AGRONOMIC AND NUTRIENT MANAGEMENT STRATEGIES TO IMPROVE WINTER WHEAT AND SUGARBEET PLANT GROWTH, YIELD, AND QUALITY

By

Seth James Purucker

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Crop and Soil Sciences – Master of Science

2020

ABSTRACT

AGRONOMIC AND NUTRIENT MANAGEMENT STRATEGIES TO IMPROVE WINTER WHEAT AND SUGARBEET PLANT GROWTH, YIELD, AND QUALITY

By

Seth James Purucker

Inconsistent winter wheat (*Triticum aestivum* L.) grain yield responses multiple-input management has generated grower interest in focusing input applications within decreased seeding rates. Field trials were initiated in Richville and Lansing, MI to evaluate the effects of seeding rate, fungicide, plant growth regulator, autumn starter fertilizer, weekly nitrogen (N) applications, and high N management on winter wheat plant growth, grain yield, and expected net return within enhanced (i.e. all inputs) and traditional management (i.e. individual input). Enhanced management increased grain yield 1.2-2.3 Mg ha^{-1} compared to traditional management in three of four site-years. Despite grain yield increases, expected net return was maximized when utilizing traditional management with only a recommended rate of N.

Management practices, such as plant population, N rate, row spacing, and subsurface banded N, have changed as sugarbeet (*Beta vulgaris* L.) tonnage has increased over the past 10 years, however climatic variability continues to influence sugar production. Two separate field studies were initiated to 1) evaluate plant population, N rate, and subsurface banded N and 2) determine whether row spacing affects the need for subsurface banded N. Across tested N rates, 179 kg N ha^{-1} produced optimal root yield, quality, and expected net return. Benefits from subsurface banded N existed under dry May-June conditions. Row spacing of 56 cm increased root yield compared to 76 cm rows. Sugarbeet response to management practices may be influenced heavily by environmental conditions and environmental trends should be considered when deliberating management strategies.

Dedicated to my family, colleagues, and friends whom have offered their love, support, and guidance along the way.

ACKNOWLEDGEMENTS

Experiencing the soil fertility and nutrient management program at Michigan State University has been an invaluable adventure. First, I would like to thank my advisor Dr. Kurt Steinke for this extraordinary opportunity. I will always think back on my experience in your program and admire your expertise, guidance, and support. I would also like to thank my committee members Dr. Martin Chilvers and Dr. Maninder Singh for their advice and quidance with my projects.

To the soil fertility research technician Andrew Chomas, thank you for your mentoring, advice, and assistance. I will always remember your guidance and offering of an ice-cold soda after a long day at the Saginaw Valley Research and Extension Center. Thank you to the MSU Farm staff Mike Particka, Tom Galecka, John Calogero, Paul Horny, and Dennis Fleischmann for your coordination and support of field projects. Thank you to the graduate students Taylor Purucker, Christian Terwillegar, Sarah MacDonald, and Dr. Jeff Rutan for field support and friendships.

Additionally, I would like to thank the Purucker, Smuda, and Mikula families for their limitless encouragement, love, and support. The best for last, I would like to thank Hannah Mikula for your unconditional love. You have been my biggest supporter and encourager and have done so with patience and understanding. I will forever be grateful to have experienced this journey with you.

TABLE OF CONTENTS

LIST OF TABLES

CHAPTER 1

LITERATURE REVIEW

Wheat Classification

Wheat consists of six classifications that are determined from plant physical factors, such as seed hardness (hard or soft), vernalization (winter or spring), and color of the kernel (red or white) (Sherman et al., 2008). Spring wheat is planted in the spring and harvested in early fall; winter wheat is planted in the fall, stays dormant during winter, and is harvested in July (Yu, 2015). Red refers to the red, or brown, color of the seed coat; white refers to the lack of the red, or brown color, and is a tan or yellow color (McFall and Fowler, 2009). The six classifications of wheat are soft red, soft white, hard red spring, hard red winter, hard white, and durum (Sherman et al., 2008). Previously, wheat consisted of only five categories until the United States recognized hard white wheat as the sixth class (Lin and Vocke, 2004). A variety of products use wheat as an ingredient, such as bread, pasta, cakes, and flour (Yu, 2015). The great lakes region is predominantly where soft white winter wheat is grown for milling and cereal purposes due to better color and less bitterness compared to soft red winter wheat (Yu, 2015). Hard white wheat possesses exceptional color genes, which is why many types of Asian noodles use it as a main ingredient (Miskelly, 1984). Wheat in Michigan typically grows best when the proceeding crop is soybeans, dry edible beans, or silage corn due to earlier harvest date of these crops and the ability to plant wheat at an optimum planting date (Warncke et al., 2009). In 2012, Michigan consisted of 40% soft white wheat and 60% soft red wheat of total wheat planted acres (Nagelkirk and Black, 2012).

Breeding white wheat can be difficult due to kernel color genetics (Sherman et al., 2008). When comparing red to white wheat, red is the dominate color gene due to the single locus containing the dominate allele; this makes breeding white wheat more difficult than red wheat. Breeding three recessive alleles will result in white wheat (Metzger and Silbaugh, 1970). On chromosomes 3A, 3B, and 3D, three independent homoeologous genes determine the color of the seeds outer layer, which is red or white (Sherman et al., 2008). Breeding programs across different regions apply more resources to improving red wheat genetics, rather than white wheat, due to the fact more growers demand improved red varieties and resulting in red wheat lines with increased agronomic performance over white wheat (Sherman et al., 2008).

The color of the seed coat, or seed coat genetics, influences pre-harvest sprouting (PHS) resistance or susceptibility (Brown et al., 2018). Red seed coat genetics tend to show more pre-harvest sprouting resistance and is used as a genetic marker when breeding for resistance (Groos et al., 2002). Pre-harvest sprouting happens when the grain head germinates prior to harvest, caused by early breaking of dormancy (Groos et al., 2002). Pre-harvest sprouting is more common in white wheat compared to red wheat (Yu et al., 2015). Grain test weight decreases when pre-harvest sprouting occurs; more importantly, it significantly decreases the bread making quality of the flour (Groos et al., 2002). Flour milled from sprouted wheat decreases its thickening power. Several products cannot use milled wheat where pre-harvest sprouting occurs (Mansour 1993; Groos et al., 2002).

Michigan Wheat Production

Wheat is grown more widely across the world than any other commercial crop and is the second grown food crop, behind rice (FAO, 2002; Yu, 2015). Out of total wheat production, less than 20% is exported from the producing country (McFall and Fowler, 2009). In Michigan, the total value of soft wheat food products was more than $3.9 billion in 2002 (Peterson et al., 2006). Michigan wheat yield ranked first in the Midwest from 2012 to 2014 and consistently ranks top five nationally; in 2015, 5447 kg ha^{-1} created a new state record in Michigan (USDA-NASS, 2014, 2015). The total production value of wheat in Michigan reached $164 million in 2017, according to the National Agriculture statistics service. In 2017, Michigan yielded 5312 kg ha^{-1}, which ranked fourth best nationally compared to the United States average of 3093 kg ha^{-1}, and accounted for 1.13% of total wheat acres harvested across the United States and (USDA-NASS, 2017). Again in 2018, Michigan yielded higher than the United States average wheat grain yield, producing 5111 kg ha^{-1} grain yield as a state, compared to the United States average of 3201 kg ha^{-1} grain yield, which ranked fourth best nationally for the second consecutive year (USDA-NASS, 2018). The future of keeping wheat in a three year (corn-soybean-wheat) rotation depends on if wheat can keep its competitiveness, relative to corn and soybeans, as a commodity and keep pace with increases of corn and soybean yield (Brinkman et al., 2014). Increased awareness of inconsistent spring weather, along with yield potential, has prompted Michigan producers to invest in enhanced wheat management practices to increase wheat grain yield (Swoish and Steinke, 2017).

Enhanced Wheat Management

Growers may feel pressured for midyear cash flow, which has led to increased interest in research of wheat inputs and their return on investment (Karlen and Gooden, 1990). Previous research on enhanced (i.e. multiple-input) wheat management focuses on high nitrogen rates and wheat varieties for insect and disease resistance (Karleen and Gooden, 1990). The purpose of enhanced management in wheat is to control yield-limiting factors by changing several management practices (Harms et al., 1989). Management practices such as planting date, seeding rate, fungicide application, N management, and plant growth regulators are determining factors of wheat grain yield and careful attention to the timing of applications is important; however high wheat yields are obtainable without all factors (Geleta et al., 2002; Beuerlein et al., 1989; Karlen and Gooden, 1990). Fungicides are included in enhanced wheat management programs to limit grain yield loss from foliar diseases (Beuerlein et al., 1989). Enhanced wheat management typically incudes increased nitrogen rates, which increases chance of lodging (Roth and Marshall, 1987). Adding plant growth regulators to an enhanced wheat management program can reduce lodging and may increase grain yield when increased N rates are applied, or a tall variety is selected (Beuerlein et al., 1989). Increasing grain yield depends on identifying yield-limiting factors; Current recommendations, derived from research studies with only one or two input factors at a time, may not show maximum economic grain yields (Brinkman et al., 2014). Using an enhanced management wheat program may show less economic return than a traditional management program of standard nitrogen rates, low seeding rates, and no use of a plant growth regulator or fungicide (Mohamed et al., 1990). Karlen and Gooden (1990) studied enhanced wheat management compared to traditional wheat management and found no significant results when comparing grain yield between the two management intensities.

According to Michigan State University Extension, in 2016 Michigan wheat production had an estimated net return on investment of US$277.89 ha^{-1} at 5380 kg ha^{-1} and US$0.183 kg^{-1} cash wheat price (Stein, 2016). Nebraska extension estimated only a profit of US$61.77 ha^{-1} at 4708 kg ha^{-1} grain yield and US$0.172 kg^{-1} cash price, with the use of a fungicide at Feekes 6 in wheat before corn on dryland crop rotation (Klein et al., 2017). Klein et al. (2017) also estimated a loss of US$11.11 ha^{-1} at 5716 kg ha^{-1} grain yield and US$0.172 kg^{-1} cash price, with the use of a fungicide at Feekes 6 in a wheat no-till system under irrigation. Quinn and Steinke (2019) researched an intensive management system compared to a traditional management system; the intensive management system included urease inhibitor, nitrification inhibitor, plant growth regulator, fungicide, foliar micronutrients, and an increased N rate while the tradition management system included only a base N rate. They found using an intensive management, compared to traditional management, reduced profitability US$205.27 ha^{-1} and US$250.60 ha^{-1} in soft white winter wheat in 2016 and 2017, respectively, and US$211.80 ha^{-1} in soft red winter wheat in 2017.

Utilizing an enhanced wheat management program, Joseph et al. (1985) reported as seeding rate increased, heads per unit area increased, kernels per head decreased, and kernel weight decreased. Multiple inputs are often viewed as prophylactic and consistently fail to increase grain yield in Michigan wheat production while often decreasing profitability (Quinn and Steinke, 2019). In most marketing scenarios, multiple-input wheat management systems are economically inefficient (Jaenisch et al., 2019).

Seeding Rate

The three components that make up grain yield are heads per unit area, kernels per head, and grain test weight (Joseph et al., 1985). An increased seeding rate can increase the number of heads per unit area, but also decrease the number of kernels per head and grain test weight (Darwinkel et al., 1977). The number of heads per unit area is dependent on the plant population and number of tillers per plant; decreased seeding rates increase the number of tillers per plant, however, increased seeding rates produce more tillers per unit area (Darwinkel, 1978; Power and Alessi, 1978; Joseph et al., 1985). At increased seeding rates, the percentage of tillers that produce healthy grain heads is low; however, 100% tiller survival does not occur even at decreased seeding rates (Joseph et al., 1985). Darwinkel (1983) found that the most important factor in determining grain yield was kernels per head.

Growers are easily able to manage seeding rate, which is a contributing factor when determining grain yield. Seeding rates vary to help the crop capture available nutrients and sunlight to optimize yield (Lloveras et al., 2004; Isidro-Sánchez et al., 2017). Increased seeding rates decrease weed competition, however, new modern chemistry typically achieves adequate weed control (Fischer and Miles, 1973; Davies and Welsh, 2002). Increased seeding rates create a favorable enjoinment for disease, which causes grain yield loss, and decreases standability due to weakening of the stems, known as lodging (Pinthus, 1973). Joseph et al. (1985) observed seeding rates from 186 seeds m^{-2} to 558 seeds m^{-2} produced optimal grain yield. At increased seeding rates, Roth et al. (1984) found optimum grain yields are obtained when wheat produces on average 1.2 tillers or more per plant.

By utilizing the correct seeding rates, grain yield can increase leading to a higher economic net return (Bhatta et al., 2017). Joseph et al. (1985) found the optimum seeding rate across two locations was between 372-558 seeds m^{-2}. The lower portion of the seeding rates observed increased yield compared to the higher portion of the seeding rates due to better light interception as well as less plant competition for moisture and nutrients in the soil (Joseph et al., 1985). At four site years, Bhatta et al. (2017) found seeding rates of 372-504 seeds m^{-2} increased grain yield 280 kg ha^{-1} compared to seeding rates between 186-252 seeds m^{-2} and the higher seeding rates increased profitability US$27.16 ha^{-1} compared to the lower seeding rates. In contrast, Geleta et al. (2002) found a seeding rate of 242 seeds m^{-2} produced the highest yield.

Research in North Dakota from Black and Bauer (1990) suggested a seeding rate of 120 seeds m^{-2} achieves maximum grain yield, while Holen et al. (2001) found 140 seeds m^{-2} achieved maximum grain yield.

Results from Stapper and Fischer (1990) showed as seeding rate increased from 50 kg ha^{-1} to 200 kg ha^{-1}, more plant competition at higher seeding rates led to weaker stems and increased lodging. Geleta et al. (2002) found plant height increased by an average of 3.2 cm at the higher seeding rate at a seeding rate of 65 kg ha^{-1} compared to 16 kg ha^{-1} due to the higher seeding rate producing fewer secondary tillers, which made the plant taller. In contrast, Wilson and Swanson (1962) found that seeding rates below 50 kg ha^{-1} produced the tallest plant height. Research in North Dakota from Black and Bauer (1990) suggested a seeding rate of 120 seeds m^{-2} achieves maximum grain yield, while Holen et al. (2001) found 140 seeds m^{-2} achieved maximum grain yield.

Plant Growth Regulator

Wheat growers utilize plant growth regulators (PGR) in their management practices to reduce lodging and improve harvestability (Swoish and Steinke, 2017). Roots not being able to anchor the plant near the culm base cause wheat plants to lodge which creates harvest difficulty due to the plant falling over and being lower than the combine head (Pinthus, 1974; Harms et al., 1989). Lodging increases grain yield loss due to threshing difficulties resulting in kernels remaining on the soil surface (Knapp et al., 1987). The first plant growth regulator registered for wheat in the United States was ethephon [(2-chloroethyl) phosphonic acid], chlormequat chloride or CCC (2-chloroethyl-N,N,N-trimethyl ammonium chloride) (Harms et a;., 1989).

Palisade EC (Syngenta) (trinexapac-ethyl) {ethyl 4-[cyclopropyl(hydroxyl)methylene]-3,5-dioxocyclohexane1-carboxylate} is a common PGR labeled to reduce plant height, which decreases the risk of lodging (Swoish and Steinke, 2017). Trinexapac-ethyl inhibits the formation of active gibberellins, resulting in increased stem strengthening and decreased plant height (Rademacher, 2000: Matysaik, 2006). Swoish and Steinke (2017) found PGR application timing does not significantly affect grain yield when comparing Feekes 7 to Feekes 8 application timing. Previous studies show similar results of no difference in grain yield when comparing PGR application timing of Feekes 5 to Feekes 8 or Feekes 6 to Feekes 7 (Penckowski et al., 2009; Wiersma et al., 2011). Knott et al. (2016) found PGR applications did not affect grain yield. Similarly, Quinn and Steinke (2019) found no difference in grain yield across four site years in both an intensive multiple input system and a traditional single input system, however PGR application on soft red winter wheat decreased profitability US$94.68 ha^{-1} in 2017 when added to traditional management and increased profitability US$80.51 ha^{-1} in 2017 when removed from intensive multiple input management.

