CORN GRAIN YIELD RESPONSE TO NITROGEN RATE AND PLANT POPULATION IN FULL AND DOUBLE-CROP SYSTEMS

By

RHIANNON NICHOLE WYMA

Bachelor of Science in Plant & Soil Sciences

Oklahoma State University

Stillwater, Oklahoma

2020

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2022

CORN GRAIN YIELD RESPONSE TO NITROGEN

RATE AND PLANT POPULATION IN FULL AND

DOUBLE-CROP SYSTEMS

Thesis Approved:

Dr. Josh Lofton

Thesis Advisor

Dr. Brian Arnall

Dr. Lisa Fultz

ACKNOWLEDGEMENTS

Successfully completing this research project and thesis report would not have been possible without the abundance of support from faculty advisors, colleagues, friends, and family.

To my research advisor, Dr. Josh Lofton, without your patience and the confidence you instilled in me throughout this process I would not be writing this admission of gratitude. Despite an unprecedented graduate school career on account of COVID and my own personal interferences, you never gave up on me. Beyond the bounds of academic advisement, you went further in helping me navigate the emotional pitfalls of becoming an adult in a high-pressure environment. That was one of the keys to helping me finish. Thank you for not only encouraging me in my future aspirations, but also unflinchingly accepting my decision to deviate from traditional career pathways. Your insight is invaluable to me and I will carry a lot of these lessons with me forever. A measly paragraph could never contain the gratitude I hold for you, thank you.

The next people I would like to acknowledge are Dr. Brian Arnall and Dr. Lisa Fultz. Like Dr. Lofton, your endless patience cannot go unrecognized. Both of your willingness to work with me on short notice and the grace you afforded where I struggled with time management is another primary reason I am able to finish this degree. To Dr. Fultz, thank you so much for your interest in furthering my education and providing support and understanding even as your portion of the project was not included in the defense. To Dr. Arnall, I have a special note – the way you have managed to gain a deeper understanding of how students really operate on a personal level is exemplary and admirable. Our meeting prior to my defense date was another key to finishing. It was a pivotal moment at a critical time – thank you so much for seeing me and believing in me.

Another important group I would like to acknowledge are my team at the Peanut Lab that have been here since day one of my research. Not only serving as coworkers, they will have a place at my table forever as friends: Matthew Drendel, Chase Harris, Josie Rice, Lance Huftalin, Anna Ballagh, and Issac Rhodes. You all were literally what stood between me and dropping out and losing my mind. I will be forever grateful not only for the research assistance extending from field work to my thesis, but for the way you never allowed me to give up. I made memories with all of you that will be with me forever, and I love you all dearly.

My field trials would not have been possible if it weren't for the lending support of ?? at Oklahoma Agricultural Experiment Stations in Bixby and Perkins, Oklahoma. Thank you to them for allowing me space to conduct my research, and a special shout out to Butch for some assistance in-season management. A huge thank you to Oklahoma State University Plant and Soil Sciences department, Oklahoma Fertilizer Checkoff, and Dr. Josh Lofton for funding my research.

The final acknowledgement rests in the hands of my blood related and found family. To my best friends and sisters, Hannah Lindell and Kylie Johnson, thank you for the guidance throughout my time spent in graduate school. You both were vital to establishing the groundwork that got me to this point – academically and personally. You laughed and cried with me, encouraged and believed in me, and fostered confidence in myself that I have not yet known. There aren't words written in any terrestrial language that describe what our friendship means to me. You were the final key to my success.

Name: RHIANNON NICHOLE WYMA

Date of Degree: DECEMBER, 2022

Title of Study: CORN GRAIN YIELD RESPONSE TO NITROGEN RATE AND PLANT POPULATION IN FULL AND DOUBLE-CROP SYSTEMS

Major Field: PLANT AND SOIL SCIENCES

Abstract: Interest in incorporating non-traditional crops like corn (*Zea mays*) into double-crop rotations in Oklahoma has increased recently. Work in other crops suggest differences in management between full season and double-crop, though there is limited information available on corn as a constituent of the double-crop system. As two of the most expensive inputs for corn production, optimizing nitrogen application and plant populations is critical for high-risk double-crop systems. One trial was conducted over two years at three locations to determine grain yield response to these factors and assess best management practices for a double-crop wheat-corn rotation.

The study was designed to evaluate the differences between grain yield and physiological yield characteristics as they were affected by nitrogen rate and plant population treatments. Tests were conducted in 2020 and 2021 in Oklahoma. The yield characteristics evaluated were grain N (%), average kernel row^{-1}, average row cob^{-1}, kernel number, kernel weight, and cob weight. The results indicate lower yield performance at plant populations exceeding 57,000 plants ha^{-1}, though not by significant margins. This phenomenon may be explained by competition-induced stress at high plant populations. Varying responses to N rate was recorded at each location, though the best performance was recorded between 82.5 and 110 kg ha^{-1}. Though statistical analysis between full season and double-crop trials was not performed, preliminary results indicate lower N requirement for the double-crop. This may be explained by reduced biomass and dry matter accumulation fostered by the short double-crop season. Average kernel row^{-1} was significantly impacted by plant population consistently, while N rate had limited effect.

It was concluded that grain yield was impacted by the combined effects of plant population and N rate, suggesting optimal management of both aspects is critical. Excessive plant populations create high levels of resource competition resulting in yield reductions. A result of rapid maturation of corn in this system is reduced biomass where less time is spent in vegetative growth stages. These factors alter the capability of corn to utilize N resources.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION AND REVIEW OF LITERATURE

Origin and History of Corn Production

Corn (*Zea mays)* is a warm season grass crop theorized to have origins in production stemming from southwestern or south-central Mexico around 8000 to 5000 BC (Troyer, 1999). Before evolving into the sizable bright yellow cobs of today, it is suspected to have begun as a humble wild grain known as teosinte (*Zea)*. It is the closest undomesticated relative of maize; this discovery by geneticists is largely responsible for the idea of the center of origin (Chen, 2020). A testament to the selective breeding practices of ancient farmers, these two crops are almost unrecognizable as relatives from a morphological standpoint. Teosinte has many lateral leaves capable of producing tassels and two-ranked ears boasting very few kernels. After centuries of natural selection, selective breeding, and more recent genetic modification, modern corn produces one or two primary lateral leaves and cobs that can surpass hundreds of kernels. (Chen, 2020) These crop-based improvements are not the only factor contributing to the yield potential of corn production today.

In current systems, corn is primarily grown for grain and is the third most produced grain crop in the United States. Across the globe, average corn production surpasses 1 billion metric tons annually (Garcia-Lara and Saldivar, 2019; Ma and Biswas 2015). Corn is grown for biofuel production, animal feed, and grain with products ranging from cooking oil to industrial alcohol available worldwide. Cereal grains are the food group responsible for meeting almost half of the caloric requirement for humans (Awika, 2020). Ninety-four percent of all cereal consumption is comprised of wheat, rice, and corn

(Ranum et al., 2014). As one of the most widely utilized commodities, extensive work has been done to improve corn varieties and the agronomic practices used to produce it. Despite the current production of record-breaking yields, research into corn genetics and systems remains necessary as the population and concern for climate change continue to increase. To compensate for these factors, it has been estimated that global corn production needs to increase by 15% over the next 20 years (Amanullah and Shah Fahad, 2018).

United States

The United States history with corn dates to the founding of the nation when the first settlers were taught to cultivate open-pollinated varieties by the indigenous people of the area. The first corn yield estimates were recorded and published by the USDA in 1866, largely maintaining yields at approximately 1,600 kg ha^{-1} until the late 1930's (Nielsen, 2022). Rapid, notable yield improvements were seen after this point with the introduction of hybrid technology. The hybrid varieties were adopted quickly by producers just coming out of the dust bowl as news of their drought tolerance spread (Nielsen, 2022). A historical review of crop yields conducted in three low yield (Kentucky, Missouri, and Tennessee) and three high yield (Indiana, Illinois, Iowa) states noted after hybrid technology was adopted, another significant jump in average yield began in the 1950's (Egli, 2008). The introduction of high-input agriculture specifically in the form of synthetic N fertilizers, pesticides, and higher seeding rates drove up the mean yield of corn 3.3% per year in the first few decades following (Egli, 2008). Yield increases did not sustain at this rate but still increased an approximately 1.8% per year in the years following. In 2005, the USDA reported an average corn grain yield of 9116 kg ha^{-1}, (Egli, 2008), nearly 1.2% increase on average per year since the 1930's. In 2020, the United States harvested approximately 34.2 million hectares of corn for grain, a 2% increase from the 2019 season (NASS-USDA, 2021).

Corn Production in Oklahoma

Like the rest of the United States, Oklahoma corn production history also begins with Indigenous Americans and the forced relocation of their people to Oklahoma territory in the early-mid 1800s (Drass, 2008). After negotiating land allotment with the Cherokee nation in 1891, the federal government opened the northern portion of Oklahoma known as the Cherokee Outlet for non-native homesteaders to settle and farm. This event kickstarted the rapid proliferation of corn production across the modern boundaries of Oklahoma as settlers from the eastern half of the United States established their production practices in the area (Kidwell, n.d.) Once corn production and communication between producers in the two areas was established, the comparatively limited yield potential of the semiarid Cherokee Outlet became obvious (Travis and Robb, 2009). The same year, the first Agricultural Experiment Station in Oklahoma was established in Stillwater alongside the Agricultural and Mechanical College following the enactment of the Hatch Act in March of 1887 (Gilmore, 1967). The first research in corn was performed at the station occurred a year after its establishment in 1892, including a corn trial with 44 varieties (Glimore, 1967). Producers in the west (encompassing the land area of modern-day Greer, Harmon, Jackson, and a portion of Beckham counties) alone harvested approximately 1,004,000 kg total in 1890 (Travis and Robb, 2009). By 1915 corn had reached all corners of Oklahoma territory, increasing total state production significantly to 6,358,600 kg (Travis and Robb, 2009). This period of success was halted when the Midwest entered devastating drought conditions during the Dust Bowl. As reference, the state yield total for 1924 and 1929 respectively were 2,990,000,000 kg ha^{-1} and 2,820,000,000 kg ha^{-1} (Census of Agriculture, 1940). In this five year period, yields fluctuated by approximately 13.4%. After the Dust Bowl began production dropped by 58.4% down to 543,7000,000 kg ha^{-1} in 1934 (Census of Agriculture, 1940). Yields had nearly made a full recovery by 1939 increasing by 56.4% to 1,593,000,000 kg ha^{-1}, placing the state at 22 in corn production for the United States (Census of Agriculture, 1940). Though the Midwest experienced an exodus of settlers during and after the Dust Bowl, many chose to stay. After surviving another drought in the 50s, the need for corn production was bolstered by the introduction of feedlots by the 1970's (Travis and Robb, 2009). Today Oklahoma is ranked 28 in the nation for corn production, and the state total production in 2021 was reported at 2,782,000,000 kg ha^{-1} (NASS/USDA, 2021).

