2018

# Evaluation of nitrogen and potassium interactions in corn

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## Recommended Citation

Hirniak, Jackson, "Evaluation of nitrogen and potassium interactions in corn" (2018). *Graduate Theses and Dissertations*. 16377.
https://lib.dr.iastate.edu/etd/16377

# Evaluation of nitrogen and potassium interactions in corn

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE

Major: Soil Science (Soil Fertility)

Program of Study Committee:
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Iowa State University

Ames, Iowa

2018

# DEDICATION

I dedicate this Thesis to 1) God, LORD of all. 2) My family for their continuous support throughout my life no matter the circumstance. 3) The H, L, N, and R families for help in shaping me into who I am today and 4) To the United States Army Infantry, FOLLOW ME!

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# CHAPTER 1: GENERAL INTRODUCTION

## Introduction

Nitrogen (N) and potassium (K) are two macronutrients needed by plants in large amounts, and in most plants they are the two nutrients needed in the highest quantities for optimum growth and development. Nitrogen has important roles in many metabolic processes and is part of many molecules including proteins and nucleic acids, which are considered base constituents of living organisms. Potassium has a major role in osmotic functions and is essential to activate many enzymes, especially those mediating amino acids, protein, and carbohydrate synthesis. Extensive research on N and K management for corn (*Zea mays* L.) including assessments on the value of soil testing and other tools to evaluate the soil N and K supply and determine optimum fertilization rates has been conducted for many decades in most states of the USA and many countries. However, there is scarce published information on interactions between N and K in corn production because most experiments have focused on one nutrient while all others are maintained or applied in non-limiting amounts.

Plant nutrients may interact when effecting nutrient uptake or crop yield. An interaction between two nutrients occurs when the crop response to different application rates of one nutrient is affected by application rates or soil supply of another nutrient. Two nutrients may increase crop yield, and yield with application of both nutrients may be higher than with each applied alone, but an interaction does not occur unless the response to the different rates of each nutrient changes compared with application of each nutrient alone. Interactions can be assessed by developing field trials with several application rates of two or more nutrients and measuring nutrient concentrations in plant tissue, nutrient uptake, yield, or nutrient removal.

A better understanding of potential N and K interactions affecting crop yield and nutrient utilization has important agronomic implications in economic and environmental contexts. Therefore, the objective of this research was to investigate potential N by K interactions in corn by evaluating the effects of various N and K combinations on grain yield, tissue N and K concentrations, and N and K removed with grain harvest.

## Thesis organization

This thesis is submitted as one paper suitable for the publication in the scientific journals of the American Society of Agronomy or Soil Science Society of America. The title of this paper is Evaluation of Nitrogen and Potassium Interactions in Corn. The paper contains sections for an abstract, introduction, materials and methods, results, discussion, summary and conclusions, reference list, tables, and figures. The paper follows a general introduction and closes with a general conclusion.

# CHAPTER 2: EVALUATION OF NITROGEN AND POTASSIUM INTERACTIONS IN CORN

*A paper to be submitted to the Soil Science Society of America Journal*

Jackson N. Hirniak and Antonio P. Mallarino

## Abstract

Research is needed to further evaluate N by K interactions in crops. The objective of this study was to evaluate potential interactions in corn (*Zea mays* L.). Two long-term trials with continuous corn were evaluated from 2013 to 2017 in two Iowa soils. Annual treatments were the combinations of five N rates (0-336 kg N ha$^{-1}$) and four K rates (0-66 kg K ha$^{-1}$) replicated three times. Grain yield, ear-leaf (R1 stage) and grain (at harvest) N and K concentrations, N and K removed with grain harvest, and post-harvest soil-test K (STK) (15-cm depth) were measured each year. Leaf N concentrations were not affected ($P \leq 0.05$) by K fertilization at either site, were increased by all N rates, and there was no N by K interaction. Leaf K concentration was increased by K, was slightly affected by N, and a significant N by K interaction indicated that N decreased leaf K without K at one site but increased leaf K with the highest K rate at the other site. Grain N concentration was increased by N at both sites, was increased by K at one site, and there was no interaction. Grain K concentration was decreased by N, was increased by K, and an interaction at one site indicated that K fertilization partially alleviated the N decreasing effect. Nitrogen and K fertilization increased grain yield, N and K removed, and significant interactions indicated that with adequate K supply the responses to N were higher and a higher N rate was needed to maximize yield compared with low K supply. The higher K removed with the higher N and

K rates sharply decreased STK over time. The study demonstrated that a K deficiency limits corn yield and also limits its capacity to respond to N fertilization.

Abbreviations: Analysis of variance, ANOVA; Completely randomized design, CRD; Randomized complete block design, RCBD; Soil-test K, STK.

## Introduction

In spite of extensive research on N and K management for corn over many decades in many states of the USA and many countries, there is scarce published information on interactions between N and K in corn production. Plant nutrients may interact and have synergistic or antagonistic effects for nutrient use efficiency, nutrient uptake, or crop yield. An interaction between two nutrients occurs when the crop response to different application rates of one nutrient is affected by application rates or soil supply of another nutrient. Two nutrients may increase crop yield, and yield with application of both nutrients may be higher than with each applied alone, but an interaction does not occur unless the response to the different rates of each nutrient changes compared with application of each nutrient alone. Interactions can be assessed by measuring nutrient concentrations in plant tissue, nutrient uptake, yield or nutrient removal.

Nitrogen often is the most limiting nutrient for crops with the exception of legume crops having the capacity to fix atmospheric N. After C, N is the second most abundant element required by plants, affecting many metabolic processes. Nitrogen dynamics in the soil is greatly affected by microorganisms' activity which mediate different types of transformations between organic and inorganic forms. Nitrogen can be lost from soils as a gas to the atmosphere through denitrification and volatilization, with surface runoff, or by leaching through the soil profile. These losses are important to consider due to the environmental footprint of N and the impact N loss has on crop growth and development. The forms of inorganic N absorbed by plants are the anionic nitrate ($NO_3^-$) form and the cationic ammonium ($NH_4^+$) form. The uptake of N from the soil to the plant occurs mostly by mass flow, which involves movement of ions in water absorbed by the plant. Diffusion and root interception are other ways by which N can reach the roots but mass flow is most prominent for N. Nitrate needs to be reduced to $NH_4^+$ in the plant in order to be assimilated. Plants cannot store large amounts of $NH_4^+$, and when the rate of $NH_4^+$ uptake is higher than the assimilation rate it has to be transformed into $NO_3^-$ (Novoa and Loomis, 1981; Mengel and Kirkby, 2001; Epstein and Bloom, 2005).

Potassium exists in the soil as a free cation ($K^+$) or as part of inorganic compounds. Due to the large composition of K in the earth's crust, soils hold anywhere from 300-50,000 kg ha$^{-1}$ of potassium to a 15-cm depth (Epstein and Bloom, 2005). Most of this K is bound in the primary and secondary minerals. Soil K fractions commonly referred to in the literature are structural K, exchangeable K, fixed or nonexchangeable K, and soil solution K (Sparks and Huang, 1985; Mengel and Kirkby, 2001). Diffusion through the soil water is the main mechanism of $K^+$ uptake by plants, although some is absorbed by mass flow and root interception mechanisms. After K is in the root system, it is rapidly distributed throughout the plant through K specific, efficient uptake systems allowing for rapid distribution (Mengel, 1996). Several books and reviews have provided extensive information concerning the role of K in cell metabolism, metabolites transport, and how those factors relate to crop growth and development. Potassium has especially important roles in the activation of many enzymes involved in carbohydrate and protein synthesis and in plant osmotic and water relations (Hsiao and Läuchli, 1986; Mengel, 1996; Oosterhuis and Eerkowitz, 1996; Mengel and Kirkby, 2001).

The corn crop responses to N and K and the optimum application rates for a variety of conditions have been studied for a long time in Iowa and the North Central Region of the USA. The most important factors determining economically optimum N rates in corn are the crop rotation (mainly the previous crop) and environmental factors (mainly temperature and rainfall) that influence N transformations in soils and N loss. Other factors, such as the source and both the timing and placement methods can also be important in some conditions. Sawyer et al. (2006), Mallarino and Sawyer (2017), and Sawyer (2018) provided comprehensive guidelines about N fertilization for corn in Iowa and how producers can identify optimum N fertilization rates. The most important differences concerning N recommendations for corn in Iowa relate to the previous crop (recommended N is the highest for corn following corn and lowest for corn following forage legumes), the Iowa region (higher for southeast Iowa where precipitation is the highest), and the crop:N price ratio. For K, the most important factors affecting the corn response to fertilization are the soil K supply and the amounts removed with harvest, although factors such as topsoil texture and mineralogy and the method of application also can be important mainly for differences across states or regions. Mallarino et al. (2013) provided soil-test K (STK) interpretations and K application guidelines for Iowa crops that are based on extensive soil-test field response research.

The vast majority of the studies conducted for N and K fertilization of corn in Iowa and elsewhere have been conducted with non-limiting application rates of the other, which has not allowed for an investigation of potential interactions between these two nutrients.

Nutrient interactions are best studied with experiments that include combinations of several fertilization rates or soil-test levels. However, these experiments are expensive and budget limitations seldom allows for conducting them in different sites and years. Barker and Bradfield (1963) working within nutrient solutions and Dibb and Welch (1976) working in a greenhouse studied the impact of $NH_4^+$ and $NO_3^-$ N sources and K application on corn growth. They reported significant interactions between N and K only when $NH_4^+$ was the main N source being absorbed. Higher $NH_4^+$ application rates required higher K rates to optimize yield and minimize tissue damage due to high $NH_4^+$ concentrations in the tissue. In reviews of K interactions with other nutrients for several crops, Dibb and Thompson (1985) and Hagin et al. (1990) referred to similar results for other crops and suggested that the most likely reason for such an interaction between $NH_4^+$ and K is the beneficial K effect on $NH_4^+$ assimilation into amino acids and not to competition for absorption sites. They suggested that since K has a role in activating enzymes required for protein and organic acids synthesis, high K concentrations enhance $NH_4^+$ assimilation and minimize toxicity. More recent research conducted with corn in the greenhouse or growth chambers found similar enhancing effects of K when the N source was $NH_4^+$ or a mixture of $NH_4^+$ and $NO_3^-$ (Xu et al., 1992; Stromberger et al., 1994).

Well-documented field studies focusing on the study of N by K interactions in corn are scarce. Loué (1978) provided an overview of results for experiments conducted in France. Arnon (1975), cited by Loué (1978), found an N by K interaction in corn 5 out of 9 years in an experiment when grain yield increases from N or K application were greater with the higher application rates of either nutrient and, interestingly, high K rates with low N rates decreased corn yield. Loué (1978) reported that a similar type of positive interaction sometimes but not always, was observed in barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), potatoes (*Solanum tuberosum*, L.), and sugar beet (*Beta vulgaris* L. subsp. v*ulgaris*). Johnston and Milford (2012) provided an overview of largely unpublished experiments conducted in the UK to study how different STK levels influence the yield and response to N fertilization of barley, potatoes and wheat. They concluded that adequate exchangeable STK levels increased crop yield and the crop response to N fertilization compared with deficient STK levels.

More recent field research focusing on N by K interactions has been conducted in the USA but has produced inconsistent results. MacKenzie et al. (1988) conducted a 4-year study with continuous corn silage in Canada that evaluated three urea N rates (0-180 kg N ha$^{-1}$) and three K (KCl) rates (0-200 kg N ha$^{-1}$). Application of N increased yield in 3 years and application of K increased yield in 2 years. In the two K responsive years there was a significant N by K interaction by which N increased yield only with the high K rates. Johnson and Reetz (1995) summarized a 4-year experiment with corn in an Ohio silt loam soil that included six spring-applied N rates (0-312 kg N ha$^{-1}$) using granulated ammonium-nitrate fertilizer and five STK levels (80 to 139 mg K kg ha$^{-1}$, no sampling depth was provided) that were created by previous KCl applications. Corn grain yield responded up to the highest N rate applied when the STK level was 100 mg kg$^{-1}$ or less, but with higher STK levels the yield was higher and the maximum yield was reached with a rate of 179 kg N ha$^{-1}$. The authors reported a similar type of interaction for N removed with grain harvest. Therefore, in contrast with previous results, in this study adequate soil K supply increased yield and reduced the N rate needed to maximize yield. A follow-up summary report (Anonymous, 1998) compared results from the Ohio study with an Illinois study with corn that evaluated five N rates (0 to 269 kg N ha$^{-1}$) and four K rates (0 to 135 kg K ha$^{-1}$). In the Illinois study (the nutrient sources and time of application were not reported) there was a positive N by K interaction by which K deficiency severely limited both grain yield and the yield response applied N. When K was not applied the maximum grain yield was 6.3 Mg ha$^{-1}$ achieved with 135 kg N ha$^{-1}$. With the highest K rate the maximum yield was 10.3 Mg ha$^{-1}$ achieved with the highest N rate applied.