Swoish and Steinke (2017) found that PGR application reduced plant lodging by 50-83% in three out of four site years, and increased grain yield 403 and 322 kg ha^{-1} in 2012 and 2014, respectively (Swoish and Steinke, 2017). In contrast, Karlen and Gooden (1990) found that yield decreased from 6059 kg ha^{-1} to 5823 kg ha^{-1} when PGR was applied compared to no PGR application. Beuerlein et al. (1989) found grain yield decreased 255 kg ha^{-1} when using a PGR rate of 0.42 kg a.i. ha^{-1} compared to 0.28 kg a.i. ha^{-1}. Similarly, Nafziger et al. (1986) found grain yield decreased 420 kg ha^{-1} when plant growth regulator rate was increased from 0.28 kg ha^{-1} to 0.56 kg ha^{-1}. If wheat does not lodge during the growing season, no yield response from a PGR will occur (Swoish and Steinke, 2017).

Nitrogen Management

Nitrogen (N) is a main factor for productivity and proper growth in winter wheat (Frink et al., 1999). Grain yield in winter wheat can be limited when insufficient rates of N are applied, or N leaves the rhizosphere (Nielsen and Halvorson, 1991). Dry soil conditions in early spring limit N movement down into the soil, which can cause N deficiencies from volatilization (Balkcom et al., 2003). Efficient use of nitrogen fertilizer is essential to produce optimal grain yield while maximizing profitability, while excessive N fertilization can create environmental contamination (Gravelle et al., 1988). Proper N management is necessary to economically improve grain yields (Bhatta et al., 2017). Modern wheat varieties show improved response to nitrogen fertilizer applications compared to older varieties (Brinkman et al., 2014). Grain yield increased by an average of 9.6% when N was applied compared to treatments without any N in 2014; Applying 34 kg ha^{-1} N at the flag leaf stage increased grain yield in 2014, but not 2015 due to heavy rainfall (Bhatta et al., 2017). In Wisconsin, Mourtzinis et al. (2017) found 48 kg N ha^{-1} resulted in the highest grain yield in two out of three site years.

As N rate increases, above ground biomass and root growth increases (Nielsen and Halvorson, 1991). Plant growth and tiller survival can be influenced by the timing and amount of N applied (Chen et al., 2008). In Europe, Dilz (1971) found two split applications of 99 kg N ha^{-1} at Feekes 3 (Greenup) and Feekes 6 (first node detectable) timing increased yield 1210 kg ha^{-1} compared to a single application of 198 kg N ha^{-1} at Feekes 3. Dilz et al. (1982) also found two split applications of 50 kg N ha^{-1} at Feekes 3 and Feekes 6 increased grain yield 605 kg ha^{-1} compared to a single application of 100 kg N ha^{-1} at Feekes 3. Gravelle et al. (1988) found that splitting N applications increased grain yield 740 kg ha^{-1} compared to a single N application, however, no yield difference was found when comparing two split N applications to three N split applications. Split applying N may decrease lodging compared to applying all nitrogen at once and may increase grain yield on soils with a high probability of leaching or denitrification loss during tillering stage (Gravelle et al., 1988).

Insufficient amounts of N during accelerated N uptake by winter wheat can reduce grain yield and growers can increase profitability by adjusting N applications to optimize N uptake (Roberts et al., 2004). Previous studies show N applications at Feekes 4 to Feekes 6 increase grain yields compared to later applications (Large, 1954; Alcoz et al., 1993; Roberts et al., 2004), while Boman et al. (1995) found N can be applied at later growth stages (Feekes 7) without decreasing grain yield. However, the optimum rate and timing of N applications can be highly variable due to unpredictable and variable weather in Michigan (Nagelkirk, 2016). Recommended N rate can change due to residual soil N from the preceding crop in a multiple crop rotation, such as wheat following soybeans (Mourtzinis et al., 2017). Wheat removes 0.019 kg N kg^{-1} wheat in the grain, and the wheat N recommendation in Michigan grown on mineral soils is A + (B*YP) where A=-13, B=1.33, and YP=yield potential (Warncke et al., 2009). The Tri-State fertilizer recommendations use the equation [(YP-50) x 1.75] + 40 (Vitosh et al., 1995). Yield potential is the amount of grain a grower aims to produce (Arnall et al., 2013). Michigan State University recommendations suggest no more than 28.02 kg N ha^{-1} should be applied in autumn to promote tillering (Warncke et al., 2009). Grant et al., (1985) found maximum grain yield was obtained when 120 kg N ha^{-1} was applied in autumn and followed with 60 kg N ha^{-1} in the spring. In Michigan, Quinn and Steinke (2019) found no yield response to an increased 20% N rate compared to University recommended N rate in both soft white winter wheat and soft red winter wheat in four site years.

Fungicide

Many wheat growers view fungicide applications as a prophylactic despite disease presence due to more concern of yield loss compared to profit loss (Mourtzinis et al., 2017; Quinn and Steinke, 2019). Foliar diseases of winter wheat can occur at economically damaging levels by decreasing grain yield (Wegulo et al., 2011). Economic return will vary from fungicide application depending on how disease intensity and variety characteristics impact grain yield (Bhatta et al., 2018). The decision to apply a fungicide to protect grain yield loss is based off disease severity, variety susceptibility, and environmental factors (Nelson and Meinhardt, 2011; Mourtzinis et al., 2017).

Foliar diseases can limit winter wheat yield potential and growers often use foliar fungicides to counter grain yield loss (Bhatta et al., 2018). Fusarium head blight of wheat, caused by *Fusarium graminearum*, is one of the most common diseases in winter wheat which can decrease yield and lower the quality of the grain by decreasing the test weight (Paul et al., 2010). Conditions that favor Fusarium head blight development in winter wheat consist of wet, humid weather (Paul et al., 2010). Other yield damaging diseases controlled by fungicides in wheat include powdery mildew (*Erysiphe graminis*), septoria leaf blotch (*Mycosphaerella graminicola*), and leaf rust (*Puccinia recondite*) (Harms et al., 1989). Since the 1990s, it is estimated that total Fusarium head blight grain yield losses were around $3 billion (Schemann and D’Arcy, 2009; Bhatta et al., 2018).

Several studies have shown that at least one application of fungicide prevent wheat grain yield loss by controlling disease, however fungicide applications may not always be economical due to uncertainty of disease pressure, weather conditions, and fungicide response (Brinkman et al., 2014). Grain prices at the local elevator also significantly influence the economic profitability of a fungicide application (Paul et al., 2010). Blandino et al. (2006) found application of a triazole fungicide at Feekes 10 decreased mycotoxin deoxynivalenol (DON) grain levels 30% and increased grain yield 17.7%. Paul et al. (2010) showed grain yield from the untreated check ranged from 1118 kg ha^{-1} to 7344 kg ha^{-1} in soft red winter wheat, while fungicide treated grain yield ranged from 1344 kg ha^{-1} to 7512 kg ha^{-1}.

In Nebraska, Bhatta et al. (2018) found that foliar fungicide application at Feekes 9 increased seed test weight 7.1 and 16.8% at two different locations due to increasing the grain fill period by protecting the flag leaf surface from disease compared to the untreated. Haidukowski et al. (2012) found application of a prothioconazole {2-[2-(1-chlorocyclopropyl)0–3-(2-chlorophenyl)-2-hydroxypropyl]-1, 2-dihydro-3H-1, 2, 4-triazole-3-thione} and tebuconazole {α-[2-(4-chlorophenyl)ethyl]-α-(1,1-dimethylethyl)-1H-1, 2, 4-triazole-1-ethanol} fungicide at the beginning of anthesis, or flowering, increased grain yield 2730 kg ha^{-1} while reducing disease severity 93%. Mourtzinis et al. (2017) found in Wisconsin, fungicide application increased grain yield 7.4-16.8% compared to no fungicide application across three site years, despite low disease severity. Bhatta et al. (2018) also found fungicide application increased grain yield 10.0-28.9% at three site years due to healthier leaf surfaces. Bhatta et al. (2018) results show foliar fungicide application increased profitability US$139-144 ha^{-1} and US$101-106 ha^{-1} in 2014 and 2015, respectively. In Michigan, Quinn and Steinke (2019) showed a triazole based fungicide application increased grain yield 0.75 Mg ha^{-1} compared to no fungicide application, and decreased flag leaf disease presence 15% in 2016 on soft red winter wheat. They concluded fungicide applications are only responsive with the presence of adverse conditions driving disease pressure. Jaenisch et al. (2019) found addition of fungicide to traditional control increased yield 0.8-2.2 Mg ha^{-1}. At two locations, removal of fungicide from enhanced control decreased yield 1.3-1.8 Mg ha^{-1} in 2016 and 1.4-2.0 Mg ha^{-1} in 2017. High disease pressure in all four site-years attributed to the positive effect of fungicide application.

Profitability of a fungicide application is dependent on weather conditions throughout the season, susceptibility of the variety to disease, and presence of disease after the application (Sutton and Roke, 1986; Brinkman et al., 2014; Thompson et al., 2014). Selection of a disease-resistant variety may be more profitable than applying fungicides during the growing season, as grain yield response is dependent on the level of disease resistance of the variety (Karlen and Gooden, 1990; Harms et al., 1989). When disease pressure was high, Wegulo et al. (2011) reported profit increased US$183 ha^{-1} with a foliar fungicide application, however profit increased only US$6 ha^{-1} when disease pressure was low. Opportunity for profitable fungicide applications may exist when using low-cost fungicides and marketing wheat with a protein premium (Jaenisch et al., 2019).

Zinc

Positive grain yield response to zinc (Zn) fertilizer applications depend greatly on the wheat variety utilized (Ranjbar and Bahmaniar, 2007). Zinc moves to plant roots mostly through diffusion, when ions move across a concentration gradient from high to low concentrations (Halvin et al., 2013). Zinc fertilization to winter wheat not only can increase grain yield but also increase the zinc nutritional value of the grain (Arif et al., 2017). Zinc deficiency in wheat grain can lead to zinc deficiency in humans who consume a large cereal diet (Arif et al., 2017). In small grains such as winter wheat, the midrib of new leaves becomes chlorotic when zinc is deficient (Havlin et al., 2013). Increased purity of N, P, and K fertilizers, along with increased crop production intensity, likely have led to increased zinc deficiencies in wheat grain worldwide

(Curtin et al., 2008). However, Warncke et al. (2009) defines winter wheat as being non-responsive to zinc fertilizer applications to increase grain yield in Michigan.

Soils with low organic matter and high pH typically show zinc deficiencies, and zinc concentrations can be raised with soil applied insoluble zinc granular fertilizers (Ranjbar and Bahmaniar, 2007). Zinc applications through the soil are more effective than foliar applications for increasing grain zinc levels (Alloway, 2009; Lu et al., 2012). Zinc is more concentrated in the phloem compared to the xylem, indicating foliar applications of zinc may increase zinc levels in plant tissue compared to soil applications, which may or may not remobilize to the grain (Marschner, 1995). In calcareous soils, zinc from fertilization often binds to soil minerals becoming immobilized and unavailable to the plant, showing more benefit to foliar applications of zinc in this soil type. (Lu et al., (2012). Ranjbar and Bahmaniar (2007) saw a positive grain yield response to 15 kg Zn ha^{-1} when soil applied, they also found 15 kg Zn ha^{-1} soil applied increased the number of tillers and 10 kg Zn ha^{-1} soil applied increased 1000 seed weight. Similarly, Arif et al. (1017) found that 15 kg Zn ha^{-1} produced maximum tillers and plant height. In contrast, Curtin et al. (2008) results showed zinc soil applied had no consistent effect on grain yield, even when soil test zinc concentration was defined as deficient.

Sulfur

Modern high yielding wheat varieties remove more secondary macronutrients nutrients than the amount of nutrients supplied through common fertilizer practices (Chatterjee, 2018). Sulfur (S) is a secondary macronutrient required for plant growth, similar to nitrogen, phosphorus, potassium, calcium, and magnesium (Dick et al., 2008). Sulfur is composed of amino acids, cysteine, and methionine (Dick et al., 2008). When S is deficient, the content of S amino acids decreases, resulting in synthesis of proteins being inhibited (Marschner, 1995). Soils that tend to show sulfur deficiencies are typically low in organic matter, well drained, coarse textured, and subject to leaching (Dick et al., 2008). Sulfur can be mineralized from soil organic matter to become plant available and is a major contributor for meeting a plant's S requirements (Naeem, 2008). Since winter wheat is grown in the cooler months during the year (April-May), insufficient amounts of S are supplied through organic matter due to the low rates of organic matter mineralization when temperatures are below 10°C (Mascagni et al., 2008). The amount of organic S in the soil determines the total plant available S released by mineralization of organic matter (Dick et al., 2008).

Wheat adsorbs sulfur in the form of sulfate (Naeem, 2008). Sulfur compounds, such as elemental S, oxidize to sulfate in the soil to become plant available (Dick et al., 2008). Common inorganic fertilizers used containing S include: elemental sulfur (0-0-0-80S), gypsum (0-0-0-18S), ammonium sulfate (21-0-0-24S), ammonium thiosulfate (12-0-0-26S), and potassium sulfate (0-0-42-18S) (Dick et al., 2008). Organic sources containing S include: biosolides (0.3-1.2% S), poultry manure (0.5% S), sheep manure (0.35% S), dairy manure (0.22% S), and crop residues (0.10-0.22% S) (Dick et al., 2008).

Sulfur fertilizer applications have decreased worldwide, while S removal from the soil has increased, causing more S deficiencies in wheat (Dick et al., 2008). Highly concentrated fertilizers which may contain minimal S have decreased the quantity of S applied through inorganic fertilizer (Scherer, 2001). However in the past 5 years, S inputs are increasing due to less S deposition in the air (National Atmospheric Deposition Program, 2007). Increased S removal from the soil is due to increased use of enhanced cropping systems that increase grain yields, as higher grain yields remove more total S from the soil (Ohio Department of Agriculture, 2006; Dick et al., 2008). Higher grain yields in the past several years have led to approximately

18-50% more total S removal from the soil by crops, compared to 25 years ago (Dick et al., 2008).

Sufficient and timely S fertilization is an essential component in wheat management (Mascagni et al., 2008). An addition of 15-20 kg SO_{4-} ha^{-1} of typically fulfills the S requirement for winter wheat (Naeem, 2008). Feyh and Lamind (1992) found that wheat grain yield had no response to autumn S fertilization, however S application increased plant tissue S concentration at Feekes 5. When sulfur was spring applied, Mascagni et al. (2008) found grain yield increased 1162 kg ha^{-1}, while autumn applied S did not affect grain yield. The optimum spring rate in both years was 11.2 kg SO_{4-} ha^{-1} (Mascagni et al., 2008). Mascagni et al. (2008) also found spring applied S increased spring tillering 28% compared to no S fertilization. Oates and Kamprath (1985) found at one location 45 kg S ha^{-1} and 90 kg S ha^{-1} applied as gypsum produced the highest grain yield, but spring versus fall applied did not affect grain yield.

LITERATURE CITED

LITERATURE CITED

Alcoz, M.M., F.M. Hons, and V.A. Haby. 1993. Nitrogen fertilization timing effects on wheat production, nitrogen uptake efficiency, and residual soil nitrogen. Agron. J. 85:1198–1203. Econometrica 24:257–263.

Alloway, B.J. 2009. Soil factors associated with zinc defi ciency in crops and humans. Environ. Geochem. Health 31:537–548. doi:10.1007/s10653-009-9255-4

Arif, M., Tasneem, M., Bashir, F., Yaseen, G. and Anwar, A. 2017. Evaluation of different levels of potassium and zinc fertilizer on the growth and yield of wheat. *Int J Biosen Bioelectron*, *3*(2), pp.1-5.

Arnall, D. B., A. P. Mallarino, M. D. Ruark, G. E. Varvel, J. B. Solie, M. L. Stone, J. L. Mullock, R. K. Taylor, and W. R. Raun. 2013. Relationship between grain crop yield potential and nitrogen response. Agron. J. 105:1335-1344. doi:10.2134/agronj2013.0034

Balkcom, K.S., A.M. Blackmer, D.J. Hansen, T.F. Morris, and A.P. Mallarino. 2003. Testing soils and cornstalks to evaluate nitrogen management on the watershed scale. J. Environ. Qual. 32(3):1015–1024. doi:10.2134/jeq2003.1015

Beuerlein, J. E., E. S. Oplinger, and D. Reicosky. 1989. Yield and yield components of winter wheat cultivars as influenced by management—A Regional Study. J. Prod. Agric. 2:257-261. doi:10.2134/jpa1989.0257

Bhatta, M., K. M. Eskridge, D. J. Rose, D. K. Santra, P. S. Baenziger, and T. Regassa. 2017. Seeding rate, genotype, and topdressed nitrogen effects on yield and agronomic characteristics of winter wheat. Crop Sci. 57:951-963. doi:10.2135/cropsci2016.02.0103

Bhatta, M., T. Regassa, S. N. Wegulo, and P. S. Baenziger. 2018. Foliar fungicide effects on disease severity, yield, and agronomic characteristics of modern winter wheat genotypes. Agron. J. 110:602-610. doi:10.2134/agronj2017.07.0383

Black, A.L., and A. Bauer. 1990. Stubble height effect on winter wheat in the northern Great Plains: I. Soil temperature, cold degree-Hhours, and plant population. Agron. J. 82(2):200–205. doi:10.2134/agronj1990.0 0021962008200020006x

Blandino, M., L. Minelli, and A. Reyneri. 2006. Strategies for the chemical control of Fusarium head blight: Effect on yield, alveographic parameters and deoxynivalenol contamination in winter wheat grain. Eur. J. Agron. 25:193–201. doi:10.1016/j.eja.2006.05.001

Boman, R.K., R.L. Westerman, W.R. Raun, and M.E. Jojola. 1995. Time of nitrogen application: Effects on winter wheat and residual soil nitrate. Soil Sci. Soc. Am. J. 59:1364–1369.

