KSU Agronomy Experiment Fields. Two studies were conducted each crop year and utilized a randomized complete block design with four replications utilizing 3 by 12 m small plots as experimental units. The protocol consisted of 10 treatments that represented three different N management practices, that is all pre-plant N, side-dress N, and simulated fertigation (Tables 4.1 and 4.2). Within each practice, three different rates of N were applied. An unfertilized check was included as control that only received starter fertilizer at planting. Treatments one through three represent traditional pre-plant N management systems that are common practice for corn production because of logistic efficiency, but have a greater potential for N loss. Treatments four through seven represent side-dress N management systems and have the potential for reducing N loss. Treatments seven through nine represent simulated fertigation systems that utilize optical sensors to determine the N rate to apply. At the conclusion of the 2012 research year, it was determined that total N rates for each treatment were too high and were reduced as shown in Table 4.2.

Table 4.1 2012 Treatment Protocol

	Nitrogen application rate					
Treatment	N Source	Starter	Pre-Plant	In-Season	Total	Timing
		kg ha^{-1}				
1	Urea	22	90	0	112	Pre-plant
2	Urea	22	180	0	202	Pre-plant
3	Urea	22	280	0	302	Pre-Plant
4	UAN	22	45	45	112	Pre-Plant/V4
5	UAN	22	90	90	202	Pre-Plant/V4
6	UAN	22	140	140	302	Pre-Plant/V4
7	UAN	22	45	Sensor-selected	60+Sensor	Sensor
8	UAN	22	90	Sensor-selected	100+Sensor	Sensor
9	UAN	22	140	Sensor-selected	140+Sensor	Sensor
10	Control	22	0	0	0	Not Applicable

Table 4.2 2013-2014 Treatment Protocol with N Rate Reductions

	Nitrogen application rate					
Treatment	N Source	Starter	Pre-Plant	In-Season	Total	Timing
		kg ha^{-1}				
1	Urea	22	67	0	89	Pre-plant
2	Urea	22	134	0	156	Pre-plant
3	Urea	22	202	0	224	Pre-Plant
4	UAN	22	34	34	90	Pre-Plant/V4
5	UAN	22	67	67	156	Pre-Plant/V4
6	UAN	22	101	101	224	Pre-Plant/V4
7	UAN	22	45	Sensor-selected	70+Sensor	Sensor
8	UAN	22	90	Sensor-selected	112+Sensor	Sensor
9	UAN	22	134	Sensor-selected	157+Sensor	Sensor
10	Check	22	0	0	0	Not Applicable

Experimental sites were selected on the basis of soil textural class and required to have irrigation system. Soil texture for each site was determined with The Web Soil Survey (NRCS, 2015). Soil textural class can have prominent effect on nitrogen recovery, and therefore it was desired to have one experiment on a coarse-textured soil that had potential for high N loss, while the second experiment would be on a medium-textured soil that would have low potential for N loss. The first experimental site was established at the KSU Department of Agronomy Scandia Experiment Field in 2012. This location has medium texture Crete Silt loam soil with low potential for N loss and is a very productive site for corn. A second experimental site was established on a coarse-textured site near Scandia in cooperation with a local producer in 2012. However, the NO_3-N in the irrigation water was determined to be too high (Table 4.8) therefore the second experimental site was moved to the KSU Department of Agronomy Kansas River Valley Experiment Field near Rossville in 2013. This site had coarse textured Eudora Sandy loam that has very variable soil conditions with the potential for high N loss, but also can produce very high yielding corn. Each year, experiment sites would be moved to different locations on the KSU Experiment Fields, resulting in six locations within two soil textural classes. Summarized site information is available in Tables 4.3 and 4.4.

Table 4.3 Site Information-Medium Soil Texture Group

Year	2012	2013	2014
Location	Scandia	Scandia	Scandia
Soil Type	Crete silt loam	Crete silt loam	Crete silt loam
Soil Textural Class	Medium	Medium	Medium
Clay lens in Soil Profile 0-92 cm	No	No	No

Table 4.4 Site Information-Coarse Soil Texture Group

Year	2012	2013	2014
Location	Scandia Producer	Rossville	Rossville
Soil Type	Carr Fine Sandy loam	Eudora sandy loam	Eudora sandy loam
Soil Textual Class	Coarse	Coarse	Coarse
Clay lens in Soil Profile 0-92 cm	No	No	60-92 cm

All Scandia locations received 22 kg N ha^{-1} as Urea Ammonium Nitrate (UAN) and Ammonium Polyphosphate (APP) mix (20-20-0) at rate of 93.5 L ha^{-1} at planting as a starter application. The Rossville sites did not have the equipment available to apply starter fertilizer at planting, and therefore it was not applied. Nitrogen sources for treatments consisted of granular urea (46-0-0) applied broadcast by hand and UAN (28-0-0) applied broadcast via backpack sprayer with drop nozzles. Sensor-based N application treatments were made prior to scheduled irrigation events to simulate a N fertigation system. Irrigation events were scheduled using the KanSched2 evapotranspiration-based irrigation scheduling tool (http://mobileirrigationlab.com/kansched2) and implemented by the KSU Experiment field crew. Irrigation dates are summarized in results. Important dates and cultural practices are summarized in Tables 4.5 and 4.6.

Table 4.5 Cultural Practices-Medium Soil Texture Group

Year	2012	2013	2014
Location	Scandia	Scandia	Scandia
Previous Crop	Soybeans	Soybeans	Soybeans
Tillage Practice	Ridge Till	Ridge Till	Ridge Till
Corn Hybrid	NA	NA	Pioneer P1602
Plant Population (plants ha^{-1})	74400	73160	74400
Irrigation Type	Sprinkler	Sprinkler	Sprinkler
Planting Date	4/27/2012	5/16/2013	5/5/2014
Second Treatment V-4	6/4/2012	6/19/2013	6/19/2014
Third Treatment V-8 through V-10	6/14/2012	7/3/2013	.
Last Treatment V-16 through R-1	6/28/2012	.	8/4/2014
Harvest Date	10/24/2012	11/1/2013	11/11/2014

Table 4.6 Cultural Practices-Coarse Soil Texture Group

Year	2012	2013	2014
Location	Scandia	Rossville	Rossville
Previous Crop	Soybeans	Soybeans	Soybeans
Tillage Practice	Ridge Till	Conventional	Conventional
Corn Hybrid	NA	Pioneer 0876	Producers Hybrid 7224 VT3
Plant Population (plants ha^{-1})	79360	79360	79360
Irrigation	Flood	Sprinkler	Sprinkler
Planting Date	4/27/2012	4/29/2013	4/23/2014
Second Treatment V-4	6/4/2012	6/3/2013	6/6/2014
Third Treatment V-10	6/14/2012	6/25/2013	.
Last Treatment V-16 through R-1	6/26/2012	.	7/8/2014
Harvest Date	9/25/2012	9/23/2013	9/17/2014

Soil and Water Sampling and Nutrient Analysis

Soil sampling was done at each site using a 2.54 cm diameter soil probe sampling at 0-15 and 0-60 cm depths with two single composite samples consisting of 15 cores per composite. Sampling took place prior to planting and fertilization. The 0-15-cm samples were analyzed for soil organic matter, Mehlich-3 phosphorus, potassium, pH, and zinc, and the 0-60 cm samples were analyzed for NO_3- N (Tables 4.7 and 4.8). All samples were analyzed by the KSU Soil Testing Laboratory using procedures standardized by NCERA-13 (Denning et al., 2011). Due to the resignation of one of the collaborating researchers, we were not able to get soil samples that had been collected for all sites in 2012 and 2013.

Irrigation water was sampled for NO_3-N at the initiation of each experimental site. Rossville and Scandia experiment stations tested with less than 1 mg kg^{-1} for NO_3-N (Table 4.7, 4.8) therefore would not have a large impact on the results of this study. The farmer's cooperative field near Scandia tested greater than 11 mg kg^{-1} NO_3-N, and therefore this site was only utilized in 2012, as this could potentially mask out any treatment effects.

Table 4.7 Soil and Irrigation Water Analysis-Medium Soil Texture Group

Year	2012	2013	2014
Location	Scandia	Scandia	Scandia
Soil pH	NA	NA	6.7
Soil 0-15 cm O.M. g kg^{-1}	NA	NA	25
Soil 0-15 cm Mehlich P mg kg^{-1}	NA	NA	13.7
Soil 0-15 cm K mg kg^{-1}	NA	NA	521
Soil 0-15 cm NH_4-N mg kg^{-1}	NA	NA	20.6
Soil 0-15 cm NO_3-N mg kg^{-1}	NA	NA	15.1
Soil 0-15 cm Zn mg kg^{-1}	NA	NA	1.7
Soil 0-60 cm NO_3-N mg kg^{-1}	NA	NA	6.5
Irrigation Water Source	Reservoir	Reservoir	Reservoir
Irrigation $N0_3$-N mg kg^{-1}	0.02	NA	NA

NA = Not Available

Table 4.8 Soil and Irrigation Water Analysis-Coarse Soil Texture Group

Year	2012	2013	2014
Location	Scandia Farmer	Rossville	Rossville
Soil pH	NA	NA	7.6
Soil 0-15 cm O.M. g kg^{-1}	NA	NA	11
Soil 0-15 cm Mehlich P mg kg^{-1}	NA	NA	30.1
Soil 0-15 cm K mg kg^{-1}	NA	NA	212
Soil 0-15 cm NH_4-N mg kg^{-1}	NA	NA	3.1
Soil 0-15 cm NO_3-N mg kg^{-1}	NA	NA	4.2
Soil 0-15 cm Zn mg kg^{-1}	NA	NA	1.9
Soil 0-60 cm NO_3-N mg kg^{-1}	NA	NA	3.6
Irrigation Water Source	Ground Water	Reservoir	Reservoir
Irrigation $N0_3$-N mg kg^{-1}	11.12	0.21	NA

NA = Not Available

Canopy reflectance of the corn was measured two times during the season, prior to each irrigation event with focus being on V10 and R1 growth stages. The optical sensor utilized was the Trimble Greenseeker (Trimble Navigation, Ag Division, Westminster, CO). Canopy reflectance was used to calculate the Normalized Difference Vegetation Index (NDVI = NIR-visible/NIR+visible) (Rouse et. al., 1973) and was averaged for each plot. The algorithms developed by Tucker and Mengel (2010) were utilized to provide sensor-based N recommendations. Each algorithm was specific to a set of corn growth stages, with the first algorithm targeting V8 to V10, while the second algorithm targeted V16 to R1. As this algorithm requires yield productivity information, prospective yield was set to 12.5 Mg ha^{-1} for all locations, as this is a common yield level for these locations. It should be noted that these algorithms were designed for one-time N applications during one of the specified growth stages. They were not designed for fertigation systems or N management systems that can make multiple N applications throughout the growing season.

Precipitation data was recorded from each site every crop year using the KSU Mesonet. Data was summarized from prior to planting through grain harvest and daily sums for precipitation were tabulated. Irrigation water applied was documented for each site by year and daily sums tabulated.

Corn grain at all KSU Experiment Field sites was machine harvested with a plot combine from an area of 1.5 m by 12 m. The corn in the farmer-cooperator field in 2012 was hand harvested from an area of 1.5 m by 5.3 m. All grain yields were adjusted to 155 g kg^{-1}.

Statistical Analysis

A generalized linear mixed effects model was utilized to model grain yield data in response to applied…. Management practice and soil textual class were treated as fixed effects. Because soil textual class cannot be randomized, it was treated as a repeated measure. The Huynh-Feldt covariance structure provided the lowest Akaike information criterion score, and therefore was used for soil textural class for analysis. Location, block within location, and block by N treatment within location were treated as random effects.

Statistical analysis of the data were conducted with SAS 9.3 (SAS Institute, 2011) utilizing UNIVARIATE and GLIMMIX procedures. Tables and graphical representations of the dataset were created with EXCEL (Microsoft, 2013).

Normality of grain yield (the response variable) across locations was assessed using the UNIVARIATE PROCEDURE with the NORMAL and HISTOGRAM NORMAL options. Table 4.9 summarizes the assessment of normality and they fail to reject the hypothesis of normally distributed data. Figure 4-1 shows the histogram distribution to be normal, but with some negative skewing. This is a result of treatments with zero N applied to serve as check plots that established the N responsiveness at a given location. Check plots should result in low grain yield at N-responsive locations and therefore some negative skewing in distribution in grain yields for each N management research experiment should be expected.

Table 4.9 Assessment of Normality

Test	Statistic	p Value	
Shapiro-Wilk	0.99	Pr<W	0.07
Kilmogorox-Smirnov	0.04	Pr>D	>0.15
Cramer-von Mises	0.54	Pr>W-Sq	>0.25
Anderson-Darling	0.42	Pr>A-Sq	>0.25

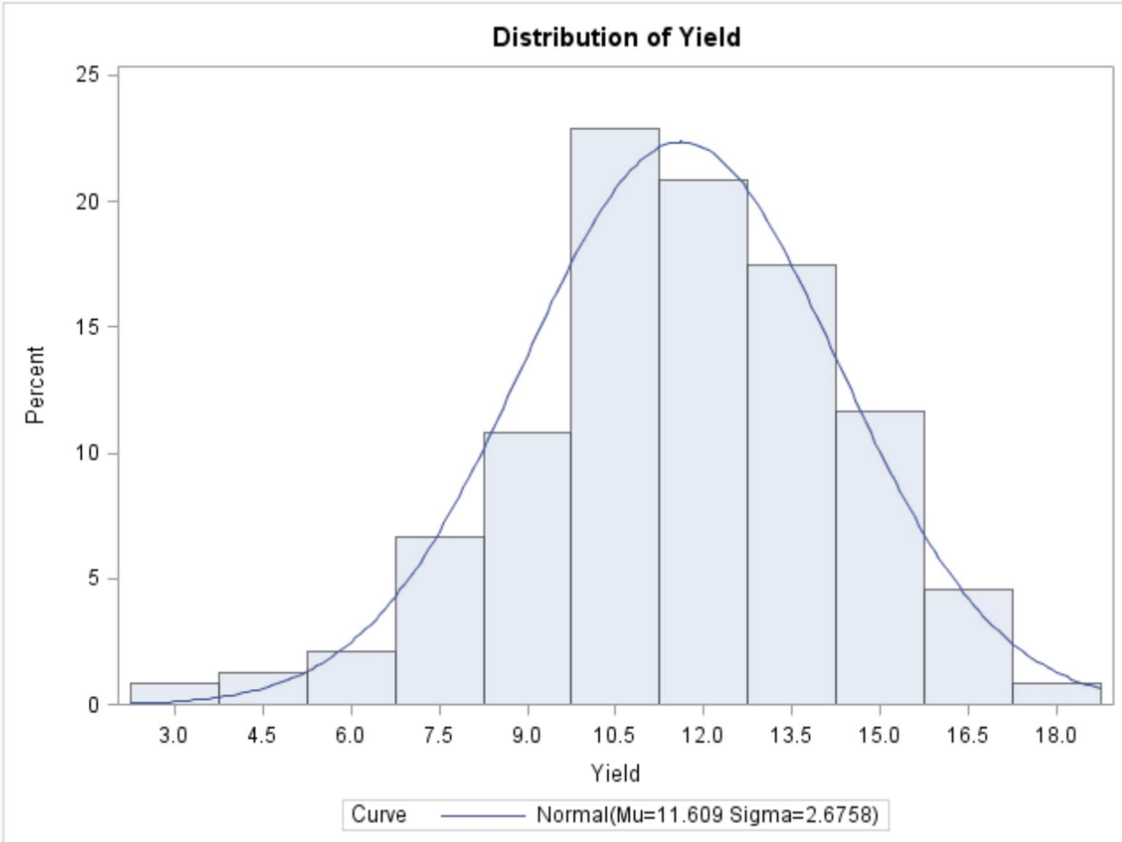

Figure 4-1 Histogram Distribution of Grain Yield Mg ha^{-1}

Hypothesis Testing

Treatment 10 (No N applied) served to assess the N responsiveness at a given location, however treatment 3 (224 kg N ha^{-1} pre-plant) was representative of the common practice for N management in the area. This treatment serves as a benchmark to compare the other management practices against. The other management practices should not generate greater grain yields, but rather should be expected that side-dress and sensor-based N management systems will generate the same level of grain yield using reduced N rates. The GLIMMIX PROCEDURE was utilized for testing hypotheses relevant to the objectives of this study. Means were separated using the Fisher LSD procedure that was conducted using LSMEANS with PDMIX800 (Saxton, 1998) for general representation of treatment effects.

Results and Discussion

Yield Response to N Management By Location

2012 Scandia Farmer Cooperative Site, Coarse Texture Soil

Data analysis from Scandia Site 2, a farmer cooperative field, (Table 4.10) shows response to applied N was low. This is likely due to the abnormally high nitrate levels in the irrigation water used at this site. Because the growing season was uncharacteristically dry, irrigation water use was above normal, giving the crop a significant N supply through the irrigation water (Figure 4-2). Approximately 67 kg ha^{-1} was added in 2012 through irrigation water.

Table 4.10 2012 Scandia Farmer Cooperative Field Summary Statistics for Grain Yield, Coarse Soil Texture

		Nitrogen application rate					
Treatment	Timing	Starter & Irrigation	Pre-plant	In-Season	Total	Grain Yield	LSD Grouping
		kg ha^{-1}				Mg ha^{-1}	
1	Pre-plant	89	67	0	156	12.71	NS
2	Pre-plant	89	157	0	246	12.61	NS
3	Pre-plant	89	258	0	347	12.49	NS
4	Pre-plant/V4	89	45	45	179	13.13	NS
5	Pre-plant/V4	89	90	90	268	12.34	NS
6	Pre-plant/V4	89	118	118	324	12.14	NS
7	Pre-plant/Sensor	89	45	105	239	12.49	NS
8	Pre-plant/Sensor	89	90	96	275	12.39	NS
9	Pre-plant/Sensor	89	140	34	263	13.09	NS
10	Check	89	0	0	89	12.13	NS

NS = Not Signicantly Different

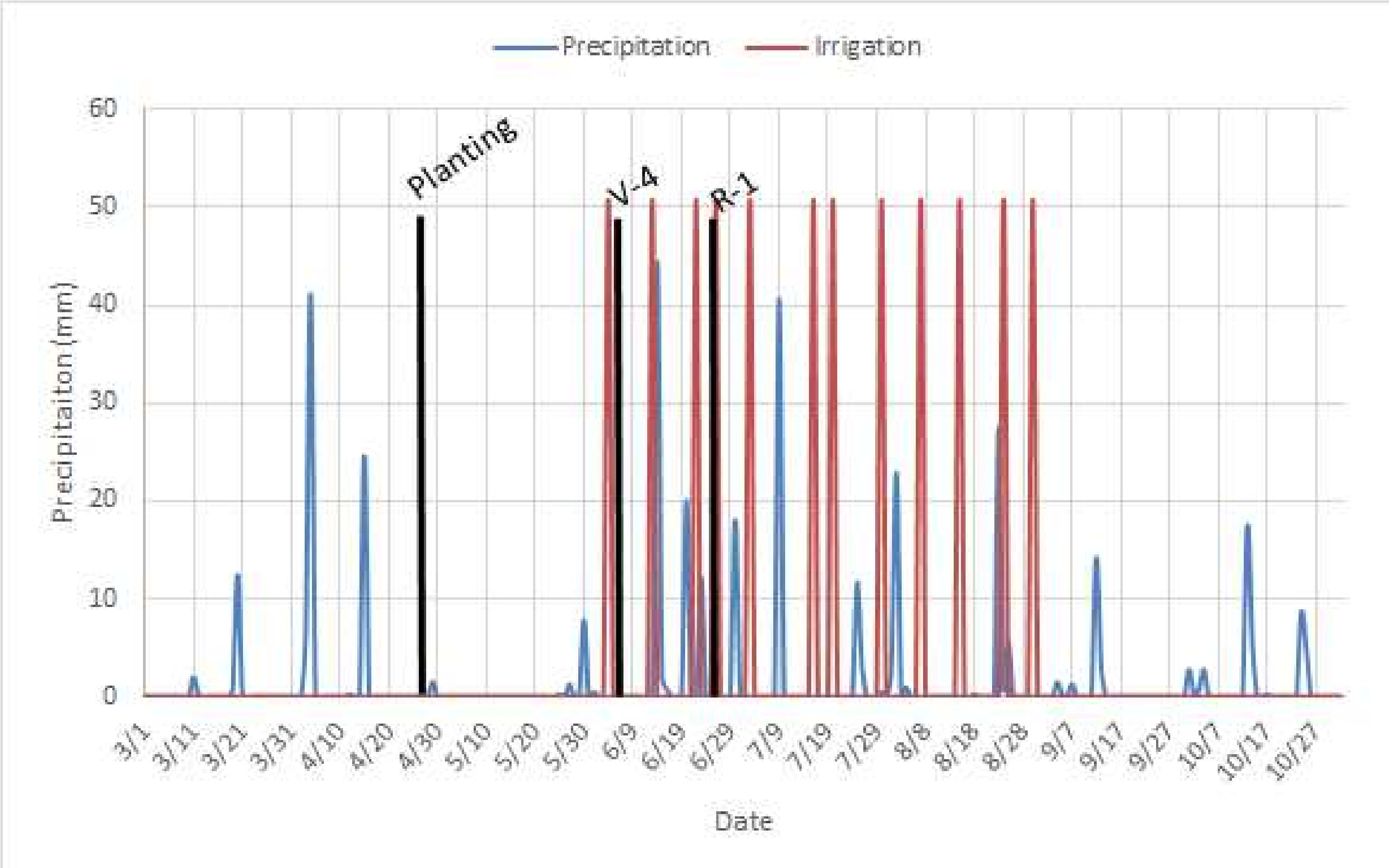

Figure 4-2 2012 Scandia Farmer Cooperative Site Precipitation, Irrigation, and Key Treatment Dates

2012 Scandia KSU Experiment Field, Medium Texture Soil

There were significant N management effects on corn yield observed at the Scandia Station in 2012 (Table 4.11). No significant denitrification events occurred in the early growing season (Figure 4-3) and environmental conditions were conducive after V4 for N mineralization. In general, the treatments that split N applications between pre-plant and in-season resulted in the greatest yields. The exception was treatment 3 (280 kg ha^{-1} pre-plant), which was equal to the greatest yielding split application treatments 5 and 6, but required an additional 80 kg N ha^{-1}. Two of the three sensor-based N treatments (Treatments 7 and 8) yielded lower than the pre-plant/V4 spilt applications (Treatments 5 and 6). The yield differences are likely attributed to the lower total N rates recommended by the sensors, indicating that the N recommendation algorithm did not properly interpret N status of the corn (at what growth stage?).

Table 4.11 2012 Scandia KSU Experiment Station Summary Statistics for Grain Yield,, Medium Soil Texture

		Nitrogen application rate					
Treatment	Timing	Starter	Pre-plant	In-Season	Total	Grain Yield	LSD Grouping
		kg ha^{-1}				Mg ha^{-1}	
1	Preplant	22	67	0	90	9.78	C
2	Preplant	22	157	0	179	10.39	BC
3	Preplant	22	258	0	280	11.60	A
4	Preplant/V4	22	45	45	112	8.66	D
5	Preplant/V4	22	90	90	202	11.73	A
6	Preplant/V4	22	118	118	258	11.77	A
7	Preplant/Sensor	22	45	102	169	10.43	BC
8	Preplant/Sensor	22	90	49	161	10.88	B
9	Preplant/Sensor	22	140	96	259	11.58	A
10	Check	22	0	0	22	7.50	E

Treatments with same letter are not statistically different at an 0.05 alpha

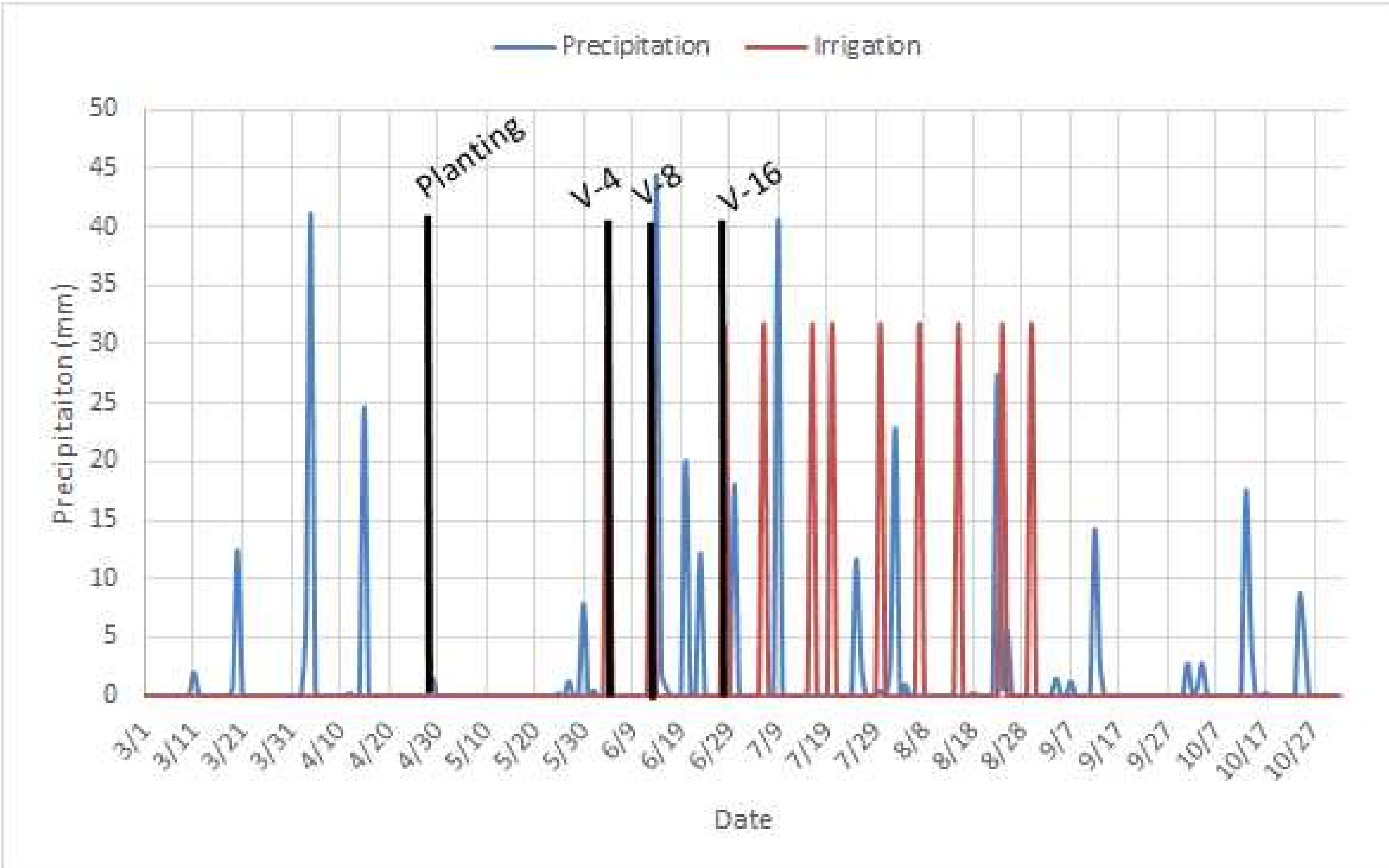

Figure 4-3 2012 Scandia KSU Experiment Field Precipitation, Irrigation, and Key Treatment Dates

2013 Rossville KSU Experiment Field, Coarse Texture Soil

The 2013 Rossville experiment site showed a significant response to applied N (Table 4.12). All sensor-based treatments generated the greatest yields and were greater than the two lowest N rate pre-plant only treatments. The soil at this location was a deep sandy loam that is prone to leaching N losses if rainfall events are high and/or frequent. Two rainfall events, one of 31.75 and another 57.15 mm as well as multiple 12.7 mm events after the pre-plant treatments were applied but prior to the V-4 treatment applications indicate potential for leaching N losses in the early season (Figure 4-4). Overall, the yields were lower than expected at this site due to the frequent leaching events that appear to have occurred throughout the season. This indicates that fertigation systems may need to make more frequent low rate N applications with limited amounts of water to satisfy N demand for high yielding corn in high N loss environments, even if plant water requirements have been met or exceeded.