Nitrogen Management in Corn

Agriculturalists today are planting at higher populations and applying more nitrogen fertilizer than any point in history. The trend can be partially explained by human population growth driving increased commodity demand and better yielding corn hybrids (Cao, Lu, and Yu, 2018). As the yield potential of the hybrids are increasing, so is the need for N (Noor 2017). As N is considered one of the most yield limiting factors in corn, it has become one of the most expensive inputs encountered by producers (Sawyer and Nafziger, 2006). Between 2002 and 2008 the cost of N increased by 10% every year (Williamson, 2011). By 2008, the price of N exceeded that of corn (Williamson, 2011). The decade since has seen several oscillations in the market, none more significant than between 2020 and 2021. Anhydrous ammonia was listed at $487 per ton in 2020; by October 2021, the price exceeded $1,000 (Schnitkey, et al., 2022). Farmer-paid prices in Illinois continued to rise over the next four months to $1,516 per ton in March 2022 (Schnitkey, et al., 2022). Besides staggering input costs, the environmental implications of excess N application necessitate further research into nutrient management optimization. The century post-introduction of the Haber-Bosch method of synthetic fertilizer production in 1908 allowed humans to produce reactive N at double the rate of naturally occurring N fixation (Sutton, et al., 2011). Meeting consumer needs without this process would have been impossible, but it is also ground zero for the trends in overapplication. Direct consequences to human health like eutrophication, nitrous oxide emissions, and potable water pollution are only a few products of excess N in the environment (Erisman, et al., 2013). The volatile state of the market coupled with these environmental concerns drive the importance of N management.

Nitrogen is an important essential nutrient for plant growth and plays several important roles throughout their life cycle. It is a constituent of chlorophyll, making it necessary for photosynthetic processes (Buchholz, 2022). N is also involved in protein production, extending to the consumable grain and enzymes in the roots that assist with nutrient uptake (Buchholz, 2022). Limited N availability is often indicated by chlorosis of older leaf tissue along the margin, with lower biomass and leaf size relative to plants in more favorable conditions (Ciampitti and Vyn, 2010). Chlorophyll reduction and smaller leaf surface area serve to inhibit the efficacy of light capture during photosynthesis. This interferes with ATP production, lowering the amount of energy available for dry matter accumulation that translates to grain yield (Ciampitti and Vyn, 2010). In maize specifically, dry matter accumulation improves with consistent leaf carbon exchange and chlorophyll content (Ding, et al., 2005). The carbon exchange rate is related to leaf N concentration as it is partitioned for various uses within the plant (Echarte, Rothstein, and Tollenaar, 2008). The use of leaf N is dictated by available light, the ratio of red to far red light, and N content in the soil (Echarte, Rothstein, and Tollenaar, 2008).

Though the total N available for uptake is ultimately important, it is also crucial to manage the timing of application to ensure adequate N at critical points. By the time corn has produced a quarter of its final biomass, approximately 50% of the total N uptake process will have been completed (Davies, Coulter, and Pagliari, 2020). Another critical time comes at silking when the number of kernels is determined. Stress during this stage (nutrient or otherwise) may result in kernel abortion and a reduction in final grain yield (Adrade, et al., 1999). One approach suggested to improve NUE and ensure adequate nutrient availability at critical stages is a split application of fertilizer. Varying results (mostly site specific) are found in literature with respect to the effect of split application on grain yield. In Iowa, Jaynes (2013) reported no considerable difference in grain yield between a single application at the beginning of the season and the split method at V2 and V6 or V12. Corroborated by an earlier study conducted in Canada, no significant gain was seen over a three-year period due to timing alone (Drury, et al., 2012). Oppositely, Randall, Vetsh, and Huffman (2003) found split application increased grain yield up to 10% on a poorly drained Mollisol. Similarly, N deficiency during critical stages in soil with low residual N was mitigated by 40/60 application at planting and V8, minimizing early season losses (Randall, Vetsch, and Huffman, 2003). Maximizing the efficiency of N use is case-specific. Nitrogen availability and losses from the system are controlled by multiple factors, from rainfall accumulation/event frequency, soil type, rate, and timing (Davies, Coulter, and Pagliari, 2020). Bennet, et al. (1989) evaluated how water and N interact to affect grain yield, biomass accumulation, and N uptake in corn. Observing no response from any of these parameters in high or low N environments where severe water stress was imposed, they concluded elevated water stress reduced the efficiency of N uptake and minimized yield response to N. Keeping that in mind, there is no single answer for the best N management practice for corn. The overall goal producers are looking to achieve are reduced losses and optimized crop uptake (Davies, Coulter, and Pagliari, 2020).

Plant Population for Full Season Corn

Like N application rates, seeding rates and plant populations for corn have increased over time (Bernhard and Below, 2020). Plant population is defined differently from seeding rate. The former refers to the number of whole plants in a given area, while the latter refers to the actual number of seeds planted in the area (Collins, 2016). The seeding rate will always be higher than the plant population, but the relationship is proportional in that as the seeding rate increases, so will the plant population. However, the degree to which the plant population increases is dependent on the conditions provided by the field and the live seed percentage of the variety (Collins, 2016). This caveat is critical for producers to keep in mind when making planting decisions, as the optimum achievable yield will be different depending on the location and abiotic/biotic factors (rainfall/temperature/pest pressure). Rising production costs extending to seed price leave little room for error to ensure a positive return from the system. Fluctuations in seed cost over time in the U.S. include an average increase of \$0.46 ha^{-1} $year^{-1}$ between 1975 and 2005 (Schnitkey, Swanson, and Paulson, 2021). After 2006, the average rate of seed cost growth increased to \$2.60 $hectares^{-1}$ $year^{-1}$ resulting in a peak at \$41 $hectare^{-1}$ in 2015 (Schnitkey, Swanson, and Paulson, 2021). Though a marginal decline to \$37 was recorded from 2015 to 2020, the trend reversed again and is expected to continue to increase through 2022 (Schnitkey, Swanson, and Paulson, 2021).

Corn yields today are achievable for multiple reasons, not the least of which being historically high planting populations. The upward trend originates in the 1930's with the introduction of hybrid corn varieties produced via traditional breeding practices. Higher seeding rates at planting have been further correlated with the integration of genetically engineered seed (Saavos, et al., 2021). The first genetically modified corn seed hit the market in 1996. These varieties could exhibit up to three targeted traits within a single plant (Saavos, et al., 2021). Targeted traits may include but are not limited to herbicide and drought tolerance, and insect or disease resistance (Saavos, et al., 2021). In the years leading up to 2000, corn yields in the United States were improving by an average of 115 kg ha^{-1} $year^{-1}$ (Troyer, 2000). Duvick (2005) contributes the increase to the interaction of an elevated understanding of management practices (nutrient management/plant population/tillage) and genetic improvements. Lending to the current success of high populations, modern corn hybrids boast lodging resistance, drought/pest tolerance, and better NUE (Duvick, 2005).

Higher populations reduce spacing between plants and can result in resource competition. Recent research conducted in Illinois compared grain yield of four populations: 94,000, 109,000, 124,000, and 139,000 plants ha^{-1}. (Bernhard and, Below 2020). For each population there were subplots evaluating the effect of 51 cm versus 76 cm row spacing. The researchers recorded the highest yield (18.5 Mg ha^{-1}) from the treatment planted on 51 cm rows at 109,000 plants ha^{-1} (Bernhard and, Below 2020). It was noted that plots with narrower row spacing exhibited more shoot biomass reducing crowding stress. This observation led to the conclusion that the phenotypic alterations that occurred in response to the closer row spacing allowed the crop to thrive at higher populations (Bernhard and, Below 2020).

Double-Crop Management and Considerations

As the demand for agricultural commodities increases, the conversation surrounding the integration of double-crop systems has been gaining traction. In the past, agriculturalists have relied heavily on cropland expansion to increase productivity (Borchers et al., 2014). Between

2000 and 2009, the amount of land dedicated to corn production rose by approximately 10% (Wallander et al., 2011). One third of the increase came from shifts in land-use from grazing, USDA Conservation Reserve property, and hay production (Wallander et al., 2011). Though farm operators have been able to successfully keep up with production needs with this method, the destruction of wildlife habitats and areas with high carbon reduction capacity calls its sustainability into question. Beyond environmental considerations, the highly unstable fertilizer market and unpredictability of overall input costs have farmers searching for lower input systems (Borchers et al., 2014). To achieve more optimized agronomic practices, a variety of multicropping systems have come up for consideration, including double cropping. This method can help to diversify producer income by allowing them to grow and harvest two crops successively in the same field and year (Lofton et al., 2021). Generally, summer crops are planted immediately following harvest of the winter crop and has been primarily achieved with winter wheat and soybean (Lofton et al., 2021).

This system has not yet been widely adopted by producers in the United States. The contingency of increased input cost and risk with limited crop protection plans from insurance entities are cause for hesitation from growers (Borchers et al., 2014). As of 2012, just 2% of the total reported crop land is dedicated to double cropping (Borchers et al., 2014). Much of the existing double crop acres are concentrated in the Southeast, Midwest, and Southern Plains. This locational trend can be partially explained by the climate dependent nature of the system (Borchers and Wallander, 2014). The success of double cropping begins with a sufficient length of suitable growing season; this factor also dictates which crops should be included in the rotation. Areas where the warm season is shorter due to location are at elevated risk of yield loss and crop failure from the lack of growing degree days (Li et al., 2013). Another important yield limiting factor in a double crop system is water availability (Lofton et al., 2021). Planting dates for the second crop are generally later than full season production, often approaching the hottest point of the season where rainfall can be limited. The field may also be depleted of existing water reserves in the process of finishing the first crop (Wells, Reberg-Horton, and Mirsky, 2016). For these reasons, non-irrigated acres especially are at risk of low germination rates and yield loss from water stress at critical points in the life cycle of the crop (Lofton et al., 2021).

An environmental factor that makes this system attractive is the reduction of erosion potential. As the soil's exposure to the elements is limited, both water and soil volume losses can be reduced (Borchers et al., 2014). A study in nutrient dynamics in double crop systems revealed the possibility for reduced NO3–N leaching compared to full season, provided the elevated extraction rate of N could indicate difficulty in ensuring proper soil fertility without increased fertilizer application (Heggenstaller et al., 2008). Producers in Oklahoma have a climatic advantage to integrate crops beyond soybeans and wheat into this rotation. On average, the southern and eastern portions of the state experience the first freeze of the season between November 1 - November 11, with the latest recorded well December (Oklahoma Climatological Survey, 2012). These weather patterns allow for an extension of the suitable production season for most summer crops, allowing them to be planted later and fully reach maturity with limited to no impact from frost (Lofton et al., 2021). One crop that has gained much interest in the region for double-crop systems is corn. However, as opposed to soybean or grain sorghum in this later planted system, corn is planted several months after traditional full-season planting periods (Lofton et al., 2021).