Brinkman, J. M. P., W. Deen, J. D. Lauzon, and D. C. Hooker. 2014. Synergism of nitrogen rate and foliar fungicides in soft red winter wheat. Agron. J. 106:491-510. doi:10.2134/agronj2013.0395

Brown, L.K., A.T. Wiersma, and E.L. Olson. 2018. Preharvest sprouting and α-amylase activity in soft winter wheat. Journal of Cereal Science. 79:311-318.

Chatterjee, Amitava. (2018). Spring wheat response to supplemental nutrient additions under silty clay loam soils of Minnesota. cftm. 4. 10.2134/cftm2017.05.0033.

Chen, C., K. Neill, D. Wichman, and M. Westcott. 2008. Hard red spring wheat response to row spacing, seeding rate, and nitrogen. Agron. J. 100:1296-1302. doi:10.2134/agronj2007.0198

Curtin, D., R.J. Martin, and C.L. Scott. 2008. Wheat (*Triticum aestivum*) response to micronutrients (Mn, Cu, Zn, B) in Canterbury, New Zealand. Journal of Crop and Horitcultural Science, 36:3 169-181. doi:10,1080/01140670809510233

Darwinkel, A. 1978. Patterns of tillering and grain production of winter wheat at a wide range of plant densities. Neth. J. Agric. Sci. 26:383-398.

Darwinkel, A. 1983. Ear formation and grain yield of winter wheat as affected by time of nitrogen supply. Neth. J. Agric. Sci. 31:211-225.

Darwinkel, A., B.A. ten-Hag, and Kuizenga. 1977. Effect of sowing date and seed rate on crop development and grain production of winter wheat. Neth. J. Agric. Sci, 25;83-94.

Davies, D.H.K., and J.P. Welsh. 2002. Weed control in organic cereals and pulses. In: D. Younie, B.R. Welsh, J.P. Welsh, J.M. Wilkinson, editors, Organic cereals and pulses. Chalcombe Publ., Lincoln, UK. p. 77–114.

Dick, W. A., D. Kost, L. Chen 2008. Availability of sulfur to crops from soil and other sources. In: J. Jez, editor, Sulfur: A Missing Link between Soils, Crops, and Nutrition, Agron. Monogr. 50. ASA, CSSA, SSSA, Madison, WI. p. 59-82. doi:10.2134/agronmonogr50.c5

Dilz, K. 1971. Effect of time of chlormequat application, level of nitrogen and split nitrogen on resistance to lodging and yield of winter wheat. Neth. Nitrogen Tech. Bull. no. 10.

Dilz, K., A. Darwinkel, R. Boon, and L.M.J. Verstraeten. 1982. Intensive wheat production as related to nitrogen fertilization, crop protection, and soil nitrogen: Experience in the Benelux. 93– 124. Fertilizer Society of London proc. no. 211, London. 10 Dec. Greenhill House London.

Feyh, R. L., and R. E. Lamond. 1992. Sulfur and nitrogen fertilization of winter wheat. J. Prod. Agric. 5:488-491. doi:10.2134/jpa1992.0488

Fischer, R.A., and R.E. Miles. 1973. The role of spatial pattern in the competition between crop plants and weeds. A theorical analysis. Math. Biosci. 18(3-4):335–350. doi:10.1016/0025-5564(73)90009-6

Food and Agriculture Organization of the United States, FAOSTAT. 2002. http://foastat.org/default.aspx.

Frink, C.R., P.E. Waggoner, and J.H. Ausubel. 1999. Nitrogen fertilizer: Retrospect and prospect. Proc. Natl. Acad. Sci. USA 96:1175–1180. doi:10.1073/pnas.96.4.1175 Quisenberry, K.S. 1928. Some plant characters determining yields in fields of winter wheat and spring wheat in 1926. J. Am. Soc. Agric. 20:492–499.

Geleta, B., M. Atak, P. S. Baenziger, L. A. Nelson, D. D. Baltenesperger, K. M. Eskridge, M. J. Shipman, and D. R. Shelton. 2002. Seeding rate and genotype effect on agronomic performance and end-use quality of winter wheat. Nebraska Agric. Res. Division, J. Series No. 13200. . Crop Sci. 42:827-832. doi:10.2135/cropsci2002.8270

Grant, C. A., E. H. Stobbe, and G. J. Racz. 1985. The effect of fall-applied N and P fertilizer timing of N application on yield and protein content of winter wheat grown on zero-tilled land in Manitoba. Can. J. Soil Sci. 65: 621-628. doi: 10.4141/cjss85-068

Gravelle, W. D., M. M. Alley, D. E. Brann, and K. D. S. M. Joseph. 1988. Split spring nitrogen application effects on yield, lodging, and nutrient uptake of soft red winter wheat. J. Prod. Agric. 1:249-256. doi:10.2134/jpa1988.0249

Groos, C., G. Gay, M.R. Perretant, L. Gervais, M. Bernard, F. Dedryver, G. Charmet. 2002. Study of the relationship between pre-harvest sprouting and grain color by quantitative trait loci analysis in a white x red grain bread-wheat cross. Theoretical and Applied Genetics. 104:39-47.

Haidukowski, M., A. Visconti, G. Perrone, S. Vanadia, D. Pancaldi, and L. Covarelli. 2012. Effect of prothioconazole-based fungicides on Fusarium head blight, grain yield and deoxynivalenol accumulation in wheat under field conditions. Phytopathol. Mediterr. 51:236–246.

Harms, C. L., J. E. Beuerlein, and E. S. Oplinger. 1989. Effects of intensive and current recommended management systems on soft winter wheat in the U.S. Corn Belt. J. Prod. Agric. 2:325-332. doi:10.2134/jpa1989.0325

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2013. Soil fertility and fertilizers: An introduction to nutrient management. 8th Edition, Pearson Educational, Inc., Upper Saddle River, New Jersey.

Holen, D.L., P.L. Bruckner, J.M. Martin, G.R. Carlson, D.M. Wichman, and J.E. Berg. 2001. Response of winter wheat to simulated stand reduction. Agron. J. 93(2):364–370. doi:10.2134/agronj2001.932364x

Isidro-Sánchez, J., B. Perry, A. K. Singh, H. Wang, R. M. DePauw, C. J. Pozniak, B. L. Beres, E. N. Johnson, and R. D. Cuthbert. 2017. Effects of seeding rate on durum crop production and physiological responses. Agron. J. 109:1981-1990. doi:10.2134/agronj2016.09.0527

Jaenisch, B. R., A. de Oliveira Silva, E. DeWolf, D. A. Ruiz-Diaz, and R. P. Lollato. 2019. Plant population and fungicide economically reduced winter wheat yield gap in Kansas. Agron. J. 0. doi:10.2134/agronj2018.03.0223

Joseph, K. D. S. M., M. M. Alley, D. E. Brann, and W. D. Gravelle. 1985. Row spacing and seeding rate effects on yield and yield components of soft red winter wheat. Agron. J. 77:211-214. doi:10.2134/agronj1985.00021962007700020009x

Karlen, D. L., and D. T. Gooden. 1990. Intensive management practices for wheat in the Southeastern Coastal Plains. J. Prod. Agric. 3:558-563. doi:10.2134/jpa1990.0558

Klein, R., R. Wilson, J. Groskopf, J. Jansen, 2017. 2018 Nebraska crop budgets. https://cropwatch.unl.edu/Economics-Real-Estate/2018-NE-crop-budgets-wheat.pdf (Accessed 15 March 2018).

Knapp, J.S., C.L. Harms, and J.J. Volenec. 1987. Growth regulator effects on wheat culm nonstructural and structural carbohydrates and lignin. Crop Sci. 27(6):1201–1205. doi:10.2135/cropsci1987.0011183X002700060022x

Knott, C.A., D.A. Van Sanford, E.L. Ritchey, and E. Swiggart. 2016. Wheat yield response and plant structure following increased nitrogen rates and plant growth regulator applications in Kentucky. Crop Forage Turfgrass Manage. 2(1). doi:10.2134/cftm2015.0202

Large, E.C. 1954. Growth stages in cereals-illustration of the Feekes' scale. Plant Pathol. 3:128–129.

Lin, W., and G. Vocke. 2004. Electronic output report from the Economic Research Service. http://www.ers. usda.gov/publications/agoutlook/aug1998/ao253e.pdf (verified 10 May 2008). USDA, Washington, DC.

Lloveras, J., J. Manent, J. Viudas, A. López, and P. Santiveri. 2004. Seeding rate influence on yield and yield components of irrigated winter wheat in a Mediterranean climate. Agron. J. 96:1258–1265. doi:10.2134/agronj2004.1258

Lu, X., J. Cui, X. Tian, J. E. Ogunniyi, W. J. Gale, and A. Zhao. 2012. Effects of Zinc Fertilization on Zinc Dynamics in Potentially Zinc-Deficient Calcareous Soil. Agron. J. 104:963-969. doi:10.2134/agronj2011.0417

Mansour K. 1993. Sprout damage in wheat and its effect on wheat flour products. In: Walker-Simmons MK, Ried JL (eds) Preharvest sprouting in cereals, 1992, pp 8–9.

Marschner, H. 1995. Mineral nutrition of higher plants. Academic Press, London.

Mascagni, H.J. Jr., S. A. Harrison & G. B. Padgett. 2008. Influence of sulfur fertility on wheat yield performance on alluvial and upland soils, communications in soil science and plant analysis, 39:13-14, 2133-2145, doi:10.1080/00103620802135328

Matysiak, K. 2006. Influence of trinexapac-ethyl on growth and development of winter wheat. J. Plant Prot. Res. 46:133–143.

McFall, K.L. and Fowler, M.E. 2009. Overview of wheat classification and trade. Wheat: Sicence and Trade. Wiley-Blackwell Press. pp:439-454.

Metzger, R.J., and B.A. Silbaugh. 1970. Location of genes for seed color in hexaploid wheat (Triticum aestivum L.). Crop Sci. 10:495–496.

Miskelly, D.M. 1984. Flour components affecting paste and noodle colour. J. Sci. Food Agric. 35:463–471.

Mohamed, M. A., J. J. Steiner, S. D. Wright, M. S. Bhangoo, and D. E. Millhouse. 1990. Intensive crop management practices on wheat yield and quality. Agron. J. 82:701-707. doi:10.2134/agronj1990.00021962008200040011x

Mourtzinis, S., D. Marburger, J. Gaska, T. Diallo, J. G. Lauer, and S. Conley. 2017. Corn, soybean, and wheat yield response to crop rotation, nitrogen rates, and foliar fungicide application. Crop Sci. 57:983-992. doi:10.2135/cropsci2016.10.0876

Naeem, H. A. 2008. Sulfur nutrition and wheat quality. In: J. Jez, editor, Sulfur: A missing link between soils, crops, and nutrition, Agron. Monogr. 50. ASA, CSSA, SSSA, Madison, WI. p. 153-169. doi:10.2134/agronmonogr50.c10

Nafziger, E.D., L.M Wax, and C.M. Brown. 1986. Response of five winter wheat cultivars to growth regulators and increased nitrogen Crop Sci. 767-770.

Nagelkirk, M., and R. Black. 2012. Wheat varieties used in Michigan. Michigan State Univ. Ext., East Lansing, MI. http://msue.anr.msu.edu/news/wheat_varieties_used_in_michigan (accessed 1 Mar. 2017).

Nagelkirk, M. 2016. Nitrogen fertilization of the 2016 wheat crop. https://www.canr.msu.edu/news /nitrogen_fertilization_of_the_2016_wheat_crop (accessed 29 Nov. 2018).

National Atmospheric Deposition Program. 2007. Annual data summary for site OH 71. Available at http://nadp.sws.uiuc.edu/sites/ntnmap.asp (verified 23 Mar. 2008).

Nelson, K.A., and C.G. Meinhardt. 2011. Foliar boron and pyraclostrobin effects on corn. Agron. J. 103:1352–1358. doi:10.2134/agronj2011.0090

Nielsen, D. C., and A. D. Halvorson. 1991. Nitrogen fertility influence on water stress and yield of winter wheat. Agron. J. 83:1065-1070. doi:10.2134/agronj1991.00021962008300060025x

Oates, K. M., and E. J. Kamprath. 1985. Sulfur fertilization of winter wheat grown on deep sandy soils. Soil Sci. Soc. Am. J. 49:925-927. doi:10.2136/sssaj1985.03615995004900040027x

Ohio Department of Agriculture. 2006. Ohio agricultural statistics annual report 2005. Columbus, OH.

Paul, P.A., M.P. McMullen, D.E. Hershman, and L.V. Madden. 2010. Metaanalysis of the effects of triazole-based fungicides on wheat yield and test weight as influenced by Fusarium head blight intensity. Phytopathology 100:160–171. doi:10.1094/PHYTO-100-2-0160

Penckowski, L.H., J. Zagonel, and E.C. Fernandes. 2009. Nitrogen and growth reducer in high yield wheat. Acta Sci. Agron.31:473–479.

Peterson, H., W. Knudson and G. Abate. 2006. The economic impact and potential of Michigan's Agri-food system. The Strategic Marketing Institute Working Paper, Department of Ag. Economics, Michigan State University.

Pinthus, M.J. 1973. Lodging in wheat, barley, and oats: Phenomenon, its causes, and preventative measures. Adv. Agron. 25:209-296.
.

Pinthus, M.J. 1974. Lodging in wheat, barley, and oats: The phenomenon, its causes, and preventative measures. Adv. Agron. 25:209–263. doi:10.1016/S0065-2113(08)60782-8

Power, J.F., and J. Alessi. 1978. Tiller development on yield of standard and semidwarf spring wheat varieties as affected by nitrogen fertilizer. J. Agric. Sci. 90:97-108.

Quinn, D., and K. Steinke. 2019. Soft red and white winter wheat response to input-intensive management. Agron. J. 111:428-439.

Rademacher, W. 2000. Growth retardants: Effects on gibberellin biosynthesis and other metabolic pathways. Annu. Rev. Plant Physiol. Plant Mol. Biol. 51:501–531.

Ranjbar, G.A., and M.A. Bahmaniar. 2007. Effects of soil and foliar application of zn fertilizer on yield and growth characteristics of bread wheat (*Triticum aestivum* L.) cultivars. Asian Journal of Plant Sciences, 6:1000-1005.

Roberts, R. K., J. T. Walters, J. A. Larson, B. C. English, and D. D. Howard. 2004. Effects of disease, nitrogen source, and risk on optimal nitrogen fertilization timing in winter wheat production. Agron. J. 96:792-799. doi:10.2134/agronj2004.0792

Roth, G.W., and H.G. Marshall. 1987. Effect of time of nitrogen fertilization and a fungicide on soft red winter wheat. Agron. J. 79: 197-200.

Roth, G. W., H. G. Marshall, O. E. Hatley, and R. R. Hill. 1984. Effect of management practices on grain yield, test weight, and lodging of soft red winter wheat. Agron. J. 76:379-383. doi:10.2134/agronj1984.00021962007600030007x

Scherer, H.W. 2001. Sulphur in crop production– invited paper. Eur. J. Agron. 14:81–111.

Schumann, G.L., and C.J. D'Arcy. 2009. Essential plant pathology, Second ed. APS Press,St. Paul, MN.

Sherman, J.D., E. Souza, D. See, and L.E. Talbert. 2008. Microsatellite markers for kernel color genes in wheat. Crop Sci., 48:1419-1424.

Stapper,M., and R.A. Fischer. 1990. Genotype, sowing date and plant spacing influence on high-yielding irrigated wheat in southern New South Wales. I. Phasic development, canopy growth and spike production. Aust. J. Agric. Res. 41:997–1019.