Table 4.12 2013 Rossville KSU Experiment Station Summary Statistics for Grain Yield,, Coarse Soil Texture

		Nitrogen application rate					
Treatment	Timing	Starter	Pre-plant	In-Season	Total	Grain Yield	LSD Grouping
		kg ha^{-1}				Mg ha^{-1}	
1	Pre-plant	0	67	0	67	6.00	D
2	Pre-plant	0	134	0	134	7.98	ABC
3	Pre-plant	0	202	0	202	7.70	BC
4	Preplant/V4	0	34	34	67	7.28	CD
5	Preplant/V4	0	67	67	134	8.47	ABC
6	Preplant/V4	0	101	101	202	8.73	AB
7	Pre-plant/Sensor	0	45	237	282	9.26	A
8	Pre-plant/Sensor	0	90	161	250	9.28	A
9	Pre-plant/Sensor	0	134	167	302	9.02	AB
10	Check	0	0	0	0	4.40	E

Treatments with same letter are not statistically different at an 0.05 alpha

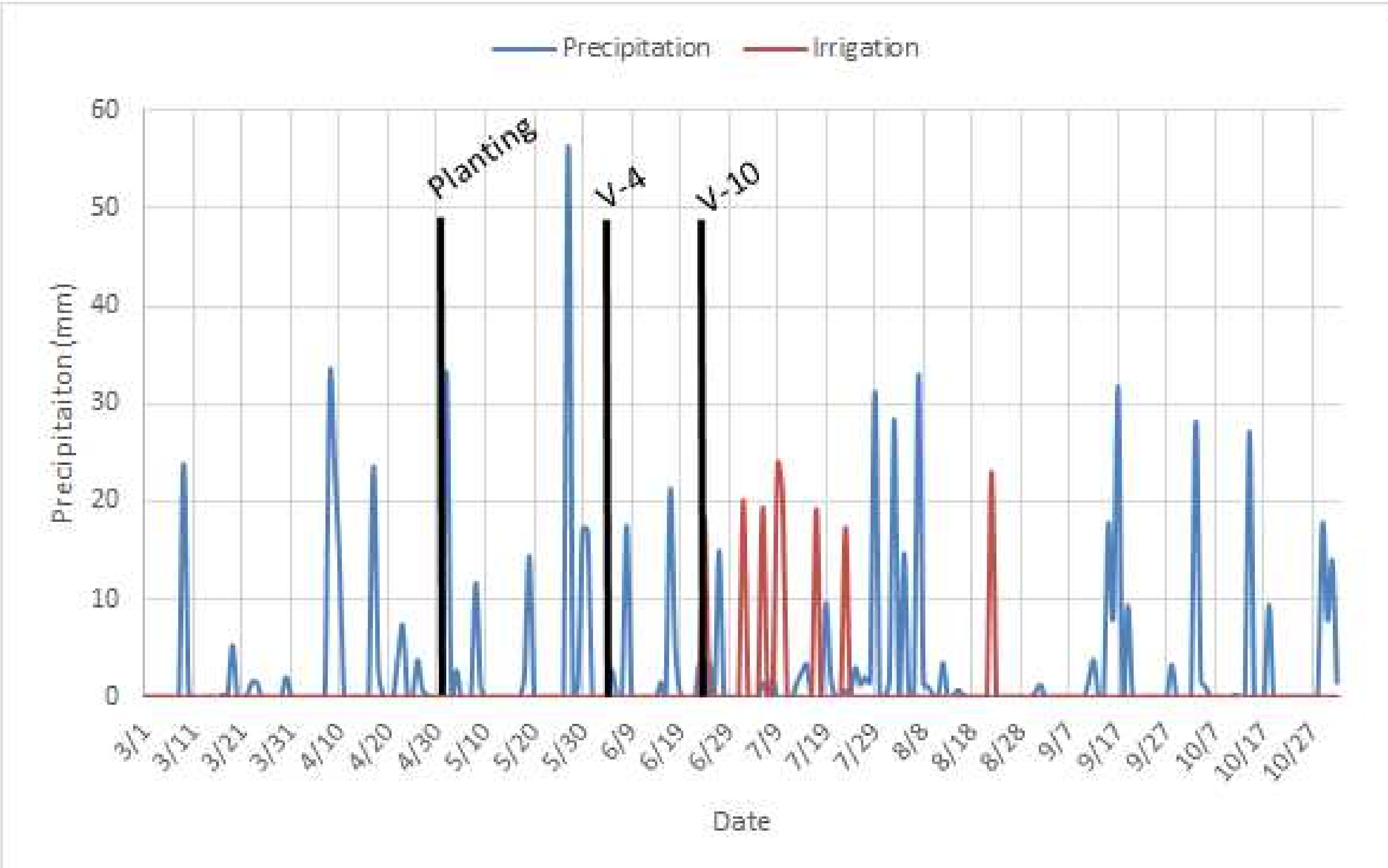

Figure 4-4 2013 Rossville KSU Experiment Field Precipitation, Irrigation, and Key Treatment Dates

2013 Scandia KSU Experiment Field, Medium Texture Soil

2013 Scandia Station experiment location showed a small response of corn grain yield to applied N (Table 4.13). Primary response of grain yield was to N rate and was only significant when compared to the check treatment. The soil at this location is a productive silt loam that is not prone to N loss through leaching, but can suffer from denitrification loss under high precipitation events. This soil is also capable of releasing significant amounts of mineralized N. Wet soil conditions before and after planting could have created some denitrification loss potential in late April-early May, and again in late May (Figure 4.5). Soil moisture remained high throughout June and July and was near optimal for mineralizing N (Figure 4-5). The highest treatment grain yield was 11.12 Mg ha^{-1} (Table 4.13) and lower than expected yields of 12.5 to 15 Mg ha^{-1} commonly obtained at this location. The overall yield reduction could be attributed in part to the late planting date. The greatest yielding treatment was a planned application of 157 kg N ha^{-1} split with starter, pre-plant and in-season (treatment 5, Table 4.13). All sensor-based treatments overestimated N requirements compared to treatment 5, and resulted in an over application of N with no gain in corn grain yield.

Table 4.13 2013 Scandia KSU Experiment Station Summary Statistics for Grain Yield,, Medium Soil Texture

		Nitrogen application rate					
Treatment	Timing	Starter	Pre-plant	In-Season	Total	Grain Yield	LSD Grouping
		kg ha^{-1}				Mg ha^{-1}	
1	Pre-plant	22	67	0	90	10.49	B
2	Pre-plant	22	134	0	157	10.63	AB
3	Pre-plant	22	202	0	224	10.85	AB
4	Preplant/V4	22	34	34	90	11.04	AB
5	Preplant/V4	22	67	67	157	11.21	A
6	Preplant/V4	22	101	101	224	10.80	AB
7	Pre-plant/Sensor	22	45	138	205	10.76	AB
8	Pre-plant/Sensor	22	90	97	209	11.12	AB
9	Pre-plant/Sensor	22	134	149	306	10.58	AB
10	Check	22	0	0	22	9.33	C

Treatments with same letter are not statistically different at an 0.05 alpha

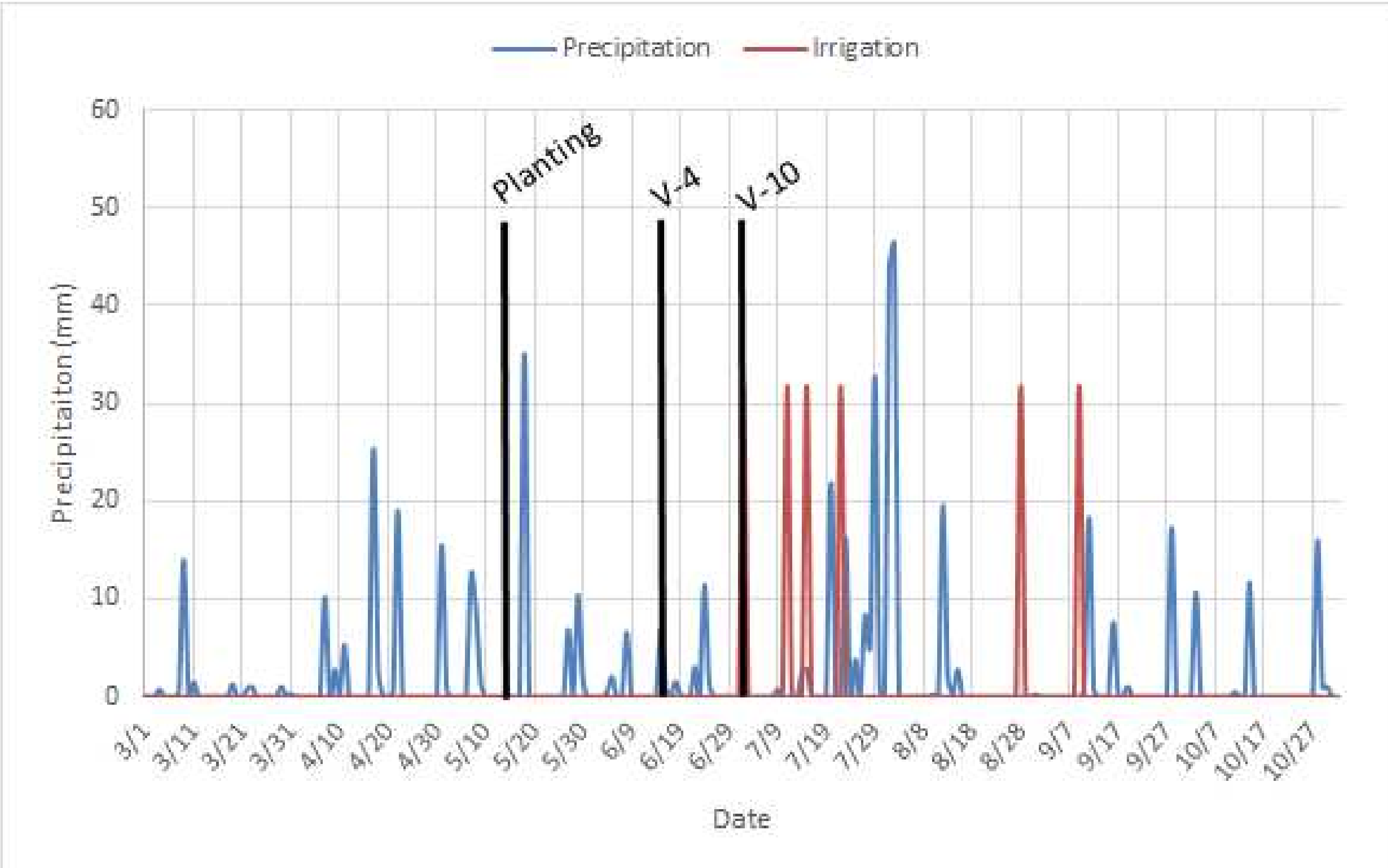

Figure 4-5 2013 Scandia KSU Experiment Field Precipitation, Irrigation, and Key Treatment Dates

2014 Rossville KSU Experiment Field, Coarse Texture Soil

The 2014 Rossville experiment site had a significant grain yield response from applied N over no N applied check treatment (Table 4.14). Rainfall events in late May and June lead to significant N leaching losses in the sandy loam soil at Rossville (Figure 4-6). However, in the study area a clay lens was located 60 to 90 cm deep. So despite these leaching events, N and water would be held up in the rooting area, resulting in much higher yields than at the 2013 Rossville site, which lacked the clay lens. Greatest corn grain yield response was to increasing total N rate. Sensor-based treatments were effective at providing enough N to reach 14.86 Mg ha^{-1} with 62 kg N ha^{-1} (Table 4.14).

Table 4.14 2014 Rossville KSU Experiment Station Summary Statistics for Grain Yield,, Coarse Soil Texure

		Nitrogen application rate					
Treatment	Timing	Starter	Pre-plant	In-Season	Total	Grain Yield	LSD Grouping
		kg ha^{-1}				Mg ha^{-1}	
1	Pre-plant	0	67	0	67	14.98	ABC
2	Pre-plant	0	134	0	134	16.12	A
3	Pre-plant	0	202	0	202	15.52	ABC
4	Preplant/V4	0	34	34	67	14.10	C
5	Preplant/V4	0	67	67	134	15.55	ABC
6	Preplant/V4	0	101	101	202	15.95	AB
7	Pre-plant/Sensor	0	45	17	62	14.86	ABC
8	Pre-plant/Sensor	0	90	0	90	13.98	C
9	Pre-plant/Sensor	0	134	0	134	14.31	BC
10	Check	0	0	0	0	11.65	D

Treatments with same letter are not statistically different at an 0.05 alpha

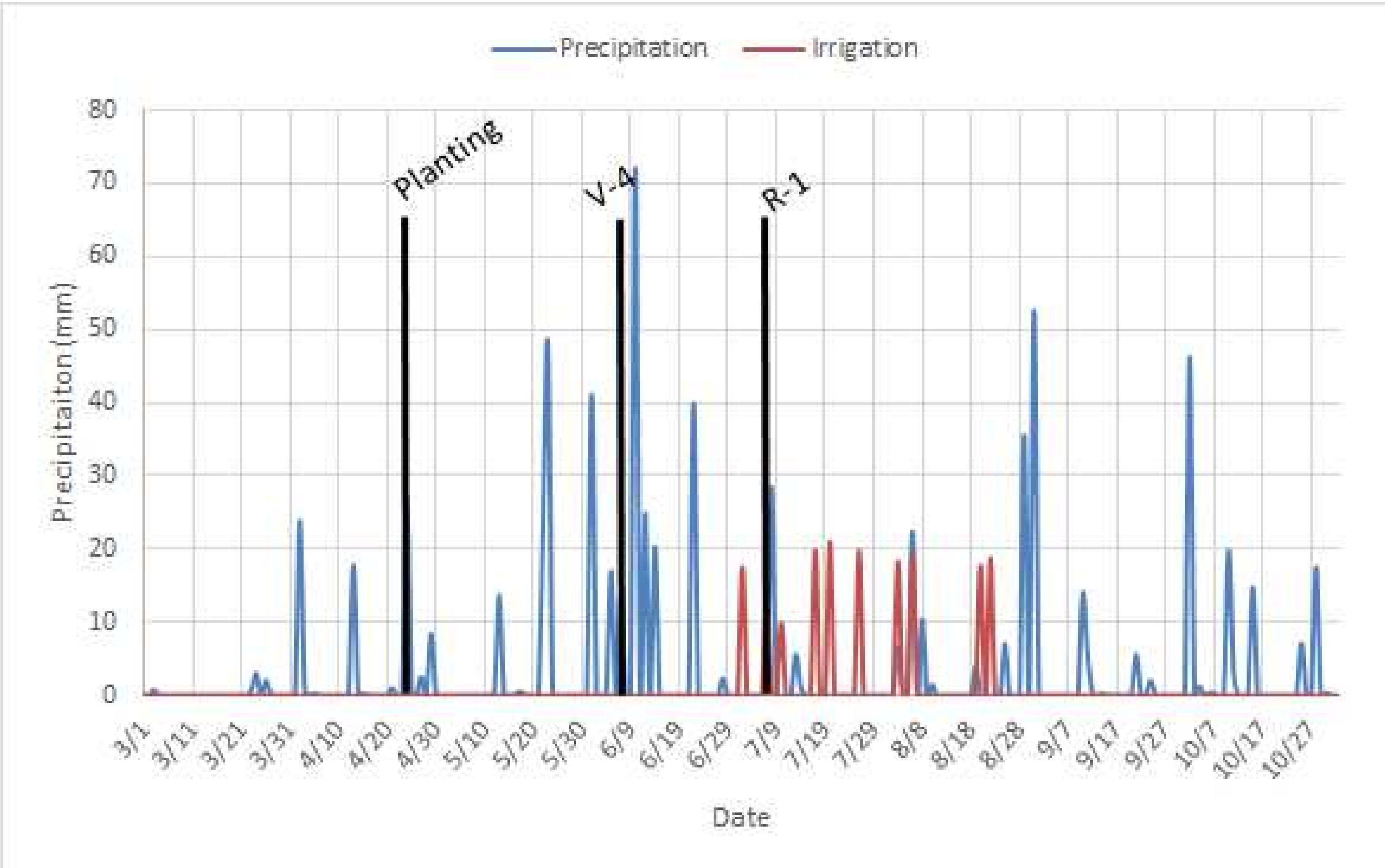

Figure 4-6 2014 KSU Rossville Experiment Field Precipitation, Irrigation, and Key Treatment Dates

2014 Scandia KSU Experiment Field, Medium Texture Soil

2014 Scandia station observed a significant grain yield response to applied N over the no N applied check treatment (Table 4.15). Rainfall and resulting N losses appeared to be low and frequent small rain events created conditions that were good for mineralizing N (Figure 4-7), which resulted in the check treatments achieving 10.19 Mg ha^{-1}. This is a strong indication that overall site productivity was high. Sensor-based treatments were effective at determining the optimum N rate for high yield and profitability.

Table 4.15 2014 Scandia KSU Experiment Station Summary Statistics for Grain Yield,, Medium Soil Texture

		Nitrogen application rate					
Treatment	Timing	Starter	Pre-plant	In-Season	Total	Grain Yield	LSD Grouping
				kg ha^{-1}		Mg ha^{-1}	
1	Pre-plant	0	67	0	67	12.78	C
2	Pre-plant	0	134	0	134	13.97	B
3	Pre-plant	0	202	0	202	14.54	AB
4	Preplant/V4	0	34	34	67	11.82	D
5	Preplant/V4	0	67	67	134	13.62	BC
6	Preplant/V4	0	101	101	202	14.99	A
7	Pre-plant/Sensor	0	45	134	179	14.33	AB
8	Pre-plant/Sensor	0	90	67	157	13.95	B
9	Pre-plant/Sensor	0	134	34	168	14.48	AB
10	Check	0	0	0	0	10.19	E

Treatments with same letter are not statistically different at an 0.05 alpha

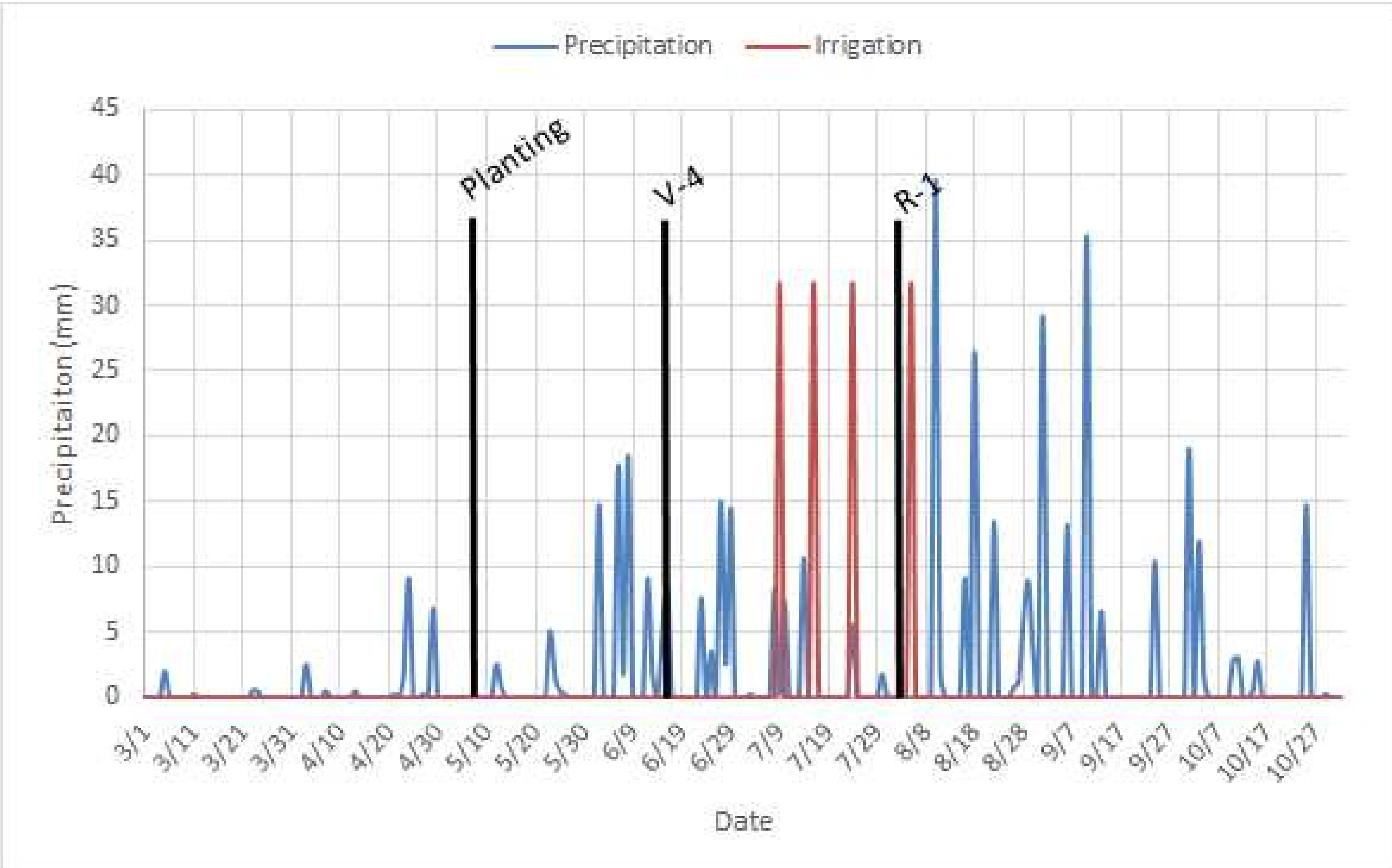

Figure 4-7 2014 Scandia KSU Experiment Field Precipitation, Irrigation, and Key Treatment Dates

Across Location Analysis, Pooled Results

There is a three-way interaction for corn grain yield response among management system, soil textural class, and year (Table 4.16). The yield response of any corn crop is highly dependent upon the soil, observed weather conditions, and management practices implemented, and therefore this kind of interaction should be expected. Fertigation systems have the potential to properly address this three-way interaction.

Statistical protocol mandates that inferences on main effects should not be made if interaction effects are observed. However, it is commonplace for agronomists to be forced to make inferences on main effects even if interaction effects are observed because producers will still expect to recommendation regardless interactions. Producers may not have the equipment or ability to address the interaction effects so they still look for a recommendation they can implement that will perform well across the observed interactions. Agronomists often develop recommendations for potential best management practices even if yearly weather data are not and in-season crop assessment tools are not always available. Therefore, a pooled analysis across management system and soil textural class will be made to determine implications across years.

Applications of 243 kg N ha^{-1} pre-plant (e.g. treatment 3) are a common management practice for the area and for Kansas' corn producers. Across multiple soil types and multiple years that experienced different weather conditions, 243 kg N ha^{-1} pre-plant (e.g. treatment 3) was able to generate yield levels in the statistically highest group (Table 4.17). Sensor-based treatment 7 had 45 kg N ha^{-1} pre-plant, and recommended an additional 122 kg N ha^{-1} be applied during the growing season. This treatment was able to achieve grain yield equal to the common management practice used in Kansas (treatment 3, pre-plant 243 kg N ha^{-1}), but with total N rate being reduced by 54 kg N ha^{-1} (Table 4.17). Similar performance was obtained by treatment 5 (pre-plant 75 kg and V-4 75 kg N ha^{-1}) in regards to producing grain yield that was equal to treatments 3 and 7, but with a lower total N rate required (Table 4.17)

Table 4.16 Pooled Analysis Across Six Locations, TYPE 3 Test for Effects

Effect	Num DF	Den DF	F Value	Pr >F
Management	9	127	38.16	<0.001
Soil	1	17	0.40	0.547
Soil*Treatment	9	127	1.89	0.055
Year	2	17	118.42	<0.001
Year*Treatment	18	127	3.58	<0.001
Year*Soil	2	17	35.75	<0.001
Year*Soil*Treatment	18	127	6.82	<0.001

Table 4.17 Pooled Summary Statistics for Grain Yield, Across Six Locations By Management Practice

		Nitrogen application rate					
Treatment	Timing	Starter	Pre-plant	In-Season	Total	Grain Yield	LSD Grouping
		kg ha^{-1}				Mg ha^{-1}	
1	Pre-plant	22	67	0	90	11.12	C
2	Pre-plant	22	142	0	164	11.95	B
3	Pre-plant	22	220	0	243	12.12	AB
4	Preplant/V4	22	37	37	97	11.01	C
5	Preplant/V4	22	75	75	172	12.16	AB
6	Preplant/V4	22	106	106	235	12.40	A
7	Pre-plant/Sensor	22	45	122	189	12.02	AB
8	Pre-plant/Sensor	22	90	78	190	11.93	B
9	Pre-plant/Sensor	22	136	80	239	12.18	AB
10	Check	22	0	0	22	9.20	D

Treatments with same letter are not statistically different at an 0.05 alpha

Conclusions

Split applications of N provide the Kansas' corn producer the ability to reduce overall N rates and still achieve greater grain yields because N applications appear to be synchronized with corn N demand. The overall performance of the sensors and algorithm utilized was effective at achieving high yields, but had the tendency to overestimate corn N requirements if too much N was applied prior to planting.

Results support that N management in corn is a complex interaction among management (treatments), soil texture class, and environmental (year) conditions. This is the paradigm of sensor-based systems, as they can monitor the corn crop and optimize N timing and rate, while fertigation provides the means of applying N at any point in the growing season. This would provide corn producers the means to determine the optimum N management strategy for any given soil in any given year. However, in order to optimize sensor-based N recommendations for fertigation systems, algorithms must be specifically designed for these systems in order take advantage of their full capabilities, thus allowing advanced N management systems to be implemented.