Corn Management in a Double-Crop System:

Soybean, the most common summer crop in double-crop systems, maturity is primarily controlled through photoperiodism. As night-length increases, past the summer solstice, the transition from vegetative to reproductive growth occurs more rapidly in soybean (McWilliams et al, 1999) With late-June and early-July planting, which is common for double-crop systems, this results in a very abbreviated vegetative period compared to the reproductive period. It is during this vegetative period that leaves are developed that provide photosynthates to the developing pods (Zhang et al, 2001). When this period is shortened, a lower amount of reproductive structures will survive to completion and ultimately be harvested. This is a major contributing factor to the decreased yield potential for double-crop soybean systems compared to those planted during early planting periods (Hoogenboom et al, 1987) Conversely, corn development depends less on photoperiodism but more on heat units being accumulated (Daynard, 1972). Corn transitions from vegetative (V-stages) to tassel production (VT) at just over 1100 GDU (Coulter, 2021). From this stage corn will spend the next 28-45 days pollinating and developing kernels, which is the most sensitive stage for stress conditions. While most double-crop systems are planted as soon as the winter crop is harvested, corn double-crop systems will typically (in Oklahoma) postpone planting until into July (Lofton et al, 2022). This is due to the development of heat units and the timing of critical growth stages in the region. When planted earlier in the season, corn may require 50-60 days to acquire enough heat units to transition from vegetative to reproductive growth (Nielsen, et al., 2002) However, later planted corn may only require 30-35 days (Hanway, 1966). Planting immediately behind winter crop harvest could put this critical heat and moisture period during the hottest and typically driest time of year, July. However, if planting is delayed until early to mid-July, this critical stage may not occur until mid-August into September July (Lofton et al, 2022). Conditions during this period are typically associated with cooler temperatures and more consistent rainfall patterns. However, because of the further delay in planting, other planting practices need to be optimized to minimize stress that could lead to decreased yield potential.

Justification

A consistent theme among literature regarding agronomic management is the driving need to increase production to compensate for an exponential rate of population growth. Beyond the surge in mouths to feed, access to land resources suitable for crop production continues to diminish while input prices trend oppositely. Though input cost is expected to rise over time with inflation and fluctuations in demand, the last two years have seen unprecedented growth for N fertilizer prices especially. Even prior to the last two years, extensive work was being done with different cropping systems, rotations, and management practices to find ways to increase production. One proposed solution that has been well established across the Great Plains and southeastern US is double-cropping. While research in Oklahoma has proved the systems viability for success in this region, information regarding best management practices is mostly concentrated within wheat and soybean rotations. Oklahoma's climate fosters an environment suitable for crops outside of the traditional rotation, extending to corn. Existing literature dictates that N application and seed compose the largest percentage of input cost for full season corn production. Though the response to these factors has been well documented for full season, little information is available regarding the impact of N rate and plant population on grain yield for double-crop. This trial has been conducted to discern any potential interactions between these factors for better understanding that may help determine best management practices for this system in Oklahoma.

CHAPTER II

METHODOLOGY

Field Experiment

To evaluate the impact of plant population and N management on full-season and double-crop corn systems, one field trial was established in 2020 and two in 2021. The first corn field trials was established at EFAW Agronomy Research Station (36°07’59”N 97°06’20”W) in Stillwater, Oklahoma in 2020. The corn trials were repeated at the Mingo Valley Research Station (35°57'49"N 95°51'44"W) in Bixby, Oklahoma, and at the Cimarron Valley Research Center (35°59'12"N 97°02'48"W) in Perkins, Oklahoma in 2021. Site descriptions and soil series by location are described in Table 1. While both the Bixby and Perkins locations had both full-season and double-crop systems in 2021, flood conditions (Bixby) and wild hog damage (Perkins) resulted in the destruction of full season trials. Therefore, only double-crop system information is available for 2021.

Table 1. Trial location, soil series and description.

Location	Soil Series	Description
Stillwater, OK	Easpur	Fine-loamy, mixed, active, thermic Udic Argiustolls
Bixby, OK	Wynona	Fine-silty, mixed, active, thermic Cumulic Epiaquolls
Perkins, OK	Teller	Fine-loamy, mixed, superactive, thermic Fluventic Haplustolls

Experimental Design

The full-season and double-crop systems were considered two separate trials and planted in individual blocks, therefore data will not be statistically compared between the two systems. The trial was conducted with randomized complete block design. Trial plots were 7.62 m by 3.05 m. The trial evaluated five different plant populations and four different N rates as a complete factorial arranged in a randomized complete block design. Each treatment was replicated four times at each location. Nitrogen rates and planting population are described in Table 2.

Table 2. Plant population treatments and Nitrogen rates applied across all site years.

Treatment	Rate
Nitrogen rate (kg ha^{-1})	55.0
	82.0
	110.0
	165.0
Plant population (plants ha^{-1})	21,000
	30,000
	44,000
	57,000
	70,000

Wheat was planted across both the full-season and double-crop systems. Wheat was planted using a FLEXII Series Grain Drill from Truax (Truax Company, Inc. New Hope, MN, USA). For the full-season production system, wheat was terminated in early March using 946 mL of glyphosate (Roundup PowerMax, Bayer CropScience LLC, Netherlands) in early March.

The corn was planted at a depth of 3.81 cm with a NG Plus 4 Series Monosem planter (Monosem Inc.; Edwardsville, Kansas, USA) on a T5040 New Holland Tractor (New Holland

Agriculture; New Holland, Pennsylvania, USA). The planter was set at 32,000 plants ha^{-1} on 75 cm rows. Plant population treatments were achieved by thinning a specific number of plants row^{-1} after the stand was established. The number of plants row^{-1} necessary to meet each treatment requirement was first calculated by converting plants ha^{-1} into plants m^{2-1}, then divided by number of rows. After visually evaluating the initial spacing, plants were removed such that the remaining interrow stand was approximately equidistant. The source of N fertilizer was urea, applied by hand at V2 once initial stands were established. Three corn cobs were collected at maturity from each plot to record the number of rows of kernels per cob, average number of kernels per row on the cob, and kernel and cob weights. The average number of kernels per row was calculated by visually determining the longest and shortest row of kernels and dividing by two. Trials were harvested mechanically using an XP9 Kincaid plot combine (Kincaid Equipment Manufacturing; Haven, KS, USA). Yield and moisture data was collected at harvest, and samples of grain were retained to grind and evaluate for seed N content using LECO compositional analysis. After grinding the grain and collecting the samples, wearing gloves to minimize the risk of contaminating the specimen with oil from skin, 0.50 g of starch was weighed into tin foil trays and rolled tightly into balls. Then, the samples are arranged in trays incorporating a rotation of corn flour and starch every ten samples for a check. The samples are then loaded into the LECO analysis machine, where they are subjected to dry combustion to ascertain grain N (%).

Full season (FS) Trial

Management practices for the full season production system for corn at EFAW in 2020 is highlighted in Table 4. The full season trial planted at EFAW in 2020 received a tank-mixed preemergent application of 17.35 kg ha^{-1} glyphosate (Roundup PowerMAX; Monsanto; St.

Louis, Missouri), 11 kg ha^{-1} atrazine + S-metolachlor (Charger Max ATZ; Winfield United; Arden Hills, MI, USA) and 0.584 kg ha^{-1} nonionic surfactant using an Enduraplas Land Champ sprayer (Enduraplas; Neche, ND, USA) on a John Deere 3320 tractor (Deere & Company; Moline, IA, USA). Weeds were managed chemically preseason and physically in-season. No other pesticides were applied, the first replication was slightly damaged shortly after silking by paraquat drift from a neighboring field. Three corn cobs were collected at physiological maturity from the two outermost rows of each plot. The middle two rows were mechanically harvested using an XP9 Kincaid plot combine (Kincaid Equipment Manufacturing; Haven, KS, USA). Yield on a per hectare basis was calculated using plot weight.

Table 3. Agronomic management dates for full season corn in Stillwater

Date	**Activity**
4/7/2020	Planted full season
4/8/2020	Preemergent applicationt
4/21/2020	N application
7/24/2020	Paraquat drift on replicate 1 of the trial
8/19/2020	Collected cobs from each plot
8/29/2020	Harvested

Double Crop (DC) Trials

All DC trials were planted at 32,000 plants ha^{-1} with the same equipment as the FS. The 2020 EFAW location was sprayed preemergent with an Enduraplas Land Champ Sprayer (Enduraplas; Neche, ND, USA) attached to a John Deere 3320 tractor (Deere & Company; Moline, IA, USA) at a rate of 17.35 kg ha^{-1} glyphosate (Roundup PowerMAX; Monsanto; St. Louis, Missouri, USA). Another in-season application of 11.83 kg ha^{-1} glyphosate (Roundup PowerMAX; Monsanto; St. Louis, Missouri) was made with a customized high clearance sprayer on a Case 55A tractor (Case IH; Racine, WI, USA). Both sites for 2021 were sprayed preemergent using the Enduraplas sprayer and John Deer 3320, with no in-season herbicide application. The Mingo Valley Research Station was treated with 17.35 kg ha^{-1} glyphosate (Roundup PowerMAX; Monsanto; St. Louis, Missouri), 11 kg ha^{-1} atrazine + S-metolachlor (Charger Max ATZ; Winfield United; Arden Hills, MI, USA) and 0.584 kg ha^{-1} nonionic surfactant. Research plots in Perkins were sprayed with 0.56 kg ha^{-1} dicamba (FeXapan; Winfield United; Arden hills, MI, USA). Pesticide application was determined based on field monitoring with Oklahoma Cooperative Extension Services guidelines and in accordance with the herbicide label. Before fertilizer application, the stand was thinned to meet each plant population criteria. Once the corn was at physiological maturity, three cobs were taken from the outside rows of the plots. The two center rows were harvested using an XP9 Kincaid plot combine (Kincaid Equipment Manufacturing; Haven, KS, USA). Important management dates for the double-crop trials are found in Tables 5-7.

Table 4. Important DC management dates for 2020 Stillwater trial

Date	**Activity**
6/26/2020	Planted DC corn
6/27/2020	Herbicide application
7/6/2020	Applied fertilizer
7/16/2020	Thinned plants
8/3/2020	Herbicide application
9/30/2020	Collected cobs from each plot
11/6/2020	Harvest

Table 5. Agronomic management dates for Perkins double-crop

Date	Activity
7/6/2021	Planted corn
7/8/2021	Sprayed dicamba
8/18/2021	Thinned stand
11/19/2021	Harvested corn and collected cob samples

Table 6. Agronomic management dates for Perkins double-crop

Date	Activity
7/18/2021	Preemergent herbicide application
7/21/2021	Planted corn
8/17/2021	Thinned plants/applied fertilizer
11/18/2021	Collected cobs
12/16/2021	Harvested corn

Statistical analysis

All analysis to determine the significant impact of N rate and plant populations on corn grain production was conducted using SAS 9.4 (SAS Institute Inc., Cary, North Carolina). A lack of significant interaction between treatments and either year or site resulted in the individual locations and years all being analyzed separately. Fixed effects for the trial included plant population and N rate, while replication and its interactions were considered random. Analysis of variance was conducted using Proc Mixed with a Tukey adjustment for means separation. An $\propto = 0.05$ were used for all analysis.