Stein, D. 2016. 2016 Estimated crop budget. Michigan State Univ. Ext., Caro, MI. http://msue.anr.msu.edu/uploads/234/68191/1_2016_MST_COP_Crop_Bud_Cost_June_07_16.pdf (Accessed 15 March 2018).

Sutton, J.C., and G. Roke. 1986. Interactive effects of foliar diseases and fungicide sprays in cultivars of winter wheat in Ontario. Can. Plant Dis. Surv. 66:37–41.

Swoish, M., and K. Steinke. 2017. Plant growth regulator and nitrogen applications for improving wheat production in michigan. Crop, Forage & Turfgrass Management 3:2016-06-0049. doi:10.2134/cftm2016.06.0049

Thompson, N.M., F.M. Epplin, J.T. Edwards, and R.M. Hunger. 2014. Economics of foliar fungicides for hard red winter wheat in the USA southern Great Plains. Crop Prot. 59:1-6. doi:10.1016/j.cropro.2014.01.009

USDA-NASS. 2014. Small grains annual summary. USDA, Washington, DC. https://www.nass.usda.gov/ (accessed 3 March 2018).

USDA-NASS. 2015. Small grains annual summary. USDA, Washington,DC. https://www.nass.usda.gov/ (accessed 5 March 2018).

USDA-NASS. 2017. Small grains annual summary. USDA, Washington, DC. https://www.nass.usda.gov/ (accessed 10 March 2018).

USDA-NASS. 2018. Small grains annual summary. USDA, Washington, DC. https://www.nass.usda.gov/ (accessed 21 December 2018).

Vitosh, M.L., J.W. Johnson, and D.B. Mengel. 1995. Tri-state fertilizer recommendations for corn, soybean, wheat, and alfalfa. Ext. Bull. E2567. Michigan State Univ. Ext., East Lansing, MI. https://soil.msu.edu (accessed 20 May 2016).

Warncke, D., J. Dahl, and L. Jacobs. 2009. Nutrient recommendations for field crops in Michigan. Ext. Bull. E2904. Michigan State Univ. Ext., East Lansing, MI. https://soil.msu.edu (accessed 20 May 2018).

Wiersma, D.W., E.S. Oplinger, and S.O. Guy. 1986. Environment and cultivar effects on winter wheat response to ethephon plant growth regulator. Agron. J. 78(5):761–764. doi:10.2134/agronj1986.00021962007800050002x

Wiersma, J. J., J. Dai, and B. R. Durgan. 2011. Optimum timing and rate of Trinexapac-ethyl to reduce lodging in spring wheat. Agron. J. 103:864-870. doi:10.2134/agronj2010.0398

Wegulo, S.N., M.V. Zwingman, J.A. Breathnach, and P.S. Baenziger. 2011. Economic returns from fungicide application to control foliar fungal diseases in winter wheat. Crop Prot.30:685–692. doi:10.1016/j.cropro.2011.02.002

Wilson, J.A., and A.F. Swanson. 1962. Effect of plant spacing on the development of winter wheat. Agron. J. 54:327–328.

Yu, N., R. Laurenz, L. Siler, P.K.W. Ng, E. Souza, and J.M. Lewis. 2015. Evaluation of α-amylase activity and falling number around maturity for soft white and soft red wheat varieties in Michigan. Cereal Research Communications 43(4):672-681. doi:10.1556/0806.43.2015.026

CHAPTER 2

INTEGRATING MULTIPLE-INPUT MANAGEMENT SYSTEMS TO IMPROVE SOFT RED AND SOFT WHITE WINTER WHEAT

Abstract

Michigan winter wheat (*Triticum aestivum* L.) growers continue to adopt enhanced (i.e. multiple input) management systems to maximize grain yield. However inconsistent responses to broadscale implementation of enhanced management have practitioners questioning whether below recommended seeding rates of modern varieties may utilize inputs more efficiently during enhanced management. This study evaluated soft winter wheat plant growth, grain yield, and expected economic net return for multiple agronomic and nutrient inputs across different production intensity levels. A four site-year field trial was established at Richville and Lansing, MI during 2017 and 2018 which evaluated six agronomic inputs including: seeding rate, fungicide, plant growth regulator (PGR), autumn starter fertilizer, weekly nitrogen (N) applications, and a high N rate. Autumn-applied starter fertilizer was the only individual input resulting in a consistent grain yield response. Removal of autumn starter fertilizer from enhanced management decreased grain yield an average of 1.6 Mg ha^{-1} while increasing grain yield 1.1 Mg ha^{-1} on average when added to traditional management. Autumn starter fertilizer accounted for 71% of the grain yield difference between enhanced and traditional management. Although enhanced management increased grain yield compared to traditional management in three of four site years, expected net return was greater when utilizing traditional management. Despite grain yield increases associated with addition of agronomic and nutrient inputs, expected net return never exceeded traditional management utilizing only a recommended rate of N. Results suggest

greater expected net return at current wheat prices may still be accomplished with traditional management despite numerically lower grain yields.

Introduction

Mean Michigan winter wheat grain yields $\geq$ 4.8 Mg ha^{-1} since 2015 combined with heightened awareness of both climate and soil spatial variabilities have growers focusing input applications within enhanced (i.e., multiple-input) management systems (Rosenzweig et al., 2001; Crane et al., 2011; Quinn and Steinke, 2017; NASS, 2019). Enhanced management systems aim to control yield-limiting factors by adjusting production practices which may include prophylactic input applications to reduce the risk for yield loss potential but may also add significant costs and diminish expected net return (Harms et al., 1989; Mourtzinis et al., 2016). In contrast to enhanced management, traditional management utilizes IPM (i.e., integrated pest management) principles which consider both grain yield and expected net return to justify input applications (Marburger et al., 2016; Mourtzinis et al., 2016; Quinn and Steinke, 2017). Previous research evaluating wheat grain yield response to multiple agronomic and nutrient inputs included additional N fertilizer, seeding rate, PGR, and fungicide (Beuerlein et al., 1989; Paul et al., 2010; Knott et al., 2016; Swoish and Steinke, 2017). However, few studies exist investigating weekly N applications or targeting multiple inputs while simultaneously utilizing a lower than recommended seeding rate.

Reduced interplant competition from decreased seeding rates (e.g., 2.2 million seeds ha^{-1}) may promote additional plant tillering through improved light interception and increased input efficiency to produce comparable grain yields as greater seeding rates (e.g., 4.4 million seeds ha^{-1}) (Darwinkel et al., 1977; Joseph et al., 1985; Rana et al., 1995; Park et al., 2003; Lloveras et al., 2004; Isidro-Sánchez et al., 2017). However, reduced plant densities may simultaneously decrease the number of heads per unit area (i.e., heads m^{-2}) decreasing grain yield (Darwinkel et al., 1977; Rana et al., 1995). Enhanced management systems typically utilize recommended seeding rate guidelines but decreased seeding rates may offer greater compensation capacities and improve nutrient use efficiency (Joseph et al., 1985; Jaenisch et al., 2019).

Enhanced management systems typically include fungicide applications to decrease disease incidence and avoid grain yield reductions (Brinkman et al., 2014; Mourtzinis et al., 2017). A problematic disease in soft red and soft white winter wheat is fusarium head blight (FHB) (*Fusarium graminearum*), which can decrease grain yield and quality through shriveled kernels and mycotoxin (e.g., deoxynivalenol [DON]) presence (Paul et al., 2010; Nagelkirk and Chilvers, 2016). Marketability of soft white and soft red winter wheat decreases when DON concentrations exceed 1 and 2 mg kg^{-1}, respectively (Nagelkirk and Chilvers, 2016). Conditions favoring FHB consist of wet, humid weather during anthesis and grain-fill (Paul et al., 2010). Wheat growers often consider fungicide applications as prophylactic due to greater concern for potential yield and quality reductions rather than profitability and may ignore environmental conditions impacting disease pressure severity (Mourtzinis et al., 2017). Economic return from fungicide application can vary by disease severity, varietal characteristics, and environmental conditions (Bhatta et al., 2018).

Enhanced management may also include above recommended N rates which can increase plant height, weaken stem strength, and cause plant lodging (Knott et al., 2016; Swoish and Steinke, 2017). When lodging occurs, water and nutrient transport from plant roots to developing grain tissues becomes restricted resulting in non-harvestable yield due to the plant falling over and located beneath the combine head (Knapp et al., 1987; Harms et al., 1989; Van Sanford et al., 1989). Trinexapac-ethyl is a PGR inhibiting gibberellin biosynthesis which can decrease plant height and reduce lodging susceptibility (Swoish and Steinke, 2017). Reduced plant lodging from PGR application can increase yield due to a greater number of harvestable grain heads (Nagelkirk, 2012). In Michigan, Swoish and Steinke (2017) found PGR application increased grain yield 0.3 to 0.4 Mg ha^{-1} while also reducing lodging 50-83% compared to no PGR. Other studies found PGR application did not consistently affect grain yield due to lack of plant height reduction and lodging susceptibility (Knott et al., 2016; Quinn and Steinke, 2019). Wheat yield response to PGR application may be dependent on varietal characteristics including plant height and lodging incidence or stem strength during the growing season (Brinkman et al., 2014; Quinn and Steinke, 2019). Benefits from PGR application may occur more frequently when using a high yielding, taller-statured, and intensively managed variety (e.g., increased N rate) that is susceptible to lodging (Swoish and Steinke, 2017).

Surface-applied broadcast is the most common method of applying granular fertilizers (Jankowski et al., 2018) including winter wheat autumn starter fertilizer. Winter wheat autumn starter fertilizer can provide developing roots greater access to soil supplied nutrients thus affecting grain yield potential (Nkebiwe et al., 2016). Moderate amounts of autumn N fertilizer (28 kg N ha^{-1}) are often suggested for winter wheat establishment (Warncke et al., 2009). However, exceeding 34 kg N ha^{-1} in an autumn fertilizer application may create excessive autumn growth and increased risk for winter kill (Alley et al., 2009; Warncke et al., 2009). Wheat grain yield responses to autumn applied N are more probable when pre-plant soil nitrate concentrations (NO_3-N) are < 10 mg kg^{-1} soil (Alley et al., 2009). Due to reduced C:N and less residual soil NO_3-N variability following soybean [*Glycine max* (L.) Merr.] compared to corn (*Zea mays* L.), winter wheat responsiveness to autumn-applied N may be greater following soybean (Roth and Fox, 1990; Forrestal et al., 2014; Mourtzinis et al., 2017). Since winter wheat growth coincides with cooler spring air and soil temperatures in Michigan (i.e., April-May), sulfur (S) mineralization from organic matter at soil temperatures < 10°C may not satisfy early-season wheat S requirements (Lecheta and Lambais, 2012). Soil temperatures in Michigan may not raise above 10°C until after the beginning to middle of May. Therefore, autumn fertilizer containing some soluble S may help fulfill early wheat S requirements (Mascagni et al., 2008). When soil test P concentrations are above critical concetrations (i.e., 25 mg kg^{-1} P (Bray-P) or 33 mg kg^{-1} P (Mehlich-3P)), grain yield response to P application is less probable (Warncke et al., 2009). Phosphorus fertilizer applications should be based off pre-plant soil test concentrations and not solely based on crop removal.

Split N applications may reduce environmental N losses on medium to fine-textured soils with leaching or denitrification conditions (Alcoz et al., 1993; Liu et al., 2018). Alcoz et al. (1993) reported grain yield increased 0.5 Mg ha^{-1} with four split N applications compared to two split applications at a total N rate of 150 kg N ha^{-1}. European researchers suggest grain yields increase with multiple split N applications compared to single N applications (Dilz, 1971; Dilz et al., 1982; Tinker and Widdowson, 1982; Gravelle et al., 1988). Although split-applied N may reduce N losses during periods of ample moisture, insufficient quantities of soluble N in the rhizosphere during peak growth periods (i.e., Feekes 5 to 9) can reduce grain yield emphasizing the importance for synchronizing N availability and N uptake (Zadoks et al., 1974; Roberts et al., 2004). Additionally, N applications following peak N uptake may greater affect grain protein than biomass or grain yield (Fuertes-Mendizábal et al., 2010; Ercoli et al., 2012). Although split N applications may allow greater flexibility for both N rates and application timings and at times improve N uptake efficiency, the cumulative costs of multiple split-N applications must be considered in the overall net economic return.

The assumption that modern (i.e., post-2010) wheat varieties appear to show an improved response to N fertilizer application as overall N rates have risen along with increases in grain yields may be incorrect as modern varieties may also contain poorer rooting systems unable to access as large of a rooting area thus requiring greater N (Wasson et al., 2012; Brinkman et al., 2014). Greater N rates than those used in traditional wheat management may improve wheat performance under enhanced management systems (Brinkman et al., 2014). Efficient use of N fertilizer is essential to increasing grain yield and longer-term sustainability of winter wheat in a multi-year cropping system (Delogu et al., 1998). However, growers often associate reduced risk with over-application of N as compared to inadequate N fertilization and the ensuing yield loss (Gravelle et al., 1988; Bhatta et al., 2017; Mourtzinis et al., 2017). Recommended N rates may supply sufficient N within a low-input traditional management system, but greater N rates may be required under enhanced management systems due to N stimulating the response of other agronomic inputs (e.g., stay-green potential) (Quinn and Steinke, 2017). In low input management systems, over-application of N typically reduces winter wheat agronomic efficiency (AE) of applied N fertilizer and may lead to water contamination (Delogu et al., 1998). Agronomic efficiency of applied N may be improved by developing management systems that increase the ability of crops to uptake additional N (Giambalvo et al., 2010) including multiple input systems or split N applications.

The objective of this trial was to investigate the grain yield, economic net return, and AE responses of soft red and soft white winter wheat to seeding rate, fungicide, PGR, autumn starter fertilizer, weekly N applications, and increased N fertilizer across enhanced and traditional production systems. An omission trial design previously used in soybean and wheat research to evaluate specific enhanced management factors (Bluck et al., 2015; Quinn and Steinke, 2017), was used to determine whether the removal of an individual input from an enhanced management system or the addition of an individual input into a traditional management system significantly influenced grain yield or expected net economic return.

Materials and Methods

Soft Red Winter Wheat (SRWW) field trials were established at the South Campus Research Farm in Lansing, MI (42°42'37.0"N, 84°28'14.6"W) on a Capac loam soil (fine loamy, mixed, active, mesic Aquic Glossudalfs). Pre-plant soil characteristics (0-20 cm) included 7.0 - 7.1 pH (1:1 soil/water) (Peters et al., 2015), 25 to 28 g kg^{-1} soil organic matter (loss-on-ignition) (Combs and Nathan, 2015), 12 - 33 mg kg^{-1} P (Bray-P1) (Frank et al., 2015), 80 - 102 mg kg^{-1} K (ammonium acetate method) (Warncke and Brown, 2015), 8 - 9 mg kg^{-1} S (monocalcium phosphate extraction) (Combs and Nathan, 2015), and 2.5 - 3.4 mg kg^{-1} Zn (0.1 M HCl) (Whitney, 2015). Prior to planting, soil samples (0-30 cm) for nitrate-N (NO_3-N) analysis were collected, air-dried, and ground to pass through a 2 mm sieve. Pre-plant soil NO_3-N concentrations were 4.3 mg NO_3-N kg^{-1} soil (nitrate electrode method) in both years (Gelderman and Beegle, 1998). Triple superphosphate (0-45-0 N-P_2O_5-K_2O) was broadcast at a rate of 146 and 73 kg P_2O_5 ha^{-1} in 2018 and 2019, respectively, while muriate of potash (0-0-62 N-P_2O_5-K_2O) was broadcast at a rate of 40 kg K_2O ha^{-1} in 2018 based on soil tests. Preceding crop was silage corn and soybean in 2018 and 2019, respectively, and tilled prior to planting. Soft White Winter Wheat (SWWW) trials were conducted at the Saginaw Valley Research and Extension Center in Richville, MI (43°23'57.3"N, 83°41'49.7"W) on a Tappan-Londo loam soil (fine-loamy, mixed, active, calcareous, mesic Typic Enduaquolls). Pre-plant soil characteristics (0-20 cm) included

7.7 – 8.0 pH (1:1 soil/water), 20 to 21 g kg^{-1} soil organic matter (loss-on-ignition), 7-9 mg kg^{-1} P (Olsen sodium bicarbonate extractant) (Frank et al., 2015), 137 - 152 mg kg^{-1} K (ammonium acetate method, 6 - 9 mg kg^{-1} S (monocalcium phosphate extraction), and 5.4 – 5.7 mg kg^{-1} Zn (0.1 M HCl). Prior to planting, soil samples (0-30 cm) for nitrate-N (NO_3-N) analysis were collected, air-dried, and ground to pass through a 2 mm sieve resulting in concentrations of 9.1 and 4.3 mg NO_3-N kg^{-1} soil in 2018 and 2019, respectively. Triple superphosphate (0-45-0 N-P_2O_5-K_2O) was broadcast at a rate of 73 and 101 kg P_2O_5 ha^{-1} in 2018 and 2019, respectively, based on soil tests. Preceding crop was dry bean (*Phaseolus vulgaris* L.) and soybean in 2018 and 2019, respectively, and tilled prior to planting.