References

Cassman, K.G., A. Dobermann, and D.T. Walters, (2002). Agroecosystems, nitrogen-use efficiency, and nitrogen management. *AMBIO* 31:132-140.

Denning, J., Eliason, R., Goos, R. J., Hoskins, B., Nathan, M. V, & Wolf, A. (2011). *Recommended Chemical Soil Test Procedures for the North Central Region*, *221*(221), 75.

Downing, J., B. Darst, T. Franci, T. Jordan, S. Nixon, G. Randall, M. Ribaudo, J. Baker, R. Diaz, T. Prato, N. Rabalais, R. Zimmerman. (1999). Gulf of Mexico hypoxia: Land and sea interactions. CAST Task Force Report No. 134. Council for Agricultural Science and Tecshnology, Ames, IA.

Cole, C.V., J. Duxbury, J. Freney, O. Heinemeyer, K. Minami, A. Mosier, K. Paus- tian, N. Rosenberg, N. Sampson, D. Sauerbeck, and Q. Zhao. (1997). Global estimates of potential mitigation of greenhouse gas emissions by agriculture. *Nutr. Cycling Agroecosyst*. 49:221–228.

Dalal, R.C., W. Wang, G.P. Robertson, and W.J. Parton. (2003). Nitrous oxide emis- sion from Australian agricultural lands and mitigation options: A review. *Aust. J. Soil Res*. 41:165–195.

Denning, J., R. Eliason, R. J. Goos, B. Hoskins, M. V. Nathan, and A. Wolf (2011). *Recommended Chemical Soil Test Procedures for the North Central Region*, *221*(221), 75.

Fageria, N.K., and V.C. Baligar. (2005). Enhancing nitrogen use efficiency in crop plants. *Adv. Agron*. 88:97-185

Feinerman, E., E.K. Choi, and S.R. Johnson. (1990). Uncertainty and split nitrogen application in crop production. *Amer. J. Agr. Econ*. 72:975-984.

Johnston, A. E. (2000). Efficient use of nutrients in agricultural production systems. *Commun. Soil Sci. Plant Anal*. 31:1599-1620.

Monteny, G.-J., A. Bannink, and D. Chadwick. (2006). Greenhouse gas abatement strategies for animal husbandry. *Agric. Ecosyst. Environ*. 112:163–170.

Microsoft. (2013). Microsoft Excel computer software. Redomond, Washington: Microsoft

Olson, R., and L. Kurtz. (1982). Crop nitrogen requirements, utilization, and fertilization. Nitrogen in Agricultural Soils, (22), 567–604.

Paustian, K., B.A. Babcock, J. Hatfield, R. Lal, B.A. McCarl, S. McLaughlin, A. Mosier, C. Rice, G.P. Robertson, N.J. Rosenberg, C. Rosenzweig, W.H. Schlesinger, and D. Zilberman. (2004). Agricultural mitigation of greenhouse gases: Science and policy options. CAST Rep. R141. Council on Agricultural Science and Technology, Ames, IA.

Rabalais, N.N. (2002). Nitrogen in aquatic ecosystems. *AMBIO* 31:102-112.

Raun, W.R., and G.V. Johnson. (1999). Improving nitrogen use efficiency for cereal production. *Agronomy J.* 91:357–363.

Robertson, G.P. (2004). Abatement of nitrous oxide, methane and other non- CO2 greenhouse gases: The need for a systems approach. p. 493–506. In C.B. Field and M.R. Raupach (ed.) The global carbon cycle. Integrating humans, climate, and the natural world. SCOPE 62, Island Press, Washington, DC.

Rouse, J. W., R. H. Haas, J. A. Schell, and D. W. Deering (1973). Monitoring vegetation systems in the Great Plains with ERTS, *Third ERTS Symposium*, NASA SP-351 I, 309- 317.

SAS Institute. (2011). Release 9.3 ed. SAS Inst., Cary, NC.

Saxton, A.M. (1998). A macro for converting mean separation output to letter groupings in Proc Mixed. In Proc. 23rd SAS Users Group Intl., SAS Institute, Cary, NC, pp1243-1246.

Schepers, J.S., G.E. Varvel, and D.G. Watts. (1995). Nitrogen and water management strategies to reduce nitrate leaching under irrigated maize. *J. Contam. Hydrol*. 20:227-239.

Schepers, J. S., D. D. Francis and J. F. Power. (1995). Tissue analysis to improve nitrogen management practices. In Clean Water - Clean Environment - 21st Century. Conf. Proc, Vol. II: Nutrients, 195-198. St. Joseph, Mich.: ASAE.

Sripada, R.P., R.W. Heiniger, J.G. White, and R. Weisz. (2005). Aerial color infrared photography for determining late-season nitrogen requirements in corn. *Agronomy J.* 97:1443-1451.

Schilling, K.E. (2002). Chemical transport from paired agricultural and restored prairie watersheds. *J. Environ. Qual*. 31:1184-1193.

Solari, F., J. F. Shanahan, R. B. Ferguson, and V. I. Adamchuk. (2010). An Active Sensor Algorithm for Corn Nitrogen Recommendations Based on a Chlorophyll Meter Algorithm. *Agronomy J. 102*(4), 1090.

Steinheimer, T.R., K.D. Scoggin, and L.A. Kramer. (1998). Agricultural chemical movement through a field size watershed in Iowa: Surface hydrology and nitrate losses in discharge. *Environmental Science & Technology* 32:1048-1052.

Tucker, A.N. (2010). Nitrogen Management of Corn with Sensor Technology. Dissertation. Kansas State University. https://krex.k-state.edu/dspace/handle/2097/4608

Turner, R.E., N.N. Rabalais. (1991). Changes in Mississippi river water-quality this century. *Bioscience* 41:140-147.

Appendix A - Chapter 2 Winter Wheat Raw Data

By Year and Location

2012 Gypsum

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Precipitation Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	mm				
0	0	0	0	13	0.341	0.365	0.419	1.274	20.272	100.584	85.598	113.030	74.676	10.160
0	0	0	0	13	0.268	0.272	0.287	0.330	26.699	100.584	85.598	113.030	74.676	10.160
0	0	0	0	13	0.350	0.383	0.432	0.790	22.347	100.584	85.598	113.030	74.676	10.160
0	0	0	0	13	0.300	0.296	0.338	0.970	23.077	100.584	85.598	113.030	74.676	10.160
34	0	0	0	47	0.387	0.460	0.571	1.400	21.894	100.584	85.598	113.030	74.676	10.160
34	0	0	0	47	0.507	0.625	0.671	2.363	18.830	100.584	85.598	113.030	74.676	10.160
34	0	0	0	47	0.502	0.621	0.660	2.781	19.693	100.584	85.598	113.030	74.676	10.160
34	0	0	0	47	0.403	0.501	0.523	2.102	20.405	100.584	85.598	113.030	74.676	10.160
67	0	0	0	81	0.536	0.734	0.780	2.474	21.426	100.584	85.598	113.030	74.676	10.160
67	0	0	0	81	0.554	0.706	0.739	2.775	20.747	100.584	85.598	113.030	74.676	10.160
67	0	0	0	81	0.511	0.645	0.711	2.256	23.097	100.584	85.598	113.030	74.676	10.160
67	0	0	0	81	0.496	0.626	0.638	2.572	22.241	100.584	85.598	113.030	74.676	10.160
101	0	0	0	114	0.562	0.799	0.816	2.782	21.674	100.584	85.598	113.030	74.676	10.160
101	0	0	0	114	0.645	0.815	0.828	3.370	20.772	100.584	85.598	113.030	74.676	10.160
101	0	0	0	114	0.600	0.795	0.821	3.231	21.573	100.584	85.598	113.030	74.676	10.160
101	0	0	0	114	0.636	0.794	0.800	3.086	21.589	100.584	85.598	113.030	74.676	10.160
134	0	0	0	148	0.582	0.823	0.836	2.583	22.639	100.584	85.598	113.030	74.676	10.160
134	0	0	0	148	0.658	0.836	0.844	3.311	22.885	100.584	85.598	113.030	74.676	10.160
134	0	0	0	148	0.651	0.826	0.834	2.905	23.081	100.584	85.598	113.030	74.676	10.160
134	0	0	0	148	0.579	0.759	0.753	2.876	21.017	100.584	85.598	113.030	74.676	10.160
34	101	0	0	148	0.486	0.781	0.832	3.500	21.710	100.584	85.598	113.030	74.676	10.160
34	101	0	0	148	0.517	0.787	0.833	3.089	23.454	100.584	85.598	113.030	74.676	10.160
34	101	0	0	148	0.447	0.754	0.820	3.022	24.626	100.584	85.598	113.030	74.676	10.160
34	101	0	0	148	0.408	0.725	0.817	3.145	22.992	100.584	85.598	113.030	74.676	10.160
67	67	0	0	148	0.529	0.813	0.844	3.492	22.694	100.584	85.598	113.030	74.676	10.160
67	67	0	0	148	0.558	0.822	0.844	2.820	23.633	100.584	85.598	113.030	74.676	10.160
67	67	0	0	148	0.531	0.815	0.840	3.228	23.664	100.584	85.598	113.030	74.676	10.160
67	67	0	0	148	0.477	0.800	0.837	3.705	22.499	100.584	85.598	113.030	74.676	10.160

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
101	34	0	0	148	0.519	0.786	0.837	3.227	21.461	100.584	85.598	113.030	74.676	10.160
101	34	0	0	148	0.486	0.803	0.828	3.096	22.816	100.584	85.598	113.030	74.676	10.160
101	34	0	0	148	0.555	0.798	0.853	3.334	23.016	100.584	85.598	113.030	74.676	10.160
101	34	0	0	148	0.526	0.807	0.835	3.634	21.533	100.584	85.598	113.030	74.676	10.160
34	0	101	0	148	0.496	0.642	0.730	3.602	22.614	100.584	85.598	113.030	74.676	10.160
34	0	101	0	148	0.425	0.508	0.591	3.146	25.042	100.584	85.598	113.030	74.676	10.160
34	0	101	0	148	0.459	0.535	0.625	3.190	25.410	100.584	85.598	113.030	74.676	10.160
34	0	101	0	148	0.391	0.418	0.496	3.210	23.981	100.584	85.598	113.030	74.676	10.160
67	0	67	0	148	0.490	0.638	0.738	2.429	22.535	100.584	85.598	113.030	74.676	10.160
67	0	67	0	148	0.377	0.559	0.645	2.429	24.740	100.584	85.598	113.030	74.676	10.160
67	0	67	0	148	0.552	0.720	0.772	3.681	21.345	100.584	85.598	113.030	74.676	10.160
67	0	67	0	148	.	0.720	0.761	3.956	22.000	100.584	85.598	113.030	74.676	10.160
101	0	34	0	148	0.513	0.793	0.828	3.311	22.252	100.584	85.598	113.030	74.676	10.160
101	0	34	0	148	0.547	0.813	0.828	3.204	22.220	100.584	85.598	113.030	74.676	10.160
101	0	34	0	148	0.496	0.746	0.806	2.978	24.013	100.584	85.598	113.030	74.676	10.160
101	0	34	0	148	.	0.791	0.817	3.685	21.713	100.584	85.598	113.030	74.676	10.160
34	0	0	101	148	0.476	0.579	0.629	2.932	25.156	100.584	85.598	113.030	74.676	10.160
34	0	0	101	148	0.342	0.342	0.451	2.228	27.481	100.584	85.598	113.030	74.676	10.160
34	0	0	101	148	0.508	0.641	0.653	3.429	25.442	100.584	85.598	113.030	74.676	10.160
34	0	0	101	148	0.452	0.587	0.627	2.678	26.398	100.584	85.598	113.030	74.676	10.160
67	0	0	67	148	0.452	0.636	0.715	2.991	24.821	100.584	85.598	113.030	74.676	10.160
67	0	0	67	148	0.483	0.643	0.747	3.184	25.380	100.584	85.598	113.030	74.676	10.160
67	0	0	67	148	0.477	0.661	0.710	3.181	24.082	100.584	85.598	113.030	74.676	10.160
67	0	0	67	148	.	0.726	0.714	3.240	23.492	100.584	85.598	113.030	74.676	10.160
101	0	0	34	148	0.548	0.783	0.818	3.362	20.398	100.584	85.598	113.030	74.676	10.160
101	0	0	34	148	0.566	0.810	0.822	3.008	21.854	100.584	85.598	113.030	74.676	10.160
101	0	0	34	148	0.497	0.736	0.786	3.508	22.950	100.584	85.598	113.030	74.676	10.160
101	0	0	34	148	0.526	0.791	0.822	3.964	21.934	100.584	85.598	113.030	74.676	10.160

2012 Manhattan Field F

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
0	0	0	0	10	0.760	0.803	0.781	4.911	17.918	96.266	145.796	132.588	49.784	27.178
0	0	0	0	10	0.848	0.885	0.880	3.026	24.231	96.266	145.796	132.588	49.784	27.178
0	0	0	0	10	0.849	0.879	0.868	3.618	22.792	96.266	145.796	132.588	49.784	27.178
0	0	0	0	10	0.843	0.881	0.864	3.722	22.767	96.266	145.796	132.588	49.784	27.178
34	0	0	0	43	0.767	0.854	0.850	4.848	20.445	96.266	145.796	132.588	49.784	27.178
34	0	0	0	43	0.857	0.884	0.835	2.277	24.921	96.266	145.796	132.588	49.784	27.178
34	0	0	0	43	0.725	0.833	0.832	4.837	18.618	96.266	145.796	132.588	49.784	27.178
34	0	0	0	43	0.776	0.850	0.850	4.900	18.475	96.266	145.796	132.588	49.784	27.178
67	0	0	0	77	0.794	0.866	0.861	4.325	20.848	96.266	145.796	132.588	49.784	27.178
67	0	0	0	77	0.853	0.886	0.851	2.642	24.359	96.266	145.796	132.588	49.784	27.178
67	0	0	0	77	0.855	0.890	0.873	2.518	25.265	96.266	145.796	132.588	49.784	27.178
67	0	0	0	77	0.849	0.886	0.855	3.057	22.802	96.266	145.796	132.588	49.784	27.178
101	0	0	0	111	0.848	0.888	0.837	2.530	25.340	96.266	145.796	132.588	49.784	27.178
101	0	0	0	111	0.810	0.884	0.857	2.314	24.891	96.266	145.796	132.588	49.784	27.178
101	0	0	0	111	0.850	0.887	0.892	2.853	24.351	96.266	145.796	132.588	49.784	27.178
101	0	0	0	111	0.735	0.857	0.873	4.533	21.618	96.266	145.796	132.588	49.784	27.178
134	0	0	0	144	0.776	0.872	0.884	4.756	22.283	96.266	145.796	132.588	49.784	27.178
134	0	0	0	144	0.835	0.887	0.877	3.070	24.123	96.266	145.796	132.588	49.784	27.178
134	0	0	0	144	0.831	0.885	0.893	3.972	22.458	96.266	145.796	132.588	49.784	27.178
134	0	0	0	144	0.793	0.878	0.887	4.312	22.595	96.266	145.796	132.588	49.784	27.178
34	101	0	0	144	0.809	0.871	0.855	4.354	23.259	96.266	145.796	132.588	49.784	27.178
34	101	0	0	144	0.844	0.886	0.891	3.064	24.311	96.266	145.796	132.588	49.784	27.178
34	101	0	0	144	0.818	0.873	0.877	4.251	21.796	96.266	145.796	132.588	49.784	27.178
34	101	0	0	144	0.816	0.881	0.872	4.308	21.689	96.266	145.796	132.588	49.784	27.178
67	67	0	0	144	0.743	0.831	0.833	5.198	19.577	96.266	145.796	132.588	49.784	27.178
67	67	0	0	144	0.730	0.814	0.835	5.152	21.295	96.266	145.796	132.588	49.784	27.178
67	67	0	0	144	0.835	0.883	0.862	3.101	23.315	96.266	145.796	132.588	49.784	27.178
67	67	0	0	144	0.821	0.876	0.877	4.207	21.867	96.266	145.796	132.588	49.784	27.178

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
101	34	0	0	144	0.848	0.883	0.845	2.648	23.342	96.266	145.796	132.588	49.784	27.178
101	34	0	0	144	0.835	0.881	0.866	3.545	22.034	96.266	145.796	132.588	49.784	27.178
101	34	0	0	144	0.758	0.811	0.816	5.175	17.333	96.266	145.796	132.588	49.784	27.178
101	34	0	0	144	0.784	0.833	0.831	5.146	19.405	96.266	145.796	132.588	49.784	27.178
34	0	101	0	144	0.767	0.817	0.820	5.215	22.826	96.266	145.796	132.588	49.784	27.178
34	0	101	0	144	0.849	0.882	0.855	2.922	24.488	96.266	145.796	132.588	49.784	27.178
34	0	101	0	144	0.778	0.827	0.845	5.204	21.187	96.266	145.796	132.588	49.784	27.178
34	0	101	0	144	0.785	0.828	0.854	4.697	22.651	96.266	145.796	132.588	49.784	27.178
67	0	67	0	144	0.826	0.860	0.834	4.303	22.461	96.266	145.796	132.588	49.784	27.178
67	0	67	0	144	0.845	0.878	0.866	3.150	24.322	96.266	145.796	132.588	49.784	27.178
67	0	67	0	144	0.828	0.876	0.848	2.567	25.341	96.266	145.796	132.588	49.784	27.178
67	0	67	0	144	0.847	0.884	0.854	3.105	23.252	96.266	145.796	132.588	49.784	27.178
101	0	34	0	144	0.741	0.794	0.801	5.278	18.982	96.266	145.796	132.588	49.784	27.178
101	0	34	0	144	0.818	0.876	0.852	3.022	23.276	96.266	145.796	132.588	49.784	27.178
101	0	34	0	144	0.748	0.788	0.795	5.615	17.980	96.266	145.796	132.588	49.784	27.178
101	0	34	0	144	0.802	0.844	0.854	5.198	20.999	96.266	145.796	132.588	49.784	27.178
34	0	0	101	144	0.767	0.815	0.794	5.221	23.594	96.266	145.796	132.588	49.784	27.178
34	0	0	101	144	0.745	0.778	0.777	5.100	25.454	96.266	145.796	132.588	49.784	27.178
34	0	0	101	144	0.824	0.869	0.880	4.440	22.684	96.266	145.796	132.588	49.784	27.178
34	0	0	101	144	0.809	0.855	0.850	4.664	24.142	96.266	145.796	132.588	49.784	27.178
67	0	0	67	144	0.767	0.828	0.762	5.117	23.166	96.266	145.796	132.588	49.784	27.178
67	0	0	67	144	0.743	0.814	0.806	4.946	22.604	96.266	145.796	132.588	49.784	27.178
67	0	0	67	144	0.827	0.875	0.860	4.480	22.337	96.266	145.796	132.588	49.784	27.178
67	0	0	67	144	0.771	0.835	0.827	5.129	23.588	96.266	145.796	132.588	49.784	27.178
101	0	0	34	144	0.726	0.781	0.749	5.129	20.346	96.266	145.796	132.588	49.784	27.178
101	0	0	34	144	0.761	0.820	0.824	5.123	21.308	96.266	145.796	132.588	49.784	27.178
101	0	0	34	144	0.831	0.877	0.865	4.140	21.823	96.266	145.796	132.588	49.784	27.178
101	0	0	34	144	0.793	0.837	0.813	4.733	21.044	96.266	145.796	132.588	49.784	27.178

2012 Manhattan Field J3

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
0	0	0	0	10	0.415	0.386	0.427	1.616	19.108	92.964	89.916	132.588	49.784	27.178
0	0	0	0	10	0.344	0.355	0.339	1.287	18.467	92.964	89.916	132.588	49.784	27.178
0	0	0	0	10	0.337	0.375	0.342	1.589	18.345	92.964	89.916	132.588	49.784	27.178
0	0	0	0	10	0.313	0.388	0.361	1.667	19.169	92.964	89.916	132.588	49.784	27.178
34	0	0	0	43	0.476	0.648	0.643	2.788	18.932	92.964	89.916	132.588	49.784	27.178
34	0	0	0	43	0.367	0.537	0.542	2.598	18.136	92.964	89.916	132.588	49.784	27.178
34	0	0	0	43	0.356	0.511	0.516	2.399	19.218	92.964	89.916	132.588	49.784	27.178
34	0	0	0	43	0.344	0.434	0.420	1.729	19.641	92.964	89.916	132.588	49.784	27.178
67	0	0	0	77	0.360	0.488	0.507	2.259	20.704	92.964	89.916	132.588	49.784	27.178
67	0	0	0	77	0.500	0.699	0.689	2.897	18.256	92.964	89.916	132.588	49.784	27.178
67	0	0	0	77	0.341	0.509	0.541	2.566	19.893	92.964	89.916	132.588	49.784	27.178
67	0	0	0	77	0.388	0.518	0.569	2.407	20.396	92.964	89.916	132.588	49.784	27.178
101	0	0	0	111	0.456	0.641	0.643	2.748	20.044	92.964	89.916	132.588	49.784	27.178
101	0	0	0	111	0.470	0.688	0.695	3.520	19.608	92.964	89.916	132.588	49.784	27.178
101	0	0	0	111	0.335	0.517	0.549	2.441	23.096	92.964	89.916	132.588	49.784	27.178
101	0	0	0	111	0.393	0.545	0.546	2.112	22.359	92.964	89.916	132.588	49.784	27.178
134	0	0	0	144	0.558	0.712	0.723	3.108	21.174	92.964	89.916	132.588	49.784	27.178
134	0	0	0	144	0.392	0.558	0.579	2.600	22.793	92.964	89.916	132.588	49.784	27.178
134	0	0	0	144	0.389	0.528	0.543	2.632	24.054	92.964	89.916	132.588	49.784	27.178
134	0	0	0	144	0.394	0.630	0.636	3.112	24.000	92.964	89.916	132.588	49.784	27.178
34	101	0	0	144	0.419	0.550	0.574	4.010	23.817	92.964	89.916	132.588	49.784	27.178
34	101	0	0	144	0.445	0.660	0.664	2.682	21.685	92.964	89.916	132.588	49.784	27.178
34	101	0	0	144	0.357	0.542	0.545	2.595	23.655	92.964	89.916	132.588	49.784	27.178
34	101	0	0	144	0.389	0.578	0.581	3.039	23.895	92.964	89.916	132.588	49.784	27.178
67	67	0	0	144	0.506	0.708	0.704	3.267	21.226	92.964	89.916	132.588	49.784	27.178
67	67	0	0	144	0.424	0.574	0.582	2.344	23.277	92.964	89.916	132.588	49.784	27.178
67	67	0	0	144	0.366	0.545	0.557	2.266	23.762	92.964	89.916	132.588	49.784	27.178
67	67	0	0	144	0.344	0.499	0.542	2.882	24.521	92.964	89.916	132.588	49.784	27.178

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
101	34	0	0	144	0.512	0.734	0.748	3.330	21.934	92.964	89.916	132.588	49.784	27.178
101	34	0	0	144	0.529	0.666	0.690	3.228	22.914	92.964	89.916	132.588	49.784	27.178
101	34	0	0	144	0.348	0.497	0.534	2.692	23.347	92.964	89.916	132.588	49.784	27.178
101	34	0	0	144	0.414	0.618	0.585	2.394	24.868	92.964	89.916	132.588	49.784	27.178
34	0	101	0	144	0.349	0.382	0.424	3.022	22.812	92.964	89.916	132.588	49.784	27.178
34	0	101	0	144	0.463	0.587	0.600	2.807	21.908	92.964	89.916	132.588	49.784	27.178
34	0	101	0	144	0.362	0.457	0.443	2.465	24.144	92.964	89.916	132.588	49.784	27.178
34	0	101	0	144	0.386	0.505	0.522	2.933	23.776	92.964	89.916	132.588	49.784	27.178
67	0	67	0	144	0.450	0.618	0.681	3.801	21.604	92.964	89.916	132.588	49.784	27.178
67	0	67	0	144	0.511	0.651	0.680	2.891	21.764	92.964	89.916	132.588	49.784	27.178
67	0	67	0	144	0.424	0.553	0.550	2.876	24.016	92.964	89.916	132.588	49.784	27.178
67	0	67	0	144	0.431	0.603	0.612	2.638	24.033	92.964	89.916	132.588	49.784	27.178
101	0	34	0	144	0.351	0.571	0.580	2.412	21.801	92.964	89.916	132.588	49.784	27.178
101	0	34	0	144	0.383	0.564	0.589	2.170	23.093	92.964	89.916	132.588	49.784	27.178
101	0	34	0	144	0.383	0.558	0.577	2.313	24.262	92.964	89.916	132.588	49.784	27.178
101	0	34	0	144	0.471	0.631	0.633	2.773	23.442	92.964	89.916	132.588	49.784	27.178
34	0	0	101	144	0.461	0.608	0.553	3.034	22.714	92.964	89.916	132.588	49.784	27.178
34	0	0	101	144	0.450	0.515	0.491	2.735	23.074	92.964	89.916	132.588	49.784	27.178
34	0	0	101	144	0.362	0.539	0.518	2.324	23.862	92.964	89.916	132.588	49.784	27.178
34	0	0	101	144	0.380	0.444	0.460	2.647	24.634	92.964	89.916	132.588	49.784	27.178
67	0	0	67	144	0.432	0.559	0.558	3.236	22.326	92.964	89.916	132.588	49.784	27.178
67	0	0	67	144	0.421	0.597	0.569	2.526	22.427	92.964	89.916	132.588	49.784	27.178
67	0	0	67	144	0.322	0.508	0.534	2.279	23.690	92.964	89.916	132.588	49.784	27.178
67	0	0	67	144	0.387	0.563	0.550	2.820	24.172	92.964	89.916	132.588	49.784	27.178
101	0	0	34	144	0.335	0.664	0.679	3.244	21.679	92.964	89.916	132.588	49.784	27.178
101	0	0	34	144	0.474	0.605	0.608	2.851	23.198	92.964	89.916	132.588	49.784	27.178
101	0	0	34	144	0.357	0.574	0.569	2.329	23.312	92.964	89.916	132.588	49.784	27.178
101	0	0	34	144	0.341	0.511	0.528	2.802	24.617	92.964	89.916	132.588	49.784	27.178