CHAPTER III

RESULTS AND DISCUSSION

Weather and Environment

2020

Of interest in this study is the impact of plant population and N rate on grain yield and yield characteristics in double-crop corn following wheat. The intention was to have a full season and double-crop trial for each site year and location, though 2020 was the only year the full season was completed. In 2021, the trial in Perkins was decimated by wild hog damage while excessive rainfall in Bixby drowned out the full season test. Temperatures across locations and site years are consistent when considering each summer overall, especially with respect to the double-crop trials. However, in 2020 the daily average temperature was higher throughout the full season than the double-crop trial (Figure 1). Milder temperatures came during critical stages (VT-grain fill) for double-crop corn, but in the week prior to harvest in November it dropped below freezing. A rain event occurring in tandem with freezing temperatures encased the corn plants in thin layer of ice. Rainfall across years and locations had more variation than temperature. The Stillwater (dryland) location in 2020 had the most rainfall of any location and year with 60.4 cm accumulated from April-November (Figure 1). The double crop trial at this location received approximately 22% more rain than the full season. Despite that, the highest yield still came from the highest population in the full season. This may be a result of the distribution of rainfall events during critical growth stages. In the 10 days after silk emergence (period which corn uses the most water), the full season accumulated 19.03 cm to 11.4 cm.

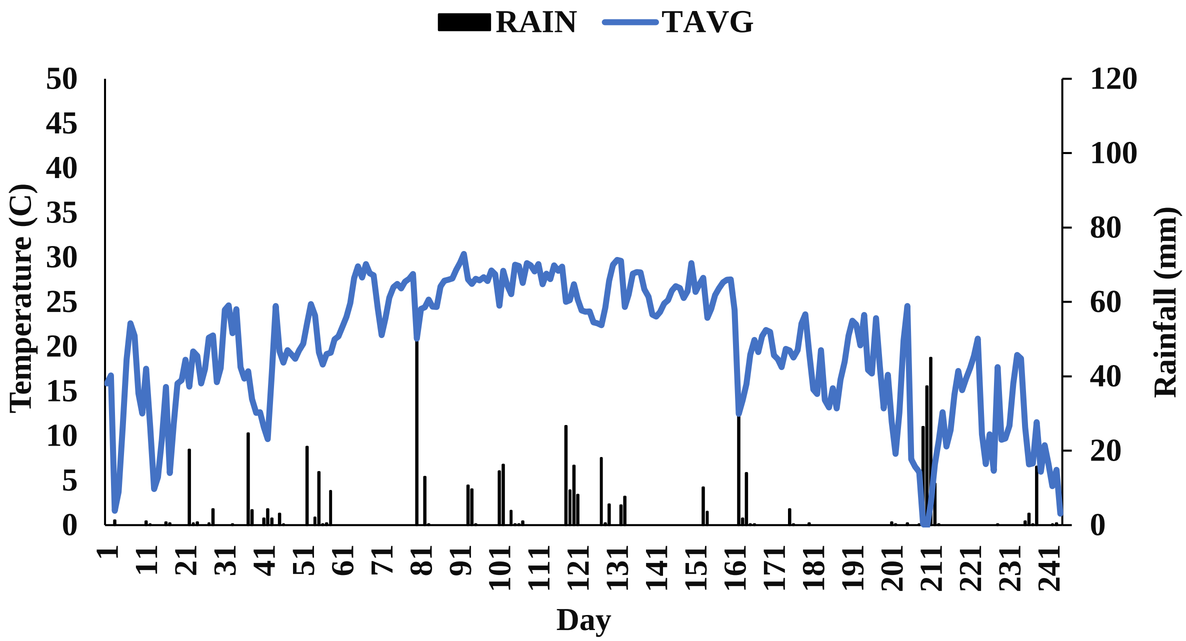

Figure 1. Average daily temperature (TAVG) and rainfall (RAIN) in EFAW in Stillwater, OK in 2020.

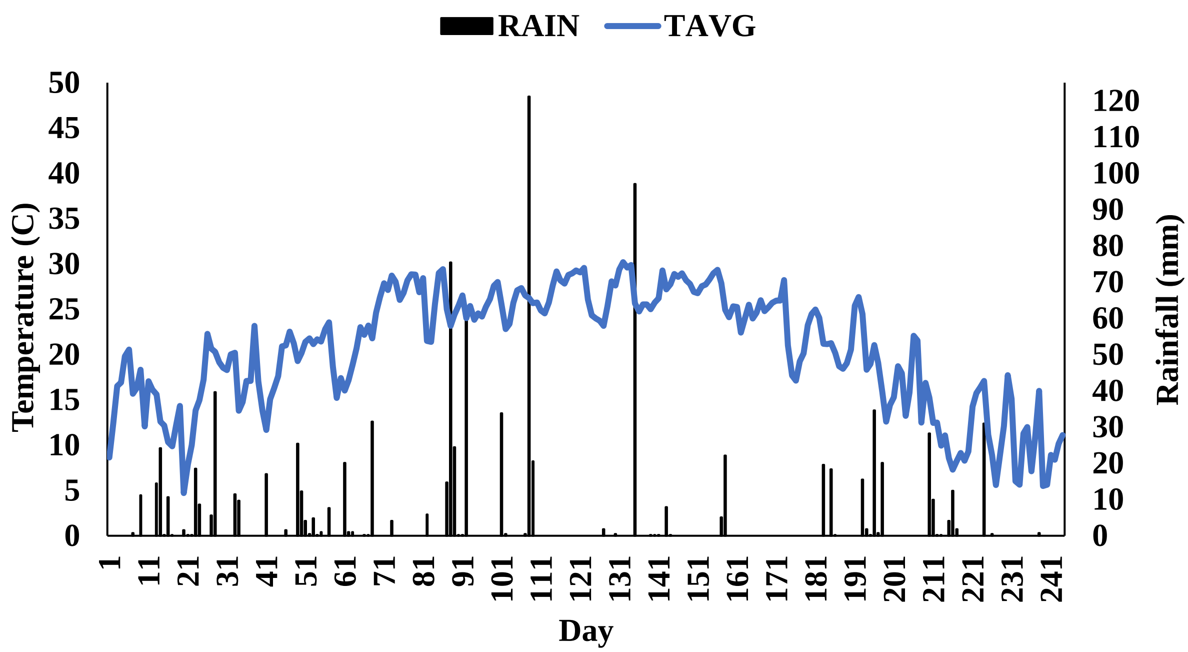

Figure 2. Average daily temperature (TAVG) and rainfall (RAIN) in Perkins, OK in 2021. (The Oklahoma Mesonet, PERK, Daily TAVG and RAIN, April 1 – November 30, 2021).

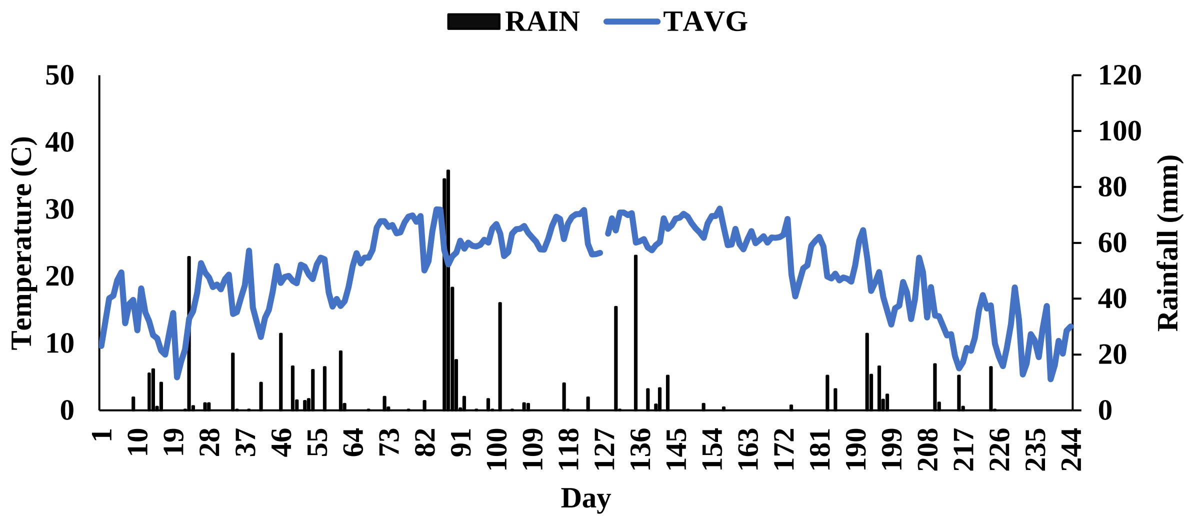

Figure 3. Average daily temperature (TAVG) and rainfall (RAIN) in Bixby, OK in 2021. (The Oklahoma Mesonet, STIL, Daily TAVG and RAIN, April 1 – November 30, 2021).

2021

For 2021 data, it is important to note that the Bixby station was irrigated while Perkins was not. Though Perkins received more rainfall (57.25 and 44.4 cm), Bixby remained competitive with water amendments (Figure 2, Figure 3). The trial in Bixby outperformed Perkins at all populations except 30,000 and 44,000. The yields of the two high populations in Bixby double-crop were substantially higher than the same treatments at Perkins and Stillwater. This may be attributed again to the amount and timing of rainfall at tassel/silk, where Bixby and Perkins received 29.9 and 23.5 cm respectively. There was more water available during the transition from vegetative to tassel, and less time passed between silk establishment and substantial rain events.

Y*ield Response to Plant Population*

Full-season

In 2020, full season grain yield at EFAW increased as target plant population increased, with the highest yielding treatment being 70,000. However, yields of the 44,000, 57,000, and 70,000 were not significantly different (Figure 4.). The 21,000 planting population achieved the lowest yield; however, yields were only different from 44,000 plant population and higher treatments (Figure 4.). Similar results were produced in the High Plains by Marsalis, Angandi, and Contreras-Govea (2009), where yields at 56,000 plants ha^{-1} did not significantly differ from 70,000 and 74,000 plants ha^{-1}. Lower plant populations may not always be successful however, as research in Louisiana indicated an optimum plant population as high as 85,900 plants ha^{-1} (Fromme, Spivey, and Grichar, 2019). This continual increase in yield with increasing temperatures would not be uncommon for areas or locations with high to non-limiting moisture status. This could be shown in the Marsalis, Angandi, and Contreras-Govea (2010) document which had irrigation but watered for water limited conditions. These conditions would be more comparable to the environment the current trials experienced throughout the growing season.

