# BALANCED NUTRITION AND CROP PRODUCTION PRACTICES FOR THE STUDY OF GRAIN SORGHUM NUTRIENT PARTITIONING AND CLOSING YIELD GAPS

by

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# Abstract

Mid-west grain sorghum (*Sorghum bicolor* (L.) Moench) producers are currently obtaining much lower than attainable yields across varying environments, therefore, closing yield gaps will be important. Yield gaps are the difference between maximum economic attainable yield and current on-farm yields. Maximum economic yield can be achieved through the optimization of utilizing the best genotypes and management practices for the specific site-environment (soil-weather) combination. This research project examines several management factors in order to quantify complex farming interactions for maximizing sorghum yields and studying nutrient partitioning. The factors that were tested include narrow row-spacing (37.5 cm) vs. standard wide row-spacing (76 cm), high (197,600 seeds $ha^{-1}$) and low (98,800 seeds $ha^{-1}$) seeding rates, balanced nutrient management practices including applications of NPKS and micronutrients (Fe and Zn), crop protection with fungicide and insecticide, the use of a plant growth regulator, and the use of precision Ag technology (GreenSeeker for N application). This project was implemented at four sites in Kansas during 2014 (Rossville, Scandia, Ottawa, and Hutchinson) and 2015 (Topeka, Scandia, Ottawa, Ashland Bottoms) growing seasons. Results from both years indicate that irrigation helped to minimize yield variability and boost yield potential across all treatments, though other factors affected the final yield. In 2014, the greatest significant yield difference under irrigation in Rossville, KS (1.32 Mg $ha^{-1}$) was documented between the 'low-input' versus the 'high-input' treatments. The treatment difference in grain sorghum yields in 2014 was not statistically significant. In 2014, the Ottawa site experienced drought-stress during reproductive stages of plant development, which resulted in low yields and was not influenced by the cropping system approach. In 2015 the treatments were significant, and in Ottawa, narrow row spacing at a lower seeding rate maximized yield for this generally

low-yielding environment (<6 Mg $ha^{-1}$) (treatment two at 6.26 vs. treatment ten at 4.89 Mg $ha^{-1}$). Across several sites, including Rossville, Hutchinson, Scandia, Topeka, and Ashland, a similar trend of narrow row spacing promoting greater yields has been documented. Additionally, when water was not limiting sorghum yields (i.e., under irrigation), a balanced nutrient application and optimization of production practices did increase grain sorghum yields ('high-input' vs. 'low-input'; the greatest difference was seen in 2014 in Rossville, 1.2 Mg $ha^{-1}$, and in 2015 in Ashland, 1.98 Mg $ha^{-1}$). In the evaluation of nutrient uptake and partitioning in different plant fractions, there was variability across all site-years which did not always follow the same patterns as the yield, however, the low-input treatment was shown to have significantly lower nutrient uptakes across all the nutrients evaluated (N, P, K, S, Fe, Zn) and across most fractions and sampling times. The objectives of this project were to identify management factors that contributed to high sorghum yields in diverse environments, and to investigate nutrient uptake and partitioning under different environments and crop production practices.

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# Dedication

This work is dedicated to the Lord who brought me here, and has helped me thus far. “And I will lead the blind in a way that they do not know, in paths that they have not known I will guide them. I will turn the darkness before them into light, the rough places into level ground. These are the things I do, and I do not forsake them.” ~ Isaiah 42:16

# Chapter 1 - Literature Review

Grain sorghum (*Sorghum bicolor* (L.) Moench) is the fifth most important cereal crop grown in the world with a production of over 67 million tons in 2014 (FAOSTAT Food and Agricultural Commodities Production, 2014). However, about 75% of the world's sorghum is used for human consumption, making it third in overall importance of food crops in the world (Acquaah, 2005). Sorghum is largely grown by small-scale subsistence farmers who have little access to production inputs under rainfed conditions (Maiti, 1996). Due to these circumstances there is a need to identify all the yield limiting factors and their complex interactions to improve the worldwide crop yields.

The improvement of sorghum during the last six decades has been associated with targeted changes in genotype (G component) and management practices (M component), as well as observing the environmental factors (E component) effect on yield. For the genotypic component, crop improvement under irrigation was documented to the change of aboveground-biomass production (increased leaf: stem ratio and greater leaf mass), longer panicle length, reduction in peduncle length, and superior root mass (Assefa & Staggenborg, 2011). The management factors that have been studied include fertilization rates, irrigation, and tillage practices (Assefa and Staggenborg, 2010; Duvick, 1999). The environment exerts a large and varying influence throughout different parts of the world; thus, endpoint sorghum productivity may be considered the outcome of a complex G x E x M interaction.

However, little is understood about the relative contribution of each component (G x E x M) and their cross-play interaction on the plant traits (primarily the plant dry mass and nutrient uptake) that influence sorghum yield. A better understanding of the plant biomass accumulation, nutrient uptake and partitioning among vegetative and reproductive plant structures at multiple-

growth stages under diverse management practices will allow for optimizing the use of all soil-plant resources. In turn, it will be possible to close the yield gaps between current on-farm yields and the maximum economic attainable yields at each specific environment.

## Nutrient Partitioning

Information relating to sorghum nutrient uptake and distribution of nitrogen (N), phosphorous (P), and potassium (K) among different plant fractions [leaves, stem, and head (grain and the rest)] at multiple-growth stages was last published by Vanderlip (1972). This publication is still being used as the preferential reference for sorghum. This study focused on N, P, and K uptake. Similar studies conducted by Roy and Wright, (1973) around the same time evaluated dry matter accumulation patterns, yield, and N content of sorghum grain. They discovered that as N and P fertilizer was applied, there was a high amount of dry matter accumulation by the head and grain N content, resulting in higher grain yields. The same authors also discovered in a study with applications of different amounts of N and P fertilizer that the accumulation of N and P proceeded almost linearly until maturity, but K accumulated more rapidly during early stages of growth, irrespective of the amount of N and P applied. They also found that very little K was translocated to the head, and much more K accumulated in the stem than N and P (Roy and Wright, 1974). Phosphorous is known to be readily remobilized within the plant, particularly to the grain during grain-fill, and at maturity over 70% of the aboveground P is found in the grain (Maiti, 1996). The extent of the impact of management practices in diverse environments on nutrient uptake is still relatively unclear. In a study on plant water stress effects on irrigated sorghum, the authors noted that there was a wide variation in nutrient uptake curves from their results compared with the results from the studies done by Roy and Wright (1974), and Vanderlip (1972), due to varietal difference, and varying soil and environmental

conditions (Eck and Musick, 1979). The same study also found that plant water stress reduced the N and P concentrations in leaves and increased the N concentration in stalks and heads, but did not affect $NO_3$-N, K, Ca, and Mg concentrations. Plant water stress also reduced dry matter and nutrient accumulation (Eck and Musick, 1979).

Some of the earliest research in micronutrient accumulation and partitioning, including Calcium (Ca), Copper (Cu), Manganese (Mn), Zinc (Zn), Iron (Fe), and Magnesium (Mg), in grain sorghum was done by Gary Lynn Jacques (1973). This study showed that there are great variations between micronutrients in their uptake and storage to different parts of the plant throughout the plant lifecycle. In general, Jacques noted that nutrient uptake curves are similar to dry matter accumulation curves, but nutrient uptake curves precede dry matter curves because the nutrients are required for dry matter accumulation. The head tissue was usually found to have the lowest nutrient concentration of all plant parts early in the season, and the culm (stem) tissue was generally the highest in concentration of nutrients early in the sorghum's growth. Looking at the specific nutrients in Jacques' study, about 40% of total Ca taken up was in the blade (leaves) at maturity, and only 10% in the head, even though the head comprised 50-60% of the total weight of the plant at maturity and the blade only 10-20%. Copper (Cu) uptake showed less than 10% of total amount taken up was located in the sheath at physiological maturity. In Mn, about 25% of total amount taken up was accumulated in the sheath at physiological maturity. Mg, Cu, and Zn showed evidences of translocation to the head from vegetative plant parts during grain development, however, no evidence of translocation of Ca and Mn appeared to occur. High amounts of Zn and Mg were shown to be removed in the grain at harvest in proportion to other plant parts, intermediate amounts of Cu and Mn and small amounts of Ca were removed at harvest. (Gary Lynn Jacques, 1973). Another more recent study showed that biomass (leaves and

stems portions) have more fluctuating nutrient concentrations than the grain portion of a sorghum plant which reflects the ability of the plant to translocate nutrients to the grain at the expense of the remaining vegetative plant parts (Hons et al., 1986).

The understanding of the sorghum nutrient partitioning for modern hybrids under the interaction between nutrient fertilizer applications and crop production practices should be pursued in depth. In recent years, more efforts were placed on updating and improving the understanding of macro and micro-nutrient partitioning among different plant components on corn under diverse crop production practices (i.e., plant density and N rate) (Ciampitti, Murrell, Camberato, and Vyn, 2013A; Ciampitti and Vyn, 2013B). Similar information is urgently needed for improving sorghum production in diverse yielding environments (i.e., dryland vs. irrigation), and under diverse crop production practices, and for estimating crop nutrient levels needed per unit of yield produced and grain nutrient removal. The latter can potentially be very helpful in deciding the right nutrient fertilizer rate to be applied. In addition, changes in nutrient uptake timing (quantity taken up before or after blooming), rates (uptake per day between growth periods), and nutrient partitioning (leaf, stem, and grain) for modern sorghum hybrids at multiple-growth stages could provide some guidance towards the best timing for nutrient application and the nutrient demand for producing superior sorghum yields.

## Nutrient Fertilization

Past research reported consistent improvements in sorghum yield when starter fertilizer (33.6 or 50.4 kg $ha^{-1}$ of N, and 33.6 kg P $ha^{-1}$) was applied as compared to no-starter check plots (Gordon, and Whitney, 2002). Gordon and Pierzynski (1998) documented a 941.6 kg $ha^{-1}$ yield increment for responding hybrids when the starter fertilizer was applied. The latter information also shed some light on crop growth changes, with a superior early-season growth and nutrient

uptake (for N and P), there was a reduction on the average days to bloom (planting to bloom), and on the final grain moisture level (Gordon and Pierzynski, 1998). In a two-year experiment (2006/07), application of inorganic N fertilizers accounted for 25% of sorghum yield improvement (Manhattan, KS) (Tucker, 2009). Diverse fertilizer N sources were compared at three-sites, application of liquid urea-ammonium nitrate (UAN) in combination with urease nitrification-inhibitor and slow release, and urea (conventional source) did not show any significant yield benefit (Texas) (Coker et al., 2012). For P, residual application of P (4-yr) improved crop yields by about 439.4 kg $ha^{-1}$, accounting for more than 10% of the increase in productivity as compared when no P was applied (Ottawa, KS) (Janssen, 1994). In a long-term evaluation of P response (10-yr), the application of 44.8 kg $P_2O_5$ $ha^{-1}$ $yr^{-1}$ accounted for about 10% of the overall sorghum yield improvement (Schlegel, 2012). For the same study, combined P and K applications increased yields 627.6 kg $ha^{-1}$ (4394 vs. 5022 kg $ha^{-1}$) as compared when no fertilizer was applied (check plot). As compared to each individual nutrient application (N, P, and K), the single application of N showed the largest yield advantage in sorghum productivity. Lastly, when all N-$P_2O_5$-$K_2O$ (120-40-40, balance application) were jointly applied, the N rate needed to maximize yields was reduced from 224.2 to 134.5 kg $ha^{-1}$ (8600 vs. 8474 kg $ha^{-1}$, respectively, average 10-yr yield trends). In addition to type and rate of fertilizer application, other management factors such as fertilizer placement and tillage effects on sorghum nutrient uptake have been studied. The positional availability of N and P that has been knife applied at a depth of 10 cm early in the growing season increased the amount and rate of N, P, and K uptake, and shortened the time for maximum plant growth and nutrient uptake. The application of fertilizer in this manner may have advanced plant maturity, compared with surface fertilizer placement methods and no fertilizer application (Sweeney, 1993).

From the micronutrient viewpoint, five elements are classified as the micronutrient metals (Fe, Zn, Mn, Cu, and Ni), and three are considered as other micronutrients (Cl, B, and Mo). From the micronutrient metals, Zn deficiency is common in corn and sorghum, while Fe deficiency was previously documented in corn, sorghum, and soybean crops. Copper and Ni deficiencies are not an issue in the state of Kansas, while Mn deficiency is of interest on soybean production (glyphosate x RR soybean interactions). From the rest of the micronutrients, Mo deficiency was documented in soybean (South-Eastern and South-Central Kansas); B occurs rarely on alfalfa (SE Kansas); whereas, Cl responses occur frequently for wheat, corn, and sorghum around the state. Thus, from the previous information the main three micronutrients that are more likely to show deficiency levels on sorghum production are Zn, Fe, and Cl. Information from Kansas documented positive and economic responses to the application of Cl (on overall, 5963 vs. 6465 kg $ha^{-1}$ for check and 22.4 kg $ha^{-1}$ NaCl or KCl, respectively) at eight of nine site-years (Lamond and Leikam, 2002; Mengel et al., 2009). When soil-applied, Fe and Zn fertilizer applications did not promote an effective improvement in the grain Fe and Zn concentrations (bio fortification goal), but a positive association was found between Fe and Zn deposition in the grains for sorghum (India) (Kumar et al., 2011). To the present, less information is available regarding the potential contribution of Zn and Fe fertilizer applications to sorghum yield (Fe is more likely to show responses in the western region of the state, where pH levels are greater than 7.8 – alkaline soils). There have been many studies over the years which aimed to test sorghum's ability to grow in some type of limiting environmental condition, but there is still a need for more all-encompassing data that captures the combined effect of management practices, soil and weather conditions, and genetic variation on sorghum plant development and nutrient uptake.

## Management Practices

Besides nutrient fertilization, diverse complex interplay among management practices highly influences the decision making process for producing grain sorghum. Among the different management practices to be considered (interacting with nutrient applications) are: hybrid, crop rotation, planting dates, plant density, row spacing, weed, insect, and disease control. Numerous studies have suggested a variety of optimum planting densities as it is directly impacted by the soil moisture status, and the length of the growing season among other factors. Due to extreme variability in growing conditions throughout the state of Kansas, the yield results show very little conclusive evidence for set guidelines for planting densities. For example, one study (Abunyewa et al., 2010) found that the effect of plant population on yield was not consistent or significant across 10 site-years; and at medium and low rainfall sites, low plant population produced equal or greater yield than high plant population with 76.2 cm row spacing. Wider positive yield response range (from 7 to 24%) resulted with early planting (May) in different locations around Kansas (Belleville, Ottawa, Manhattan, and Hutchinson) (Maiga, 2012). An earlier study done by David Koch (1966), showed the effects of plant density with high plant density (193,746 plants $ha^{-1}$) producing superior yields under favorable moisture and fertility conditions, and low plant density (35,226 plants $ha^{-1}$) consistently displaying lower yields, even under drought conditions, where a lower plant density is often suggested. He also found that late maturity hybrids accumulated more nitrogen and dry matter per plant at half-bloom and took up more nitrogen after half-bloom, than early and medium maturity hybrids. This study also concluded the nitrogen percentage in the grain generally increased with a decreased stand density and decreased yield (Koch, 1966).

In summary, there are very mixed conclusions about optimum management practices, and more research information is needed to understand the interactions among crop production practices and nutrient fertilization for optimizing inputs and maximizing sorghum yield at very diverse environments across the state of Kansas. In addition, previous information related to nutrient concentration in different plant tissue for sorghum in Kansas (and the region) needs to be updated (Vanderlip, 1972, 1993). Information for modern hybrids is scarce, and the effect of combined management practices on the nutrient partitioning process is relatively unknown. Balanced nutrient application for maximizing yields under crop management practices should be further studied for grain sorghum under diverse environments around the state. The objectives of this research project are to fill in some of the aforementioned gaps in knowledge about grain sorghum production. The specific objectives are: to identify management factors that contribute to high yields and investigate how nutrient uptake is affected by different environments, to update information related to nutrient uptake for modern sorghum hybrids under different environments and crop production practices, and to understand the effect of fertilizer applications and their interaction with diverse management practices for sorghum under diverse environments.

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# Chapter 2 - Sorghum Grain Yield, Biomass Accumulation and Nutrient Uptake


## Abstract

Mid-west grain sorghum (*Sorghum bicolor* (L.) Moench) producers are currently obtaining much lower than attainable yields across varying environments, therefore, closing yield gaps will be important. Yield gaps are the difference between maximum economic attainable yield and current on-farm yields. Maximum economic yield can be achieved through the optimization of utilizing the best genotypes and management practices for the specific site-environment (soil-weather) combination. This research project examines several management factors in order to quantify complex farming interactions for maximizing sorghum yields and studying nutrient partitioning. The factors that were tested include narrow row-spacing (37.5 cm) vs. standard wide row-spacing (76 cm), high (197,600 seeds $ha^{-1}$) and low (98,800 seeds $ha^{-1}$) seeding rates, balanced nutrient management practices including applications of NPKS and micronutrients (Fe and Zn), crop protection with fungicide and insecticide, the use of a plant growth regulator, and the use of precision Ag technology (GreenSeeker for N application). This project was implemented at four sites in Kansas during 2014 (Rossville, Scandia, Ottawa, and Hutchinson) and 2015 (Topeka, Scandia, Ottawa, Ashland Bottoms) growing seasons. Results from both years indicate that irrigation helped to minimize yield variability and boost yield potential across all treatments, though other factors affected the final yield. In 2014, the greatest significant yield difference under irrigation in Rossville, KS (1.32 Mg $ha^{-1}$) was documented between the 'low-input' versus the 'high-input' treatments. The treatment difference in grain sorghum yields in 2014 was not statistically significant. In 2014, the Ottawa site experienced drought-stress during reproductive stages of plant development, which resulted in low yields and was not influenced by the cropping system approach. In 2015 the treatments were significant,

and in Ottawa, narrow row spacing at a lower seeding rate maximized yield for this generally low-yielding environment (<6 Mg $ha^{-1}$) (treatment two at 6.26 vs. treatment ten at 4.89 Mg $ha^{-1}$). Across several sites, including Rossville, Hutchinson, Scandia, Topeka, and Ashland, a similar trend of narrow row spacing promoting greater yields has been documented. Additionally, when water was not limiting sorghum yields (i.e., under irrigation), a balanced nutrient application and optimization of production practices did increase grain sorghum yields ('high-input' vs. 'low-input'; the greatest difference was seen in 2014 in Rossville, 1.2 Mg $ha^{-1}$, and in 2015 in Ashland, 1.98 Mg $ha^{-1}$). In the evaluation of nutrient uptake and partitioning in different plant fractions, there was variability across all site-years which did not always follow the same patterns as the yield, however, the low-input treatment was shown to have significantly lower nutrient uptakes across all the nutrients evaluated (N, P, K, S, Fe, Zn) and across most fractions and sampling times. The objectives of this project were to identify management factors that contributed to high sorghum yields in diverse environments, and to investigate nutrient uptake and partitioning under different environments and crop production practices.

## Introduction

Grain sorghum (*Sorghum bicolor* (L.) Moench) is one of the most important cereal crops globally grown. In the United States, one of the top producing countries of grain sorghum, almost 11 million tons were produced in 2014 (FAOSTAT Food and Agricultural Commodities Production, 2014). This crop is particularly important in Kansas, however, the research and improvement of modern sorghum hybrids has lagged behind that of other cereal crops.

Previous improvements of this crop have been focused on targeting changes in the genotype (G) of modern hybrids and some management (M) practices. The complex interplay among management practices highly influences the decision making process for producing grain

sorghum, and the extent of the impact of management practices in diverse environments on nutrient uptake is still relatively unclear. Among the different management practices to be considered (interacting with nutrient applications) are: hybrid, crop rotation, planting dates, plant density, row spacing, weed, insect, and disease control. Numerous studies have suggested a variety of optimum planting densities based on the soil moisture status and the length of the growing season among other factors. One such study suggested that the optimum planting density for early to medium maturing hybrids should be between 123,550 and 185,325 plants $ha^{-1}$ (Staggenborg et al., 1999). Due to extreme variability in growing conditions throughout the state of Kansas, the yield results show very little conclusive evidence for set guidelines for management factors. For example, higher plant density (from 24,710 to 98,840 plants $ha^{-1}$) showed contrasting yield trends, with positive effects (14%) in some locations (e.g. Garden City) but neutral behavior in some others (Pidaran, 2012). The row spacing effect on sorghum grain yield was also tested under diverse locations, with narrower rows (25.4 vs. 76.2 cm) presenting a benefit in yield ranging from 3-14% when tested in different environments across Kansas during the same season (Belleville, Ottawa, Manhattan, and Hutchinson) (Maiga, 2012). Additionally, nutrient uptake in grain sorghum has been studied very little in the last 30 years, with some of the most relevant information still being from the 1970's (Jacques, 1973; Jacques et al., 1975; Roy and Wright, 1974; Vanderlip, 1972). There is a need for information on nutrient uptake in modern commercial sorghum hybrids.

In summary, there are very mixed conclusions about optimum management practices, and more research information is needed as related to the interactions among crop production practices and nutrient fertilization for maximizing yields at diverse environments in the mid-west. There is also a need for all encompassing data that looks at the effect of genotype,

environmental factors, and management factors on grain yield, biomass accumulation and nutrient uptake. A better understanding of the plant biomass accumulation, nutrient uptake and partitioning among vegetative and reproductive plant structures at multiple-growth stages and under diverse management practices will allow the optimized use of all soil-plant resources. In turn, it will be possible to close the yield gaps between current on-farm yields and the maximum economic attainable yields at each specific environment.

## Materials and Methods

### *Site Description*

Field studies were conducted during the 2014 and 2015 growing seasons at four sites during each year. Experiments were established at Rossville in 2014 (Soil Survey Staff, 2015) (39°07'N 95°55'W, well-drained Eudora silt loam, 0-1% slope), Scandia in 2014 and 2015 (39°49'N 97°50'W, moderately well-drained Crete silt loam, 0-1% slope), Ottawa in 2014 and 2015 (38°32'N 95°14'W, somewhat poorly-drained Woodson silt loam, 1-3% slope), and Hutchinson in 2014 (37°56'N 98°06'W, well-drained Nalim loam, 0-1% slope) at the Kansas State University Experiment Research Stations. In 2015, experiments were also conducted in Topeka (39°04'N 95°46'W, well-drained Eudora-Bismarckgrove silt loams, 0-1% slope), and at Ashland Bottoms Research Farm south of Manhattan (39°08'N 96°38'W well-drained Belvue silt loam, 0-1% slope), KS. In both years, two sites were irrigated and two were grown under dryland conditions. In 2014, Rossville and Hutchinson were irrigated with a linear and center pivot system, receiving 223 mm and 199 mm of irrigation, respectively; and Scandia and Ottawa were grown under dryland conditions. In 2015, Topeka and Ashland Bottoms were irrigated with a linear pivot and a sub-surface drip irrigation system, receiving 106 mm and 576 mm of irrigation respectively; and Scandia and Ottawa were grown under dryland conditions (Table 2.1). The

amount of irrigation applied was mainly targeted during the hottest part of the season and especially prior to stage six. The sub-surface drip irrigation system in Ashland Bottoms applied water every day from just before stage six until harvest. These sites were chosen for their highly variable environmental conditions in order to achieve the objective of understanding interactions among crop production practices and nutrient fertilization for optimizing inputs and maximizing sorghum yield at very diverse environments across the state of Kansas.

## *Treatment and Plot Descriptions*

### *Plot Descriptions*

The experiment was set up as a randomized complete block design with five replications, with 3 replications for destructive plant sampling (plant biomass and nutrient uptake), and eleven treatments per replication at each site. In 2014, the dimensions of the plots at all sites (Rossville, Scandia, Ottawa, and Hutchinson) were 3.05 m wide x 15.24 m long. In 2015, the dimensions of the plots in Topeka were 3.05 m x 21.34 m, in Ottawa and Scandia the plots were 3.05 m x 15.24 m, and in Manhattan the plots were 3.05 m x 18.29 m. The dimensions differed based on the area available at each experiment station. Each plot was comprised of four or eight rows, depending on the row-spacing (76 cm or 37.5 cm, respectively). Treatment applications were performed in the center of the plot, same position from which measurements, plant tissue sampling, and combine yield data were taken to avoid potential issues related to edge effect.

One medium-full season hybrid was chosen for 2014, Sorghum Partners NK 7633, due to its high yield potential and adaptability for irrigation and favorable dryland. The 2015 hybrids used were: DKS 53-67 for Topeka, this hybrid was a medium-full season maturity, with excellent yield potential and stay-green. In Ottawa, DKS 44-20 was chosen, which has a medium maturity group, excellent seedling vigor, and high yield potential. For Scandia, DKS 51-01 was selected which is

a medium-full maturity, has excellent seedling vigor, post-flower stress tolerance, and high yield potential. Finally, for Ashland, DKS 41-50 which is a medium maturity group hybrid with excellent potential for yield for maturity and test weight. These hybrids were chosen based on the Kansas Grain Sorghum Performance Tests for their suitability to each specific site. Tillage practices were implemented at these sites before planting, along with pre-plant fertilizer to ensure adequate soil fertility for maximum growth. Pre-plant N fertilization of 56 kg $ha^{-1}$ of UAN was applied in Ottawa, Scandia, and Hutchinson in 2014, and the same amount was applied in Ottawa, Topeka, Scandia, and Ashland in 2015. Planting was done in late May in 2014 in all locations and late May and early June in 2015 (Table 2.2). Weeds were controlled by hand weeding as needed throughout both seasons, and in 2015 all sites were sprayed post-emergence with an herbicide mixture of Callisto (0.22 L $ha^{-1}$), Dual II Magnum (1.53 L $ha^{-1}$), and Atrazine (1.17 L $ha^{-1}$), according to the labels.

***Treatment Descriptions***

The treatment combinations were set up as a 'full-input' approach with the removal of one input per treatment in order to evaluate the effect of that one input on the yield and other aspects of growth (Table 2.3). The inputs that were evaluated were a high seeding rate (197,600 plants $ha^{-1}$) vs. a low seeding rate (98,800 plants $ha^{-1}$), narrow row spacing (37.5 cm) vs. wide row spacing (76 cm), GreenSeeker meter (Trimble Navigation, Westminster, CO) use for in-season N recommendation for application, crop protection with foliar fungicide and insecticide application (Table 2.4), micronutrients of Fe and Zn applied at planting, a plant growth regulator (PGR) 1-Methylcyclopropene (1-MCP) (Table 2.4), starter fertilizer of NPKS applied at planting, and chloride (Cl) application at planting. Treatment one was the 'high input' approach, with high seeding rate, narrow row-spacing, GreenSeeker use, fungicide and insecticide, PGR

application, micronutrients, starter fertilizer and Cl application. Each of the following ten treatments removed one factor, with treatment ten being the control or 'low input' treatment, consisting of low seeding rate, wide row-spacing, no GreenSeeker use, no fungicide and insecticide application, no micronutrients applied, no PGR, only NP starter fertilizer, and no Cl application. Treatment eleven consisted of all the inputs, the same as treatment one, plus an additional 55 kg $ha^{-1}$ of N was applied with the GreenSeeker recommendation to ensure a non-limiting N environment.

***Treatment Specifications***

The fertilizer N source employed for the treatments was a fluid N (7-7-7-7S-7Cl) for planting and in-season N applications (GreenSeeker-N management). Other mixtures including 7-7-0, and 7-7-7-7S were used in the treatments corresponding with the removal of one nutrient to examine the effects (Table 2.3). The starter fertilizer and the in-season N were applied with the backpack sprayers in 2014 at the plot level. In 2015, the fertilizer was applied with the use of an all-terrain vehicle (ATV) with a 1.5 m boom attached to the back, with an adjustable pressure control system for plots with the bulk solution, and with the backpack sprayers for the treatments testing the removal of one nutrient. The starter fertilizer rates that were applied are found in Table 2.5. Micronutrients of Fe and Zn were applied as a mixture with the starter fertilizer at planting. Micronutrient rates were applied according to the label. For Fe, 0.123 kg elemental Fe $ha^{-1}$ was applied, using Fe EDTA (4.5%). For Zn, chelate EDTA Zn (9%) 0.279 kg elemental Zn $ha^{-1}$ was applied.

The starter fertilizer was surface dribbled next to the row of the sorghum crop to apply 25 kg N $ha^{-1}$. The correction for N with the GreenSeeker was implemented at about 8 to 10 leaves (for sensing the N status of the crop), and a sufficient N rate (7-7-7-7-7Cl) was added as

determined by the sorghum N rate algorithm calculator developed by Dave Mengel (Kansas State University). The rates and application amounts for each plot are in Tables 2.6 and 2.7.

The plant growth regulator (PGR) (1-MCP) was applied to determine if it could potentially modify the plant growth with a final impact on late-season growth and yield. 1-MCP is an ethylene inhibitor, which occupies ethylene receptors so that ethylene cannot bind and begin to react, causing ripening and shedding of leaves (Blankenship & Dole, 2003). For the plant growth regulator application, a mid-reproductive-phase (at soft-dough) was chosen as the application time. The plant growth regulator was applied with backpack sprayers at each individual plot-scale at the recommended rate of 0.25 kg $ha^{-1}$.

Foliar fungicide was applied during the mid- reproductive-phase (around soft-dough, 70-to-80 days after crop emergence). The fungicide, Tilt (Syngenta), with an active ingredient of propiconazole, fungicide class 3 was used as the fungicide treatment, applied at the recommended rate of 0.22 L $ha^{-1}$. The insecticide applied was Sevin XLR (Bayer) at the recommended rate of 2.34 L $ha^{-1}$ (jointly with the fungicide), with the active ingredient carbaryl, which was employed to control sorghum webworm, fall armyworms, and grasshoppers, among others. Foliar fungicides/ insecticides were added with backpack sprayers along with the PGR at each individual plot-scale.

### *Soil and Plant Characterization Measurements*

Before planting, composite soil samples (10-15 cores) were taken at a depth of 15 cm and 60 cm, done with a hand probe, to characterize the soil fertility at each site (Table 2.8). The soil samples were analyzed for pH, Mehlich P, K, Summation CEC, soil organic matter, and profile ammonium and nitrate at the Kansas State University Soil Testing Lab which uses the soil testing methods as described in the Recommended Chemical Soil Test Procedures for the North

Central Region, published by the University of Missouri Agricultural Experiment Station, Columbia, MO. These methods include measuring the pH directly using a 1:1 slurry of 10g of prepared soil with deionized water with an automated system, Mehlich III P analysis using a universal extractant that removes a wide range of elements, CEC is measured using the displacement method with saturating ammonium acetate to measure the CEC. Organic matter was measured using the Walkley-Black procedure, which digests 1 g of prepared soil with sulfuric acid and dichromate, followed by a direct colorimetric measurement of the reduced Cr2O72- ion; and both inorganic nitrogen forms, $NH\ 4^{+}$ and $NO\ 3^{-}$, are extracted with 1 M KCl, using 2 g of prepared soil. Cadmium reduction is used for nitrate and colorimetric procedures are run in a flow analyzer to measure these ions at the same time (Nathan and Gelderman, 2012).

Measurements for plant characterization were taken at growth stage two ($5^{th}$ leaf) (Ciampitti, 2015; Vanderlip, 1993), stage six (around half-bloom), and at stage nine (physiological maturity), these measurements were taken in each plot of three replications. Plant density stand counts were taken from four 5.3 m sections in each plot (all replications) at around the 3-leaf stage (Table 2.10). Plant measurements including plant height and diameter, and chlorophyll index, measured by a Konica Minolta SPAD-502 chlorophyll meter (Konica Minolta Sensing Americas, Inc., Ramsey, NJ), were taken at each of the previously mentioned growth stages from 10 marked plants in one of the middle rows within each plot, so that the same plants could be observed throughout the season. Plant height was taken at the collar of the $5^{th}$ leaf at the stage two stage, and the height at the flag leaf at stage six, and stem diameter was taken at the base of the stem using digital calipers at stage two and stage six. Also, leaf area index (LAI) was measured using a plant canopy analyzer (LAI-2000, LI-COR, Lincoln, Nebraska, USA) at stage two and stage six; the instrument sensor was shaded to avoid direct radiance as one data point

was collected above the canopy and then four successive data points were collected below the crop canopy at four equally-spaced points across the row-spacing gap between the middle two rows. The below canopy readings were taken with the sensor as close to the soil surface as possible. SPAD readings were taken at stage two and stage six, this was done by collecting three data points on the uppermost developed leaf from one plant, or from the flag leaf at stage six, and averaging them for one composite data point, 10 composite data points were taken within each plot. An additional set of SPAD data was collected during the 2014 season just before in-season N was applied to observe any chlorophyll index value differences from the levels observed at stage six after N fertilization, only one composite data point was collected from each plot for all five replications at each site. In 2015, the Line Quantum Sensor (LI-191SA, LI-COR, Lincoln, Nebraska, USA) was used for canopy light transmittance at the stage two and stage six growth stages. The transmittance was determined by the ratio of quantum flux incident above the canopy to quantum flux transmitted below the canopy at the soil surface. One measurement was taken above the canopy, and three measurements were taken below the canopy in each plot with the sensor centered between two middle rows at three points throughout each plot. Due to malfunctioning equipment, this measurement was not able to be taken during 2014. Canopy temperature was taken with the FLIR E5 infrared thermal imaging camera (FLIR Systems, Inc., Wilsonville, OR, USA) at the stage six stage in 2014 to see if any difference could be detected between head thermal temperature and flag leaf thermal temperature (Table 2.9). These readings were taken from a distance of about 0.5 m from the head or flag leaf, positioned directly level with the respective plant component.

Aboveground biomass and nutrient concentrations were determined at these growth stages for 10 representative plants from the middle rows of each plot in three of the five

replications, and grain yield and its components (grain number and grain weight). Plants were fractioned into leaves and stems at stage two; and into leaves, stems, and heads/grains at stage six and stage nine. The 10 plants for each respective fraction were combined into a single composite sample, of which sub-samples were taken when the wet weight was greater than around 1 kg (this was done to save space in the oven-dryers and to allow the drying of samples to be more uniform). After being fractioned and sub-sampled, plant samples were oven-dried at 60°C for about one week, or until a constant dry-weight was achieved and then were weighed. Dried plant samples were ground in a Thomas-Wiley laboratory mill (Model 4, Arthur H. Thomas Company, Philadelphia, PA, USA) to pass through a 1 mm screen. At the stage six stage, the head was ground in the same manner, as it did not contain fully formed grains yet. At stage nine, when the kernels reached black layer (Ciampitti, 2015; Vanderlip, 1993), the heads were threshed in a mobile thresher, and the grain was weighed by itself without the other head components, and then a sub-sample of grain was weighed and counted in an automatic seed counter to calculate the total grain number from the ten collected heads. This was done to observe if grain size and grain weight have an impact on yield. Finally, the grain was ground to 1 mm particle size in a coffee grinder. At the physiological maturity biomass collection time in 2015, the 10 plants collected were the plants that had been previously marked out and continuously measured for plant height, diameter, and chlorophyll index (SPAD). The area from which the plants were removed was measured to be subtracted out of the total harvestable area for the adjustment of final combine yields based on plot length. From the biomass data collected, the grain harvest index (HI) was calculated by dividing grain yield (13% moisture) by total biomass produced (stover and grain, assuming 0% moisture in dried stover). The plots were mechanically harvested after the stage nine biomass collection was taken using a two row plot

combine, from which grain samples were taken to determine moisture content and test weight. At all sites, yields were adjusted to a 13% moisture content.

Accurate meteorological measurements were recorded at each site throughout the growing season, including minimum and maximum daily temperatures, precipitation, and growing degree units were calculated from this data (Figures 2.1 and 2.2) (Weather Data Library- Kansas Mesonet · Historical Weather, 2014-2015).

### *Statistical Analysis*

Plots were arranged in a randomized complete block design with 5 replications in all site-years. Treatments were randomly assigned to experimental units within each replication with a different randomization for each of the eight experiments. Analysis of variance was conducted using the PROC MIXED procedure in SAS 9.4 (SAS Institute, 2004) at an alpha level of 0.05 to determine the significance of treatment factors. Data for 2014 and 2015 were analyzed separately due to the different hybrids used in both years. Treatment and site were considered as fixed factors, and block nested within the sites was considered as a random factor. For all factors tested, the site, treatment, and site by treatment interaction was examined. Appendix B contains an example of the SAS code used for the analysis.

## Results and Discussion

### *Climate Conditions*

In 2014 and 2015 across all the sites, a wide range of climatic conditions were present which impacted our yields and changed our treatment outcomes. Precipitation was the main factor that had the greatest impact. Figure 2.1 and 2.2 show the 2014 and 2015 weekly temperature and precipitation for the duration of each growing season, respectively. In 2014, Rossville and Hutchinson were irrigated, each receiving 223 mm and 199 mm of irrigation,

respectively; and in 2015, Topeka and Ashland Bottoms were irrigated, receiving 106 mm and 305 mm of irrigation, respectively. In the irrigated sites for both years, the irrigation helped to minimize the impacts of drought stress and greater differences were seen between the treatments. The irrigation also functioned to minimize variability across all the plots at each site. In the water limiting environments, i.e. dryland production, all the yields were limited and the effects of the treatments were minimized. This was seen particularly in Ottawa 2014, this site experienced severe drought stress for about a month prior to stage six and during grain-fill, which then resulted in inferior yields as compared with the other sites, and no significant result of the production practices evaluated. The following year the same site also received low rainfall which impacted the yields likewise, however, it was not as severe in water limitations, so the production practices had a greater impact, indicating better management practices to implement at water-limited environments.

### *Yield and Yield Components*

The average yields across the treatments showed greater variability in 2014 than in the 2015 season. The average yields for each treatment are found in Figures 2.3 and 2.4 for 2014 and 2015, respectively. There was very little consistency in which treatments yielded highest as it was highly related to the environment, and in some cases, the management practices occurring at each site. Overall, 2015 displayed higher average yields across all the treatments than 2014. For the 2014 data, the sites were tested together and no significant difference was found in the treatment or the treatment by site interaction. The site, however, had a significant effect on the final yield ($P < 0.0001$). Table 2.11 shows the means of the treatments and sites, as well as the P-values for significance for both years. In 2015 all the sites were tested together, and the site, treatment, and site by treatment interaction were all significant ($P < 0.05$) on the grain yield

factor. This provides information on how the yields responded differently at diverse sites to the treatments applied. The following sections will describe each site for both years.

***Rossville, KS (2014)***

In 2014, Rossville (irrigated) (Figure 2.3) out-yielded the other sites significantly, however, the treatments did not display significance during this year. In this site, the soil variability was extremely high which impacted early growth of the sorghum. At this site, the highest yields were observed in the 'high-input' treatments, particularly treatments eleven and nine (high-input + extra N, and high-input without Cl). The lowest yielding treatment was ten, (standard practice, or 'low-input') which was quite a bit lower than all the other treatments. The greatest yield gap between the highest and the lowest average yields was 1254 kg $ha^{-1}$ which came from the range between 7191 and 8445 kg $ha^{-1}$. From this generally high-yielding (>7 Mg $ha^{-1}$) environment, it can be observed that the high-input treatment has important yield advantages over the standard practices.