2013 Manhattan Field C

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
0	0	0	0	20	0.379	0.517	0.562	3.311	14.411	148.590	32.766	59.944	186.690	88.392
0	0	0	0	20	0.365	0.470	0.524	3.253	16.142	148.590	32.766	59.944	186.690	88.392
0	0	0	0	20	0.278	0.352	0.428	2.217	19.216	148.590	32.766	59.944	186.690	88.392
0	0	0	0	20	0.284	0.320	0.353	2.163	17.852	148.590	32.766	59.944	186.690	88.392
34	0	0	0	54	0.411	0.593	0.690	4.482	16.253	148.590	32.766	59.944	186.690	88.392
34	0	0	0	54	0.458	0.700	0.747	4.585	17.155	148.590	32.766	59.944	186.690	88.392
34	0	0	0	54	0.309	0.443	0.557	3.285	15.636	148.590	32.766	59.944	186.690	88.392
34	0	0	0	54	0.279	0.382	0.448	3.078	17.103	148.590	32.766	59.944	186.690	88.392
67	0	0	0	87	0.389	0.725	0.795	4.855	16.369	148.590	32.766	59.944	186.690	88.392
67	0	0	0	87	0.349	0.587	0.677	4.767	18.625	148.590	32.766	59.944	186.690	88.392
67	0	0	0	87	0.363	0.646	0.709	4.019	17.002	148.590	32.766	59.944	186.690	88.392
67	0	0	0	87	0.282	0.443	0.559	3.857	17.931	148.590	32.766	59.944	186.690	88.392
101	0	0	0	121	0.419	0.725	0.783	4.866	15.229	148.590	32.766	59.944	186.690	88.392
101	0	0	0	121	0.483	0.807	0.850	5.405	18.256	148.590	32.766	59.944	186.690	88.392
101	0	0	0	121	0.361	0.534	0.629	4.404	19.221	148.590	32.766	59.944	186.690	88.392
101	0	0	0	121	0.310	0.411	0.600	4.157	19.540	148.590	32.766	59.944	186.690	88.392
134	0	0	0	155	0.464	0.809	0.855	5.693	17.158	148.590	32.766	59.944	186.690	88.392
134	0	0	0	155	0.464	0.822	0.866	5.249	19.841	148.590	32.766	59.944	186.690	88.392
134	0	0	0	155	0.354	0.641	0.764	4.816	21.470	148.590	32.766	59.944	186.690	88.392
134	0	0	0	155	0.264	0.391	0.558	4.105	22.497	148.590	32.766	59.944	186.690	88.392
34	101	0	0	155	0.321	0.605	0.694	4.936	17.219	148.590	32.766	59.944	186.690	88.392
34	101	0	0	155	0.410	0.775	0.842	5.156	17.513	148.590	32.766	59.944	186.690	88.392
34	101	0	0	155	0.302	0.440	0.552	4.297	22.027	148.590	32.766	59.944	186.690	88.392
34	101	0	0	155	0.288	0.540	0.739	4.061	21.429	148.590	32.766	59.944	186.690	88.392
67	67	0	0	155	0.479	0.798	0.850	5.073	15.934	148.590	32.766	59.944	186.690	88.392
67	67	0	0	155	0.425	0.793	0.864	5.508	21.566	148.590	32.766	59.944	186.690	88.392
67	67	0	0	155	0.320	0.492	0.628	4.457	22.083	148.590	32.766	59.944	186.690	88.392
67	67	0	0	155	0.274	0.492	0.692	4.388	21.106	148.590	32.766	59.944	186.690	88.392

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
101	34	0	0	155	0.474	0.794	0.827	4.628	17.298	148.590	32.766	59.944	186.690	88.392
101	34	0	0	155	0.458	0.838	0.864	5.572	20.859	148.590	32.766	59.944	186.690	88.392
101	34	0	0	155	0.333	0.633	0.781	4.172	23.030	148.590	32.766	59.944	186.690	88.392
101	34	0	0	155	0.291	0.539	0.734	4.408	21.177	148.590	32.766	59.944	186.690	88.392
34	0	101	0	155	0.443	0.652	0.788	5.345	18.223	148.590	32.766	59.944	186.690	88.392
34	0	101	0	155	0.440	0.635	0.721	5.488	19.969	148.590	32.766	59.944	186.690	88.392
34	0	101	0	155	0.296	0.370	0.510	4.297	21.164	148.590	32.766	59.944	186.690	88.392
34	0	101	0	155	0.277	0.432	0.561	3.785	22.299	148.590	32.766	59.944	186.690	88.392
67	0	67	0	155	0.390	0.627	0.725	4.436	16.828	148.590	32.766	59.944	186.690	88.392
67	0	67	0	155	0.442	0.739	0.802	5.589	17.691	148.590	32.766	59.944	186.690	88.392
67	0	67	0	155	0.339	0.571	0.733	4.050	21.864	148.590	32.766	59.944	186.690	88.392
67	0	67	0	155	0.312	0.602	0.744	4.210	22.241	148.590	32.766	59.944	186.690	88.392
101	0	34	0	155	0.421	0.791	0.841	5.221	17.185	148.590	32.766	59.944	186.690	88.392
101	0	34	0	155	0.348	0.786	0.849	5.432	18.227	148.590	32.766	59.944	186.690	88.392
101	0	34	0	155	0.318	0.494	0.674	4.889	20.524	148.590	32.766	59.944	186.690	88.392
101	0	34	0	155	0.367	0.772	0.831	5.276	19.800	148.590	32.766	59.944	186.690	88.392
34	0	0	101	155	0.445	0.674	0.718	5.894	19.870	148.590	32.766	59.944	186.690	88.392
34	0	0	101	155	0.459	0.696	0.744	5.809	20.597	148.590	32.766	59.944	186.690	88.392
34	0	0	101	155	0.380	0.542	0.593	3.817	23.216	148.590	32.766	59.944	186.690	88.392
34	0	0	101	155	0.309	0.524	0.624	3.982	22.538	148.590	32.766	59.944	186.690	88.392
67	0	0	67	155	0.413	0.620	0.624	5.168	18.987	148.590	32.766	59.944	186.690	88.392
67	0	0	67	155	0.480	0.748	0.782	5.767	23.210	148.590	32.766	59.944	186.690	88.392
67	0	0	67	155	0.317	0.416	0.557	4.432	22.170	148.590	32.766	59.944	186.690	88.392
67	0	0	67	155	0.298	0.484	0.667	4.302	22.954	148.590	32.766	59.944	186.690	88.392
101	0	0	34	155	0.431	0.792	0.851	5.659	19.023	148.590	32.766	59.944	186.690	88.392
101	0	0	34	155	0.386	0.764	0.822	5.290	18.714	148.590	32.766	59.944	186.690	88.392
101	0	0	34	155	0.328	0.595	0.707	4.404	21.329	148.590	32.766	59.944	186.690	88.392
101	0	0	34	155	0.319	0.429	0.584	4.239	23.371	148.590	32.766	59.944	186.690	88.392

2013 Partridge

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
0	0	0	0	73	0.545	0.606	0.632	3.434	19.329	112.014	11.430	55.118	211.836	63.754
0	0	0	0	73	0.611	0.670	0.698	3.397	19.299	112.014	11.430	55.118	211.836	63.754
0	0	0	0	73	0.519	0.586	0.609	3.117	18.568	112.014	11.430	55.118	211.836	63.754
0	0	0	0	73	0.557	0.626	0.670	2.758	19.627	112.014	11.430	55.118	211.836	63.754
34	0	0	0	106	0.623	0.719	0.722	3.815	18.316	112.014	11.430	55.118	211.836	63.754
34	0	0	0	106	0.516	0.617	0.666	3.045	19.821	112.014	11.430	55.118	211.836	63.754
34	0	0	0	106	0.543	0.647	0.648	3.281	21.483	112.014	11.430	55.118	211.836	63.754
34	0	0	0	106	0.580	0.661	0.671	2.904	19.495	112.014	11.430	55.118	211.836	63.754
67	0	0	0	140	0.690	0.809	0.792	4.244	20.793	112.014	11.430	55.118	211.836	63.754
67	0	0	0	140	0.583	0.747	0.746	3.092	26.959	112.014	11.430	55.118	211.836	63.754
67	0	0	0	140	0.558	0.729	0.740	3.209	21.682	112.014	11.430	55.118	211.836	63.754
67	0	0	0	140	0.649	0.789	0.759	3.818	20.790	112.014	11.430	55.118	211.836	63.754
101	0	0	0	174	0.605	0.808	0.776	2.938	25.046	112.014	11.430	55.118	211.836	63.754
101	0	0	0	174	0.603	0.791	0.787	3.285	26.368	112.014	11.430	55.118	211.836	63.754
101	0	0	0	174	0.619	0.785	0.764	3.100	24.362	112.014	11.430	55.118	211.836	63.754
101	0	0	0	174	0.668	0.797	0.769	3.364	22.037	112.014	11.430	55.118	211.836	63.754
134	0	0	0	207	0.611	0.822	0.801	2.994	26.474	112.014	11.430	55.118	211.836	63.754
134	0	0	0	207	0.655	0.841	0.822	3.252	27.489	112.014	11.430	55.118	211.836	63.754
134	0	0	0	207	0.621	0.822	0.793	2.834	28.344	112.014	11.430	55.118	211.836	63.754
134	0	0	0	207	0.643	0.792	0.770	3.085	24.362	112.014	11.430	55.118	211.836	63.754
34	101	0	0	207	0.584	0.799	0.805	2.973	28.784	112.014	11.430	55.118	211.836	63.754
34	101	0	0	207	0.565	0.784	0.794	3.284	24.960	112.014	11.430	55.118	211.836	63.754
34	101	0	0	207	0.626	0.805	0.804	3.433	27.044	112.014	11.430	55.118	211.836	63.754
34	101	0	0	207	0.554	0.790	0.801	3.619	22.633	112.014	11.430	55.118	211.836	63.754
67	67	0	0	207	0.577	0.822	0.808	3.070	25.892	112.014	11.430	55.118	211.836	63.754
67	67	0	0	207	0.588	0.807	0.824	3.034	27.624	112.014	11.430	55.118	211.836	63.754
67	67	0	0	207	0.639	0.811	0.801	2.928	27.393	112.014	11.430	55.118	211.836	63.754
67	67	0	0	207	0.637	0.792	0.785	3.172	23.807	112.014	11.430	55.118	211.836	63.754

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
101	34	0	0	207	0.591	0.805	0.797	3.009	25.895	112.014	11.430	55.118	211.836	63.754
101	34	0	0	207	0.592	0.816	0.812	2.994	25.645	112.014	11.430	55.118	211.836	63.754
101	34	0	0	207	0.583	0.806	0.788	3.125	26.281	112.014	11.430	55.118	211.836	63.754
101	34	0	0	207	0.613	0.804	0.784	3.470	22.346	112.014	11.430	55.118	211.836	63.754
34	0	101	0	207	0.561	0.720	0.779	2.727	28.920	112.014	11.430	55.118	211.836	63.754
34	0	101	0	207	0.601	0.737	0.785	3.501	27.455	112.014	11.430	55.118	211.836	63.754
34	0	101	0	207	0.584	0.642	0.772	2.942	27.857	112.014	11.430	55.118	211.836	63.754
34	0	101	0	207	0.539	0.689	0.780	4.249	23.405	112.014	11.430	55.118	211.836	63.754
67	0	67	0	207	0.580	0.752	0.777	2.910	26.394	112.014	11.430	55.118	211.836	63.754
67	0	67	0	207	0.634	0.748	0.796	3.591	24.014	112.014	11.430	55.118	211.836	63.754
67	0	67	0	207	0.569	0.740	0.784	3.165	26.518	112.014	11.430	55.118	211.836	63.754
67	0	67	0	207	0.602	0.725	0.775	4.191	22.344	112.014	11.430	55.118	211.836	63.754
101	0	34	0	207	0.589	0.797	0.808	2.717	25.160	112.014	11.430	55.118	211.836	63.754
101	0	34	0	207	0.609	0.824	0.814	3.176	28.274	112.014	11.430	55.118	211.836	63.754
101	0	34	0	207	0.666	0.808	0.785	2.891	27.645	112.014	11.430	55.118	211.836	63.754
101	0	34	0	207	0.632	0.802	0.813	3.172	27.588	112.014	11.430	55.118	211.836	63.754
34	0	0	101	207	0.566	0.691	0.685	3.704	23.935	112.014	11.430	55.118	211.836	63.754
34	0	0	101	207	0.638	0.701	0.725	3.731	23.217	112.014	11.430	55.118	211.836	63.754
34	0	0	101	207	0.538	0.629	0.643	3.546	24.832	112.014	11.430	55.118	211.836	63.754
34	0	0	101	207	0.549	0.675	0.715	3.940	22.361	112.014	11.430	55.118	211.836	63.754
67	0	0	67	207	0.562	0.661	0.714	3.504	23.595	112.014	11.430	55.118	211.836	63.754
67	0	0	67	207	0.613	0.750	0.750	3.437	25.068	112.014	11.430	55.118	211.836	63.754
67	0	0	67	207	0.644	0.764	0.743	3.234	24.664	112.014	11.430	55.118	211.836	63.754
67	0	0	67	207	0.602	0.735	0.722	4.133	20.206	112.014	11.430	55.118	211.836	63.754
101	0	0	34	207	0.682	0.837	0.812	4.085	24.380	112.014	11.430	55.118	211.836	63.754
101	0	0	34	207	0.654	0.803	0.764	4.007	24.363	112.014	11.430	55.118	211.836	63.754
101	0	0	34	207	0.627	0.802	0.786	2.878	26.286	112.014	11.430	55.118	211.836	63.754
101	0	0	34	207	0.629	0.811	0.795	3.121	26.196	112.014	11.430	55.118	211.836	63.754

2013 McCune

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
0	0	0	0	93	0.654	0.732	0.729	5.106	15.073	159.512	20.828	152.908	232.664	30.226
0	0	0	0	93	0.651	0.673	0.639	4.257	14.149	159.512	20.828	152.908	232.664	30.226
0	0	0	0	93	0.626	0.715	0.712	5.139	13.943	159.512	20.828	152.908	232.664	30.226
0	0	0	0	93	0.564	0.543	0.450	2.857	13.044	159.512	20.828	152.908	232.664	30.226
34	0	0	0	127	0.686	0.721	0.703	4.565	15.828	159.512	20.828	152.908	232.664	30.226
34	0	0	0	127	0.688	0.794	0.786	5.667	15.597	159.512	20.828	152.908	232.664	30.226
34	0	0	0	127	0.693	0.737	0.689	5.091	12.930	159.512	20.828	152.908	232.664	30.226
34	0	0	0	127	0.696	0.760	0.733	5.361	14.665	159.512	20.828	152.908	232.664	30.226
67	0	0	0	160	0.731	0.753	0.713	4.688	15.577	159.512	20.828	152.908	232.664	30.226
67	0	0	0	160	0.660	0.763	0.726	5.395	15.359	159.512	20.828	152.908	232.664	30.226
67	0	0	0	160	0.691	0.780	0.773	5.586	12.926	159.512	20.828	152.908	232.664	30.226
67	0	0	0	160	0.790	0.820	0.823	6.788	15.261	159.512	20.828	152.908	232.664	30.226
101	0	0	0	194	0.723	0.855	0.856	7.641	19.352	159.512	20.828	152.908	232.664	30.226
101	0	0	0	194	0.671	0.815	0.806	6.207	15.403	159.512	20.828	152.908	232.664	30.226
101	0	0	0	194	0.693	0.818	0.821	6.869	14.736	159.512	20.828	152.908	232.664	30.226
101	0	0	0	194	0.746	0.831	0.851	7.107	16.725	159.512	20.828	152.908	232.664	30.226
134	0	0	0	227	0.799	0.843	0.836	7.183	16.810	159.512	20.828	152.908	232.664	30.226
134	0	0	0	227	0.759	0.849	0.841	6.735	15.396	159.512	20.828	152.908	232.664	30.226
134	0	0	0	227	0.699	0.820	0.802	6.061	14.147	159.512	20.828	152.908	232.664	30.226
134	0	0	0	227	0.724	0.777	0.762	5.695	14.367	159.512	20.828	152.908	232.664	30.226
34	101	0	0	227	0.716	0.866	0.880	7.307	20.670	159.512	20.828	152.908	232.664	30.226
34	101	0	0	227	0.708	0.859	0.860	6.990	18.657	159.512	20.828	152.908	232.664	30.226
34	101	0	0	227	0.604	0.836	0.836	5.695	15.601	159.512	20.828	152.908	232.664	30.226
34	101	0	0	227	0.702	0.864	0.868	7.146	18.074	159.512	20.828	152.908	232.664	30.226

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
67	67	0	0	227	0.731	0.835	0.832	7.085	17.389	159.512	20.828	152.908	232.664	30.226
67	67	0	0	227	0.750	0.837	0.852	7.183	18.716	159.512	20.828	152.908	232.664	30.226
67	67	0	0	227	0.713	0.829	0.828	7.033	16.373	159.512	20.828	152.908	232.664	30.226
67	67	0	0	227	0.725	0.872	0.870	6.900	18.288	159.512	20.828	152.908	232.664	30.226
101	34	0	0	227	0.682	0.830	0.823	6.713	17.020	159.512	20.828	152.908	232.664	30.226
101	34	0	0	227	0.696	0.838	0.826	6.944	18.023	159.512	20.828	152.908	232.664	30.226
101	34	0	0	227	0.769	0.832	0.840	7.047	16.162	159.512	20.828	152.908	232.664	30.226
101	34	0	0	227	0.742	0.846	0.858	7.070	16.413	159.512	20.828	152.908	232.664	30.226
34	0	101	0	227	0.692	0.841	0.852	7.275	21.114	159.512	20.828	152.908	232.664	30.226
34	0	101	0	227	0.674	0.789	0.842	7.470	18.317	159.512	20.828	152.908	232.664	30.226
34	0	101	0	227	0.712	0.742	0.801	7.176	16.976	159.512	20.828	152.908	232.664	30.226
34	0	101	0	227	0.703	0.761	0.821	7.534	16.798	159.512	20.828	152.908	232.664	30.226
67	0	67	0	227	0.669	0.778	0.822	6.505	16.493	159.512	20.828	152.908	232.664	30.226
67	0	67	0	227	0.744	0.773	0.825	7.332	14.407	159.512	20.828	152.908	232.664	30.226
67	0	67	0	227	0.704	0.787	0.803	7.100	16.301	159.512	20.828	152.908	232.664	30.226
67	0	67	0	227	0.748	0.797	0.832	7.511	16.989	159.512	20.828	152.908	232.664	30.226
101	0	34	0	227	0.724	0.792	0.815	6.579	16.104	159.512	20.828	152.908	232.664	30.226
101	0	34	0	227	0.663	0.848	0.857	7.050	19.576	159.512	20.828	152.908	232.664	30.226
101	0	34	0	227	0.707	0.830	0.843	7.562	16.243	159.512	20.828	152.908	232.664	30.226
101	0	34	0	227	0.686	0.736	0.752	5.843	13.970	159.512	20.828	152.908	232.664	30.226
34	0	0	101	227	0.703	0.739	0.717	6.228	21.691	159.512	20.828	152.908	232.664	30.226
34	0	0	101	227	0.704	0.665	0.636	4.778	18.163	159.512	20.828	152.908	232.664	30.226
34	0	0	101	227	0.643	0.752	0.748	6.333	19.206	159.512	20.828	152.908	232.664	30.226
34	0	0	101	227	0.737	0.765	0.772	6.340	19.310	159.512	20.828	152.908	232.664	30.226
67	0	0	67	227	0.676	0.744	0.759	6.176	18.267	159.512	20.828	152.908	232.664	30.226
67	0	0	67	227	0.674	0.796	0.774	6.251	19.796	159.512	20.828	152.908	232.664	30.226
67	0	0	67	227	0.723	0.680	0.672	4.927	18.779	159.512	20.828	152.908	232.664	30.226
67	0	0	67	227	0.687	0.743	0.741	6.065	17.829	159.512	20.828	152.908	232.664	30.226
101	0	0	34	227	0.676	0.747	0.702	4.728	18.259	159.512	20.828	152.908	232.664	30.226
101	0	0	34	227	0.687	0.741	0.705	4.604	16.151	159.512	20.828	152.908	232.664	30.226
101	0	0	34	227	0.687	0.846	0.852	7.123	18.714	159.512	20.828	152.908	232.664	30.226
101	0	0	34	227	0.707	0.756	0.725	5.947	17.892	159.512	20.828	152.908	232.664	30.226

2013 Pittsburg

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
0	0	0	0	221	0.807	0.836	0.840	5.654	18.766	159.512	20.828	152.908	232.664	30.226
0	0	0	0	221	0.866	0.887	0.901	.	.	159.512	20.828	152.908	232.664	30.226
0	0	0	0	221	0.832	0.810	0.832	4.689	16.958	159.512	20.828	152.908	232.664	30.226
0	0	0	0	221	0.844	0.859	0.876	4.887	22.097	159.512	20.828	152.908	232.664	30.226
34	0	0	0	254	0.825	0.868	0.856	.	.	159.512	20.828	152.908	232.664	30.226
34	0	0	0	254	0.863	0.877	0.887	1.179	23.525	159.512	20.828	152.908	232.664	30.226
34	0	0	0	254	0.813	0.823	0.834	4.974	18.505	159.512	20.828	152.908	232.664	30.226
34	0	0	0	254	0.863	0.882	0.893	.	.	159.512	20.828	152.908	232.664	30.226
67	0	0	0	288	0.833	0.855	0.846	3.658	21.562	159.512	20.828	152.908	232.664	30.226
67	0	0	0	288	0.849	0.867	0.863	2.712	20.290	159.512	20.828	152.908	232.664	30.226
67	0	0	0	288	0.857	0.862	0.869	2.342	18.085	159.512	20.828	152.908	232.664	30.226
67	0	0	0	288	0.857	0.861	0.880	.	.	159.512	20.828	152.908	232.664	30.226
101	0	0	0	321	0.865	0.876	0.869	.	.	159.512	20.828	152.908	232.664	30.226
101	0	0	0	321	0.863	0.879	0.874	.	.	159.512	20.828	152.908	232.664	30.226
101	0	0	0	321	0.870	0.883	0.886	.	.	159.512	20.828	152.908	232.664	30.226
101	0	0	0	321	0.853	0.881	0.884	.	.	159.512	20.828	152.908	232.664	30.226
134	0	0	0	355	0.844	0.878	0.875	.	.	159.512	20.828	152.908	232.664	30.226
134	0	0	0	355	0.858	0.881	0.881	.	.	159.512	20.828	152.908	232.664	30.226
134	0	0	0	355	0.848	0.876	0.872	2.781	21.530	159.512	20.828	152.908	232.664	30.226
134	0	0	0	355	0.874	0.886	0.902	.	.	159.512	20.828	152.908	232.664	30.226
34	101	0	0	355	0.804	0.885	0.867	.	.	159.512	20.828	152.908	232.664	30.226
34	101	0	0	355	0.864	0.878	0.860	.	.	159.512	20.828	152.908	232.664	30.226
34	101	0	0	355	0.844	0.885	0.880	3.119	22.682	159.512	20.828	152.908	232.664	30.226
34	101	0	0	355	0.844	0.879	0.886	1.358	23.136	159.512	20.828	152.908	232.664	30.226

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
67	67	0	0	355	0.853	0.880	0.867	2.118	21.400	159.512	20.828	152.908	232.664	30.226
67	67	0	0	355	0.859	0.877	0.875	1.665	20.916	159.512	20.828	152.908	232.664	30.226
67	67	0	0	355	0.863	0.890	0.883	.	.	159.512	20.828	152.908	232.664	30.226
67	67	0	0	355	0.861	0.875	0.885	.	.	159.512	20.828	152.908	232.664	30.226
101	34	0	0	355	0.855	0.883	0.865	3.432	20.746	159.512	20.828	152.908	232.664	30.226
101	34	0	0	355	0.853	0.875	0.877	2.303	23.531	159.512	20.828	152.908	232.664	30.226
101	34	0	0	355	0.855	0.871	0.872	2.085	20.496	159.512	20.828	152.908	232.664	30.226
101	34	0	0	355	0.826	0.861	0.868	4.291	22.185	159.512	20.828	152.908	232.664	30.226
34	0	101	0	355	0.838	0.870	0.878	2.500	22.675	159.512	20.828	152.908	232.664	30.226
34	0	101	0	355	0.831	0.876	0.860	.	.	159.512	20.828	152.908	232.664	30.226
34	0	101	0	355	0.866	0.873	0.877	.	.	159.512	20.828	152.908	232.664	30.226
34	0	101	0	355	0.831	0.835	0.863	2.661	21.008	159.512	20.828	152.908	232.664	30.226
67	0	67	0	355	0.830	0.868	0.865	3.624	21.098	159.512	20.828	152.908	232.664	30.226
67	0	67	0	355	0.872	0.881	0.884	.	.	159.512	20.828	152.908	232.664	30.226
67	0	67	0	355	0.842	0.835	0.864	2.676	19.791	159.512	20.828	152.908	232.664	30.226
67	0	67	0	355	0.852	0.855	0.870	2.300	20.379	159.512	20.828	152.908	232.664	30.226
101	0	34	0	355	0.856	0.884	0.865	1.270	20.010	159.512	20.828	152.908	232.664	30.226
101	0	34	0	355	0.830	0.883	0.880	.	.	159.512	20.828	152.908	232.664	30.226
101	0	34	0	355	0.851	0.877	0.875	.	.	159.512	20.828	152.908	232.664	30.226
101	0	34	0	355	0.849	0.872	0.882	2.842	21.529	159.512	20.828	152.908	232.664	30.226
34	0	0	101	355	0.835	0.858	0.858	3.715	21.097	159.512	20.828	152.908	232.664	30.226
34	0	0	101	355	0.858	0.890	0.881	.	.	159.512	20.828	152.908	232.664	30.226
34	0	0	101	355	0.826	0.814	0.844	4.740	22.532	159.512	20.828	152.908	232.664	30.226
34	0	0	101	355	0.850	0.864	0.879	1.995	23.468	159.512	20.828	152.908	232.664	30.226
67	0	0	67	355	0.824	0.863	0.848	4.695	22.216	159.512	20.828	152.908	232.664	30.226
67	0	0	67	355	0.824	0.868	0.865	.	.	159.512	20.828	152.908	232.664	30.226
67	0	0	67	355	0.858	0.873	0.869	3.899	22.957	159.512	20.828	152.908	232.664	30.226
67	0	0	67	355	0.841	0.856	0.868	3.394	23.420	159.512	20.828	152.908	232.664	30.226
101	0	0	34	355	0.823	0.858	0.834	3.941	23.805	159.512	20.828	152.908	232.664	30.226
101	0	0	34	355	0.864	0.892	0.885	.	.	159.512	20.828	152.908	232.664	30.226
101	0	0	34	355	0.862	0.872	0.868	.	.	159.512	20.828	152.908	232.664	30.226
101	0	0	34	355	0.868	0.885	0.896	.	.	159.512	20.828	152.908	232.664	30.226