Plots were twelve rows wide measuring 2.5 m in width by 7.6 m in length with 19.1 cm row spacing. Plots were planted with a Great Plains 3P600 drill (Great Plains Manufacturing, Salina, KS) at plant populations of 2.2 and 4.4 million seeds ha^{-1}. Plant emergence was counted in Spring before Feekes 4 applications to validate plant populations. Trials were arranged in a randomized complete block design with four replications. Soft red winter wheat variety 'Starburst' (Michigan Crop Improvement Assoc., Okemos, MI) a short strawed, high yielding, variety was planted in Lansing on 20 Sept. 2017 and 19 Oct. 2018 (delayed planting due to wet soil conditions). Soft white winter wheat variety 'Jupiter' (Michigan Crop Improvement Assoc., Okemos, MI) a short strawed, high yielding, variety was planted in Richville on 22 Sept. 2017 and 24 Sept. 2018.

Nitrogen was applied as UAN (28-0-0) utilizing a backpack sprayer equipped with streamer bars (Chafer Machinery Ltd, Upton, UK) at the Feekes 4 growth stage (5 April 2018 and 6 April 2019, Lansing; 11 April 2018 and 3 April 2019, Richville). Traditional management N rates were based on Michigan State University recommendations for Lansing and Richville locations. Traditional management N rates were 112.1 kg N ha^{-1} and 145.7 kg N ha^{-1} for SRWW and SWWW, respectively. Enhanced management N rates were 33 percent greater from traditional management (149.1 kg N ha^{-1} and 193.9 kg N ha^{-1} for SRWW and SWWW, respectively). Weekly N applications (18.6 kg N ha^{-1} and 24.2 kg N ha^{-1} per application for SRWW and SWWW, respectively) began at Feekes 4 and included 8 weekly applications (5 April 2018 and 6 April 2019, 11 April 2018 and 10 April 2019, 17 April 2018 and 15 April 2019, 24 April 2018 and 25 April 2019, 2 May 2018 and 30 April 2019, 8 May 2018 and 7 May 2019, 16 May 2018 and 14 May 2019, and 24 May 2018 and 21 May 2019 for SRWW; 11 April 2018 and 3 April 2019, 18 April 2018 and 10 April 2019, 25 April 2018 and 16 April 2019, 1 May 2018 and 24 April 2019, 9 May 2018 and 30 April 2019, 16 May 2018 and 7 May 2019, 23 May 2018 and 14 May 2019, and 30 May 2018 and 21 May 2019 for SWWW). Autumn starter (12-40-0-10-1N-P-K-S-Zn) (MicroEssentials® SZ® (MESZ) (Mosaic CO., Plymouth, MN) fertilizer was autumn topdressed (3 Oct. 2017 and 12 Nov. 2018, Lansing; 10 Oct. 2017 and 15 Oct. 2018, Richville) at 280 kg ha^{-1}. Plant growth regulator (Palisade EC, Trinexapac-ethyl [0.8 L ha^{-1}]; Syngenta Crop Protection, Cambridge, UK) was applied at Feekes 6 (30 April 2018 and 10 May 2019, Lansing; 1 May 2018 and 30 April 2019, Richville) using a backpack sprayer calibrated at 140.3 L ha^{-1} with Teejet XR8002 nozzles (Teejet Technologies, Wheaton, IL). Fungicide (Prosaro 421 SC, prothioconazole {2-[2-(1-chlorocyclopropyl0-3-(2-chlorophenyl)-2-hydroxypropyl]-1, 2-dihydro-3H-1, 2, 4-triazole-3-thione} and tebuconazole {alpha-[2-(4-chlorophenyl)ethyl]-alpha-(1,1-dimethylethyl)-1H-1, 2, 4-triazole-1-ethanol}[0.6 L ha^{-1}]; Bayer CropScience Research Triangle Park, NC) was applied at Feekes 10.5.1 (29 May 2018 and 11 June 2019, Lansing; 31 May 2018 and 11 June 2019, Richville) using a backpack sprayer calibrated at 140.3 L ha^{-1} with Teejet tt11002 nozzles (Teejet Technologies, Wheaton, IL).

An omission treatment structure was utilized to demonstrate responses to individual inputs (Table 2.01). Two treatment controls are included in an omission trial design, one containing all inputs (i.e., enhanced management) and one containing no inputs and only a base nitrogen rate (i.e., traditional management) (Bluck et al., 2015; Quinn and Steinke, 2019). To evaluate individual input response, inputs removed from enhanced management were compared only with the enhanced treatment and inputs added to traditional management were only compared to the traditional treatment (Bluck et al., 2015; Quinn and Steinke, 2019).

Environmental data were recorded throughout the growing season and obtained from MSU Enviro-weather (https://enviroweather.msu.edu, Michigan State University, East Lansing, MI). Temperature and precipitation 30-year means were collected from the National Oceanic and Atmospheric Administration (NOAA, 2019). Tiller counts were collected outside yield harvest areas at Feekes 4 while head counts were collected at Feekes 11.2. Percent of grain heads affected by FHB were taken three weeks after fungicide application. Agronomic efficiency of applied N fertilizer was calculated as the difference between grain yield of treatments with N and yield of unfertilized control, divided by N rate (Sawyer et al., 2017).

Grain yield was harvested from the center 1.2 m of each plot utilizing a small-plot combine (Almaco, Nevada, IA) on 11 July 18 and 23 July 2019 in Lansing and 12 July 2018 and 24 July 2019 in Richville and adjusted to 135 g kg^{-1} moisture. Grain subsamples were collected from each plot to evaluate DON concentration and sent to the U.S. Wheat and Barley Scab Initiative mycotoxin testing laboratory (University of Minnesota, St. Paul, MN). Additional grain samples were taken from SWWW plots due to the pre-harvest sprouting susceptibility of SWWW variety 'Jupiter' (Brown et al., 2017) and evaluated for α-amylase activity and pre-harvest sprouting incidence. Sprout damage and α-amylase activity of SWWW flour was determined using the falling number procedure (Perten Instruments, Springfield, IL).

Expected net return was assessed using input cost estimates from Star of the West Milling Company (Frankenmuth, MI), Jorgenson Farm Elevator (Williamston, MI), and Nutrien Ag Solutions (Lake Odessa, MI) and consisted of US\$0.90 kg^{-1}, \$0.64 kg^{-1}, \$34.18, \$45.91 ha^{-1} in 2018 and US\$1.02 kg^{-1}, \$0.65 kg^{-1}, \$34.83, \$45.91 ha^{-1} in 2019 for N fertilizer, autumn starter fertilizer, plant growth regulator, and fungicide, respectively (Table 2.02). Seed costs were \$0.59 and \$0.51 kg^{-1} for SRWW and US\$0.53 and \$0.47 kg^{-1} for SWWW in 2018 and 2019, respectively. Application costs were estimated from the Michigan State University Extension Custom Machine and Work Rate Estimates and included \$19.15 ha^{-1} for N fertilizer, plant growth regulator, and fungicide (Stein, 2018). Weekly N applications added \$19.15 ha^{-1} per N application. An additional cost of \$16.16 ha^{-1} was utilized for the application of autumn starter fertilizer. Net returns were calculated by multiplying harvest grain price estimates received from Star of the West Milling Company (Frankenmuth, MI), Jorgenson Farm Elevator (Williamston, MI), and Michigan Agricultural Commodities (Lansing, MI) and consisted of \$0.16 and \$0.18 kg^{-1} in 2018, \$0.17, and \$0.18 kg^{-1} in 2019 for SRWW and SWWW, respectively, by grain yield and subtracting total treatment costs.

Data were analyzed in SAS 9.4 (SAS Institute, 2012) using the GLIMMIX procedure at α=0.10. Each site year was analyzed individually due to a significant treatment by year interaction. Due to different SRWW and SWWW varieties and locally recommended N rates, locations were analyzed individually. Replication was considered a random factor with all other factors considered fixed. Treatment mean separations were calculated utilizing single degree of freedom contrasts. Due to unequal comparisons concerning treatments incorporating an individual input and treatments excluding that input, authors could not contrast input responses across both management systems.

Results and Discussion

Environmental Conditions

Total precipitation during March – July differed from the 30-yr mean by -41 and +20% and -26 and +20% in 2018 and 2019 at Richville and Lansing, respectively (Table 2.03). June 2018 precipitation was 57 and 58% below the 30-yr mean for Richville and Lansing, respectively, which likely impacted grain fill and decreased yield potential due to dry soil conditions. May and June cumulative 2019 rainfall was 55-75% above 30-yr means at both locations increasing the potential for leaching and denitrification N losses on the medium to fine-textured soils of these studies. Except for May 2018 at Richville, May through July mean air temperatures did not deviate more than 10% from the 30-yr mean across site-years.

Enhanced vs Traditional Management Systems

Enhanced management containing all inputs (i.e. decreased seeding rate, fungicide, PGR, autumn starter fertilizer, weekly N applications, and high N management) increased grain yield compared to traditional management containing only a recommended base rate of N fertilizer in three of four site years (Table 2.04). Richville 2018 was the only site-year where grain yield did not significantly differ between enhanced and traditional management. Lack of additional yield-limiting conditions (e.g., N loss, pest pressure, plant lodging) combined with deficit precipitation in Richville 2018 may have contributed to the lack of yield response to additional inputs. Compared to traditional wheat management, enhanced management increased SWWW grain yield from 6.7 to 8.4 Mg ha^{-1} in Richville 2019 while also increasing SRWW grain yield from

5.8 to 7.0 and 5.4 to 7.7 Mg ha^{-1} in Lansing 2018 and 2019, respectively. Averaged across the three responsive site-years, enhanced management increased yield 1.7 Mg ha^{-1} compared to traditional management. Autumn starter fertilizer accounted for nearly 71% or 1.2 Mg ha^{-1} of the grain yield difference between enhanced and traditional management within the three significant site-years. Soft white winter wheat falling number data are not presented due to lack of pre-harvest sprouting incidence across both years. Results agree with previous research that show positive grain yield responses to specific input applications (e.g., fungicide, PGR, weekly N applications, high-N) are unlikely without the presence of yield-limiting factors (i.e. disease occurrence, plant lodging, leaching, denitrification, or deficient soil nutrient concentrations) (Paul et al., 2010; Wegulo et al., 2012; Knott et al., 2016; Swoish and Steinke, 2017; Jaenisch et al., 2019; Quinn and Steinke, 2019).

Expected Economic Net Return

Product and application costs for enhanced management across all four site years averaged US$694 ha^{-1} with a break-even yield of 3.9 Mg ha^{-1}, while traditional management costs and break-even yield were US$249 ha^{-1} and 1.4 Mg ha^{-1}, respectively. Traditional SWWW and SRWW management containing only a university recommended N rate increased expected net return US$136.8 - 422.36 ha^{-1} compared to the enhanced treatment containing all inputs in three of four site years (Table 2.05). Results agree with Quinn and Steinke (2019) where traditional management containing only a university recommended N rate increased expected net return US$221 ha^{-1} compared to a multiple-input intensive management system. Due to application costs exceeding grain yield increases, weekly N applications decreased expected net return when added to traditional management in three of four site years and increased net returns when removed from enhanced management in all four site years. Averaged across site-years, removing weekly N application from enhanced management increased expected net return US$196 ha^{-1} and decreased returns by US$175 ha^{-1} when added to traditional management (Table 2.05). Despite some yield gains, no individual input increased expected net return across all four site-years. Producers may often consider yield loss as a greater liability than losing net return (Mourtzinis et al., 2017; Rutan and Steinke, 2017). However, results from this study were consistent with previous research indicating that both grain yield and profitability must be integrated for optimal wheat management (Jaenisch et al., 2019; Quinn and Steinke, 2019). At current wheat prices and input costs coupled with predicted stagnant future commodity prices, wheat producers may benefit from greater emphasis upon expected net returns in lieu of protecting yield losses which may or may not occur (Quinn and Steinke, 2019). Despite wheat grain yield increases from many of the inputs within the environments tested, the economic net returns may not be sufficient to offset the costs to attain greater yield.

Seeding Rate

Decreased seeding rate (i.e., 2.2 million vs. 4.4 million seeds ha^{-1}) within traditional management reduced grain yield 1.1 Mg ha^{-1} in one of four site-years (i.e. Lansing 2018), while removing the decreased seeding rate component (i.e., utilizing a recommended seed rate) from the enhanced managed system had little impact on grain yield at either location in 2018 or 2019 (Table 2.04). Fewer plants per unit area may allow for greater light interception, reduced interplant competition for moisture and nutrients, and overall more efficient utilization of individual inputs as compared to greater seeding rates and still produce comparable grain yield (Darwinkel et al., 1977; Joseph et al., 1985; Chen et al., 2008). Lansing 2018 deficit June through July precipitation (i.e., 60% below the 30-yr mean) combined with 52% of June daytime temperatures > 24 ^{o}C likely produced dry soil conditions during grain-fill contributing to grain yield reductions (Table 2.03). During grain fill, wheat reproductive development is optimal under cooler (< 24 ^{o}C) daytime air temperatures as temperatures > 24 ^{o}C may reduce kernel size and reduce grain yield (Prasad and Djanaguiraman, 2014; Akter and Rafiqul Islam, 2017). Results correspond with Geleta et al. (2002) who found lower than recommended seeding rates reduced yield 0.8 Mg ha^{-1}, but results were influenced by environmental conditions rather than decreased seeding rate alone. Current data suggest decreased seeding rates may offer greater opportunity in an enhanced as compared to traditional management system while still achieving similar grain yield and expected net return.

Plant growth measurements showed tiller production increased 59% when removing the decreased seeding rate from enhanced management at Lansing 2019 (Table 2.06). Growing degree days (GDD) from planting to Feekes 4 totaled 758 in 2019 which were 54% fewer than 2018. Winter wheat tiller development begins at 720 GDDs producing an additional tiller every 180 GDDs (Klepper et al., 2014). Lansing 2019 wheat was planted 29 days later than 2018 which resulted in less tiller development due to fewer GDDs. Lansing 2019 decreased seeding rate development was limited to an average of two tillers per plant as compared to an average of four tillers per plant in 2018. Reduced seeding rates may better utilize May-June GDDs to produce additional tillers per plant resulting in an equivalent heads per unit area compared to the greater seeding rates and thus result in comparable grain yields (Darwinkel, 1978; Masle, 1985; Klepper et al., 2014). Results from this study suggest that delayed winter wheat planting dates (i.e., after 5 Oct) may increase the risk of reduced yield potential when utilizing decreased seeding rates as autumn climatic variability and spring GDD accumulation are difficult to forecast ahead of time. Recent variable winter precipitation patterns including more frequent freeze/thaw cycling and ice sheeting from winter rainfall over frozen soils in combination with variable spring precipitation may add additional risks including reduced plant hardiness and spring plant survival when choosing to reduce winter wheat seeding rates.

Fungicide

Adding or removing fungicide application each affected grain yield in one of four site-years (Table 2.04). Dry soil conditions at Richville 2018 provided low FHB risk with little foliar disease pressure resulting in no response to fungicide. Lansing 2018 fungicide removal from enhanced management reduced grain yield 0.8 Mg ha^{-1} while fungicide addition to traditional management increased grain yield 0.8 Mg ha^{-1} at Lansing 2019 (Table 2.04). Lansing received 7.2 cm greater May rainfall than Richville in 2018 likely creating a more favorable environment for FHB development (Table 2.03). Despite Richville May 2019 receiving above average rainfall, dry April soil conditions may have absorbed some of the excess May rainfall leading to a less humid microenvironment and reduced disease development. Moist conditions and frequent rainfall during wheat anthesis (Feekes 10.5.1) can increase risk of FHB infection and DON accumulation. Local areas within Michigan experienced warm temperatures and increased humidity levels during anthesis that promoted 2019 FHB development (Pennington et al., 2019). Growers should implement routine field scouting and utilize disease development prediction models as FHB protecting fungicides are mostly applied prior to infection and may not increase yield or profit without disease pressure.