Mallarino and Rueber (2003) summarized the last ten years of a long-term Iowa experiment that evaluated the effects of N, P, K, and lime annual applications to continuous corn managed with tillage. They reported that all treatments increased corn yield compared with non-fertilized soil but only N and K showed an interaction. The N was applied in the spring (urea) and the K in the fall (KCl). With optimum P and K levels, N increased grain yield with decreasing increments up to the highest N rate (269 kg N ha$^{-1}$) with no plateau yield and a maximum for the highest N rate used of 10.67 Mg ha$^{-1}$. With optimum P and low K, however, corn responded only up to a rate of 212 kg N ha$^{-1}$ rate and the maximum yield was 8.47 Mg ha$^{-1}$. Therefore, this study showed a positive N by K interaction because adequate K increased yield and the N rate needed to maximize yield. More recently, Bruns and Ebelhar (2006) conducted two one-year experiments at one Mississippi location to evaluate the corn response to five N rates (134 to 314 kg N ha$^{-1}$, a zero N rate was not included) and four K application rates (0 to 134 kg K ha$^{-1}$). The N (ammonium- nitrate solution) was applied before planting and sidedressed at the V6 growth stage, whereas liquid K was sidedressed only at the V6 growth stage. The authors reported that N fertilization increased grain yield but K fertilization did not (presumably because of adequate STK levels even without K application). Nitrogen increased the N concentration of ear leaves at the R2 growth stage, immature ears, grain, and stover whereas K addition increased the K concentration in most tissues except grain. There were no N by K interactions for tissue concentrations and nutrient removal. Rutkowska et al. (2014) evaluated several N fertilization rates (0-250 kg N ha$^{-1}$) with or without K application during 4 years for a barley-corn rotation in Poland, with each crop grown each year (the nutrient sources and time of application were not reported). In corn, they reported no N by K interaction for grain yield but there was an interaction for N and K uptake at harvest, by which the response to K was much greater for the higher N rates than the lower rates. In barley there were interactions for yield and both N and K uptake, by which the responses to K were much greater for the higher N rates than the lower rates.

The summarized literature indicated that an N by K interaction in corn is likely but the type of interaction was inconsistent across trials and many of the published studies did not provide adequate soil and STK information to help understand possible reasons for the inconsistent results. A better understanding of how K supply influences corn grain yield and the response to applied N is especially important given current lower grain prices and profits for producers and increasing public concerns about N management effects on water quality. Therefore, the objective of this research was the investigate the potential for N by K interactions in corn by evaluating the effects of various N and K combinations on grain yield, tissue N and K concentrations, and N and K removed with grain harvest.

## Materials and Methods

### Sites and Treatments

Two field experiments with continuous corn harvested for grain were established at Iowa State University Research farms in 2013 and were evaluated until 2017. One trial was located at the Northern Iowa Research Farm (NIRF site) near Kanawha in Hancock County, on an area with Nicollet soil series (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). The other trial was located at the Southeast Iowa Research Farm (SERF site) near Crawfordsville in Washington County, on an area with Mahaska soil series (fine, smectitic, mesic Aquertic Argiudolls). Fertilization treatments replicated three times at both sites were the factorial combinations of five annual N rates (0, 84, 168, 252, 336 kg N $ha^{-1}$) and four annual K rates (0, 22, 44, 66 kg K $ha^{-1}$). At SERF, additional treatments were 0 and 56 kg S $ha^{-1}$. Treatments and replications were arranged as a completely randomized design (CRD) at NIRF and as a randomized complete block (RCBD) split-plot design at SERF with S treatments in large plots and the N and K treatment combinations in subplots. Plot size was 6 m (eight rows spaced 76.2 cm) by 12 m at NIRF and 6 m (eight rows spaced 76.2 cm) by 16.5 m at SERF.

Both trials were managed with a fall chisel-plow tillage and spring disk tillage. The chisel plow used had shanks that tilled the soil 15 to 25 cm deep and were spaced 30 cm apart, and the disk harrow mixed the top 10- to 12-cm of soil. The N fertilizer source at NIRF was granulated urea, which was broadcast in the spring and incorporated into the soil by disking 1 to 2 wk before planting corn. The N source at SERF was urea ammonium-nitrate solution (UAN), injected between the corn rows to a depth of 10 to 15 cm at the V4 to V5 growth stage (Abendroth et al., 2011). The K source at both sites was granulated KCl (potash), which was broadcast in the spring before disking prior to planting corn. Table 1 shows the hybrids used, planting dates, and plant populations measured between the R1 and R4 growth stages depending on the site and year. The plant populations were close to desired targets, except at SERF in 2013 when emergence was poor and stands were reduced by excess spring rainfall. Use of appropriate pre-emergent and post-emergent herbicides eliminated the presence of weeds at both sites. Non-limiting rates of P (granulated triple superphosphate) were applied periodically at both sites to maintain soil-test P within the high interpretation category (21 to 30 mg P kg$^{-1}$, Bray-P1 test, 15-cm depth), for which no P is recommended in Iowa (Mallarino et al., 2013). Sulfur rates ranging from 28 to 34 kg S ha$^{-1}$ were applied each year across all NIRF plots to avert S deficiency.

The trial sites had been managed with continuous corn, similar soil management, and similar N and K fertilization treatments from 2009 until 2012. During this period, however, plots at NIRF had been subdivided into two 4-row plots to evaluate two corn hybrids and plots at SERF had two hybrids as the large plot treatment (which were subdivided to apply the 20 N by K treatment combinations). The results from this previous period were summarized only for a poster and published abstract (Oltmans and Mallarino, 2103). For the study reported here (2013 through 2017), only one hybrid was planted across the 8-row plots at NIRF. At SERF, where two hybrids had been evaluated in large plots, the hybrid treatments were discontinued to use only one hybrid for the entire trial, and the two S treatments were re-randomized to the large plots of each block in which the two hybrids had been evaluated.

## Soil and Plant Measurements

Table 2 shows soil properties characterization from a composite soil sample (12 soil cores, 15-cm depth) collected across the entire area of each site in fall of 2012 (after the 2012 crop harvest and before planting corn in 2013). The soil samples were dried at 40 °C and crushed to pass through a 2-mm sieve. Soil pH was measured by the 1:1 soil-water ratio method (Peters et al., 2012). Soil organic matter was measured by a combustion method described by Wang and Anderson (1998). Extractable Ca, Mg, K, and Na were measured by the ammonium-acetate extractant (Warncke and Brown, 1998) and measuring concentrations in extracts by inductively-coupled plasma (ICP) spectrometry. The soil cation exchange capacity (CEC) was estimated by the summation method suggested for the North Central Region of the U.S. by Warncke and Brown (1998).

Table 3 shows the initial STK for the current study from samples collected from all plots of both trials in the fall of 2012. At NIRF, the previous history of N and K applications for corn crops grown from 2009 until 2012 determined different STK values but there was no significant N by K interaction. On average across the N rates, the K rates increased STK linearly, with an observed decrease of 84 mg K kg$^{-1}$. The previous N applications decreased STK linearly at this site, probably because of the impact of increased yield and K removal with increasing N rates, but the effect was smaller and more variable compared with increases by K application (a decrease of approximately 40 mg K kg$^{-1}$). At SERF, the previous history of K applications from 2009 until 2012 determined an increase in STK as the K rate increased but there was no significant N rate or N by K interaction effect. On average across the N rates, the K rates increased STK linearly, with an observed decrease of 50 mg K kg$^{-1}$. According to current Iowa State University STK interpretations for the ammonium acetate method using dried samples (Mallarino et al., 2013), STK values encompassed the low to very high interpretation categories at NIRF and the optimum to high categories at SERF. The STK interpretation categories for the low, optimum, high, and very high interpretation categories are 121 – 160, 161 – 200, 201 – 240, and > 240 mg K $kg^{-1}$, respectively. Potassium recommendations for corn are 84 kg K $ha^{-1}$ for the low category, a rate based on estimated K removal for the optimum category, and none for the high and very high categories except for a common starter rate under some conditions (Mallarino et al., 2013).

At both sites, the corn leaf blade below and opposite to the primary ear was taken from ten plants of each plot at the R1 growth stage (Abendroth et al., 2011). The leaf samples were dried in a forced-air oven at 60 °C and ground to pass through a 2-mm sieve. Grain was harvested with a plot combine from central areas of each plot (32.4 $m^2$ at NIRF and 45 $m^2$ at SERF). A grain sample was taken from each plot at harvest time and was ground to flour particle size using a flour mill. The total K concentration in both tissues was measured by digesting the samples in concentrated $HNO_3$-$H_2O_2$ (Zarcinas et al., 1987) and measuring the concentration in the digests by ICP spectrometry. The N and K concentrations shown for both tissues are expressed on a dry matter basis. Grain yield was adjusted to a moisture concentration of 155 g $kg^{-1}$. Precipitation and growing degree days information was obtained from weather stations distant 25 km from the NIRF site and 22 km from the SERF site, and data is summarized in Table 4.

## Data Management and Statistical Analyses

Analysis of variance (ANOVA) evaluated treatment effects on all measurements for each site and year and across years for each site. The analyses were conducted using PROC MIXED of SAS (SAS, 2012) for a CRD design at NIRF and a RCBD at SERF assuming fixed treatment effects, random replication and year effects, and year as repeated measures. Sources of variation of analyses by site and year for NIRF data were N rate, K rate, and the interaction N rate by K rate whereas the analyses across years by site also included year and the corresponding interactions. Sources of variation of analyses by site and year for SERF data were S rate, N rate, K rate, and the corresponding interactions whereas the analyses across years by site also included year and the corresponding interactions. The study included four K application rates (including the control) and the measurements response to the applied K often did not differ between rates of 22, 44, and 66 kg K ha$^{-1}$. Therefore, when the main effect of K was significant ($P \leq 0.05$), differences between the K rates were assessed by orthogonal comparisons for the control vs. average of fertilized, the 22 kg vs. the mean of the two highest rates, and between the two highest rates. Because the study included five N rates and often there were large differences among the N rates, the differences between the N rates were assessed by linear and quadratic orthogonal comparisons. When the N by K interaction was significant ($P \leq 0.05$), the sums of squares of the interaction was partitioned by using the SLICE option of the LSMEANS procedure of SAS (SAS, 2012) and by orthogonal comparisons of the type used for main effects of N and K.

Response models were fit to summarize the average measurements response to N and K application across years for each site. When the ANOVA indicated significant ($P \leq 0.05$) for N application rate or the interaction N by K, the response to N rate was further studied by fitting response models. A single response model was fit when there were no significant differences among the four K rates, and two or more models were fit when there were differences between two or more K rates. The models linear, quadratic, segmented quadratic-plateau, and exponential asymptotic to a maximum or minimum were fit using the REG or NLIN procedures of SAS (SAS, 2012) or Sigmaplot 13.0 (Systat Software Inc., 1735 Technology Drive, Suite 430, San Jose, CA 95110, USA). A curvilinear model was chosen to describe the response only when its residual sums of squares were significantly smaller ($P \leq 0.05$) than for the linear model, which was tested by $F$ test of the model residual sums of squares. When more than one curvilinear model was statistically similar and the distribution of residuals showed no significant trend, we fit the curvilinear model with the highest $R^2$ value.

At the SERF site, the S application had no statistically significant effects ($P \leq 0.05$) on any crop measurement or STK and there were no significant interactions with N rate or K rate. Therefore, results for S are not shown, and the data and corresponding statistics presented are across the two S application rates. There was excessive rainfall in 2013 at the SERF site (Table 4), especially during spring, which resulted in corn stand loss, very low grain yield, and very high variability for all measurements. Therefore, data from this year are not included in ANOVAs across years and in tables or figures.