***Hutchinson, KS (2014)***

The second irrigated site in 2014 was Hutchinson (Figure 2.3), which displayed average yields that ranged from 3810 kg $ha^{-1}$ to 5531 kg $ha^{-1}$, with the yield gap being 1721 kg $ha^{-1}$ between treatments three (high-input with wide row-spacing) and eleven (high-input + extra N), respectively. Treatment ten was the next lowest-yielding treatments, though the treatment effect was not significant during 2014, these results do indicate that the low-input approach results in lower yields under irrigation. There was more variability in this site due to management errors and problematic field conditions, including poor planting conditions (a heavy corn residue mat on the ground from the previous year's harvest which was hard to plant through, and resulted in poor stands, in which many plots had to have small sections replanted by hand to achieve the

desired densities), also this site was harvested late in the season which resulted in lodging and grain being left on the ground. There was also bird damage to some of the heads during the season which lowered the overall grain yield. All of these factors contributed to a lower-yielding environment, despite the fact that it was irrigated.

***Scandia, KS (2014)***

Scandia was a dryland site for both years, and in 2014 the greatest average yield gap was 932 kg $ha^{-1}$, within the range of 6350 and 7282 kg $ha^{-1}$, which corresponds to treatments seven and one, respectively (Figure 2.3). Treatment seven was the high-input without plant growth regulator and treatment one was the high-input treatment (no variables removed). Treatment ten (low-input approach) also displayed low yields, just slightly above treatment seven at 6455 kg $ha^{-1}$. These results continue to show the trend that the high-input approach will out-yield the low-input approach in favorable dryland conditions, although this year was not significantly different in the treatment analysis. This site also had poor stands at the beginning of the season and had to be replanted by hand in sections of many plots, and this contributed to greater variability across the field.

***Ottawa, KS (2014)***

Ottawa was the final dryland site in 2014, which experienced the lowest yields as a result of drought stress before and during the stage six stages of growth. There was a stretch of several weeks before and during stage six in which little to no rainfall events occurred, see Figure 2.1. In this site, there was very little difference in average yields across all the treatments, as they were all limited by the drought conditions. However, the variability seen across all the plots and treatments was quite large, as seen by the error bars on the graph in Figure 2.3. Therefore, the cropping system approach had no effect on final yields in this water-limiting environment.

Although it was not significant, the highest yielding was treatment ten (low-input), with an average of 4637 kg $ha^{-1}$, and the lowest yielding was treatment six (high-input without micronutrients) with an average of 4063 kg $ha^{-1}$, resulting in a yield gap of 574 kg $ha^{-1}$. This low-yielding site (<6 Mg $ha^{-1}$) indicates that under the influence of severe drought stress, the standard practice approach yield is the same as the high input, perhaps even with slight advantages over any high-input approach.

***Ottawa, KS (2015)***

This site was also used in 2015, and it was still a low-yielding environment, although the drought stress was less severe. Average yields ranged from 4888 kg $ha^{-1}$ to 6253 kg $ha^{-1}$, with the greatest yield gap being 1365 kg $ha^{-1}$. The lowest yielding was treatment ten (low-input), and the highest was treatment two (high-input with low density) (Figure 2.4). Both of which were significant ($P < 0.05$), along with treatments four and nine being significantly lower than the rest in addition to treatment ten. This large yield gap showed that in a water-limiting, but not severe drought stress environment, using a high-input, narrow row-spacing cropping system approach, at a lower plant density, did help increase yields significantly.

***Scandia, KS (2015)***

Scandia was also used in 2015 (Figure 2.4), under dryland conditions, and this site showed much more variability across treatments than it did in 2014. The range of average yields was from 5608 kg $ha^{-1}$ to 9369 kg $ha^{-1}$, with the greatest yield gap out of all the locations at 3761 kg $ha^{-1}$. This was between treatments two (high-input, low density) and four (high-input, pre-plant N only) ($P < 0.05$). Treatments three, four, and ten were among the highest yielding treatments, and this can be partially explained by the in-season N application through the use of the GreenSeeker. When N was applied, there was damage done to the green leaves which was

counter-productive by inhibiting photosynthesis and limiting yields. Treatments four and ten did not receive in-season N (used a standard pre-plant N program), and treatment three had wide row-spacing which limited the damage done to the leaves as the N fertilizer reached the soil surface with less interception from the leaves. This problem also occurred at the Topeka site in 2015. This error could be avoided through the proper timing (8-10 leaf stage, no later) and application (drop-tubes to better reach soil surface) of the GreenSeeker N recommendation.

***Topeka, KS (2015)***

Topeka was an irrigated site in 2015, and this, being similar to Rossville from the previous year, is generally a high-yielding environment (>7 Mg $ha^{-1}$). Despite the damage done to the leaves from the N application, high yields were still achieved across all the treatments due to balanced nutrition and proper irrigation. Treatments ten and four out-yielded the others significantly with a P-value < 0.05. All the other treatments yielded very similarly, with the variability being reduced by the application of irrigation, 106 mm, during the season. The average yield ranged between 9360 kg $ha^{-1}$ and 10437 kg $ha^{-1}$, in treatment eleven (high-input + extra N) and treatment ten (low-input), respectively, with the yield gap being 1077 kg $ha^{-1}$ (Figure 2.4). Treatments ten and four were not expected to be the highest yielding, but due to the N damage to the leaves, these treatments that did not received in-season N faired the best, especially with the addition of the irrigation.

***Ashland Bottoms, KS (2015)***

The final site in 2015 was Ashland Bottoms, near Manhattan. This site was irrigated through a sub-surface drip irrigation system. In this site, the soil test results exhibited an alkaline pH of 7.9 (Table 2.8), this may have impacted the nutrient uptake and subsequent yields at this

site. Additionally, this site was impacted by weed competition throughout the season, despite having been sprayed with a pre- and post-emergence herbicide. The average yields ranged from 6141 kg $ha^{-1}$ in treatment ten, to 8119 kg $ha^{-1}$ in treatment four (Figure 2.4). The yield gap was 1978 kg $ha^{-1}$. Treatment four was significantly greater, and again, this may have been due to the damage done by the in-season N application, of which treatment four did not receive. Lower yields in treatment ten might have been associated with the wider row-spacing and lower plant density, despite adequate irrigation of 305 mm.

***Grain Number***

Another important yield component that was measured was the grain number. This number was found to be highly related to the final yield. Figures 2.8 and 2.9 display the strong relationship between the grain number per head and the yield per plant, expressed in grams (also could be called grain weight per plant), for 2014 and 2015, respectively. In both years the $P < 0.0001$, indicating that the correlation is significant and that the final yield per plant is highly related to the grain number per plant. The 2014 season showed slightly less strongly-correlated results, and this may have been in part due to data collection error. In relation to the treatment, the grain number was significantly impacted by the site in both years, and also by the treatment in 2015 ($P < 0.0001$) (Table 2.11). In 2015, treatment two (high-input with low density) and treatment ten (low input, low density) were significantly greater in the per-plant grain number than the other treatments. Due to the low plant density in these two treatments, there was less competition between plants and the plants were larger which allowed for significantly greater grain numbers per head. Overall, the grain number as a yield component is central for all management and nutrient practices, as crop production practices should be targeted to impact the grain number per head.

### *Total Biomass*

The total biomass is calculated as the sum of the dry weight of the fractions (heads, leaves, and stems) in g $m^{-2}$ at the physiological maturity sampling time. For both years the site was significant on the total biomass, and in 2015 the treatment was significant at $P < 0.05$. (Table 2.11) A trend documented in this study is that high yielding sites (>7 Mg $ha^{-1}$) had a greater average biomass than the lower yielding sites (<6 Mg $ha^{-1}$), and the 2015 values were higher on average than the 2014 total biomass values across all the sites and treatments. In 2015 when the treatment factor was significant, treatment four (high-input, pre-plant N only) presented the largest biomass, followed by treatment one (high-input) and treatment nine (high-input without Cl). Treatment eleven (high-input + extra in-season N) had the lowest total biomass. This variable followed a similar pattern as the yield variable, as the same treatments were the highest and lowest yielding. As previously discussed, this was due in part to the damage that was done from the in-season N application which burned the leaves and decreased the total biomass at the final sampling time. It is important to note that as a management tool, the GreenSeeker can be very valuable to sense the crop N requirement, but if not properly timed, the effect of this practice can be negligible.

### *Grain Harvest Index*

The grain harvest index (HI) is calculated by the ratio of the grain weight to the total biomass (heads + stems + leaves) weight. This allows another way of viewing the yield results to see how the plants are partitioning the biomass accumulated. These ratios indicate what portion the grain represents relative to the total aboveground biomass weight. For 2014 the HI percent values for all sites are found in Figure 2.5, and for 2015 they are found in Figure 2.6. The averages and P-values are also found in Table 2.11. In 2014, the values for the HI were

significant by the sites, with the highest HI values corresponding to the highest yielding sites; Rossville had the highest values for HI, with an average of 58%, Scandia, the second highest yielding, had an average of 55%, Ottawa and Hutchinson had the lowest HI's of 52% and 50%, respectively. In 2015, the HIs were lower as a whole, than in 2014, with the values showing significance for the treatments, but not for the sites. Treatment ten had the highest HI values across the 2015 sites, and treatment two had the next highest HI values, however, it was determined that the HI values were not related specifically to the yield values. Figure 2.7 shows the relationship between the yield and HI, and that is in 2014 the relationship between the HI and the yield was slightly higher than in 2015, though neither displayed significance for the HI and yield relationship. The HI values were calculated from ten plants that were collected in each of the plots, and due to the different levels of plant density and row spacing, the plants expressed great variability in individual size. This is because grain sorghum can compensate its plant size based on the availability of space and nutrients. Therefore, the HI values are not necessarily a representation of the treatment effect in this experiment, but rather due to the management practices that affect plant size. Additionally, this helps explain why the HI values are not related specifically to the yield levels achieved by treatment, but they can correspond to different yield levels.

### *Biomass Accumulation by Fraction*

The biomass was further examined by plant fraction (leaves, stems, heads), and at three sampling times. Figure 2.10 and 2.11 display the biomass accumulation for 2014 and 2015, respectively. Only treatments one and ten were examined for the nutrient uptake curve, due to the quantity of data and expected difference between these two, high-input vs. low-input, treatments. In the top two nutrient uptake curves of the 2014 (Figure 2.10, upper panels), there is

a lot of similarity between the two treatments across all three fractions. Very little difference has been documented in biomass accumulation between any of the treatments under irrigation, as the irrigation helped to increase biomass more uniformly across the irrigated site. In the lower two graphs of the 2014 (Figure 2.10, lower panels), there are much greater differences to be observed between the two treatments. Treatment one exhibited greater early-season accumulation in the stem and head portion, however, it appears to level off, and even drop off for the stem fraction, and the final biomass for each fraction ends at nearly the same amount for both treatments. This was the site that experienced severe drought stress around reproductive stages, which limited the yield potential for the site as a whole, and could be a main cause for the leveling-off and dropping-off of the high-input fractions.

The same site was observed in 2015, and shown in Figure 2.11, the bottom two graphs show what happened under more favorable (less severely drought-stressed) dryland conditions. There is a much greater difference between the two treatments during this growing season. The high-input treatment accumulated much more biomass for all three fractions throughout the whole season, ending with a final biomass accumulation considerably greater than the low-input treatment. These results also concur with the final yield achieved, as previously discussed, the treatment ten was the lowest yielding at this site. This gives a good indication that the high-input approach produces more biomass which translates to a greater yield, even in a yield-limiting environment. Also, in the 2015 figure, the irrigated site (top two graphs) showed results very similar to the previous year under irrigation. The high-input and low-input treatment accumulated biomass very equally, there was little to no difference documented in this environment. The graphs continue to show upward accumulation to the very end, and did not

level-off, which could be promising that the biomass production, including the grain portion, might have the potential to increase even greater in high-yielding environments.

With the biomass data, a full analysis was done for each year separately for all sites in that year, with the dry weight (kg) and the biomass (g $m^{-2}$) being the factors tested for both years. The analysis was done by testing the significance of the treatment, the site, and the site by treatment interaction. In the 2014 dry weight analysis of biomass (Table 2.12), the site was significant at every sampling time and within each fraction (stage two- leaf, stem; stage six- leaf, stem, head; stage nine- leaf, stem, grain). The treatment and the treatment by site interaction was not significant at any of the stages or fractions. Therefore, the biomass uptake expressed in dry weight (kg) was influenced only by the site (environment) in which it was grown and not by the treatment applied in 2014. The biomass expressed in g $m^{-2}$ for 2014 (Table 2.13) exhibited significance, again, at each site for every sampling time and within each fraction. At the stage two sampling time, the treatment was significant on the leaf portion only. Treatments ten and two were significantly lower than the rest of the treatments. This is explained by the low plant densities that were part of both of those treatments; the biomass over an area (g $m^{-2}$) was less because the density of the plants was lower. At the stage six sampling time, the treatment was significant for the leaf and stem portion. Similar to stage two, treatments ten and two were among the lowest biomass produced in g $m^{-2}$, and treatments one, four and eleven were among the highest producing biomass for all the sites. These are the high-input, high-input with pre-plant N only, and high-input + extra N. This displays the importance of the N program on biomass production at a crucial time in the season. At the final sampling, stage nine, only the site was significant on the biomass production, and the sites follows similar trends as the yield results, with the same sites being the highest in both biomass and final grain yield. This reflects

that the biomass differences among treatments was clear until stage six and then disappeared during the reproductive stages.

The 2015 analysis of biomass (Table 2.14) exhibited more significance than the previous year, with the site being significant at all sampling times and for each fraction, and the treatment displaying significance for all the fractions within the stage six and stage nine sampling times. Stage two showed no significance from the treatment. The site by treatment interaction was not significant for any of the sampling times or fractions. The main reason why the sites always appear to be significant is because they are very diverse environments and that is always having a tremendous impact on the biomass produced, largely due to precipitation and the addition of irrigation. The treatment effect that was seen in the biomass produced showed that treatments ten and two produced a greater dry weight of biomass across all three fractions at both the stage six and stage nine sampling times. This did not necessarily correspond to the yield because these two treatments were the low plant density treatments, so it is logical that the biomass from a specific number of plants would be greater, but that did not transfer to greater yields because of the low density of plants in those treatments. As expected, the biomass expressed in g $m^{-2}$ for the low plant density treatments was significantly less than that of the high-input treatments during stage two, stage six and stage nine for most of the fractions (Table 2.15). There was an interaction between the site and the treatment in this year for the stage two stem portion, and at stage six for the leaves and stems. This interaction did not remain through to the end of the season. Sources of error in the biomass data can attributed to the exact time when the plant samples were collected, particularly during the vegetative stages when the plants are rapidly growing, a couple of days' difference in biomass accumulation can alter the dry weight and biomass in g $m^{-2}$. These differences tend to be less noticeable as the plants reach a mature size.

## *Nutrient Uptake*

A complete nutrient analysis was done on the plant tissue samples that were collected for the biomass data. This including testing levels of N, P, K, S, Fe, and Zn for all the plant fractions at each of the three sampling times. The soil tests from the beginning of both seasons show that the soil at each of the sites was at or above critical limits for sorghum growth for the macro-nutrients (Table 2.8); with the exception being in Ottawa during 2015, the P levels were just under what most would consider a critical limit (Nathan & Gelderman, 2012). Two sites from each year were analyzed for nutrient levels. In 2014, Rossville and Ottawa were analyzed, and in 2015 Topeka and Ottawa were analyzed. The years were kept separate, and again the site, treatment, and site by treatment interaction were examined. Tables 2.16 through 2.21 display the results from both years by nutrient (N, P, K, S, Fe, and Zn, respectively).

### *Nitrogen*

Nitrogen uptake in 2014 (Table 2.16) showed significance for most of the sites, treatments, and the treatment by site interaction for the stage two on the leaf and stem plant fractions. During stage two, treatment three showed the highest N uptake, 6.8 and 1.7 g $m^{-2}$ for leaves and stems, respectively, and treatment ten showed the lowest N uptake, 4.2 and 1.1 g $m^{-2}$ for leaves and stems, respectively. There was very little consistency in N uptake values in this sampling time for 2014, as Figure 2.14 displays the range of the N uptake values at stage two. The remaining stages and fractions in 2014 showed no significant difference between treatments in N uptake, however, there is a trend of treatments ten and four having lower N contents in all fractions than the other treatments. These treatments received the pre-plant N only, with no in-season N applied from the GreenSeeker recommendation. Perhaps in a more N- limiting environment, these treatments might have showed some N deficiency, however, that was not the

case from a visual analysis of the plots. Also, from the chlorophyll index readings from the SPAD meter, (Figure 2.12) treatment four showed slightly lower SPAD readings in dryland and irrigated sites during the vegetative growth stage, but no strong relationships were documented between SPAD readings collected and the N content in the tissue samples. At the stage six stage, the SPAD readings and the N content levels do not show the same trends, and in fact no significance was found at this sampling time, and the variability in N content in the leaves portion was quite high, ranging from 1 to 8 g $m^{-2}$ (Figure 2.15). The comparison between the leaf N content and the SPAD readings in this experiment has its limitations in that the SPAD readings were collected from different plants than the ones used for destructive biomass.

In 2015, a similar trend has been reported with treatment ten presenting the lowest N content in most fractions and sampling times, along with treatment four in some instances (Table 2.16). During this year, the treatment showed significance at all the fractions from the stage two and stage six growth stages. There was also less variability in the N uptake (g $m^{-2}$) during 2015 at both stage two and stage six (Figures 2.14 and 2.15). Similarly, the %N concentration (g $100g^{-1}$) in the leaves and stems showed less variability in 2015 than in 2014 for both the stage two and stage six sampling times (Figures 2.16 and 2.17). In particular, within the fractions, the leaf portion tended to have a greater amount of variation than the stem and head portions, which indicates that the leaf has a greater flexibility in storing N as it is available to the plant. The 2015 SPAD readings (Figure 2.13) do not display any clear trends at stage two; but at the stage six stage, treatment four is significantly lower in the dryland environment. Besides this one treatment, the SPAD data was not corresponding to the N content at either growing stage, similar to the previous year. Across both years, a consistent trend has been documented in treatment ten containing the lowest N content across most fractions and stages, conversely, there were no

trends observed in any treatment consistently being the highest N content. Implications from these findings suggest that the N program is of great importance to sorghum growth for maximizing yields, and plant tissue N content was shown to be boosted with the addition of in-season N application. There was also a significant interaction in the grain portion of the plant at physiological maturity in 2015 (Table 2.16). This indicates that treatments were having a different effect on the final grain N uptake at the different environments.

Figure 2.28 illustrates the 2014 N uptake curves for treatments one (high-input) and ten (standard practice or low-input) in order to show the different impact of these treatments at different environments (dryland and irrigated). Figure 2.29 shows the same illustration for the 2015 data in similar sites under irrigation and dryland. From the 2014 figure, the two treatments under irrigation appear to have a very similar N uptake pattern, which is consistent with the total biomass uptake under irrigation observed in Figure 2.10. The stem and leaf N contents were greater for dryland relative to irrigated sites, with an opposite trend for the grain N content. All the fractions in this year in dryland show the curve to be dropping off or leveling off after stage six, as a result of the drought stress in that environment. From these graphs it can be concluded that the irrigated sites had advantages over the dryland sites in N uptake to the grain portion. The 2015 graph (Figure 2.29) shows similar results with little difference between the treatments in the irrigated environment, and with great differences seen between irrigated and dryland. The dryland showed much smaller uptake curves, with treatment one have a particularly strong advantage over treatment ten in dryland. This year gives a better understanding of how N uptake is responding in a low-yielding environment (<6 Mg $ha^{-1}$), because it did not experience such severe drought stress as the previous year, which impeded normal plant growth and development and nutrient uptake.

### *Phosphorous*

Phosphorous uptake in 2014 (Figure 2.30) displays similar uptake trends for both treatments within irrigation regimes, however, the irrigated site portrayed a moderate advantage in P uptake over the dryland. In 2015, (Figure 2.31) much greater advantages are seen in the irrigated over the dryland in P uptake for both treatments. Table 2.17 takes an in-depth look at each sampling time for P uptake and in 2014, the leaf and stem fraction at stage two was the only stage that had significance from the treatment effect. In both of those fractions, treatment ten was the lowest in P uptake. In 2015, all the fractions at stage two and stage six showed significance from the treatment effect, and at both stages, treatment two (high-input, low density) and ten (low-input) were consistently the lowest in P uptake, while treatment four (high-input, pre-plant N only) and eleven (high-input + extra N) were among the highest. The leaf fraction at physiological maturity was also significant, with treatment four being the highest, and no significant difference among the other treatments. In 2015, the Ottawa, KS dryland site, showed that the pre-plant soil test levels of P were slightly deficient, as they were just under the critical limits, defined by the Tri-State Fertilizer Recommendations' critical soil test levels for various agronomic crops (Nathan and Gelderman, 2012). This is why there was a greater benefit shown by the high-input treatments over the low-input treatment at this site-year (Figure 2.31, lower panels). In 2014, there was more variation in the %P concentration in the leaves and stems at stage two than in 2015 (Figure 2.18). At stage six, the 2015 data exhibited greater variation than the 2014 data in %P concentrations in the leaves and stems (Figure 2.19).

### *Potassium*

The pre-plant soil test levels of K in both years showed a sufficient level to meet all the crops needs at all the sites. In Figure 2.32 the 2014 K uptake curves show that in the dryland

environment (lower panels), treatment ten showed slight advantages over treatment one in terms of K uptake to the grain portion, and in treatment one the K uptake leveled off at the end of the growing season. This was most likely related to the drought experienced in this site, which limited the plant growth and nutrient uptake as a whole, and the same trend was not seen in the following year. The values for the final grain K uptake in the irrigated site were taken from the stage six data, because the grain K concentrations from 2014 are being reevaluated. In 2015 (Figure 2.33), K uptake showed extreme differences between the irrigated and the dryland sites in K partitioning to the stems. This partitioning to the stem is consistent with previous research which concluded that most of the K taken up is stored in the stem portion of the sorghum plant (Eck and Musick, 1979; Roy and Wright, 1974; Vanderlip, 1972). Table 2.18 indicates that the leaf and stem fraction at stage two and stage six were significant from the treatment effect in 2014. In these sampling times, treatment ten displayed consistently lower concentrations of K across all the fractions, and the other treatments showed contrasting results for the highest K levels. In 2015, all the fractions in the stage two and stage six sampling times exhibited significance from the treatment effect. In particular, treatment ten was consistently lower than the others, along with treatment two (high-input, low density), and in the stage six sample, treatment eleven was among the highest in K uptake. This could be attributed to the extra fertilizer that was applied in this treatment. The %K concentrations exhibited greater variations in 2015 than in 2014 at both stage two and stage six (Figures 2.20 and 2.21).

### *Sulfur*

The micronutrient S was applied with the other nutrients in the high-input treatments, with the omissions being in treatments eight and ten. In Table 2.19, the 2014 results show that the treatment was significant in the stage two sampling for the leaf and stem, and at the stage six

sampling time for the leaf. Treatment ten was consistently lower in the S uptake, but treatment eight showed no particular trend in S uptake. In 2015, the S uptake was significant at all the fractions in the stage two and stage six sampling times. Similarly, in this year treatment ten was consistently the lowest in S uptake, followed closely by treatment two, once again however, treatment eight showed no real trends in S uptake. Figures 2.34 and 2.35 show the S uptake for 2014 and 2015, respectively, and they display a large difference in S uptake between the dryland and irrigated sites for both years. In 2014, a majority of the S taken up is stored in the grain, with very little difference seen between the treatments at both sites. In 2015, treatment one shows greater proportions of S accumulating in the stem and leaf fraction than treatment ten at both sites, and treatment one out-performing treatment ten in the dryland site. The %S concentrations displayed similar variations during both years at both stage two and stage six (Figures 2.22 and 2.23).

***Iron***

In Table 2.20, the Fe uptake for both years shows that only the leaf fraction during the stage two sampling time was significant from the treatment effect. In both years, treatment ten (low-input) and two (high-input, low density) were the lowest in Fe uptake, and treatment three (high-input, wide row-spacing) and eleven (high input + extra N) were among the highest. Treatment six was the treatment without the addition of Fe, and there was no difference seen in this treatment compared with the rest; it was quite average across all the sampling times and fractions. This was probably due to the fact that these environments were not limited in their nutrient profile from the beginning of the season. Iron deficiency is more commonly reported in western Kansas, but not particularly in the sites that were examined for nutrient uptake. Figures 2.36 and 2.37 display the Fe uptake for 2014 and 2015, respectively. These uptake curves are

similar across both sites in 2014, and show greater differences in 2015 in accumulation between the irrigated and dryland environments, with the irrigated accumulating greater quantities of Fe than the dryland environment, though little differences were seen between treatments within each environment. The variations in Fe concentrations (ppm) are documented in Figures 2.24 and 2.25, for stage two and stage six, respectively, which display higher levels and greater variations of Fe concentrations in 2014 than in 2015.

***Zinc***

Table 2.21 displays the Zn uptake for 2014 and 2015, and in this table the 2014 data expresses significance in Zn uptake in the leaf fraction during the stage two and stage six sampling time. In these fractions, treatment ten was the lowest in Zn uptake. In 2015, more significance was seen in other fractions and sampling times, including the leaf and stem at stage two, the leaf and head at stage six, and the leaf at maturity. In these same fractions, treatment ten was consistently lower than the other fractions, followed by treatment two, often being significantly lower as well. Treatment six, without the addition of Zn, showed no significant trends in Zn deficiency. The variations in Zn concentrations (ppm) are displayed in Figures 2.26 and 2.27, for stage two and stage six, respectively, which show similar concentration variations for both years within each sampling time. Additionally, the Zn uptake curves for 2014 and 2015, are found in Figures 2.38 and 2.39, respectively. In 2014, the high-input showed advantages over the low-input in Zn uptake in both irrigated and dryland environments. In 2015, the Zn uptake was very similar for both environments, however, in the dryland site, the high-input treatment showed slightly greater Zn uptake than the low-input treatment.

# Conclusions

Across all the sites for the final grain yield, the irrigated sites showed consistently better yields for the high-input treatments, having a significant advantage over the low-input treatment ten. In dryland conditions, the yield results varied, but the high-input with the lower plant densities showed superior yields, and gives a strong indication that narrowing rows and having a balanced nutrient application approach can close the yield gaps in these environments. The grain HI values were greater in treatments two and ten in most cases, however this was shown to not be related to the final yield, but rather it was due to the management practices that allowed for a greater individual plant size, thus more biomass partitioned to the grain over the total biomass. The biomass was found to be greater for the irrigated sites, and more yield advantages were found in high input treatments under dryland (to an extent, as long as it's not drought stressed). Not as much difference in biomass accumulation was documented under the irrigated treatments. Treatments two and ten produced larger individual size of plants, but lower yields at the unit area basis due to the lower plant densities.

For the nutrient analysis, the N uptake displayed little difference between treatments under irrigation, but substantial differences were documented between the low-input and high-input treatments in a dryland environment. Implications from these findings suggest that the N program is of great importance to sorghum growth for maximizing yields, and plant tissue N content was shown to be boosted with the addition of in-season N application. Phosphorous uptake was notably greater in the irrigated than in the dryland sites, particularly in 2015 where the soil test P levels showed a deficiency in the dryland site prior to planting. Across the sampling times and fractions, treatment ten (low-input) was consistently the lowest in P uptake, with no clear trends in which treatment was the highest. Potassium uptake showed similar

results, both years, with treatment ten accumulating less K than the other treatments, particularly during the stage two and stage six sampling times. The stem portion accumulated more K during both years, which is consistent with previous research. Sulfur uptake was greater in the irrigated sites, and the high-input treatments showed advantages over treatment ten in S uptake across most sampling times and fractions. For Fe and Zn, lowest nutrient uptake was documented in treatment ten and often in treatment two, but treatment six, which was the treatment specifically without Zn and Fe, showed no deficiency or trend in accumulating less of these nutrients than the other high-input treatments, this was most likely due to the non-limiting environments in which the nutrient accumulations were tested, and due to the acceptable pH soil test levels which would allow for proper nutrient availability.

Further research into these topics, particularly the nutrient partitioning in other environments could be proven to be useful for producers in other parts of Kansas and the mid-west. Additionally, a full economic analysis should be completed for different environments in order to help producers make best management decisions with the economic impact in mind.

# Figures and Tables

**Figure 2.1 Weekly maximum and minimum temperatures (°C) and precipitation (mm) (rainfall + irrigation) during 2014 for all sites.**

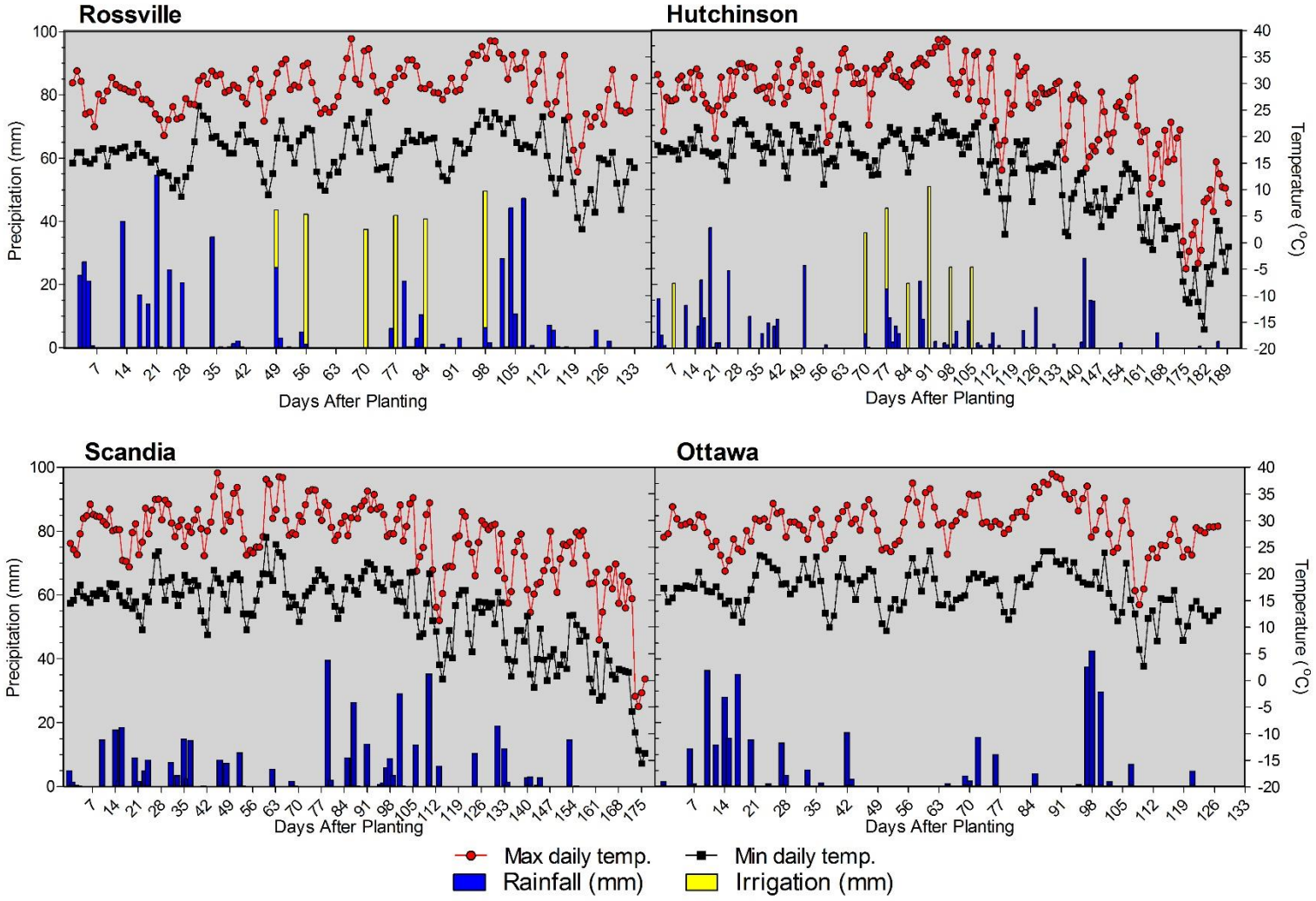


**Figure 2.2 Weekly maximum and minimum temperatures (°C) and precipitation (mm) (rainfall + irrigation) during 2015 for all sites.**

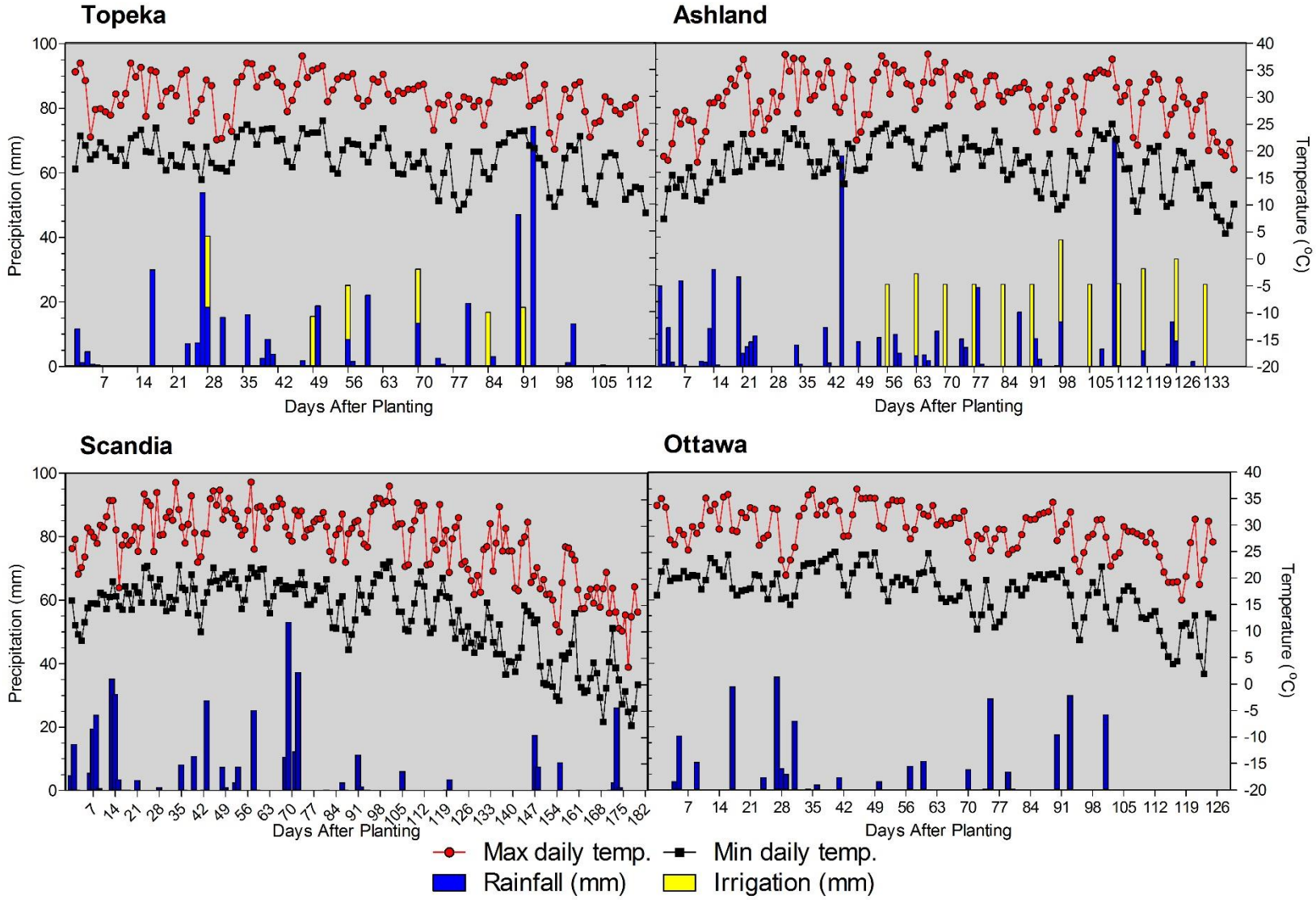
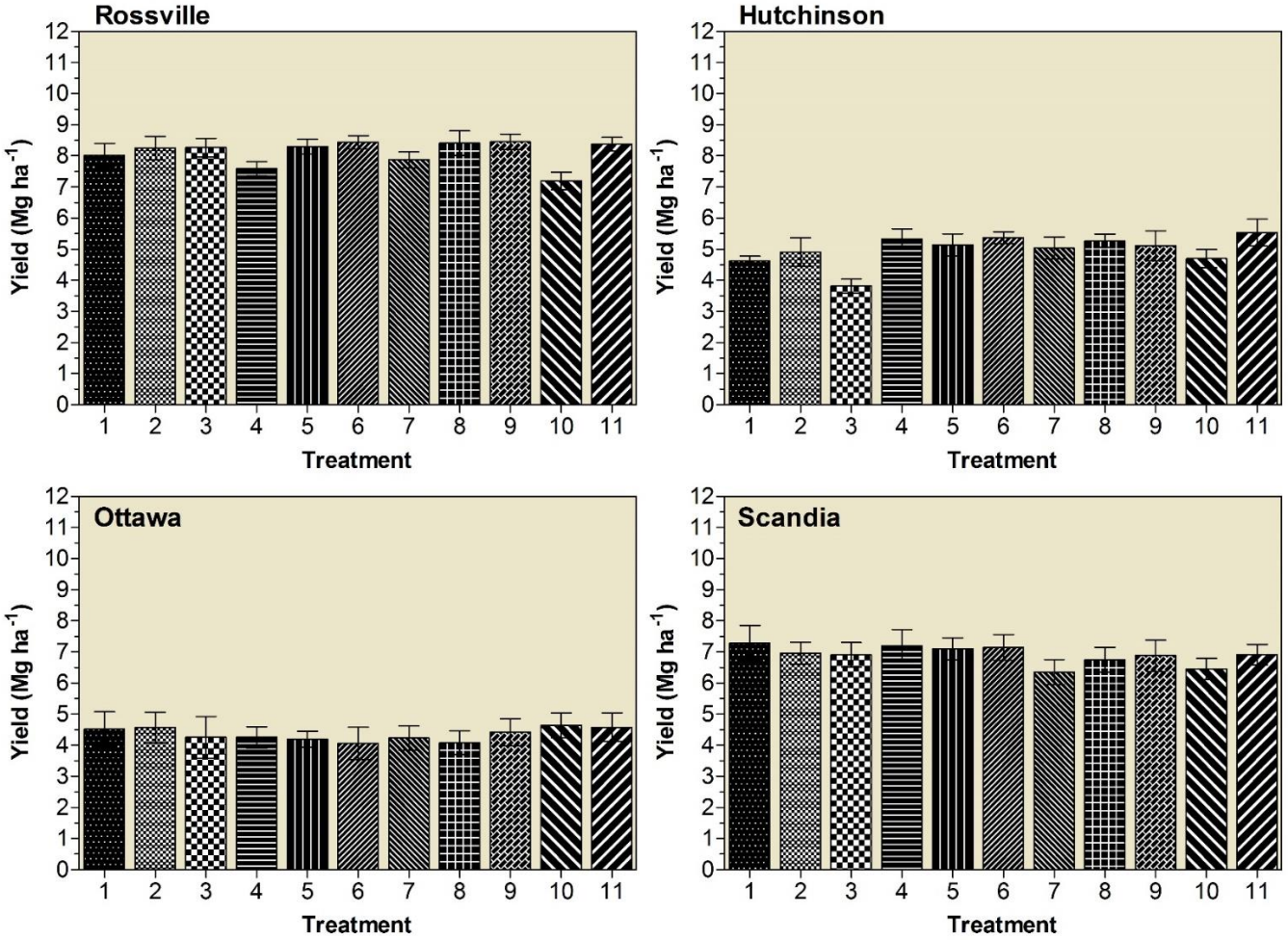
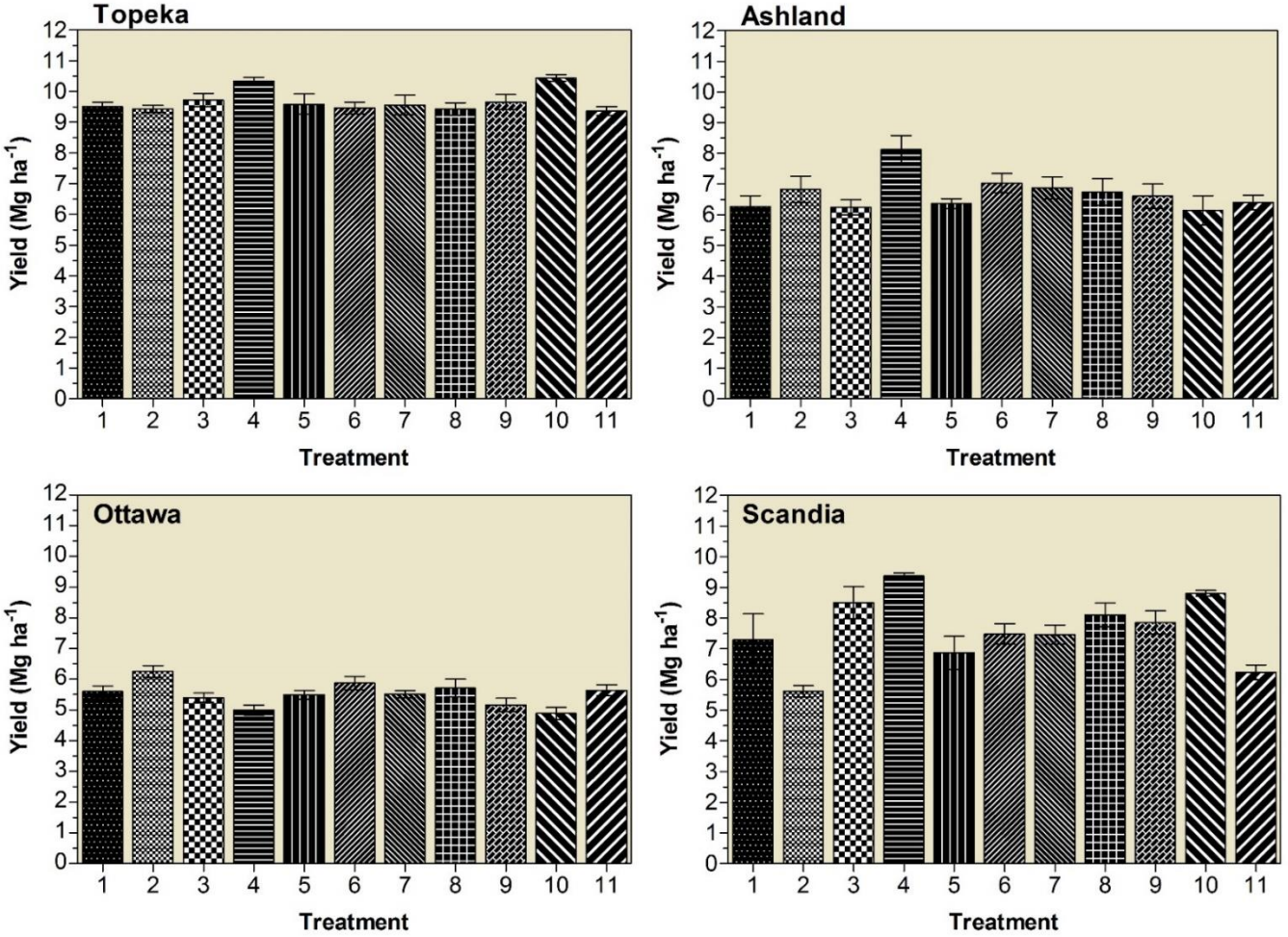