Visual assessment of disease presence showed removal of fungicide from enhanced management increased FHB incidence 10.9% at Richville 2019 (Table 2.07). Fungicide removal from enhanced management at Lansing increased FHB incidence 8.2% and 2.4% in 2018 and 2019, respectively. Adding fungicide to traditional management reduced FHB occurrence 2.9% at Lansing 2019 with no effects in other site years (Table 2.07). Data support Blandino et al.

(2006) who reported a 52% reduction of FHB incidence from a triazole fungicide applied during anthesis which resulted in a 20% yield increase. Additionally, McMullen et al. (2008) observed triazole fungicide application applied during anthesis reduced FHB incidence 8.9% compared to no fungicide application. Fungicide application appeared to offer greater consistency in reducing FHB incidence when applied to enhanced management compared to traditional management. In years FHB was present, enhanced management produced on average 28% more heads than traditional management (Table 2.08) likely creating a favorable disease environment due to a denser area limiting wind movement. Results suggest greater wheat head production may offer opportunities for a fungicide application to reduce FHB. Aside from grain yield benefits, greater advantages from fungicide application may exist in SWWW to decrease DON levels as critical DON concentrations are lower compared to SRWW due to SWWW usage within the milling and cereal industries. Producers should consider incorporating a disease resistant variety along with utilizing IPM practices to improve fungicide efficacy and response (Wegulo et al., 2011; Quinn and Steinke, 2019).

Plant Growth Regulator

Adding plant growth regulator to traditional management reduced grain yield 0.9 Mg ha^{-1} at Lansing 2018, while removing PGR from enhanced management did not significantly influence grain yield across any site-year (Table 2.04). Grain yield reduction at Lansing 2018 may have been due an 11% decrease in number of kernels per head when PGR was added to traditional management (data now shown). Dry June conditions at Lansing 2018 may have contributed to reduced kernel development and grain yield by limiting nutrient uptake from lack of soil moisture during the grain fill period. A combination of the PGR application that inhibited gibberellins to promote growth (Matysiak, 2006) and dry conditions likely resulted in the grain yield and kernels per head decrease at Lansing 2018. Results agree with Karlen and Gooden (1990) who found grain yield decreased 0.2 Mg ha^{-1} with PGR application compared to no PGR application. Multiple researchers have reported inconsistent grain yield responses from PGR application without plant lodging (Wiersma et al., 2011; Swoish and Steinke, 2017; Quinn and Steinke, 2019). However, Matysiak (2006) reported PGR application increased kernels per head 5.4% which lead to a 7% grain yield increase in the absence of lodging.

Plant height reductions were inconsistent when PGR was added individually to the traditional system. No plant lodging occurred across either location or management intensity when utilizing N rates up to 194 kg N ha^{-1}. Results agree with Swoish and Steinke (2017) who determined grain yield increases from a PGR application were more likely in taller-statured varieties with weak-stem strength to increase lodging potential. Both varieties ('Jupiter' and 'Starburst') utilized in this study contain short-strawed, high stem-strength physical characteristics (Pennington et al., 2019; Michigan Crop Improvement Assoc., Okemos, MI) which likely explains the lack of response to PGR application. As small grain yield potential continues to increase from a shorter plant size and greater harvest index (Evans and Fisher, 1999), positive responses from PGR application may depend more upon varietal characteristics including cultivar structure and lodging susceptibility rather than applying a PGR to account for greater than recommended N rates.

Autumn Starter Fertilizer

Removal of autumn starter fertilizer from enhanced management decreased grain yield 1.0-2.5 Mg ha^{-1} in three of four site-years while including autumn starter fertilizer to traditional management significantly increased grain yield 0.6 -1.7 kg ha^{-1} in all four site-years (Table 2.04). Wheat grain yield responses to P fertilizer applications are less probable when soil test P concentrations are above critical (i.e., 25 mg P kg^{-1} (Bray-P) (Warncke et al., 2009). Soil test P concentrations from this study consisted of 12-33 mg P kg^{-1} across site-years (Table 2.09). Despite below critical soil P concentrations for wheat, broadcast applied P to all plots and locations reduces the likelihood of a singular P_2O_5 response from within the autumn starter fertilizer. Wheat is classified as low in responsiveness to zinc applications in Michigan (Warncke et al. 2009). However, positive grain yield responses to autumn starter fertilizer may have been due to the N and or S components within the autumn starter fertilizer.

Pre-plant soil nitrate concentrations (0 – 30 cm) were < 10 mg NO_3-N kg^{-1} across all site-years. Low soil nitrate concentrations increase the likelihood for a positive winter wheat yield response to autumn N-containing starter fertilizer (Alley et al., 2009). Results corroborate with Forrestal et al. (2014) who found no grain yield response to 34 kg N ha^{-1} autumn applied when soil test nitrate concentrations were ≥ 16 mg NO_3-N kg^{-1} thus the need to consider residual soil N concentrations. At both locations, autumn starter fertilizer had a greater impact on 2019 grain yield when removed from enhanced management and added to traditional management when compared to 2018 (Table 2.04). Richville soil nitrate concentrations consisted of 9.1 and 4.3 mg NO_3-N kg^{-1} in 2018 and 2019, respectively, suggesting the lower pre-plant nitrate concentration in 2019 increased potential for a positive response to autumn starter fertilizer. Lansing 2018 and 2019 pre-plant soil nitrate concentrations were similar (4.3 mg NO_3-N kg^{-1}), but preceding crops were silage corn and soybean in 2018 and 2019, respectively, likely contributing to the degree of responsiveness between the two years. Response to autumn applied N may be greater for wheat following soybean rather than following corn as corn often leaves greater, more variable residual pre-plant N concentrations for wheat due to a lower N removal rate from the soil combined with N fertilizer applications (Forrestal et al., 2014; Mourtzinis et al., 2017). Soil testing for predicting an S response has been shown to be unreliable (Franzen et al., 2018; Kaiser et al., 2019). Reduced atmospheric deposition since the 1980’s has resulted in increased winter wheat yield responses to applied S (Girma et al., 2005; Dhillon et al., 2019). The sulfur component within the autumn starter fertilizer consisted of 50% sulfate-sulfur and 50% elemental sulfur. Sulfate-sulfur is immediately available to the winter wheat crop for uptake while elemental sulfur is oxidized to sulfate-sulfur to later become plant available (Mahler and Maples, 1987). In this study, sulfate-sulfur was immediately available in autumn for the winter wheat while the elemental sulfur purportedly oxidized to become available later in the growing season (April-June) for continuous spring sulfur uptake. Results from this study correlate with McKay (1996) who found 20 kg S ha^{-1} increased wheat grain yield 0.4 Mg ha^{-1} across three site-years. Site-specific field conditions, sulfur source, soil texture, crop rotation, and local environmental factors may influence grain yield responses to winter wheat sulfur applications.

Removal of autumn starter fertilizer from enhanced management decreased tiller production in one site-year while addition of autumn starter fertilizer to traditional management increased tiller production in three site-years (Table 2.06). Increases in tiller production from autumn starter fertilizer were likely due to the N component within the starter fertilizer. University recommendations suggest 34 kg N ha^{-1} autumn applied can promote additional autumn tillering in winter wheat (Alley et al., 2009). Tiller production at Feekes 4 may not always equate to final head production as wheat forms additional grain producing tillers until Feekes 5 (Wise et al., 2011). Tiller production and head production showed similar increases from addition of autumn starter fertilizer to traditional management across site-years (Table 2.06, 2.08). In one of four site years, removal of autumn starter fertilizer from enhanced management decreased head production 37% and increased 17-70% in three of four site-years with addition of autumn starter fertilizer to traditional management (Table 2.08). Similar to grain yield, tiller and head production both showed significant increases from addition of autumn starter fertilizer to traditional management in three of four site-years (Table 2.04, 2.06, 2.08). Results suggest pre-plant soil test concentrations and tiller production may both indicate whether a wheat crop will respond to autumn starter fertilizer. Autumn fertilizer applications may be one component to accelerate plant growth and grain yield potential, but producers should base the analysis of an autumn starter fertilizer from pre-plant soil test concentrations and the likelihood of a positive grain yield response to specific nutrients.

Weekly N Applications

Removal of weekly N applications from the enhanced managed system increased grain yield 0.5 Mg ha^{-1} in one of four site-years, while the addition of weekly N to traditional management had no effect across any site-year (Table 2.04). No visual N deficiency symptoms occurred within fertilized plots at any location throughout the study. Minimal rainfall (< 0.65 cm) occurred 17 days following the second and third weekly N application at Richville 2018 which coincided with accelerated N uptake (i.e., Feekes 7) (Table 2.10). Precipitation events $\geq$ 0.65 cm may be needed within two days of surface N application to eliminate or reduce volatilization potential (Sawyer, 2018). Lack of rainfall between the second and third weekly N applications likely limited N movement into the rhizosphere during accelerated N uptake leading to the grain yield increase when removing weekly N at Richville 2018. Results coincide with Roberts et al. (2004) who suggested insufficient amounts of available N during accelerated N uptake and plant growth (May-April) can reduce wheat grain yield. Volatilization likely also occurred to surface applied weekly N during the period of absent rainfall between the second and third application, as canopy coverage was merely 34% (data not shown) indicating a lack of dense ground cover. Results are supported by Bacon et al. (1985) who found surface applied N volatilized 35% within five days after application when rainfall was less than 0.65 cm. Although May through June total rainfall during 2019 was 75 and 55% greater compared to the 30-yr mean in Richville and Lansing, respectively, a longer duration of N loss conditions (i.e., leaching and denitrification) on the medium to fine textured soils of this study may be needed to realize benefits from weekly N applications (Gravelle et al., 1998). Compared to one-pass N applications between green-up and Feekes 5, weekly N applications showed no benefit in the current study but may benefit in situations where greater rainfall intensities promote N loss by transporting soluble N out of the rhizosphere. Data from this study suggests excessive rainfall to create N loss conditions throughout the growing season may be required to substantiate a grain yield benefit from weekly N applications in Michigan winter wheat growing conditions. Although weekly N applications may minimize risks for N loss in some situations, application costs continued to offset any grain yield increase.

High N Rate

Application of a 33% greater N rate did not influence grain yield in any site year or either management system (Table 2.04). The 2019 growing season produced excessive (+20%) total growing season rainfall for both locations (Table 2.03) which likely provided potential for N loss conditions (i.e. denitrification and leaching). However, minimal grain yield responses suggest the traditional base N rate was sufficient to optimize wheat grain yield at current production levels within the environments tested. Bauer (2016) concluded an N rate of 84 kg N ha^{-1} produced optimal soft red winter wheat grain yield in Michigan. Data from this study correspond with university recommended N rates suggested by Warncke et al. (2009), however recommendations are based off the expectation that yield response to applied N is independent from agronomic factors (e.g., cultivar, seeding rate) (Brinkman et al., 2014). Applying multiple inputs may increase the stay-green potential of the flag leaf and prolong grain-fill resulting in greater N requirements to support greater grain yield potential (Mourtzinis et al., 2017; Salgado et al., 2017; Quinn and Steinke, 2019). No differences in green canopy cover or normalized difference vegetation index (NDVI) occurred at any location throughout the study (data not shown). Previous studies from Quinn and Steinke (2019) and Jaenisch et al. (2019) both suggested enhanced management systems may require additional N to influence grain yield responses from other agronomic inputs. Further research may be needed to explore possible relationships between multiple agronomic inputs and N fertilizer across additional wheat varieties and environmental conditions to determine whether recommended wheat N rates require modification but data from the current study do not support this concept.

Agronomic Efficiency

Agronomic efficiency and grain yield responded similarly under both management intensities with the exception of high N rate (Table 2.11). Richville 2018 AE was lower than all other site-years due to decreased overall grain yields caused by dry conditions lowering yield potential. Averaged across both management systems, fungicide and autumn starter fertilizer increased AE 27% and 41%, respectively. However, decreased seeding rate, weekly N applications, and high N rate decreased AE 25%, 26%, and 36%, respectively, when averaged across both management systems. Reduced AE from decreased seeding rate and weekly N applications was due to grain yield reductions at Richville 2018 which were likely caused by environmental conditions. Data suggest that as inputs increase grain yield, the AE of applied N fertilizer also increases when applying university recommended N rates. Reduced AE associated with high N was due to lack of positive grain yield response to additional N under both management systems. Precipitation events during the growing season were insufficient to produce substantial N loss conditions (leaching, denitrification) in order to observe an AE response to high N management. Results agree with Austin et al. (2019) who found AE decreased 12% with an increased N rate (+25%) compared to university wheat N recommendations. Results from this study indicate N rates greater than university recommendations decreased efficiency of applied N fertilizer per unit of grain yield with minimal N loss conditions. Consideration of AE may become more important in Michigan winter wheat production areas (i.e., the Eastern Lakebed Region) due to greater concern for Great Lakes water quality.

Conclusion

In the environments tested for this study, minimal SRWW and SWWW grain yield responses were observed from applications of fungicide, PGR, weekly N, and high N management. However, benefits from these inputs may occur when utilizing disease susceptible or tall statured varieties, or when greater rainfall intensities promote N loss conditions. Decreased seeding rate (i.e. 2,223,900 seeds ha^{-1}) produced comparable grain yield to the increased seeding rate (i.e. 4,447,800 seeds ha^{-1}) under enhanced management across all site-years. However harsh winter conditions and increase spring weather variability may add additional risk to reducing winter wheat seeding rates below recommended guidelines. Autumn-applied starter fertilizer was the only individual agronomic input to consistently provide grain yield responses across site-years which accounted for 71% of the grain yield difference between enhanced and traditional management. Although enhanced SWWW and SRWW management increased grain yield, traditional management containing only a university recommended N rate increased expected net return in three of four site-years. Trial results emphasize that producers should be cognizant of pre-plant soil nutrient concentrations (i.e. phosphorus and nitrate levels) as responses to at-plant autumn fertilizer are unlikely when nutrient concentrations are at or above critical levels. Wheat producers should incorporate IPM practices which utilize multiple production approaches (i.e. disease prediction models, crop scouting, varietal resistance, nutrient recommendations) to justify input applications and take advantage of proven benefits identified with agronomic inputs used in this trial. Producers should consider commodity prices, fertilizer cost, and potential yield response prior to adopting widely implemented enhanced management strategies. However site-specific considerations including soil and plant characteristics, attainable yield potentials, and economics must still be considered within an integrated management program. Despite grain yield increases to input additions, greater expected net return may still be achieved at reduced grain yields if specific inputs turn out to protect or insure against yield losses that may or may not occur.

Acknowledgements

The authors would like to thank the USDA National Institute of Food and Agriculture, the Michigan Wheat Program, Michigan State University College of Agriculture and Natural Resources, and Michigan State University AgBioResearch for partial funding and support of these trials. The authors would like to also thank Andrew Chomas, research farm staff, graduate research assistants, and undergraduate research assistants for their help.

APPENDIX

Table 2.01. Overview of omission treatment design, treatment names, and inputs applied to winter wheat in 2018-19.

		Agronomic input applied					
Trt.	Treatment name	D.S.†	Fungicide§	PGR¶	Autumn starter #	Weekly N††	High-N‡‡
1	Enhanced (E), D.S.†	Yes	Yes	Yes	Yes	Yes	Yes
2	E - D.S.	No	Yes	Yes	Yes	Yes	Yes
3	E - Fungicide	Yes	No	Yes	Yes	Yes	Yes
4	E - PGR	Yes	Yes	No	Yes	Yes	Yes
5	E - Autumn starter	Yes	Yes	Yes	No	Yes	Yes
6	E - Weekly N	Yes	Yes	Yes	Yes	No	Yes
7	E - High-N	Yes	Yes	Yes	Yes	Yes	No
8	Traditional (T), I.S. ‡	No	No	No	No	No	No
9	T + D.S.	Yes	No	No	No	No	No
10	T + Fungicide	No	Yes	No	No	No	No
11	T + PGR	No	No	Yes	No	No	No
12	T + Autumn starter	No	No	No	Yes	No	No
13	T + Weekly N	No	No	No	No	Yes	No
14	T + High-N	No	No	No	No	No	Yes
15	Check	No	No	No	No	No	No

† Decreased seeding (D.S.) rate of SRWW/SWWW at 2,223,900 seeds ha^{-1}.
‡ Increased seeding (I.S.) rate of SRWW/SWWW at 4,447,800 seeds ha^{-1}.
§ Prothioconazole + tebuconazole fungicide applied at a rate of 0.6 L ha^{-1} at F10.5.1 growth stage.
¶ Trinexapac-ethyl plant growth regulator (PGR) applied at a rate of 0.88 L ha^{-1} at F6 growth stage.
# Autumn starter fertilizer (12-40-0-10-1 N-P-K_S-Zn) at a rate of 280 kg ha^{-1} autumn applied.
†† Weekly applications of UAN (28%) starting at Feekes 4 growth stage applied at a rate of 18.6 and 24.2 kg N ha^{-1} for Lansing and Richville locations, respectively.
‡‡High-nitrogen applied at F4 growth stage at a rate of 149 and 194 kg N ha^{-1} for Lansing and Richville locations, respectively.