# Results

## Treatment Effects on Corn Grain Yield

Table 5 shows the effects of N and K fertilization on corn grain yield across five years at NIRF and four years at SERF (excluding 2013). Nitrogen and K fertilization increased grain yield at both sites, and the N by K interaction was significant ($P \leq 0.05$) at both sites. At both sites, the average yield response to N across all K rates was curvilinear with decreasing increments (as indicated by significant linear and quadratic orthogonal coefficients). The yield response to K was different between the two sites. At NIRF, the average yield response to K across all N rates was statistically similar for rates of 22, 44, and 66 kg K ha$^{-1}$ as indicated by categorical orthogonal comparisons. At SERF, there was a yield response up to the highest K rate (66 kg K ha$^{-1}$). Observation of the yield results for the N and K rate combinations in Table 5 shows that the significant N by K interaction at both sites is explained by a higher yield response to N when K was applied or a higher response to K when the higher N rates were applied. A partition of the N by K interaction sums of squares (not shown) indicated that at NIRF, the interaction was due to a larger response to N for the mean of plots receiving K compared with the control whereas at SERF the interaction was due to increasing response to N as the K rate increased. The results for NIRF indicates that K application rates higher than 22 kg ha$^{-1}$ yr$^{-1}$ were not needed to achieve maximum corn yield or for efficient N uptake and utilization.

Graphs provide a better visual representation of interaction effects, and Fig. 1 summarizes data in Table 5. The graph for NIRF depicts the corn yield response to N without K application and the mean of the three K rates. With no K application, the fitted quadratic-plateau response model indicates that a maximum yield of 11.74 Mg ha$^{-1}$ occurred with 192 kg N ha$^{-1}$. With K application, however, the fitted exponential model rising to a maximum indicates that the maximum yield would have been achieved with an N rate higher than the highest rate of 336 kg N ha$^{-1}$. The yield response to K was statistically significant but very small for the N rates of 0 to 168 kg N ha$^{-1}$ and was much larger for the two highest N rates. The graph for SERF depicts the corn yield response to N without K application and with the highest K rate of 66 kg ha$^{-1}$. Data for the intermediate K rates were not depicted in the graph to avoid excessive clutter. The type of N by K interaction at this site was similar to that observed at NIRF but there was a notable difference. At SERF, quadratic-plateau response models with a maximum within the range of applied N rates fitted the response to N when K was not applied and when the highest K rate was applied. Both the maximum yield and the N needed to achieve the maximum were higher for the highest K application rate (13.92 Mg ha$^{-1}$ and 241 kg N ha$^{-1}$) than for the zero K rate (12.82 Mg ha$^{-1}$ and 210 kg N ha$^{-1}$). A lack of parallelism of the lines of the two fitted models for each site clearly shows the interaction between N and K.

Statistics in Table 5 show that the interaction N by year was significant at both sites but the K by year and the triple interactions were not significant at either site. The yields for each year and results of analysis of variance (not shown) from both sites indicated that the N by year interaction was explained by different magnitude of yield increases and in some years different N rates needed to achieve the maximum yield. The responses to K and the type of N by K interactions were similar to results for the means across years. The magnitude of yield responses to K increased over time at both sites, however. Average yields for the two highest N rates and plots receiving K fertilization were 12.16, 10.62, 13.57, 14.58, and 17.81 Mg ha$^{-1}$ from 2013-2017 at NIRF, respectively. Average yields for the two highest N rates and plots receiving K fertilization were 8.60, 13.84, 15.32, 14.18, and 16.13 Mg ha$^{-1}$ from 2013-2017 at SERF, respectively.

## Treatment Effects on Corn Ear-Leaf Nitrogen and Potassium Concentrations

Table 6 shows the effects of N and K fertilization on corn ear-leaf N concentrations across five years at NIRF and four years at SERF (excluding 2013). Nitrogen fertilization increased N leaf concentration at both sites. Potassium fertilization did not affect leaf N concentrations at any site. The N by K interaction was not significant ($P \leq 0.05$) at either site. At both sites, orthogonal comparisons indicated that the average leaf N response to N fertilization was curvilinear with decreasing increments to a maximum. Figure 2 summarizes data in Table 6 by depicting the N leaf concentration response to N fertilization for means across all K rates (including the 0-K rate) since there was no K fertilization effect and no N by K interaction. Statistics in Table 6 show that the interaction N by year was significant at both sites, the K by year interaction was not significant at either site, and the triple interaction was significant only at NIRF. The leaf N concentration data for each year and corresponding results of analysis of variance (not shown) from both sites indicated that the N by year interaction was explained by different magnitude of the N concentration increases and in some years different N rates were needed to achieve the maximum concentration. The significant N by K by year interaction at NIRF was explained by a significant N by K interaction in 2013 when K increased the leaf N concentration only when 0 or 84 kg N ha$^{-1}$ was applied, which has no reasonable explanation because K did not increase the leaf N concentration in any other year.

Table 7 shows the effects of N and K fertilization on corn ear-leaf K concentration across five years at NIRF and four years at SERF (excluding 2013). Nitrogen and K fertilization affected the leaf K concentration at both sites, and the N by K interaction was significant ($P \leq 0.05$) at both sites. Fig. 3 allows for a better visualization and understanding of leaf K data in Table 7. The graphs for both sites depict the leaf K response to N fertilization with data points for each of the four K rates because these rates differed for leaf K means across all N rates (Table 7), whereas response models were fitted according to results of a partitioning of the sums of squares of the N by K interaction with orthogonal comparisons (not shown). The effect of N on leaf K concentrations and the type of interaction with K differed between the sites. At NIRF, N fertilization affected the leaf K concentration response only for the 0-kg K rate, and the K concentration decreased asymptotically to a minimum with increasing N rates. At SERF, N fertilization affected leaf K concentration response only for the highest K rate (66 kg K ha$^{-1}$) and the K concentration increased asymptotically to a maximum.

Statistics for corn ear leaf K concentrations in Table 7 show that the interaction K by year was significant ($P \leq 0.05$) at both sites, the interaction N by year was significant at $P \leq 0.05$ at SERF but only at $P = 0.06$ at NIRF, and the N by K by year interaction was not significant at either site. Observation of data and statistics by year indicated that at both sites the K by year interaction was explained by a different magnitude of the response to K and in the early years the two highest K rates did not differ (in 2013 and 2014 at NIRF and in 2014 at SERF). The data by year indicated inconsistent leaf K responses to N fertilization at both sites (not shown). At NIRF, there were no N effects in 2013 and 2016, a small decreasing N effect in 2014 and 2015, and a small increase in 2017.

## Treatment Effects on Corn Grain Nitrogen and Potassium Concentrations

Table 8 shows the effects of N and K fertilization on corn grain N concentration at harvest across five years at NIRF and four years at SERF (excluding 2013). Nitrogen fertilization increased the grain N concentration at both sites, K fertilization did not affect the grain N concentration at NIRF but increased it at SERF, and the N by K interaction was not significant ($P \leq 0.05$) for either site. Orthogonal linear and quadratic comparisons indicated that the average grain N concentration responses to N across all K rates was curvilinear with decreasing increments to a maximum at both sites. Categorical orthogonal comparisons for SERF indicated that the response to K fertilization occurred only up to the 22-kg rate (statistically similar concentrations for the rates of 22, 44, and 66 kg K). Figure 4 summarizes the data in Table 8 by depicting the N concentration response to N fertilization rates. The graph for NIRF depicts the average of N concentration responses across all K rates because there were no significant K effects. The graph for SERF shows one model fit to the data for the 0 K and another to means across rates of 22, 44, and 66 kg K ha$^{-1}$ because of the different N concentration response to K. Although the data for SERF seems to indicate an N by K interaction, this was not significant for 0.05 or 0.10 probability levels. Statistics in Table 8 show that the interaction of N by year was significant at both sites, but the K by year and triple interactions were not significant at either site. The N concentrations for each year and results of analysis of variance (not shown) indicated that the N by year interaction was explained by different magnitude of N grain concentration increases and in some years different N rates needed to achieve the highest concentration.

Table 9 shows the effects of N and K fertilization on corn grain K concentration across five years at NIRF and four years at SERF (excluding 2013). Nitrogen fertilization decreased the grain K concentration and K fertilization increased K concentrations at both sites. Orthogonal linear and quadratic comparisons indicated that the N fertilization decreasing K concentrations was linear at both sites. Categorical orthogonal comparisons indicated that the K fertilization effect at increasing K concentrations occurred only up to the 22-kg rate (statistically similar concentrations for the rates of 22, 44, and 66 kg K). The N by K interaction was statistically significant ($P \leq 0.05$) only at SERF. Fig. 5 summarizes data in Table 9 by showing the grain K concentration response to N without K application and the mean of the three K rates. The data points and fitted lines for models clearly show a large K effect but lack of N by K interaction at NIRF, and a smaller K effect but an interaction N by K at SERF with smaller decreasing effect of N when K was applied. Statistics in Table 9 show that the interaction N by year was significant at both sites. The interaction was explained by different N rates needed to achieve the maximum K concentration in different years (not shown). Table 9 indicates that the K by year and the N by K by year interactions were not significant at either site.

## Treatment Effects on Nitrogen and Potassium Removed with Corn Grain Harvest

Fertilization with N and K increased N and K removed with grain harvest and the responses were approximately similar to results for grain yield because the magnitude of differences for yield were relatively much larger than for concentrations. Table 10 shows results for N removed. At both sites, the average N removal response to N across all K rates was curvilinear with decreasing increments (as indicated by linear and quadratic orthogonal coefficients). The N removal response to K was different between the two sites. At NIRF, categorical orthogonal comparisons indicated that the average N removal response to K across all N rates was statistically similar for rates of 22, 44, and 66 kg K ha$^{-1}$. At SERF, however, and in contrast to results for yield, there was an N removal response up to the highest K rate applied of 66 kg K ha$^{-1}$. The N by K interaction was significant ($P \leq 0.05$) at both sites. Observation of the N removed results for the N and K combinations in Table 10 shows that the interaction is explained by a higher removal response to N when K was applied at both sites. A partition of the N by K interaction sums of squares (not shown) indicated that at NIRF, the interaction was due to a larger response to N for the mean of plots receiving K compared with the control whereas at SERF the interaction was due to increasing response to N as the K rate increased.

Figure 6 summarizes N removal responses to N rates in Table 10 according to the response to K. The graph for NIRF depicts the N removal response to N without K application and for the mean of the three K rates. The fitted quadratic-plateau response model indicates a maximum removal of 124.5 kg N ha$^{-1}$ with a rate of 232 kg N ha$^{-1}$ without K application. With K application, however, the fitted exponential model indicates maximum N removal would have been achieved with an N rate higher than the highest rate applied of 336 kg N ha$^{-1}$. The graph for SERF depicts the N removal response to N without K application and with the highest K rate of 66 kg K ha$^{-1}$. The type of N by K interaction at this site was similar to that observed at NIRF but in this site quadratic-plateau response models with a maximum within the range of applied N rates fitted the response to N with or without K application. At both sites, the N removal response to K was statistically significant but very small for the N rates 0-168 kg N ha$^{-1}$ and was much larger for the two highest N rates.

Statistics in Table 10 show that the interaction N by year was significant at both sites, the K by year interaction was significant only at SERF, and the N by K by year interaction was not significant at either site. The N removal for each year and results of analysis of variance (not shown) for both sites indicated that the N by year interaction was explained by different magnitude of the N removal increases and different N rates needed to achieve the maximum N removed across the years. The K by year interaction at SERF was explained by an N removal response up to higher K rates in the recent years compared with the early years.