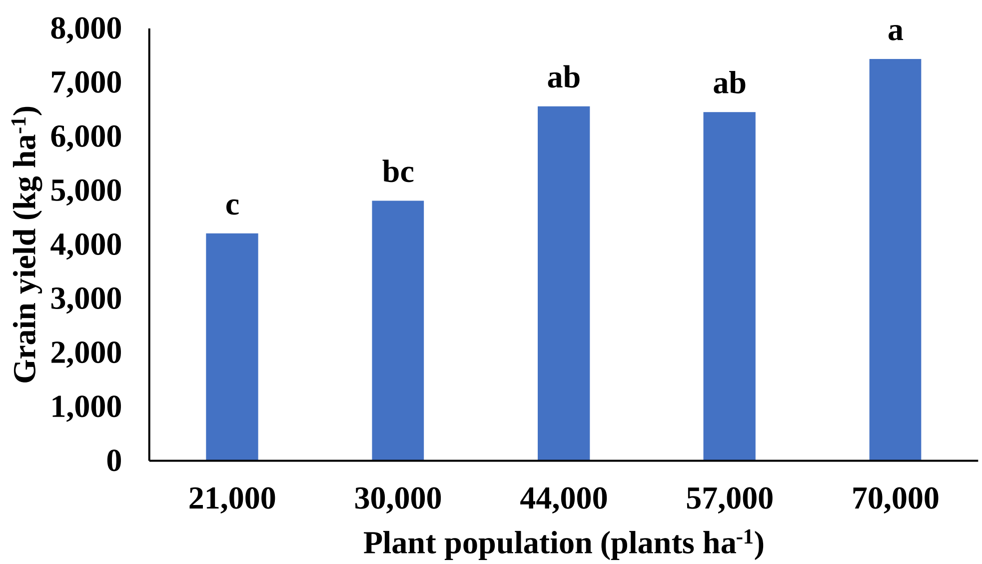

Figure 4. Full season corn grain yield response as influenced by plant population in Stillwater, OK in 2020.

Double-crop

Like the full season at EFAW in 2020, double-crop yield significantly increased between 21,000 and 30,000, 44,000 plant populations. However, unlike the full-season, yield did decrease at the highest plant population (70,000). Although not significantly different from other treatments, yields did decrease enough to observe no significant differences between 21,000 and 70,000 plant populations (Figure 5).

A similar trend to EFAW location was found at the Bixby in 2021 (Figure 6). A significant yield increase is observed between 21,000, 30,000, and 57,000 plants ha^{-1}. The highest yield achieved at this location was 4,457 kg ha^{-1} at 57,000 plants ha^{-1}. In addition, trends reinforced the observation of reduced yield potential at above optimal plant populations (70,000) in double crop systems. Yield at 70,000 plants $ha^{-1}$was approximately 9% lower than 57,000 plants ha^{-1}, though there is no statistical significance associated with the difference between these treatments or 44,000.

The results at Perkins in 2021 test varied from the previous tests almost entirely. Only one point of significance was found in the lowest population (21,000) yielding significantly lower than all other treatments, with no significant differences between the other treatments (Figure 7). The highest yielding treated was at 44,000 plants ha^{-1} which yielded 3,215 kg ha^{-1}. This location yielded approximately 12% less than Bixby at the same treatment level. The highest yield recorded in Bixby (57,000) was also 39% higher than Perkins.

At two site years, the highest plant population's yield decreased and was not significantly different from the lowest plant population. In semi-arid, dryland conditions this would not be unexpected and was the hypothesis for this experiment. However, the authors do not know why this occurred in the double-crop but not the full-season system. In most double-crop systems, higher plant populations are frequently recommended to compensate for limited biomass accumulation (Lee, Egli, and TeKrony, 2008; Lofton et al., 2022). However, the reason for this decrease in corn could be associated with higher stress typically associated with double-crop systems (Lofton et al., 2022). Therefore, this decrease, while not significant from the optimum planting population but also not significant from the lowest plant populations could be due to added or accumulated stress associated with higher populations in double-crop systems.

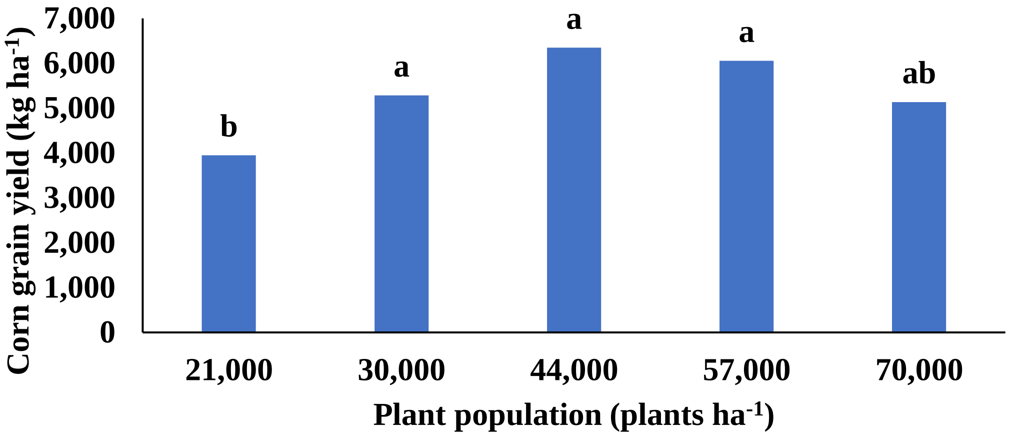

Figure 5. Double-crop corn grain yield response as influenced by plant population in Stillwater, OK in 2020

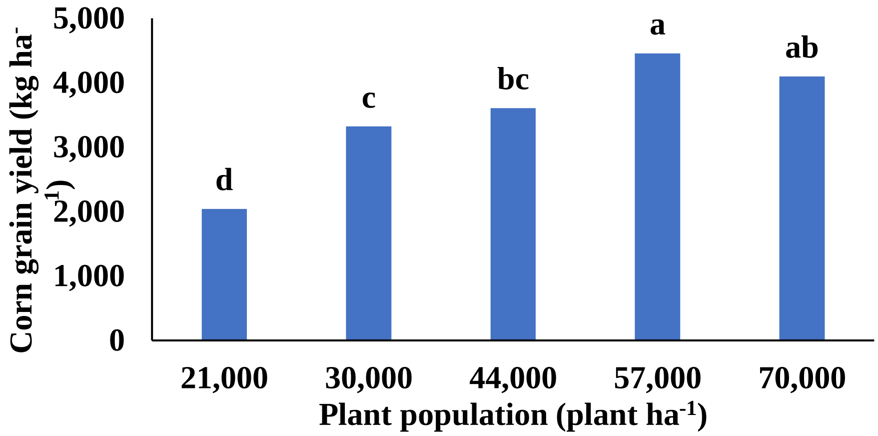

Figure 6. Double-crop corn grain yield response as influenced by plant population in Bixby, OK in 2021.

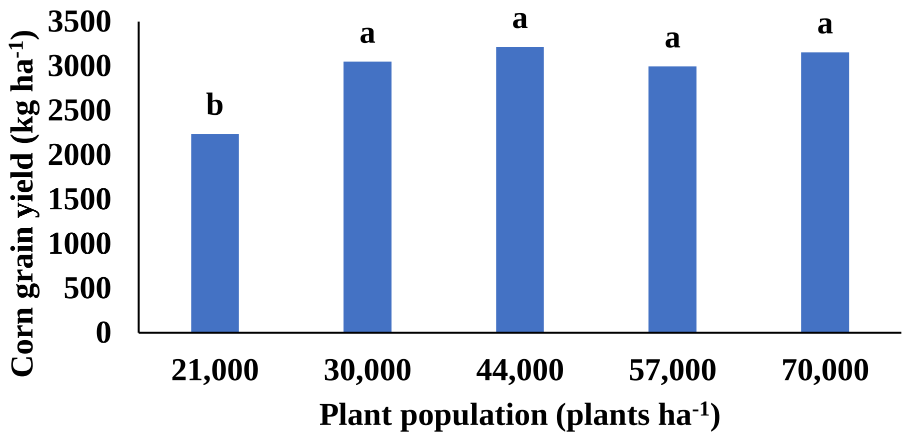

Figure 7. Double-crop corn grain yield response as influenced by plant population in Perkins, OK in 2021.

Yield Response to N Rate

Full Season

When considering N rate, the most significant response was observed in 2020 for both full-season and double-crop trials (Figure 8). In the full-season trial, a significant linear relationship between yield and N rate was detected when averaged across plant populations. Nitrogen rate accounted for nearly 33% of variation in corn grain yield and the model indicated in increase of approximately 225 kg ha^{-1} in grain yield was achieve for every additional 10 kg N ha^{-1} applied. The linear relationship without a plateau indicated that N was limiting in this system and the highest N rate applied did not definitively optimize yields. While higher N rates could have been applied, these N rate levels are at or above what would currently be recommended given the yield potential and achieved yield at this location.

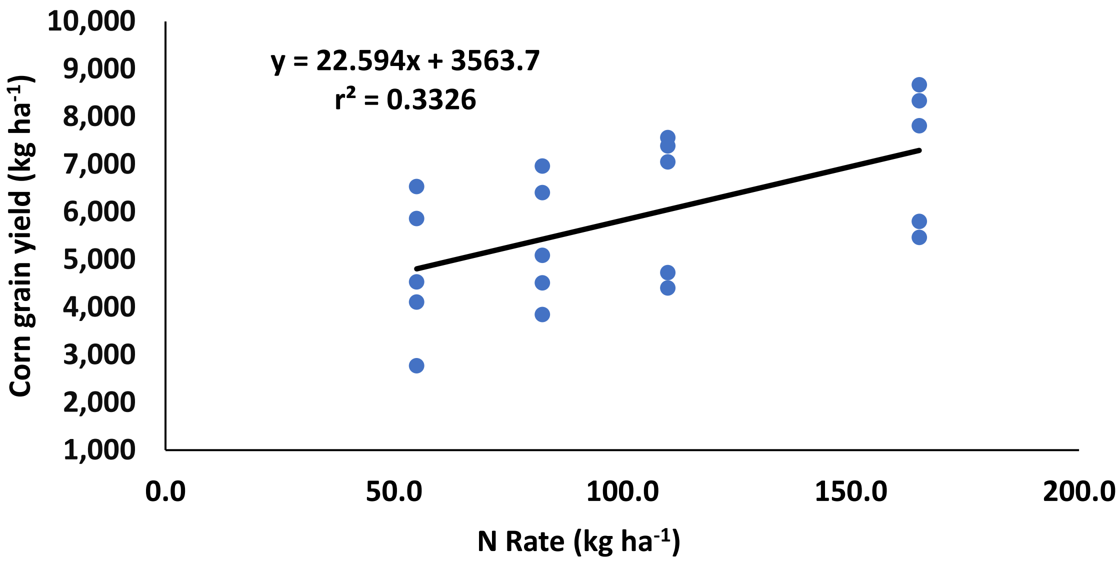

Figure 8. Full season corn grain yield response as influenced by N rate in Stillwater, OK in 2020.