2013 Solomon

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
0	0	0	0	46	0.358	0.449	0.471	3.278	14.238	120.900	38.500	103.700	237.700	56.900
0	0	0	0	46	0.401	0.501	0.492	3.875	14.339	120.900	38.500	103.700	237.700	56.900
0	0	0	0	46	0.352	0.483	0.481	3.647	14.636	120.900	38.500	103.700	237.700	56.900
0	0	0	0	46	0.401	0.533	0.556	3.886	14.450	120.900	38.500	103.700	237.700	56.900
34	0	0	0	80	0.450	0.604	0.591	4.356	13.863	120.900	38.500	103.700	237.700	56.900
34	0	0	0	80	0.375	0.554	0.520	3.804	13.199	120.900	38.500	103.700	237.700	56.900
34	0	0	0	80	0.396	0.643	0.596	4.153	13.112	120.900	38.500	103.700	237.700	56.900
34	0	0	0	80	0.433	0.645	0.618	3.875	13.692	120.900	38.500	103.700	237.700	56.900
67	0	0	0	113	0.471	0.761	0.744	5.562	13.941	120.900	38.500	103.700	237.700	56.900
67	0	0	0	113	0.384	0.659	0.629	4.785	14.249	120.900	38.500	103.700	237.700	56.900
67	0	0	0	113	0.406	0.707	0.700	4.655	13.501	120.900	38.500	103.700	237.700	56.900
67	0	0	0	113	0.399	0.733	0.676	5.072	13.779	120.900	38.500	103.700	237.700	56.900
101	0	0	0	147	0.373	0.786	0.738	5.541	14.227	120.900	38.500	103.700	237.700	56.900
101	0	0	0	147	0.442	0.817	0.766	5.801	14.703	120.900	38.500	103.700	237.700	56.900
101	0	0	0	147	0.483	0.805	0.792	5.383	14.732	120.900	38.500	103.700	237.700	56.900
101	0	0	0	147	0.414	0.723	0.716	4.785	14.159	120.900	38.500	103.700	237.700	56.900
134	0	0	0	180	0.387	0.811	0.782	5.814	13.798	120.900	38.500	103.700	237.700	56.900
134	0	0	0	180	0.446	0.817	0.777	5.395	15.215	120.900	38.500	103.700	237.700	56.900
134	0	0	0	180	0.422	0.836	0.797	5.804	16.416	120.900	38.500	103.700	237.700	56.900
134	0	0	0	180	0.436	0.793	0.768	5.296	15.081	120.900	38.500	103.700	237.700	56.900
34	101	0	0	180	0.415	0.842	0.818	5.714	16.067	120.900	38.500	103.700	237.700	56.900
34	101	0	0	180	0.459	0.856	0.844	5.205	17.188	120.900	38.500	103.700	237.700	56.900
34	101	0	0	180	0.420	0.814	0.799	5.812	16.133	120.900	38.500	103.700	237.700	56.900
34	101	0	0	180	0.410	0.803	0.768	5.251	15.941	120.900	38.500	103.700	237.700	56.900

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield	Grain N	Pre-plant	Fall Tillering	Spring Tillering	G&D	Grain Fill
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}	g kg^{-1}	Precipitation mm				
67	67	0	0	180	0.371	0.805	0.758	4.810	14.622	120.900	38.500	103.700	237.700	56.900
67	67	0	0	180	0.437	0.849	0.831	5.871	16.847	120.900	38.500	103.700	237.700	56.900
67	67	0	0	180	0.456	0.808	0.782	5.686	15.426	120.900	38.500	103.700	237.700	56.900
67	67	0	0	180	0.403	0.778	0.732	5.140	14.380	120.900	38.500	103.700	237.700	56.900
101	34	0	0	180	0.425	0.820	0.782	5.127	15.754	120.900	38.500	103.700	237.700	56.900
101	34	0	0	180	0.406	0.827	0.802	5.737	13.751	120.900	38.500	103.700	237.700	56.900
101	34	0	0	180	0.445	0.835	0.808	5.862	16.326	120.900	38.500	103.700	237.700	56.900
101	34	0	0	180	0.428	0.827	0.785	5.473	16.151	120.900	38.500	103.700	237.700	56.900
34	0	101	0	180	0.414	0.604	0.738	6.083	15.819	120.900	38.500	103.700	237.700	56.900
34	0	101	0	180	0.408	0.638	0.756	5.761	15.603	120.900	38.500	103.700	237.700	56.900
34	0	101	0	180	0.455	0.688	0.773	5.864	16.790	120.900	38.500	103.700	237.700	56.900
34	0	101	0	180	0.412	0.579	0.749	5.503	17.260	120.900	38.500	103.700	237.700	56.900
67	0	67	0	180	0.422	0.755	0.793	6.014	16.320	120.900	38.500	103.700	237.700	56.900
67	0	67	0	180	0.458	0.723	0.777	5.491	15.433	120.900	38.500	103.700	237.700	56.900
67	0	67	0	180	0.408	0.766	0.781	5.533	15.648	120.900	38.500	103.700	237.700	56.900
67	0	67	0	180	0.396	0.705	0.774	5.671	16.573	120.900	38.500	103.700	237.700	56.900
101	0	34	0	180	0.391	0.815	0.796	5.464	15.302	120.900	38.500	103.700	237.700	56.900
101	0	34	0	180	0.391	0.752	0.773	5.566	15.054	120.900	38.500	103.700	237.700	56.900
101	0	34	0	180	0.428	0.801	0.783	5.527	15.223	120.900	38.500	103.700	237.700	56.900
101	0	34	0	180	0.433	0.796	0.789	5.401	15.242	120.900	38.500	103.700	237.700	56.900
34	0	0	101	180	0.447	0.697	0.642	6.165	18.081	120.900	38.500	103.700	237.700	56.900
34	0	0	101	180	0.455	0.656	0.680	6.181	19.528	120.900	38.500	103.700	237.700	56.900
34	0	0	101	180	0.391	0.717	0.675	6.091	19.567	120.900	38.500	103.700	237.700	56.900
34	0	0	101	180	0.417	0.742	0.709	6.014	19.081	120.900	38.500	103.700	237.700	56.900
67	0	0	67	180	0.444	0.816	0.766	6.631	17.121	120.900	38.500	103.700	237.700	56.900
67	0	0	67	180	0.401	0.757	0.729	6.369	16.866	120.900	38.500	103.700	237.700	56.900
67	0	0	67	180	0.469	0.729	0.700	6.099	16.729	120.900	38.500	103.700	237.700	56.900
67	0	0	67	180	0.352	0.784	0.777	6.375	18.739	120.900	38.500	103.700	237.700	56.900
101	0	0	34	180	0.453	0.811	0.779	5.733	15.713	120.900	38.500	103.700	237.700	56.900
101	0	0	34	180	0.474	0.787	0.766	5.727	15.584	120.900	38.500	103.700	237.700	56.900
101	0	0	34	180	0.435	0.787	0.736	5.806	15.349	120.900	38.500	103.700	237.700	56.900
101	0	0	34	180	0.426	0.786	0.745	5.769	15.678	120.900	38.500	103.700	237.700	56.900

Appendix B - Chapter 3 Winter Wheat Algorithm Raw Data

By Year and Location

2006 Manhattan

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	67.2	0	0	67.2	0.470	0.670	0.701	4.27
0	67.2	0	0	67.2	0.372	0.578	0.587	3.81
0	67.2	0	0	67.2	0.485	0.550	0.601	3.25
0	67.2	0	0	67.2	0.518	0.578	0.626	3.38
0	100.8	0	0	100.8	0.484	0.741	0.809	5.09
0	100.8	0	0	100.8	0.349	0.550	0.583	3.97
0	100.8	0	0	100.8	0.439	0.484	0.618	2.99
0	100.8	0	0	100.8	0.491	0.529	0.649	3.32
0	134.4	0	0	134.4	0.371	0.552	0.656	3.81
0	134.4	0	0	134.4	0.471	0.714	0.738	5.07
0	134.4	0	0	134.4	0.448	0.548	0.692	3.40
0	134.4	0	0	134.4	0.585	0.712	0.746	4.40
0	168	0	0	168	0.306	0.407	0.476	2.09
0	168	0	0	168	0.422	0.664	0.677	4.34
0	168	0	0	168	0.441	0.515	0.609	3.37
0	168	0	0	168	0.598	0.730	0.774	4.22
16.8	50.4	0	0	67.2	0.499	0.600	0.660	3.95
16.8	50.4	0	0	67.2	0.317	0.420	0.467	2.52
16.8	50.4	0	0	67.2	0.408	0.456	0.560	2.85
16.8	50.4	0	0	67.2	0.465	0.549	0.626	3.28
16.8	84	0	0	100.8	0.426	0.636	0.719	4.34
16.8	84	0	0	100.8	0.340	0.526	0.581	3.44
16.8	84	0	0	100.8	0.401	0.453	0.548	2.60
16.8	84	0	0	100.8	0.422	0.469	0.572	3.40
16.8	117.6	0	0	134.4	0.395	0.667	0.728	4.72
16.8	117.6	0	0	134.4	0.333	0.424	0.553	3.11
16.8	117.6	0	0	134.4	0.418	0.453	0.597	2.65
16.8	117.6	0	0	134.4	0.480	0.560	0.689	3.41

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
16.8	151.2	0	0	168	0.438	0.680	0.745	4.78
16.8	151.2	0	0	168	0.535	0.747	0.826	5.32
16.8	151.2	0	0	168	0.392	0.446	0.545	2.43
16.8	151.2	0	0	168	0.448	0.484	0.593	3.37
33.6	33.6	0	0	67.2	0.479	0.681	0.706	4.52
33.6	33.6	0	0	67.2	0.360	0.504	0.621	3.25
33.6	33.6	0	0	67.2	0.399	0.446	0.535	2.64
33.6	33.6	0	0	67.2	0.504	0.577	0.657	3.31
33.6	67.2	0	0	100.8	0.459	0.706	0.759	4.86
33.6	67.2	0	0	100.8	0.482	0.732	0.775	5.21
33.6	67.2	0	0	100.8	0.409	0.486	0.587	2.95
33.6	67.2	0	0	100.8	0.502	0.569	0.687	3.51
33.6	100.8	0	0	134.4	0.467	0.692	0.736	4.58
33.6	100.8	0	0	134.4	0.498	0.733	0.704	5.11
33.6	100.8	0	0	134.4	0.439	0.479	0.596	2.77
33.6	100.8	0	0	134.4	0.457	0.572	0.655	3.74
33.6	134.4	0	0	168	0.369	0.507	0.608	3.18
33.6	134.4	0	0	168	0.386	0.645	0.658	4.25
33.6	134.4	0	0	168	0.479	0.543	0.681	3.18
33.6	134.4	0	0	168	0.540	0.686	0.736	4.14
67.2	0	0	0	67.2	0.318	0.391	0.505	2.28
67.2	0	0	0	67.2	0.434	0.625	0.643	3.47
67.2	0	0	0	67.2	0.418	0.470	0.591	2.93
67.2	0	0	0	67.2	0.508	0.597	0.648	3.35
67.2	33.6	0	0	100.8	0.473	0.689	0.695	3.99
67.2	33.6	0	0	100.8	0.545	0.762	0.789	5.38
67.2	33.6	0	0	100.8	0.513	0.594	0.672	3.44
67.2	33.6	0	0	100.8	0.411	0.500	0.588	3.14
67.2	67.2	0	0	134.4	0.427	0.676	0.745	4.81
67.2	67.2	0	0	134.4	0.384	0.686	0.672	4.65
67.2	67.2	0	0	134.4	0.481	0.583	0.682	3.45
67.2	67.2	0	0	134.4	0.474	0.535	0.641	3.18

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
67.2	100.8	0	0	168	0.432	0.645	0.680	4.36
67.2	100.8	0	0	168	0.423	0.686	0.731	4.67
67.2	100.8	0	0	168	0.467	0.535	0.622	
67.2	100.8	0	0	168	0.625	0.778	0.761	4.48
100.8	0	0	0	100.8	0.486	0.708	0.777	5.16
100.8	0	0	0	100.8	0.464	0.739	0.744	4.34
100.8	0	0	0	100.8	0.497	0.545	0.659	3.32
100.8	0	0	0	100.8	0.463	0.537	0.635	2.98
100.8	33.6	0	0	134.4	0.450	0.710	0.780	4.94
100.8	33.6	0	0	134.4	0.432	0.731	0.739	4.62
100.8	33.6	0	0	134.4	0.439	0.581	0.677	3.33
100.8	33.6	0	0	134.4	0.498	0.560	0.682	3.50
100.8	67.2	0	0	168	0.602	0.825	0.825	5.67
100.8	67.2	0	0	168	0.554	0.814	0.817	5.50
100.8	67.2	0	0	168	0.311	0.330	0.458	1.93
100.8	67.2	0	0	168	0.507	0.646	0.709	4.03
134.4	0	0	0	134.4	0.509	0.775	0.804	4.96
134.4	0	0	0	134.4	0.360	0.567	0.761	4.04
134.4	0	0	0	134.4	0.530	0.634	0.715	3.75
134.4	0	0	0	134.4	0.461	0.576	0.657	3.63
134.4	33.6	0	0	168	0.404	0.663	0.785	4.67
134.4	33.6	0	0	168	0.413	0.627	0.729	3.87
134.4	33.6	0	0	168	0.532	0.700	0.764	3.90
134.4	33.6	0	0	168	0.546	0.695	0.744	4.11
168	0	0	0	168	0.574	0.825	0.838	5.61
168	0	0	0	168	0.389	0.620	0.646	4.53
168	0	0	0	168	.	0.541	.	.
168	0	0	0	168	0.501	0.670	0.722	4.16

2007 Manhattan

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	0	0.466	.	.	3.05
0	0	0	0	0	0.440	.	.	2.85
0	0	0	0	0	0.468	.	.	3.23
0	0	0	0	0	0.451	.	.	3.06
0	33.6	0	0	33.6	0.419	.	.	3.08
0	33.6	0	0	33.6	0.425	.	.	3.06
0	33.6	0	0	33.6	0.460	.	.	3.43
0	33.6	0	0	33.6	0.428	.	.	3.10
33.6	0	0	0	33.6	0.438	.	.	3.03
33.6	0	0	0	33.6	0.427	.	.	3.15
33.6	0	0	0	33.6	0.501	.	.	3.39
33.6	0	0	0	33.6	0.461	.	.	3.06
0	67.2	0	0	67.2	0.451	.	.	3.07
0	67.2	0	0	67.2	0.455	.	.	2.76
0	67.2	0	0	67.2	0.455	.	.	3.15
0	67.2	0	0	67.2	0.470	.	.	3.49
16.8	50.4	0	0	67.2	0.474	.	.	2.95
16.8	50.4	0	0	67.2	0.466	.	.	3.12
16.8	50.4	0	0	67.2	0.472	.	.	3.09
16.8	50.4	0	0	67.2	0.482	.	.	3.31
33.6	33.6	0	0	67.2	0.430	.	.	2.83
33.6	33.6	0	0	67.2	0.429	.	.	3.19
33.6	33.6	0	0	67.2	0.427	.	.	2.60
33.6	33.6	0	0	67.2	0.437	.	.	2.99
67.2	0	0	0	67.2	0.460	.	.	3.11
67.2	0	0	0	67.2	0.431	.	.	3.05
67.2	0	0	0	67.2	0.468	.	.	2.84
67.2	0	0	0	67.2	0.434	.	.	3.15

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	100.8	0	0	100.8	0.463	.	.	2.92
0	100.8	0	0	100.8	0.492	.	.	3.34
0	100.8	0	0	100.8	0.429	.	.	2.98
0	100.8	0	0	100.8	0.524	.	.	3.65
16.8	84	0	0	100.8	0.496	.	.	2.66
16.8	84	0	0	100.8	0.469	.	.	3.30
16.8	84	0	0	100.8	0.452	.	.	.
16.8	84	0	0	100.8	0.484	.	.	3.48
33.6	67.2	0	0	100.8	0.485	.	.	2.86
33.6	67.2	0	0	100.8	0.490	.	.	3.19
33.6	67.2	0	0	100.8	0.489	.	.	2.82
33.6	67.2	0	0	100.8	0.484	.	.	3.04
67.2	33.6	0	0	100.8	0.512	.	.	3.17
67.2	33.6	0	0	100.8	0.478	.	.	3.08
67.2	33.6	0	0	100.8	0.522	.	.	2.98
67.2	33.6	0	0	100.8	0.455	.	.	3.26
100.8	0	0	0	100.8	0.493	.	.	2.90
100.8	0	0	0	100.8	0.498	.	.	3.21
100.8	0	0	0	100.8	0.418	.	.	2.94
100.8	0	0	0	100.8	0.475	.	.	3.57
0	134.4	0	0	134.4	0.452	.	.	2.56
0	134.4	0	0	134.4	0.396	.	.	2.49
0	134.4	0	0	134.4	0.479	.	.	2.85
0	134.4	0	0	134.4	0.461	.	.	2.75
16.8	117.6	0	0	134.4	0.501	.	.	2.70
16.8	117.6	0	0	134.4	0.429	.	.	2.73
16.8	117.6	0	0	134.4	0.441	.	.	2.86
16.8	117.6	0	0	134.4	0.507	.	.	2.98

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
33.6	100.8	0	0	134.4	0.514	.	.	2.85
33.6	100.8	0	0	134.4	0.478	.	.	2.78
33.6	100.8	0	0	134.4	0.438	.	.	2.41
33.6	100.8	0	0	134.4	0.432	.	.	3.27
67.2	67.2	0	0	134.4	0.488	.	.	2.59
67.2	67.2	0	0	134.4	0.482	.	.	2.94
67.2	67.2	0	0	134.4	0.566	.	.	2.84
67.2	67.2	0	0	134.4	0.480	.	.	3.47
100.8	33.6	0	0	134.4	0.559	.	.	2.83
100.8	33.6	0	0	134.4	0.513	.	.	3.00
100.8	33.6	0	0	134.4	0.449	.	.	2.81
100.8	33.6	0	0	134.4	0.454	.	.	3.31
134.4	0	0	0	134.4	0.459	.	.	2.93
134.4	0	0	0	134.4	0.471	.	.	2.87
134.4	0	0	0	134.4	0.453	.	.	3.10
134.4	0	0	0	134.4	0.433	.	.	3.25
134.4	33.6	0	0	168	0.471	.	.	2.69
134.4	33.6	0	0	168	0.439	.	.	2.69
134.4	33.6	0	0	168	0.473	.	.	2.82
134.4	33.6	0	0	168	0.495	.	.	2.97
168	0	0	0	168	0.522	.	.	2.98
168	0	0	0	168	0.462	.	.	2.87
168	0	0	0	168	0.454	.	.	2.86
168	0	0	0	168	0.453	.	.	3.08

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Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}
0	100.8	0	0	100.8	0.820	.	.	3.54
0	100.8	0	0	100.8	0.767	.	.	3.81
0	100.8	0	0	100.8	0.791	.	.	3.90
0	100.8	0	0	100.8	0.805	.	.	4.11
16.8	84	0	0	100.8	0.834	.	.	3.86
16.8	84	0	0	100.8	0.847	.	.	3.24
16.8	84	0	0	100.8	0.851	.	.	3.65
16.8	84	0	0	100.8	0.821	.	.	3.33
33.6	67.2	0	0	100.8	0.790	.	.	4.10
33.6	67.2	0	0	100.8	0.761	.	.	4.06
33.6	67.2	0	0	100.8	0.846	.	.	3.68
33.6	67.2	0	0	100.8	0.838	.	.	3.59
67.2	33.6	0	0	100.8	0.803	.	.	4.08
67.2	33.6	0	0	100.8	0.822	.	.	3.82
67.2	33.6	0	0	100.8	0.850	.	.	3.05
67.2	33.6	0	0	100.8	0.837	.	.	3.45
100.8	0	0	0	100.8	0.829	.	.	3.71
100.8	0	0	0	100.8	0.819	.	.	3.76
100.8	0	0	0	100.8	0.834	.	.	3.98
100.8	0	0	0	100.8	0.794	.	.	3.78
0	134.4	0	0	134.4	0.838	.	.	3.94
0	134.4	0	0	134.4	0.792	.	.	3.45
0	134.4	0	0	134.4	0.812	.	.	2.91
0	134.4	0	0	134.4	0.822	.	.	3.28
16.8	117.6	0	0	134.4	0.786	.	.	3.64
16.8	117.6	0	0	134.4	0.812	.	.	3.56
16.8	117.6	0	0	134.4	0.841	.	.	3.13
16.8	117.6	0	0	134.4	0.848	.	.	2.86

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}
33.6	100.8	0	0	134.4	0.836	.	.	3.26
33.6	100.8	0	0	134.4	0.837	.	.	3.26
33.6	100.8	0	0	134.4	0.805	.	.	3.72
33.6	100.8	0	0	134.4	0.811	.	.	3.15
67.2	67.2	0	0	134.4	0.833	.	.	3.54
67.2	67.2	0	0	134.4	0.846	.	.	3.20
67.2	67.2	0	0	134.4	0.820	.	.	3.74
67.2	67.2	0	0	134.4	0.840	.	.	3.69
100.8	33.6	0	0	134.4	0.854	.	.	3.37
100.8	33.6	0	0	134.4	0.827	.	.	3.46
100.8	33.6	0	0	134.4	0.831	.	.	3.84
100.8	33.6	0	0	134.4	0.803	.	.	3.40
134.4	0	0	0	134.4	0.824	.	.	3.91
134.4	0	0	0	134.4	0.866	.	.	2.77
134.4	0	0	0	134.4	0.829	.	.	3.73
134.4	0	0	0	134.4	0.861	.	.	3.50
134.4	33.6	0	0	168	0.833	.	.	3.39
134.4	33.6	0	0	168	0.799	.	.	3.13
134.4	33.6	0	0	168	0.862	.	.	2.98
134.4	33.6	0	0	168	0.860	.	.	3.05
168	0	0	0	168	0.847	.	.	3.34
168	0	0	0	168	0.864	.	.	2.58
168	0	0	0	168	0.828	.	.	3.71
168	0	0	0	168	0.863	.	.	3.12

2008 Johnson Irrigation

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	0	0.168	.	0.262	1.05
0	0	0	0	0	0.170	.	0.311	1.21
0	0	0	0	0	0.156	.	0.269	0.87
0	0	0	0	0	0.185	.	0.292	1.13
0	33.6	0	0	33.6	0.201	.	0.468	1.65
0	33.6	0	0	33.6	0.200	.	0.495	1.92
0	33.6	0	0	33.6	0.210	.	0.432	1.63
0	33.6	0	0	33.6	0.224	.	0.505	1.68
0	67.2	0	0	67.2	0.244	.	0.619	1.55
0	67.2	0	0	67.2	0.226	.	0.666	1.93
0	67.2	0	0	67.2	0.189	.	0.600	2.35
0	67.2	0	0	67.2	0.170	.	0.518	1.34
0	100.8	0	0	100.8	0.222	.	0.656	1.62
0	100.8	0	0	100.8	0.224	.	0.658	2.18
0	100.8	0	0	100.8	0.175	.	0.581	1.52
0	100.8	0	0	100.8	0.202	.	0.590	1.70
0	134.4	0	0	134.4	0.202	.	0.646	1.62
0	134.4	0	0	134.4	0.195	.	0.671	2.37
0	134.4	0	0	134.4	0.215	.	0.694	2.01
0	134.4	0	0	134.4	0.231	.	0.621	1.14
0	0	0	33.6	33.6	0.168	.	0.316	1.09
0	0	0	33.6	33.6	0.170	.	0.347	1.96
0	0	0	33.6	33.6	0.149	.	0.235	1.09
0	0	0	33.6	33.6	0.199	.	0.296	1.72
0	0	0	67.2	67.2	0.171	.	0.251	1.12
0	0	0	67.2	67.2	0.167	.	0.231	0.79
0	0	0	67.2	67.2	0.172	.	0.289	1.07
0	0	0	67.2	67.2	0.186	.	0.225	1.35

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
33.6	0	0	0	33.6	0.220	.	0.535	1.49
33.6	0	0	0	33.6	0.234	.	0.418	2.10
33.6	0	0	0	33.6	0.202	.	0.439	1.67
33.6	0	0	0	33.6	0.232	.	0.483	1.48
33.6	33.6	0	0	67.2	0.237	.	0.589	2.60
33.6	33.6	0	0	67.2	0.242	.	0.604	2.25
33.6	33.6	0	0	67.2	0.226	.	0.543	1.90
33.6	33.6	0	0	67.2	0.219	.	0.495	2.05
33.6	67.2	0	0	100.8	0.187	.	0.596	2.28
33.6	67.2	0	0	100.8	0.234	.	0.590	1.87
33.6	67.2	0	0	100.8	0.263	.	0.735	2.34
33.6	67.2	0	0	100.8	0.204	.	0.591	1.17
33.6	100.8	0	0	134.4	0.216	.	0.678	2.19
33.6	100.8	0	0	134.4	0.276	.	0.733	2.38
33.6	100.8	0	0	134.4	0.228	.	0.670	1.88
33.6	100.8	0	0	134.4	0.230	.	0.591	1.45
33.6	0	0	33.6	67.2	0.206	.	0.469	1.25
33.6	0	0	33.6	67.2	0.260	.	0.469	2.58
33.6	0	0	33.6	67.2	0.214	.	0.433	1.26
33.6	0	0	33.6	67.2	0.198	.	0.464	1.69
33.6	0	0	67.2	100.8	0.181	.	0.442	1.34
33.6	0	0	67.2	100.8	0.248	.	0.427	2.22
33.6	0	0	67.2	100.8	0.230	.	0.427	1.52
33.6	0	0	67.2	100.8	0.197	.	0.360	1.57
33.6	0	0	100.8	134.4	0.221	.	0.509	1.64
33.6	0	0	100.8	134.4	0.216	.	0.544	2.17
33.6	0	0	100.8	134.4	0.214	.	0.380	1.31
33.6	0	0	100.8	134.4	0.194	.	0.374	.