Table 11 shows the effects of N and K fertilization on K removed with corn grain harvest across five years at NIRF and four years at SERF. Nitrogen fertilization increased K removed with harvest at both sites. The average K removal response to N across all K rates was curvilinear with decreasing N rate increments at both sites. At NIRF, K removed responded up to the 22-kg rate at NIRF (rates of 22, 44, and 66 kg K ha$^{-1}$ did not differ) and up to the 44-kg rate at SERF (rates of 44 and 66 kg K ha$^{-1}$ did not differ). The N by K interaction was significant ($P \leq 0.05$) at both sites. Figure 7 allows for a better visualization of the interaction effects in Table 11 by showing the K removal response to N fertilization rates. The graph for NIRF depicts the K removal response to N without K application and the mean of the three K rates. With no K application, the fitted quadratic-plateau response model indicates a maximum K removal of 36.8 kg K ha$^{-1}$ occurred with 193 kg N ha$^{-1}$. With K application, however, the fitted exponential model rising to a maximum indicates that the maximum K removal would have been achieved with an N rate higher than the highest N rate applied. The graph for SERF depicts K removal response to N without K application and with the average of the two highest K rates (44 and 66 kg K ha$^{-1}$). At this site, quadratic-plateau models fitted the K removal response with maxima achieved with 169 kg K ha$^{-1}$ when K was not applied and 192 kg K ha$^{-1}$ for the average of 44 and 66 kg K ha$^{-1}$ rates. Therefore, K fertilization at SERF and application of the two highest K rates increased the K removal response to N and the maximum removal occurred for higher N rates compared with no K application or lower K rates.

Statistics in Table 11 show that the interaction N by year was significant at both sites but the K by year and the triple interactions were not significant at either site. The removal rates each year and results of analysis of variance for both sites (not shown) indicated that the N by year interaction was explained by different magnitude of the K removal increases and different N rates needed to achieve maximum K removal.

## Treatment Effects on Soil-Test Potassium

Table 12 shows the effects of N and K fertilization on STK from post-harvest soil samples (15-cm depth) taken at both sites from fall 2013 until fall 2016. Soil-test K levels ranged from 93 – 250 mg K kg $^{-1}$ and 111 – 235 mg K mg$^{-1}$ at NIRF and SERF, respectively. These values range from the very low (0 to 120 mg K kg$^{-1}$) at both sites to very high at NIRF (> 240 mg K kg$^{-1}$) and high at SERF (201 to 240 mg K kg$^{-1}$) according to Iowa State University interpretation categories for STK measured on dried soil samples (Mallarino et al., 2013). Nitrogen fertilization with incremental N rates decreased STK linearly ($P \leq 0.05$) in all years at NIRF but only from 2014 to 2016 at SERF. Potassium fertilization with incremental K rates increased STK linearly in all years of both sites. There was no significant N by K interaction except for 2015 at SERF. Study of this interaction by partitioning its sums of squares (not shown) indicated that the effect of N at decreasing STK was more pronounced (steeper slope) for the two highest K rates than for the two lowest rates. Also, the STK increase from K fertilization was greater for the lower N rates than for the higher N rates.

This type of response was also observed in 2016 at SERF and in the last two years at NIRF, but the interaction did not reach statistical significance even at the 0.10 probability level.

Soil-test K values decreased over time for most N and K treatment combinations at both sites. An ANOVA across years for NIRF using data for each treatment combination including the initial (Table 2) and post-harvest STK data (Table 12) indicated that STK decreased over time for all N by K combinations (not shown). This analysis of variance showed significant effects of N rate, K rate, year, and the interaction K rate by year but the interaction N by K was not significant ($P \leq 0.05$) (not shown). Regression analyses of STK on year for each treatment combination indicated significant linear effects for all treatment combinations (not shown).

An ANOVA for STK across all 5 years for SERF also indicated that STK decreased over time but the decreases were less pronounced, and there was higher temporal unexplained variation compared with NIRF results. At this site, all STK values were unreasonably low in 2015 and all values were unreasonably high in 2016 (Table 12 and Fig. 8). Previous research has shown that the temporal variability of STK can be very high (and much higher than for soil-test P) and be unrelated to K removal with harvest (Mallarino, 2016) and may be due to poorly understood reactions between K in different soil pools affected by soil moisture changes. The ANOVA indicated significant effects of N rate, K rate, and year as well as a significant interactions of N by K and K by year (not shown). A partition of the interaction sums of squares with the SLICE options of SAS or orthogonal comparisons showed that the interaction was explained by a smaller N rate effect when rates of 0 or 22 kg K ha$^{-1}$ were applied. Regression analyses of STK on year for each treatment combination (not shown) indicated significant linear decreasing effects for all treatment combinations with only three exceptions. The exceptions were that STK did not decrease over time for the treatment combinations 44-kg K rate with zero N and the 66-kg K rate with the two lowest N rates (0 and 84 kg N ha$^{-1}$). In spite of a significant N by K interaction for STK at SERF, the graphs for means of one nutrient across the other summarize in a useful way the impacts of K and N rates on STK trends over time.

## Discussion

Results showed a similar, general type of positive N by K interaction in corn grain yield and amounts of both nutrients removed with harvest at both sites. The yield and removal responses to K were smaller with low N rates and higher with the higher N rates. At the same time, the yield and removal responses to N fertilization were higher and to higher N rates when K was applied. The magnitude of yield responses to N and its variation across sites and years were within what has been observed for continuous corn in Iowa (Sawyer et al., 2006; Sawyer, 2018). The yield and removal responses to K were to a higher rate at SERF than at NIRF, although initial STK of plots receiving no K were slightly lower at NIRF (149 mg K kg$^{-1}$ on average) than at SERF (169 mg K kg$^{-1}$ on average). Both values are borderline between the low and optimum interpretation categories (160 mg K kg$^{-1}$), and the results should not be surprising. Research on correlation of STK methods across many sites has shown this magnitude of differences across sites and years which could not be clearly explained by differences in soil series or properties (Barbagelata and Mallarino, 2013). Soil-test K results indicated that the observed interaction occurred between deficient and adequate levels. There was no evidence for a need for higher STK than recommended in Iowa for corn production (maintain levels in the optimum category by applying removal-based K rates) even with the highest N rates.

The observed N and K effects on STK (Table 12 and Fig. 8) are reasonable given the effects of these nutrients on K removal with grain harvest across the years that were shown in Table 11 and Fig. 7. At NIRF, the largest amounts of K removed were for the three higher K rates (which did not differ) and the highest N rate. At SERF, the largest amounts of K removed were for the two highest K rates (which did not differ) and the two highest N rates (which did not differ). The K applied with the highest annual K rate of 66 kg K ha$^{-1}$ was much higher than the K removed with harvest. The amount of K applied with the 44-kg K rate also was higher than the K removed except for the highest N rate at NIRF. The very large corn yield response to N resulted in a large increase in K removal with the higher N rates, and the annual rate of 66 kg K ha$^{-1}$ did not maintain initial STK values. These results might be explained by applied K movement below the 15-cm sampling depth or transformations to soil K forms not measured by the soil-test method used.

The type of positive interaction between N and K identified in this study for corn yield and nutrient removal (higher corn responses to N with higher K rates) is in agreement with results reported for some studies but not with others. The observed interaction agrees with results of studies with corn reviewed by Loué (1978) and Johnston and Milford (2012) and with results of studies by MacKenzie et al. (1988), Anonymous (1998), and Mallarino and Rueber (2003). Our results contrast with others showing a higher corn yield response to N with high K rates but the N rate needed to maximize yield was lower than with deficient K (Johnson and Reetz, 1995), no interaction for grain yield but a positive interaction for N and K removed (Rutkowska et al., 2014), or no interaction (Bruns and Ebelhar (2006). Reasons for different types of interaction are not clear or straightforward. Potassium soil-test levels could play a role. Most studies, including ours, have shown that a higher corn response to N with K occurs when it is compared with deficient levels (lower than normally recommended). This may explain a lack of interaction and a yield decrease with high K when no N is applied but not necessarily that a lower N rate may be needed to maximize yield.

Results from this study showed a stronger N by K interaction for K removed with harvest than for yield or N removed. Few of the reviewed studies measured nutrient removal, and our results were also observed by (Rutkowska et al., 2014) but not by (Johnson and Reetz, 1995). Treatment effects on grain K concentrations partly explain the stronger interaction for removed K in our study. Potassium fertilization greatly increased the grain K concentration at NIRF, this effect was similar for all N rates, and did not alleviate a strong N fertilization effect at reducing grain K concentration (Table 9 and Fig. 5). At SERF, K fertilization increased the grain K concentration only with the higher N rates, which alleviated the negative effect of increasing N rates (Table 9 and Fig. 5). Results for leaf K concentrations were in great contrast to effects on grain K concentrations. The leaf K results (Table 7 and Fig. 3) confirmed results of previous studies in that K fertilization greatly increases the K concentration of corn vegetative tissues compared with increases of K concentration in grain (Clover and Mallarino, 2013). Another important result shown by Table 7 and Fig. 3 was that N fertilization had very small effects on leaf K concentrations and the effects were inconsistent across sites.

The measurements in this study and published field studies were not adequate to assess if effects of K on $NH_4^+$ absorption and assimilation shown by studies under controlled conditions could explain the observed N by K interaction (Barker and Bradfield, 1963; Dibb and Welch, 1976; Dibb and Thompson, 1985; Hagin et al., 1990; Xu et al., 1992; Stromberger et al., 1994). The N sources used were urea at NIRF and urea-ammonium nitrate solution at SERF, both applied in the spring (1-2 wk before planting corn at NIRF and at the V4-V5 growth stage at SERF). Some of those effects might have occurred because research has shown rapid nitrification of $NH_4^+$ to $NO_3^-$ in the spring but also significant concentrations of $NH_4^+$ weeks after the application.

## Summary and Conclusions

Results from both sites revealed significant grain yield increases from N and K fertilization and there was a positive interaction by which responses to both nutrients were higher when both were applied together. At one site, the yield response to K was similar for rates of 22, 44, and 66 kg K $ha^{-1}$ for all N application rates but the magnitude of the yield increase was greater with the two highest N application rates, and yield increases from N application were greater and up to a higher N rate when K was applied. At the other site, the yield response to K was up to the 44-kg K rate for all N application rates but the magnitude of the yield increase was greater with the two highest N application rates, and the yield increases from N application were greater and up to a higher rate when K was applied. Nitrogen and K removal responses were approximately similar to yield responses and showed the same type of N by K interaction. However, the interaction effects were greater for K removed than for grain yield and N removed because of different N and K effects on grain nutrient concentrations. Nitrogen fertilization increased the grain N concentration at both sites but K fertilization increased it only slightly at one site, and there was no N by K interaction. However, N fertilization greatly decreased grain K concentration at both sites but

K fertilization increased it at both sites, and there was an N by K interaction only at one site (K fertilization alleviated the decreasing effect of N fertilization).

Soil-test K results indicated that the observed N by K interaction for grain yield occurred between deficient and adequate levels. There was no evidence of a need for STK levels higher than levels recommended in Iowa for corn production. However, the much higher N and K removal with the higher N rates determined large STK decreases that even the highest annual K rate of 66 kg K ha$^{-1}$ could not avoid. Such a rate is slightly higher than currently recommended maintenance K rates in Iowa for comparable yield levels.

The N, K, and interaction effects for leaf tissue differed from those for yield and nutrient removal. Leaf N concentrations were not affected by K fertilization at either site, were greatly increased by all N fertilization rates at both sites, and there was no N by K interaction. Leaf K concentrations were greatly increased by all K fertilization rates at both sites, and were only slightly affected by N fertilization with inconsistent results across sites.

Overall, this study confirmed the positive type of N by K interaction observed in a previous Iowa study. Adequate fertilization of N and K is needed to maximize grain yield. A K deficiency not only limits corn yield but also limits its capacity to respond to N fertilization. The measurements did not allow determination of supported reasons for the interaction. The interaction occurred when comparing corn response with deficient or adequate K supply. Higher than currently recommended STK or K fertilization levels were not needed to maximize yield and the response to N. However, higher yields with adequate K supply and the higher N rates needed to maximize yield resulted in large amounts of K removed with harvest that sharply decreased STK over time. Therefore, the study showed that adequate K supply is essential to optimize yield and N utilization by corn.