**Figure 2.3 Average yield of grain sorghum per treatment† at all sites during 2014, error bars indicate standard error of the mean.**



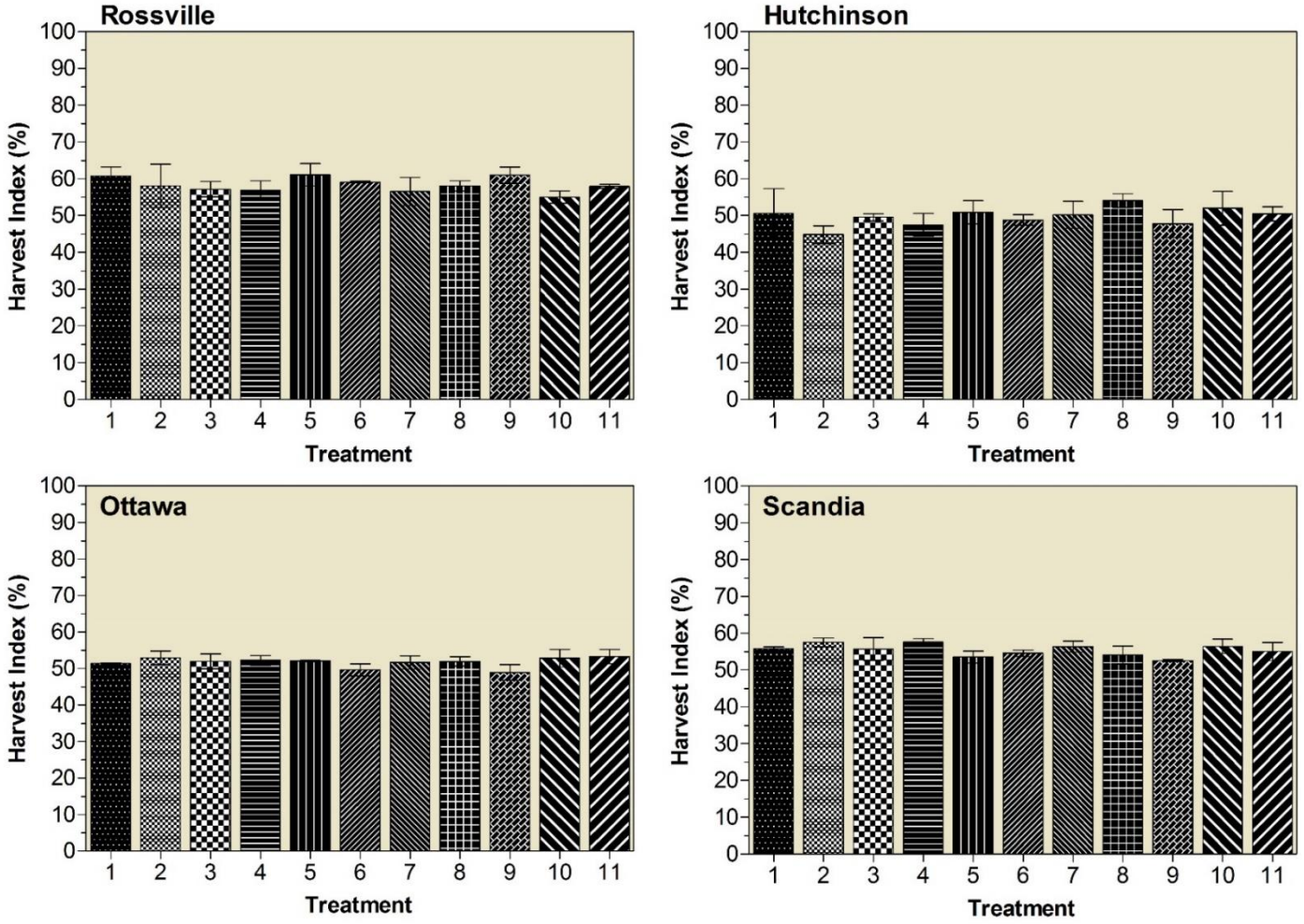

†Treatments: 1=High-input, 2=low seeding rate, 3=wide row-spacing, 4=standard N program (no GreenSeeker), 5=no fungicide & insecticide, 6=no micronutrients (Fe, Zn), 7=no plant growth regulator, 8=NP starter fertilizer only, 9=no chloride, 10=standard practice (low-input), 11=high-input + extra N.

**Figure 2.4 Average yield of grain sorghum per treatment† at all sites during 2015, error bars indicate standard error of the mean.**



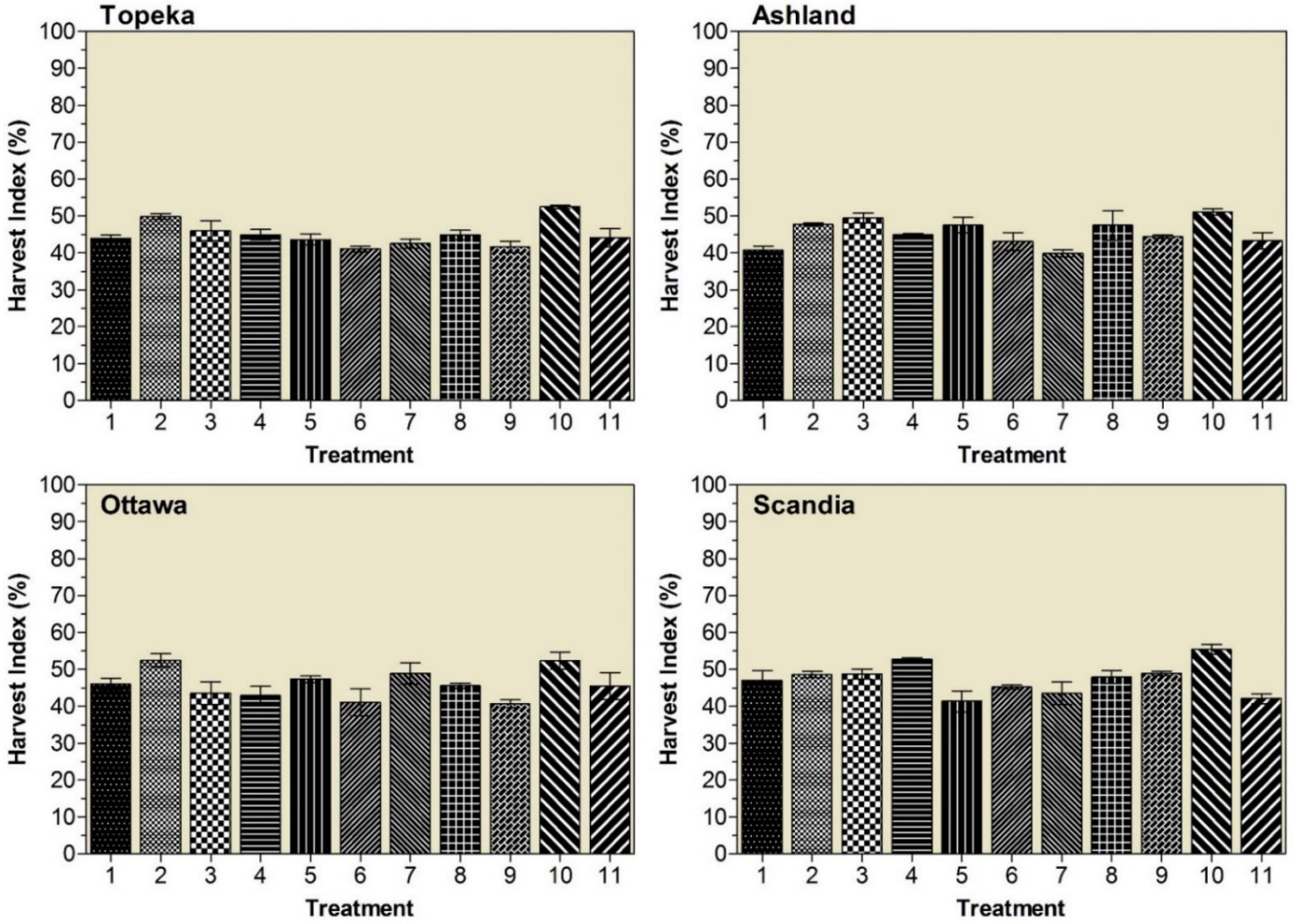

†Treatments: 1=High-input, 2=low seeding rate, 3=wide row-spacing, 4=standard N program (no GreenSeeker), 5=no fungicide & insecticide, 6=no micronutrients (Fe, Zn), 7=no plant growth regulator, 8=NP starter fertilizer only, 9=no chloride, 10=standard practice (low-input), 11=high-input + extra N.

**Figure 2.5 Harvest index (%) for grain sorghum in 2014 by treatment†, calculated as the ratio of the grain weight to the total biomass (head + leaves + stem) weight.**




†Treatments: 1=High-input, 2=low seeding rate, 3=wide row-spacing, 4=standard N program (no GreenSeeker), 5=no fungicide & insecticide, 6=no micronutrients (Fe, Zn), 7=no plant growth regulator, 8=NP starter fertilizer only, 9=no chloride, 10=standard practice (low-input), 11=high-input + extra N.

**Figure 2.6 Harvest index (%) for grain sorghum in 2015 by treatment†, calculated as the ratio of the grain weight to the total biomass (head + leaves + stem) weight.**




†Treatments: 1=High-input, 2=low seeding rate, 3=wide row-spacing, 4=standard N program (no GreenSeeker), 5=no fungicide & insecticide, 6=no micronutrients (Fe, Zn), 7=no plant growth regulator, 8=NP starter fertilizer only, 9=no chloride, 10=standard practice (low-input), 11=high-input + extra N.

**Figure 2.7 Harvest index (%) and grain yield (kg ha$^{-1}$) relationship for 2014 & 2015; all 8 sites included, 3 replications, 11 treatments per replications (n = 132, per year).**

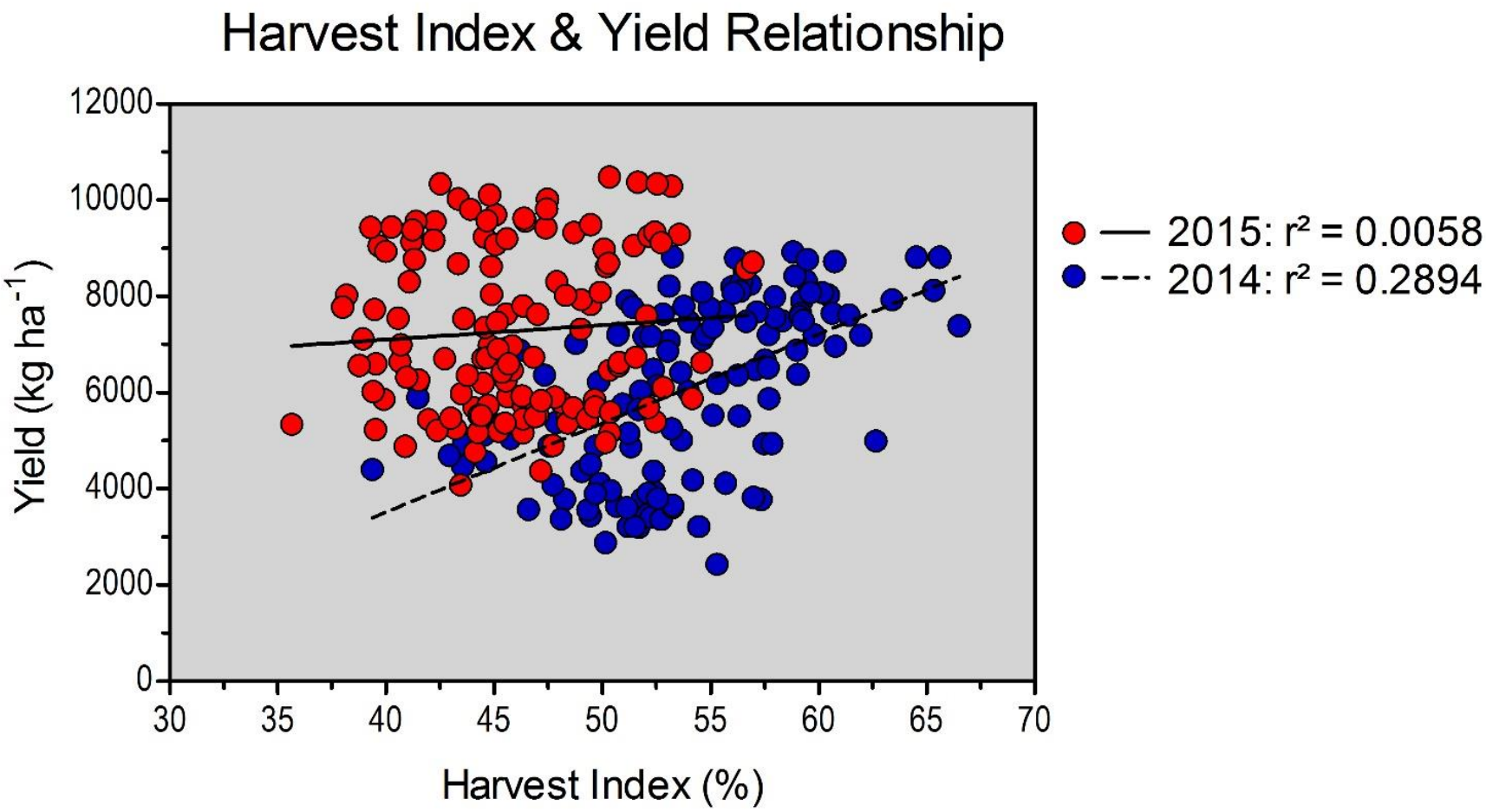


**Figure 2.8 Sorghum grain number per head vs. yield per plant (g) relationship from four sites in 2014, 3 replications per site, 11 treatments per replication.**

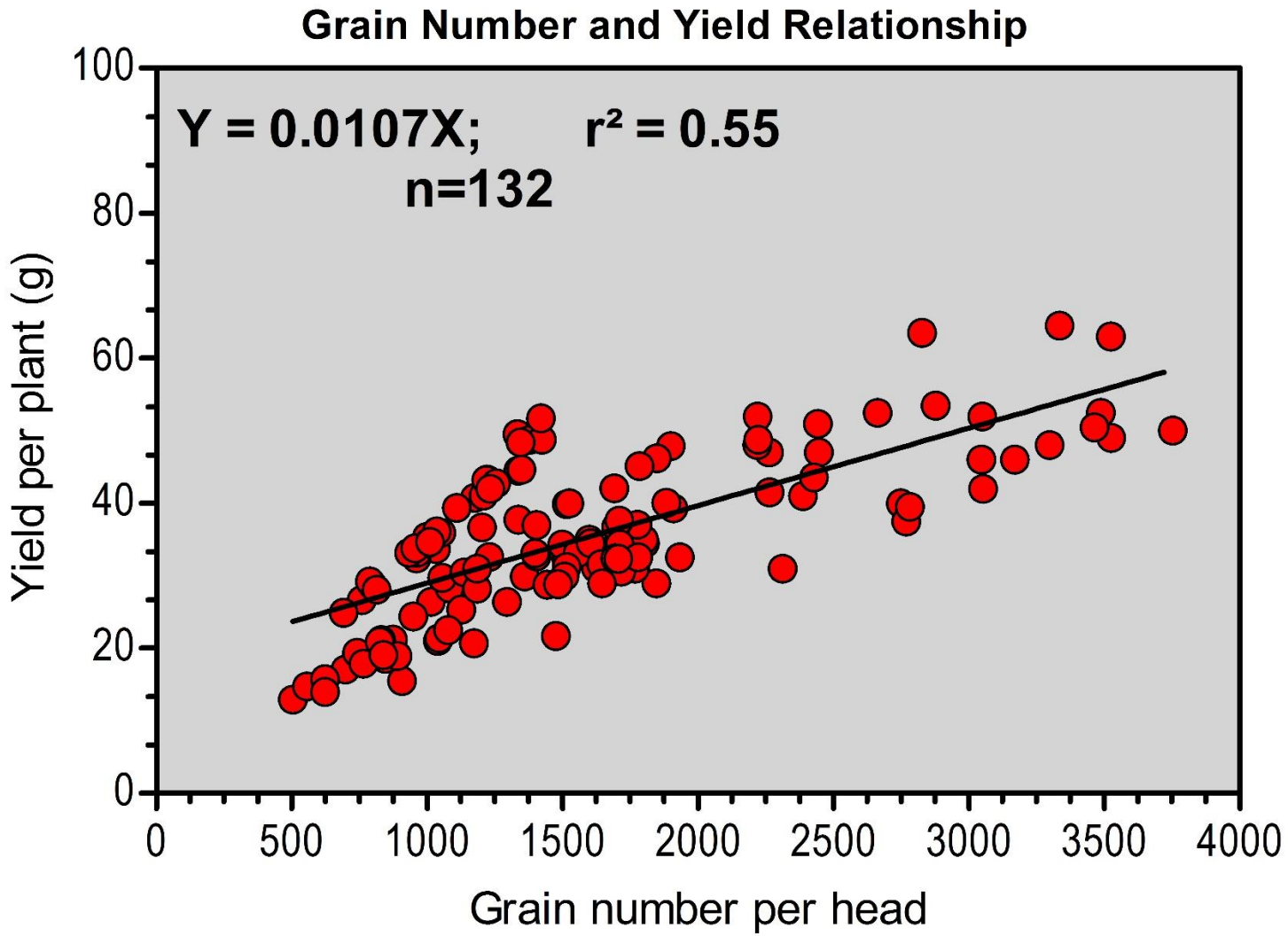


**Figure 2.9 Sorghum grain number per head vs. yield per plant (g) relationship from four sites in 2015, 3 replications per site, 11 treatments per replication.**

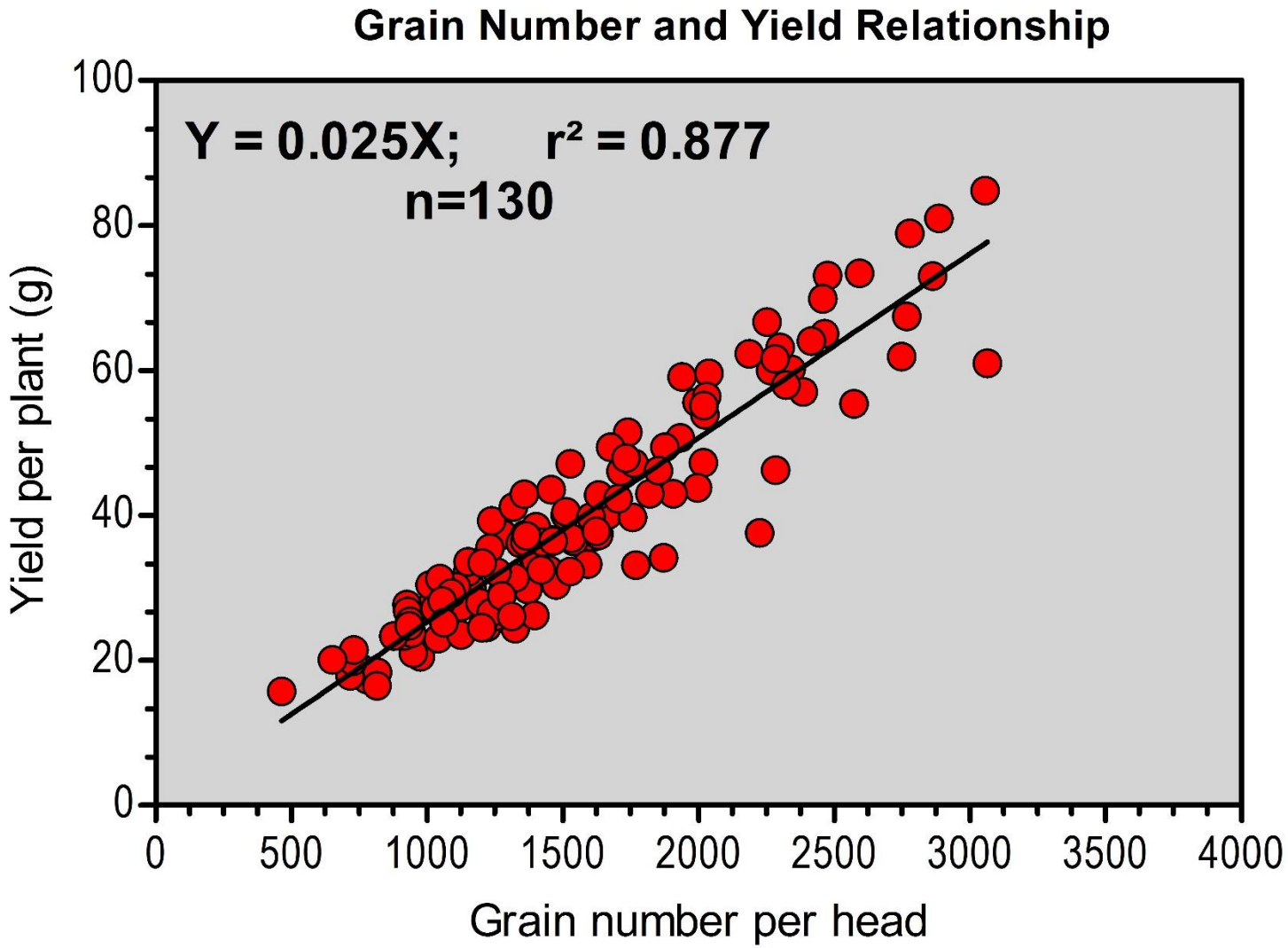


**Figure 2.10 Sorghum biomass accumulation (g $m^{-2}$) comparison by fraction (leaf- green, stem- yellow, and head- red) between treatment one (high-input) and treatment ten (standard practice or low-input), during 2014 in Rossville, KS = irrigated environment (upper panels), and in Ottawa, KS = rainfed environment (lower panels).**

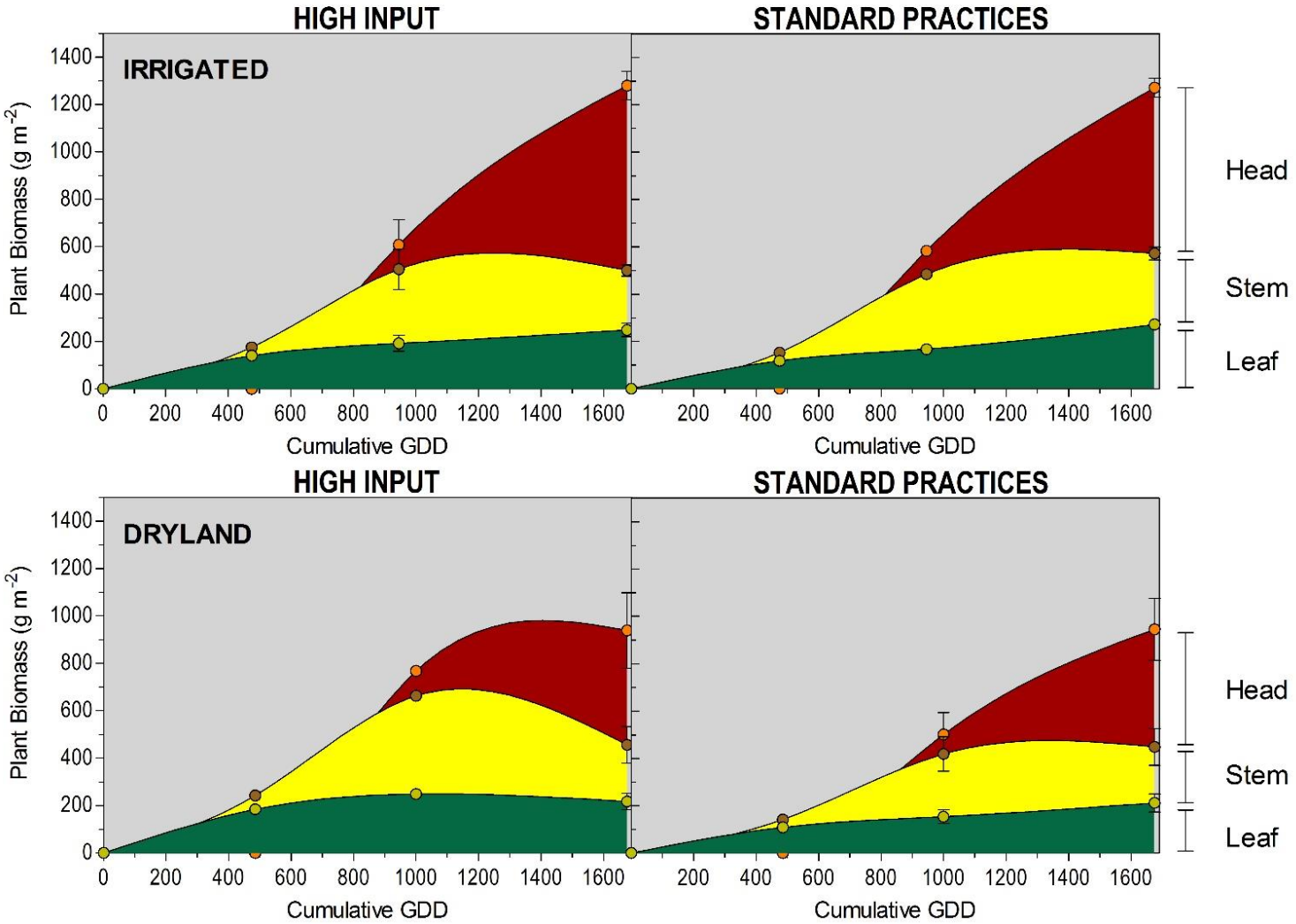


**Figure 2.11 Sorghum biomass accumulation (g $m^{-2}$) comparison by fraction (leaf- green, stem- yellow, and head- red) between treatment one (high-input) and treatment ten (standard practice or low-input), during 2015 in Topeka, KS = irrigated environment (upper panels), and in Ottawa, KS = rainfed environment (lower panels).**

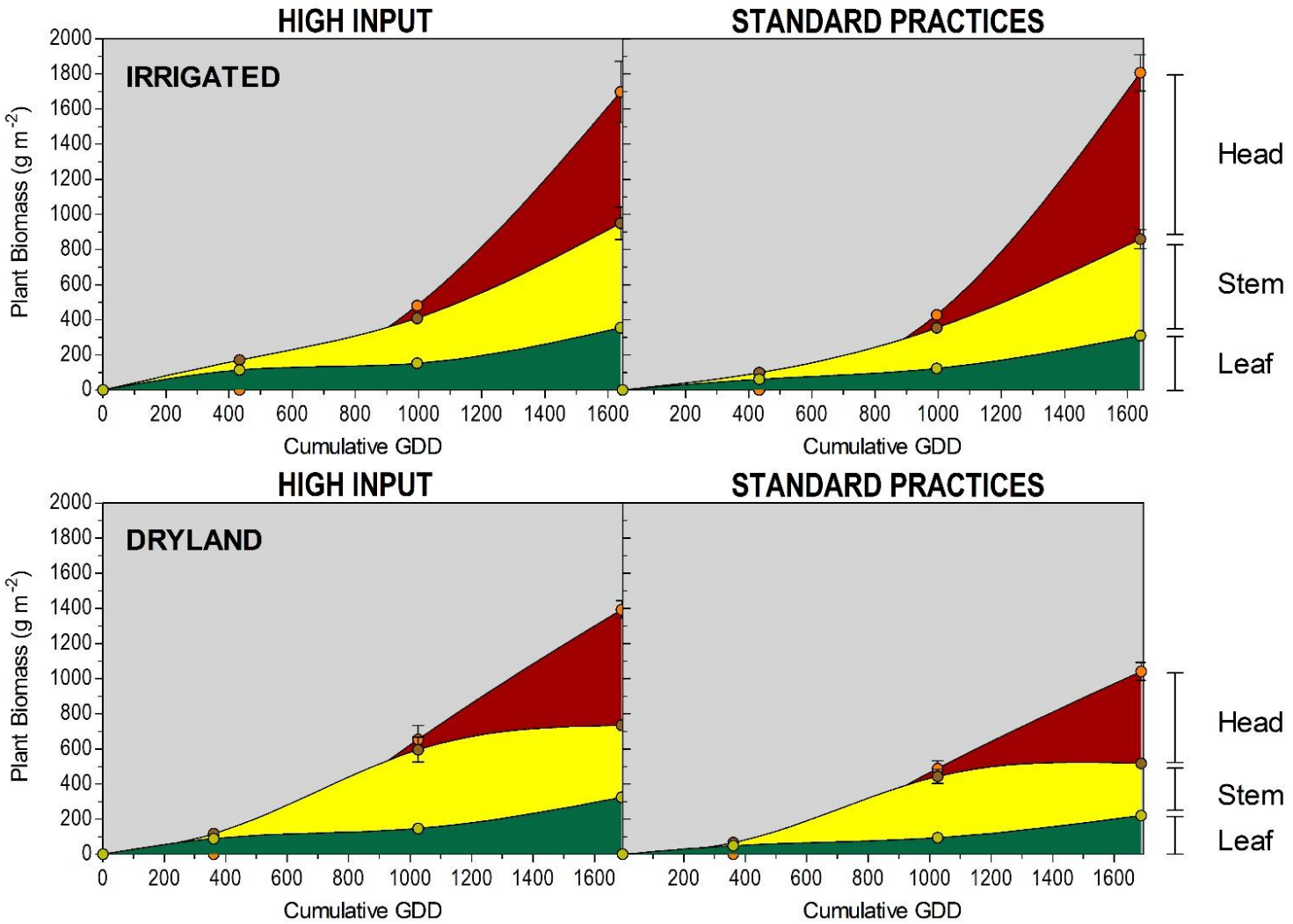
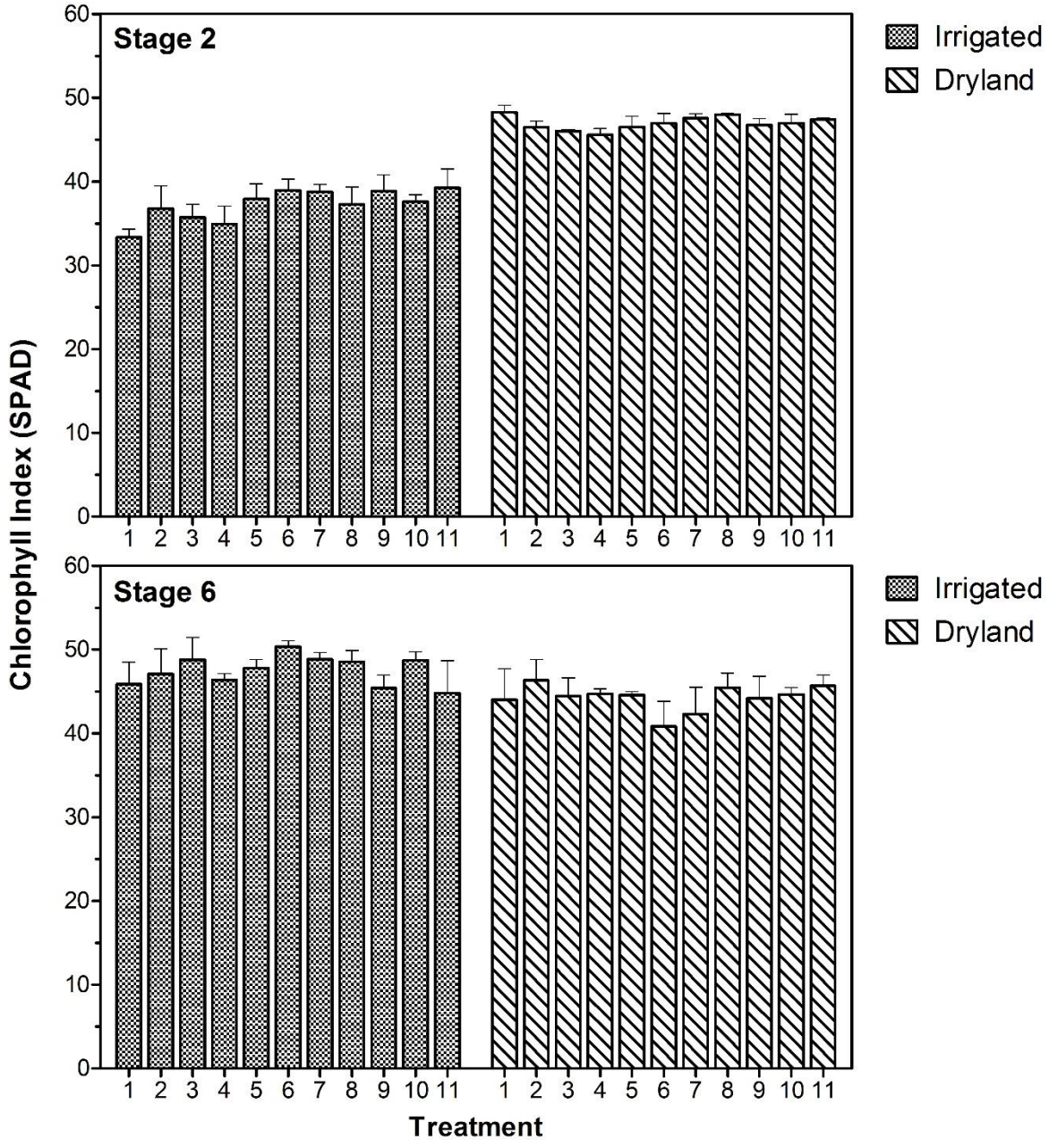
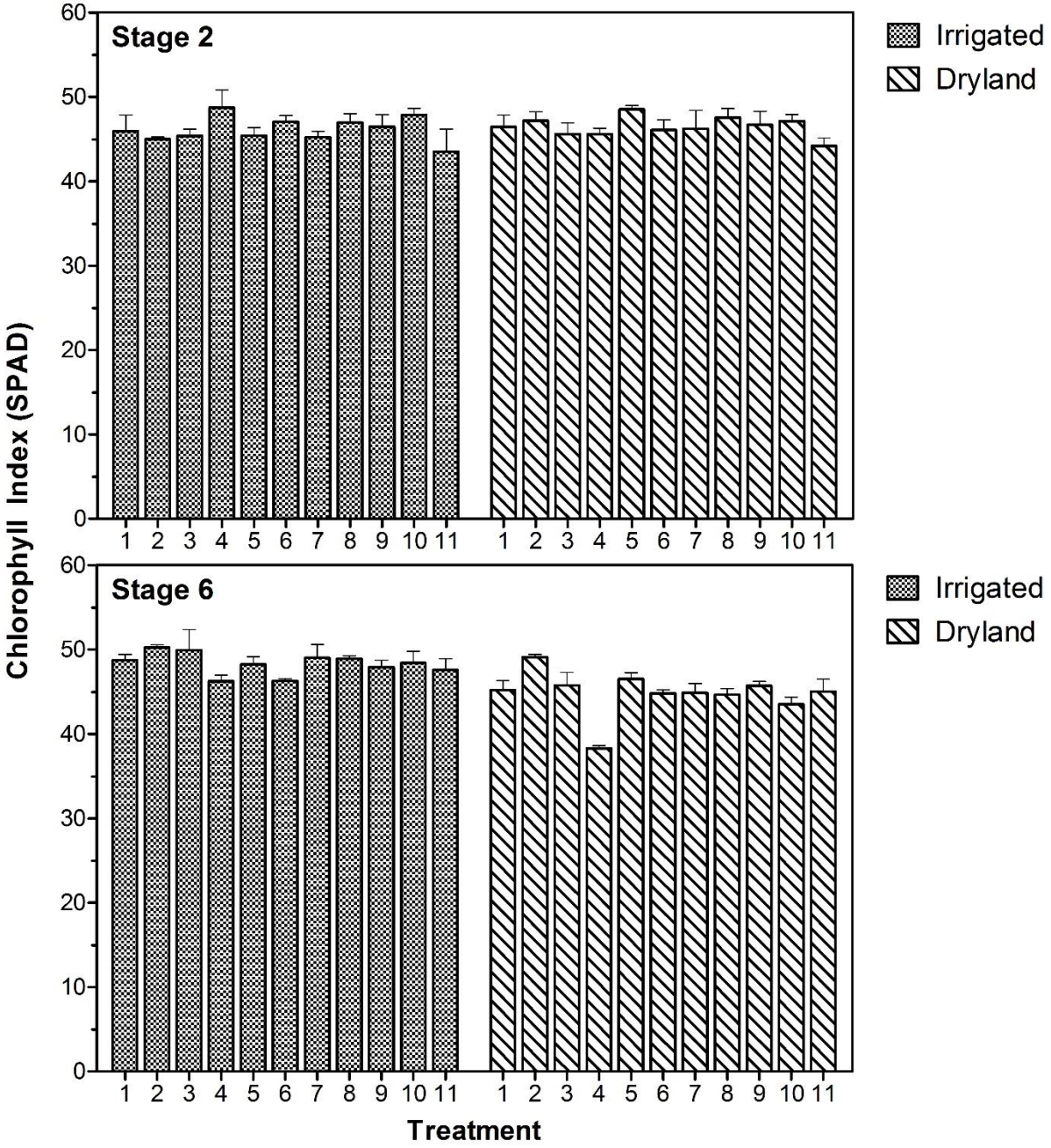


**Figure 2.12 Stage two and stage six chlorophyll index of grain sorghum in 2014 for Rossville, KS (irrigated), and Ottawa, KS (dryland), error bars indicate standard error of the mean, readings averaged from 10 upper-most leaves per plot, then averaged by treatment.**




Treatments: 1=High-input, 2=low seeding rate, 3=wide row-spacing, 4=standard N program (no GreenSeeker), 5=no fungicide & insecticide, 6=no micronutrients (Fe, Zn), 7=no plant growth regulator, 8=NP starter fertilizer only, 9=no chloride, 10=standard practice (low-input), 11=high-input + extra N. Vegetative stage under irrigation may have had lower index values than dryland due to soil variability and the sampling time being earlier in irrigated site.