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
67.2	0	0	0	67.2	0.253	.	0.523	1.72
67.2	0	0	0	67.2	0.230	.	0.580	2.94
67.2	0	0	0	67.2	0.247	.	0.510	1.82
67.2	0	0	0	67.2	0.211	.	0.517	1.57
67.2	0	0	33.6	100.8	0.233	.	0.530	1.59
67.2	0	0	33.6	100.8	0.250	.	0.535	2.28
67.2	0	0	33.6	100.8	0.233	.	0.615	.
67.2	0	0	33.6	100.8	0.239	.	0.537	.
67.2	0	0	67.2	134.4	0.195	.	0.488	1.28
67.2	0	0	67.2	134.4	0.244	.	0.561	2.29
67.2	0	0	67.2	134.4	0.180	.	0.489	.
67.2	0	0	67.2	134.4	0.198	.	0.602	3.46
100.8	0	0	0	100.8	0.183	.	0.607	1.37
100.8	0	0	0	100.8	0.238	.	0.681	2.50
100.8	0	0	0	100.8	0.216	.	0.654	1.89
100.8	0	0	0	100.8	0.281	.	0.681	2.46
100.8	0	0	33.6	134.4	0.231	.	0.616	1.77
100.8	0	0	33.6	134.4	0.230	.	0.684	2.41
100.8	0	0	33.6	134.4	0.220	.	0.637	.
100.8	0	0	33.6	134.4	0.208	.	0.571	.
134.4	0	0	0	134.4	0.208	.	0.586	1.65
134.4	0	0	0	134.4	0.221	.	0.601	2.16
134.4	0	0	0	134.4	0.246	.	0.634	1.51
134.4	0	0	0	134.4	0.238	.	0.728	3.68

2008 Manhattan

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	0	0.347	0.609	0.651	1.46
0	0	0	0	0	0.243	0.486	0.556	1.64
0	0	0	0	0	0.263	0.549	0.618	1.84
0	0	0	0	0	0.336	0.578	0.580	1.11
0	33.6	0	0	33.6	0.323	0.741	0.788	1.69
0	33.6	0	0	33.6	0.261	0.730	0.791	2.82
0	33.6	0	0	33.6	0.328	0.759	0.780	1.18
0	33.6	0	0	33.6	0.271	0.730	0.793	1.95
0	67.2	0	0	67.2	0.322	0.762	0.818	2.04
0	67.2	0	0	67.2	0.375	0.810	0.823	1.51
0	67.2	0	0	67.2	0.289	0.780	0.818	2.60
0	67.2	0	0	67.2	0.305	0.786	0.815	1.93
0	100.8	0	0	100.8	0.328	0.702	0.748	1.31
0	100.8	0	0	100.8	0.287	0.766	0.814	2.66
0	100.8	0	0	100.8	0.262	0.769	0.837	2.62
0	100.8	0	0	100.8	0.364	0.820	0.830	0.91
0	134.4	0	0	134.4	0.293	0.804	0.847	2.11
0	134.4	0	0	134.4	0.267	0.775	0.842	2.09
0	134.4	0	0	134.4	0.312	0.814	0.840	1.51
0	134.4	0	0	134.4	0.302	0.777	0.847	2.49
0	0	0	33.6	33.6	0.264	0.538	0.615	2.09
0	0	0	33.6	33.6	0.272	0.601	0.684	1.86
0	0	0	33.6	33.6	0.291	0.521	0.571	1.42
0	0	0	33.6	33.6	0.288	0.548	0.568	1.73
0	0	0	67.2	67.2	0.314	0.625	0.699	2.11
0	0	0	67.2	67.2	0.298	0.554	0.627	1.44
0	0	0	67.2	67.2	0.276	0.567	0.618	2.22
0	0	0	67.2	67.2	0.373	0.625	0.642	0.95

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}
33.6	0	0	0	33.6	0.302	0.699	0.751	2.17
33.6	0	0	0	33.6	0.356	0.696	0.763	1.84
33.6	0	0	0	33.6	0.310	0.680	0.743	1.89
33.6	0	0	0	33.6	0.336	0.673	0.713	1.62
33.6	33.6	0	0	67.2	0.363	0.779	0.810	1.89
33.6	33.6	0	0	67.2	0.396	0.737	0.782	0.98
33.6	33.6	0	0	67.2	0.348	0.781	0.811	1.98
33.6	33.6	0	0	67.2	0.352	0.820	0.813	2.29
33.6	67.2	0	0	100.8	0.334	0.811	0.836	2.42
33.6	67.2	0	0	100.8	0.352	0.797	0.825	1.69
33.6	67.2	0	0	100.8	0.309	0.795	0.833	2.22
33.6	67.2	0	0	100.8	0.332	0.802	0.841	2.62
33.6	100.8	0	0	134.4	0.334	0.801	0.839	2.00
33.6	100.8	0	0	134.4	0.316	0.801	0.850	2.64
33.6	100.8	0	0	134.4	0.327	0.817	0.847	2.44
33.6	100.8	0	0	134.4	0.385	0.842	0.852	1.89
33.6	0	0	33.6	67.2	0.281	0.636	0.701	2.33
33.6	0	0	33.6	67.2	0.352	0.679	0.722	1.44
33.6	0	0	33.6	67.2	0.268	0.614	0.675	2.55
33.6	0	0	33.6	67.2	0.374	0.673	0.682	1.71
33.6	0	0	67.2	100.8	0.295	0.668	0.746	2.57
33.6	0	0	67.2	100.8	0.402	0.702	0.715	0.00
33.6	0	0	67.2	100.8	0.295	0.652	0.716	2.24
33.6	0	0	67.2	100.8	0.315	0.668	0.716	2.24
33.6	0	0	100.8	134.4	0.305	0.645	0.695	2.35
33.6	0	0	100.8	134.4	0.311	0.684	0.743	2.29
33.6	0	0	100.8	134.4	0.314	0.670	0.705	2.15
33.6	0	0	100.8	134.4	0.400	0.707	0.711	1.78

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
67.2	0	0	0	67.2	0.427	0.756	0.791	1.62
67.2	0	0	0	67.2	0.304	0.727	0.804	2.46
67.2	0	0	0	67.2	0.352	0.739	0.808	2.02
67.2	0	0	0	67.2	0.290	0.678	0.727	2.31
67.2	0	0	33.6	100.8	0.370	0.746	0.782	2.26
67.2	0	0	33.6	100.8	0.307	0.715	0.781	2.73
67.2	0	0	33.6	100.8	0.309	0.737	0.811	2.11
67.2	0	0	33.6	100.8	0.339	0.695	0.713	2.35
67.2	0	0	67.2	134.4	0.340	0.762	0.791	2.46
67.2	0	0	67.2	134.4	0.319	0.753	0.806	2.95
67.2	0	0	67.2	134.4	0.307	0.759	0.806	2.04
67.2	0	0	67.2	134.4	0.359	0.741	0.764	1.22
100.8	0	0	0	100.8	0.300	0.771	0.824	2.49
100.8	0	0	0	100.8	0.396	0.830	0.834	2.15
100.8	0	0	0	100.8	0.311	0.730	0.782	2.24
100.8	0	0	0	100.8	0.390	0.775	0.780	1.82
100.8	0	0	33.6	134.4	0.352	0.782	0.802	2.13
100.8	0	0	33.6	134.4	0.437	0.784	0.803	1.51
100.8	0	0	33.6	134.4	0.267	0.724	0.798	2.82
100.8	0	0	33.6	134.4	0.354	0.775	0.805	2.29
134.4	0	0	0	134.4	0.375	0.796	0.822	1.69
134.4	0	0	0	134.4	0.328	0.787	0.815	2.69
134.4	0	0	0	134.4	0.328	0.759	0.803	2.73
134.4	0	0	0	134.4	0.297	0.784	0.841	2.64

2008 Partridge

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	0	0.479	.	0.574	3.45
0	0	0	0	0	0.511	.	0.535	3.14
0	0	0	0	0	0.503	.	0.525	3.39
0	0	0	0	0	0.433	.	0.427	2.56
0	33.6	0	0	33.6	0.618	.	0.738	5.00
0	33.6	0	0	33.6	0.564	.	0.660	4.25
0	33.6	0	0	33.6	0.494	.	0.662	4.02
0	33.6	0	0	33.6	0.520	.	0.612	3.69
0	67.2	0	0	67.2	0.517	.	0.675	4.36
0	67.2	0	0	67.2	0.556	.	0.697	4.37
0	67.2	0	0	67.2	0.450	.	0.645	4.18
0	67.2	0	0	67.2	0.466	.	0.651	4.12
0	100.8	0	0	100.8	0.598	.	0.789	4.99
0	100.8	0	0	100.8	0.591	.	0.770	4.65
0	100.8	0	0	100.8	0.569	.	0.742	4.51
0	100.8	0	0	100.8	0.435	.	0.728	4.18
0	134.4	0	0	134.4	0.490	.	0.742	4.52
0	134.4	0	0	134.4	0.508	.	0.777	4.60
0	134.4	0	0	134.4	0.580	.	0.800	4.65
0	134.4	0	0	134.4	0.436	.	0.722	4.31
0	0	0	33.6	33.6	0.531	.	0.559	3.53
0	0	0	33.6	33.6	0.443	.	0.499	3.27
0	0	0	33.6	33.6	0.543	.	0.574	3.35
0	0	0	33.6	33.6	0.471	.	0.431	3.19
0	0	0	67.2	67.2	0.607	.	0.654	3.96
0	0	0	67.2	67.2	0.546	.	0.590	3.85
0	0	0	67.2	67.2	0.473	.	0.563	3.97
0	0	0	67.2	67.2	0.476	.	0.511	3.71

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
33.6	0	0	0	33.6	0.532	.	0.629	3.51
33.6	0	0	0	33.6	0.594	.	0.721	4.72
33.6	0	0	0	33.6	0.507	.	0.559	3.37
33.6	0	0	0	33.6	0.433	.	0.469	3.15
33.6	33.6	0	0	67.2	0.598	.	0.742	4.08
33.6	33.6	0	0	67.2	0.581	.	0.740	4.52
33.6	33.6	0	0	67.2	0.535	.	0.731	4.13
33.6	33.6	0	0	67.2	0.420	.	0.602	3.70
33.6	67.2	0	0	100.8	0.656	.	0.795	5.17
33.6	67.2	0	0	100.8	0.557	.	0.754	4.97
33.6	67.2	0	0	100.8	0.571	.	0.760	4.75
33.6	67.2	0	0	100.8	0.515	.	0.714	4.35
33.6	100.8	0	0	134.4	0.640	.	0.780	5.09
33.6	100.8	0	0	134.4	0.589	.	0.814	5.38
33.6	100.8	0	0	134.4	0.533	.	0.762	4.80
33.6	100.8	0	0	134.4	0.561	.	0.734	4.75
33.6	0	0	33.6	67.2	0.699	.	0.771	5.47
33.6	0	0	33.6	67.2	0.572	.	0.666	4.20
33.6	0	0	33.6	67.2	0.655	.	0.682	3.94
33.6	0	0	33.6	67.2	0.503	.	0.518	3.63
33.6	0	0	67.2	100.8	0.571	.	0.660	3.85
33.6	0	0	67.2	100.8	0.609	.	0.678	4.05
33.6	0	0	67.2	100.8	0.468	.	0.542	4.02
33.6	0	0	67.2	100.8	0.537	.	0.583	3.92
33.6	0	0	100.8	134.4	0.646	.	0.754	4.32
33.6	0	0	100.8	134.4	0.667	.	0.746	4.05
33.6	0	0	100.8	134.4	0.574	.	0.533	4.17
33.6	0	0	100.8	134.4	0.504	.	0.616	3.88

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
67.2	0	0	0	67.2	0.535	.	0.672	3.99
67.2	0	0	0	67.2	0.666	.	0.791	4.33
67.2	0	0	0	67.2	0.556	.	0.677	4.10
67.2	0	0	0	67.2	0.475	.	0.558	3.92
67.2	0	0	33.6	100.8	0.603	.	0.752	4.55
67.2	0	0	33.6	100.8	0.650	.	0.756	4.81
67.2	0	0	33.6	100.8	0.534	.	0.588	4.40
67.2	0	0	33.6	100.8	0.568	.	0.533	3.90
67.2	0	0	67.2	134.4	0.607	.	0.715	4.45
67.2	0	0	67.2	134.4	0.645	.	0.736	4.52
67.2	0	0	67.2	134.4	0.558	.	0.639	4.52
67.2	0	0	67.2	134.4	0.501	.	0.536	4.25
100.8	0	0	0	100.8	0.634	.	0.738	5.35
100.8	0	0	0	100.8	0.654	.	0.812	4.76
100.8	0	0	0	100.8	0.550	.	0.664	4.87
100.8	0	0	0	100.8	0.553	.	0.597	4.59
100.8	0	0	33.6	134.4	0.661	.	0.802	4.79
100.8	0	0	33.6	134.4	0.698	.	0.826	5.23
100.8	0	0	33.6	134.4	0.654	.	0.646	4.63
100.8	0	0	33.6	134.4	0.577	.	0.714	4.44
134.4	0	0	0	134.4	0.571	.	0.763	4.37
134.4	0	0	0	134.4	0.744	.	0.846	4.49
134.4	0	0	0	134.4	0.650	.	0.798	4.38
134.4	0	0	0	134.4	0.535	.	0.682	5.30

2009 Johnson Hanke

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	0	0.279	.	0.340	1.43
0	0	0	0	0	0.269	.	0.354	1.28
0	0	0	0	0	0.250	.	0.300	0.75
0	0	0	0	0	0.238	.	0.272	0.73
134.4	0	0	0	134.4	0.306	.	0.483	1.77
134.4	0	0	0	134.4	0.342	.	0.621	1.75
134.4	0	0	0	134.4	0.324	.	0.511	1.13
134.4	0	0	0	134.4	0.290	.	0.484	1.12
33.6	0	0	0	33.6	0.276	.	0.379	1.48
33.6	0	0	0	33.6	0.274	.	0.398	1.10
33.6	0	0	0	33.6	0.299	.	0.447	0.71
33.6	0	0	0	33.6	0.229	.	0.330	0.59
0	33.6	0	0	33.6	0.297	.	0.425	1.47
0	33.6	0	0	33.6	0.278	.	0.444	1.43
0	33.6	0	0	33.6	0.326	.	0.519	0.87
0	33.6	0	0	33.6	0.249	.	0.426	0.76

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	67.2	0	0	67.2	0.303	.	0.489	1.75
0	67.2	0	0	67.2	0.332	.	0.587	1.60
0	67.2	0	0	67.2	0.278	.	0.495	0.78
0	67.2	0	0	67.2	0.261	.	0.473	0.82
0	100.8	0	0	100.8	0.304	.	0.507	1.65
0	100.8	0	0	100.8	0.300	.	0.528	1.55
0	100.8	0	0	100.8	0.344	.	0.658	1.06
0	100.8	0	0	100.8	0.300	.	0.582	1.16
33.6	33.6	0	0	67.2	0.315	.	0.479	1.71
33.6	33.6	0	0	67.2	0.293	.	0.546	1.44
33.6	33.6	0	0	67.2	0.358	.	0.606	1.07
33.6	33.6	0	0	67.2	0.289	.	0.501	0.97
33.6	67.2	0	0	100.8	0.278	.	0.480	1.75
33.6	67.2	0	0	100.8	0.322	.	0.581	1.56
33.6	67.2	0	0	100.8	0.343	.	0.642	1.21
33.6	67.2	0	0	100.8	0.302	.	0.529	1.07

2009 Manhattan

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	0	0.231	.	0.736	3.71
0	0	0	0	0	0.238	.	0.711	3.27
0	0	0	0	0	0.222	.	0.709	2.87
0	0	0	0	0	0.239	.	0.695	3.25
134.4	0	0	0	134.4	0.237	.	0.880	5.48
134.4	0	0	0	134.4	0.252	.	0.902	5.68
134.4	0	0	0	134.4	0.225	.	0.888	4.65
134.4	0	0	0	134.4	0.265	.	0.896	5.11
33.6	0	0	0	33.6	0.262	.	0.886	5.92
33.6	0	0	0	33.6	0.240	.	0.871	5.28
33.6	0	0	0	33.6	0.224	.	0.860	5.24
33.6	0	0	0	33.6	0.220	.	0.864	5.18
0	33.6	0	0	33.6	0.230	.	0.818	4.79
0	33.6	0	0	33.6	0.297	.	0.791	4.07
0	33.6	0	0	33.6	0.226	.	0.853	4.73
0	33.6	0	0	33.6	0.223	.	0.845	5.29
0	67.2	0	0	67.2	0.245	.	0.880	5.90
0	67.2	0	0	67.2	0.231	.	0.885	6.00
0	67.2	0	0	67.2	0.220	.	0.870	5.43
0	67.2	0	0	67.2	0.229	.	0.868	5.29
0	100.8	0	0	100.8	0.232	.	0.880	5.29
0	100.8	0	0	100.8	0.226	.	0.871	4.71
0	100.8	0	0	100.8	0.227	.	0.889	5.26
0	100.8	0	0	100.8	0.243	.	0.879	5.47
33.6	33.6	0	0	67.2	0.238	.	0.842	5.07
33.6	33.6	0	0	67.2	0.253	.	0.839	4.42
33.6	33.6	0	0	67.2	0.231	.	0.874	5.45
33.6	33.6	0	0	67.2	0.233	.	0.860	4.86

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
33.6	0	67.2	0	100.8	0.250	.	0.847	5.82
33.6	0	67.2	0	100.8	0.253	.	0.803	5.45
33.6	0	67.2	0	100.8	0.218	.	0.811	5.09
33.6	0	67.2	0	100.8	0.250	.	0.754	4.97
33.6	0	0	33.6	67.2	0.236	.	0.845	4.94
33.6	0	0	33.6	67.2	0.243	.	0.836	4.79
33.6	0	0	33.6	67.2	0.218	.	0.830	4.81
33.6	0	0	33.6	67.2	0.223	.	0.775	4.18
33.6	0	0	67.2	100.8	0.241	.	0.778	4.09
33.6	0	0	67.2	100.8	0.235	.	0.785	4.00
33.6	0	0	67.2	100.8	0.257	.	0.833	5.10
33.6	0	0	67.2	100.8	0.220	.	0.764	4.30

2009 Partridge

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
N Rate kg ha^{-1}					Red NDVI			Mg ha^{-1}
0	0	0	0	0	0.366	.	.	0.99
0	0	0	0	0	0.368	.	.	1.46
0	0	0	0	0	0.471	.	.	1.73
0	0	0	0	0	0.371	.	.	1.48
134.4	0	0	0	134.4	0.536	.	.	2.75
134.4	0	0	0	134.4	0.415	.	.	3.22
134.4	0	0	0	134.4	0.509	.	.	2.85
134.4	0	0	0	134.4	0.425	.	.	2.85
33.6	0	0	0	33.6	0.384	.	.	1.75
33.6	0	0	0	33.6	0.399	.	.	2.18
33.6	0	0	0	33.6	0.380	.	.	2.09
33.6	0	0	0	33.6	0.504	.	.	2.73
0	33.6	0	0	33.6	0.387	.	.	2.12
0	33.6	0	0	33.6	0.394	.	.	2.05
0	33.6	0	0	33.6	0.410	.	.	2.00
0	33.6	0	0	33.6	0.456	.	.	2.79

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	67.2	0	0	67.2	0.346	.	.	2.16
0	67.2	0	0	67.2	0.387	.	.	2.72
0	67.2	0	0	67.2	0.505	.	.	2.53
0	67.2	0	0	67.2	0.381	.	.	2.52
0	100.8	0	0	100.8	0.354	.	.	2.59
0	100.8	0	0	100.8	0.486	.	.	2.83
0	100.8	0	0	100.8	0.387	.	.	2.97
0	100.8	0	0	100.8	0.417	.	.	2.75
33.6	33.6	0	0	67.2	0.409	.	.	2.47
33.6	33.6	0	0	67.2	0.470	.	.	3.17
33.6	33.6	0	0	67.2	0.403	.	.	2.75
33.6	33.6	0	0	67.2	0.390	.	.	2.72
33.6	67.2	0	0	100.8	0.421	.	.	2.47
33.6	67.2	0	0	100.8	0.397	.	.	2.69
33.6	67.2	0	0	100.8	0.397	.	.	3.09
33.6	67.2	0	0	100.8	0.413	.	.	2.87

2010 Johnson

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	0	0.439	.	0.664	4.59
0	0	0	0	0	0.508	.	0.722	4.92
0	0	0	0	0	0.440	.	0.636	4.37
0	0	0	0	0	0.479	.	0.688	4.59
140	0	0	0	140	0.476	.	0.786	4.82
140	0	0	0	140	0.478	.	0.748	4.48
140	0	0	0	140	0.527	.	0.767	4.27
140	0	0	0	140	0.538	.	0.796	4.41
28	0	0	0	28	0.485	.	0.734	4.68
28	0	0	0	28	0.512	.	0.760	5.11
28	0	0	0	28	0.498	.	0.699	4.18
28	0	0	0	28	0.561	.	0.753	5.09
28	28	0	0	56	0.447	.	0.738	5.01
28	28	0	0	56	0.440	.	0.717	5.10
28	28	0	0	56	0.496	.	0.717	3.88
28	28	0	0	56	0.515	.	0.764	4.78
28	56	0	0	84	0.398	.	0.675	4.24
28	56	0	0	84	0.557	.	0.797	5.24
28	56	0	0	84	0.498	.	0.721	4.88
28	56	0	0	84	0.550	.	0.779	5.09

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
28	84	0	0	112	0.484	.	0.773	5.16
28	84	0	0	112	0.472	.	0.752	4.69
28	84	0	0	112	0.490	.	0.739	4.51
28	84	0	0	112	0.433	.	0.723	4.41
28	112	0	0	140	0.408	.	0.742	5.28
28	112	0	0	140	0.499	.	0.787	5.29
28	112	0	0	140	0.471	.	0.749	4.48
28	112	0	0	140	0.505	.	0.760	4.88
28	140	0	0	168	0.500	.	0.770	5.02
28	140	0	0	168	0.477	.	0.755	4.72
28	140	0	0	168	0.496	.	0.711	3.75
28	140	0	0	168	0.518	.	0.769	4.89
56	84	0	0	140	0.439	.	0.745	4.95
56	84	0	0	140	0.503	.	0.772	5.03
56	84	0	0	140	0.485	.	0.728	4.38
56	84	0	0	140	0.506	.	0.760	4.95

2010 Manhattan

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	8.8	0.561	0.577	0.596	2.13
0	0	0	0	8.8	0.438	0.474	0.499	1.89
0	0	0	0	8.8	0.491	0.511	0.524	2.23
0	0	0	0	8.8	0.466	0.509	0.532	2.25
140	0	0	0	148.8	0.618	0.738	0.754	4.21
140	0	0	0	148.8	0.552	0.686	0.735	3.54
140	0	0	0	148.8	0.597	0.713	0.758	3.52
140	0	0	0	148.8	0.601	0.730	0.756	3.68
28	0	0	0	36.8	0.487	0.556	0.597	2.47
28	0	0	0	36.8	0.536	0.616	0.649	2.90
28	0	0	0	36.8	0.528	0.568	0.624	2.96
28	0	0	0	36.8	0.474	0.539	0.596	2.48
28	28	0	0	64.8	0.528	0.613	0.659	3.13
28	28	0	0	64.8	0.492	0.587	0.681	3.30
28	28	0	0	64.8	0.530	0.635	0.686	3.21
28	28	0	0	64.8	0.639	0.689	0.722	3.33
28	56	0	0	92.8	0.526	0.631	0.679	3.04
28	56	0	0	92.8	0.552	0.665	0.716	3.38
28	56	0	0	92.8	0.625	0.677	0.727	3.54
28	56	0	0	92.8	0.453	0.558	0.646	3.19
28	84	0	0	120.8	0.553	0.644	0.697	3.13
28	84	0	0	120.8	0.600	0.707	0.752	3.78
28	84	0	0	120.8	0.541	0.646	0.684	3.70
28	84	0	0	120.8	0.517	0.625	0.661	3.23

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
28	112	0	0	148.8	0.549	0.665	0.708	3.74
28	112	0	0	148.8	0.577	0.713	0.757	3.77
28	112	0	0	148.8	0.515	0.601	0.683	2.97
28	112	0	0	148.8	0.567	0.656	0.726	3.45
28	140	0	0	176.8	0.547	0.667	0.729	4.08
28	140	0	0	176.8	0.631	0.712	0.753	3.92
28	140	0	0	176.8	0.510	0.617	0.688	3.56
28	140	0	0	176.8	0.529	0.652	0.727	3.95
28	0	28	0	64.8	0.583	0.630	0.651	3.00
28	0	28	0	64.8	0.523	0.599	0.641	3.59
28	0	28	0	64.8	0.559	0.656	0.684	3.55
28	0	28	0	64.8	0.583	0.660	0.703	3.44
28	0	56	0	92.8	0.528	0.608	0.633	3.63
28	0	56	0	92.8	0.590	0.645	0.672	3.52
28	0	56	0	92.8	0.526	0.620	0.677	3.60
28	0	56	0	92.8	0.552	0.589	0.619	3.37
28	0	0	28	64.8	0.478	0.544	0.589	3.08
28	0	0	28	64.8	0.496	0.575	0.601	2.92
28	0	0	28	64.8	0.377	0.448	0.540	2.19
28	0	0	28	64.8	0.536	0.554	0.611	2.75
28	0	0	56	92.8	0.559	0.641	0.665	3.47
28	0	0	56	92.8	0.544	0.612	0.640	2.97
28	0	0	56	92.8	0.582	0.647	0.655	2.79
28	0	0	56	92.8	0.537	0.592	0.629	2.71

2010 McPherson West

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	0	0.336	.	0.489	3.44
0	0	0	0	0	0.373	.	0.703	4.05
0	0	0	0	0	0.385	.	0.602	3.78
0	0	0	0	0	0.386	.	0.600	3.46
140	0	0	0	140	0.750	.	0.834	5.44
140	0	0	0	140	0.788	.	0.826	4.84
140	0	0	0	140	0.748	.	0.816	4.66
140	0	0	0	140	0.718	.	0.776	4.54
28	0	0	0	28	0.606	.	0.682	4.15
28	0	0	0	28	0.596	.	0.744	4.71
28	0	0	0	28	0.491	.	0.665	4.33
28	0	0	0	28	0.535	.	0.736	3.66
28	28	0	0	56	0.576	.	0.645	4.36
28	28	0	0	56	0.493	.	0.739	5.10
28	28	0	0	56	0.533	.	0.728	4.57
28	28	0	0	56	0.455	.	0.640	4.37
28	56	0	0	84	0.709	.	0.750	4.29
28	56	0	0	84	0.539	.	0.780	4.08
28	56	0	0	84	0.530	.	0.763	4.60
28	56	0	0	84	0.604	.	0.755	5.02
28	84	0	0	112	0.748	.	0.795	5.12
28	84	0	0	112	0.511	.	0.774	4.96
28	84	0	0	112	0.540	.	0.799	4.45
28	84	0	0	112	0.636	.	0.668	4.77

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
28	112	0	0	140	0.702	.	0.805	5.16
28	112	0	0	140	0.614	.	0.787	4.99
28	112	0	0	140	0.576	.	0.817	4.67
28	112	0	0	140	0.572	.	0.766	5.02
28	140	0	0	168	0.664	.	0.800	5.14
28	140	0	0	168	0.563	.	0.781	4.87
28	140	0	0	168	0.549	.	0.813	5.17
28	140	0	0	168	0.630	.	0.825	5.31
28	0	28	0	56	0.725	.	0.662	4.07
28	0	28	0	56	0.631	.	0.755	4.89
28	0	28	0	56	0.489	.	0.677	4.30
28	0	28	0	56	0.464	.	0.549	4.00
28	0	56	0	84	0.461	.	0.647	4.46
28	0	56	0	84	0.500	.	0.706	4.45
28	0	56	0	84	0.603	.	0.758	5.05
28	0	56	0	84	0.482	.	0.686	4.54
28	0	0	28	56	0.493	.	0.672	4.48
28	0	0	28	56	0.503	.	0.712	4.67
28	0	0	28	56	0.530	.	0.674	4.41
28	0	0	28	56	0.510	.	0.712	4.15
28	0	0	56	84	0.405	.	0.623	4.45
28	0	0	56	84	0.549	.	0.718	4.79
28	0	0	56	84	0.471	.	0.747	4.07
28	0	0	56	84	0.517	.	0.643	4.12