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## Tables and Figures

Table 1. Corn hybrids, planting dates, and plant populations at two sites.

| Site | Year | Hybrid | Planting date | Population |
|---|---|---|---|---|
| NIRF | 2013 | Dekalb DKC53-56RIB | 13 May | 82362 |
| | 2014 | Channel 202-64STXRIB | 23 May | 81871 |
| | 2015 | Channel 203-44STXRIB | 28 Apr | 71893 |
| | 2016 | Becks 5337STX | 23 Apr | 72241 |
| | 2017 | Dekalb DKC51-38RIB | 7 May | 78366 |
| SERF | 2013 | Pioneer 1395AMX | 1 May | 57246 |
| | 2014 | Pioneer P0636AMX | 6 May | 81595 |
| | 2015 | Dekalb DKC62-97RIB | 1 May | 74725 |
| | 2016 | Dekalb DKC64-87RIB | 20 Apr | 75741 |
| | 2017 | Dekalb DKC60-67RIB | 9 May | 82362 |

Table 2. Initial soil characterization for two sites (15-cm depth).

| Property | NIRF | SERF |
|---|---|---|
| pH | 5.5 | 5.4 |
| Org. matter (g $kg^{-1}$) | 42.5 | 47.8 |
| Sand (g $kg^{-1}$) | 210 | 10 |
| Silt (g $kg^{-1}$) | 440 | 610 |
| Clay (g $kg^{-1}$) | 350 | 380 |
| Textural class | Clay loam | Silty clay loam |
| K (cmol $kg^{-1}$) | 0.33 | 0.34 |
| Ca (cmol $kg^{-1}$) | 15.0 | 11.7 |
| Mg (cmol $kg^{-1}$) | 3.1 | 4.9 |
| Na (cmol $kg^{-1}$) | 0.1 | 0.0 |
| Acidity (cmol $kg^{-1}$) | 6.9 | 8.7 |
| Total bases (cmol $kg^{-1}$) | 18.5 | 16.9 |
| CEC (cmol $kg^{-1}$) | 25.4 | 25.6 |

† CEC, cation exchange capacity.

Table 3. Initial soil-test K results (fall 2012, 15-cm depth) for all N and K treatments (means across replications).†

| | | K rate (kg K ha$^{-1}$) | | | | |
|---|---|---|---|---|---|---|
| Site | N rate | 0 | 22 | 44 | 66 | Means |
| | kg N ha$^{-1}$ | mg K kg$^{-1}$ | | | | |
| NIRF | 0 | 164 | 198 | 217 | 268 | 212 |
| | 84 | 166 | 187 | 197 | 227 | 194 |
| | 168 | 146 | 187 | 218 | 231 | 196 |
| | 252 | 139 | 180 | 195 | 216 | 183 |
| | 336 | 130 | 163 | 175 | 222 | 172 |
| | Means | 149 | 183 | 201 | 233 | |
| SERF | 0 | 172 | 190 | 208 | 225 | 199 |
| | 84 | 168 | 178 | 197 | 226 | 192 |
| | 168 | 164 | 184 | 184 | 207 | 185 |
| | 252 | 166 | 182 | 189 | 214 | 188 |
| | 336 | 172 | 179 | 198 | 222 | 193 |
| | Means | 169 | 183 | 195 | 219 | |

† Significant ($P \leq 0.05$) main effects of N and K at NIRF (with a linear increase from K application and a linear decrease with N application) but only significant K main effect at SERF (a linear increase). The N by K interaction was not significant at either site.

Table 4. Precipitation and growing degree days for two research sites.

| Site | Month | 30-yr avg. | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|
| | | Precipitation (mm) | | | | | |
| NIRF | January | 19 | 14 | 10 | 13 | 17 | 51 |
| | February | 24 | 20 | 42 | 32 | 25 | 54 |
| | March | 52 | 64 | 25 | 14 | 62 | 72 |
| | Apr | 100 | 187 | 185 | 83 | 38 | 113 |
| | May | 120 | 179 | 85 | 120 | 133 | 119 |
| | Jun | 143 | 74 | 253 | 122 | 112 | 131 |
| | July | 117 | 43 | 106 | 88 | 117 | 34 |
| | Aug | 98 | 36 | 116 | 168 | 127 | 108 |
| | Sept | 82 | 27 | 111 | 41 | 248 | 57 |
| | Oct | 60 | 42 | 74 | 31 | 34 | 136 |
| | Nov | 49 | 41 | 16 | 72 | 29 | 6 |
| | Dec | 33 | 14 | 40 | 127 | 35 | 22 |
| | | Growing degree days (days) † | | | | | |
| | May-Sep | 529 | 539 | 515 | 541 | 568 | 531 |
| | | Precipitation (mm) | | | | | |
| SERF | January | 28 | 45 | 14 | 22 | 10 | 36 |
| | February | 32 | 43 | 67 | 34 | 17 | 8 |
| | March | 63 | 71 | 18 | 13 | 51 | 75 |
| | Apr | 84 | 202 | 118 | 77 | 50 | 103 |
| | May | 115 | 202 | 33 | 119 | 133 | 127 |
| | Jun | 126 | 96 | 201 | 176 | 52 | 39 |
| | July | 101 | 40 | 123 | 174 | 151 | 87 |
| | Aug | 105 | 4 | 144 | 87 | 168 | 86 |
| | Sept | 97 | 26 | 194 | 100 | 41 | 62 |
| | Oct | 75 | 111 | 102 | 43 | 47 | 152 |
| | Nov | 61 | 56 | 48 | 116 | 27 | 19 |
| | Dec | 45 | 21 | 25 | 116 | 26 | 23 |
| | | Growing degree days (days) | | | | | |
| | May-Sep | 586 | 584 | 557 | 588 | 614 | 558 |

† 10 to 30 °C base.

Table 5. Effects of N and K fertilization on corn grain yield across 5 years at NIRF and 4 years at SERF.†

| | | K rate (kg K ha$^{-1}$) | | | | |
|---|---|---|---|---|---|---|
| Site | N rate | 0 | 22 | 44 | 66 | Means |
| | kg N ha$^{-1}$ | Mg ha$^{-1}$ | | | | |
| NIRF | 0 | 5.05 | 5.56 | 5.34 | 5.25 | 5.30 |
| | 84 | 9.72 | 10.08 | 9.88 | 10.00 | 9.92 |
| | 168 | 11.48 | 11.98 | 11.69 | 12.07 | 11.81 |
| | 252 | 11.99 | 12.74 | 12.36 | 12.70 | 12.45 |
| | 336 | 11.62 | 13.08 | 12.74 | 13.11 | 12.64 |
| | Means | 9.97 | 10.69 | 10.40 | 10.63 | |
| SERF | 0 | 6.21 | 6.14 | 5.98 | 5.60 | 5.98 |
| | 84 | 10.56 | 10.68 | 11.22 | 10.38 | 10.71 |
| | 168 | 12.41 | 12.87 | 13.23 | 13.16 | 12.92 |
| | 252 | 12.77 | 13.31 | 13.84 | 13.87 | 13.45 |
| | 336 | 12.95 | 13.39 | 13.78 | 13.97 | 13.52 |
| | Means | 10.98 | 11.28 | 11.61 | 11.40 | |

| | Statistics | | | | | |
|---|---|---|---|---|---|---|
| | N ‡ | K § | NxK | NxYear | KxYear | NxKxYear |
| | *P > F* | | | | | |
| NIRF | 0.01 | 0.01 | 0.03 | 0.01 | 0.37 | 0.14 |
| SERF | 0.01 | 0.01 | 0.01 | 0.01 | 0.56 | 0.92 |

† The year 2013 was excluded from SERF due to extremely low yield.

‡ Significant linear and quadratic orthogonal N response comparisons at both sites.

§ Orthogonal categorical comparisons indicated a response up to the 22-kg K rate at NIRF and to the highest K rate at SERF.

Table 6. Effects of N and K fertilization on corn ear-leaf N concentration at the R1 growth stage across 5 years at NIRF and 4 years at SERF.†

| | | K rate (kg K ha$^{-1}$) | | | | |
|---|---|---|---|---|---|---|
| Site | N rate | 0 | 22 | 44 | 66 | Means |
| | kg N ha$^{-1}$ | g kg$^{-1}$ | | | | |
| NIRF | 0 | 18.4 | 18.2 | 18.7 | 19.0 | 18.6 |
| | 84 | 24.7 | 24.2 | 24.1 | 24.2 | 24.3 |
| | 168 | 27.8 | 27.5 | 27.0 | 27.2 | 27.4 |
| | 252 | 29.9 | 27.0 | 30.1 | 28.9 | 29.0 |
| | 336 | 29.8 | 30.3 | 28.9 | 30.3 | 29.8 |
| | Means | 26.1 | 25.4 | 25.8 | 25.9 | |
| SERF | 0 | 16.7 | 17.0 | 16.8 | 16.4 | 16.7 |
| | 84 | 26.6 | 26.1 | 26.5 | 25.5 | 26.2 |
| | 168 | 29.1 | 29.1 | 29.3 | 28.6 | 29.0 |
| | 252 | 29.7 | 29.8 | 28.7 | 29.7 | 29.5 |
| | 336 | 30.5 | 29.9 | 29.3 | 30.0 | 29.9 |
| | Means | 26.5 | 26.4 | 26.1 | 26.0 | |

| | Statistics | | | | | |
|---|---|---|---|---|---|---|
| | N ‡ | K | NxK | NxYear | KxYear | NxKxYear |
| | *P* > *F* | | | | | |
| NIRF | 0.01 | 0.52 | 0.38 | 0.01 | 0.33 | 0.02 |
| SERF | 0.01 | 0.46 | 0.80 | 0.01 | 0.78 | 0.99 |

† The year 2013 was excluded from SERF due to extremely low yield.

‡ Significant linear and quadratic orthogonal N response comparisons at both sites.

Table 7. Effects of N and K fertilization on corn ear-leaf K concentration at the R1 growth stage across 5 years at NIRF and 4 years at SERF.†

| | | K rate (kg K $ha^{-1}$) | | | | |
|---|---|---|---|---|---|---|
| Site | N rate | 0 | 22 | 44 | 66 | Means |
| | kg N $ha^{-1}$ | ------------------------ g $kg^{-1}$ | | | | -------------------------- |
| NIRF | 0 | 13.5 | 16.9 | 18.2 | 19.1 | 16.9 |
| | 84 | 11.0 | 15.0 | 17.9 | 18.3 | 15.6 |
| | 168 | 9.4 | 15.5 | 19.1 | 19.7 | 15.9 |
| | 252 | 10.3 | 14.8 | 17.7 | 19.8 | 15.6 |
| | 336 | 10.4 | 15.6 | 17.1 | 20.2 | 15.8 |
| | Means | 10.9 | 15.6 | 18.0 | 19.4 | |
| SERF | 0 | 13.1 | 15.9 | 16.8 | 17.7 | 15.9 |
| | 84 | 13.1 | 15.8 | 18.2 | 19.4 | 16.6 |
| | 168 | 12.8 | 16.7 | 17.7 | 19.2 | 16.6 |
| | 252 | 12.9 | 16.3 | 17.8 | 19.7 | 16.7 |
| | 336 | 12.4 | 15.8 | 18.4 | 19.7 | 16.6 |
| | Means | 12.8 | 16.1 | 17.8 | 19.1 | |

| | ------------------------------------ Statistics ---------------------------- | | | | | |
|---|---|---|---|---|---|---|
| | N ‡ | K § | NxK | NxYear | KxYear | NxKxYear |
| | ------------------------------------ *P* > *F* ----------------------------- | | | | | |
| NIRF | 0.01 | 0.01 | 0.01 | 0.06 | 0.01 | 0.09 |
| SERF | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.99 |

† The year 2013 was excluded from SERF due to extremely low yield.

‡ Significant linear and quadratic orthogonal N response comparisons at both sites.

§ Orthogonal categorical comparisons indicated a response up to the highest K rate at both sites.

Table 8. Effects of N and K fertilization on corn grain N concentration at harvest across 5 years at NIRF and 4 years at SERF.†

| | | K rate (kg K $ha^{-1}$) | | | | |
|---|---|---|---|---|---|---|
| Site | N rate | 0 | 22 | 44 | 66 | Means |
| | kg N $ha^{-1}$ | | | g $kg^{-1}$ | | |
| NIRF | 0 | 10.6 | 10.7 | 10.4 | 10.5 | 10.5 |
| | 84 | 11.0 | 10.7 | 11.0 | 11.0 | 10.9 |
| | 168 | 11.6 | 11.9 | 11.6 | 11.1 | 11.5 |
| | 252 | 12.0 | 11.8 | 12.1 | 12.4 | 12.1 |
| | 336 | 12.0 | 12.3 | 12.2 | 12.4 | 12.2 |
| | Means | 11.4 | 11.5 | 11.4 | 11.5 | |
| SERF | 0 | 10.4 | 10.8 | 10.9 | 10.7 | 10.7 |
| | 84 | 10.9 | 11.0 | 11.4 | 11.1 | 11.1 |
| | 168 | 11.9 | 12.1 | 12.0 | 11.7 | 11.9 |
| | 252 | 12.2 | 12.3 | 12.2 | 12.1 | 12.2 |
| | 336 | 12.2 | 12.2 | 12.4 | 12.4 | 12.3 |
| | Means | 11.5 | 11.7 | 11.8 | 11.6 | |

| | Statistics | | | | | |
|---|---|---|---|---|---|---|
| | N ‡ | K | NxK | NxYear | KxYear | NxKxYear |
| | | | | *P > F* | | |
| NIRF | 0.01 | 0.98 | 0.19 | 0.01 | 0.27 | 0.81 |
| SERF | 0.01 | 0.01 § | 0.48 | 0.01 | 0.11 | 0.94 |

† The year 2013 was excluded from SERF due to extremely low yield.