Double-crop

The double-crop trial in EFAW in 2020 produced similar yields as the full-season with a significant N rate effect. However, a linear plateau model was able to be fit to the double-crop N rate effect indicating that an optimal N rate was achieved, and additional N did not further increase yields (Figure 9). This model indicated that below 90 kg ha^{-1}, a 309 kg ha^{-1} increase in grain yield was achieved with every 10 kg N ha^{-1} applied. Above the 90 kg ha^{-1} critical limit, which corresponded to 5,744 kg ha^{-1} corn grain yield, no additional significant changes were noted. While no statistical analysis was conducted between the full-season and double-crop trials, it is interesting to note the lower N rate requirement for the double-crop compared to the full-season trial. Even more so, yields for the full-season and double-crop trial at 90 kg ha^{-1} level were similar, 5,597 and 5,744 kg ha^{-1} for the full-season and double-crop, respectively. Similar findings were observed in terms of double-crop yield response in China, where an LPM was fit for N rate and yield data. Grain yield increased linearly with N rate until 100 kg ha^{-1} N was applied, at which point a plateau was observed and no significant yield gain occurred (Fang et al., 2008). They found that reducing fertilizer rates from 300.0 to between 100.0 and 200.0 kg ha^{-1} was a viable option while maintaining yield (Fang et al., 2008). Higher yield potential for full season corn dictated by time available for maturation and biomass accumulation could explain the positive linear N rate response in the full-season compared to the double crop (Harper et al., 1997). On average, the number of days to tasseling for biomass accumulation in these systems are 50-80 and 30-50 days respectively (Lofton et al, 2022 and Anandhi 2016). This suggests that double-crop corn spends between 20-50 fewer days developing photosynthetically active stalk and leaf tissue. Heggenstaller, Liebman, and Anex (2009) analyzed growth rate and characteristics of full season and double-crop corn following triticale. The study was conducted by measuring aboveground dry matter and leaf area weekly and net dry matter production at harvest. Supporting the visual observations in this study, they recorded consistently lower LAI in the double-crop. Additionally, the full season spent 2-3 weeks longer with higher maximum LAI; further statistical analysis showed a positive relationship between duration of time at max LAI and total harvested dry matter (Heggenstaller, Liebman, and Anex, 2009).

Neither Bixby (Figure 10) or Perkins (Figure 11) in 2021 revealed a significant response to N rate, though a mild decrease in yield as N rate increases is observed. The reduced N response may be a function of crop rotation history per location. At EFAW, three grass crops were grown successively - wheat harvested from the double-crop field was planted after grain sorghum. Conversely, Bixby and Perkins double-crop trials were planted after soybeans. Due to the overall lower yield potential of the double-crop system, having soybean in the rotation could have minimized the impact that the N rate treatment had on the corn yield (Lauer, Porter, and Oplinger, 1997). However, since the full-season trials of these two locations were either terminated or destroyed, the authors do not know if a higher yielding full-season trial would have responded to additional N. Furthermore, excessively hot, dry conditions during a majority of the double-crop season decrease corn grain potential of these two locations compared to even the double-crop trial in 2020. These conditions could have resulted in N not being the most limiting factor for production and, therefore, no significant response was observed.

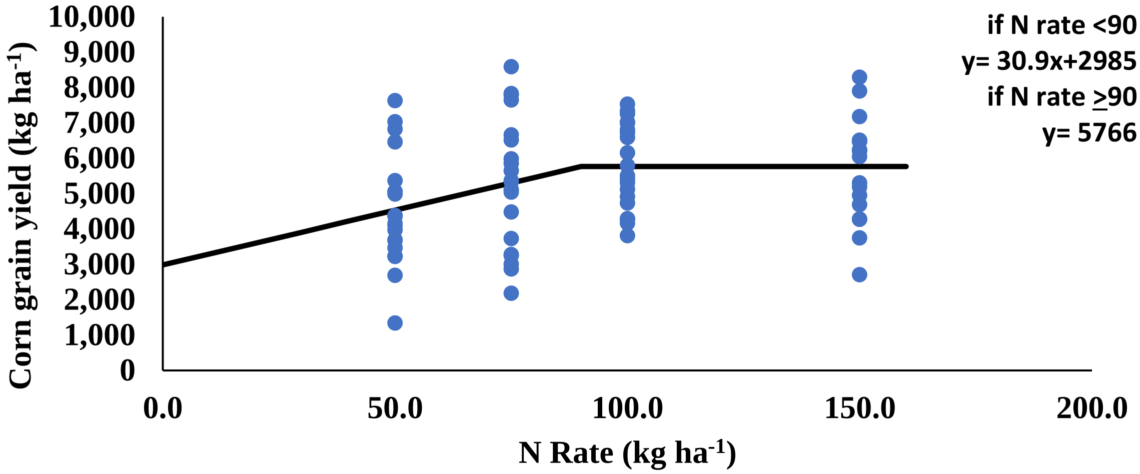

Figure 9. Double-crop corn grain yield response as influenced by N rate in Stillwater, OK in 2020.

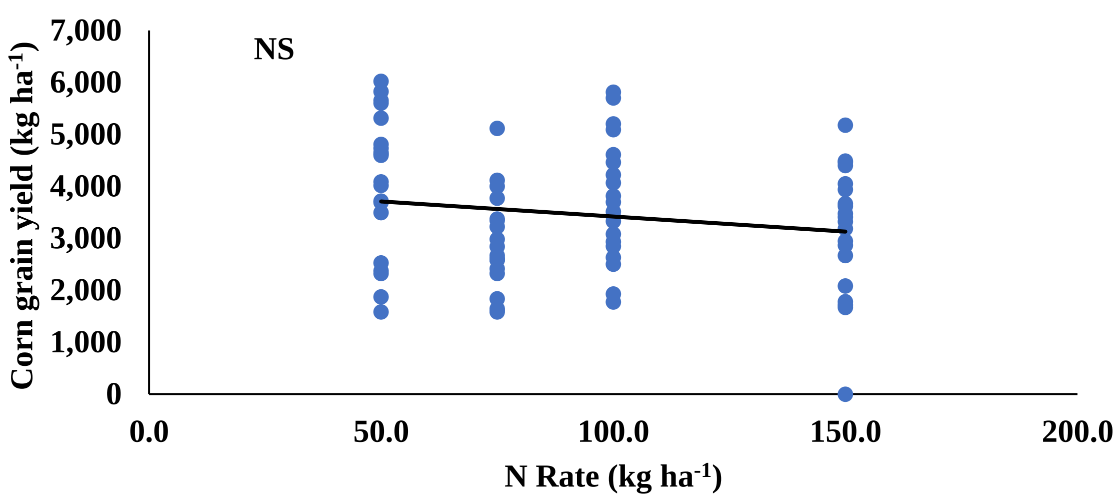

Figure 10. Double-crop corn grain yield response as influenced by N rate in Bixby, OK in 2021.

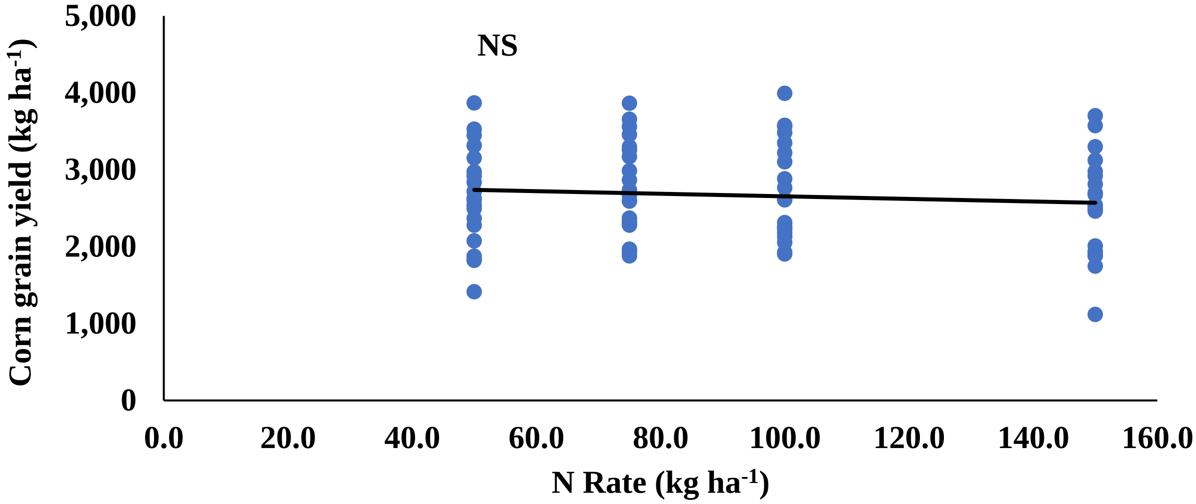

Figure 11. Full season corn grain yield response as influenced by N rate in Perkins, OK in 2021.

Yield Characteristics

Full Season

Only a single significant effect was noted for the full-season trial in 2020. The P-values associated with this test are listed in Table 9. For the full-season trial, kernel count significantly increased linearly from 21,000 through 70,000. However, kernel count beyond 44,000 did not significantly increase compared to 57,000 or 70,000.

Double-Crop

Information regarding P-values for all double-crop trials are found in Tables 10-12. Both kernels row^{-1} and grain N were significantly influenced by plant population in the double-crop trial at EFAW. This location had the lowest overall average kernels row^{-1} of all double-crop trials. The best performance was observed in 30,000 plants ha^{-1}, where the result was not significantly different from treatments with 44,000 or 57,000 plants. Cobs pulled from plots with 70,000 plants had the least number of kernels row^{-1}, though not significantly less than 21,000 and 44,000. A negative relationship was observed between grain N (%) and plant population until

57,000 plants was surpassed, though the increase at 70,000 was not significant. The highest concentration of N in the grain was recorded in 21,000, significantly better than all populations except 30,000. This treatment was significantly higher than 57,000 and 70,000 plants ha^{-1}.

Limited interactions were recorded for the trial in Perkins. Like other double-crop locations, plant population had a significant effect on kernels row^{-1}. However, the results from Perkins were opposite in the performance of the highest and lowest populations. The most kernels were established among 70,000 plants, and the least generated from 21,000. On the high end, there were no significant differences recorded between 70,000, 30,000, and 44,000. Additionally, no statistical increase was found between 21,000, 44,000, and 57,000.

The Bixby double-crop in 2021 produced the most significant results as well as having impacts of both plant population and N rate. For plant population, kernels row^{-1}, cob weight, kernel count, and kernel weight were all significantly influenced. Nitrogen rate had fewer significant response with only kernel row^{-1} being significantly influenced. As kernel row^{-1} was a common theme throughout double-crop trials with respect to population, and again in N rate for Bixby, it will remain the focus of the discussion. It could also be argued that the rest of the yield characteristics affected at this location are determined by kernel row^{-1}. Linear regression analysis of this data showed a negative, linear relationship across all populations. The model suggests a loss of 0.2 kernel row^{-1} occurred for each additional plant in the plots. This translates to approximately 26% less kernels row^{-1} at 70,000 when compared to the initial performance at 21,000. The regression also accounts for 36% of variability in kernel number came from the interaction with plant population. With respect to N rate, the response was unexpected in some aspects. The general upward trend in kernel number as N rate increased makes sense, but there was an exception for 82.5 kg ha^{-1}. This rate produced the lowest average number of kernels row-

[1]. It is also interesting that N rate had a significant impact on yield parameters but did not have a significant impact on yield. Therefore, these differences could indicate just high amount of variability.