2010 Yates Center

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	0	0.360	0.430	0.502	1.64
0	0	0	0	0	0.254	0.490	0.363	0.66
0	0	0	0	0	0.277	0.455	0.335	0.71
0	0	0	0	0	0.372	0.394	0.467	1.13
140	0	0	0	140	0.591	0.440	0.766	3.45
140	0	0	0	140	0.677	0.353	0.807	3.09
140	0	0	0	140	0.422	0.428	0.643	2.84
140	0	0	0	140	0.495	0.423	0.674	2.31
28	0	0	0	28	0.450	0.322	0.436	1.62
28	0	0	0	28	0.403	0.260	0.436	1.47
28	0	0	0	28	0.334	0.559	0.341	0.96
28	0	0	0	28	0.340	0.539	0.383	1.25
28	28	0	0	56	0.408	0.603	0.562	2.29
28	28	0	0	56	0.392	0.435	0.546	1.72
28	28	0	0	56	0.362	0.378	0.515	1.63
28	28	0	0	56	0.327	0.433	0.513	1.42
28	56	0	0	84	0.525	0.626	0.729	2.88
28	56	0	0	84	0.437	0.511	0.646	2.16
28	56	0	0	84	0.358	0.760	0.557	2.10
28	56	0	0	84	0.327	0.424	0.538	1.72

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
28	84	0	0	112	0.393	0.393	0.647	2.41
28	84	0	0	112	0.416	0.674	0.677	2.42
28	84	0	0	112	0.442	0.483	0.648	2.47
28	84	0	0	112	0.330	0.587	0.584	2.31
28	112	0	0	140	0.489	0.415	0.832	3.29
28	112	0	0	140	0.441	0.469	0.658	2.35
28	112	0	0	140	0.298	0.381	0.552	1.70
28	112	0	0	140	0.296	0.422	0.602	1.76
28	140	0	0	168	0.463	0.464	0.762	3.34
28	140	0	0	168	0.273	0.562	0.547	2.19
28	140	0	0	168	0.412	0.350	0.686	2.33
28	140	0	0	168	0.314	0.368	0.549	2.23
28	0	28	0	56	0.509	0.340	0.552	2.31
28	0	28	0	56	0.386	0.434	0.491	2.09
28	0	28	0	56	0.384	0.402	0.472	1.67
28	0	28	0	56	0.330	0.501	0.474	1.53
28	0	56	0	84	0.429	0.588	0.479	2.46
28	0	56	0	84	0.340	0.680	0.548	2.08
28	0	56	0	84	0.358	0.347	0.490	2.29
28	0	56	0	84	0.387	0.389	0.532	2.55
28	0	0	28	56	0.471	0.265	0.476	2.05
28	0	0	28	56	0.414	0.550	0.457	2.10
28	0	0	28	56	0.320	0.792	0.465	1.80
28	0	0	28	56	0.428	0.455	0.532	1.96
28	0	0	56	84	0.494	0.733	0.555	2.76
28	0	0	56	84	0.394	0.418	0.507	2.05
28	0	0	56	84	0.328	0.490	0.397	1.78
28	0	0	56	84	0.290	0.381	0.412	1.64

2011 Partridge

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	0	0.346	0.635	.	1.33
0	0	0	0	0	0.238	0.513	.	1.93
0	0	0	0	0	0.303	0.543	.	1.75
0	0	0	0	0	0.263	0.578	.	2.19
140	0	0	0	140	0.209	0.549	.	1.64
140	0	0	0	140	0.246	0.515	.	1.61
140	0	0	0	140	0.207	0.474	.	2.07
140	0	0	0	140	0.313	0.600	.	2.10
28	0	0	0	28	0.313	0.660	.	1.91
28	0	0	0	28	0.286	0.482	.	1.98
28	0	0	0	28	0.296	0.652	.	1.80
28	0	0	0	28	0.161	0.228	.	1.83
28	28	0	0	56	0.313	0.621	.	1.68
28	28	0	0	56	0.345	0.606	.	2.24
28	28	0	0	56	0.201	0.427	.	1.70
28	28	0	0	56	0.186	0.379	.	1.72
28	56	0	0	84	0.342	0.667	.	1.89
28	56	0	0	84	0.242	0.476	.	1.70
28	56	0	0	84	0.292	0.605	.	1.68
28	56	0	0	84	0.284	0.575	.	1.83
28	84	0	0	112	0.413	0.677	.	1.90
28	84	0	0	112	0.221	0.512	.	1.86
28	84	0	0	112	0.229	0.540	.	1.26
28	84	0	0	112	0.222	0.607	.	1.96

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
28	112	0	0	140	0.308	0.586	.	1.74
28	112	0	0	140	0.278	0.584	.	1.52
28	112	0	0	140	0.273	0.591	.	1.77
28	112	0	0	140	0.259	0.650	.	2.01
28	140	0	0	168	0.257	0.475	.	1.59
28	140	0	0	168	0.242	0.534	.	1.61
28	140	0	0	168	0.251	0.543	.	1.58
28	140	0	0	168	0.188	0.492	.	1.86
28	0	28	0	56	0.293	0.526	.	1.58
28	0	28	0	56	0.283	0.467	.	1.54
28	0	28	0	56	0.331	0.603	.	1.56
28	0	28	0	56	0.192	0.369	.	2.05
28	0	56	0	84	0.378	0.654	.	1.51
28	0	56	0	84	0.229	0.439	.	1.83
28	0	56	0	84	0.226	0.429	.	1.84
28	0	56	0	84	0.245	0.520	.	1.93
28	0	0	28	56	0.227	0.510	.	1.76
28	0	0	28	56	0.265	0.563	.	1.97
28	0	0	28	56	0.212	0.388	.	2.05
28	0	0	28	56	0.204	0.399	.	1.90
28	0	0	56	84	0.286	0.507	.	1.58
28	0	0	56	84	0.209	0.420	.	1.96
28	0	0	56	84	0.315	0.517	.	1.62
28	0	0	56	84	0.245	0.438	.	1.77

2011 Randolph

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	0	0.451	.	0.586	2.10
0	0	0	0	0	0.433	.	0.576	2.06
0	0	0	0	0	0.490	.	0.598	2.37
0	0	0	0	0	0.437	.	0.590	2.53
140	0	0	0	140	0.472	.	0.585	2.63
140	0	0	0	140	0.345	.	0.748	2.89
140	0	0	0	140	0.427	.	0.705	2.99
140	0	0	0	140	0.366	.	0.763	2.76
28	0	0	0	28	0.467	.	0.610	3.22
28	0	0	0	28	0.476	.	0.642	2.57
28	0	0	0	28	0.414	.	0.638	2.72
28	0	0	0	28	0.372	.	0.767	2.17
28	28	0	0	56	0.404	.	0.626	2.84
28	28	0	0	56	0.429	.	0.652	2.74
28	28	0	0	56	0.340	.	0.700	2.77
28	28	0	0	56	0.429	.	0.736	2.88
28	56	0	0	84	0.396	.	0.622	2.79
28	56	0	0	84	0.390	.	0.669	3.07
28	56	0	0	84	0.455	.	0.734	3.48
28	56	0	0	84	0.472	.	0.714	2.81
28	84	0	0	112	0.273	.	0.590	0.00
28	84	0	0	112	0.479	.	0.724	2.88
28	84	0	0	112	0.445	.	0.768	3.09
28	84	0	0	112	0.358	.	0.696	2.99
28	112	0	0	140	0.468	.	0.688	2.45
28	112	0	0	140	0.413	.	0.641	3.02
28	112	0	0	140	0.510	.	0.750	2.62
28	112	0	0	140	0.493	.	0.761	2.99

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
28	140	0	0	168	0.367	.	0.686	2.77
28	140	0	0	168	0.442	.	0.555	3.37
28	140	0	0	168	0.374	.	0.666	2.94
28	140	0	0	168	0.469	.	0.780	2.79
28	0	28	0	56	0.338	.	0.639	2.99
28	0	28	0	56	0.414	.	0.635	2.90
28	0	28	0	56	0.494	.	0.698	2.49
28	0	28	0	56	0.506	.	0.727	2.72
28	0	56	0	84	0.393	.	0.629	2.70
28	0	56	0	84	0.471	.	0.630	2.66
28	0	56	0	84	0.371	.	0.645	3.12
28	0	56	0	84	0.461	.	0.700	3.26
28	0	0	28	56	0.385	.	0.568	2.84
28	0	0	28	56	0.358	.	0.657	2.33
28	0	0	28	56	0.426	.	0.651	2.48
28	0	0	28	56	0.456	.	0.652	2.58
28	0	0	56	84	0.440	.	0.651	2.93
28	0	0	56	84	0.509	.	0.699	2.45
28	0	0	56	84	0.396	.	0.654	2.53
28	0	0	56	84	0.445	.	0.738	2.80
28	0	0	0	28	0.356	.	0.623	3.06
28	0	0	0	28	0.452	.	0.727	2.70
28	0	0	0	28	0.469	.	0.713	2.27
28	0	0	0	28	0.428	.	0.693	2.66
56	0	0	0	56	0.472	.	0.683	2.71
56	0	0	0	56	0.346	.	0.742	2.42
56	0	0	0	56	0.435	.	0.741	3.19
56	0	0	0	56	0.463	.	0.729	3.05
84	0	0	0	84	0.461	.	0.658	3.03
84	0	0	0	84	0.423	.	0.725	2.94
84	0	0	0	84	0.445	.	0.813	2.99
84	0	0	0	84	0.409	.	0.756	3.06

2011 Rossville

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	0	0.628	0.455	.	2.57
0	0	0	0	0	0.647	0.658	.	3.14
0	0	0	0	0	0.643	0.675	.	3.20
0	0	0	0	0	0.603	0.606	.	2.97
140	0	0	0	140	0.663	0.823	.	4.81
140	0	0	0	140	0.685	0.733	.	4.32
140	0	0	0	140	0.679	0.736	.	4.62
140	0	0	0	140	0.659	0.770	.	4.04
28	0	0	0	28	0.649	0.614	.	3.50
28	0	0	0	28	0.663	0.665	.	3.78
28	0	0	0	28	0.680	0.763	.	3.77
28	0	0	0	28	0.627	0.590	.	2.90
28	28	0	0	56	0.644	0.687	.	3.42
28	28	0	0	56	0.651	0.695	.	3.35
28	28	0	0	56	0.646	0.656	.	3.46
28	28	0	0	56	0.627	0.635	.	2.98
28	56	0	0	84	0.589	0.644	.	2.86
28	56	0	0	84	0.652	0.594	.	3.54
28	56	0	0	84	0.640	0.675	.	3.32
28	56	0	0	84	0.636	0.667	.	3.15
28	84	0	0	112	0.611	0.650	.	3.33
28	84	0	0	112	0.668	0.673	.	3.53
28	84	0	0	112	0.640	0.600	.	3.47
28	84	0	0	112	0.624	0.720	.	3.48
28	112	0	0	140	0.629	0.593	.	3.53
28	112	0	0	140	0.610	0.708	.	3.24
28	112	0	0	140	0.670	0.679	.	3.72
28	112	0	0	140	0.633	0.677	.	2.92

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
28	140	0	0	168	0.635	0.606	.	2.73
28	140	0	0	168	0.655	0.684	.	3.86
28	140	0	0	168	0.693	0.681	.	3.50
28	140	0	0	168	0.679	0.681	.	3.28
28	0	28	0	56	0.632	0.564	.	3.82
28	0	28	0	56	0.617	0.668	.	3.63
28	0	28	0	56	0.650	0.757	.	4.10
28	0	28	0	56	0.639	0.637	.	3.60
28	0	56	0	84	0.653	0.547	.	2.92
28	0	56	0	84	0.715	0.686	.	3.83
28	0	56	0	84	0.644	0.580	.	3.45
28	0	56	0	84	0.648	0.638	.	3.61
28	0	0	28	56	0.649	0.663	.	3.89
28	0	0	28	56	0.650	0.618	.	3.67
28	0	0	28	56	0.670	0.692	.	4.13
28	0	0	28	56	0.589	0.603	.	3.90
28	0	0	56	84	0.637	0.622	.	3.50
28	0	0	56	84	0.657	0.703	.	4.04
28	0	0	56	84	0.687	0.726	.	3.94
28	0	0	56	84	0.621	0.564	.	3.39
28	28	0	0	56	0.613	0.657	.	3.89
28	28	0	0	56	0.654	0.678	.	4.00
28	28	0	0	56	0.641	0.672	.	3.82
28	28	0	0	56	0.627	0.748	.	3.84
56	0	0	0	56	0.648	0.755	.	4.06
56	0	0	0	56	0.671	0.717	.	4.12
56	0	0	0	56	0.716	0.762	.	4.05
56	0	0	0	56	0.629	0.702	.	3.91

2011 Scandia

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	0	0.309	0.330	0.357	1.39
0	0	0	0	0	0.296	0.344	0.327	0.78
0	0	0	0	0	0.340	0.380	0.429	0.83
0	0	0	0	0	0.330	0.384	0.358	0.67
140	0	0	0	140	0.423	0.442	0.549	1.93
140	0	0	0	140	0.360	0.514	0.554	1.54
140	0	0	0	140	0.341	0.540	0.562	1.24
140	0	0	0	140	0.330	0.492	0.485	1.22
28	0	0	0	28	0.382	0.405	0.479	1.86
28	0	0	0	28	0.351	0.424	0.421	1.75
28	0	0	0	28	0.304	0.448	0.416	1.00
28	0	0	0	28	0.310	0.423	0.374	0.66
28	28	0	0	56	0.361	0.420	0.467	1.75
28	28	0	0	56	0.348	0.458	0.492	1.02
28	28	0	0	56	0.326	0.405	0.472	0.85
28	28	0	0	56	0.286	0.414	0.387	0.51
28	56	0	0	84	0.312	0.363	0.496	1.40
28	56	0	0	84	0.378	0.501	0.500	1.22
28	56	0	0	84	0.313	0.411	0.491	1.09
28	56	0	0	84	0.324	0.390	0.477	0.87
28	84	0	0	112	0.426	0.461	0.580	2.46
28	84	0	0	112	0.387	0.442	0.555	1.39
28	84	0	0	112	0.320	0.496	0.505	1.16
28	84	0	0	112	0.310	0.447	0.519	1.23
28	112	0	0	140	0.324	0.493	0.497	1.72
28	112	0	0	140	0.363	0.554	0.546	1.31
28	112	0	0	140	0.325	0.498	0.466	0.93
28	112	0	0	140	0.351	0.552	0.538	1.24

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
28	140	0	0	168	0.343	0.393	0.515	1.65
28	140	0	0	168	0.359	0.523	0.566	1.17
28	140	0	0	168	0.374	0.456	0.571	0.79
28	140	0	0	168	0.340	0.417	0.493	0.89
28	140	0	0	168	0.403	0.383	0.494	1.04
28	0	28	0	56	0.335	0.449	0.452	2.19
28	0	28	0	56	0.321	0.402	0.381	1.10
28	0	28	0	56	0.340	0.455	0.422	0.97
28	0	56	0	84	0.304	0.313	0.432	1.32
28	0	56	0	84	0.367	0.345	0.430	1.71
28	0	56	0	84	0.355	0.367	0.428	0.82
28	0	56	0	84	0.321	0.359	0.393	1.11
28	0	0	28	56	0.371	0.449	0.442	2.18
28	0	0	28	56	0.367	0.417	0.448	1.71
28	0	0	28	56	0.308	0.349	0.399	1.19
28	0	0	28	56	0.296	0.356	0.384	1.17
28	0	0	56	84	0.409	0.490	0.491	2.54
28	0	0	56	84	0.328	0.379	0.410	1.36
28	0	0	56	84	0.358	0.418	0.467	1.21
28	0	0	56	84	0.331	0.386	0.399	1.19
28	0	0	0	28	0.414	0.404	0.499	1.96
28	0	0	0	28	0.295	0.441	0.498	1.17
28	0	0	0	28	0.370	0.382	0.439	0.79
28	0	0	0	28	0.342	0.492	0.425	0.75
56	0	0	0	56	0.417	0.416	0.540	1.25
56	0	0	0	56	0.374	0.486	0.502	1.76
56	0	0	0	56	0.363	0.478	0.495	0.83
56	0	0	0	56	0.331	0.515	0.525	1.17
84	0	0	0	84	0.466	0.532	0.613	2.50
84	0	0	0	84	0.415	0.465	0.565	2.58
84	0	0	0	84	0.366	0.494	0.564	1.23
84	0	0	0	84	0.389	0.527	0.530	0.97

2012 Gypsum

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	13.44	0.341	0.365	0.419	1.15
0	0	0	0	13.44	0.268	0.272	0.287	0.30
0	0	0	0	13.44	0.350	0.383	0.432	0.71
0	0	0	0	13.44	0.300	0.296	0.338	0.87
33.6	0	0	0	47.04	0.387	0.460	0.571	1.26
33.6	0	0	0	47.04	0.507	0.625	0.671	2.13
33.6	0	0	0	47.04	0.502	0.621	0.660	2.50
33.6	0	0	0	47.04	0.403	0.501	0.523	1.89
67.2	0	0	0	80.64	0.536	0.734	0.780	2.23
67.2	0	0	0	80.64	0.554	0.706	0.739	2.50
67.2	0	0	0	80.64	0.511	0.645	0.711	2.03
67.2	0	0	0	80.64	0.496	0.626	0.638	2.32
100.8	0	0	0	114.24	0.562	0.799	0.816	2.51
100.8	0	0	0	114.24	0.645	0.815	0.828	3.04
100.8	0	0	0	114.24	0.600	0.795	0.821	2.91
100.8	0	0	0	114.24	0.636	0.794	0.800	2.78
134.4	0	0	0	147.84	0.582	0.823	0.836	2.33
134.4	0	0	0	147.84	0.658	0.836	0.844	2.98
134.4	0	0	0	147.84	0.651	0.826	0.834	2.62
134.4	0	0	0	147.84	0.579	0.759	0.753	2.59
168	0	0	0	181.44	0.486	0.807	0.836	2.39
168	0	0	0	181.44	0.503	0.812	0.838	2.93
168	0	0	0	181.44	0.599	0.835	0.849	2.76
168	0	0	0	181.44	0.529	0.800	0.839	3.38
33.6	134.4	0	0	181.44	0.449	0.777	0.831	2.60
33.6	134.4	0	0	181.44	0.412	0.735	0.817	2.72
33.6	134.4	0	0	181.44	0.421	0.711	0.815	2.84
33.6	134.4	0	0	181.44	0.427	0.758	0.836	2.72

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
33.6	100.8	0	0	147.84	0.486	0.781	0.832	3.15
33.6	100.8	0	0	147.84	0.517	0.787	0.833	2.78
33.6	100.8	0	0	147.84	0.447	0.754	0.820	2.72
33.6	100.8	0	0	147.84	0.408	0.725	0.817	2.83
67.2	67.2	0	0	147.84	0.529	0.813	0.844	3.15
67.2	67.2	0	0	147.84	0.558	0.822	0.844	2.54
67.2	67.2	0	0	147.84	0.531	0.815	0.840	2.91
67.2	67.2	0	0	147.84	0.477	0.800	0.837	3.34
100.8	33.6	0	0	147.84	0.519	0.786	0.837	2.91
100.8	33.6	0	0	147.84	0.486	0.803	0.828	2.79
100.8	33.6	0	0	147.84	0.555	0.798	0.853	3.00
100.8	33.6	0	0	147.84	0.526	0.807	0.835	3.27
33.6	42.56	0	0	89.6	0.467	0.729	0.812	2.48
33.6	90.72	0	0	137.76	0.387	0.631	0.705	2.28
33.6	29.12	0	0	76.16	0.533	0.707	0.754	2.72
33.6	63.84	0	0	110.88	0.417	0.706	0.790	2.67
33.6	0	100.8	0	147.84	0.496	0.642	0.730	3.24
33.6	0	100.8	0	147.84	0.425	0.508	0.591	2.83
33.6	0	100.8	0	147.84	0.459	0.535	0.625	2.87
33.6	0	100.8	0	147.84	0.391	0.418	0.496	2.89
67.2	0	67.2	0	147.84	0.490	0.638	0.738	2.19
67.2	0	67.2	0	147.84	0.377	0.559	0.645	2.19
67.2	0	67.2	0	147.84	0.552	0.720	0.772	3.32
67.2	0	67.2	0	147.84	0.473	0.720	0.761	3.56
100.8	0	33.6	0	147.84	0.513	0.793	0.828	2.98
100.8	0	33.6	0	147.84	0.547	0.813	0.828	2.89
100.8	0	33.6	0	147.84	0.496	0.746	0.806	2.68
100.8	0	33.6	0	147.84	0.519	0.791	0.817	3.32

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
33.6	0	36.96	0	84	0.444	0.590	0.624	2.54
33.6	0	66.08	0	113.12	0.372	0.417	0.472	2.01
33.6	0	38.08	0	85.12	0.488	0.601	0.683	2.60
33.6	0	54.88	0	101.92	0.381	0.474	0.486	2.26
33.6	0	0	100.8	147.84	0.476	0.579	0.629	2.64
33.6	0	0	100.8	147.84	0.342	0.342	0.451	2.01
33.6	0	0	100.8	147.84	0.508	0.641	0.653	3.09
33.6	0	0	100.8	147.84	0.452	0.587	0.627	2.41
67.2	0	0	67.2	147.84	0.452	0.636	0.715	2.69
67.2	0	0	67.2	147.84	0.483	0.643	0.747	2.87
67.2	0	0	67.2	147.84	0.477	0.661	0.710	2.86
67.2	0	0	67.2	147.84	0.471	0.726	0.714	2.92
100.8	0	0	33.6	147.84	0.548	0.783	0.818	3.03
100.8	0	0	33.6	147.84	0.566	0.810	0.822	2.71
100.8	0	0	33.6	147.84	0.497	0.736	0.786	3.16
100.8	0	0	33.6	147.84	0.526	0.791	0.822	3.57
33.6	0	0	47.04	94.08	0.379	0.528	0.607	2.19
33.6	0	0	53.76	100.8	0.381	0.536	0.574	2.48
33.6	0	0	49.28	96.32	0.421	0.587	0.607	2.28
33.6	0	0	78.4	125.44	0.325	0.431	0.454	2.24

2012 Manhattan Field F

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	9.856	0.760	0.803	0.781	4.42
0	0	0	0	9.856	0.848	0.885	0.880	2.73
0	0	0	0	9.856	0.849	0.879	0.868	3.26
0	0	0	0	9.856	0.843	0.881	0.864	3.35
33.6	0	0	0	43.456	0.767	0.854	0.850	4.37
33.6	0	0	0	43.456	0.857	0.884	0.835	2.05
33.6	0	0	0	43.456	0.725	0.833	0.832	4.36
33.6	0	0	0	43.456	0.776	0.850	0.850	4.41
67.2	0	0	0	77.056	0.794	0.866	0.861	3.90
67.2	0	0	0	77.056	0.853	0.886	0.851	2.38
67.2	0	0	0	77.056	0.855	0.890	0.873	2.27
67.2	0	0	0	77.056	0.849	0.886	0.855	2.75
100.8	0	0	0	110.656	0.848	0.888	0.837	2.28
100.8	0	0	0	110.656	0.810	0.884	0.857	2.08
100.8	0	0	0	110.656	0.850	0.887	0.892	2.57
100.8	0	0	0	110.656	0.735	0.857	0.873	4.08
134.4	0	0	0	144.256	0.776	0.872	0.884	4.28
134.4	0	0	0	144.256	0.835	0.887	0.877	2.77
134.4	0	0	0	144.256	0.831	0.885	0.893	3.58
134.4	0	0	0	144.256	0.793	0.878	0.887	3.88
33.6	100.8	0	0	144.256	0.809	0.871	0.855	3.92
33.6	100.8	0	0	144.256	0.844	0.886	0.891	2.76
33.6	100.8	0	0	144.256	0.818	0.873	0.877	3.83
33.6	100.8	0	0	144.256	0.816	0.881	0.872	3.88
67.2	67.2	0	0	144.256	0.743	0.831	0.833	4.68
67.2	67.2	0	0	144.256	0.730	0.814	0.835	4.64
67.2	67.2	0	0	144.256	0.835	0.883	0.862	2.79
67.2	67.2	0	0	144.256	0.821	0.876	0.877	3.79

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
100.8	33.6	0	0	144.256	0.848	0.883	0.845	2.38
100.8	33.6	0	0	144.256	0.835	0.881	0.866	3.19
100.8	33.6	0	0	144.256	0.758	0.811	0.816	4.66
100.8	33.6	0	0	144.256	0.784	0.833	0.831	4.63
33.6	0	0	0	43.456	0.726	0.752	0.780	3.78
33.6	0	0	0	43.456	0.815	0.867	0.857	4.37
33.6	0	0	0	43.456	0.816	0.881	0.856	2.80
33.6	0	0	0	43.456	0.843	0.880	0.865	3.64
33.6	0	100.8	0	144.256	0.767	0.817	0.820	4.70
33.6	0	100.8	0	144.256	0.849	0.882	0.855	2.63
33.6	0	100.8	0	144.256	0.778	0.827	0.845	4.69
33.6	0	100.8	0	144.256	0.785	0.828	0.854	4.23
67.2	0	67.2	0	144.256	0.826	0.860	0.834	3.88
67.2	0	67.2	0	144.256	0.845	0.878	0.866	2.84
67.2	0	67.2	0	144.256	0.828	0.876	0.848	2.31
67.2	0	67.2	0	144.256	0.847	0.884	0.854	2.80
100.8	0	33.6	0	144.256	0.741	0.794	0.801	4.75
100.8	0	33.6	0	144.256	0.818	0.876	0.852	2.72
100.8	0	33.6	0	144.256	0.748	0.788	0.795	5.06
100.8	0	33.6	0	144.256	0.802	0.844	0.854	4.68

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
33.6	0	0	0	43.456	0.812	0.857	0.834	3.77
33.6	0	0	0	43.456	0.800	0.841	0.840	4.46
33.6	0	0	0	43.456	0.843	0.883	0.864	2.93
33.6	0	0	0	43.456	0.781	0.856	0.846	4.67
33.6	0	0	100.8	144.256	0.767	0.815	0.794	4.70
33.6	0	0	100.8	144.256	0.745	0.778	0.777	4.59
33.6	0	0	100.8	144.256	0.824	0.869	0.880	4.00
33.6	0	0	100.8	144.256	0.809	0.855	0.850	4.20
67.2	0	0	67.2	144.256	0.767	0.828	0.762	4.61
67.2	0	0	67.2	144.256	0.743	0.814	0.806	4.45
67.2	0	0	67.2	144.256	0.827	0.875	0.860	4.03
67.2	0	0	67.2	144.256	0.771	0.835	0.827	4.62
100.8	0	0	33.6	144.256	0.726	0.781	0.749	4.62
100.8	0	0	33.6	144.256	0.761	0.820	0.824	4.61
100.8	0	0	33.6	144.256	0.831	0.877	0.865	3.73
100.8	0	0	33.6	144.256	0.793	0.837	0.813	4.26
33.6	0	0	0	43.456	0.822	0.866	0.852	3.31
33.6	0	0	0	43.456	0.785	0.835	0.831	4.58
33.6	0	0	0	43.456	0.811	0.851	0.842	4.45
33.6	0	0	0	43.456	0.794	0.858	0.865	3.90