‡ Significant linear and quadratic orthogonal N response comparisons at both sites.

§ Orthogonal categorical comparisons indicated a response up to the 22-kg K rate.

Table 9. Effects of N and K fertilization on corn grain K concentration at harvest across 5 years at NIRF and 4 years at SERF.†

| | | K rate (kg K ha$^{-1}$) | | | | |
|---|---|---|---|---|---|---|
| Site | N rate | 0 | 22 | 44 | 66 | Means |
| | kg N ha$^{-1}$ | ------------------------ g kg$^{-1}$ -------------------------- | | | | |
| NIRF | 0 | 3.82 | 3.85 | 3.95 | 3.96 | 3.89 |
| | 84 | 3.68 | 3.96 | 3.81 | 3.95 | 3.85 |
| | 168 | 3.69 | 3.77 | 3.83 | 3.91 | 3.80 |
| | 252 | 3.68 | 3.85 | 3.73 | 3.77 | 3.76 |
| | 336 | 3.63 | 3.79 | 3.76 | 3.70 | 3.72 |
| | Means | 3.70 | 3.84 | 3.82 | 3.86 | |
| SERF | 0 | 3.85 | 3.74 | 3.71 | 3.76 | 3.77 |
| | 84 | 3.54 | 3.64 | 3.58 | 3.65 | 3.60 |
| | 168 | 3.37 | 3.44 | 3.39 | 3.53 | 3.43 |
| | 252 | 3.27 | 3.27 | 3.34 | 3.45 | 3.33 |
| | 336 | 3.27 | 3.32 | 3.35 | 3.39 | 3.33 |
| | Means | 3.46 | 3.48 | 3.47 | 3.56 | |

| | ------------------------------------ Statistics ---------------------------- | | | | | |
|---|---|---|---|---|---|---|
| | N ‡ | K § | NxK | NxYear | KxYear | NxKxYear |
| | ------------------------------------ $P > F$ ----------------------------- | | | | | |
| NIRF | 0.01 | 0.01 | 0.26 | 0.01 | 0.47 | 0.82 |
| SERF | 0.01 | 0.01 | 0.01 | 0.01 | 0.48 | 0.97 |

† The year 2013 was excluded from SERF due to extremely low yield.

‡ Significant linear and quadratic orthogonal N response comparisons at both sites.

§ Orthogonal categorical comparisons indicated a response up to the 22-kg K rate at both sites.

Table 10. Effects of N and K fertilization on N removed with corn grain harvest across 5 years at NIRF and 4 years at SERF.†

| | | K rate (kg K ha$^{-1}$) | | | | |
|---|---|---|---|---|---|---|
| Site | N rate | 0 | 22 | 44 | 66 | Means |
| | kg N ha$^{-1}$ | ------------------------ kg ha$^{-1}$ -------------------------- | | | | |
| NIRF | 0 | 46.0 | 50.7 | 47.8 | 48.1 | 48.1 |
| | 84 | 93.1 | 94.0 | 94.3 | 95.2 | 94.2 |
| | 168 | 115.1 | 123.2 | 117.8 | 116.6 | 118.2 |
| | 252 | 124.2 | 130.9 | 130.0 | 136.7 | 130.4 |
| | 336 | 121.2 | 139.3 | 134.5 | 140.4 | 133.8 |
| | Means | 99.9 | 107.6 | 104.9 | 107.4 | |
| SERF | 0 | 56.2 | 57.7 | 56.9 | 52.3 | 55.7 |
| | 84 | 99.8 | 101.9 | 110.9 | 100.2 | 103.2 |
| | 168 | 128.0 | 134.2 | 137.7 | 132.9 | 133.2 |
| | 252 | 134.1 | 141.6 | 146.4 | 145.1 | 141.8 |
| | 336 | 137.2 | 141.4 | 148.2 | 149.3 | 144.0 |
| | Means | 111.1 | 115.4 | 120.0 | 115.9 | |

| | ------------------------------------ Statistics ---------------------------- | | | | | |
|---|---|---|---|---|---|---|
| | N ‡ | K § | NxK | NxYear | KxYear | NxKxYear |
| | ------------------------------------ *P* > *F* ----------------------------- | | | | | |
| NIRF | 0.01 | 0.01 | 0.02 | 0.01 | 0.23 | 0.36 |
| SERF | 0.01 | 0.01 | 0.01 | 0.01 | 0.05 | 0.43 |

† The year 2013 was excluded from SERF due to extremely low yield.

‡ Significant linear and quadratic orthogonal N response comparisons at both sites.

§ Orthogonal categorical comparisons indicated a response up to the 22-kg K rate at NIRF and to the highest K rate at SERF.

Table 11. Effects of N and K fertilization on K removed with corn grain harvest across 5 years at NIRF and 4 years at SERF.†

| | | K rate (kg K ha$^{-1}$) | | | | |
|---|---|---|---|---|---|---|
| Site | N rate | 0 | 22 | 44 | 66 | Means |
| | kg N ha$^{-1}$ | ------------------------ kg ha$^{-1}$ -------------------------- | | | | |
| NIRF | 0 | 16.6 | 18.3 | 18.1 | 17.8 | 17.7 |
| | 84 | 30.5 | 34.2 | 32.2 | 33.7 | 32.7 |
| | 168 | 36.0 | 38.6 | 38.3 | 40.4 | 38.3 |
| | 252 | 37.7 | 41.8 | 39.3 | 41.0 | 39.9 |
| | 336 | 36.2 | 42.2 | 40.9 | 41.6 | 40.2 |
| | Means | 31.4 | 35.0 | 33.7 | 34.9 | |
| SERF | 0 | 20.6 | 19.8 | 19.1 | 18.1 | 19.4 |
| | 84 | 32.1 | 33.4 | 34.5 | 32.6 | 33.2 |
| | 168 | 36.0 | 38.0 | 38.5 | 40.2 | 38.2 |
| | 252 | 35.9 | 37.4 | 39.6 | 41.1 | 38.5 |
| | 336 | 36.3 | 38.2 | 39.6 | 40.7 | 38.7 |
| | Means | 32.2 | 33.4 | 34.3 | 34.5 | |

| | ------------------------------------ Statistics ---------------------------- | | | | | |
|---|---|---|---|---|---|---|
| | N ‡ | K § | NxK | NxYear | KxYear | NxKxYear |
| | ------------------------------------ *P* > *F* ----------------------------- | | | | | |
| NIRF | 0.01 | 0.01 | 0.04 | 0.01 | 0.50 | 0.51 |
| SERF | 0.01 | 0.01 | 0.01 | 0.01 | 0.71 | 0.87 |

† The year 2013 was excluded from SERF due to extremely low yield.

‡ Significant linear and quadratic orthogonal N response comparisons at both sites.

§ Orthogonal categorical comparisons indicated a response up to the 22-kg K rate at NIRF and to the 44-kg rate at SERF.

Table 12. Soil-test K as affected by N and K treatments for post-harvest soil samples taken at two sites from fall 2013 until fall 2016 (15-cm depth).†

| | | NIRF | | | | SERF | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | ---------------------- K rate (kg K $ha^{-1}$) ---------------------- | | | | | | | |
| Year | N rate | 0 | 22 | 44 | 66 | 0 | 22 | 44 | 66 |
| | kg N $ha^{-1}$ | --------------------------- mg K $kg^{-1}$ --------------------------- | | | | | | | |
| 2013 | 0 | 143 | 186 | 214 | 231 | 164 | 189 | 209 | 217 |
| | 84 | 149 | 164 | 187 | 230 | 162 | 190 | 208 | 227 |
| | 168 | 135 | 151 | 204 | 226 | 158 | 189 | 189 | 209 |
| | 252 | 128 | 151 | 187 | 220 | 162 | 185 | 194 | 221 |
| | 336 | 121 | 149 | 169 | 171 | 159 | 188 | 198 | 229 |
| 2014 | 0 | 136 | 182 | 200 | 238 | 138 | 169 | 187 | 210 |
| | 84 | 151 | 165 | 185 | 216 | 141 | 153 | 168 | 194 |
| | 168 | 128 | 155 | 190 | 213 | 133 | 175 | 151 | 190 |
| | 252 | 114 | 145 | 174 | 210 | 123 | 147 | 153 | 183 |
| | 336 | 116 | 157 | 157 | 192 | 127 | 145 | 171 | 204 |
| 2015 | 0 | 119 | 182 | 197 | 224 | 134 | 157 | 217 | 223 |
| | 84 | 135 | 144 | 165 | 240 | 135 | 158 | 179 | 235 |
| | 168 | 127 | 146 | 182 | 250 | 128 | 160 | 158 | 203 |
| | 252 | 107 | 151 | 149 | 210 | 126 | 148 | 163 | 195 |
| | 336 | 105 | 135 | 176 | 177 | 111 | 150 | 161 | 194 |
| 2016 | 0 | 113 | 154 | 187 | 218 | 147 | 178 | 202 | 223 |
| | 84 | 122 | 134 | 141 | 202 | 145 | 167 | 190 | 231 |
| | 168 | 107 | 127 | 162 | 192 | 138 | 160 | 168 | 196 |
| | 252 | 103 | 124 | 132 | 177 | 136 | 158 | 179 | 214 |
| | 336 | 93 | 130 | 134 | 175 | 137 | 164 | 177 | 211 |

† Significant ($P \leq 0.05$) main effects of N and K and linear response in every year at both sites except for a lack of response to N in 2013 at SERF. No significant N by K interaction except in 2015 at SERF, where the slope of the linear decreasing effect of N was greater for the two highest K rates.

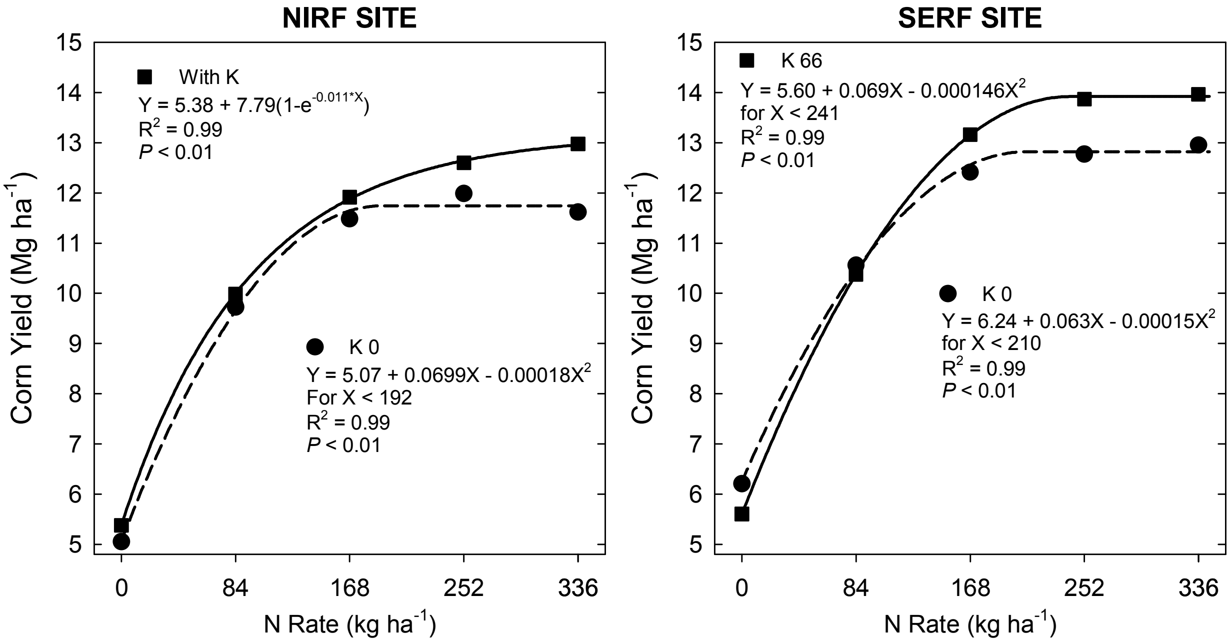

Fig. 1. Corn grain yield across 5 years at NIRF and 4 years at SERF. K 0, no K applied; With K, average across rates of 22, 44, and 66 kg K ha$^{-1}$ (which at NIRF did not differ); K 66, rate of 66 kg K ha$^{-1}$ (all K rates differed at SERF; see Table 5).