Table 7. P-values of yield characteristics for Stillwater, OK full season trial in 2020

Yield Component	P-value (N)	P-value (population)
Row cob^{-1}	0.673	0.126
Kernel row^{-1}	0.15	0.2
Cob weight (g)	0.1128	0.0552
Kernel count	0.9238	0.0181
Kernel weight (g)	0.0697	0.1621
Grain N (%)	0.234	0.239

Table 8. P-values of yield characteristics for Stillwater, OK double-crop trial in 2020

Yield Component	P-value (N)	P-value (population)
Row cob^{-1}	0.0836	0.4093
Kernel row^{-1}	0.2794	0.0436
Cob weight (g)	0.514	0.756
Kernel count	0.5942	0.0857
Kernel weight (g)	0.649	0.505
Grain N (%)	0.7833	0.0138

Table 9. P-values of yield characteristics for Perkins, OK double-crop trial in 2021

Yield Component	P-value (N)	P-value (population)
Row cob^{-1}	0.626	0.474
Kernel row^{-1}	0.2794	0.0436
Cob weight (g)	0.221	0.526
Kernel count	0.577	0.911
Kernel weight (g)	0.307	0.136
Grain N (%)	0.458	0.952

Table 10. P-values of yield characteristics for Bixby, OK double-crop trial in 2021

Yield Component	P-value (N)	P-value (population)
Row cob^{-1}	0.0271	0.5475
Kernel row^{-1}	0.0179	9.48E-10
Cob weight (g)	0.072	6.26E-12
Kernel count	0.195	4.74E-08
Kernel weight (g)	0.0864	3.42E-09
Grain N (%)	0.317	0.746

CHAPTER IV

CONCLUSION

Corn grain yield is highly susceptible to losses from water, nutrient and heat stress during critical growth stages. The availability of resources during this period determines the number of kernels per cob, which has a significant correlation with grain yield. A way to mitigate the heat stress risk associated with double-crop corn systems in Oklahoma is to plant as soon as conditions allow in July. This pushes the window of time during critical stages into milder temperatures and better chance of adequate rain. Focusing input application in relation to physiological need at critical points is one way to minimize resource losses while working to provide some level of return.

Playing a large part in the crop use efficiency of water and N, plant population provides further considerations for overall input management. The linear relationship found between plant population and grain yield only continues when resources are not limiting crop growth. There is no universal recommendation in terms of plant population regardless of the production system. Optimum achievable yield will be different on a site-by-site basis. This data supports optimum yield for the three sites is within a range of 44,000-57,000 plants ha^{-1}. Exceeding this population reduced interrow space between plants, creating high levels of competition in a system where time to utilize resources is already limited.

Like plant population, N rate application is a site-specific practice dependent on environmental conditions. Yield and N responses observed between the double-crop trials of

2020 and 2021 indicate no less. Yields in Bixby and Perkins were substantially lower than Stillwater, declining by 1900 and 3080 kg ha^{-1} respectively. The authors contribute the yield decline to severe water stress limiting yield potential and interfering with N uptake. The field was planted as soon as moisture was available in July and approximately 10 cm of rain accumulated over the course of the vegetative cycle. Visual indicators of water stress were apparent early on in Perkins as leaves rolled up on young plants. This was not unexpected, and the harsh environmental conditions during vegetative growth reiterated the benefit of delaying planting in favor of critical stages. However, after the field transitioned into VT there was no respite from extreme heat and drought in the critical two weeks after tassel emergence, accumulating only 1 cm of rainfall. Despite precautions with the planting date, the high-risk nature of this system is revealed once more when it comes to dryland production of double-crop corn. Further, where corn could not assimilate N at its usual efficiency, there was more available for persistent weeds to utilize and compete for. This may explain the decrease in yield at high N rates for Bixby and Perkins.

The overall difference in N response between the double-crop and full season trials may be further explained by the rapid maturation of late planted corn. Between emergence and CT, corn uses N to increase biomass to a larger surface area for photosynthesis. Though no leaf measurements were taken throughout this study, we were able to visually observe smaller leaves in double-crop corn compared to the full season. These findings suggest it would not be economical to apply N to a double-crop corn system at full season rates due to the limitations to biomass and yield potential with the time constraint. The N rate that performed the best among these tests ranged between 82.5 and 110.0 kg $ha^{-1.}$

Despite rapid advancements in precision agriculture and crop technology, the threat of climate catastrophe, overpopulation, and volatile input markets drive the need for continual research into input optimization and production expansion. That effort includes understanding how the mechanisms behind stress factors like water and nutrient deficiency, pest pressure, and competition interact to effect end-of-season yield goals. Keeping these things in mind can help make more sound agronomic decisions, especially in the frame of a high-risk system like double-cropping. As water and N availability are the two most limiting factors for corn grain yield, dryland production can be especially risky. Double-crop systems perform the best in regions where the growing season is extended and water is plentiful.

REFERENCES

Anandhi, A. (2016). Growing degree days – ecosystem indicator for changing diurnal temperatures and their impact on corn growth stages in Kansas. *Ecological Indicators*, *61*, 149–158. https://doi.org/10.1016/j.ecolind.2015.08.023

Andrade, F. H., Vega, C., Uhart, S., Cirilo, A., Cantarero, M., & Valentinuz, O. (1999). Kernel Number Determination in Maize. *Crop Science*, *39*(2), 453–459. https://doi.org/https://doi.org/10.2135/cropsci1999.0011183X0039000200026x

Bennett, J. M., Mutti, L. S. M., Rao, P. S. C., & Jones, J. W. (1989). Interactive effects of nitrogen and water stresses on biomass accumulation, nitrogen uptake, and seed yield of maize. *Field Crops Research*, *19*(4), 297–311. https://doi.org/10.1016/0378-4290(89)90100-7

Bernhard, B. J., & Below, F. E. (2020). Plant population and row spacing effects on corn: Plant growth, phenology, and grain yield. *Agronomy Journal*, *112*(4), 2456-2465. doi:10.1002/agj2.20245

Boomsma, Santini, Tollenaar, Vyn. (2009, November). *Maize morphophysiological responses to intense crowding and low ...* Retrieved October 27, 2022, from https://acsess.onlinelibrary.wiley.com/doi/10.2134/agronj2009.0082

Cao, P., Lu, C., & Yu, Z. (2018, June 4). *Historical nitrogen fertilizer use in agricultural ecosystems of the contiguous United States during 1850–2015: Application rate, timing, and fertilizer types*.

Earth System Science Data. Retrieved October 27, 2022, from https://essd.copernicus.org/articles/10/969/2018/

Chen, Q., Samayoa, L. F., Yang, C. J., Bradbury, P. J., Olukolu, B. A., Neumeyer, M. A., Romay, M. C., Sun, Q., Lorant, A., Buckler, E. S., Ross-Ibarra, J., Holland, J. B., & Doebley, J. F. (2020). The genetic architecture of the maize progenitor, teosinte, and how it was altered during maize domestication. *PLOS Genetics, 16*(5). https://doi.org/10.1371/journal.pgen.1008791

Ciampitti, I. A., & Vyn, T. J. (2010, December 23). *A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages*. Field Crops Research. Retrieved October 27, 2022, from

Collins, — W. B. G., & Written ByDr. Guy CollinsExtension Cotton SpecialistCall Dr. Guy Email Dr. Guy Crop & Soil Sciences NC State Extension. (2016, April 12). *Seeding rate and plant population considerations (Collins & Edmisten)*. NC State Extension News. Retrieved October 27, 2022, from https://cotton.ces.ncsu.edu/2016/04/seeding-rate-and-plant-population-considerations-collins-edmisten/

Danforth, A. T., Subedi, K. D., & Ma, B. L. (2009). Chapter 1. In *Corn crop production: Growth, fertilization and yield* (pp. 11–32). essay, Nova Science Publishers.

Daynard, T. B. (1972). Relationships among black layer formation, grain moisture percentage, and heat unit accumulation in corn 1. *Agronomy Journal*, *64*(6), 716–719. https://doi.org/10.2134/agronj1972.00021962006400060003x

DeFelice, K., Wollenhaupt, N., & Buchholz, D. (2022, March). *Nitrogen in the plant*. University of Missouri Extension. Retrieved October 27, 2022, from https://extension.missouri.edu/publications/wq259

Dehlinger, K. M. (2021, October 20). Urea Price Climbs 26% Since Mid-September, a $147-Per-Ton Jump. Retrieved from https://www.dtnpf.com/agriculture/web/ag/crops/article/2021/10/20/urea-price-climbs-26-since-mid-147

Ding L, Wang KJ, Jiang GM,Biswas DK,Xu H,Li LF,Li YH; (2005, October). *Effects of nitrogen deficiency on photosynthetic traits of maize hybrids released in different years2005*. Annals of botany. Retrieved n.d., from https://pubmed.ncbi.nlm.nih.gov/16103036/

Drury, C. F., Reynolds, W. D., Yang, X. M., McLaughlin, N. B., Welacky, T. W., Calder, W., & Grant, C. A. (2012). Nitrogen Source, application time, and tillage effects on soil nitrous oxide emissions and corn grain yields. *Soil Science Society of America Journal*, *76*(4), 1268–1279. https://doi.org/10.2136/sssaj2011.0249

Duvick, D. N. (2005). GENETIC PROGRESS IN YIELD OF UNITED STATES MAIZE (Zea mays L.). *Maydica*, 193–202. https://doi.org/http://www.ask-force.org/web/Yield/Duvick-Genetic-Progress-Yield-Maize-US-2005.pdf

Egli, D. B. (2008). Comparison of corn and soybean yields in the United States: Historical Trends and future prospects. *Agronomy Journal*, *100*(S3). https://doi.org/10.2134/agronj2006.0286c

Erisman, J. W., Galloway, J. N., Seitzinger, S., Bleeker, A., Dise, N. B., Petrescu, A. M. R., Leach, A. M., & de Vries, W. (2013, May 27). *Consequences of human modification of the global nitrogen cycle*. Philosophical transactions of the Royal Society of London. Series B, Biological sciences. Retrieved October 27, 2022, from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3682738/

ERS-USDA. (2019, October 30). Fertilizer Use and Price. Retrieved January 11, 2022, from https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx

Fahad, S., & Fahad, A. (2018). *Corn: Production and human health in changing climate*. *Google Books*. IntechOpen.

Fang, Q., Ma, L., Yu, Q.,Malone, R.W.; Saseendran, S. A. and Ahuja L.R. (2008). Modeling nitrogen and water management effects in a wheat-maize double-cropping system. Journal of Environmental Quality, 7, 2232-2242.