**Figure 2.13 Stage two and stage six chlorophyll index of grain sorghum in 2015 for Topeka, KS (irrigated), and Ottawa, KS (dryland), error bars indicate standard error of the mean, readings averaged from 10 upper-most leaves per plot, then averaged by treatment.**




Treatments: 1=High-input, 2=low seeding rate, 3=wide row-spacing, 4=standard N program (no GreenSeeker), 5=no fungicide & insecticide, 6=no micronutrients (Fe, Zn), 7=no plant growth regulator, 8=NP starter fertilizer only, 9=no chloride, 10=standard practice (low-input), 11=high-input + extra N.

**Figure 2.14 Sorghum plant tissue N uptake variability for leaf and stem fractions at stage two, measured at two sites per year, Rossville and Ottawa in 2014, Topeka and Ottawa in 2015 (n = 66 observations per year, bars indicate the maximum and the minimum values).**

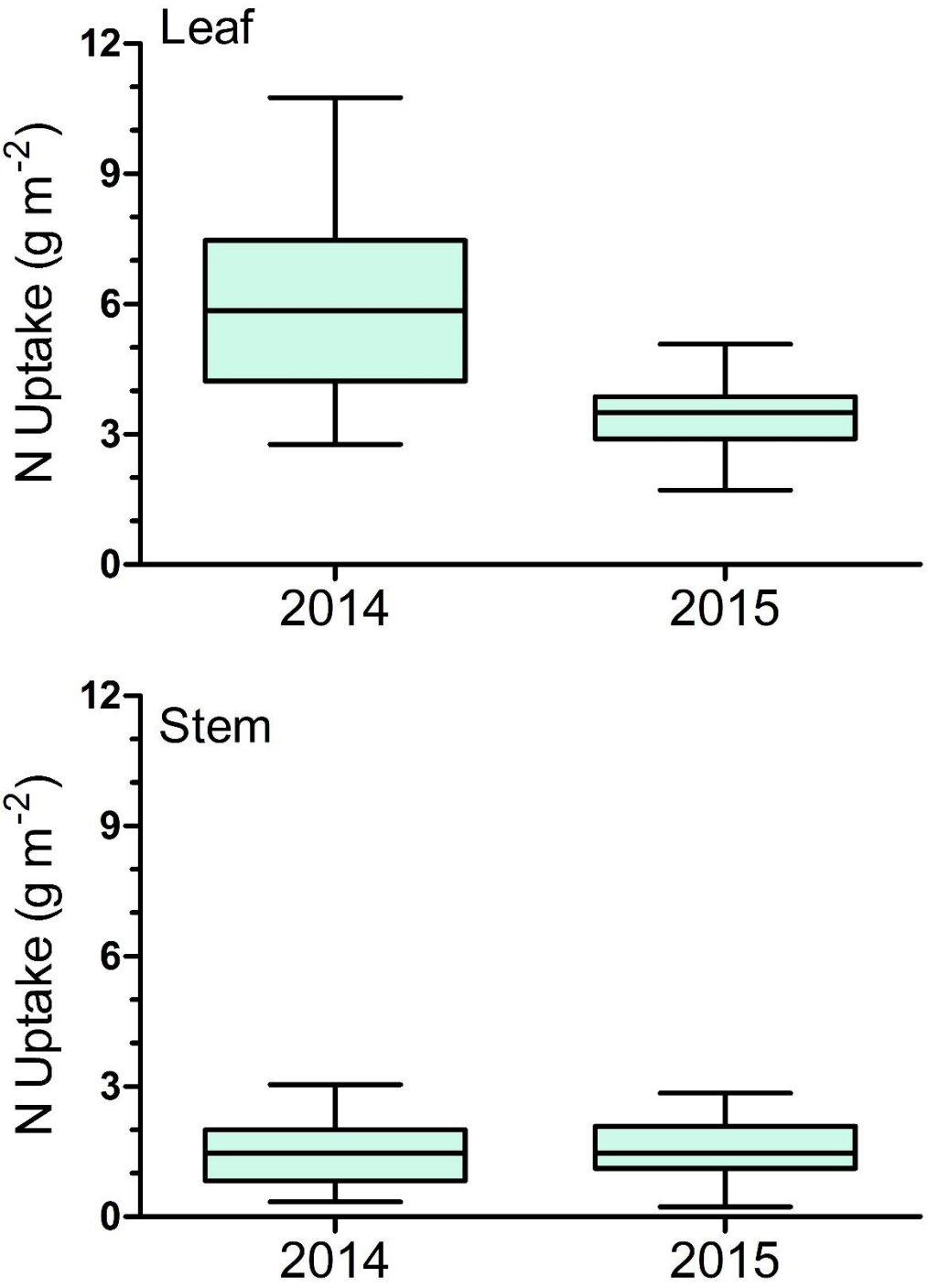


**Figure 2.15 Sorghum plant tissue N uptake variability for leaf, stem, and head fractions at stage six, measured at two sites per year, Rossville and Ottawa in 2014, Topeka and Ottawa in 2015 (n = 66 observations per year, bars indicate the maximum and the minimum values).**

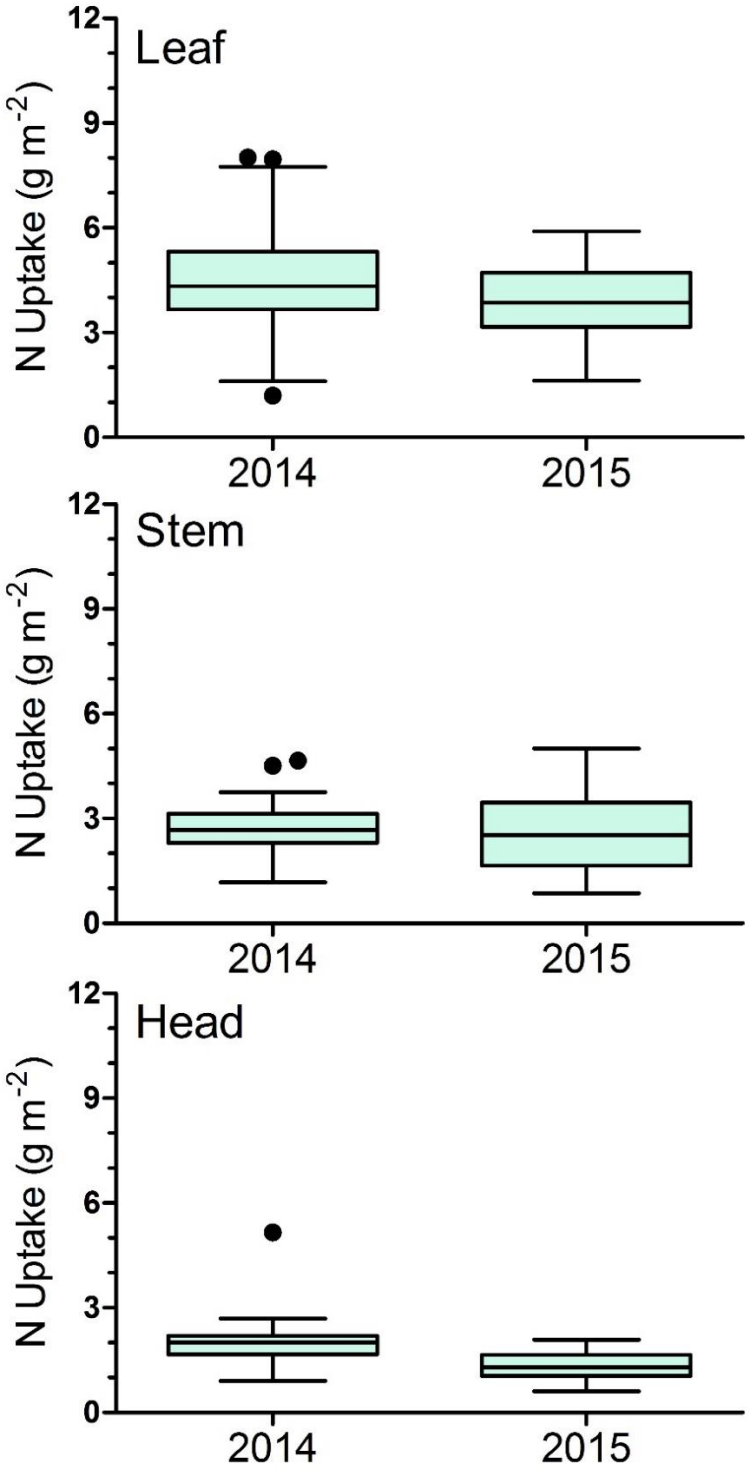


**Figure 2.16 Sorghum plant tissue %N concentration (g $100g^{-1}$) variability for leaf and stem fractions at stage two, measured at two sites per year, Rossville and Ottawa in 2014, Topeka and Ottawa in 2015 (n = 66 observations per year, bars indicate the maximum and the minimum values).**

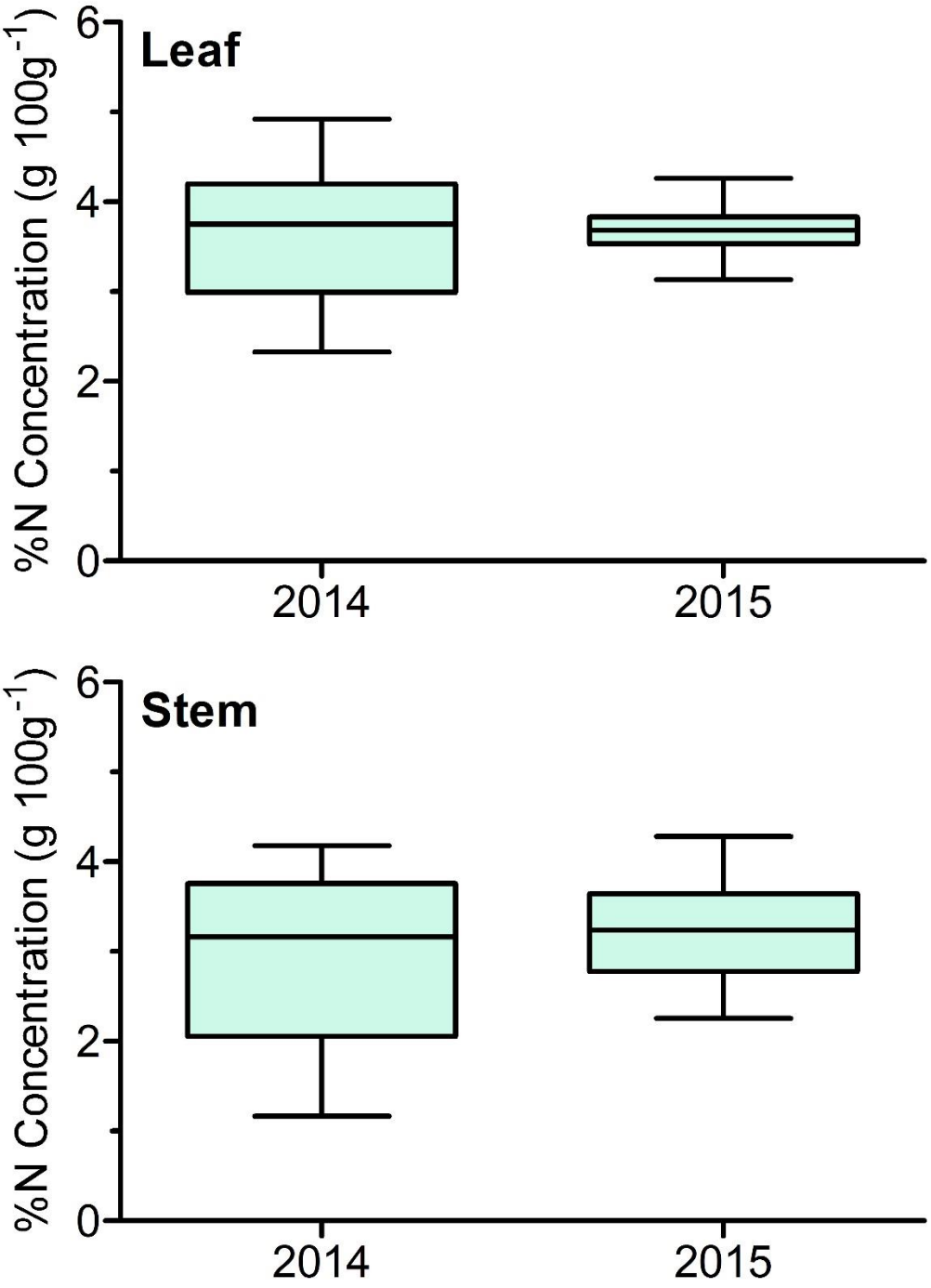


**Figure 2.17 Sorghum plant tissue %N concentration (g $100g^{-1}$) variability for leaf, stem and head fractions at stage six, measured at two sites per year, Rossville and Ottawa in 2014, Topeka and Ottawa in 2015 (n = 66 observations per year, bars indicate the maximum and the minimum values).**

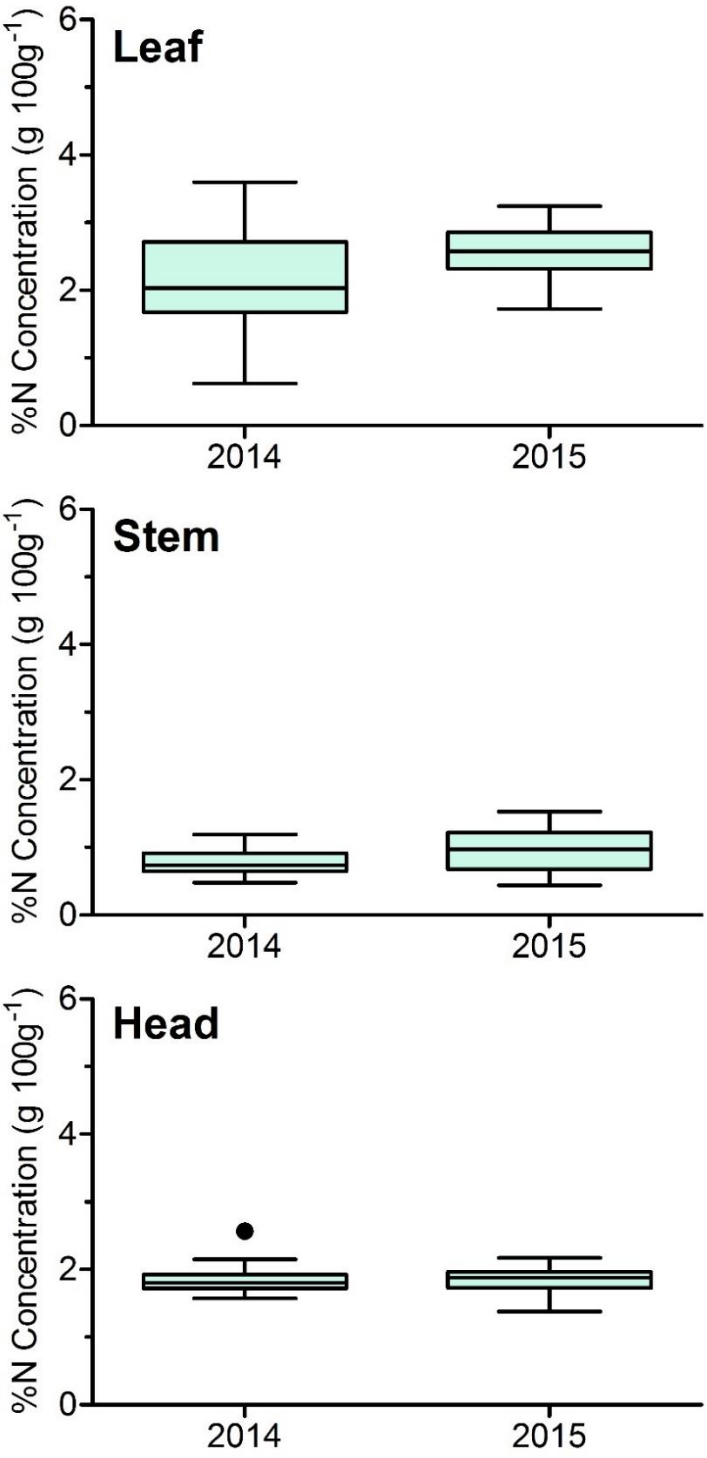


**Figure 2.18 Sorghum plant tissue %P concentration (g $100g^{-1}$) variability for leaf and stem fractions at stage two, measured at two sites per year, Rossville and Ottawa in 2014, Topeka and Ottawa in 2015 (n = 66 observations per year, bars indicate the maximum and the minimum values).**

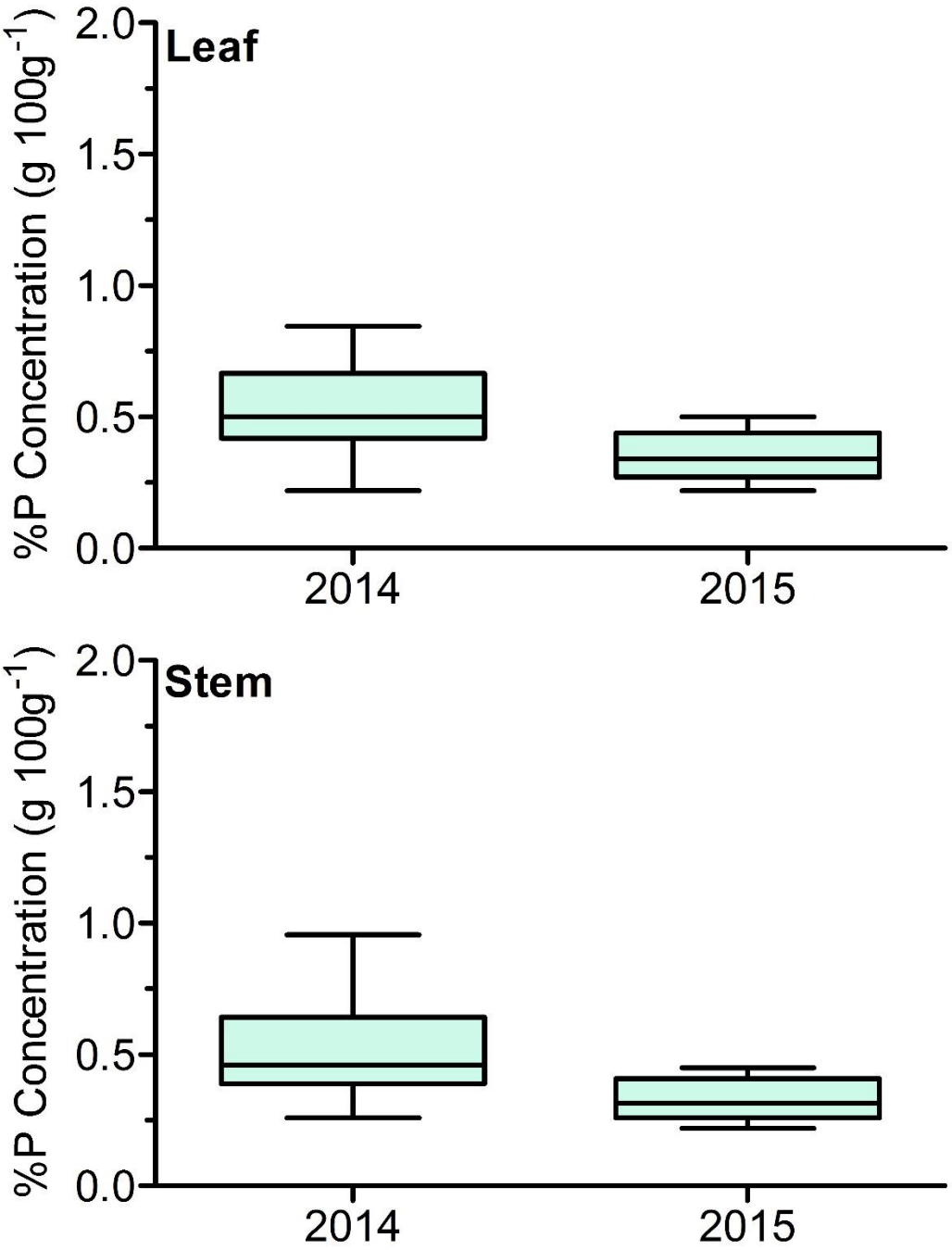


**Figure 2.19 Sorghum plant tissue %P concentration (g $100g^{-1}$) variability for leaf, stem and head fractions at stage six, measured at two sites per year, Rossville and Ottawa in 2014, Topeka and Ottawa in 2015 (n = 66 observations per year, bars indicate the maximum and the minimum values).**

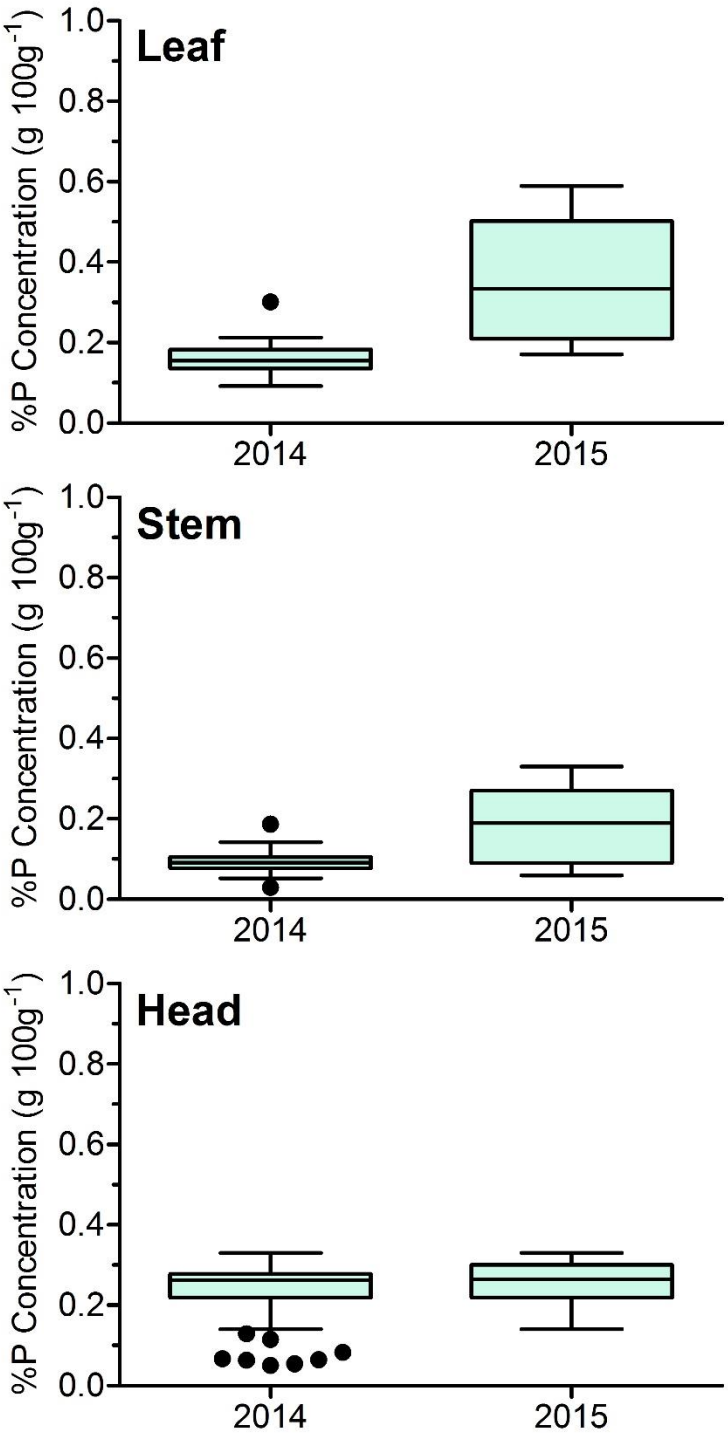


**Figure 2.20 Sorghum plant tissue %K concentration (g $100g^{-1}$) variability for leaf and stem fractions at stage two, measured at two sites per year, Rossville and Ottawa in 2014, Topeka and Ottawa in 2015 (n = 66 observations per year, bars indicate the maximum and the minimum values).**

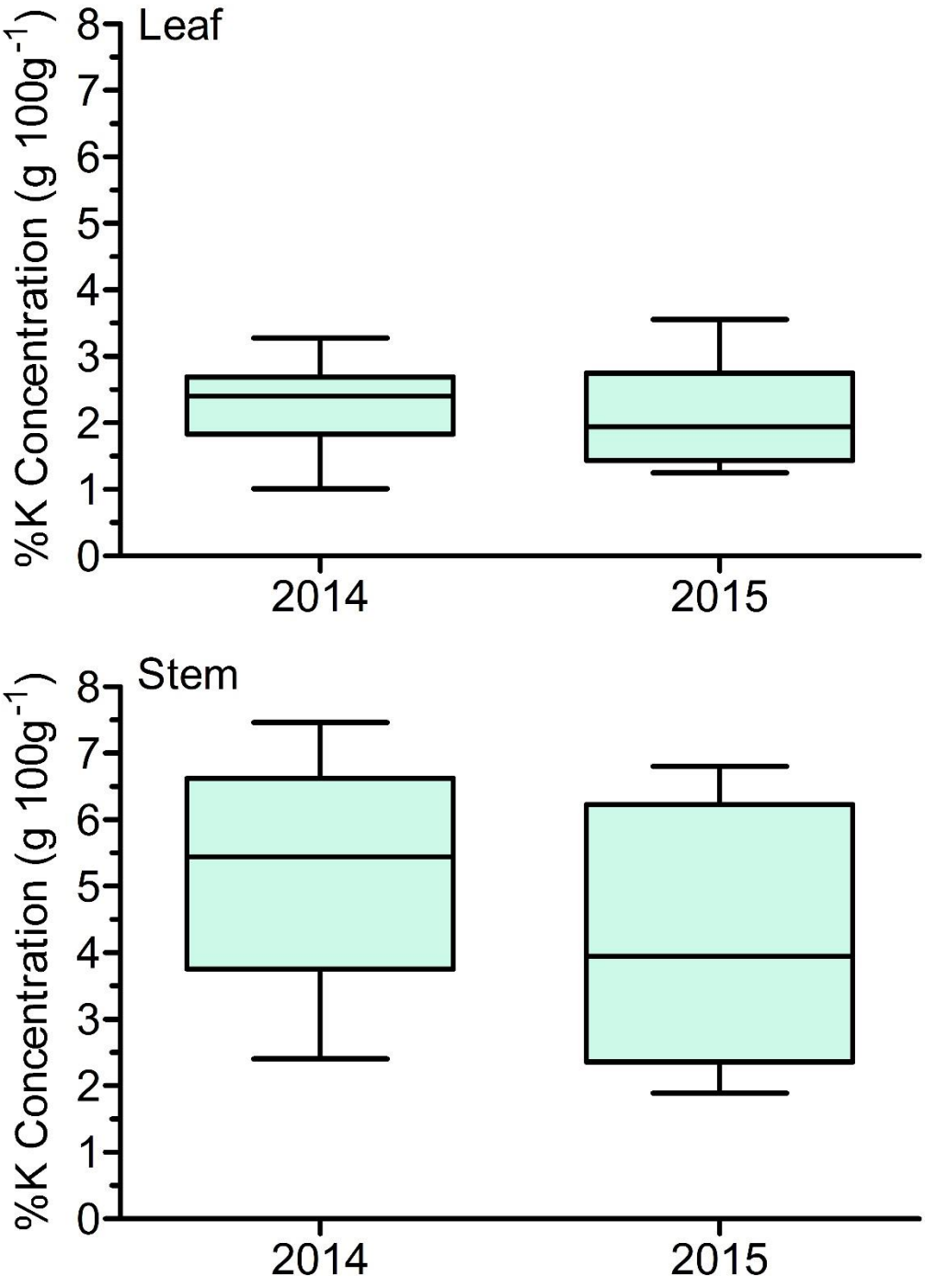


**Figure 2.21 Sorghum plant tissue %K concentration (g $100g^{-1}$) variability for leaf, stem and head fractions at stage six, measured at two sites per year, Rossville and Ottawa in 2014, Topeka and Ottawa in 2015 (n = 66 observations per year, bars indicate the maximum and the minimum values).**

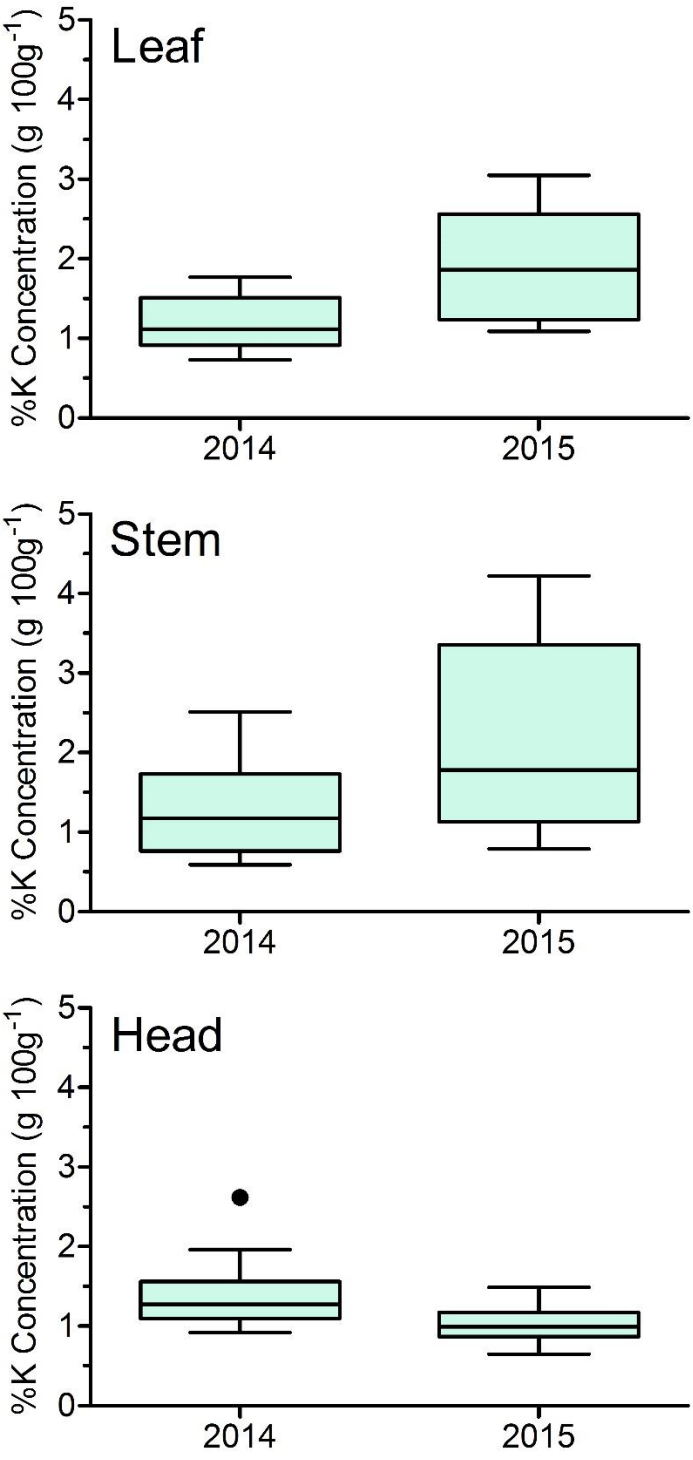


**Figure 2.22 Sorghum plant tissue %S concentration (g $100g^{-1}$) variability for leaf and stem fractions at stage two, measured at two sites per year, Rossville and Ottawa in 2014, Topeka and Ottawa in 2015 (n = 66 observations per year, bars indicate the maximum and the minimum values).**

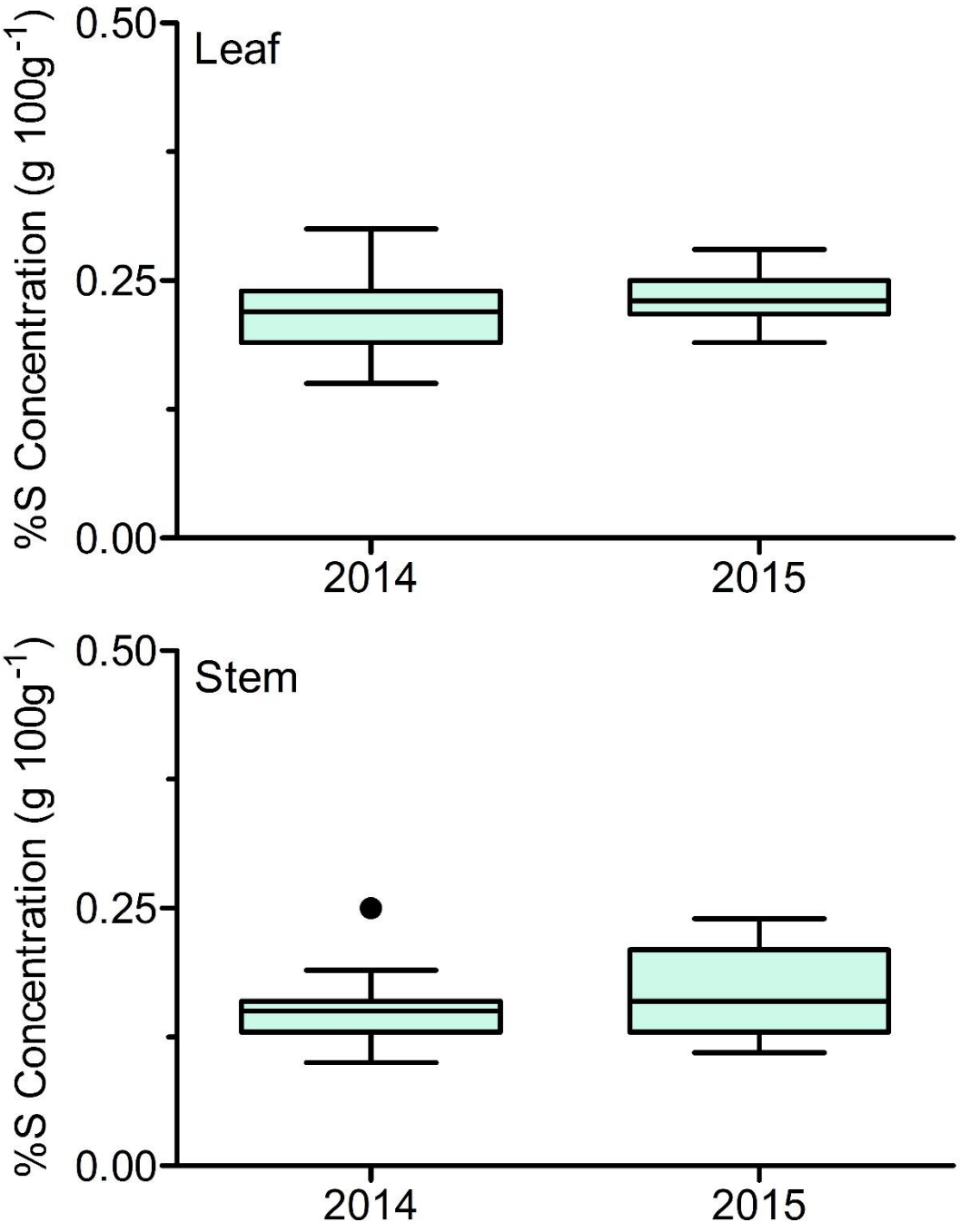


**Figure 2.23 Sorghum plant tissue %S concentration (g $100g^{-1}$) variability for leaf, stem and head fractions at stage six, measured at two sites per year, Rossville and Ottawa in 2014, Topeka and Ottawa in 2015 (n = 66 observations per year, bars indicate the maximum and the minimum values).**