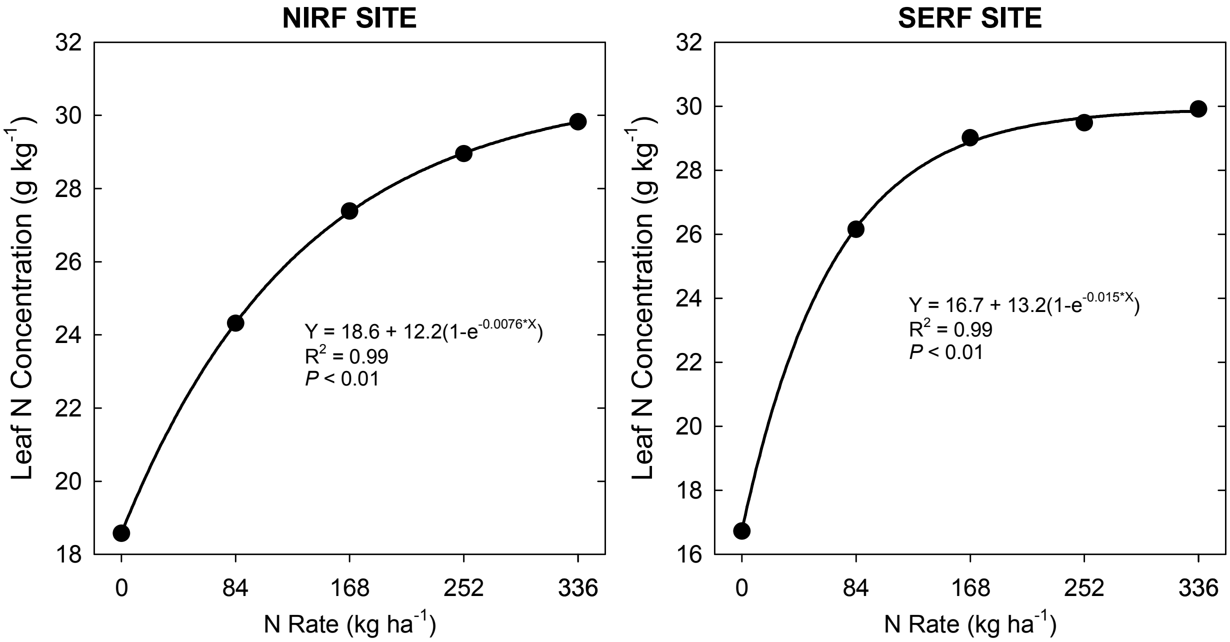

Fig. 2. Corn ear-leaf N concentration at the R1 growth stage across 5 years at NIRF and 4 years at SERF. Means across all K rates at both sites because there were no significant K effects.

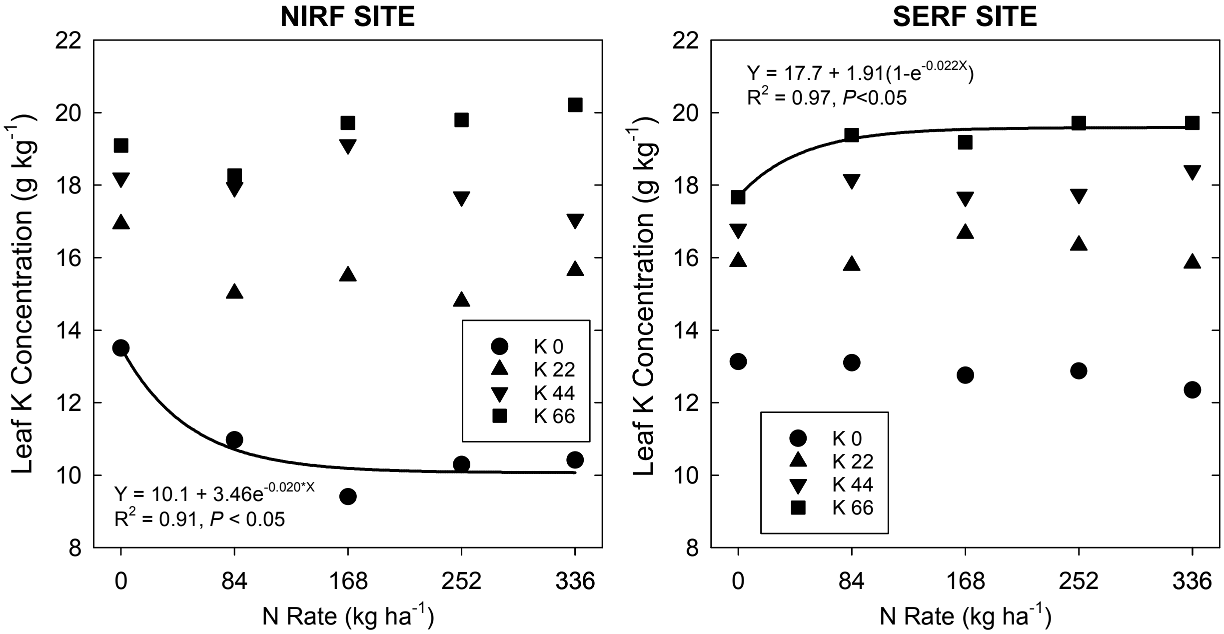

Fig. 3. Corn ear-leaf K concentration at the R1 growth stage across 5 years at NIRF and 4 years at SERF. All K rates differed at increasing leaf K at both sites but N affected leaf K only for the 0-kg K rate at NIRF and the 66-kg rate at SERF.

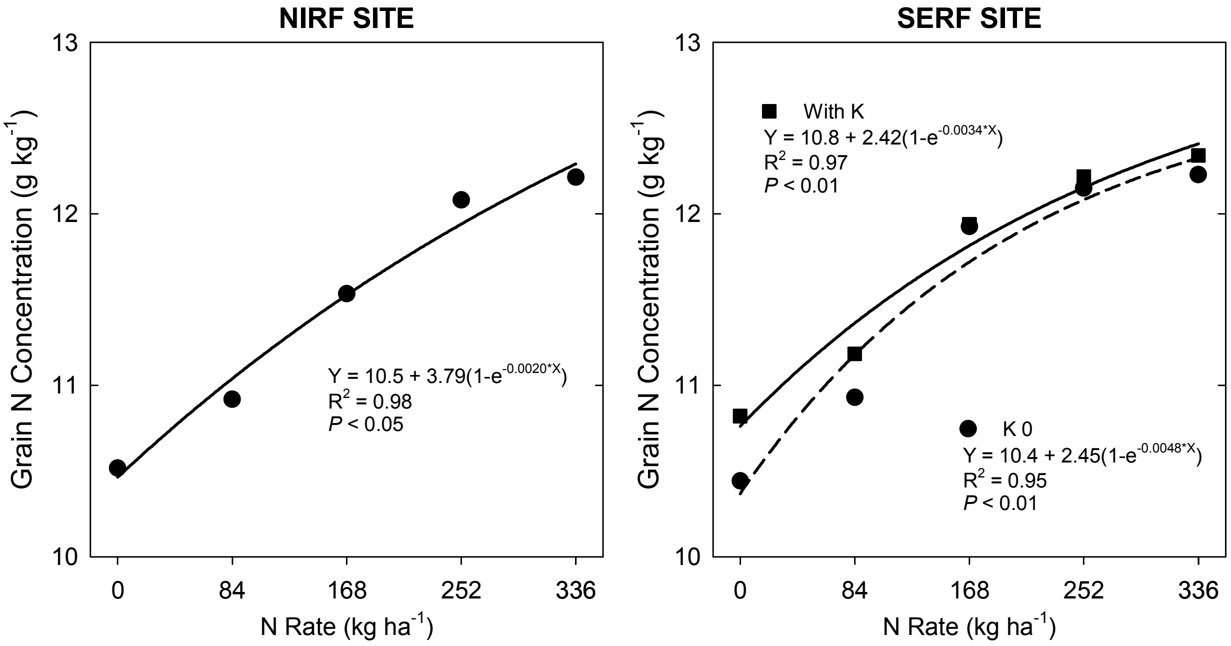

Fig. 4. Corn grain N concentration at harvest across 5 years at NIRF and 4 years at SERF. Means across all K rates at NIRF because there were no significant K effects. K 0, no K applied; With K, average across rates of 22, 44, and 66 kg K ha$^{-1}$ (which at SERF did not differ; see Table 8).

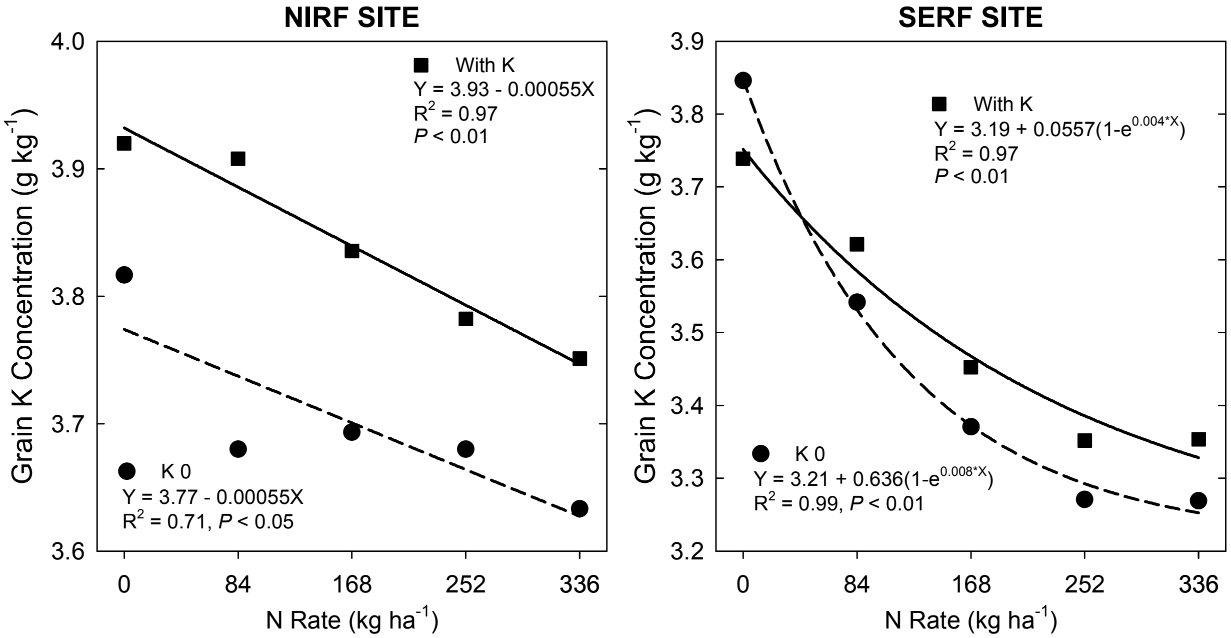

Fig. 5. Corn grain K concentration at harvest across 5 years at NIRF and 4 years at SERF. K 0, no K applied; With K, average across rates of 22, 44, and 66 kg K ha$^{-1}$ (which did not differ at both sites; see Table 9).