Fang, Q., Yu, Q., Wang, E. (June 2006). *Soil nitrate accumulation, leaching and crop nitrogen use as influenced by fertilization and irrigation in an intensive wheat–maize double cropping system in the North China Plain*. (2006, June 1). SpringerLink. https://link.springer.com/article/10.1007/s11104-006-0055-7?error=cookies_not_supported&code=413a9a04-71f1-4c31-9a3d-19fc997aa916

Frate, C., & Schwankl, L. (n.d.). *Corn*. UC Drought Management. Retrieved October 28, 2022, from https://ucmanagedrought.ucdavis.edu/Agriculture/Crop_Irrigation_Strategies/Corn/

Fromme, D., Spivey, T.A., Grichar, W. (2019). *Agronomic Response of Corn (Zea mays L.) Hybrids to Plant Populations,* International Journal of Agronomy, vol. 2019, Article ID 3589768, 8 pages, 2019. https://doi.org/10.1155/2019/3589768

García-Lara, S., & Serna-Saldivar, S. O. (2018, November 23). Corn History and Culture. Retrieved from https://www.sciencedirect.com/science/article/pii/B9780128119716000012

Giimore, F. R. (1967). *A Historical Study of the Oklahoma Agricultural Experiment Station* (thesis).

Hanway, J. (1966, September). *How a Corn Plant Develops*. https://core.ac.uk/download/pdf/83024409.pdf

Harper, Roth, Curran, & Calvin. (1997, January 1). *Considerations for double-cropping corn following Hay in Pennsylvania*. Penn State Extension. Retrieved November 3, 2022, from https://extension.psu.edu/considerations-for-double-cropping-corn-following-hay-in-pennsylvania

Heggenstaller, A. H., Anex, R. P., Liebman, M., Sundberg, D. N., & Gibson, L. R. (2008). Productivity and nutrient dynamics in bioenergy double-cropping systems. *Agronomy Journal*, *100*(6), 1740–1748. https://doi.org/10.2134/agronj2008.0087

Heggenstaller, A. H., Liebman, M., & Anex, R. P. (2009). Growth analysis of biomass production in sole-crop and double-crop corn systems. *Crop Science*, *49*(6), 2215–2224. https://doi.org/10.2135/cropsci2008.12.0709

Hoogenboom, G., Peterson, C. M., & Huck, M. G. (1987). Shoot growth rate of soybean as affected by drought stress 1. *Agronomy Journal*, *79*(4), 598–607. https://doi.org/10.2134/agronj1987.00021962007900040003x

Jaynes, D. B. (2013). Nitrate loss in subsurface drainage and corn yield as affected by timing of sidedress nitrogen. *Agricultural Water Management*, *130*, 52–60. https://doi.org/10.1016/j.agwat.2013.08.010

Jiao, H. (2021, June 29). *Historical Relationships Suggest Rising Corn Seed Costs for 2022*. Farmdoc Daily. https://farmdocdaily.illinois.edu/2021/06/historical-relationships-suggest-rising-corn-seed-costs-+for-2022.html

Jiao, H. (2022, April 6). *Nitrogen fertilizer prices and supply in light of the Ukraine-russia conflict*. farmdoc daily. Retrieved October 27, 2022, from https://farmdocdaily.illinois.edu/2022/04/nitrogen-fertilizer-prices-and-supply-in-light-of-the-ukraine-russia-conflict.html

Kidwell, C. S. (n.d.). *Allotment*. Oklahoma Historical Society | OHS. Retrieved October 27, 2022, from https://www.okhistory.org/publications/enc/entry.php?entry=AL011

Laishram, J., Saxena, K., Maikhuri, R., & Rao, K. (n.d.). Soil quality and soil health: A review. *International Journal of Ecology and Environmental Sciences*, *38*(1). Retrieved from https://www.researchgate.net/publication/232237296_Soil_quality_and_soil_health_A_review.

Lauer, J., Porter, P., & Opilinger, E. (1997, April). *The corn and soybean rotation effect*. The Corn and Soybean Rotation Effect - Wisconsin Corn Agronomy. Retrieved November 3, 2022, from http://corn.agronomy.wisc.edu/AA/A014.aspx

Lee, C.D., D.B. Egli, and D.M. TeKrony. 2008. Soybean response to plant population at early and late planting dates in the Mid-South. Agron. J. 100:971-976.

Liu, C., Wang, K., Meng, S., Zheng, X., Zhou, Z., Han, S., Chen, D., & Yang, Z. (2011). *Effects of irrigation, fertilization and crop straw management on nitrous oxide and nitric oxide emissions from a wheat–maize rotation field in northern China.* Agriculture, Ecosystems &Amp; Environment, 140(1–2), 226–233. https://doi.org/10.1016/j.agee.2010.12.009

Lofton, J., Zander, A., Wyma, N., & Harris, C. (2021, September 15). Impacts of Winter and Summer Crop Selection on the Performance of Double-crop Systems - Oklahoma State University. Retrieved from https://extension.okstate.edu/fact-sheets/impacts-of-winter-and-summer-crop-selection-on-the-performance-of-double-crop-systems.html

Marsalis, M., Angadi, S., & Contreras-Govea, F. (2010). *Dry matter yield and nutritive value of corn, forage sorghum, and BMR forage sorghum at different plant populations and nitrogen rates.* Field Crops Research, *116*(1–2), 52–57. https://doi.org/10.1016/j.fcr.2009.11.009

NASS USDA. (2021, January 12). Annual Crop Production. Retrieved from https://www.nass.usda.gov/Statistics_by_State/Oklahoma/Publications/Recent_Reports/2021/spr-ann-crop-prod-2021.pdf

NASS USDA. (2021, June 30). Acreage. Retrieved from https://downloads.usda.library.cornell.edu/usda-esmis/files/j098zb09z/00000x092/kw52k657g/acrg0621.pdf

Nielsen, R. L. (2022, April). *Historical corn grain yields in the U.S.* Historical Corn Grain Yields in the U.S. (Purdue University). Retrieved October 27, 2022, from https://www.agry.purdue.edu/ext/corn/news/timeless/yieldtrends.html

Nielsen, R. L., Thomison, P. R., Brown, G. A., Halter, A. L., Wells, J., & Wuethrich, K. L. (2002). *Delayed Planting Effects on Flowering and Grain Maturation of Dent Corn.* Agronomy Journal, 94(3), 549–558. https://doi.org/10.2134/agronj2002.5490

Noor, M. A. (2017). Nitrogen management and regulation for optimum NUE in maize – A mini review. *Cogent Food & Agriculture, 3*(1). doi:10.1080/23311932.2017.1348214

Nunes, M. R., Karlen, D. L., Veum, K. S., Moorman, T. B., & Cambardella, C. A. (2020). Biological soil health indicators respond to tillage intensity: A US meta-analysis. *Geoderma, 369*, 114335. doi:10.1016/j.geoderma.2020.114335

Oklahoma Climatological Survey. (2012). Average date of first freeze. Retrieved from http://climate.ok.gov/index.php/climate/map/average_date_of_first_freeze/oklahoma_climate

Randall, G. W., Vetsch, J. A., & Huffman, J. R. (2003). Corn production on a subsurface-drained Mollisol as affected by time of nitrogen application and nitrapyrin. *Agronomy Journal*, *95*(5), 1213–1219. https://doi.org/10.2134/agronj2003.1213

Ranum, P., Peña-Rosas, J. P., & Garcia-Casal, M. N. (2014). Global maize production, utilization, and consumption. Annals of the New York Academy of Sciences, 1312(1), 105-112. doi:10.1111/nyas.12396

Ritchie, S.W., Hanway, J.J., and Benon, G.O. (1993). How a maize plant develops. Sp. Rpt. No. 48. Iowa State University of Science and Technology. Co-operative Extension Services, Ames, IA.

Saavoss, M., Capehart, T., McBride, W., & Effland, A. (2021, July). *Trend in Production Practices and Costs of the U.S. Corn Sector*. https://www.ers.usda.gov/webdocs/publications/101722/err-294.pdf?v=2482.5

Sutton, M. A., Oenema, O., Erisman, J. W., Leip, A., van Grinsven, H., & Winiwarter, W. (2011, April 10). *Too much of a good thing*. Nature News. Retrieved October 27, 2022, from https://www.nature.com/articles/472159a

The response of leaf photosynthesis and dry ... - wiley online library. (2008, March). Retrieved October 27, 2022, from https://acsess.onlinelibrary.wiley.com/doi/full/10.2135/cropsci2007.06.0366

The role of information and prices in the nitrogen fertilizer ... - JSTOR. (n.d.). Retrieved October 27, 2022, from https://www.jstor.org/stable/23243524

Tollenaar, M. (1977). Sink source relationships during reproductive development in maize: A review. Maydica, 22, 49-75.

Travis, P. D., & Robb, J. B. (n.d.). *Corn*. Oklahoma Historical Society | OHS. Retrieved October 27, 2022, from https://www.okhistory.org/publications/enc/entry.php?entry=CO059#:~:text=By%20the%20late%201890s%20corn%20surpassed%20all%20other,the%20southern%2C%20central%2C%20and%20southeastern%20sectors%20of%20Oklahoma

Troyer, A.F. (1999), Background of U.S. Hybrid Corn. Crop Science, 39: 601-626 cropsci1999.0011183X003900020001x. https://doi.org/10.2135/cropsci1999.0011183X003900020001xa

USDA. (n.d.). *Census of Agriculture: 1940*. United States Department of Agriculture Census of Agriculture Historical Archive. Retrieved October 28, 2022, from https://agcensus.library.cornell.edu/census_parts/1940-field-crops-and-vegetables/

Westgate, M.E,Forcella, F., Reicosky, D.C., and Somsen, J. (1997). Rapid canopy closure for maize production in the northern US Corn Belt: Radiation use efficiency and grain yield. Field Crops Research, 49, 249-258.

Yao, Z., Yan, G., Zheng, X., Wang, R., Liu, C., & Butterbach-Bahl, K. (2017). Reducing N2O and NO emissions while sustaining crop productivity in a Chinese vegetable-cereal double cropping system. *Environmental Pollution*, *231*, 929–941. https://doi.org/10.1016/j.envpol.2017.08.108

Zhang, L., Wang, R., & Hesketh, J. D. (2001). Effects of photoperiod on growth and development of soybean floral bud in different maturity. *Agronomy Journal*, *93*(4), 944–948. https://doi.org/10.2134/agronj2001.934944x

Zuber, S. M., & Villamil, M. B. (2016). Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities. *Soil Biology and Biochemistry, 97*, 176-187. doi:10.1016/j.soilbio.2016.03.011

VITA

Rhiannon Nichole Wyma

Candidate for the Degree of

Master of Science

Thesis: CORN GRAIN YIELD RESPONSE TO NITROGEN RATE AND PLANT POPULATION IN FULL AND DOUBLE-CROP SYSTEMS

Major Field: Plant and Soil Sciences

Biographical:

Education:

Completed the requirements for the Master of Science in Plant and Soil Science at Oklahoma State University, Stillwater, Oklahoma in December, 2022.

Completed the requirements for the Bachelor of Science in Plant and Soil Science at Oklahoma State University, Stillwater, Oklahoma in 2020.

Experience:

2020-2022 – Graduate Research Assistant – Oklahoma State University

2017-2020 – Laboratory, Greenhouse, and Field Assistant (Hourly) – Oklahoma State University

Summer 2018 – Undergraduate Internship – Crop Quest Agronomic Services Inc.

Professional Memberships:

American Society of Agronomy

Crop Science Society of America

Soil Science Society of America