Table 2.02. Estimates of winter wheat prices received and input costs per hectare used for expected net return analysis, Richville and Lansing, MI, 2018-19.

		2018		2019	
Investments	Returns	Richville	Lansing	Richville	Lansing
		---------------------US$ kg^{-1}---------------------			
Price received	Wheat	0.59	0.51	0.53	0.47
	Costs	---------------------US$ ha^{-1}---------------------			
Inputs applied	Decreased seeding rate†	59	53	47	51
	Increased seeding rate‡	118	106	94	102
	Fungicide	46	46	46	46
	Plant growth regulator	34	34	34	34
	Autumn starter fertilizer	181	181	181	181
	Weekly N applications	132	101	132	101
	Base N rate§	132	101	132	101
	High N rate¶	175	135	175	135
Application#	Spray application††	19	19	19	19
	Weekly N application‡‡	153	153	153	153
	Dry fertilizer application§§	16	16	16	16

† Decreased seeding (D.S.) rate of SRWW/SWWW at 2,223,900 seeds ha^{-1}.
‡ Increased seeding (I.S.) rate of SRWW/SWWW at 4,447,800 seeds ha^{-1}.
§Base-nitrogen applied at a rate of 112 and 146 kg N ha^{-1} for Lansing and Richville locations, respectively.
¶High-nitrogen applied at a rate of 149 and 194 kg N ha^{-1} for Lansing and Richville locations, respectively.
#Application cost estimates obtained from Michigan State University Extension custom machine and work rate.
††Application spray cost estimates for fungicide, plant growth regulator, base N rate, and high N rate.
‡‡Application spray cost total estimate for all weekly N applications.
§§Application cost estimate for autumn starter fertilizer.

Table 2.03. Mean monthly and 30-yr temperature and precipitation† for the winter wheat growing season, Richville and Lansing, MI, 2018 - 2019.

Site	Year	Mar.	Apr.	May	Jun.	Jul.	Total
		cm					
Richville	2018	1.4	7.1	5.4	3.8	5.0	22.7
	2019	3.4	5.8	12.8	17.7	6.0	45.7
	30-yr‡	4.9	8.1	8.4	9.0	7.9	38.2
Lansing	2018	2.5	6.0	12.6	3.7	2.7	27.5
	2019	5.0	7.2	8.5	18.3	5.8	44.8
	30-yr	5.2	7.7	8.5	8.8	7.2	37.4
		°C					
Richville	2018	-0.6	3.6	17.6	19.7	22.1	--
	2019	-0.8	7.4	12.8	18.4	22.6	--
	30-yr	0.4	7.4	13.2	18.7	20.9	--
Lansing	2018	0.7	4.4	17.7	20.0	21.8	--
	2019	-0.3	8.0	14.1	18.3	23.1	--
	30-yr	1.7	8.6	14.3	19.8	21.9	--

† Precipitation and air temperature data were collected from MSU Enviro-weather (https://enviroweather.msu.edu/).
‡ 30-yr means obtained from the National Oceanic and Atmospheric Administration (https://www.ncdc.noaa.gov/cdo-web/datatools/normals).

Table 2.04. Winter wheat grain yield for Richville and Lansing, MI, 2018-2019. Mean grain yield of enhanced and traditional control treatments displayed. All other treatments display change in grain yield from respective enhanced or traditional control, respectively, using single degree of freedom contrasts.

	2018		2019	
Treatment†	Richville	Lansing	Richville	Lansing
	Mg ha^{-1}			
Enhanced (E), D.S.	6.2	7.0	8.4	7.7
E - D.S. ‡	+0.3	+0.3	-0.1	+0.4
E - Fungicide	+0.0	-0.8*	-0.6	-0.6
E - PGR	+0.2	+0.2	-0.2	+0.3
E - Autumn starter	-0.2	-1.0*	-1.3*	-2.5*
E - Weekly N	+0.5*	+0.2	+0.3	+0.4
E - High-N	+0.3	+0.2	+0.2	+0.0
Traditional (T), I.S.	6.1	5.8	6.7	5.4
T + D.S. §	-0.3	-1.1*	-0.3	-0.3
T + Fungicide	-0.1	-0.1	+0.6	+0.8*
T + PGR	-0.3	-0.9*	+0.6	+0.5
T + Autumn starter	+0.6*	+0.7*	+1.2*	+1.7*
T + Weekly N	-0.1	-0.3	+0.1	+0.4
T + High-N	+0.0	-0.2	+0.6	+0.4
Check¶	4.2	2.9	3.2	3.5
E vs. T#	ns††	*	*	*
CV %	5.1	10.5	8.0	11.3

* Significantly different at α=0.1 using single degree of freedom contrasts.
† Decreased seeding rate (D.S.), trinexapac-ethyl plant growth regulator (PGR), weekly N applications (Weekly N), 33% increase in nitrogen fertilizer rate (High-N), increased seeding rate (I.S.).
‡Values in E - input rows indicate a yield (Mg ha^{-1}) change from respective enhanced (E) treatment.
§Values in T + input rows indicate a yield (Mg ha^{-1}) change from respective traditional (T) treatment.
¶ Non-treated check containing no fertilizer or additional inputs was not included in statistical analysis.
# Comparison between the enhanced and traditional treatment utilizing single degree of freedom contrasts
†† Non-significant α=0.10 using single degree of freedom contrasts.

Table 2.05. Expected economic net return for winter wheat, Richville and Lansing, MI, 2018-2019. Mean expected net return from enhanced and traditional control treatments displayed. All other treatments display change in expected net return from respective enhanced or traditional treatment using single degree of freedom contrasts.

	2018		2019	
Treatment†	Richville	Lansing	Richville	Lansing
	---------------------------------- US$ ha^{-1}	----------------------------------		
Enhanced (E), D.S.	426.50	500.70	819.16	656.52
E - D.S. ‡	-6.75	-3.51	-62.15	+24.71
E - Fungicide	+76.45*	-65.23	-44.03	-41.96
E - PGR	+92.42*	+96.22	+28.42	+107.96
E - Autumn starter	+152.31*	+39.07	-32.30	-239.24*
E - Weekly N	+228.77*	+165.04*	+181.12*	+210.97*
E - High-N	+92.86*	+61.53	+85.82	+38.40
Traditional (T), I.S.	848.86	740.29	955.96	693.36
T + D.S. §	+6.62	-123.33*	-9.34	-3.85
T + Fungicide	-87.13*	-81.86	+40.92	+74.77
T + PGR	-104.38*	-199.83*	+43.71	+33.41
T + Autumn starter	-85.13*	-84.43	+16.58	+103.26
T + Weekly N	-198.55*	-230.08*	-163.68*	-107.09
T + High-N	+46.50	-64.25	+65.23	+25.67
Check¶	649.68	365.24	482.14	499.09
E vs. T#	*	*	*	ns††
CV %	8.9	18.3	12.3	18.5

* Significantly different at α=0.10 using single degree of freedom contrasts.

† Decreased seeding rate (D.S.), trinexapac-ethyl plant growth regulator (PGR), weekly N applications (Weekly N), 33% increase in nitrogen fertilizer rate (High-N), increased seeding rate (I.S.).

‡Values in E - input rows indicate an expected return (US$ ha^{-1}) change from respective enhanced (E) treatment.

§Values in T + input rows indicate an expected return (US$ ha^{-1}) change from respective traditional (T) treatment.

¶ Non-treated check containing no fertilizer or additional inputs was not included in statistical analysis.

\# Comparison between the enhanced and traditional treatment utilizing single degree of freedom contrasts

†† Non-significant α=0.1 using single degree of freedom contrasts.

Table 2.06. Winter wheat seeding rate and autumn starter fertilizer effects on Feekes 4 tiller production, Richville and Lansing, MI, 2018 to 2019. Mean tiller production displayed for enhanced and traditional management systems with other treatments displaying change in tiller counts from respective enhanced or traditional treatment.

		Treatment					
Site	Year	Enhanced, D.S.† (E)	Enhanced, I.S.‡ §	E–Autumn Starter	Traditional, I.S. (T)	Traditional, D.S.¶	T+Autumn Starter
		--tillers m^2--	--------% change--------		--tillers m^2--	--------% change--------	
Richville	2018	1049	+16	-24*	885	+19	+0
	2019	607	+14	-1	651	+13	+42*
Lansing	2018	829	+25	-21	671	+31	+116*
	2019	581	+59*	-15	547	+19	+42*

* Significantly different at α=0.1 using single degree of freedom contrasts

† Decreased seeding (D.S.) rate of SRWW/SWWW (Starburst/Jupiter) at 2,223,900 seeds ha^{-1}.

‡ Increased seeding (I.S.) rate of SRWW/SWWW (Starburst/Jupiter) at 4,447,800 seeds ha^{-1}.

§ Values in column indicate percent tiller production (m^{-2}) change from respective enhanced (E) treatment.

¶ Values in column indicate percent tiller production (m^{-2}) change from respective traditional (T) treatment.

Table 2.07. Effect of Feekes 10.5.1 fungicide on winter wheat Fusarium head blight occurrence (infected heads) three weeks after fungicide application, Richville and Lansing, MI, 2018 to 2019.

		Treatment					
Site	Year	Enhanced (E)	E – Fungicide	Change†	Traditional (T)	T + Fungicide	Change‡
		--% infected heads m^{-2}--		--%--	--% infected heads m^{-2}---		--%--
Richville	2018	0.0	0.0	0.0	0.0	0.0	+0.0
	2019	6.6	17.5	+10.9*	15.9	10.7	-5.2
Lansing	2018	9.3	17.5	+8.2*	16.9	12.1	-4.8
	2019	0.3	2.7	+2.4*	4.5	1.6	-2.9*

* Significantly different at α=0.10 using single degree of freedom contrasts

† Values indicate percent change in heads affected (%) between 'Enhanced (E)' and 'E-Fungicide' treatment

‡ Values indicate percent change in heads affected (%) between 'Traditional (T)' and 'T+Fungicide' treatment

Table 2.08. Impact of enhanced or traditional management and autumn starter fertilizer on winter wheat grain head production. Mean head production displayed for enhanced and traditional management systems with other treatments displaying change in head production from respective enhanced or traditional treatment. Richville and Lansing, MI, 2018-2019.

		Treatment					
Site	Year	Enhanced (E)	E – Autumn Starter	Change†	Traditional (T)	T + Autumn Starter	Change‡
		--------heads m^{-2}--------		---%---	--------heads m^{-2}--------		---%---
Richville	2018	700	762	+9	786	756	-4
	2019	823	699	-15	671	789	+18*
Lansing	2018	832	741	-11	780	912	+17*
	2019	1074	681	-37*	681	1160	+70*

* Significantly different at α=0.10 using single degree of freedom contrasts

† Values indicate percent change in heads affected (%) between 'Enhanced (E)' and 'E-Autumn Starter treatment

‡ Values indicate percent change in heads affected (%) between 'Traditional (T)' and 'T+Autumn Starter treatment

Table 2.09. Site year and soil descriptions including soil chemical properties and mean P, K, S, and Zn soil test (0 – 20 cm) nutrient concentrations obtained prior to winter wheat planting, Richville and Lansing, MI, 2018-2019.

Site	Year	Soil description	Soil test†						
			P	K	S	Zn	pH	OM	CEC
			----------mg kg^{-1}-------					g kg^{-1}	cmolc kg^{-1}
Richville†	2018	Tappan-Londo loam	9	15	9	5.4	7.7	21	16.0
	2019	Tappan-Londo loam	7	13	6	5.7	8.0	20	20.3
Lansing	2018	Capac loam	12	80	8	2.5	7.0	25	12.1
	2019	Capac loam	33	102	8	3.4	7.1	28	12.0

†P, phosphorus (Olsen sodium bicarbonate extractant or Bray-P1 depending on soil pH); K, potassium (ammonium acetate extractable K); S, sulfur (monocalcium phosphate extraction); Zn, zinc (0.1 M HCl)

Table 2.10. Precipitation† volumes the week following weekly winter wheat N applications in Richville and Lansing, MI, 2018-2019.

Site	Year	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8‡	Total
		-----	-----	-----	-----	-----cm-----	-----	-----	-----	-----
Richville	2018	5.18	0.05	0.03	1.75	1.88	1.14	0.20	0.74	10.97
	2019	0.36	2.97	8.97	1.07	2.97	0.71	0.79	8.23	26.07
Lansing	2018	0.25	4.50	0.10	0.07	1.40	6.76	2.34	2.11	17.53
	2019	0.02	2.24	1.75	3.02	2.72	1.83	1.70	1.63	14.91

† Precipitation data were collected from Michigan State University Enviro-weather (https://enviroweather.msu.edu/).

‡ Volume precipitation totals represent the seven consecutive days following previous weekly N application.

Table 2.11. Agronomic efficiency† (AE) of applied winter wheat nitrogen (N) fertilizer for Richville and Lansing, MI, 2018-2019. Mean AE of enhanced and traditional control treatments displayed. All other treatments display change in AE from respective enhanced or traditional control, respectively, using single degree of freedom contrasts.

	2018		2019	
Treatment†	Richville	Lansing	Richville	Lansing
	---------- kg grain kg N^{-1} ----------			
Enhanced (E), D.S. ‡	10.3	28.0	27.1	28.5
E - D.S. §	+1.5	+2.0	-0.4	+2.9
E - Fungicide	+0.2	-5.6*	-3.2	-4.3
E - PGR	+1.0	+1.9	-0.8	+1.9
E - Autumn Starter	-1.2	-6.4*	-6.5*	-16.9*
E - Weekly N	+2.7*	+1.3	+1.3	+3.0
E - High-N	+5.2*	+10.6*	+10.3*	+9.5*
Traditional (T), I.S.	13.0	26.7	24.0	16.9
T + D.S. ¶	-2.0*	-9.5*	-2.1	-2.8
T + Fungicide	-0.7	-0.9	+4.1*	+7.4*
T + PGR	-1.8*	-7.7*	+3.8	+4.7
T + Autumn Starter	+4.2*	+6.1*	+8.0*	+15.5*
T + Weekly N	-1.0	-3.1	+0.3	+3.4
T + High-N	-3.3*	-8.0*	-2.7	-1.7
E vs. T#	*	ns††	ns	*
CV %	14.6	19.8	13.1	24.7

*****Significantly different at α=0.10 using single degree of freedom contrasts.

†Agronomic efficiency calculated by subtracting yield of unfertilized control from mean yield of treatments with N and dividing by total N rate.

‡ Decreased seeding rate (D.S.), trinexapac-ethyl plant growth regulator (PGR), weekly N applications (Weekly N), 33% increase in nitrogen fertilizer rate (High-N), increased seeding rate (I.S.).

§Values in E - input rows indicate a yield (Mg ha^{-1}) change from respective enhanced (E) treatment.

¶Values in T + input rows indicate a yield (Mg ha^{-1}) change from respective traditional (T) treatment.

#Comparison between the enhanced and traditional treatment utilizing single degree of freedom contrasts

††Non-significant α=0.10 using single degree of freedom contrasts.

LITERATURE CITED

LITERATURE CITED

Akter, N., and Rafiqul Islam, M. 2017. Heat stress effects and management in wheat. A review.Agron Sustain. Dev. 37. Doi:10.1007/s13593-017-0443-9

Alcoz, M. M., F. M. Hons, and V. A. Haby. 1993. Nitrogen fertilization timing effect on wheat production, nitrogen uptake efficiency, and residual soil nitrogen. Agron. J. 85:1198-1203. doi:10.2134/agronj1993.00021962008500060020x

Alley, M.M., P. Scharf, D.E. Brann, W.E. Baethgen, and J.L. Hammons. 2009. Nitrogen management for winter wheat. Principles and recommendations. Virginia Coop. Ext. Circ. 424–026. Virginia Polytechnic Inst. and State Univ., Blacksburg.

Anderson, E., B. MacKellar. 2019. Soil temperatures and planting time – part 2 of 3: tracking soil temperature trends. Michigan State Uni. Ext., Ann Arbor, MI. https://www.canr.msu.edu/news/soil-temperatures-and-planting-timing-part-2-of-3 (accessed 30 Oct. 2019).