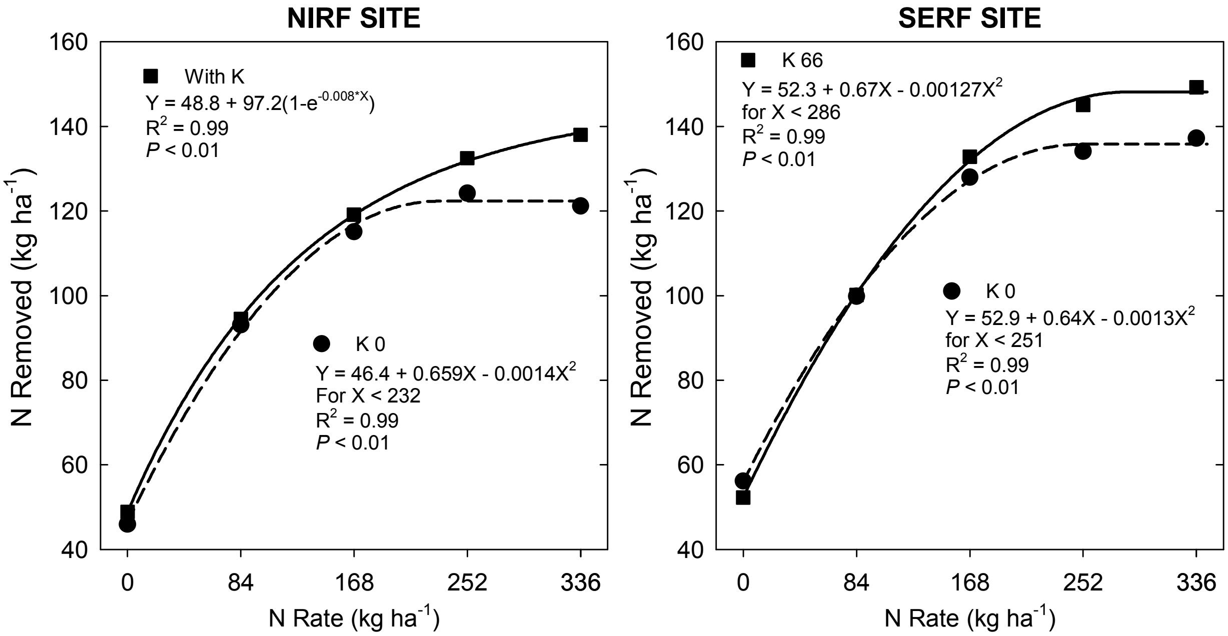

Fig. 6. Nitrogen removed with corn grain harvest across 5 years at NIRF and 4 years at SERF. K 0, no K applied; With K, average across rates of 22, 44, and 66 kg K ha$^{-1}$ (which at NIRF did not differ); K 66, rate of 66 kg K ha$^{-1}$ (all K rates differed at SERF; see Table 10).

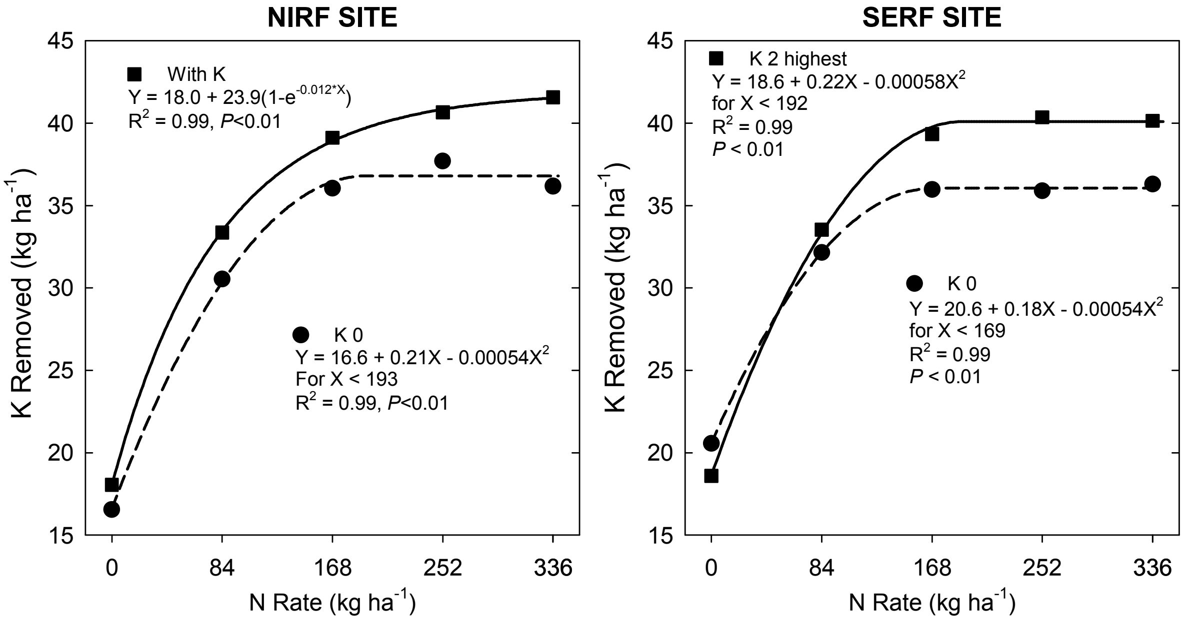

Fig. 7. Potassium removed with corn grain harvest across 5 years at NIRF and 4 years at SERF. K 0, no K applied; With K, average across rates of 22, 44, and 66 kg K ha$^{-1}$ (which at NIRF did not differ); K 2 highest, average across rates of 44 and 66 kg K ha$^{-1}$ (which at SERF did not differ; see Table 11).

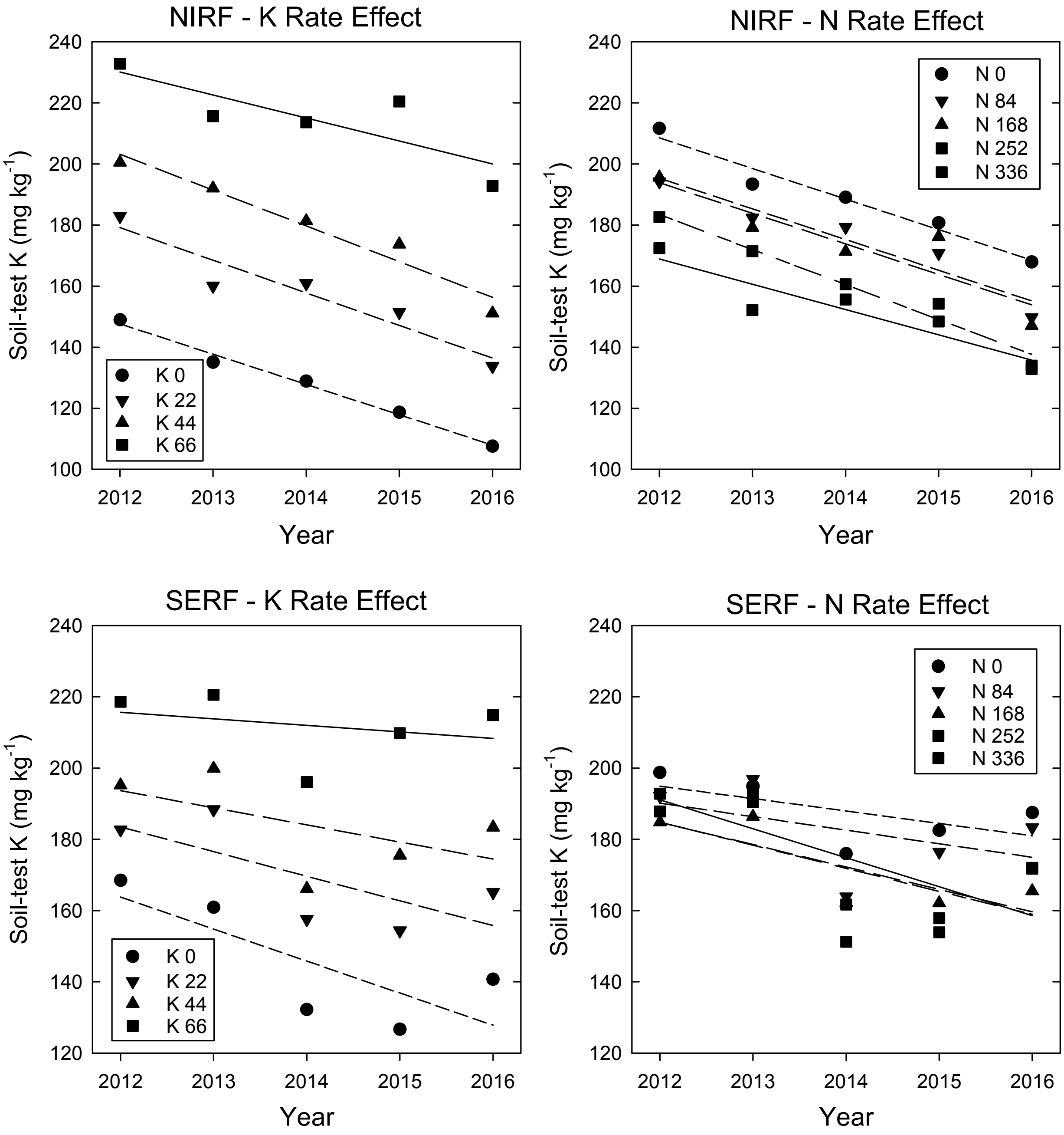

Fig. 8. Soil-test K change over time at NIRF and SERF sites. Means across all N rates for K effects and means across all K rates for N effects. Values for 2012 are initial values for samples taken in fall 2012 whereas other values are from post-harvest samples taken the fall of each indicated year. All linear trends were significant at $P \leq 0.05$. At SERF, quadratic trends were significant for some N or K rates but models were not fitted due to unreasonably low values in 2015 and high values in 2017.

# CHAPTER 3. GENERAL CONCLUSIONS

The objective of this study was to investigate potential nitrogen (N) by potassium (K) interactions in corn by evaluating various N and K fertilization rates on grain yield, leaf (at the R1 growth stage) and grain (at harvest) tissue concentrations, nutrient removal with grain harvest, and soil-test K (STK) levels. The study involved establishing two 5-year trials (2013-2017) with continuous corn at two Iowa State affiliated research farms in Iowa with different soil properties and weather patterns. Treatments were the combinations of five N application rates and four K rates. Crop measurements were made each year to assess responses to N and K applied.

The results from both sites revealed significant grain yield increases from N and K fertilization, and there was a positive interaction by which responses to both nutrients were higher when both were applied together. Nitrogen and K removal responses were approximately similar to grain yield responses and showed the same type of N by K interaction. However, the interaction effects were greater for K removed than for grain yield and N removed because of different N and K effects on grain nutrient concentrations. The N, K, and interaction effects for leaf tissue differed from those for yield and nutrient removal. Leaf N concentrations were not affected by K fertilization at either site, were greatly increased by all N fertilization rates at both sites, and there was no N by K interaction. Leaf K concentrations were greatly increased by all K fertilization rates and were only slightly affected by some N fertilization rates.

Overall, the study showed that adequate fertilization of N and K is needed to maximize grain yield, and that a K deficiency limits corn yield but also limits its capacity to respond to N fertilization. Soil-test K results indicated that the observed interactions occurred between deficient and adequate levels. Soil-test K or K fertilization rates higher than currently recommended in Iowa were not needed to maximize yield and the response to N. However, higher yields with adequate K supply and the higher rates needed to maximize yield resulted in large amounts of K removed with harvest that sharply decreased STK over time. Therefore, the study showed that adequate K supply is essential to optimize yield and N utilization by corn.

# ACKNOWLEDGEMENTS

First and foremost, I acknowledge that Christ Jesus is my Lord and Savior and without Him I am nothing. I will forever be grateful for my Major Professor Dr. Antonio P. Mallarino. Thank you for taking a chance on me, for your relentless pursuit of excellence in the research you conduct, and your guidance the past two years. To the Iowa State University Army ROTC Cyclone Battalion; Strong and Courageous! Ms. Jaci Severson: You are the reason I was able to Commission from this fine institution and also receive a degree. There were a lot of moving parts between the Army and ISU and vice versa and you made the parts fit together, thank you. Thank you to the Mallarino Research Team: Dr. Mazhar Haq, John Jones, Mariana Mantovani, Ryan Oltmans, Camila Rivero, and Mr. Louis Thompson; I could not have done this without any and all of you. S.A.H.: I promised you I would complete this. A.R.: Thank you for taking me under your wing and teaching me about life the past two years. Most importantly-thank you to my family: Mom and Dad- Love y'all, it's been a crazy eight years and you supported me no matter what. Caroline and Matt- Thank you for your support and blessing me with LM and MC. Honored and humbled by all who have been alongside me during this endeavor.