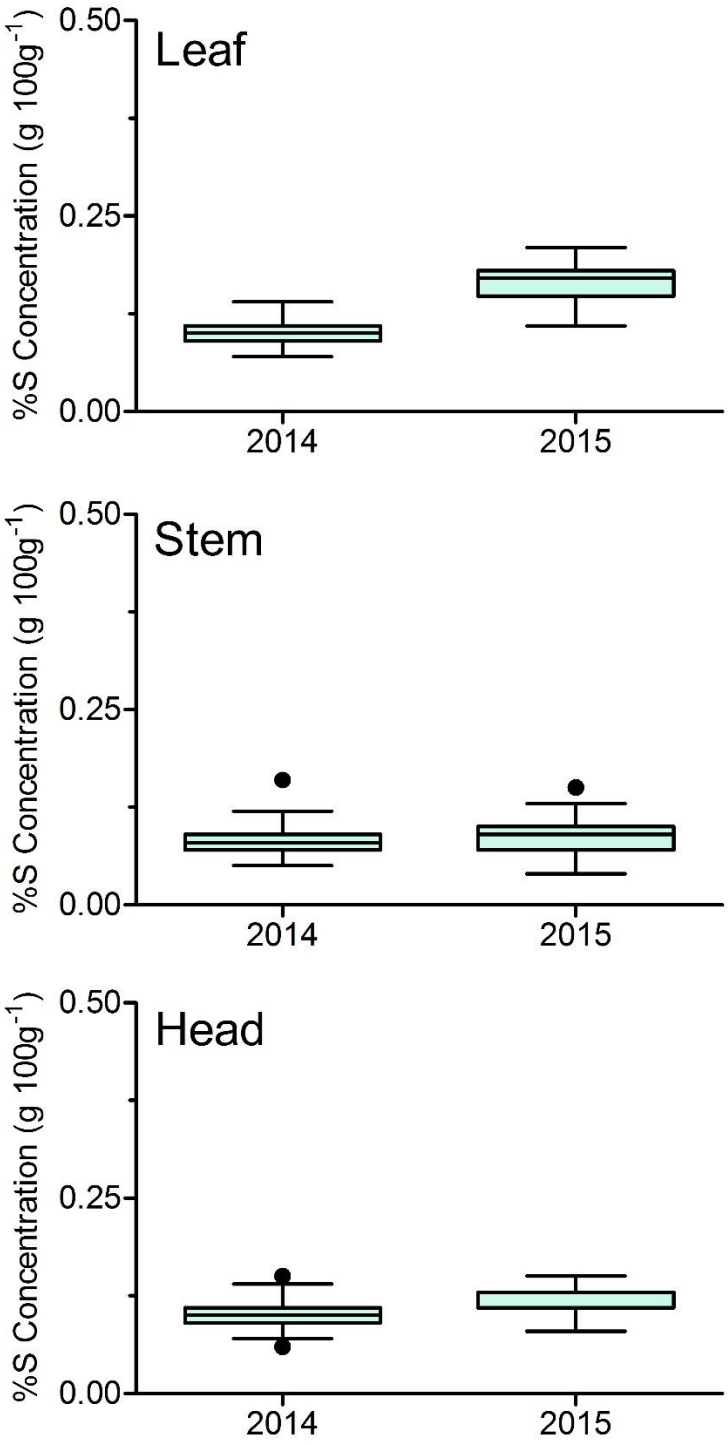


**Figure 2.24 Sorghum plant tissue Fe concentration (ppm) variability for leaf and stem fractions at stage two, measured at two sites per year, Rossville and Ottawa in 2014, Topeka and Ottawa in 2015 (n = 66 observations per year, bars indicate the maximum and the minimum values).**

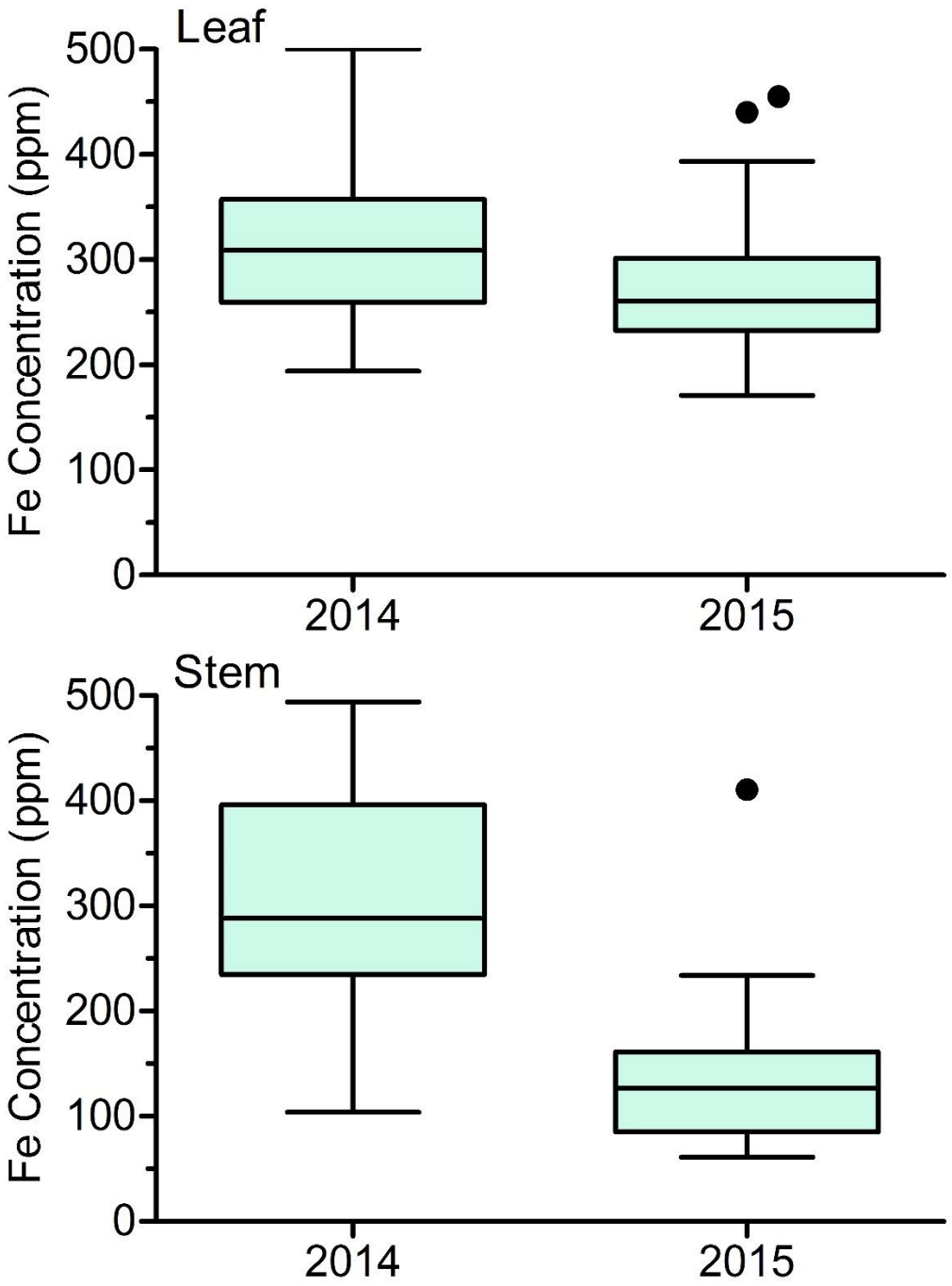


**Figure 2.25 Sorghum plant tissue Fe concentration (ppm) variability for leaf, stem and head fractions at stage six, measured at two sites per year, Rossville and Ottawa in 2014, Topeka and Ottawa in 2015 (n = 66 observations per year, bars indicate the maximum and the minimum values).**

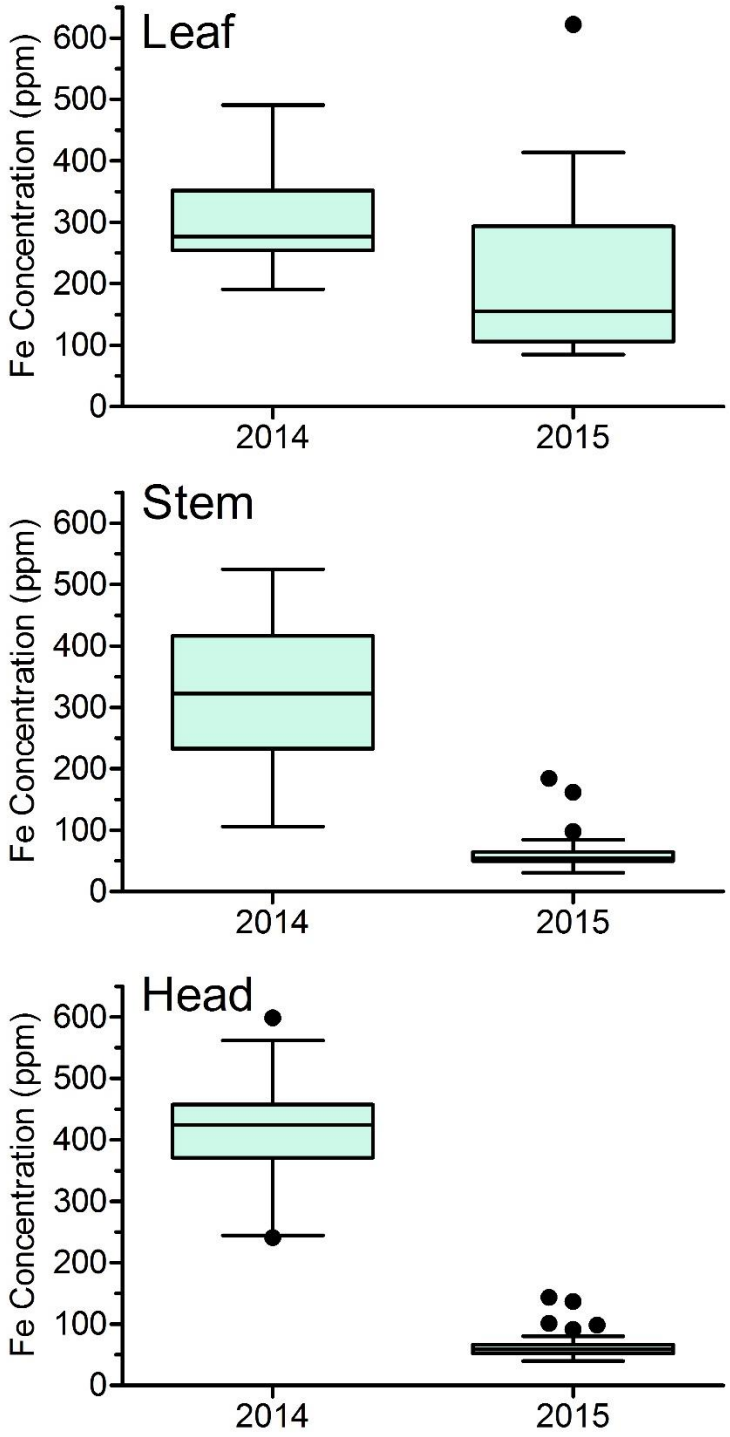


**Figure 2.26 Sorghum plant tissue Zn concentration (ppm) variability for leaf and stem fractions at stage two, measured at two sites per year, Rossville and Ottawa in 2014, Topeka and Ottawa in 2015 (n = 66 observations per year, bars indicate the maximum and the minimum values).**

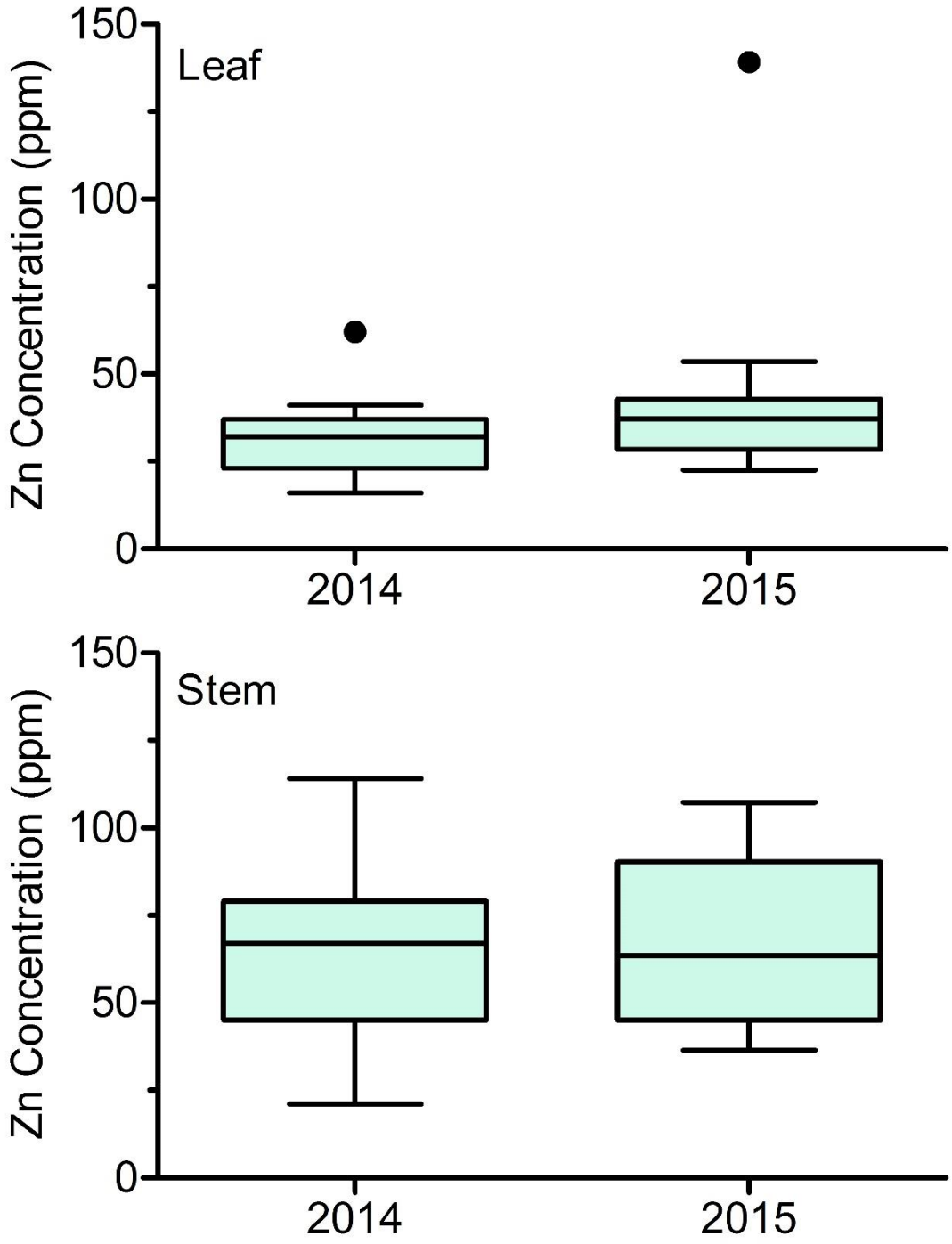


**Figure 2.27 Sorghum plant tissue Zn concentration (ppm) variability for leaf, stem and head fractions at stage six, measured at two sites per year, Rossville and Ottawa in 2014, Topeka and Ottawa in 2015 (n = 66 observations per year, bars indicate the maximum and the minimum values).**

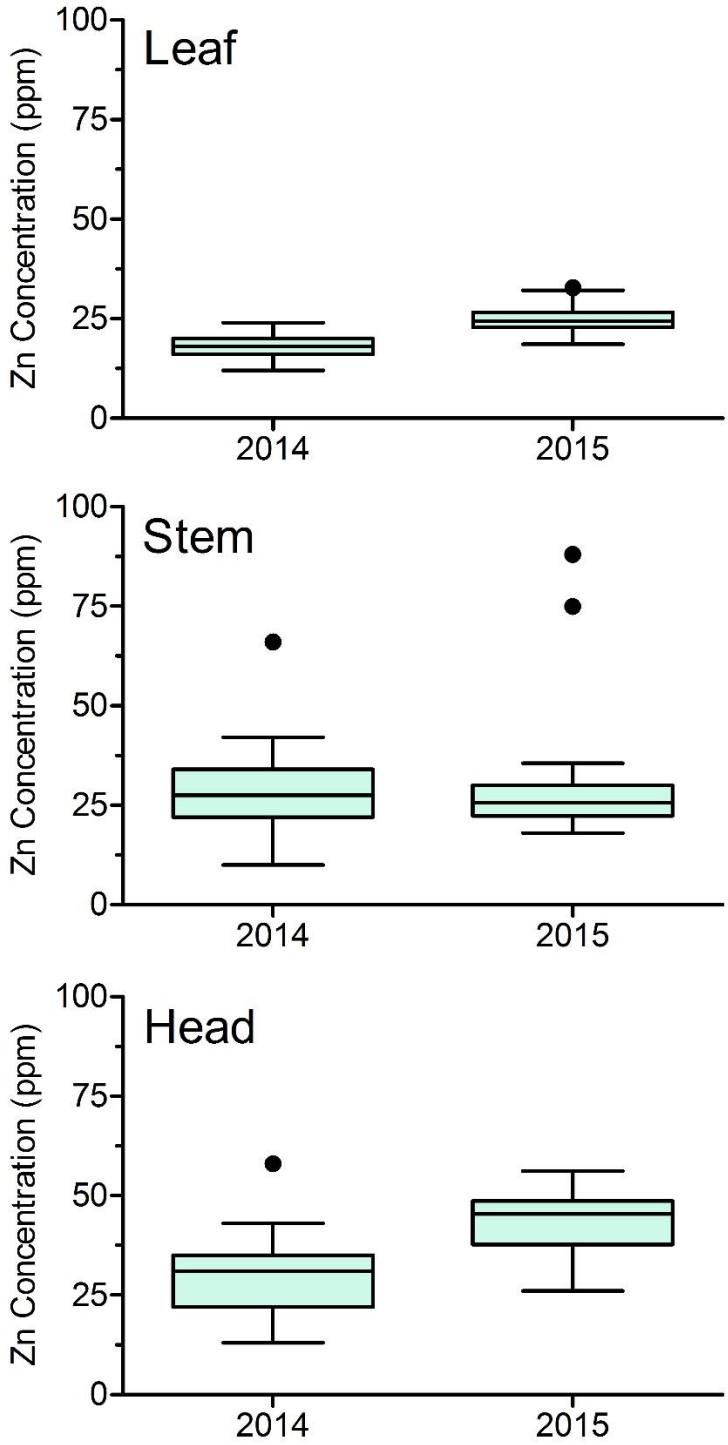


**Figure 2.28 Nitrogen uptake curves (g $m^{-2}$) by fraction (leaf- green, stem- yellow, and head- red) between treatment one (high-input) and treatment ten (standard practice or low-input), during 2014 in Rossville, KS = irrigated environment (upper panels), and in Ottawa, KS = rainfed environment (lower panels).**

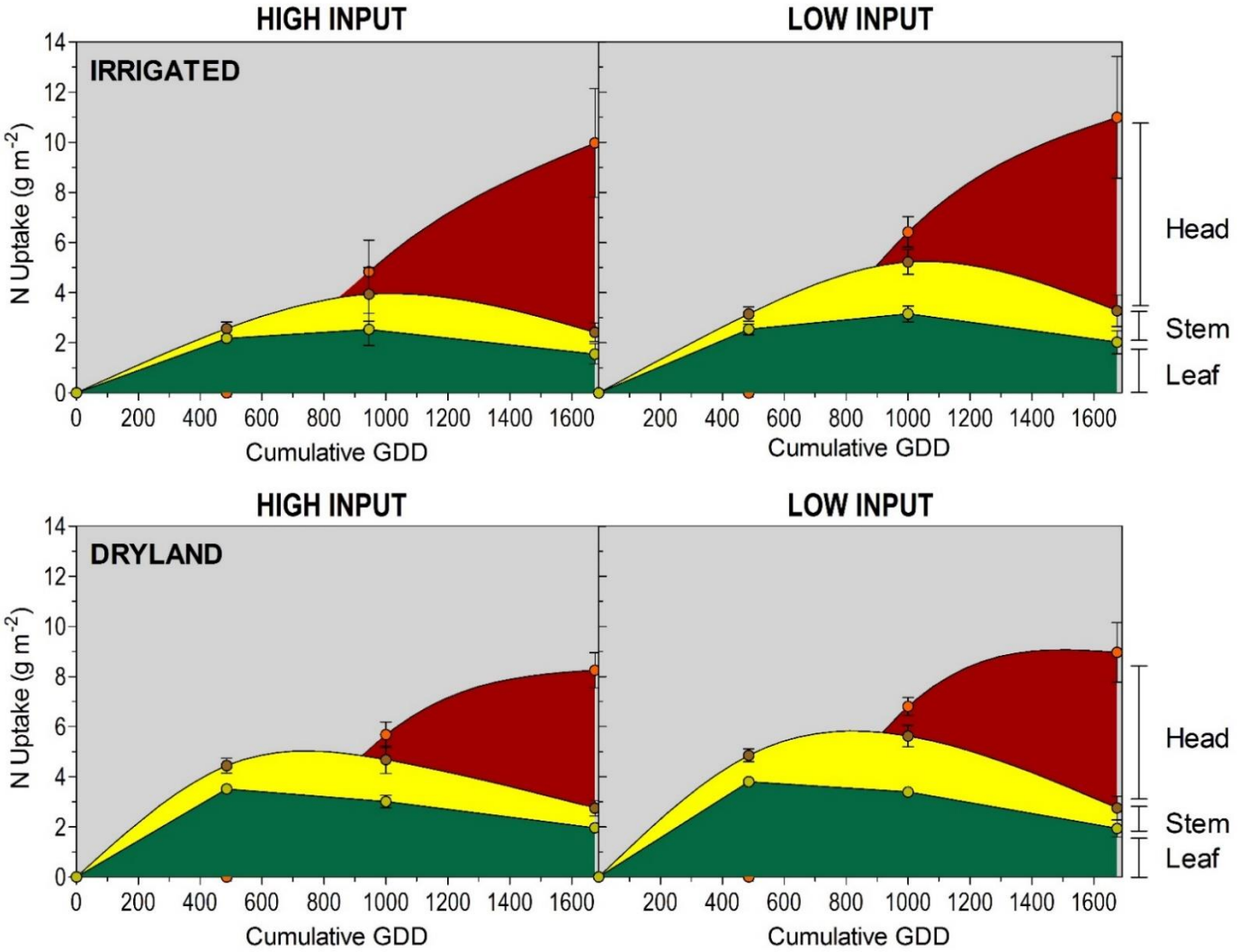


**Figure 2.29 Nitrogen uptake curves (g $m^{-2}$) by fraction (leaf- green, stem- yellow, and head- red) between treatment one (high-input) and treatment ten (standard practice or low-input), during 2015 in Topeka, KS = irrigated environment (upper panels), and in Ottawa, KS = rainfed environment (lower panels).**

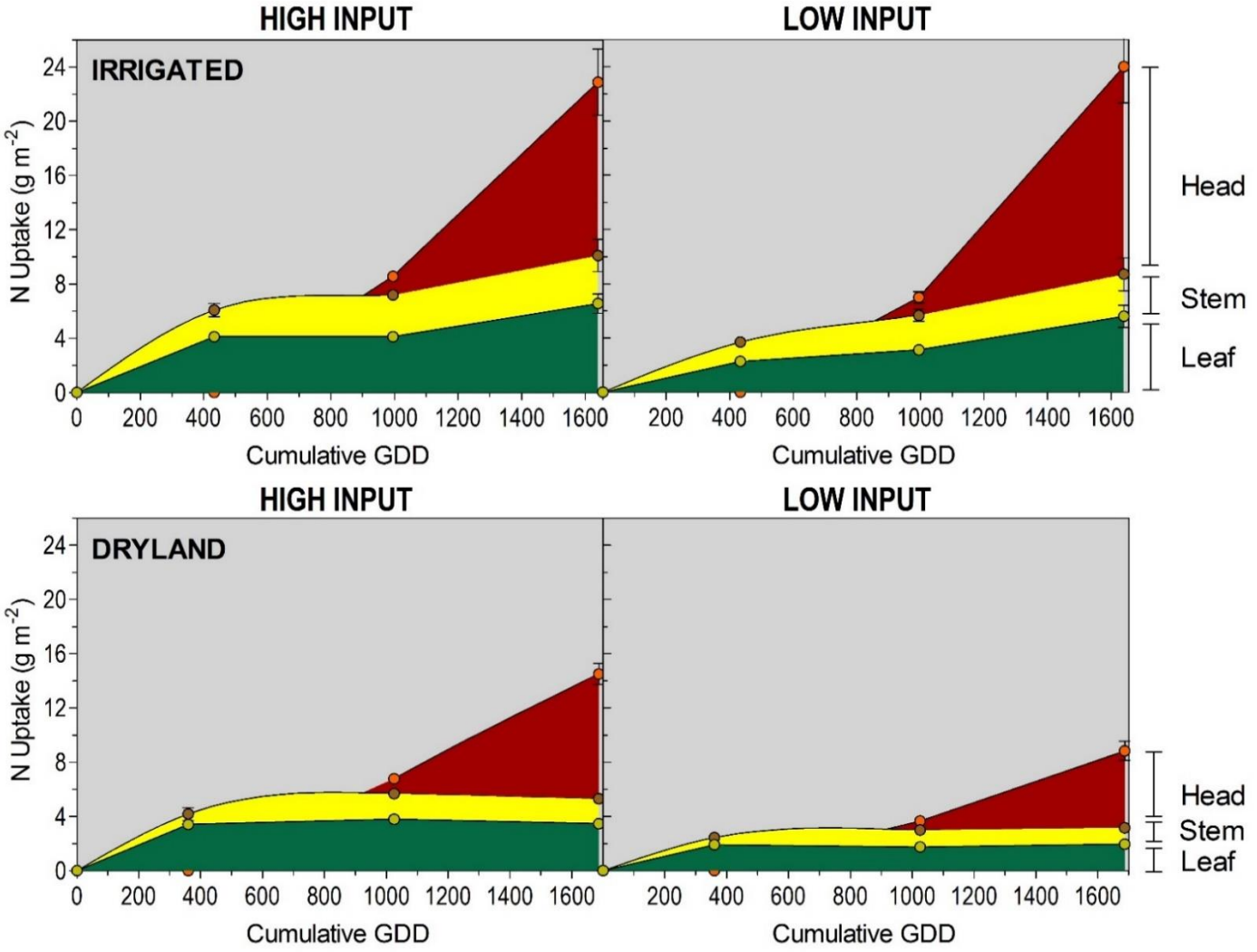


**Figure 2.30 Phosphorous uptake curves (g $m^{-2}$) by fraction (leaf- green, stem- yellow, and head- red) between treatment one (high-input) and treatment ten (standard practice or low-input), during 2014 in Rossville, KS = irrigated environment (upper panels), and in Ottawa, KS = rainfed environment (lower panels).**

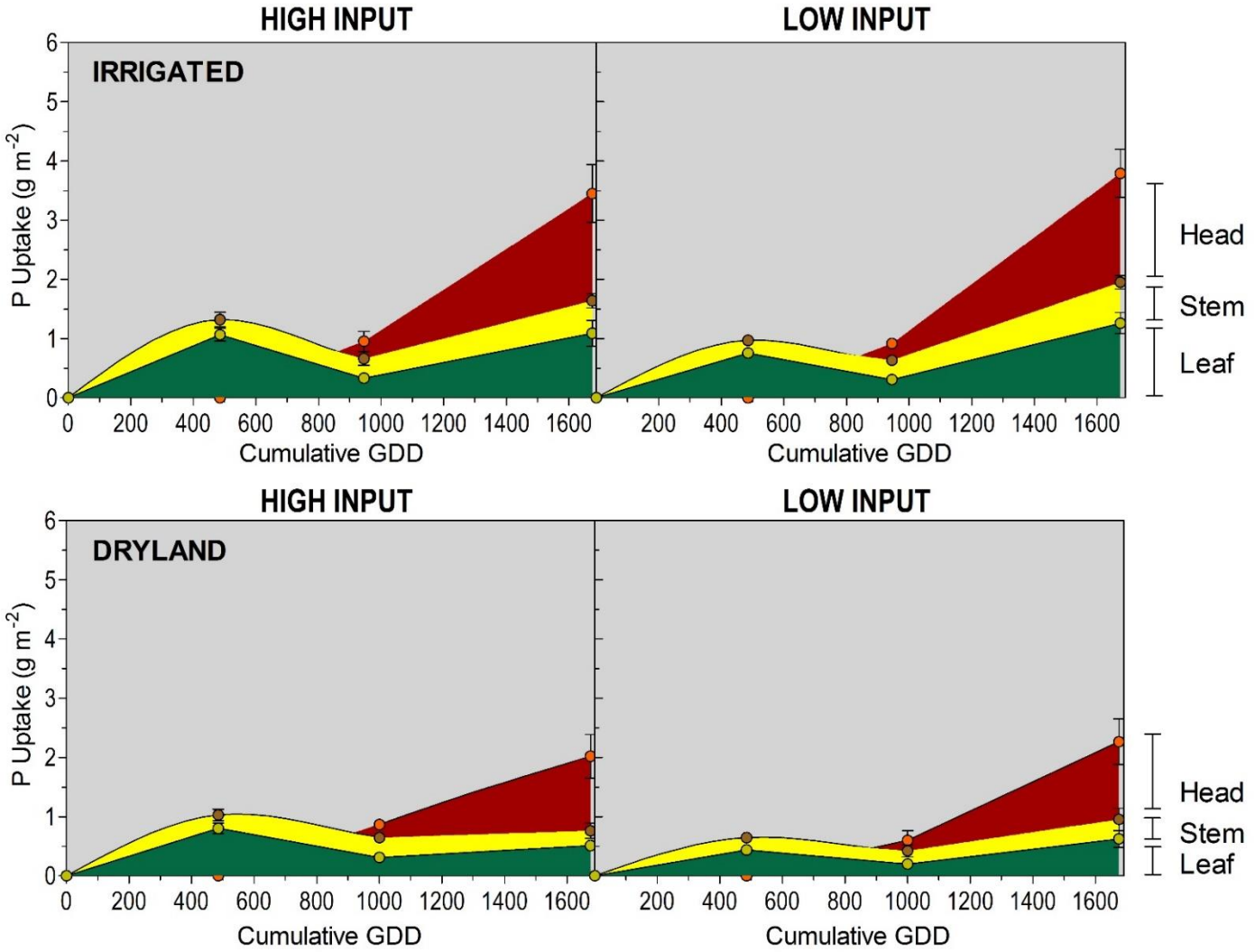


**Figure 2.31 Phosphorous uptake curves (g $m^{-2}$) by fraction (leaf- green, stem- yellow, and head- red) between treatment one (high-input) and treatment ten (standard practice or low-input), during 2015 in Topeka, KS = irrigated environment (upper panels), and in Ottawa, KS = rainfed environment (lower panels).**

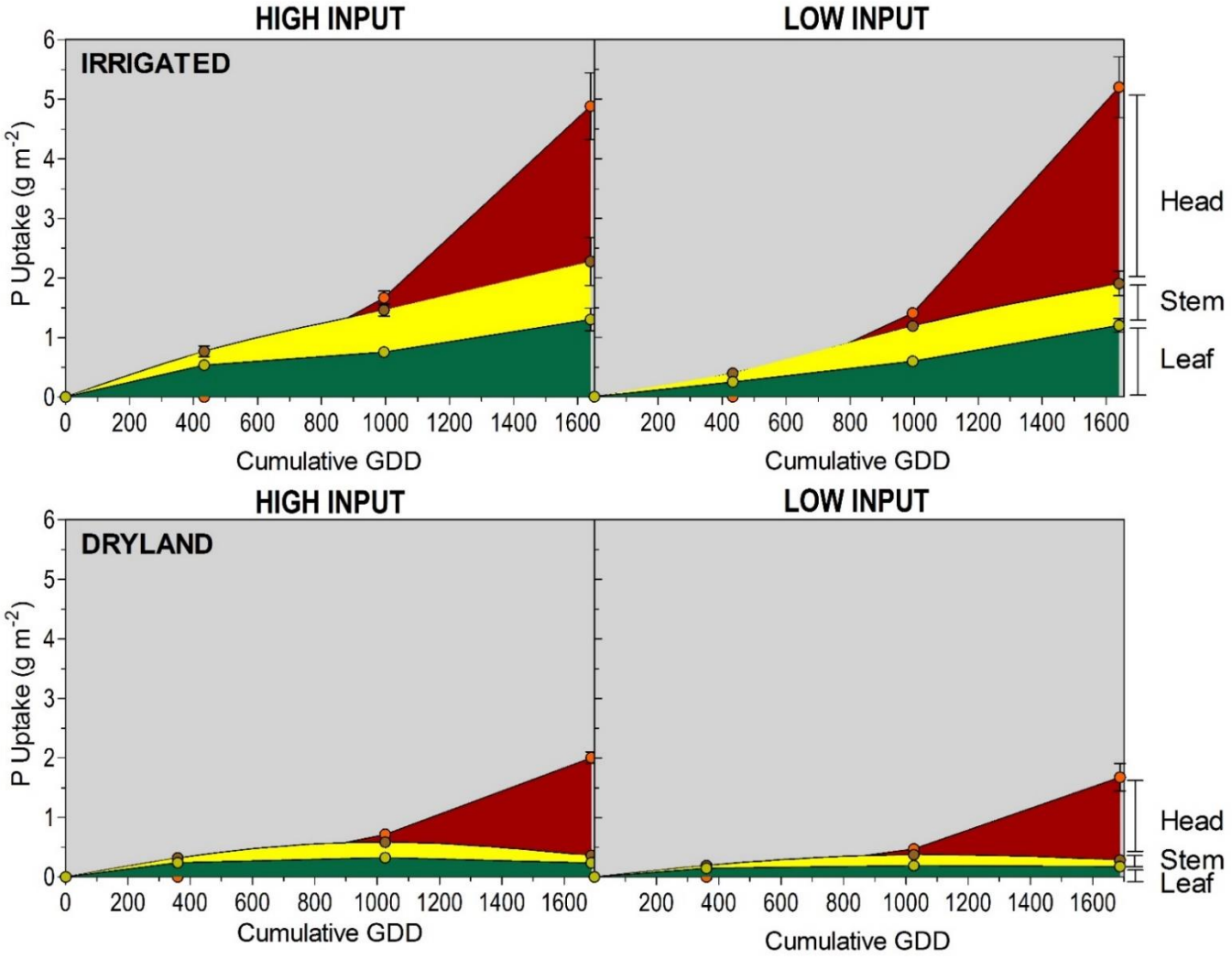


**Figure 2.32 Potassium uptake curves (g $m^{-2}$) by fraction (leaf- green, stem- yellow, and head- red) between treatment one (high-input) and treatment ten (standard practice or low-input), during 2014 in Rossville, KS = irrigated environment (upper panels), and in Ottawa, KS = rainfed environment (lower panels).**

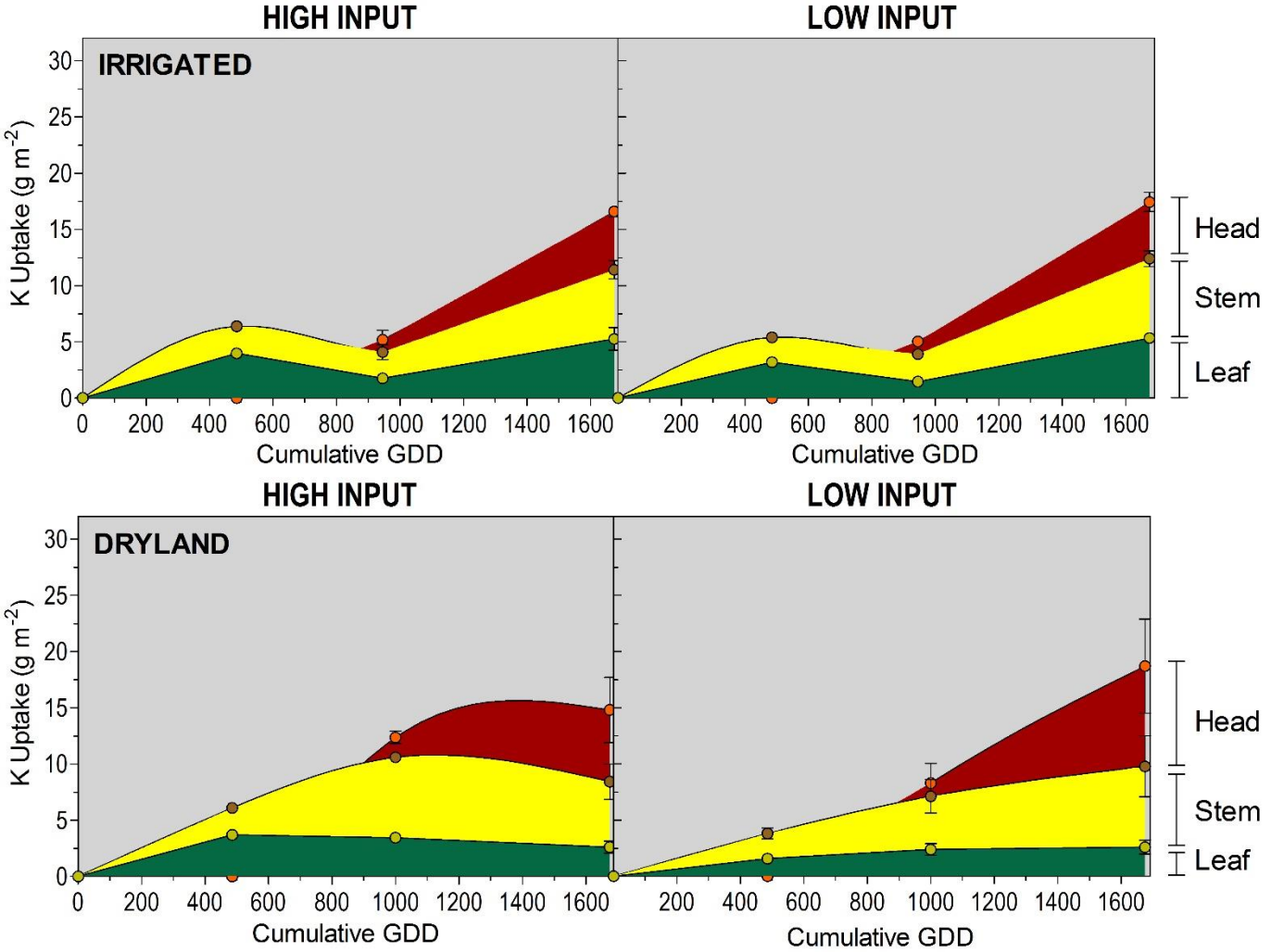


**Figure 2.33 Potassium uptake curves (g $m^{-2}$) by fraction (leaf- green, stem- yellow, and head- red) between treatment one (high-input) and treatment ten (standard practice or low-input), during 2015 in Topeka, KS = irrigated environment (upper panels), and in Ottawa, KS = rainfed environment (lower panels).**