2012 Manhattan Field J3

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
0	0	0	0	9.856	0.415	0.386	0.427	1.46
0	0	0	0	9.856	0.344	0.355	0.339	1.16
0	0	0	0	9.856	0.337	0.375	0.342	1.43
0	0	0	0	9.856	0.313	0.388	0.361	1.50
33.6	0	0	0	43.456	0.476	0.648	0.643	2.51
33.6	0	0	0	43.456	0.367	0.537	0.542	2.34
33.6	0	0	0	43.456	0.356	0.511	0.516	2.16
33.6	0	0	0	43.456	0.344	0.434	0.420	1.56
67.2	0	0	0	77.056	0.360	0.488	0.507	2.03
67.2	0	0	0	77.056	0.500	0.699	0.689	2.61
67.2	0	0	0	77.056	0.341	0.509	0.541	2.31
67.2	0	0	0	77.056	0.388	0.518	0.569	2.17
100.8	0	0	0	110.656	0.456	0.641	0.643	2.47
100.8	0	0	0	110.656	0.470	0.688	0.695	3.17
100.8	0	0	0	110.656	0.335	0.517	0.549	2.20
100.8	0	0	0	110.656	0.393	0.545	0.546	1.90
134.4	0	0	0	144.256	0.558	0.712	0.723	2.80
134.4	0	0	0	144.256	0.392	0.558	0.579	2.34
134.4	0	0	0	144.256	0.389	0.528	0.543	2.37
134.4	0	0	0	144.256	0.394	0.630	0.636	2.80
168	0	0	0	177.856	0.492	0.639	0.654	2.52
168	0	0	0	177.856	0.440	0.653	0.644	2.68
168	0	0	0	177.856	0.362	0.552	0.580	1.88
168	0	0	0	177.856	0.374	0.599	0.619	2.14
33.6	134.4	0	0	177.856	0.436	0.677	0.688	2.21
33.6	134.4	0	0	177.856	0.387	0.542	0.536	1.96
33.6	134.4	0	0	177.856	0.362	0.508	0.508	2.41
33.6	134.4	0	0	177.856	0.384	0.571	0.589	2.25

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
33.6	100.8	0	0	144.256	0.419	0.550	0.574	
33.6	100.8	0	0	144.256	0.445	0.660	0.664	2.42
33.6	100.8	0	0	144.256	0.357	0.542	0.545	2.34
33.6	100.8	0	0	144.256	0.389	0.578	0.581	2.74
67.2	67.2	0	0	144.256	0.506	0.708	0.704	2.94
67.2	67.2	0	0	144.256	0.424	0.574	0.582	2.11
67.2	67.2	0	0	144.256	0.366	0.545	0.557	2.04
67.2	67.2	0	0	144.256	0.344	0.499	0.542	2.60
100.8	33.6	0	0	144.256	0.512	0.734	0.748	3.00
100.8	33.6	0	0	144.256	0.529	0.666	0.690	2.91
100.8	33.6	0	0	144.256	0.348	0.497	0.534	2.42
100.8	33.6	0	0	144.256	0.414	0.618	0.585	2.16
33.6	76.16	0	0	119.616	0.417	0.543	0.556	2.69
33.6	124.32	0	0	167.776	0.332	0.435	0.445	2.02
33.6	62.72	0	0	106.176	0.325	0.481	0.494	2.11
33.6	97.44	0	0	140.896	0.343	0.463	0.454	2.31
33.6	0	100.8	0	144.256	0.349	0.382	0.424	2.72
33.6	0	100.8	0	144.256	0.463	0.587	0.600	2.53
33.6	0	100.8	0	144.256	0.362	0.457	0.443	2.22
33.6	0	100.8	0	144.256	0.386	0.505	0.522	2.64
67.2	0	67.2	0	144.256	0.450	0.618	0.681	.
67.2	0	67.2	0	144.256	0.511	0.651	0.680	2.60
67.2	0	67.2	0	144.256	0.424	0.553	0.550	2.59
67.2	0	67.2	0	144.256	0.431	0.603	0.612	2.38
100.8	0	33.6	0	144.256	0.351	0.571	0.580	2.17
100.8	0	33.6	0	144.256	0.383	0.564	0.589	1.95
100.8	0	33.6	0	144.256	0.383	0.558	0.577	2.08
100.8	0	33.6	0	144.256	0.471	0.631	0.633	2.50

Fall	Fks 4	Fks 7	Fks 9	Total N	Fks 4	Fks 7	Fks 9	Grain Yield
		N Rate kg ha^{-1}				Red NDVI		Mg ha^{-1}
33.6	0	70.56	0	114.016	0.329	0.353	0.365	2.17
33.6	0	99.68	0	143.136	0.359	0.471	0.445	1.85
33.6	0	71.68	0	115.136	0.412	0.520	0.529	2.20
33.6	0	88.48	0	131.936	0.369	0.454	0.447	2.55
33.6	0	0	100.8	144.256	0.461	0.608	0.553	2.73
33.6	0	0	100.8	144.256	0.450	0.515	0.491	2.46
33.6	0	0	100.8	144.256	0.362	0.539	0.518	2.09
33.6	0	0	100.8	144.256	0.380	0.444	0.460	2.38
67.2	0	0	67.2	144.256	0.432	0.559	0.558	2.91
67.2	0	0	67.2	144.256	0.421	0.597	0.569	2.28
67.2	0	0	67.2	144.256	0.322	0.508	0.534	2.05
67.2	0	0	67.2	144.256	0.387	0.563	0.550	2.54
100.8	0	0	33.6	144.256	0.335	0.664	0.679	2.92
100.8	0	0	33.6	144.256	0.474	0.605	0.608	2.57
100.8	0	0	33.6	144.256	0.357	0.574	0.569	2.10
100.8	0	0	33.6	144.256	0.341	0.511	0.528	2.53
33.6	0	0	80.64	124.096	0.473	0.622	0.577	2.68
33.6	0	0	87.36	130.816	0.474	0.594	0.557	1.78
33.6	0	0	82.88	126.336	0.319	0.450	0.475	2.04
33.6	0	0	112	155.456	0.370	0.503	0.477	2.29

Appendix C - Chapter 3 Algorithm Component Selection Criteria

Yield Potential Selection Criteria

Unfertilized with and without Starter N

SAS coded for creating dataset with only unfertilized check plots:

```
Data YPcheck;
Set Wheat;
if Treatment = '1';
if Location = 'Manhattan' and Year = '2006' then delete;
if Yield = '0' then delete;
run;
```

The 2006 Manhattan location was removed due to the lack of an unfertilized treatment.

Well Fertilized Fall and Feekes 4

SAS code for creating dataset with only well fertilized Fall and Feekes 4 treatments:

```
Data YPF4;
Set Wheat;
if TotAppliedN < '80' then delete;
if F7N > '0' then delete;
if F9N > '0' then delete;
if Yield = '0' then delete;
if Year = '2012' and Location = 'Manhattan Field F' then delete;
if Year = '2007' and Location = 'Tribune' then delete;
run;
```

Criteria was established to only allow treatments that had a total N rate greater than 80 kg N ha^{-1} in order to minimize the inclusion of data that experienced N stress which would skew the interpretation of the results. The 2007 Tribune and 2012 Manhattan Field F locations experience negative response to applied N due to generation of excess biomass during the fall and spring. Although very relevant for providing information on when not to apply N in specific environmental situations found in Kansas, the algorithms developed are not yet area specific, and therefore this data was removed.

Well Fertilized Feekes 7

SAS code for creating dataset with only fertilized Feekes 7 treatments:

```
Data YPF7;
 Set Wheat;
if TotAppliedN < '60' then delete;
if F7NDVI = '0' then delete;
if F4N > '0' then delete;
if F9N > '0' then delete;
if Yield = '0' then delete;
if Year = '2008' and Location = 'Manhattan' then delete;
if Year = '2012' and Location = 'Gypsum' then delete;
if Year = '2012' and Location = 'North Farm F' then delete;
run;
```

Criteria was established to only allow Feekes 7 treatments that had total applied N rates greater than 60 kg N ha-^{1}. Minimum total N applied required for this dataset was reduced in respects to Feekes 4 criteria because Feekes 7 treatments attempted to create management schemes that optimize N application timing so overall total N rate could be reduced and yet still retain high yields. Therefore, this was factored into the selection criteria. 2008 Manhattan and 2012 Gypsum was removed due to drought conditions that onset after Feekes 9. The 2007 Tribune and 2012 Manhattan Field F were removed for the same reasons as the Feekes 4 criteria.

Well Fertilized Feekes 9

SAS code for creating dataset with only fertilized Feekes Seven treatments:

```
Data YPF9;
 Set Wheat;
if TotAppliedN < '40' then delete;
```

```
if F9NDVI = '0' then delete;
if F4N > '0' then delete;
if F7N > '0' then delete;
if Yield = '0' then delete;
if Year = '2008' and Location = 'Manhattan' then delete;
if Year = '2012' and Location = 'Gypsum' then delete;
if Year = '2012' and Location = 'North Farm F' then delete;
run;
```

The selection criteria for Feekes 9 was the same as Feekes 7 with the exception of the further reduction of overall total applied N to 40 kg N ha^{-1}.

Recoverable Yield Selection Criteria

Feekes 4

SAS code for creating dataset for evaluating yield response to applied N at Feekes 4:

```
Data RYF4;
 Set Wheat;
 if F4N < '80' then delete;
if F7N >'0' then delete;
if F9N >'0' then delete;
if Yield = '0' then delete;
if Yield < '2' then delete;
if RecoverYRelativeDiff > '.05' then delete;
if RI4 < '1.11' and RecoverableYield < '.75' then delete;
if Year = '2006' and Location = 'Manhattan' and Block = '3' then delete;
if Year = '2006' and Location = 'Manhattan' and Block = '4' then delete;
if Year = '2010' and Location = 'Yates Center' then delete;
run;
```

Selection criteria with reasoning are as follows:

1. Total applied N rate greater than 80 kg N ha^{-1}

    a. Minimize noise from lack for yield response due to too low of applied N rate.

2. Observed grain yield greater than 2 Mg ha^{-1}
    a. Removed observations where N was not the most limiting factor such as water, bad stands, and disease.
3. Recoverable Yield and Relative Yield within five percent of each other
    a. Recoverable and Relative Yield difference greater than five percent marked loss of integrity of the N reference strip would was no longer the highest yielding treatment. Therefore, it no longer provided accurate assessment of yield recovery.
4. Observations with RI less than 1.11 and Recoverable yield less than 0.75 removed
    a. Predominately issues of plots with bad stands or heavy infestations of bugs or disease after time of spectral readings. Leading to yield reductions for reasons other than N.
5. 2006 Manhattan Blocks three and four
    a. Specific issue addressed by former graduate who noted in plot history that these blocks were on a different soil type than blocks one and two and experience heavy water stress due to very high clay content. This resulted in yield response being limited by available water.
6. 2010 Yates Center
    a. Stripe rust heavily infected most of the study area and became the dominant yield-limiting factor.

Feekes 7 and 9

SAS Codes for creating dataset for evaluating yield response to applied N at Feekes 4 and 9:

```
Data RYF7;
 Set Wheat;
 if RI7 = '0' then delete;
if F7N ='0' then delete;
if Yield = '0' then delete;
if Yield < '2' then delete;
if RecoverYRelativeDiff > '.05' then delete;
if Year = '2006' and Location = 'Manhattan' and Block = '3' then delete;
if Year = '2006' and Location = 'Manhattan' and Block = '4' then delete;
if Year = '2012' and Location = 'North Farm F' then delete;
if Year = '2007' and Location = 'Tribune' then delete;
if Year = '2010' and Location = 'Yates Center' then delete;
run;
 Data RYF9;
 set Wheat;
 if RI9 = '0' then delete;
if F9N ='0' then delete;
if Yield = '0' then delete;
if Yield < '2' then delete;
if RecoverYRelativeDiff > '.05' then delete;
if Year = '2006' and Location = 'Manhattan' and Block = '3' then delete;
if Year = '2006' and Location = 'Manhattan' and Block = '4' then delete;
if Year = '2012' and Location = 'North Farm F' then delete;
if Year = '2007' and Location = 'Tribune' then delete;
if Year = '2010' and Location = 'Yates Center' then delete;
run;
```

Selection criteria utilized was the same as Feekes 4 with exception it was not necessary to create a filter to catch outlier observations that had noted non-N related issues. Therefore, it was not included in the code. Overall available data for Feekes 7 was low and therefore was combined with the Feekes 9 dataset.

Production Efficiency

SAS codes for creating datasets for addressing the production efficiency by growth stage:

```
Data PFPfallF4;
 Set Wheat;
if F7N >'0' then delete;
if F9N >'0' then delete;
if RelativeYield < '0.89' then delete;
if RelativeYield > '0.91' then delete;
if Yield = '0' then delete;
if PFP = '0' then delete;
run;
 Data PFPF7;
 Set Wheat;
if F7N ='0' then delete;
if RelativeYield < '0.9' then delete;
if RelativeYield > '1.0' then delete;
if Yield = '0' then delete;
if PFP = '0' then delete;
run;
 Data PFPF9;
 Set Wheat;
if F9N ='0' then delete;
if RelativeYield < '0.9' then delete;
if RelativeYield > '1.0' then delete;
if Yield = '0' then delete;
if PFP = '0' then delete;
run;
```

Selection criteria for production efficiency was fairly straightforward. Assessment of the Feekes 4 production efficiency focused on the agronomic/economic optimum range with a relative yield 0.89 to 0.91. Since N response is not linear, and it is usually not economical to fertilize for the last five to ten percent, a more reserved approach for N requirements per Mg of yield was taken to provide better profit per acre potential.

Feekes 7 and 9 will only be fertilized in intensive management operations. Therefore, achieving maximum yield with optimum N rates with highest profit per acre at the expense of more invested personnel hours is the goal. Selection criteria for relative yield ranging from 0.9 to 1 were adjusted for this purpose. Although there is an increased N requirement that is imposed with the last 10 percent of grain yield, the increased N recovery efficiency with a later season N application will offset this penalty, thus promoting more efficient, highly productive grain yield.

Feekes 4 to Feekes 9 Biomass Response to Applied Nitrogen

SAS code for creating dataset for assessing Feekes 4 biomass response:

```
Data F4toF9Bmass;
Set Wheat;
if F4N < '100' then delete;
if F7N > '0' then delete;
if F9N > '0' then delete;
if Yield = '0' then delete;
if F4toF9BR = '0' then delete;
if RelativeYield < '0.75' then delete;
run;
```

Selection criteria for the Feekes 4 biomass response function:

1. Feekes 4 applied N rate greater than 100 kg N ha^{-1}
    a. Maximum potential biomass/tiller response to applied N required removing lower N rates that may limit response due to insufficient N.
2. Relative Yield greater than 0.75
    a. Removes water stress and disease conditions that limited overall response yield and biomass response.

Appendix D - Chapter 4 Corn Raw Data

By Year and Location

2012 Scandia KSU Experiment Field

Starter	Pre-plant	V4	V6	V8-V10	V16-R1	Total N	Grain Yield
N Rate kg ha^{-1}							Mg ha^{-1}
22	90	0	0	0	0	112	10.12
22	90	0	0	0	0	112	9.87
22	90	0	0	0	0	112	9.98
22	90	0	0	0	0	112	9.16
22	180	0	0	0	0	202	11.01
22	180	0	0	0	0	202	10.85
22	180	0	0	0	0	202	10.52
22	180	0	0	0	0	202	9.21
22	280	0	0	0	0	302	12.30
22	280	0	0	0	0	302	11.60
22	280	0	0	0	0	302	11.87
22	280	0	0	0	0	302	10.65
22	45	45	0	0	0	112	8.83
22	45	45	0	0	0	112	8.13
22	45	45	0	0	0	112	8.95
22	45	45	0	0	0	112	8.77
22	90	90	0	0	0	202	12.16
22	90	90	0	0	0	202	10.91
22	90	90	0	0	0	202	11.57
22	90	90	0	0	0	202	12.32
22	140	140	0	0	0	302	11.94
22	140	140	0	0	0	302	11.54
22	140	140	0	0	0	302	11.88
22	140	140	0	0	0	302	11.75
22	45	0	48	30	24	145	10.59
22	45	0	48	30	24	145	10.99
22	45	0	48	30	24	145	10.01
22	45	0	48	30	24	145	10.16
22	90	0	0	30	19	142	10.90
22	90	0	0	30	19	142	11.05
22	90	0	0	30	19	142	10.70
22	90	0	0	30	19	142	10.90
22	140	0	38	39	19	239	12.40
22	140	0	38	39	19	239	11.68
22	140	0	38	39	19	239	11.34
22	140	0	38	39	19	239	10.94
22	0	0	0	0	0	22	8.31
22	0	0	0	0	0	22	7.97
22	0	0	0	0	0	22	6.67
22	0	0	0	0	0	22	7.02

2012 Scandia Farmer Cooperative Field

Starter	Pre-plant	V4	V6	V8-V10	V16-R1	Total N	Grain Yield
			N Rate kg ha^{-1}				Mg ha^{-1}
22	67	0	0	0	0	89	12.31
22	67	0	0	0	0	89	12.76
22	67	0	0	0	0	89	12.08
22	67	0	0	0	0	89	13.73
22	157	0	0	0	0	179	12.06
22	157	0	0	0	0	179	12.87
22	157	0	0	0	0	179	12.80
22	157	0	0	0	0	179	12.78
22	258	0	0	0	0	280	11.83
22	258	0	0	0	0	280	12.78
22	258	0	0	0	0	280	12.73
22	258	0	0	0	0	280	12.66
22	22	22	0	0	0	67	13.17
22	22	22	0	0	0	67	13.48
22	22	22	0	0	0	67	12.89
22	22	22	0	0	0	67	13.03
22	90	90	0	0	0	201	12.30
22	90	90	0	0	0	201	12.80
22	90	90	0	0	0	201	12.90
22	90	90	0	0	0	201	11.42
22	118	118	0	0	0	257	10.35
22	118	118	0	0	0	257	12.47
22	118	118	0	0	0	257	13.32
22	118	118	0	0	0	257	12.44
22	45	0	82	0	24	149	11.94
22	45	0	82	0	24	149	13.23
22	45	0	82	0	24	149	12.46
22	45	0	82	0	24	149	12.39
22	90	0	75	0	21	187	12.11
22	90	0	75	0	21	187	12.77
22	90	0	75	0	21	187	12.75
22	90	0	75	0	21	187	12.00
22	140	0	34	0	0	196	12.44
22	140	0	34	0	0	196	13.23
22	140	0	34	0	0	196	13.28
22	140	0	34	0	0	196	13.44
22	0	0	0	0	0	22	11.41
22	0	0	0	0	0	22	12.64
22	0	0	0	0	0	22	12.77
22	0	0	0	0	0	22	11.73

2013 Scandia KSU Experiment Field

Starter	Pre-plant	V4	V6	V8-V10	V16-R1	Total N	Grain Yield
			N Rate kg ha^{-1}				Mg ha^{-1}
22	67	0	0	0	0	89	10.38
22	67	0	0	0	0	89	11.21
22	67	0	0	0	0	89	10.25
22	67	0	0	0	0	89	10.19
22	134	0	0	0	0	156	11.34
22	134	0	0	0	0	156	10.32
22	134	0	0	0	0	156	11.08
22	134	0	0	0	0	156	9.81
22	202	0	0	0	0	224	10.83
22	202	0	0	0	0	224	11.34
22	202	0	0	0	0	224	10.83
22	202	0	0	0	0	224	10.38
22	34	34	0	0	0	90	11.97
22	34	34	0	0	0	90	10.13
22	34	34	0	0	0	90	10.89
22	34	34	0	0	0	90	11.15
22	67	67	0	0	0	156	10.83
22	67	67	0	0	0	156	11.66
22	67	67	0	0	0	156	10.89
22	67	67	0	0	0	156	11.40
22	101	101	0	0	0	224	11.15
22	101	101	0	0	0	224	10.76
22	101	101	0	0	0	224	10.96
22	101	101	0	0	0	224	10.38
22	45	0	0	138	0	205	10.96
22	45	0	0	138	0	205	10.76
22	45	0	0	138	0	205	10.70
22	45	0	0	138	0	205	10.70
22	90	0	0	97	0	209	11.78
22	90	0	0	97	0	209	11.08
22	90	0	0	97	0	209	10.19
22	90	0	0	97	0	209	11.40
22	134	0	0	149	0	305	10.64
22	134	0	0	149	0	305	10.51
22	134	0	0	149	0	305	10.76
22	134	0	0	149	0	305	10.57
22	0	0	0	0	0	22	9.62
22	0	0	0	0	0	22	9.55
22	0	0	0	0	0	22	9.24
22	0	0	0	0	0	22	8.98

2013 Rossville KSU Experiment Field

Starter	Pre-plant	V4	V6	V8-V10	V16-R1	Total N	Grain Yield
			N Rate kg ha^{-1}				Mg ha^{-1}
0	67	0	0	0	0	67	6.73
0	67	0	0	0	0	67	9.21
0	67	0	0	0	0	67	4.74
0	67	0	0	0	0	67	3.34
0	134	0	0	0	0	134	7.78
0	134	0	0	0	0	134	9.55
0	134	0	0	0	0	134	7.86
0	134	0	0	0	0	134	6.76
0	202	0	0	0	0	202	7.91
0	202	0	0	0	0	202	9.29
0	202	0	0	0	0	202	6.98
0	202	0	0	0	0	202	6.64
0	34	34	0	0	0	68	7.48
0	34	34	0	0	0	68	7.54
0	34	34	0	0	0	68	6.74
0	34	34	0	0	0	68	7.39
0	67	67	0	0	0	134	7.04
0	67	67	0	0	0	134	10.49
0	67	67	0	0	0	134	7.86
0	67	67	0	0	0	134	8.53
0	101	101	0	0	0	202	8.96
0	101	101	0	0	0	202	10.05
0	101	101	0	0	0	202	7.08
0	101	101	0	0	0	202	8.85
0	45	0	0	237	0	282	9.72
0	45	0	0	237	0	282	9.22
0	45	0	0	237	0	282	10.36
0	45	0	0	237	0	282	7.79
0	90	0	0	161	0	251	9.68
0	90	0	0	161	0	251	9.70
0	90	0	0	161	0	251	8.74
0	90	0	0	161	0	251	9.02
0	134	0	0	167	0	301	9.30
0	134	0	0	167	0	301	9.17
0	134	0	0	167	0	301	8.19
0	134	0	0	167	0	301	9.43
0	0	0	0	0	0	0	4.13
0	0	0	0	0	0	0	6.37
0	0	0	0	0	0	0	4.25
0	0	0	0	0	0	0	2.87

2014 Scandia KSU Experiment Field

Starter	Pre-plant	V4	V6	V8-V10	V16-R1	Total N	Grain Yield
			N Rate kg ha^{-1}				Mg ha^{-1}
22	67	0	0	0	0	89	13.12
22	67	0	0	0	0	89	12.93
22	67	0	0	0	0	89	11.91
22	67	0	0	0	0	89	13.18
22	134	0	0	0	0	156	15.41
22	134	0	0	0	0	156	13.31
22	134	0	0	0	0	156	13.25
22	134	0	0	0	0	156	14.01
22	202	0	0	0	0	224	15.35
22	202	0	0	0	0	224	14.46
22	202	0	0	0	0	224	13.38
22	202	0	0	0	0	224	15.03
22	34	34	0	0	0	90	11.66
22	34	34	0	0	0	90	12.74
22	34	34	0	0	0	90	10.19
22	34	34	0	0	0	90	12.74
22	67	67	0	0	0	156	14.52
22	67	67	0	0	0	156	12.80
22	67	67	0	0	0	156	12.29
22	67	67	0	0	0	156	15.03
22	101	101	0	0	0	224	15.48
22	101	101	0	0	0	224	14.65
22	101	101	0	0	0	224	13.82
22	101	101	0	0	0	224	16.05
22	45	0	0	0	17	67	14.14
22	45	0	0	0	17	67	14.90
22	45	0	0	0	17	67	13.57
22	45	0	0	0	17	67	14.84
22	90	0	0	0	0	112	15.41
22	90	0	0	0	0	112	12.99
22	90	0	0	0	0	112	12.99
22	90	0	0	0	0	112	14.46
22	134	0	0	0	0	156	15.29
22	134	0	0	0	0	156	14.33
22	134	0	0	0	0	156	13.50
22	134	0	0	0	0	156	14.90
22	0	0	0	0	0	22	9.94
22	0	0	0	0	0	22	11.34
22	0	0	0	0	0	22	9.49
22	0	0	0	0	0	22	10.06

2014 Rossville KSU Experiment Field

Starter	Pre-plant	V4	V6	V8-V10	V16-R1	Total N	Grain Yield
		N Rate kg ha^{-1}					Mg ha^{-1}
0	67	0	0	0	0	67	13.41
0	67	0	0	0	0	67	14.88
0	67	0	0	0	0	67	16.45
0	67	0	0	0	0	67	15.24
0	134	0	0	0	0	134	13.89
0	134	0	0	0	0	134	16.32
0	134	0	0	0	0	134	16.73
0	134	0	0	0	0	134	17.57
0	202	0	0	0	0	202	14.30
0	202	0	0	0	0	202	14.11
0	202	0	0	0	0	202	18.14
0	202	0	0	0	0	202	15.59
0	34	34	0	0	0	68	11.34
0	34	34	0	0	0	68	14.61
0	34	34	0	0	0	68	15.93
0	34	34	0	0	0	68	14.57
0	67	67	0	0	0	134	15.57
0	67	67	0	0	0	134	16.31
0	67	67	0	0	0	134	16.72
0	67	67	0	0	0	134	13.65
0	101	101	0	0	0	202	17.03
0	101	101	0	0	0	202	15.74
0	101	101	0	0	0	202	16.05
0	101	101	0	0	0	202	15.04
0	45	0	0	0	134	45	14.39
0	45	0	0	0	134	45	13.64
0	45	0	0	0	134	45	15.86
0	45	0	0	0	134	45	15.61
0	90	0	0	0	67	90	12.66
0	90	0	0	0	67	90	13.94
0	90	0	0	0	67	90	14.44
0	90	0	0	0	67	90	14.92
0	134	0	0	0	34	134	13.81
0	134	0	0	0	34	134	13.51
0	134	0	0	0	34	134	14.11
0	134	0	0	0	34	134	15.85
0	0	0	0	0	0	0	9.93
0	0	0	0	0	0	0	10.27
0	0	0	0	0	0	0	12.69
0	0	0	0	0	0	0	13.74