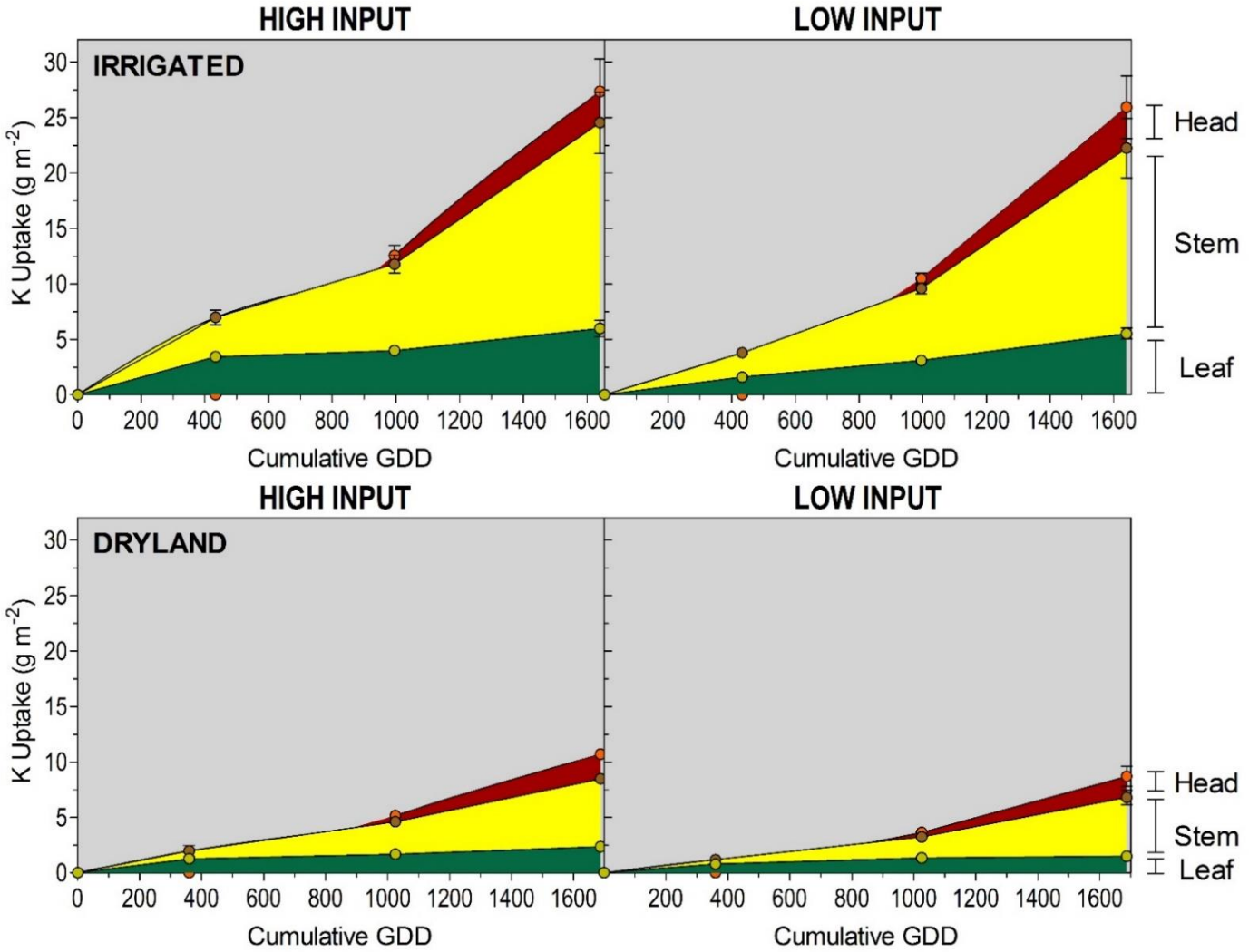


**Figure 2.34 Sulfur uptake curves (g $m^{-2}$) by fraction (leaf- green, stem- yellow, and head- red) between treatment one (high-input) and treatment ten (standard practice or low-input), during 2014 in Rossville, KS = irrigated environment (upper panels), and in Ottawa, KS = rainfed environment (lower panels).**

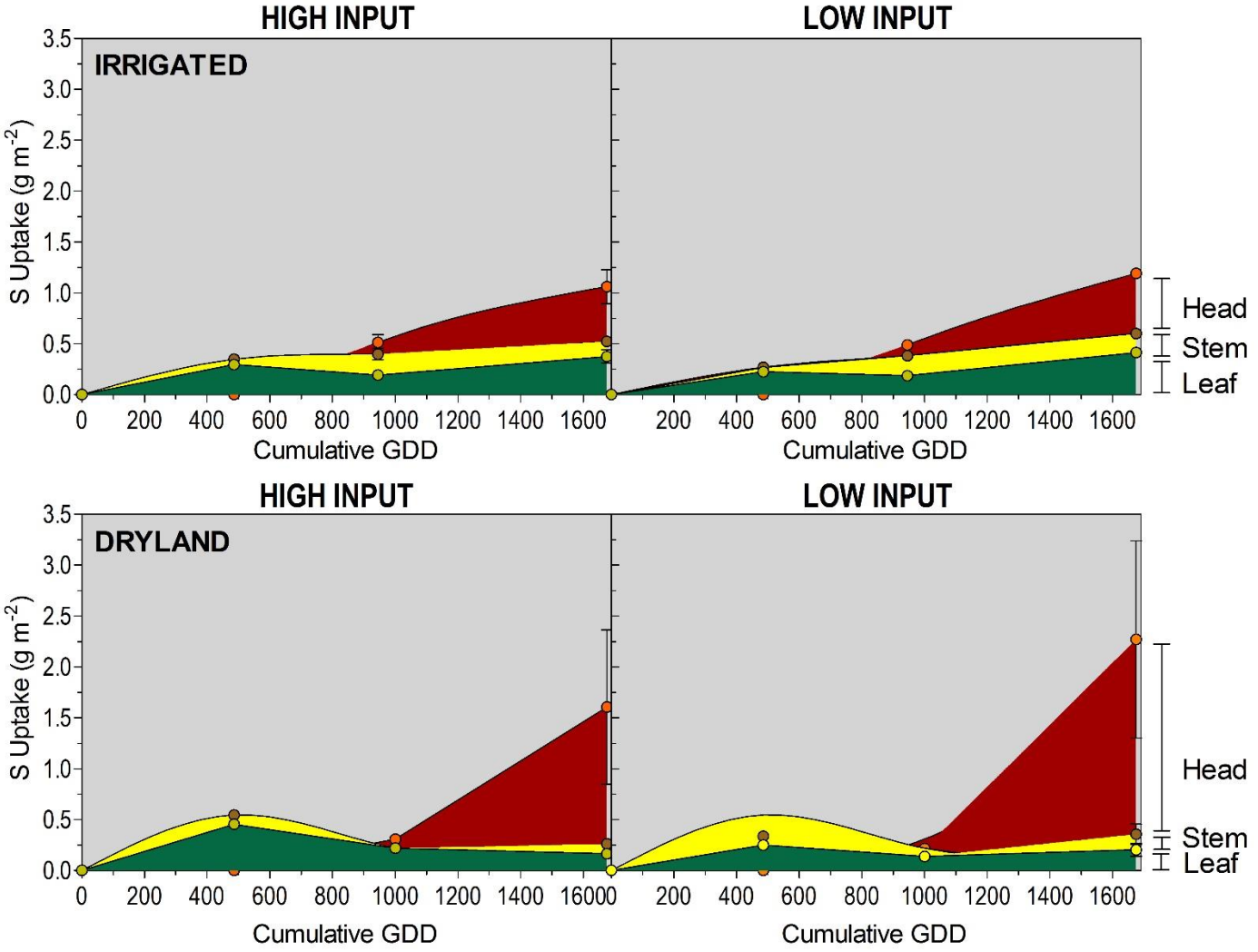


**Figure 2.35 Sulfur uptake curves (g $m^{-2}$) by fraction (leaf- green, stem- yellow, and head- red) between treatment one (high-input) and treatment ten (standard practice or low-input), during 2015 in Topeka, KS = irrigated environment (upper panels), and in Ottawa, KS = rainfed environment (lower panels).**

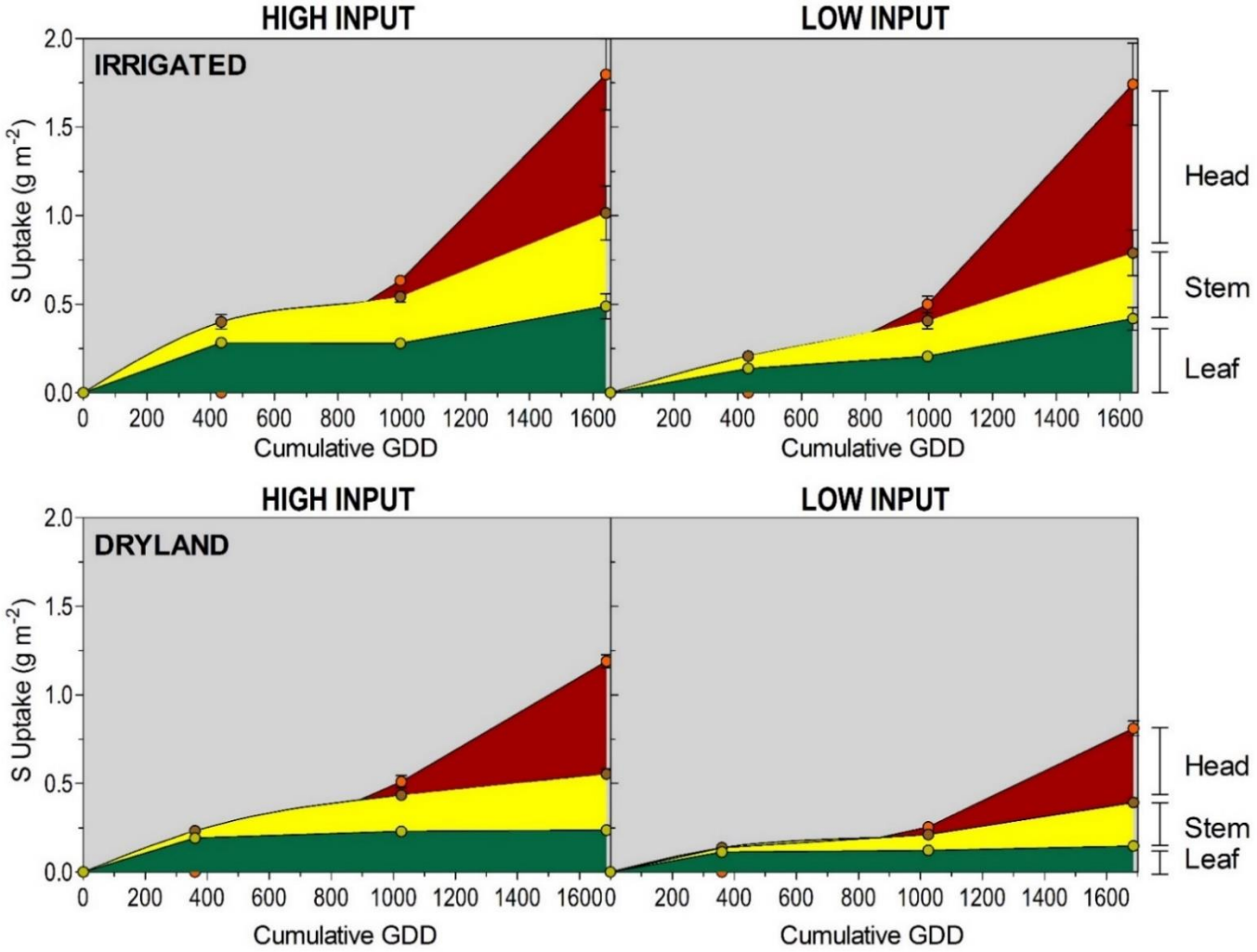


**Figure 2.36 Iron uptake curves (g $m^{-2}$) by fraction (leaf- green, stem- yellow, and head- red) between treatment one (high-input) and treatment ten (standard practice or low-input), during 2014 in Rossville, KS = irrigated environment (upper panels), and in Ottawa, KS = rainfed environment (lower panels).**

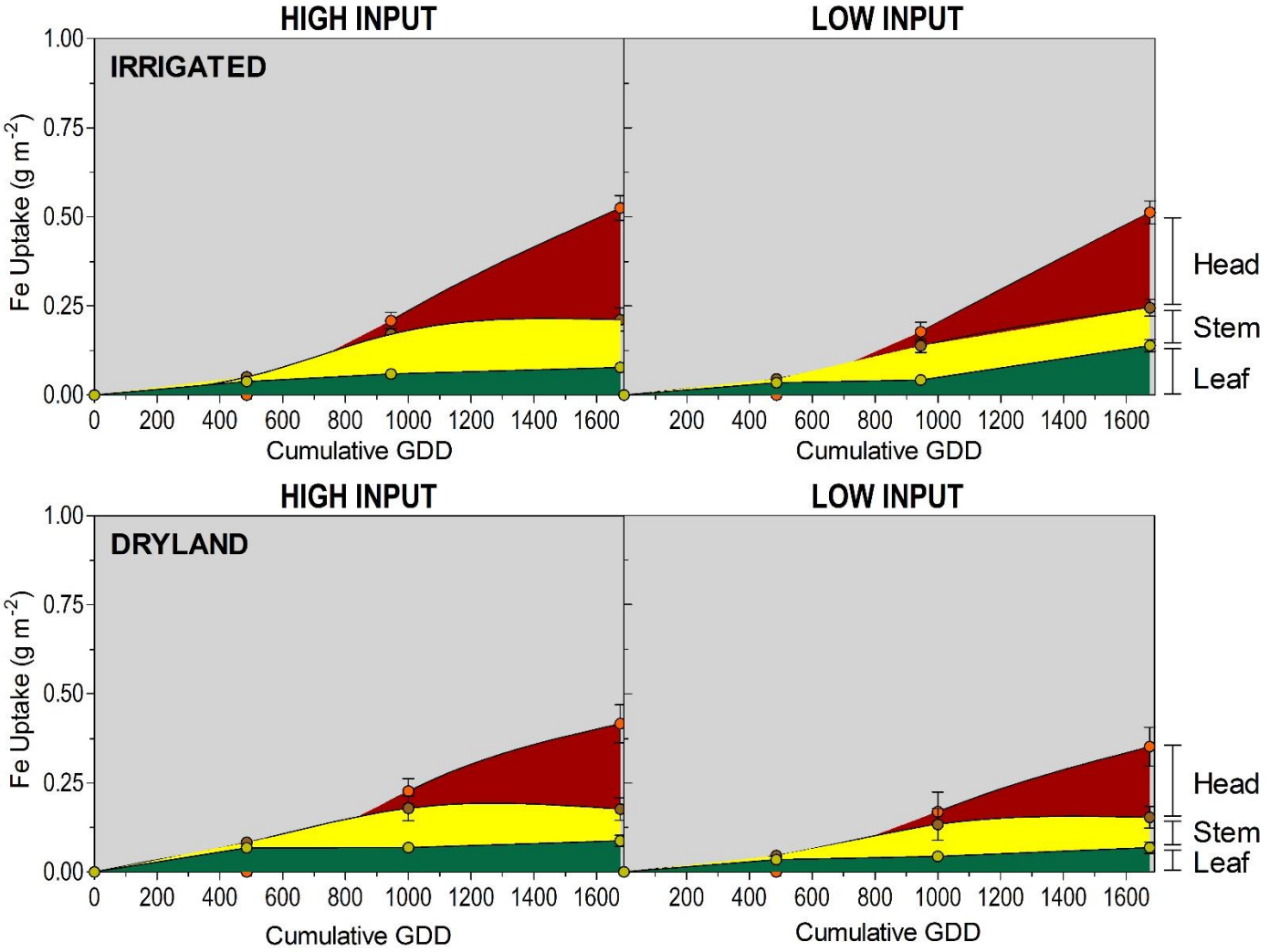


**Figure 2.37 Iron uptake curves (g $m^{-2}$) by fraction (leaf- green, stem- yellow, and head- red) between treatment one (high-input) and treatment ten (standard practice or low-input), during 2015 in Topeka, KS = irrigated environment (upper panels), and in Ottawa, KS = rainfed environment (lower panels).**

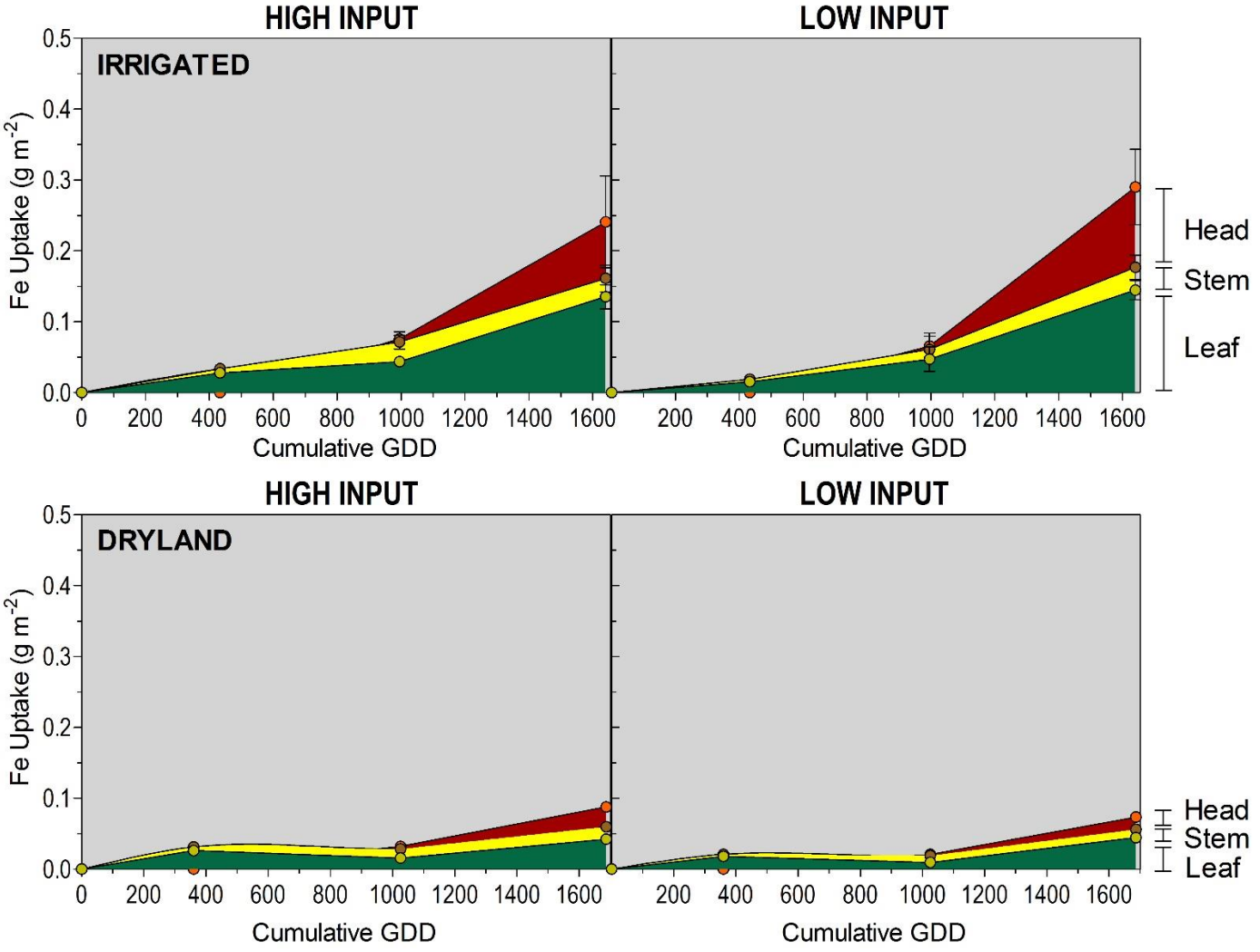


**Figure 2.38 Zinc uptake curves (g $m^{-2}$) by fraction (leaf- green, stem- yellow, and head- red) between treatment one (high-input) and treatment ten (standard practice or low-input), during 2014 in Rossville, KS = irrigated environment (upper panels), and in Ottawa, KS = rainfed environment (lower panels).**

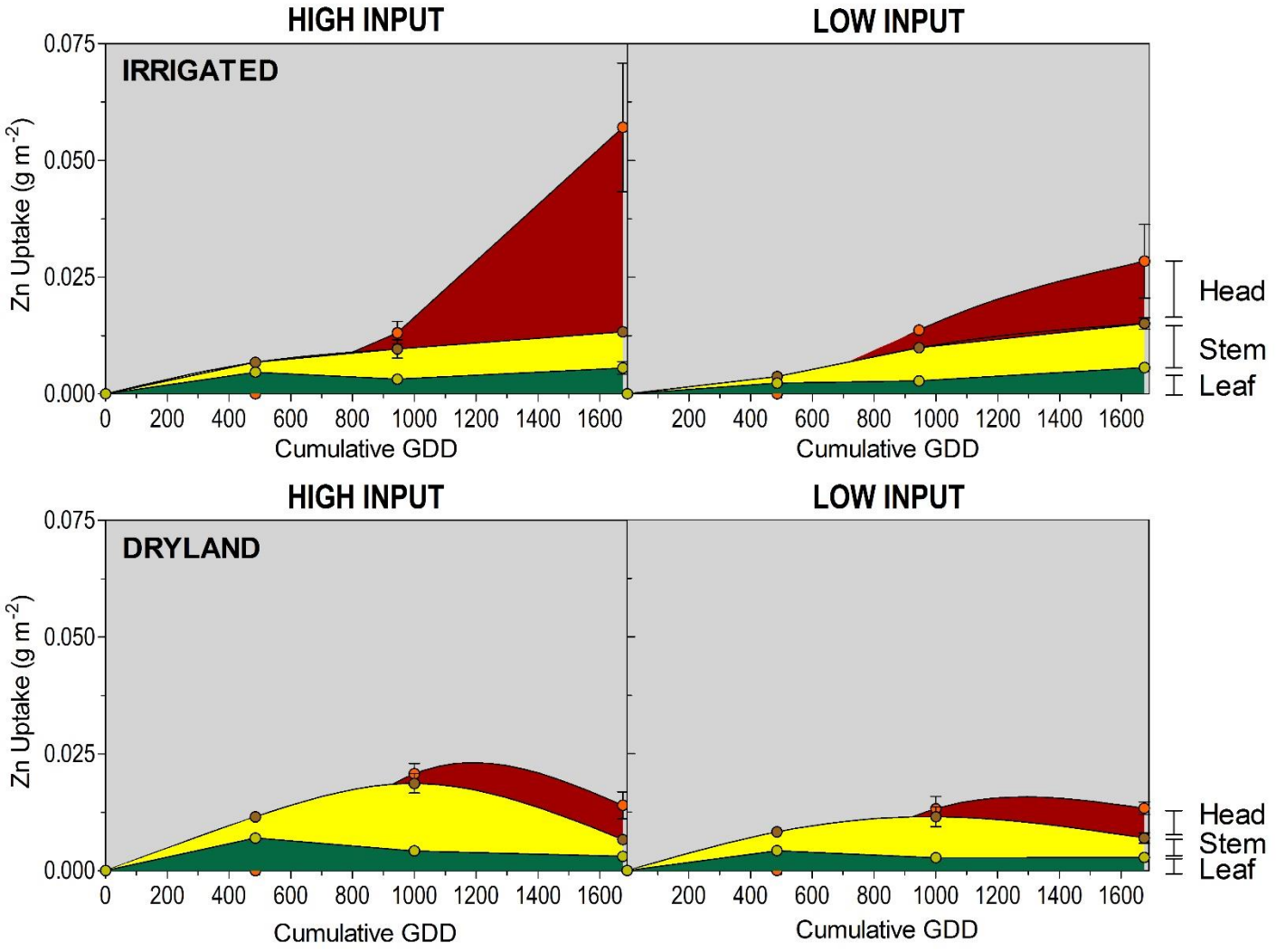


**Figure 2.39 Zinc uptake curves (g $m^{-2}$) by fraction (leaf- green, stem- yellow, and head- red) between treatment one (high-input) and treatment ten (standard practice or low-input), during 2015 in Topeka, KS = irrigated environment (upper panels), and in Ottawa, KS = rainfed environment (lower panels).**

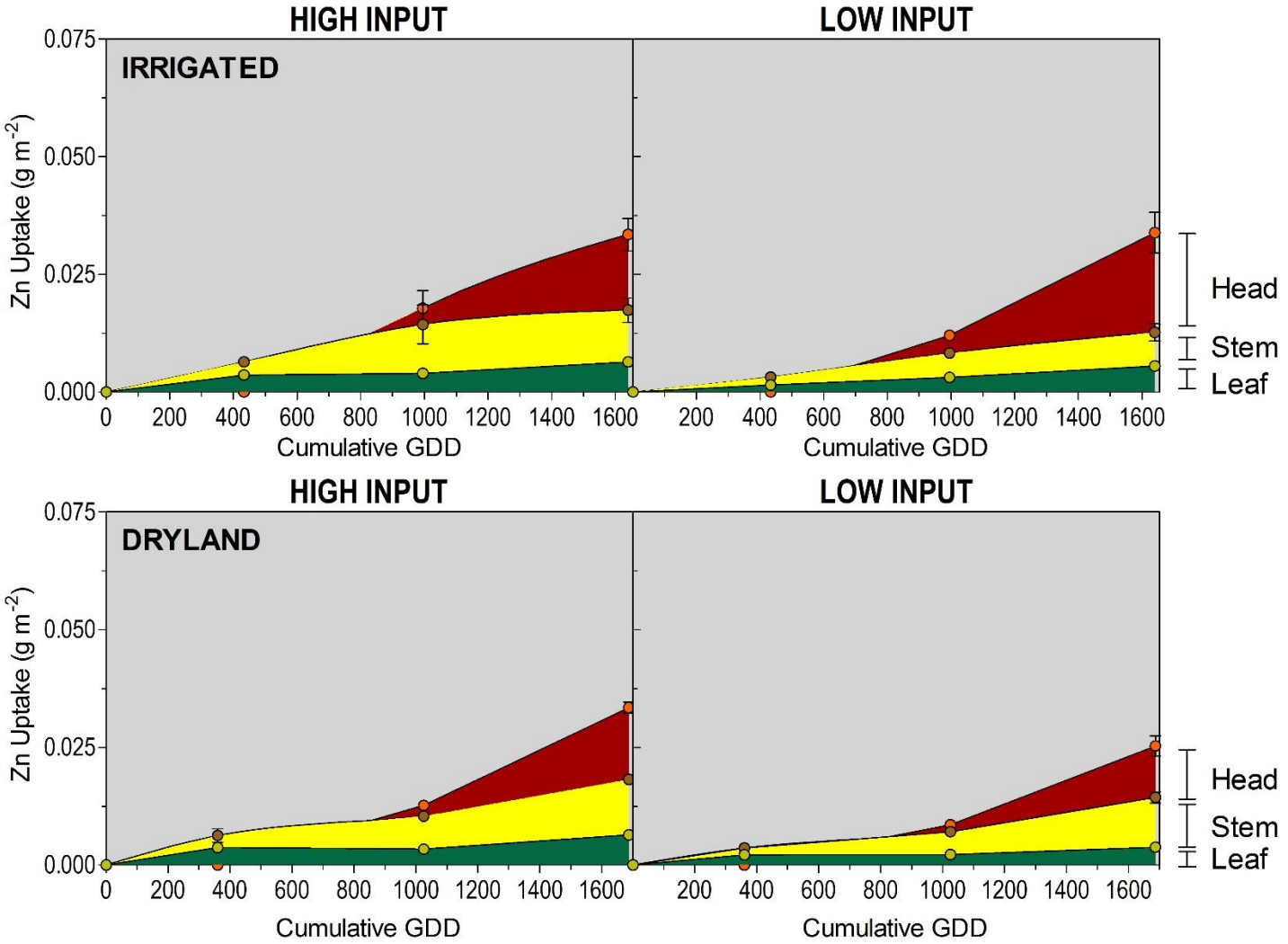


**Table 2.1 Irrigation amounts and timing during 2014 and 2015**

| Days after planting | Site & year | | | |
|---|---|---|---|---|
| | Rossville 2014 | Hutchinson 2014 | Topeka 2015 | Ashland 2015 |
| | mm | | | |
| 7 | 0 | 20.32 | 0 | 0 |
| 14 | 0 | 0 | 0 | 0 |
| 21 | 0 | 0 | 0 | 0 |
| 28 | 0 | 0 | 22.10 | 0 |
| 35 | 0 | 0 | 0 | 0 |
| 42 | 0 | 0 | 0 | 0 |
| 49 | 18.13 | 0 | 15.49 | 0 |
| 56 | 41.18 | 0 | 16.76 | 25.4 |
| 63 | 0 | 0 | 0 | 25.4 |
| 70 | 37.45 | 31.75 | 16.76 | 25.4 |
| 77 | 41.85 | 25.4 | 0 | 25.4 |
| 84 | 40.78 | 20.32 | 16.76 | 25.4 |
| 91 | 0 | 50.8 | 18.29 | 25.4 |
| 98 | 43.18 | 25.4 | 0 | 25.4 |
| 105 | 0 | 25.4 | 0 | 25.4 |
| 112 | 0 | 0 | 0 | 25.4 |
| 119 | 0 | 0 | 0 | 25.4 |
| 126 | 0 | 0 | 0 | 25.4 |
| 133 | 0 | 0 | 0 | 25.4 |
| 137 | 0 | 0 | 0 | 0 |
| Total Irrigation Applied | 222.55 | 199.39 | 106.17 | 304.80 |

**Table 2.2 Phenology for 8 site-years during the 2014 and 2015 growing seasons.**

| Sites | Plant Phenology | | | |
|---|---|---|---|---|
| | Planting Date | Stage two | Stage six | Stage nine |
| Rossville | 5/19/14 | 6/27/14 (476)† | 8/1/14 (948) | 9/26/14 (1669) |
| Scandia | 5/22/14 | 7/2/14 (526) | 8/4/14 (955) | 11/14/14 (1743) |
| Ottawa | 5/26/14 | 7/1/14 (485) | 8/8/14 (1003) | 9/30/14 (1677) |
| Hutchinson | 5/21/14 | 6/30/14 (562) | 8/11/14 (1103) | 11/26/14 (1968) |
| Ashland | 5/22/15 | 6/30/15 (525) | 7/31/15 (1033) | 10/5/15 (1878) |
| Scandia | 5/28/15 | 7/1/15 (448) | 8/6/15 (985) | 11/24/15 (1859) |
| Ottawa | 6/9/15 | 7/7/15 (440) | 8/12/15 (1025) | 10/12/15 (1687) |
| Topeka | 6/9/15 | 7/7/15 (433) | 8/10/15 (995) | 9/30/15 (1639) |

†Numbers in parentheses represent growing degree days

**Table 2.3 Description of treatments**

| | Treatments | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Seeding rate | Optimum | Normal | Optimum | Optimum | Optimum | Optimum | Optimum | Optimum | Optimum | Normal | Optimum |
| Row Spacing | 15 in. | 15 in. | 30 in. | 15 in. | 15 in. | 15 in. | 15 in. | 15 in. | 15 in. | 30 in. | 15 in. |
| N Program | GS | GS | GS | Standard | GS | GS | GS | GS | GS | Standard | GS |
| Fungicide/ insecticide | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes | No | Yes |
| Micronutrients | Fe, Zn | Fe, Zn | Fe, Zn | Fe, Zn | Fe, Zn | None | Fe, Zn | Fe, Zn | Fe, Zn | None | Fe, Zn |
| Plant growth regulator | Yes | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | No | Yes |
| Starter fertilizer | NPKS | NPKS | NPKS | NPKS | NPKS | NPKS | NPKS | NP | NPKS | NP | NPKS |
| Chloride | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | No | Yes |
| GreenSeeker + N | No | No | No | No | No | No | No | No | No | No | Yes |

Optimum seeding rate = 90,000 plants/acre; Normal = 45,000 plants/acre; 15 in. = narrow row spacing; 30 in. = wide row spacing; GS = GreenSeeker meter (Trimble Navigation, Westminster, CO); Standard = conventional N application prior to planting (without precision ag technology); Fe = Iron; Zn = Zinc; N = Nitrogen; P = Phosphorous; K = Potassium; S = Sulfur.

**Table 2.4 Fungicide, insecticide and plant growth regulator application rates**

| Treatment | PGR (MCP)* (g/plot)† | Fungicide (Tilt) (mL/plot)† | Insecticide (Sevin) (mL/plot)† |
|---|---|---|---|
| 1 | 1 | 1.4 | 11 |
| 2 | 1 | 1.4 | 11 |
| 3 | 1 | 1.4 | 11 |
| 4 | 1 | 1.4 | 11 |
| 5 | 1 | 0 | 0 |
| 6 | 1 | 1.4 | 11 |
| 7 | 0 | 1.4 | 11 |
| 8 | 1 | 1.4 | 11 |
| 9 | 1 | 1.4 | 11 |
| 10 | 0 | 0 | 0 |
| 11 | 1 | 1.4 | 11 |

*1-Methylcyclopropene; applied at mid- reproductive-phase (around soft-dough, 70-to-80 days after crop emergence).
†Calculated based on label recommendations to the plot scale

**Table 2.5 Starter fertilizer rates 2014 and 2015**

| Treatment | Nutrients applied | Elemental Fe applied | Elemental Zn applied | Elemental N applied | $P_2O_5$ applied | $K_2O$ applied | Elemental S applied | Elemental Cl applied |
|---|---|---|---|---|---|---|---|---|
| | | kg $ha^{-1}$ | kg $ha^{-1}$ | kg N $ha^{-1}$ | kg P $ha^{-1}$ | kg K $ha^{-1}$ | kg S $ha^{-1}$ | kg Cl $ha^{-1}$ |
| 1 | NPKS Cl + Fe, Zn | 0.123 | 0.279 | 25 | 25 | 25 | 25 | 25 |
| 2 | NPKS Cl + Fe, Zn | 0.123 | 0.279 | 25 | 25 | 25 | 25 | 25 |
| 3 | NPKS Cl + Fe, Zn | 0.123 | 0.279 | 25 | 25 | 25 | 25 | 25 |
| 4 | NPKS Cl + Fe, Zn | 0.123 | 0.279 | 25 | 25 | 25 | 25 | 25 |
| 5 | NPKS Cl + Fe, Zn | 0.123 | 0.279 | 25 | 25 | 25 | 25 | 25 |
| 6 | NPKS Cl | 0 | 0 | 25 | 25 | 25 | 25 | 25 |
| 7 | NPKS Cl + Fe, Zn | 0.123 | 0.279 | 25 | 25 | 25 | 25 | 25 |
| 8 | NP Cl + Fe, Zn | 0.123 | 0.279 | 25 | 25 | 0 | 0 | 25 |
| 9 | NPKS + Fe, Zn | 0.123 | 0.279 | 25 | 25 | 25 | 25 | 0 |
| 10 | NP | 0 | 0 | 25 | 25 | 0 | 0 | 0 |
| 11 | NPKS Cl + Fe, Zn | 0.123 | 0.279 | 25 | 25 | 25 | 25 | 25 |

**Table 2.6 GreenSeeker N average application rates 2014**

| Treatment | Rossville | Scandia | Ottawa | Hutchinson |
|---|---|---|---|---|
| | Kg $ha^{-1}$ | | | |
| 1 | 57 | 22 | 68 | 39 |
| 2 | 54 | 35 | 85 | 50 |
| 3 | 23 | 23 | 53 | 32 |
| 4 | 0 | 0 | 0 | 0 |
| 5 | 43 | 25 | 76 | 44 |
| 6 | 36 | 24 | 72 | 58 |
| 7 | 37 | 25 | 77 | 43 |
| 8 | 43 | 26 | 67 | 48 |
| 9 | 49 | 27 | 52 | 62 |
| 10 | 0 | 0 | 0 | 0 |
| 11 | 91 | 84 | 122 | 106 |

**Table 2.7 GreenSeeker N average application rates 2015**

| Treatment | Topeka | Scandia | Ottawa | Ashland |
|---|---|---|---|---|
| | Kg $ha^{-1}$ | | | |
| 1 | 70 | 73 | 90 | 87 |
| 2 | 90 | 107 | 112 | 104 |
| 3 | 74 | 56 | 84 | 91 |
| 4 | 0 | 0 | 0 | 0 |
| 5 | 63 | 76 | 80 | 78 |
| 6 | 70 | 59 | 84 | 74 |
| 7 | 67 | 66 | 80 | 82 |
| 8 | 70 | 63 | 84 | 83 |
| 9 | 63 | 66 | 80 | 95 |
| 10 | 0 | 0 | 0 | 0 |
| 11 | 119 | 119 | 142 | 135 |

**Table 2.8 Soil analysis† for 2014 and 2015 for all sites prior to planting.**

| Location | Sample Depth | pH | Mehlich P | K | Summation CEC | OM | $NH_4$-N | $N0_3$-N |
|---|---|---|---|---|---|---|---|---|
| | cm | | ppm | ppm | meq/100g | % | ppm | ppm |
| ……..……..……2014 sites……..…….. | | | | | | | | |
| Scandia | 15 | 6.2 | 27.2 | 614.7 | 28.5 | 2.8 | 6.4 | 17.0 |
| Rossville | 15 | 7.4 | 22.7 | 102.3 | 5.6 | 1.2 | - | - |
| Hutchinson | 15 | 6.5 | 26.2 | 224.7 | 17.2 | 2.5 | - | - |
| ……..……..……2015 sites……..……..……. | | | | | | | | |
| Topeka | 15 | 6.9 | 67.1 | 395 | 17.9 | 2.86 | - | - |
| | 60 | 6.9 | 40.2 | 287.9 | 19.4 | 2.26 | 12.05 | 11.16 |
| Ottawa | 15 | 6.3 | 12.1 | 128.1 | 20.5 | 3.15 | - | - |
| | 60 | 6.5 | 4.6 | 248.9 | 28.4 | 2.71 | 6.69 | 2.43 |
| Scandia | 15 | 6.4 | 11.9 | 476.6 | 19.9 | 3.16 | - | - |
| | 60 | 6.7 | 8.9 | 331.6 | 22.6 | 2.47 | 15.25 | 4.86 |
| Ashland | 15 | 7.9 | 59.8 | 264.3 | 12.1 | 1.58 | - | - |

†Soil analysis conducted by the K-State Soil Testing Laboratory using methods prescribed by the Recommended Chemical Soil Test Procedures for the North Central Region, published by the University of Missouri Agricultural Experiment Station, Columbia, MO.

**Table 2.9 Canopy temperature (degrees centigrade) readings during 2014.**

| Treatment | Rossville | | Scandia | | Ottawa | | Hutchinson | |
|---|---|---|---|---|---|---|---|---|
| | Flag Leaf | Head | Flag Leaf | Head | Flag Leaf | Head | Flag Leaf | Head |
| 1 | 27.1 | 27.1 | 30.8 | 29.8 | 26.2 | 25.1 | 27.0 | 26.8 |
| 2 | 27.6 | 26.6 | 30.2 | 30.9 | 26.1 | 24.9 | 25.9 | 26.5 |
| 3 | 28.2 | 27.1 | 29.5 | 29.7 | 26.6 | 25.5 | 27.3 | 25.9 |
| 4 | 28.1 | 26.9 | 30.1 | 29.5 | 25.8 | 25.2 | 26.0 | 26.1 |
| 5 | 28.1 | 26.8 | 30.7 | 29.8 | 26.1 | 24.7 | 26.1 | 26.7 |
| 6 | 28.6 | 27.5 | 30.9 | 30.5 | 26.3 | 25.4 | 26.9 | 26.0 |
| 7 | 27.8 | 27.7 | 30.9 | 29.6 | 26.8 | 25.1 | 27.1 | 26.8 |
| 8 | 27.9 | 27.5 | 29.3 | 30.2 | 26.4 | 24.9 | 25.7 | 25.5 |
| 9 | 27.2 | 26.6 | 29.0 | 29.9 | 25.9 | 25.0 | 26.0 | 25.9 |
| 10 | 26.9 | 26.8 | 30.0 | 28.6 | 26.1 | 25.2 | 26.3 | 26.0 |
| 11 | 27.5 | 26.9 | 28.7 | 29.8 | 26.6 | 25.1 | 26.2 | 26.3 |

**Table 2.10 Stand counts for 2014 and 2015 in all sites, measured in 5.3 m sections in 4 rows of each plot, averaged by treatment.**

| | ……..2014…..…… | | | | …….2015…….. | | | |
|---|---|---|---|---|---|---|---|---|
| Treatments | Rossville | Scandia | Ottawa | Hutchinson | Topeka | Scandia | Ottawa | Ashland |
| | Pl $ha^{-1}$ | | | | | | | |
| 1 | 213408 | 180804 | 214561 | 216619 | 227487 | 192660 | 218101 | 169689 |
| 2 | 144989 | 110656 | 188379 | 144742 | 118560 | 114608 | 112879 | 96577 |
| 3 | 201182 | 168084 | 210691 | 191796 | 216619 | 158945 | 221806 | 125353 |
| 4 | 211679 | 193154 | 206163 | 229710 | 227240 | 192166 | 221312 | 153881 |
| 5 | 208468 | 149929 | 213079 | 219583 | 235638 | 193401 | 221559 | 164996 |
| 6 | 207480 | 166478 | 214725 | 215878 | 226499 | 160056 | 220324 | 190437 |
| 7 | 210691 | 138814 | 211432 | 223288 | 225264 | 174135 | 221806 | 162279 |
| 8 | 205504 | 131898 | 211761 | 239837 | 227240 | 226746 | 224029 | 145977 |
| 9 | 209950 | 149188 | 214725 | 227981 | 226252 | 189449 | 224770 | 162279 |
| 10 | 149435 | 99047 | 133215 | 128934 | 119795 | 92008 | 115843 | 63356 |
| 11 | 213902 | 152646 | 208797 | 226993 | 227487 | 207233 | 217113 | 174629 |

2014 the treatment and the site were significant at the P< 0.0001. 2015 the treatment and the site were significant at the P< 0.0001.

**Table 2.11 Yield and yield components during 2014 and 2015**

| | | | Grain Yield | | Grain Number | | Total Biomass g $m^{-2}$ | | Harvest Index % | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2014 | 2015 | 2014 | 2015 | 2014 | 2015 | 2014 | 2015 |
| Treatment | 1 | | 6.05 | 7.19 BCD | 1594.9 | 1400.4 B | 1101.1 | 1676.1 AB | 55 | 45 C |
| | 2 | | 6.09 | 6.87 CD | 1635.6 | 2190.6 A | 1141.4 | 1412.2 CD | 53 | 49 AB |
| | 3 | | 5.82 | 7.40 ABC | 1667.3 | 1529.5 B | 1074.5 | 1423.4 CD | 54 | 47 BC |
| | 4 | | 6.02 | 7.94 A | 1569.0 | 1585.5 B | 1127.7 | 1850.2 A | 54 | 46 BC |
| | 5 | | 6.22 | 7.04 BCD | 1627.5 | 1409.7 B | 1140.5 | 1495.1 BCD | 54 | 44 C |
| | 6 | | 6.24 | 7.55 AB | 1479.8 | 1416.5 B | 1164.2 | 1552.6 BCD | 53 | 44 C |
| | 7 | | 5.90 | 7.28 BCD | 1380.5 | 1457.0 B | 1098.1 | 1571.4 BCD | 54 | 45 C |
| | 8 | | 6.03 | 7.45 ABC | 1644.2 | 1294.0 B | 1100.6 | 1513.2 BCD | 55 | 46 BC |
| | 9 | | 6.37 | 7.08 BCD | 1532.2 | 1394.1 B | 1205.2 | 1646.9 ABC | 53 | 44 C |
| | 10 | | 5.77 | 7.59 AB | 1773.9 | 2334.3 A | 1070.4 | 1437.9 BCD | 54 | 51 A |
| | 11 | | 6.41 | 6.77 D | 1515.4 | 1268.8 B | 1177.4 | 1390.5 D | 54 | 45 C |
| | 2014 | 2015 | | | | | | | | |
| Sites | Rossville | Topeka | 7.85 A | 9.53 A | 2558.4 A | 1566.1 A | 1350.4 A | 1760.5 A | 58 A | 45 |
| | Ottawa | Ottawa | 4.78 D | 5.51 D | 1635.6 B | 1240.2 B | 922.7 D | 1213.9 C | 52 C | 46 |
| | Scandia | Scandia | 6.47 B | 7.32 B | 1088.6 C | 1714.2 A | 1170.9 B | 1458.3 B | 55 B | 47 |
| | Hutchinson | Ashland | 5.24 C | 6.79 C | 1052.0 C | 1763.3 A | 1065.4 C | 1738.1 A | 50 C | 45 |
| ANOVA | Site | | *** | *** | *** | *** | *** | *** | *** | ns |
| | Trt | | ns | ** | ns | *** | ns | * | ns | ** |
| | Site*Trt | | ns | ** | ns | ns | ns | ns | ns | ns |

ns = not significant; * = P < 0.05; ** = P < 0.01; *** = P < 0.0001

**Table 2.12 Biomass dry weight accumulation (per 10 plants biomass in kg) during 2014**

| | | Dry Weight (kg) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| Treatment | 1 | 0.094 | 0.036 | 0.109 | 0.174 | 0.052 | 0.149 | 0.138 | 0.364 |
| | 2 | 0.101 | 0.04 | 0.116 | 0.199 | 0.069 | 0.157 | 0.146 | 0.369 |
| | 3 | 0.099 | 0.036 | 0.098 | 0.167 | 0.056 | 0.155 | 0.143 | 0.355 |
| | 4 | 0.098 | 0.038 | 0.108 | 0.185 | 0.059 | 0.145 | 0.141 | 0.341 |
| | 5 | 0.098 | 0.036 | 0.108 | 0.161 | 0.054 | 0.149 | 0.144 | 0.354 |
| | 6 | 0.093 | 0.037 | 0.114 | 0.182 | 0.054 | 0.142 | 0.146 | 0.336 |
| | 7 | 0.095 | 0.038 | 0.118 | 0.171 | 0.057 | 0.143 | 0.143 | 0.347 |
| | 8 | 0.094 | 0.04 | 0.094 | 0.148 | 0.045 | 0.147 | 0.144 | 0.353 |
| | 9 | 0.094 | 0.039 | 0.107 | 0.147 | 0.05 | 0.137 | 0.136 | 0.318 |
| | 10 | 0.095 | 0.039 | 0.116 | 0.195 | 0.06 | 0.157 | 0.153 | 0.376 |
| | 11 | 0.098 | 0.04 | 0.108 | 0.183 | 0.057 | 0.145 | 0.154 | 0.361 |
| Sites | Rossville | 0.074 C | 0.020 C | 0.099 C | 0.161 BC | 0.052 B | 0.159 A | 0.148 B | 0.437 A |
| | Ottawa | 0.088 B | 0.027 B | 0.112 AB | 0.196 A | 0.058 AB | 0.146 AB | 0.162 A | 0.334 B |
| | Scandia | 0.135 A | 0.074 A | 0.117 A | 0.156 C | 0.051 B | 0.150 AB | 0.151 AB | 0.378 B |
| | Hutchinson | 0.089 B | 0.031 B | 0.105 BC | 0.182 AB | 0.062 A | 0.136 B | 0.117 C | 0.261 C |
| ANOVA | Trt | ns | ns | ns | ns | ns | ns | ns | ns |
| | Site | *** | *** | ** | ** | * | * | *** | *** |
| | Trt*Site | ns | ns | ns | ns | ns | ns | ns | ns |

ns = not significant; * = P < 0.05; ** = P < 0.01; *** = P < 0.0001

**Table 2.13 Biomass dry matter accumulation (g $m^{-2}$) by fraction at three developmental stages during 2014**

| | | Biomass (g $m^{-2}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| Treatment | 1 | 200.4 A | 76.6 | 230.7 A | 370.4 AB | 109.9 | 253.8 | 242.5 | 604.8 |
| | 2 | 150.5 B | 56.2 | 178.5 CD | 303.9 BC | 107.1 | 275.4 | 256.8 | 609.2 |
| | 3 | 194.4 A | 70.5 | 190.8 BC | 328.1 AB | 110.3 | 254.6 | 237.8 | 582.1 |
| | 4 | 210.4 A | 83.6 | 227.5 A | 394.0 A | 124.8 | 267.7 | 258.0 | 602.0 |
| | 5 | 189.3 A | 66.6 | 212 ABC | 323.1 BC | 107.6 | 263.8 | 254.8 | 621.9 |
| | 6 | 182.1 A | 71.4 | 218.2 AB | 347.2 AB | 102.6 | 267.4 | 272.5 | 624.3 |
| | 7 | 188.1 A | 69.9 | 237.0 A | 352.9 AB | 116.1 | 254.4 | 254.2 | 589.5 |
| | 8 | 189.5 A | 76.5 | 191.4 BC | 305.7 BC | 94.6 | 252.0 | 245.2 | 603.3 |
| | 9 | 189.2 A | 74.3 | 220.2 AB | 302.5 BC | 106.9 | 286.9 | 281.4 | 636.9 |
| | 10 | 122.9 B | 49.0 | 152.5 D | 257.5 C | 79.4 | 248.1 | 245.1 | 577.3 |
| | 11 | 193.0 A | 75.5 | 216.4 AB | 369.4 AB | 115.5 | 262.0 | 274.8 | 640.6 |
| Sites | Rossville | 145.0 C | 39.8 C | 195.0 B | 313.0 B | 101.4 BC | 288.5 A | 276.9 A | 785.0 A |
| | Ottawa | 179.7 B | 54.6 B | 225.6 A | 393.4 A | 115.4 AB | 211.3 C | 233.9 B | 477.6 D |
| | Scandia | 224.7 A | 123.2 A | 194.3 B | 255.6 C | 85.2 C | 260.4 B | 263.7 AB | 646.8 B |
| | Hutchinson | 181.4 B | 62.4 B | 212.5 AB | 367.1 A | 125.2 A | 289.3 A | 252.1 AB | 524.0 C |
| ANOVA | Trt | *** | ns | ** | * | ns | ns | ns | ns |
| | Site | *** | *** | * | *** | *** | *** | * | *** |
| | Trt*Site | ns | ns | ns | ns | ns | ns | ns | ns |

ns = not significant; * = P < 0.05; ** = P < 0.01; *** = P < 0.0001

**Table 2.14 Biomass dry weight accumulation (per 10 plants biomass in kg) during 2015**

| | | Dry Weight (kg) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| Treatment | 1 | 0.074 | 0.047 | 0.074 C | 0.116 C | 0.031 B | 0.193 BC | 0.243 B | 0.355 BC |
| | 2 | 0.079 | 0.050 | 0.099 A | 0.165 A | 0.049 A | 0.232 A | 0.339 A | 0.549 A |
| | 3 | 0.071 | 0.048 | 0.077 BC | 0.128 BC | 0.036 B | 0.182 BCD | 0.253 B | 0.385 BC |
| | 4 | 0.074 | 0.050 | 0.079 BC | 0.141 B | 0.037 B | 0.211 AB | 0.263 B | 0.415 B |
| | 5 | 0.074 | 0.048 | 0.078 BC | 0.128 BC | 0.036 B | 0.180 BCD | 0.244 B | 0.341 BC |
| | 6 | 0.069 | 0.045 | 0.085 BC | 0.140 B | 0.040 B | 0.192 BC | 0.255 B | 0.378 BC |
| | 7 | 0.073 | 0.050 | 0.075 BC | 0.125 BC | 0.034 B | 0.184 BCD | 0.259 B | 0.356 BC |
| | 8 | 0.074 | 0.047 | 0.076 BC | 0.122 BC | 0.033 B | 0.154 D | 0.226 B | 0.328 BC |
| | 9 | 0.071 | 0.042 | 0.077 BC | 0.127 BC | 0.035 B | 0.185 BCD | 0.251 B | 0.345 BC |
| | 10 | 0.076 | 0.050 | 0.099 A | 0.184 A | 0.055 A | 0.233 A | 0.361 A | 0.634 A |
| | 11 | 0.072 | 0.048 | 0.086 B | 0.135 BC | 0.038 B | 0.164 CD | 0.228 B | 0.322 C |
| Sites | Topeka | 0.049 C | 0.027 C | 0.079 BC | 0.143 A | 0.042 A | 0.180 C | 0.320 A | 0.425 B |
| | Ottawa | 0.041 D | 0.019 D | 0.073 C | 0.129 B | 0.031 B | 0.146 D | 0.182 C | 0.288 C |
| | Scandia | 0.107 A | 0.075 A | 0.085 AB | 0.124 B | 0.040 A | 0.209 B | 0.218 B | 0.404 B |
| | Ashland | 0.096 B | 0.069 B | 0.092 A | 0.154 A | 0.042 A | 0.232 A | 0.342 A | 0.486 A |
| ANOVA | Trt | ns | ns | *** | *** | *** | *** | *** | *** |
| | Site | *** | *** | *** | *** | ** | *** | *** | *** |
| | Trt*Site | ns | ns | ns | ns | ns | ns | ns | ns |

ns = not significant; * = P < 0.05; ** = P < 0.01; *** = P < 0.0001

**Table 2.15 Biomass dry matter accumulation (g $m^{-2}$) by fraction at three developmental stages during 2015**

| | | Biomass (g $m^{-2}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| Treatment | 1 | 144.3 AB | 89.2 AB | 148.1 B | 281.8 B | 61.2 BCD | 409.9 AB | 515.4 ABC | 750.8 |
| | 2 | 93.5 DE | 56.0 C | 109.5 C | 224.0 C | 54.8 CD | 298.8 EF | 429.8 DE | 683.7 |
| | 3 | 116.9 CD | 77.3 B | 139.0 B | 294.6 AB | 65.9 ABCD | 312.4 DEF | 445 CDE | 666.0 |
| | 4 | 140.8 ABC | 95.0 AB | 157.0 AB | 331.1 AB | 72.8 AB | 441.1 A | 554.8 A | 854.4 |
| | 5 | 143.7 AB | 91.6 AB | 159.1 AB | 323.3 AB | 71.6 AB | 354.5 BCDE | 474.9 ABCDE | 665.7 |
| | 6 | 141.6 ABC | 91.1 AB | 177.4 A | 341.5 A | 80.9 A | 373.1 ABCD | 491.0 ABCDE | 688.6 |
| | 7 | 132.8 ABC | 89.3 AB | 144.3 B | 297.1 AB | 67.1 ABCD | 368.1 ABCDE | 504.9 ABCD | 698.4 |
| | 8 | 156.0 A | 97.6 A | 162.1 AB | 311.3 AB | 69.7 ABC | 331.1 CDEF | 480.6 ABCDE | 701.5 |
| | 9 | 137.5 ABC | 79.0 AB | 152.0 B | 306.3 AB | 68.5 ABCD | 394.2 ABC | 530.1 AB | 722.7 |
| | 10 | 68.5 E | 42.6 C | 95.1 C | 213.4 C | 52.9 D | 280.4 F | 419.4 E | 738.2 |
| | 11 | 125.5 BC | 81.6 AB | 156.1 AB | 301.2 AB | 70.3 ABC | 313.9 DEF | 455.9 BCDE | 620.7 |
| Sites | Topeka | 101.7 C | 55.2 C | 158.8 A | 287.2 B | 83.8 A | 349.0 A | 618.5 A | 793.0 A |
| | Ottawa | 81.9 D | 38.8 D | 143.6 AB | 454.7 A | 59.5 B | 293.7 B | 359.9 C | 560.2 C |
| | Scandia | 182.6 A | 128.4 A | 142.5 B | 203.8 C | 62.6 B | 376.1 A | 384.6 C | 697.6 B |
| | Ashland | 143.3 B | 101.5 B | 136.9 B | 227.3 C | 61.6 B | 391.0 A | 564.8 B | 782.3 A |
| ANOVA | Trt | *** | *** | *** | *** | * | ** | * | ns |
| | Site | *** | *** | * | *** | *** | *** | *** | *** |
| | Trt*Site | ns | * | ** | ** | ns | ns | ns | ns |

ns = not significant; * = P < 0.05; ** = P < 0.01; *** = P < 0.0001

**Table 2.16 Nitrogen uptake (g $m^{-2}$) by plant component at different stages during 2014 and 2015**

| | | N (g $m^{-2}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2014 | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| Treatment | 1 | 6.25 AB | 1.53 ABC | 4.66 | 2.68 | 1.89 | 3.66 | 1.36 | 10.6 |
| | 2 | 5.96 AB | 1.35 BCD | 4.41 | 2.82 | 2.49 | 4.41 | 1.37 | 10.7 |
| | 3 | 6.80 A | 1.74 A | 4.36 | 2.67 | 2.07 | 4.44 | 1.49 | 10.8 |
| | 4 | 5.57 B | 1.33 BCD | 3.34 | 2.30 | 1.71 | 3.29 | 1.30 | 9.5 |
| | 5 | 5.83 AB | 1.50 ABC | 4.96 | 2.84 | 2.25 | 4.30 | 1.36 | 11.4 |
| | 6 | 6.23 AB | 1.68 AB | 4.79 | 2.68 | 1.72 | 4.15 | 1.67 | 11.4 |
| | 7 | 6.58 AB | 1.51 ABC | 5.23 | 3.20 | 2.04 | 3.90 | 1.57 | 10.5 |
| | 8 | 6.27 AB | 1.62 AB | 5.07 | 6.73 | 1.98 | 3.94 | 2.72 | 10.6 |
| | 9 | 5.92 AB | 1.23 CD | 4.79 | 2.66 | 1.92 | 4.23 | 1.55 | 11.3 |
| | 10 | 4.22 C | 1.09 D | 3.63 | 2.39 | 1.61 | 3.94 | 1.57 | 10.2 |
| | 11 | 6.29 AB | 1.44 ABCD | 4.70 | 2.84 | 2.06 | 4.14 | 1.62 | 11.4 |
| ANOVA | Site | *** | *** | *** | ns | ns | *** | ** | *** |
| | Treatment | ** | * | ns | ns | ns | ns | ns | ns |
| | Site*Treatment | * | * | ns | ns | ns | ns | ns | ns |
| 2015 | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| Treatment | 1 | 3.78 AB | 1.35 AB | 3.95 ABC | 2.50 DEF | 1.23 BCD | 5.02 | 2.68 | 11.0 |
| | 2 | 2.23 C | 1.02 B | 3.17 D | 2.17 FG | 1.21 CD | 4.49 | 2.61 | 11.4 |
| | 3 | 3.29 B | 1.80 A | 4.44 AB | 2.99 AB | 1.50 AB | 4.86 | 2.74 | 11.0 |
| | 4 | 3.57 AB | 1.77 A | 3.85 BC | 2.40 EF | 1.41 ABC | 5.28 | 2.66 | 10.4 |
| | 5 | 3.92 A | 1.69 A | 4.52 A | 2.89 BCD | 1.45 ABC | 4.68 | 2.77 | 10.8 |
| | 6 | 3.42 AB | 1.38 AB | 4.47 A | 2.93 BC | 1.35 ABC | 5.46 | 2.93 | 10.4 |
| | 7 | 3.57 AB | 1.73 A | 3.70 CD | 2.57 CDE | 1.42 ABC | 5.15 | 3.11 | 10.1 |
| | 8 | 3.69 AB | 1.59 A | 4.22 ABC | 2.75 BCDE | 1.32 ABC | 5.26 | 2.99 | 11.1 |
| | 9 | 3.70 AB | 1.79 A | 3.70 CD | 2.50 DEF | 1.21 CD | 5.31 | 3.18 | 10.5 |
| | 10 | 2.09 C | 0.98 B | 2.44 E | 1.90 G | 0.99 D | 3.79 | 2.15 | 10.5 |
| | 11 | 3.62 AB | 1.74 A | 4.42 AB | 3.33 A | 1.53 A | 4.94 | 2.69 | 10.5 |
| ANOVA | Site | *** | *** | *** | *** | *** | *** | *** | *** |
| | Treatment | *** | ** | *** | *** | * | ns | ns | ns |
| | Site*Treatment | ns | ns | ns | ** | ns | ns | ns | * |

ns = not significant; * = P < 0.05; ** = P < 0.01; *** = P < 0.0001

**Table 2.17 Phosphorous uptake (g $m^{-2}$) by plant component at different stages during 2014 and 2015**

| | | P (g $m^{-2}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2014 | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| | 1 | 0.93 A | 0.24 A | 0.32 | 0.33 | 0.25 | 0.80 | 0.40 | 1.54 |
| | 2 | 0.84 A | 0.22 A | 0.34 | 0.26 | 0.34 | 1.05 | 0.34 | 1.80 |
| | 3 | 0.89 A | 0.26 A | 0.35 | 0.35 | 0.27 | 0.99 | 0.49 | 1.85 |
| | 4 | 0.86 A | 0.25 A | 0.32 | 0.30 | 0.20 | 0.78 | 0.38 | 1.82 |
| | 5 | 0.82 A | 0.22 A | 0.40 | 0.37 | 0.29 | 0.85 | 0.35 | 1.93 |
| Treatment | 6 | 0.85 A | 0.24 A | 0.34 | 0.29 | 0.23 | 0.97 | 0.52 | 1.88 |
| | 7 | 0.95 A | 0.26 A | 0.37 | 0.38 | 0.28 | 0.93 | 0.50 | 1.63 |
| | 8 | 0.80 A | 0.26 A | 0.33 | 0.30 | 0.22 | 0.88 | 0.51 | 1.87 |
| | 9 | 0.90 A | 0.23 A | 0.29 | 0.28 | 0.24 | 0.93 | 0.55 | 1.90 |
| | 10 | 0.60 B | 0.17 B | 0.25 | 0.28 | 0.23 | 0.94 | 0.51 | 1.58 |
| | 11 | 0.88 A | 0.22 A | 0.37 | 0.37 | 0.26 | 0.91 | 0.59 | 2.04 |
| | Site | *** | *** | ** | ns | ns | *** | *** | *** |
| ANOVA | Treatment | ** | ** | ns | ns | ns | ns | ns | ns |
| | Site*Treatment | ns | ns | ns | ns | ns | ns | ns | ns |
| 2015 | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| | 1 | 0.39 A | 0.15 A | 0.54 AB | 0.48 B | 0.17 CD | 0.77 B | 0.55 | 2.13 |
| | 2 | 0.22 B | 0.10 B | 0.43 CD | 0.39 C | 0.16 D | 0.62 B | 0.44 | 2.17 |
| | 3 | 0.34 A | 0.18 A | 0.61 AB | 0.57 AB | 0.22 AB | 0.77 B | 0.52 | 2.16 |
| | 4 | .036 A | 0.20 A | 0.64 A | 0.64 A | 0.19 ABCD | 1.05 A | 0.57 | 2.22 |
| | 5 | 0.40 A | 0.17 A | 0.61 AB | 0.50 B | 0.21 ABC | 0.70 B | 0.49 | 2.13 |
| Treatment | 6 | 0.34 A | 0.16 A | 0.61 AB | 0.55 AB | 0.19 ABCD | 0.78 B | 0.54 | 2.06 |
| | 7 | 0.35 A | 0.18 A | 0.56 AB | 0.51 B | 0.21 AB | 0.66 B | 0.48 | 1.99 |
| | 8 | 0.37 A | 0.17 A | 0.57 AB | 0.49 B | 0.18 BCD | 0.72 B | 0.60 | 2.11 |
| | 9 | 0.34 A | 0.18 A | 0.51 BC | 0.49 B | 0.17 CD | 0.76 B | 0.62 | 1.93 |
| | 10 | 0.20 B | 0.10 B | 0.40 D | 0.39 C | 0.16 D | 0.69 B | 0.41 | 2.34 |
| | 11 | 0.36 A | 0.19 A | 0.60 AB | 0.61 A | 0.23 A | 0.69 B | 0.44 | 1.86 |
| | Site | *** | *** | *** | *** | *** | *** | *** | *** |
| ANOVA | Treatment | *** | ** | ** | *** | * | * | ns | ns |
| | Site*Treatment | ns | ns | ns | *** | ns | ns | ns | ns |

ns = not significant; * = P < 0.05; ** = P < 0.01; *** = P < 0.0001

**Table 2.18 Potassium uptake (g $m^{-2}$) by plant component at different stages during 2014 and 2015**

| | | K (g $m^{-2}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2014 | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain† |
| | 1 | 3.85 AB | 2.40 AB | 2.61 ABC | 4.72 A | 1.44 | 3.93 | 5.99 | - |
| | 2 | 3.34 AB | 2.19 BC | 2.95 A | 4.75 A | 2.11 | 4.45 | 4.11 | - |
| | 3 | 4.12 A | 2.88 A | 2.31 CD | 4.78 A | 1.55 | 0.39 | 4.16 | - |
| | 4 | 3.55 AB | 2.43 AB | 2.36 CD | 4.47 AB | 1.24 | 4.01 | 5.88 | - |
| | 5 | 4.09 A | 2.20 BC | 2.93 A | 4.69 A | 1.63 | 4.13 | 6.07 | - |
| Treatment | 6 | 3.56 AB | 2.52 AB | 2.52 ABC | 4.45 AB | 1.23 | 4.31 | 5.96 | - |
| | 7 | 4.03 AB | 2.59 AB | 2.91 A | 5.32 A | 1.53 | 4.34 | 6.28 | - |
| | 8 | 3.27 B | 2.61 AB | 2.62 ABC | 4.26 AB | 1.48 | 4.19 | 6.05 | - |
| | 9 | 3.60 AB | 2.08 BC | 2.37 BCD | 4.49 AB | 1.35 | 4.33 | 6.05 | - |
| | 10 | 2.39 C | 1.66 C | 1.93 D | 3.58 B | 1.16 | 3.96 | 7.13 | - |
| | 11 | 4.05 AB | 2.40 AB | 2.87 AB | 5.24 A | 1.63 | 4.09 | 5.92 | - |
| | Site | ** | *** | *** | *** | *** | *** | ns | ** |
| ANOVA | Treatment | ** | ** | ** | ns | ns | ns | ns | ns |
| | Site*Treatment | ns | ns | ns | ns | ns | ns | ns | ns |
| 2015 | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| | 1 | 2.35 AB | 2.13 AB | 2.84 A | 5.37 CDE | 0.65 DE | 4.17 | 12.3 | 2.52 |
| | 2 | 1.30 C | 1.37 C | 2.23 B | 4.34 DE | 0.67 DE | 3.72 | 12.5 | 2.55 |
| | 3 | 1.93 B | 2.47 AB | 3.15 A | 6.93 AB | 0.88 AB | 4.16 | 12.7 | 2.37 |
| | 4 | 2.14 AB | 2.65 A | 3.40 A | 7.49 A | 0.72 BCDE | 5.23 | 13.7 | 2.6 |
| | 5 | 2.46 A | 2.36 AB | 3.16 A | 6.65 ABC | 0.81 ABCD | 3.9 | 12.6 | 2.48 |
| Treatment | 6 | 2.12 AB | 2.03 B | 3.13 A | 6.87 AB | 0.78 ABCDE | 4.37 | 13.7 | 2.35 |
| | 7 | 2.02 AB | 2.26 AB | 3.04 A | 6.27 ABC | 0.87 ABC | 3.71 | 12.6 | 2.3 |
| | 8 | 2.33 AB | 2.25 AB | 3.20 A | 6.60 ABC | 0.71 CDE | 3.81 | 12.5 | 2.4 |
| | 9 | 2.04 AB | 2.38 AB | 2.85 A | 5.74 BCD | 0.67 DE | 4.18 | 14.3 | 2.24 |
| | 10 | 1.19 C | 1.30 C | 2.22 B | 4.20 E | 0.63 E | 3.52 | 11 | 2.8 |
| | 11 | 2.23 AB | 2.57 AB | 3.28 A | 6.93 AB | 0.95 A | 3.7 | 11.7 | 2.24 |
| | Site | *** | *** | *** | *** | *** | *** | *** | *** |
| ANOVA | Treatment | *** | ** | ** | ** | ** | ns | ns | ns |
| | Site*Treatment | ns | ns | ns | ** | * | ns | ns | * |

ns = not significant; * = P < 0.05; ** = P < 0.01; *** = P < 0.0001;
† 2014 Grain K levels at stage nine are under reevaluation.

**Table 2.19 Sulfur uptake (g $m^{-2}$) by plant component at different stages during 2014 and 2015**

| | | S (g $m^{-2}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2014 | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| | 1 | 0.37 ABC | 0.072 AB | 0.21 ABC | 0.30 | 0.10 | 0.27 | 0.12 | 2.0 |
| | 2 | 0.34 BC | 0.076 AB | 0.20 ABC | 0.29 | 0.13 | 0.33 | 0.09 | 1.15 |
| | 3 | 0.41 A | 0.082 A | 0.19 BCD | 0.27 | 0.11 | 0.32 | 0.14 | 2.11 |
| | 4 | 0.33 C | 0.072 AB | 0.19 CD | 0.29 | 0.09 | 0.25 | 0.14 | 0.93 |
| | 5 | 0.35 ABC | 0.065 B | 0.24 A | 0.30 | 0.12 | 0.30 | 0.13 | 2.66 |
| Treatment | 6 | 0.37 ABC | 0.077 AB | 0.23 AB | 0.28 | 0.09 | 0.31 | 0.17 | 1.05 |
| | 7 | 0.39 AB | 0.074 AB | 0.23 ABC | 0.33 | 0.11 | 0.31 | 0.17 | 1.05 |
| | 8 | 0.34 BC | 0.072 AB | 0.20 ABCD | 0.26 | 0.10 | 0.30 | 0.17 | 1.18 |
| | 9 | 0.36 ABC | 0.066 B | 0.20 ABCD | 0.25 | 0.09 | 0.32 | 0.18 | 0.85 |
| | 10 | 0.24 D | 0.047 C | 0.16 D | 0.21 | 0.09 | 0.31 | 0.17 | 1.25 |
| | 11 | 0.40 AB | 0.072 AB | 0.23 AB | 0.29 | 0.11 | 0.30 | 0.20 | 1.33 |
| | Site | *** | *** | ns | *** | ns | *** | ** | ns |
| ANOVA | Treatment | *** | ** | * | ns | ns | ns | ns | ns |
| | Site*Treatment | * | ** | ns | ns | * | ns | ns | ns |
| 2015 | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| | 1 | 0.24 AB | 0.08 B | 0.25 AB | 0.23 ABC | 0.08 BCD | 0.36 | 0.42 | 0.71 |
| | 2 | 0.14 C | 0.05 C | .20 CD | 0.21 C | 0.08 CD | 0.32 | 0.36 | 0.71 |
| | 3 | 0.21 B | 0.09 AB | 0.28 AB | 0.27 A | 0.10 AB | 0.34 | 0.36 | 0.72 |
| | 4 | 0.23 AB | 0.11 A | 0.26 AB | 0.24 ABC | 0.08 BCD | 0.37 | 0.40 | 0.67 |
| | 5 | 0.26 A | 0.09 AB | 0.28 AB | 0.26 ABC | 0.10 AB | 0.34 | 0.41 | 0.71 |
| Treatment | 6 | 0.21 B | 0.08 B | 0.28 AB | 0.26 AB | 0.09 ABC | 0.37 | 0.40 | 0.69 |
| | 7 | 0.23 AB | 0.08 AB | 0.4 BC | 0.23 ABC | 0.10 AB | 0.33 | 0.41 | 0.66 |
| | 8 | 0.24 AB | 0.09 AB | 0.27 AB | 0.22 BC | 0.09 ABC | 0.34 | 0.33 | 0.71 |
| | 9 | 0.23 AB | 0.10 AB | 0.24 ABC | 0.21 C | 0.08 BCD | 0.36 | 0.42 | 0.65 |
| | 10 | 0.13 C | 0.05 C | 0.16 D | 0.15 D | 0.07 D | 0.28 | 0.31 | 0.69 |
| | 11 | 0.23 AB | 0.09 AB | 0.28 A | 0.26 ABC | 0.10 A | 0.33 | 0.34 | 0.67 |
| | Site | *** | *** | *** | *** | *** | *** | *** | *** |
| ANOVA | Treatment | *** | *** | *** | ** | ** | ns | ns | ns |
| | Site*Treatment | ns | ns | ns | * | ns | ns | ns | ** |

ns = not significant; * = P < 0.05; ** = P < 0.01; *** = P < 0.0001

**Table 2.20 Iron uptake (g $m^{-2}$) by plant component at different stages during 2014 and 2015**

| | | Fe (g $m^{-2}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2014 | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| | 1 | 0.053 AB | 0.014 | 0.064 | 0.111 | 0.043 | 0.083 | 0.111 | 0.276 |
| | 2 | 0.048 AB | 0.014 | 0.053 | 0.116 | 0.050 | 0.131 | 0.117 | 0.236 |
| | 3 | 0.078 A | 0.018 | 0.068 | 0.117 | 0.048 | 0.121 | 0.121 | 0.265 |
| | 4 | 0.048 AB | 0.015 | 0.057 | 0.101 | 0.043 | 0.088 | 0.124 | 0.241 |
| | 5 | 0.055 AB | 0.015 | 0.062 | 0.118 | 0.044 | 0.091 | 0.092 | 0.231 |
| Treatment | 6 | 0.051 AB | 0.013 | 0.071 | 0.103 | 0.040 | 0.112 | 0.108 | 0.295 |
| | 7 | 0.055 AB | 0.014 | 0.074 | 0.110 | 0.045 | 0.109 | 0.11 | 0.267 |
| | 8 | 0.057 AB | 0.013 | 0.064 | 0.108 | 0.039 | 0.102 | 0.116 | 0.249 |
| | 9 | 0.051 AB | 0.013 | 0.066 | 0.104 | 0.048 | 0.112 | 0.106 | 0.265 |
| | 10 | 0.035 B | 0.009 | 0.043 | 0.092 | 0.038 | 0.104 | 0.095 | 0.233 |
| | 11 | 0.074 A | 0.018 | 0.067 | 0.120 | 0.052 | 0.111 | 0.096 | 0.253 |
| | Site | * | ns | ** | ns | ** | *** | * | *** |
| ANOVA | Treatment | ns | ns | ns | ns | ns | ns | ns | ns |
| | Site*Treatment | ns | ns | ns | ns | ns | * | ns | ns |
| 2015 | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| | 1 | 0.027 ABC | 0.006 | 0.030 | 0.020 | 0.004 | 0.09 | 0.02 | 0.05 |
| | 2 | 0.017 D | 0.003 | 0.024 | 0.016 | 0.004 | 0.07 | 0.02 | 0.05 |
| | 3 | 0.032 A | 0.007 | 0.031 | 0.020 | 0.005 | 0.09 | 0.02 | 0.04 |
| | 4 | 0.023 CD | 0.008 | 0.034 | 0.016 | 0.004 | 0.11 | 0.02 | 0.04 |
| | 5 | 0.032 AB | 0.005 | 0.034 | 0.017 | 0.005 | 0.08 | 0.02 | 0.03 |
| Treatment | 6 | 0.023 CD | 0.005 | 0.034 | 0.016 | 0.005 | 0.09 | 0.02 | 0.03 |
| | 7 | 0.024 BCD | 0.009 | 0.028 | 0.015 | 0.005 | 0.08 | 0.02 | 0.03 |
| | 8 | 0.027 ABC | 0.005 | 0.033 | 0.015 | 0.004 | 0.09 | 0.02 | 0.03 |
| | 9 | 0.024 CD | 0.009 | 0.026 | 0.014 | 0.004 | 0.09 | 0.03 | 0.05 |
| | 10 | 0.017 D | 0.003 | 0.028 | 0.012 | 0.003 | 0.09 | 0.02 | 0.07 |
| | 11 | 0.025 ABC | 0.008 | 0.035 | 0.018 | 0.006 | 0.07 | 0.02 | 0.03 |
| | Site | ns | ns | *** | *** | *** | *** | *** | ** |
| ANOVA | Treatment | ** | ns | ns | ns | ns | ns | ns | ns |
| | Site*Treatment | ns | ns | ns | ns | ns | ns | ns | ns |

ns = not significant; * = P < 0.05; ** = P < 0.01; *** = P < 0.0001

**Table 2.21 Zinc uptake (g $m^{-2}$) by plant component at different stages during 2014 and 2015**

| | | Zn (g $m^{-2}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2014 | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| | 1 | 0.0058 A | 0.0033 | 0.0037 ABC | 0.010 | 0.003 | 0.004 | 0.006 | 0.026 |
| | 2 | 0.0050 A | 0.0030 | 0.0039 ABC | 0.009 | 0.004 | 0.004 | 0.006 | 0.030 |
| | 3 | 0.0054 A | 0.0029 | 0.0035 BCD | 0.011 | 0.003 | 0.005 | 0.007 | 0.016 |
| | 4 | 0.0048 A | 0.0035 | 0.0031 CD | 0.009 | 0.003 | 0.004 | 0.006 | 0.012 |
| | 5 | 0.0048 A | 0.0030 | 0.0043 AB | 0.011 | 0.004 | 0.004 | 0.005 | 0.018 |
| Treatment | 6 | 0.0052 A | 0.0032 | 0.0045 A | 0.010 | 0.003 | 0.004 | 0.006 | 0.024 |
| | 7 | 0.0054 A | 0.0031 | 0.0041 AB | 0.013 | 0.004 | 0.004 | 0.007 | 0.015 |
| | 8 | 0.0048 A | 0.0032 | 0.0036 BCD | 0.010 | 0.003 | 0.004 | 0.006 | 0.016 |
| | 9 | 0.0054 A | 0.0035 | 0.0039 ABC | 0.010 | 0.003 | 0.004 | 0.006 | 0.018 |
| | 10 | 0.0033 B | 0.0019 | 0.0028 D | 0.008 | 0.003 | 0.004 | 0.007 | 0.014 |
| | 11 | 0.0054 A | 0.0031 | 0.0041 AB | 0.012 | 0.004 | 0.004 | 0.007 | 0.019 |
| | Site | *** | *** | *** | *** | ** | *** | *** | *** |
| ANOVA | Treatment | * | ns | ** | ns | ns | ns | ns | ns |
| | Site*Treatment | ns | ns | ns | ns | ns | ns | ns | ns |
| 2015 | | Stage two | | Stage six | | | Stage nine | | |
| | | Leaf | Stem | Leaf | Stem | Head | Leaf | Stem | Grain |
| | 1 | 0.0037 AB | 0.0027 BC | 0.0037 AB | 0.009 | 0.0028 BC | 0.0064 AB | 0.011 | 0.016 |
| | 2 | 0.0030 B | 0.0019 CD | 0.0032 BC | 0.009 | 0.0028 C | 0.0050 CD | 0.009 | 0.016 |
| | 3 | 0.0030 B | 0.0033 AB | 0.0041 A | 0.012 | 0.0037 A | 0.0054 BCD | 0.010 | 0.015 |
| | 4 | 0.0033 AB | 0.0038 A | 0.0042 A | 0.008 | 0.0032 ABC | 0.0069 A | 0.012 | 0.016 |
| | 5 | 0.0039 A | 0.0031 AB | 0.0042 A | 0.007 | 0.0035 AB | 0.0066 AB | 0.011 | 0.017 |
| Treatment | 6 | 0.0034 AB | 0.0029 ABC | 0.0042 A | 0.007 | 0.0031 ABC | 0.0056 BCD | 0.010 | 0.015 |
| | 7 | 0.0033 AB | 0.0034 AB | 0.0037 AB | 0.007 | 0.0036 A | 0.0054 BCD | 0.010 | 0.014 |
| | 8 | 0.0036 AB | 0.0031 AB | 0.0040 A | 0.007 | 0.0032 ABC | 0.0056 BCD | 0.011 | 0.016 |
| | 9 | 0.0033 AB | 0.0035 AB | 0.0037 AB | 0.006 | 0.0029 BC | 0.0061 ABC | 0.012 | 0.014 |
| | 10 | 0.0019 C | 0.0016 D | 0.0027 C | 0.005 | 0.0026 C | 0.0047 D | 0.009 | 0.016 |
| | 11 | 0.0035 AB | 0.0033 AB | 0.0038 AB | 0.008 | 0.0037 A | 0.0055 BCD | 0.009 | 0.014 |
| | Site | ** | ** | *** | ns | *** | ns | *** | *** |
| ANOVA | Treatment | ** | ** | ** | ns | * | * | ns | ns |
| | Site*Treatment | * | ns | ns | ns | ns | ns | ns | ** |

ns = not significant; * = P < 0.05; ** = P < 0.01; *** = P < 0.0001

# Appendix A - Raw Data

**Table A.1 Raw Yield Data 2014**

| Site | Treatment | Irrigation | plot | Stand Count | Plants hectare$^{-1}$ | Grain Yield (Mg ha$^{-1}$) | Total Biomass (g m$^{-2}$) | Harvest Index (%) | Grain Number |
|---|---|---|---|---|---|---|---|---|---|
| Rossville | 1 | 1 | 101 | 83 | 205010 | 6.67 | 1160.35 | 0.5751 | 1767.26 |
| Rossville | 2 | 1 | 102 | 56 | 137085 | 6.89 | 1491.58 | 0.4619 | 1038.78 |
| Rossville | 3 | 1 | 103 | 84 | 206863 | 7.21 | 1250.00 | 0.5768 | 2746.94 |
| Rossville | 4 | 1 | 104 | 83 | 205010 | 7.11 | 1301.99 | 0.5463 | 1803.75 |
| Rossville | 5 | 1 | 105 | 84 | 207480 | 7.39 | 1112.14 | 0.6648 | 1598.23 |
| Rossville | 6 | 1 | 106 | 84 | 207480 | 7.66 | 1293.92 | 0.5917 | 2311.19 |
| Rossville | 7 | 1 | 107 | 84 | 206245 | 7.03 | 1441.98 | 0.4877 | 906.55 |
| Rossville | 8 | 1 | 108 | 84 | 206245 | 6.97 | 1147.30 | 0.6076 | 1800.76 |
| Rossville | 9 | 1 | 109 | 82 | 201305 | 8.13 | 1244.22 | 0.6532 | 2445.53 |
| Rossville | 10 | 1 | 110 | 61 | 150053 | 7.08 | 1334.19 | 0.5309 | 1845.45 |
| Rossville | 11 | 1 | 111 | 83 | 203775 | 8.47 | 1438.36 | 0.5890 | 1766.42 |
| Rossville | 10 | 1 | 201 | 62 | 151905 | 6.42 | 1197.00 | 0.5361 | 3052.00 |
| Rossville | 1 | 1 | 202 | 94 | 230945 | 7.90 | 1334.36 | 0.5922 | 2767.50 |
| Rossville | 4 | 1 | 203 | 84 | 206245 | 7.20 | 1162.11 | 0.6194 | 3524.04 |
| Rossville | 5 | 1 | 204 | 85 | 208715 | 8.20 | 1465.19 | 0.5599 | 3752.17 |
| Rossville | 8 | 1 | 205 | 84 | 206245 | 8.55 | 1512.05 | 0.5656 | 3168.00 |
| Rossville | 11 | 1 | 206 | 92 | 227240 | 8.71 | 1530.39 | 0.5693 | 2262.15 |
| Rossville | 6 | 1 | 207 | 84 | 207480 | 8.92 | 1517.43 | 0.5882 | 2218.97 |
| Rossville | 9 | 1 | 208 | 89 | 218595 | 8.09 | 1356.40 | 0.5962 | 3486.41 |
| Rossville | 2 | 1 | 209 | 61 | 149435 | 8.82 | 1367.11 | 0.6451 | 3523.11 |
| Rossville | 3 | 1 | 210 | 83 | 204393 | 8.83 | 1657.64 | 0.5324 | 2387.11 |
| Rossville | 7 | 1 | 211 | 82 | 202540 | 8.53 | 1417.93 | 0.6017 | 2441.95 |
| Rossville | 9 | 1 | 301 | 84 | 207480 | 7.99 | 1379.22 | 0.5796 | 2781.46 |
| Rossville | 11 | 1 | 302 | 83 | 205010 | 7.56 | 1304.56 | 0.5797 | 3044.36 |
| Rossville | 2 | 1 | 303 | 62 | 151905 | 7.93 | 1251.74 | 0.6338 | 3462.11 |
| Rossville | 4 | 1 | 304 | 82 | 202540 | 7.48 | 1384.55 | 0.5400 | 2262.99 |
| Rossville | 7 | 1 | 305 | 88 | 217360 | 7.65 | 1262.04 | 0.6062 | 2217.52 |
| Rossville | 8 | 1 | 306 | 85 | 208715 | 8.25 | 1452.12 | 0.5685 | 3297.39 |
| Rossville | 10 | 1 | 307 | 58 | 143260 | 7.49 | 1284.85 | 0.5832 | 2825.75 |
| Rossville | 6 | 1 | 308 | 81 | 200070 | 8.33 | 1401.14 | 0.5942 | 2663.10 |
| Rossville | 3 | 1 | 309 | 81 | 198835 | 8.03 | 1328.72 | 0.6045 | 3048.13 |
| Rossville | 1 | 1 | 310 | 86 | 211185 | 8.82 | 1344.64 | 0.6558 | 3334.42 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Rossville | 5 | 1 | 311 | 81 | 198835 | 8.73 | 1437.20 | 0.6074 | 2875.63 |
| Ottawa | 9 | 0 | 301 | 87 | 215713 | 4.56 | 899.81 | 0.5067 | 1402.18 |
| Ottawa | 11 | 0 | 302 | 81 | 200893 | 3.96 | 753.99 | 0.5254 | 1504.47 |
| Ottawa | 2 | 0 | 303 | 72 | 177840 | 4.12 | 767.96 | 0.5365 | 2222.21 |
| Ottawa | 4 | 0 | 304 | 81 | 200893 | 3.94 | 789.39 | 0.4988 | 1775.66 |
| Ottawa | 7 | 0 | 305 | 87 | 215713 | 3.36 | 699.58 | 0.4809 | 1697.28 |
| Ottawa | 8 | 0 | 306 | 81 | 200893 | 3.66 | 741.42 | 0.4932 | 1512.68 |
| Ottawa | 10 | 0 | 307 | 59 | 145730 | 3.78 | 725.58 | 0.5211 | 2426.45 |
| Ottawa | 6 | 0 | 308 | 83 | 205833 | 3.41 | 731.53 | 0.4659 | 1077.26 |
| Ottawa | 3 | 0 | 309 | 84 | 207480 | 3.47 | 719.98 | 0.4825 | 1908.60 |
| Ottawa | 1 | 0 | 310 | 81 | 200893 | 3.20 | 623.35 | 0.5131 | 1397.29 |
| Ottawa | 5 | 0 | 311 | 81 | 199247 | 4.37 | 843.27 | 0.5183 | 1497.99 |
| Ottawa | 11 | 0 | 401 | 81 | 199247 | 5.19 | 911.14 | 0.5697 | 1783.74 |
| Ottawa | 4 | 0 | 402 | 87 | 215713 | 4.76 | 873.33 | 0.5446 | 1443.20 |
| Ottawa | 3 | 0 | 403 | 88 | 217360 | 5.41 | 979.11 | 0.5529 | 1690.01 |
| Ottawa | 1 | 0 | 404 | 91 | 224770 | 5.41 | 1055.69 | 0.5120 | 1621.40 |
| Ottawa | 7 | 0 | 405 | 85 | 210773 | 4.84 | 893.03 | 0.5417 | 1707.64 |
| Ottawa | 5 | 0 | 406 | 88 | 217360 | 5.00 | 961.19 | 0.5206 | 1554.70 |
| Ottawa | 8 | 0 | 407 | 95 | 233827 | 4.05 | 761.40 | 0.5326 | 1603.85 |
| Ottawa | 6 | 0 | 408 | 86 | 212420 | 4.67 | 930.75 | 0.5015 | 1716.87 |
| Ottawa | 10 | 0 | 409 | 32 | 78217 | 5.79 | 1180.82 | 0.4905 | 1931.53 |
| Ottawa | 2 | 0 | 410 | 118 | 291460 | 4.00 | 809.78 | 0.4944 | 1293.60 |
| Ottawa | 9 | 0 | 411 | 89 | 220653 | 5.46 | 1059.40 | 0.5150 | 1642.01 |
| Ottawa | 3 | 0 | 501 | 90 | 221065 | 6.16 | 1177.14 | 0.5234 | 1515.02 |
| Ottawa | 4 | 0 | 502 | 76 | 187720 | 5.22 | 996.53 | 0.5240 | 1709.69 |
| Ottawa | 2 | 0 | 503 | 70 | 172900 | 6.25 | 1121.83 | 0.5570 | 1881.38 |
| Ottawa | 1 | 0 | 504 | 91 | 223947 | 5.88 | 1138.30 | 0.5167 | 1506.07 |
| Ottawa | 6 | 0 | 505 | 84 | 207480 | 5.78 | 1107.06 | 0.5225 | 1644.84 |
| Ottawa | 11 | 0 | 506 | 83 | 205833 | 6.10 | 1210.59 | 0.5037 | 1482.65 |
| Ottawa | 10 | 0 | 507 | 62 | 151905 | 5.34 | 931.58 | 0.5733 | 1779.17 |
| Ottawa | 9 | 0 | 508 | 85 | 210773 | 5.20 | 1164.83 | 0.4461 | 1474.76 |
| Ottawa | 7 | 0 | 509 | 93 | 230533 | 5.37 | 1018.70 | 0.5271 | 1171.30 |
| Ottawa | 5 | 0 | 510 | 87 | 215713 | 4.34 | 828.97 | 0.5236 | 1693.21 |
| Ottawa | 8 | 0 | 511 | 83 | 204187 | 5.55 | 1042.67 | 0.5325 | 1704.63 |
| Scandia | 11 | 0 | 301 | 76.5 | 188955 | 7.20 | 1307.81 | 0.5508 | 1221.38 |
| Scandia | 4 | 0 | 302 | 75.5 | 186485 | 6.48 | 1089.70 | 0.5947 | 1332.93 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Scandia | 3 | 0 | 303 | 70 | 172900 | 7.24 | 1179.19 | 0.6138 | 1378.52 |
| Scandia | 1 | 0 | 304 | 94.5 | 233415 | 8.31 | 1479.19 | 0.5616 | 1175.51 |
| Scandia | 7 | 0 | 305 | 65 | 160550 | 6.39 | 1187.60 | 0.5377 | 1032.10 |
| Scandia | 5 | 0 | 306 | 63.5 | 156845 | 7.48 | 1462.70 | 0.5112 | 945.75 |
| Scandia | 8 | 0 | 307 | 72 | 177840 | 7.17 | 1395.37 | 0.5139 | 756.98 |
| Scandia | 6 | 0 | 308 | 51.5 | 127205 | 6.86 | 1224.62 | 0.5604 | 1207.74 |
| Scandia | 9 | 0 | 309 | 43.5 | 107445 | 8.22 | 1573.92 | 0.5222 | 959.94 |
| Scandia | 10 | 0 | 310 | 44 | 108680 | 6.15 | 1039.35 | 0.5913 | 1335.22 |
| Scandia | 2 | 0 | 311 | 45 | 111150 | 7.67 | 1283.47 | 0.5979 | 1422.63 |
| Scandia | 9 | 0 | 401 | 99 | 244530 | 7.34 | 1402.35 | 0.5235 | 797.32 |
| Scandia | 11 | 0 | 402 | 65 | 160550 | 6.84 | 1153.69 | 0.5926 | 1419.59 |
| Scandia | 10 | 0 | 403 | 49.75 | 122882.5 | 5.56 | 963.54 | 0.5765 | 990.83 |
| Scandia | 4 | 0 | 404 | 113 | 279110 | 6.40 | 1135.75 | 0.5635 | 1108.46 |
| Scandia | 7 | 0 | 405 | 63 | 155610 | 5.65 | 1004.12 | 0.5625 | 961.97 |
| Scandia | 8 | 0 | 406 | 63.5 | 156845 | 6.52 | 1105.86 | 0.5897 | 1346.77 |
| Scandia | 6 | 0 | 407 | 71.5 | 176605 | 6.68 | 1222.98 | 0.5460 | 997.77 |
| Scandia | 2 | 0 | 408 | 41.5 | 102505 | 5.99 | 1076.48 | 0.5564 | 932.88 |
| Scandia | 1 | 0 | 409 | 59 | 145730 | 5.92 | 1081.44 | 0.5475 | 1000.84 |
| Scandia | 3 | 0 | 410 | 80.25 | 198217.5 | 6.04 | 1099.24 | 0.5494 | 1004.87 |
| Scandia | 5 | 0 | 411 | 51 | 125970 | 6.37 | 1206.40 | 0.5280 | 1051.04 |
| Scandia | 4 | 0 | 501 | 89.5 | 221065 | 6.22 | 1090.32 | 0.5706 | 1202.86 |
| Scandia | 1 | 0 | 502 | 78.5 | 193895 | 6.19 | 1096.82 | 0.5643 | 1217.70 |
| Scandia | 10 | 0 | 503 | 46.5 | 114855 | 6.49 | 1234.53 | 0.5255 | 954.52 |
| Scandia | 5 | 0 | 504 | 75.5 | 186485 | 6.11 | 1078.96 | 0.5665 | 1254.14 |
| Scandia | 8 | 0 | 505 | 63 | 155610 | 5.38 | 1036.16 | 0.5192 | 788.44 |
| Scandia | 11 | 0 | 506 | 64 | 158080 | 5.69 | 1121.57 | 0.5071 | 691.68 |
| Scandia | 6 | 0 | 507 | 95.5 | 235885 | 6.00 | 1130.85 | 0.5302 | 813.44 |
| Scandia | 9 | 0 | 508 | 71 | 175370 | 5.20 | 979.94 | 0.5309 | 1035.37 |
| Scandia | 2 | 0 | 509 | 48.5 | 119795 | 6.25 | 1093.36 | 0.5715 | 1231.45 |
| Scandia | 3 | 0 | 510 | 63.25 | 156227.5 | 5.88 | 1159.33 | 0.5075 | 1010.05 |
| Scandia | 7 | 0 | 511 | 64 | 158080 | 5.57 | 942.79 | 0.5903 | 1344.32 |
| Hutchinson | 1 | 1 | 101 | 110.5 | 272935 | 4.40 | 1118.23 | 0.3937 | 504.30 |
| Hutchinson | 2 | 1 | 102 | 65.5 | 161785 | 6.19 | 1492.78 | 0.4145 | 739.67 |
| Hutchinson | 3 | 1 | 103 | 97 | 239590 | 4.08 | 854.30 | 0.4773 | 873.24 |
| Hutchinson | 4 | 1 | 104 | 105 | 259350 | 6.04 | 1166.10 | 0.5177 | 1013.45 |
| Hutchinson | 5 | 1 | 105 | 95 | 234650 | 5.52 | 979.50 | 0.5633 | 1359.22 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Hutchinson | 6 | 1 | 106 | 101.5 | 250705 | 5.58 | 1191.35 | 0.4685 | 843.84 |
| Hutchinson | 7 | 1 | 107 | 104.5 | 258115 | 6.37 | 1345.78 | 0.4731 | 829.75 |
| Hutchinson | 8 | 1 | 108 | 108 | 266760 | 5.25 | 986.90 | 0.5320 | 890.42 |
| Hutchinson | 10 | 1 | 109 | 60.5 | 149435 | 5.54 | 1004.58 | 0.5511 | 1676.78 |
| Hutchinson | 9 | 1 | 110 | 113 | 279110 | 4.93 | 1131.94 | 0.4357 | 554.86 |
| Hutchinson | 11 | 1 | 111 | 96.5 | 238355 | 6.23 | 1249.96 | 0.4983 | 698.25 |
| Hutchinson | 11 | 1 | 201 | 86 | 212420 | 4.89 | 1029.85 | 0.4752 | 1082.06 |
| Hutchinson | 4 | 1 | 202 | 76 | 187720 | 5.90 | 1423.83 | 0.4147 | 811.76 |
| Hutchinson | 3 | 1 | 203 | 75.25 | 185867.5 | 3.90 | 784.57 | 0.4968 | 1042.65 |
| Hutchinson | 1 | 1 | 204 | 101.5 | 250705 | 5.00 | 797.69 | 0.6265 | 1898.13 |
| Hutchinson | 7 | 1 | 205 | 70 | 172900 | 5.05 | 1103.84 | 0.4575 | 741.02 |
| Hutchinson | 5 | 1 | 206 | 97 | 239590 | 5.35 | 1179.61 | 0.4533 | 763.96 |
| Hutchinson | 8 | 1 | 207 | 102 | 251940 | 5.15 | 1006.56 | 0.5121 | 1335.99 |
| Hutchinson | 6 | 1 | 208 | 84.5 | 208715 | 5.38 | 1124.49 | 0.4785 | 1125.78 |
| Hutchinson | 10 | 1 | 209 | 55 | 135850 | 4.69 | 1093.70 | 0.4293 | 622.43 |
| Hutchinson | 2 | 1 | 210 | 59.5 | 146965 | 4.51 | 913.30 | 0.4943 | 1054.47 |
| Hutchinson | 9 | 1 | 211 | 91.5 | 226005 | 5.12 | 1149.79 | 0.4451 | 622.87 |
| Hutchinson | 2 | 1 | 301 | 50.5 | 124735 | 4.47 | 1026.88 | 0.4354 | 824.47 |
| Hutchinson | 4 | 1 | 302 | 78.5 | 193895 | 5.49 | 1118.37 | 0.4910 | 838.63 |
| Hutchinson | 3 | 1 | 303 | 68.75 | 169812.5 | 3.60 | 704.93 | 0.5113 | 1402.38 |
| Hutchinson | 1 | 1 | 304 | 68.5 | 169195 | 4.88 | 982.84 | 0.4967 | 948.69 |
| Hutchinson | 6 | 1 | 305 | 58 | 143260 | 5.65 | 1094.69 | 0.5164 | 1137.17 |
| Hutchinson | 11 | 1 | 306 | 81 | 200070 | 6.03 | 1117.17 | 0.5397 | 1228.19 |
| Hutchinson | 5 | 1 | 307 | 75 | 185250 | 5.76 | 1130.75 | 0.5092 | 1183.97 |
| Hutchinson | 9 | 1 | 308 | 64 | 158080 | 6.20 | 1119.94 | 0.5532 | 1183.21 |
| Hutchinson | 10 | 1 | 309 | 52.25 | 129057.5 | 4.94 | 854.90 | 0.5783 | 1847.20 |
| Hutchinson | 7 | 1 | 310 | 94 | 232180 | 4.94 | 859.41 | 0.5748 | 1514.06 |
| Hutchinson | 8 | 1 | 311 | 90.5 | 223535 | 5.88 | 1019.33 | 0.5769 | 1524.42 |

**Table A.2 Raw Yield Data 2015**

| Site | Treatment | Irrigation | plot | Stand Count | Plants hectare $^{-1}$ | Grain Yield (Mg ha$^{-1}$) | Total Biomass (g m$^{-2}$) | Harvest Index (%) | Grain Number |
|---|---|---|---|---|---|---|---|---|---|
| Ashland | 1 | 1 | 101 | 73 | 180310 | 6.706769 | 2695.451 | 0.42703 | 1712.23 |
| Ashland | 2 | 1 | 102 | 45.5 | 112385 | 5.905633 | 2162.946 | 0.478031 | 2360.23 |
| Ashland | 3 | 1 | 103 | 54.75 | 135232.5 | 6.734871 | 1630.71 | 0.468138 | 1365.40 |
| Ashland | 4 | 1 | 104 | 60 | 148200 | 7.357227 | 2253.2 | 0.445773 | 2029.95 |
| Ashland | 5 | 1 | 105 | 66.5 | 164255 | 5.933902 | 1648.05 | 0.462891 | 1513.59 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Ashland | 6 | 1 | 106 | 70.5 | 174135 | 6.975322 | 1846.252 | 0.458375 | 2063.67 |
| Ashland | 7 | 1 | 107 | 59.5 | 146965 | 6.996592 | 2356.731 | 0.406801 | 1930.29 |
| Ashland | 8 | 1 | 108 | 60.5 | 149435 | 7.552075 | 1617.152 | 0.405524 | 1379.07 |
| Ashland | 9 | 1 | 109 | 78.5 | 193895 | 7.540682 | 1414.39 | 0.435952 | 1671.35 |
| Ashland | 10 | 1 | 110 | 31.25 | 77187.5 | 6.107272 | 1573.698 | 0.52793 | 2563.50 |
| Ashland | 11 | 1 | 111 | 64.5 | 159315 | 6.567448 | 2179.659 | 0.387716 | 1078.95 |
| Ashland | 1 | 1 | 201 | 56.5 | 139555 | 8.623026 | 2150.899 | 0.448694 | 2256.78 |
| Ashland | 10 | 1 | 202 | 16.25 | 40137.5 | 8.022359 | 1341.131 | 0.48298 | 2266.55 |
| Ashland | 6 | 1 | 203 | 96 | 237120 | 6.552261 | 1453.346 | 0.5074 | 2042.58 |
| Ashland | 5 | 1 | 204 | 76 | 187720 | 6.325178 | 1667.505 | 0.409564 | 1621.48 |
| Ashland | 11 | 1 | 205 | 66.5 | 164255 | 5.834109 | 1239.361 | 0.471663 | 1516.82 |
| Ashland | 9 | 1 | 206 | 64.5 | 159315 | 7.469488 | 2889.735 | 0.451301 | 1831.00 |
| Ashland | 8 | 1 | 207 | 55.5 | 137085 | 6.425729 | 923.589 | 0.453716 | 970.79 |
| Ashland | 7 | 1 | 208 | 59 | 145730 | 6.737574 | 1786.013 | 0.515453 | 2242.24 |
| Ashland | 3 | 1 | 209 | 36.5 | 90155 | 6.911123 | 1223.082 | 0.451864 | 2641.55 |
| Ashland | 2 | 1 | 210 | 60.5 | 149435 | 5.592631 | 1573.357 | 0.503545 | 2245.41 |
| Ashland | 4 | 1 | 211 | 74 | 182780 | 7.118482 | 2147.497 | 0.389319 | 1168.85 |
| Ashland | 7 | 1 | 301 | 81 | 200070 | 7.782824 | 1711.085 | 0.379884 | 1280.89 |
| Ashland | 2 | 1 | 302 | 26.5 | 65455 | 7.62777 | 1210.926 | 0.47001 | 1776.17 |
| Ashland | 3 | 1 | 303 | 47.75 | 117942.5 | 6.622797 | 1400.224 | 0.507852 | 2101.28 |
| Ashland | 5 | 1 | 304 | 64.5 | 159315 | 6.727943 | 1293.466 | 0.446446 | 1143.92 |
| Ashland | 11 | 1 | 305 | 71 | 175370 | 6.597781 | 1426.871 | 0.456716 | 1242.11 |
| Ashland | 8 | 1 | 306 | 60.5 | 149435 | 6.627908 | 1528.348 | 0.545918 | 1416.64 |
| Ashland | 4 | 1 | 307 | 58 | 143260 | 6.917393 | 2386.309 | 0.454849 | 2140.56 |
| Ashland | 9 | 1 | 308 | 59 | 145730 | 5.526263 | 1641.797 | 0.443933 | 2021.16 |
| Ashland | 1 | 1 | 309 | 65.5 | 161785 | 6.649265 | 1889.591 | 0.406415 | 964.73 |
| Ashland | 10 | 1 | 310 | 23 | 56810 | 4.968287 | 1213.379 | 0.501431 | 2709.21 |
| Ashland | 6 | 1 | 311 | 87.5 | 216125 | 8.030984 | 1881.677 | 0.381762 | 918.16 |
| Ottawa | 1 | 0 | 101 | 89.5 | 221065 | 5.520539 | 1480.63 | 0.483658 | 1357.27 |
| Ottawa | 2 | 0 | 102 | 44.5 | 109915 | 5.91985 | 1067.819 | 0.456128 | 1445.88 |
| Ottawa | 3 | 0 | 103 | 88.5 | 218595 | 5.693522 | 1093.686 | 0.44055 | 1029.54 |
| Ottawa | 4 | 0 | 104 | 96.5 | 238355 | 5.445841 | 1252.507 | 0.419526 | 871.56 |
| Ottawa | 5 | 0 | 105 | 85.5 | 211185 | 5.748329 | 1591.377 | 0.463285 | 1455.82 |
| Ottawa | 6 | 0 | 106 | 94.5 | 233415 | 5.867275 | 1419.201 | 0.399003 | 909.14 |
| Ottawa | 7 | 0 | 107 | 92 | 227240 | 5.689444 | 1400.36 | 0.486405 | - |
| Ottawa | 8 | 0 | 108 | 93 | 229710 | 6.248608 | 1226.561 | 0.455262 | 1175.25 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Ottawa | 9 | 0 | 109 | 94.5 | 233415 | 4.377509 | 1245.849 | 0.471548 | 1124.74 |
| Ottawa | 10 | 0 | 110 | 47.5 | 117325 | 5.393638 | 1079.452 | 0.524519 | 2051.53 |
| Ottawa | 11 | 0 | 111 | 90 | 222300 | 5.172547 | 1058.986 | 0.442464 | 1151.71 |
| Ottawa | 6 | 0 | 201 | 89 | 219830 | 5.801437 | 1152.747 | 0.480903 | 989.62 |
| Ottawa | 5 | 0 | 202 | 93.5 | 230945 | 5.589318 | 1227.602 | 0.493196 | 1198.37 |
| Ottawa | 10 | 0 | 203 | 47.25 | 116707.5 | 4.902337 | 941.044 | 0.477181 | 1606.88 |
| Ottawa | 11 | 0 | 204 | 85 | 209950 | 5.53003 | 1038.686 | 0.442941 | 748.39 |
| Ottawa | 2 | 0 | 205 | 48.5 | 119795 | 5.88157 | 1152.938 | 0.541478 | 2369.04 |
| Ottawa | 7 | 0 | 206 | 94 | 232180 | 5.459043 | 1079.247 | 0.463246 | 952.90 |
| Ottawa | 1 | 0 | 207 | 89.5 | 221065 | 5.165548 | 1393.531 | 0.463213 | 1383.95 |
| Ottawa | 9 | 0 | 208 | 92.5 | 228475 | 5.231997 | 1508.451 | 0.395161 | 780.38 |
| Ottawa | 4 | 0 | 209 | 90.5 | 223535 | 4.767434 | 1082.859 | 0.441062 | 1126.54 |
| Ottawa | 3 | 0 | 210 | 92.75 | 229092.5 | 4.882832 | 1031.638 | 0.408911 | 752.31 |
| Ottawa | 8 | 0 | 211 | 91.5 | 226005 | 5.201207 | 1182.557 | 0.45195 | 921.89 |
| Ottawa | 1 | 0 | 301 | 87 | 214890 | 5.527532 | 1305.463 | 0.470189 | 1233.97 |
| Ottawa | 7 | 0 | 302 | 85.5 | 211185 | 5.84626 | 1375.163 | 0.496466 | 1302.45 |
| Ottawa | 10 | 0 | 303 | 44.5 | 109915 | 5.165587 | 1103.595 | 0.50344 | 2174.91 |
| Ottawa | 4 | 0 | 304 | 82.5 | 203775 | 5.253377 | 1044.395 | 0.432139 | 828.92 |
| Ottawa | 5 | 0 | 305 | 88 | 217360 | 5.733511 | 1478.102 | 0.44706 | 1411.98 |
| Ottawa | 6 | 0 | 306 | 88 | 217360 | 6.603898 | 1193.966 | 0.395246 | 725.64 |
| Ottawa | 2 | 0 | 307 | 45.5 | 112385 | 6.466788 | 1349.886 | 0.503052 | 2027.81 |
| Ottawa | 9 | 0 | 308 | 88 | 217360 | 5.214683 | 1084.866 | 0.423543 | 1128.38 |
| Ottawa | 11 | 0 | 309 | 87 | 214890 | 5.689119 | 1226.55 | 0.5213 | 1347.30 |
| Ottawa | 3 | 0 | 310 | 84.5 | 208715 | 5.366814 | 1153.401 | 0.483805 | 1253.89 |
| Ottawa | 8 | 0 | 311 | 92.5 | 228475 | 5.370884 | 1034.502 | 0.454969 | 959.77 |
| Scandia | 1 | 0 | 101 | 84.5 | 208715 | 4.077954 | 973.9011 | 0.43445 | 1279.94 |
| Scandia | 2 | 0 | 102 | 41.5 | 102505 | 5.468456 | 995.3313 | 0.493118 | 2157.06 |
| Scandia | 3 | 0 | 103 | 83.5 | 206245 | 6.466746 | 1139.515 | 0.458336 | 1566.05 |
| Scandia | 4 | 0 | 104 | 85.5 | 211185 | 9.297665 | 1441.733 | 0.535484 | 2257.56 |
| Scandia | 5 | 0 | 105 | 85 | 209950 | 5.341859 | 1202.804 | 0.356417 | 786.91 |
| Scandia | 6 | 0 | 106 | 73.5 | 181545 | 8.045278 | 1161.831 | 0.448791 | 1854.44 |
| Scandia | 7 | 0 | 107 | 63 | 155610 | 6.262466 | 1370.662 | 0.415005 | 1442.05 |
| Scandia | 8 | 0 | 108 | 77.5 | 191425 | 6.715163 | 1556.24 | 0.444756 | 1233.91 |
| Scandia | 9 | 0 | 109 | 76.5 | 188955 | 7.325324 | 1263.731 | 0.489826 | 1605.05 |
| Scandia | 10 | 0 | 110 | 31.25 | 77187.5 | 8.569098 | 1491.624 | 0.56646 | 2763.13 |
| Scandia | 11 | 0 | 111 | 66.5 | 164255 | 5.470297 | 994.1366 | 0.429931 | 1198.42 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Scandia | 7 | 0 | 201 | 81.5 | 201305 | 7.599928 | 1605.531 | 0.520305 | 1841.70 |
| Scandia | 10 | 0 | 202 | 43 | 106210 | 7.807454 | 1793.974 | 0.463088 | 907.96 |
| Scandia | 8 | 0 | 203 | 153 | 377910 | 8.618697 | 1451.187 | 0.501707 | 1325.76 |
| Scandia | 2 | 0 | 204 | 68 | 167960 | 6.018405 | 1680.013 | 0.393975 | 1351.43 |
| Scandia | 5 | 0 | 205 | 70 | 172900 | 8.08928 | 1775.027 | 0.498926 | 2324.44 |
| Scandia | 4 | 0 | 206 | 72.5 | 179075 | 9.256345 | 2057.777 | 0.52141 | 2526.80 |
| Scandia | 9 | 0 | 207 | 69.5 | 171665 | 5.980515 | 1414.351 | 0.434832 | 1290.98 |
| Scandia | 11 | 0 | 208 | 35 | 86450 | 5.502495 | 1736.243 | 0.468805 | 2545.40 |
| Scandia | 3 | 0 | 209 | 35.25 | 87067.5 | 7.929765 | 1121.276 | 0.490234 | 1359.60 |
| Scandia | 6 | 0 | 210 | 62.5 | 154375 | 8.711032 | 1880.381 | 0.569402 | 3046.14 |
| Scandia | 1 | 0 | 211 | 73.5 | 181545 | 7.834576 | 1538.146 | 0.49461 | 1453.61 |
| Scandia | 6 | 0 | 301 | 85.5 | 211185 | 6.195705 | 1382.47 | 0.444912 | 1115.40 |
| Scandia | 1 | 0 | 302 | 88 | 217360 | 7.635063 | 1593.931 | 0.455512 | 1399.72 |
| Scandia | 10 | 0 | 303 | 40.75 | 100652.5 | 9.119034 | 1298.49 | 0.527171 | 2458.40 |
| Scandia | 9 | 0 | 304 | 79.5 | 196365 | 8.308063 | 1802.427 | 0.478855 | 1865.29 |
| Scandia | 2 | 0 | 305 | 25 | 61750 | 5.708152 | 723.8989 | 0.496626 | 2264.43 |
| Scandia | 8 | 0 | 306 | 78.5 | 193895 | 8.695066 | 2036.711 | 0.502763 | 1812.52 |
| Scandia | 11 | 0 | 307 | 71.5 | 176605 | 6.360377 | 863.3103 | 0.437526 | 1034.47 |
| Scandia | 5 | 0 | 308 | 72.5 | 179075 | 6.986544 | 1343.252 | 0.447564 | 1484.71 |
| Scandia | 4 | 0 | 309 | 76 | 187720 | 9.338676 | 2240.519 | 0.524206 | 1995.87 |
| Scandia | 3 | 0 | 310 | 85.75 | 211802.5 | 8.982039 | 1873.04 | 0.500745 | 1833.32 |
| Scandia | 7 | 0 | 311 | 56 | 138320 | 7.731445 | 1320.372 | 0.394696 | 1185.54 |
| Topeka | 1 | 1 | 101 | 87.5 | 216125 | 9.558173 | 1543.447 | 0.422547 | 1079.57 |
| Topeka | 2 | 1 | 102 | 50.5 | 124735 | 9.331474 | 1670.083 | 0.486649 | 2365.86 |
| Topeka | 3 | 1 | 103 | 94 | 232180 | 10.48569 | 1967.02 | 0.503207 | 1846.32 |
| Topeka | 4 | 1 | 104 | 92 | 227240 | 10.02718 | 2668.675 | 0.474519 | 1564.64 |
| Topeka | 5 | 1 | 105 | 98 | 242060 | 8.307478 | 1620.911 | 0.410776 | 1214.83 |
| Topeka | 6 | 1 | 106 | 91 | 224770 | 9.170434 | 1781.848 | 0.422045 | 1255.78 |
| Topeka | 7 | 1 | 107 | 95.5 | 235885 | 8.771559 | 1500.564 | 0.412992 | 1333.25 |
| Topeka | 8 | 1 | 108 | 94 | 232180 | 8.686589 | 2356.96 | 0.433305 | 1416.95 |
| Topeka | 9 | 1 | 109 | 94 | 232180 | 8.937642 | 1650.909 | 0.399839 | 961.94 |
| Topeka | 10 | 1 | 110 | 47.5 | 117325 | 10.37359 | 1990.474 | 0.516372 | 2872.79 |
| Topeka | 11 | 1 | 111 | 87.5 | 216125 | 9.818112 | 1724.917 | 0.474112 | 1239.14 |
| Topeka | 6 | 1 | 201 | 93 | 229710 | 9.051452 | 1750.386 | 0.396731 | 1012.10 |
| Topeka | 7 | 1 | 202 | 90 | 222300 | 9.383763 | 1754.005 | 0.412198 | 1320.98 |
| Topeka | 3 | 1 | 203 | 91.25 | 225387.5 | 9.132713 | 1850.838 | 0.4118 | 1175.41 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Topeka | 1 | 1 | 204 | 94 | 232180 | 9.242108 | 2044.478 | 0.445397 | 1439.90 |
| Topeka | 4 | 1 | 205 | 91.5 | 226005 | 10.3473 | 1643.458 | 0.425065 | 1040.30 |
| Topeka | 9 | 1 | 206 | 90.5 | 223535 | 9.576129 | 1672.272 | 0.446607 | 1309.04 |
| Topeka | 2 | 1 | 207 | 44.5 | 109915 | 9.062558 | 1615.255 | 0.514447 | 3046.06 |
| Topeka | 11 | 1 | 208 | 92.5 | 228475 | 9.436204 | 1507.619 | 0.392751 | 824.29 |
| Topeka | 5 | 1 | 209 | 96 | 237120 | 10.02754 | 1762.179 | 0.433171 | 1337.48 |
| Topeka | 10 | 1 | 210 | 49 | 121030 | 10.29788 | 1795.637 | 0.531895 | 3181.02 |
| Topeka | 8 | 1 | 211 | 91.5 | 226005 | 9.431839 | 1611.475 | 0.473871 | 1471.09 |
| Topeka | 9 | 1 | 301 | 88.5 | 218595 | 9.447959 | 2174.518 | 0.402438 | 1139.55 |
| Topeka | 2 | 1 | 302 | 48.5 | 119795 | 9.495658 | 1744.278 | 0.494551 | 2877.36 |
| Topeka | 10 | 1 | 303 | 49.25 | 121647.5 | 10.3482 | 1632.672 | 0.525261 | 2455.12 |
| Topeka | 4 | 1 | 304 | 94 | 232180 | 10.11568 | 1983.704 | 0.447832 | 1474.87 |
| Topeka | 5 | 1 | 305 | 95 | 234650 | 9.623044 | 1330.858 | 0.463787 | 1423.06 |
| Topeka | 7 | 1 | 306 | 91.5 | 226005 | 9.079645 | 1596.938 | 0.450645 | 1524.43 |
| Topeka | 11 | 1 | 307 | 98.5 | 243295 | 9.205029 | 1689.382 | 0.455816 | 1298.07 |
| Topeka | 8 | 1 | 308 | 90 | 222300 | 9.812649 | 1632.863 | 0.438874 | - |
| Topeka | 6 | 1 | 309 | 91 | 224770 | 9.561617 | 1726.935 | 0.413863 | 1064.80 |
| Topeka | 3 | 1 | 310 | 87.75 | 216742.5 | 9.568043 | 1596.796 | 0.464356 | 1428.68 |
| Topeka | 1 | 1 | 311 | 91.5 | 226005 | 9.698741 | 1504.243 | 0.450623 | 1243.62 |

# Appendix B - SAS Code

**Table B.1 SAS code for yield, biomass and nutrient uptake analysis**

```
proc sort;
by Site irr trt row;
run;

proc mixed data=nutrients2014 covtest cl plots=studentpanel;
class    Site Row Trt;
model    N = Site|Trt;
random   Row;
lsmeans  Site|Trt / pdiff Alpha=0.05;
ods output diffs=ppp lsmeans=mmm;
run;


%include 'C:\Users\lab\Desktop\pdmix800.sas';
%pdmix800(ppp,mmm,alpha=.05,sort=yes);
run;
```