Austin, R., D. Osmond, and S. Shelton. 2019. Optimum Nitrogen Rates for Maize and Wheat in North Carolina. Agron. J. 111:2558-2568. doi:10.2134/agronj2019.04.0286

Bacon, P. E., E. H. Hoult, and J. W. Mcgarity. 1986. Ammonia volatilization from fertilizers applied to irrigated wheat soils. Fert Res 10:27–42.

Bauer, C.A. 2016. Optimizing agronomic practices on Michigan winter wheat and sugarbeet production. M.S. Thesis. *ProQuest Diss. Publ. UMI 10108870.* Michigan State Univ., Ann Arbor, MI (accessed 21 Oct. 2019).

Beuerlein, J. E., E. S. Oplinger, and D. Reicosky. 1989. Yield and yield components of winter wheat cultivars as influenced by management—A Regional Study. J. Prod. Agric. 2:257-261. doi:10.2134/jpa1989.0257

Bhatta, M., T. Regassa, S. N. Wegulo, and P. S. Baenziger. 2018. Foliar fungicide effects on disease severity, yield, and agronomic characteristics of modern winter wheat genotypes. Agron. J. 110:602-610. doi:10.2134/agronj2017.07.0383

Blandino, M., L. Minelli, A. Reyneri. 2006. Strategies for the chemical control of fusarium head blight: effect on yield, alvegraphic parameters and deoxynivalenol contamination in winter wheat grain. Eur. J. Agron., 25:193-201.

Bluck, G.M., L.E. Lindsey, A.E. Dorrance, and J.D. Metzger. 2015. Soybean yield response to rhizobia inoculant, gypsum, manganese fertilizer, insecticide, and fungicide. Agron. J. 107:1757-1765.

Brinkman, J. M. P., W. Deen, J. D. Lauzon, and D. C. Hooker. 2014. Synergism of nitrogen rate and foliar fungicides in soft red winter wheat. Agron. J. 106:491-510. doi:10.2134/agronj2013.0395

Brown, L.K., M.L. Nagelkirk, A.T. Wiersma, L.F. Siler, and E.L. Olson. 2017. Wheat variety comments. Michigan State Univ. Ext., East Lansing, MI. http://fieldcrop.msu.edu/uploads/files/Wheat/ Wheat_Variety_Comments_2017_Field_Day_Handout.pdf (accessed 03 Sept. 2019).

Chen, C., K. Neill, D. Wichman, and M. Westcott. 2008. Hard red spring wheat response to row spacing, seeding rate, and nitrogen. Agron. J. 100:1296-1302. doi:10.2134/agronj2007.0198

Combs, S.M., and M.V. Nathan. 2015. Soil organic matter. In: M.V. Nathan and R. Gelderman, editors, Recommended chemical soil test procedures for the North Central Region. North Central Region Res. Publ. 221 (rev.). SB 1001. Missouri Agric. Exp. Stn, Columbia. p. 12.1-12.6.

Crane, T.A., C. Roncoli, and G. Hoogenboom. 2011. Adaptation to climate change and climate variability: The importance of understanding agriculture as performance. NJAS-Wageningen J. Life Sci. 57:179-185.

Darwinkel, A., B.A. ten-Hag, and Kuizenga. 1977. Effect of sowing date and seed rate on crop development and grain production of winter wheat. Neth. J. Agric. Sci, 25;83-94.

Darwinkel, A. 1978. Patterns of tillering and grain production of winter wheat at a wide range of plant densities. Netherlands Journal of Agricultural Science, v.26, p.383-398.

Delogu, G., L. Cattivelli, N. Pecchioni, D. De Falcis, T. Maggiore, and A.M. Stanca. 1998. Uptake and agronomic efficiency of nitrogen in winter barley and winter wheat. European Journal of Agronomy, 9(1), 11-20.

Dhillon, J., S. Dhital, T. Lynch, B. Figueiredo, P. Omara, and W. R. Raun. 2019. In-Season Application of Nitrogen and Sulfur in Winter Wheat. Agrosystems, Geosciences & Environment 2:180047. doi:10.2134/age2018.10.0047

Dilz, K. 1971. Effect of time of chlormequat application, level of nitrogen and split nitrogen on resistance to lodging and yield of winter wheat. Neth. Nitrogen Tech. Bull. no. 10.

Dilz, K., A. Darwinkel, R. Boon, and L.M.J. Verstraeten. 1982. Intensive wheat production as related to nitrogen fertilization, crop protection, and soil nitrogen: Experience in the Benelux. 93– 124. Fertilizer Society of London proc. no. 211, London. 10 Dec. Greenhill House London.

Ercoli L., A. Masoni, S. Pampana, M. Mariotti, I. Arduini. 2012. As durum wheat productivity is affected by nitrogen fertilisation management in Central Italy. European Journal of Agronomy, 44:38-45.

Evans, L.T. and R.A. Fischer. 1999. Yield potential: Its definition, measurement, and significance. Crop Sci., 39: 1544-1551. doi:10.2135/cropsci1999.3961544x

Forrestal, P., J. Meisinger, and R. Kratochvil. 2014. Winter wheat starter Nitrogen Management: A preplant soil nitrate test and site-specific nitrogen loss potential. Soil Sci. Soc. Am. J. 78:1021-1034. doi:10.2136/sssaj2013.07.0282

Frank, K., D. Beegle, and J. Denning. 2015. Phosphorus. In: M.V. Nathan and R. Gelderman, editors, Recommended chemical soil test procedures for the North Central Region. North Central Region Res. Publ. 221 (rev.). SB 1001. Missouri Agric. Exp. Stn, Columbia. p. 6.1-6.6.

Franzen, D.W. 2018. Limitations of the sulfate-sulfur soil test as a predictor of sulfur response. Ext. Publ. SF1880. North Dakota St. Ext., Fargo, ND.

Fuertes-Mendizábal, T., A. Aizpurua, M.B. González-Moro, J.M. Estavillo. 2010. Improving wheat breadmaking quality by splitting the N fertilizer rate. European Journal of Agronomy, 33:52-61.

Gelderman, R.H., and D. Beegle. 2015. Nitrate-nitrogen. In: M.V. Nathan and R. Gelderman, editors, Recommended chemical soil test procedures for the North Central Region. North Central Region Res. Publ. 221 (rev.). SB 1001. Missouri Agric. Exp. Stn, Columbia. p. 5.1-7.4.

Geleta, B., M. Atak, P. S. Baenziger, L. A. Nelson, D. D. Baltenesperger, K. M. Eskridge, M. J. Shipman, and D. R. Shelton. 2002. Seeding rate and genotype effect on agronomic performance and end-use quality of winter wheat. Nebraska Agric. Res. Division, J. Series No. 13200. Crop Sci. 42:827-832. doi:10.2135/cropsci2002.8270

Giambalvo, D., P. Ruisi, G. Di Miceli, A. S. Frenda, and G. Amato. 2010. Nitrogen use efficiency and nitrogen fertilizer recovery of durum wheat genotypes as affected by interspecific competition. Agron. J. 102:707-715. doi:10.2134/agronj2009.0380

Girma, K., J. Mosali, K. W. Freeman, W. R. Raun, K. L. Martin & W. E. Thomason. 2005. Forage and grain yield response to applied sulfur in winter wheat as influenced by source and rate, Journal of Plant Nutrition, 28:9, 1541-1553, DOI: 10.1080/01904160500203259

Gravelle, W. D., M. M. Alley, D. E. Brann, and K. D. S. M. Joseph. 1988. Split spring nitrogen application effects on yield, lodging, and nutrient uptake of soft red winter wheat. J. Prod. Agric. 1:249-256. doi:10.2134/jpa1988.0249

Harms, C. L., J. E. Beuerlein, and E. S. Oplinger. 1989. Effects of intensive and current recommended management systems on soft winter wheat in the U.S. corn belt. J. Prod. Agric. 2:325-332. doi:10.2134/jpa1989.0325

Isidro-Sánchez, J., B. Perry, A. K. Singh, H. Wang, R. M. DePauw, C. J. Pozniak, B. L. Beres, E. N. Johnson, and R. D. Cuthbert. 2017. Effects of seeding rate on durum crop production and physiological responses. Agron. J. 109:1981-1990. doi:10.2134/agronj2016.09.0527

Jaenisch, B. R., A. de Oliveira Silva, E. DeWolf, D. A. Ruiz-Diaz, and R. P. Lollato. 2019. Plant population and fungicide economically reduced winter wheat yield gap in Kansas. Agron. J. 0. doi:10.2134/agronj2018.03.0223

Jankowski, K. J., M. Sokólski, B. Bogucka, and B. Dubis. 2018. Micro-Granulated starter fertilizer effects on growth and productivity of winter oilseed rape. Agron. J. 110:2250-2258. doi:10.2134/agronj2018.01.0046

Joseph, K. D. S. M., M. M. Alley, D. E. Brann, and W. D. Gravelle. 1985. Row spacing and seeding rate effects on yield and yield components of soft red winter wheat. Agron. J. 77:211-214. doi:10.2134/agronj1985.00021962007700020009x

Kaiser, D. E., A. K. Sutradhar, and J. J. Wiersma. 2019. Do hard red spring wheat varieties vary in their response to sulfur?. Agron. J. 111:2422-2434. doi:10.2134/agronj2018.12.0798

Karlen, D. L., and D. T. Gooden. 1990. Intensive management practices for wheat in the Southeastern Coastal Plains. J. Prod. Agric. 3:558-563. doi:10.2134/jpa1990.0558

Klepper, B., Richman, R., and T. Johlke. 2014. Wheat development and growth. http://smallgrains.wsu.edu/additional-resources/wheat-academy-resources (accessed 17 Oct. 2019).

Knapp, J. S., C. L. Harms, and J. J. Volenec. 1987. Growth regulator effects on wheat culm nonstructural and structural carbohydrates and lignin. Crop Sci. 27:1201–1205.

Knott, C.A., D.A. Van Sanford, E.L. Ritchey, and E. Swiggart. 2016. Wheat yield response and plant structure following increased nitrogen rates and plant growth regulator applications in Kentucky. Crop Forage Turfgrass Manage. 2:1-7 doi:10.2134/cftm2015.0202

Liu, Z. F., Gao, Y. Liu, J. Yang, X. Zhen, X. Li, Y. Li, J. Zhao, J. Li, B. Qian, D. Yang, X. Li. 2018. Timing and splitting of nitrogen fertilizer supply to increase crop yield and efficiency of nitrogen utilization in a wheat-peanut relay intercropping system in China. The Crop Journal. 7:101-112. doi:10.1016/j.cj.2018.08.006

Lloveras, J., J. Manent, J. Viudas, A. López, and P. Santiveri. 2004. Seeding rate influence on yield and yield components of irrigated winter wheat in a Mediterranean climate. Agron. J. 96:1258–1265. doi:10.2134/agronj2004.1258

Lucheta, A. R., and M. R. Lambais. 2012. Sulfur in agriculture. R. Bras. Ci. Solo. 36:1369:1379. doi:10.1590/S0100-06832012000500001

Mahler, R.J., and R.L. Maples. 1987. Effect of sulfur additions on soil and the nutrition of wheat, Communications in Soil Science and Plant Analysis, 18:6, 653-673, DOI: 10.1080/00103628709367849

Marburger, D.A., B.J. Haverkamp, R.G. Laurenz, J.M. Orlowski, E.W. Wilson, and S. Casteel. 2016. Characterizing genotype × management interactions on soybean seed yield. Crop Sci. 56:786–796. doi:10.2135/cropsci2015.09.0576

Mascagni, H.J. Jr., S. A. Harrison & G. B. Padgett. 2008. Influence of sulfur fertility on wheat yield performance on alluvial and upland soils, communications in soil science and plant analysis, 39:13-14, 2133-2145, doi:10.1080/00103620802135328

Masle, J. 1985. Competition among tillers in winter wheat: consequences for growth and development of the crop. In Wheat growth and modelling. p. 33-54.

Matysiak, K. 2006. Influence of trinexapac-ethyl on growth and development of winter wheat. Journal of Plant Protection Research, 46(2), 133-143.

McKay, K. 1996. Fertility Study, McClean, Co. North Central Research Experiment Station Report. Minot, ND.

McMullen, M., S. Halley, B. Schatz. S. Meyer. J. Jordahl, J. Ransom. 2008. Integrated strategies for Fusarium head blight management in the United States. Cereal Research Communications. 36:563-568.

Mourtzinis, S., D.A. Marburger, J.M. Gaska, and S.P. Conley. 2016. Characterizing soybean yield and quality response to multiple prophylactic inputs and synergies. Agron. J. 108:1337-1345.

Mourtzinis, S., D. Marburger, J. Gaska, T. Diallo, J. G. Lauer, and S. Conley. 2017. Corn, soybean, and wheat yield response to crop rotation, nitrogen rates, and foliar fungicide application. Crop Sci. 57:983-992. doi:10.2135/cropsci2016.10.0876

Nagelkirk, M. 2012. The effect of Palisade EC plant growth regulator on the performance of soft winter wheat. http://fieldcrop.msu.edu/ uploads/files/Palisade%20report12.pdf (accessed 12 Sept. 2019).

Nagelkirk, M., and M. Chilvers. 2016. Managing fusarium head blight. Michigan State Univ. Ext., East Lansing, MI. msue.anr.msu.edu/uploads/234/89014/disease/ Managing_Fusarium_Head_Blight. pdf (accessed 10 Sept. 2019).

National Agricultural Statistics Service. 2019. USDA-NASS agricultural statistics 2019. USDA-NASS. http://www.nass.usda.gov (accessed 23 Dec. 2019).

Nkebiwe, P.M., M. Weinmann, A. Bar-Tal, and T. Müller. 2016. Fertilizer placement to improve crop nutrient acquisition and yield: A review and meta-analysis. Field Crops Res. 196:389–401. doi:10.1016/j.fcr.2016.07.018

Park, S.E., L.R. Benjamin, and A.R. Watkinson. 2003. The theory and application of plant competition models: An agronomic perspective. Ann. Bot. (Lond.) 92(6):741–748. doi:10.1093/aob/mcg204

Paul, P.A., M.P. McMullen, D.E. Hershman, and L.V. Madden. 2010. Meta-analysis of the effects of triazole-based fungicides on wheat yield and test weight as influenced by Fusarium head blight intensity. Phytopathology 100:160–171. doi:10.1094/PHYTO-100-2-0160

Pennington, D., E. Olsen, S. Martin, and A. Noble. 2019. Michigan state wheat performance trials. http://www.varietytrials.msu.edu/wheat (accessed 08 Oct. 2019).

Peters, J.B., M.V. Nathan, and C.A.M. Laboski. 2015. pH and lime requirement. In: M.V. Nathan and R. Gelderman, editors, Recommended chemical soil test procedures for the North Central Region. North Central Region Res. Publ. No. 221 (rev.) Missouri Agric. Exp. Stn., Columbia. p. 4.1-4.7.

Prasad, P.V.V., and Djanaguiraman M. 2014. Response of floret fertility and individual grain weight of wheat to high temperature stress: sensitive stages and thresholds for temperature and duration. Funct Plant Biol. 41:1261–1269. doi:10.1071/FP14061

Quinn, D., and K. Steinke. 2019. Soft red and white winter wheat response to input-intensive management. Agron. J. 111:428-439.

Rana, D.S., S. Ganga, D.K. Pachauri, and G. Saran. 1995. Response of wheat seeding rates and row spacing under dryland conditions. Annu. Agric. Res. 16:339–342.

Roberts, R. K., J. T. Walters, J. A. Larson, B. C. English, and D. D. Howard. 2004. Effects of disease, nitrogen source, and risk on optimal nitrogen fertilization timing in winter wheat production. Agron. J. 96:792-799. doi:10.2134/agronj2004.0792

Rosenzweig, C., A. Iglesias, X.B. Yang, P.R. Epstein, and E. Chivian. 2001. Climate change and extreme weather events; implications for food production, plant diseases, and pests. Global Change and Human Health. 2:90-104.

Roth, G.W., R.H. Fox. 1990. Soil nitrate accumulations following nitrogen-fertilized corn in Pennsylvania. J. Environ. Qual. 19:243-248. doi:10.2134/jeq1990.00472425001900020008x

Rutan, J., and K. Steinke. 2017. Determining corn nitrogen rates using multiple prediction models. J. Crop Improve. 31:780-800.

Salgado, J. D., L. Lindsey, and P. A. Paul. 2017. Effects of row spacing and nitrogen rate on wheat grain yield and profitability as influenced by diseases. Plant Dis. 101:1998-2011.

SAS Institute. 2012. The SAS System for windows. Version 9.4. SAS Inst., Cary, NC.

Sawyer, J., E. Nafziger, G. Randall, L. Bundy, G. Rehm, and B. Joern. 2006. Concepts and rationale for regional nitrogen rate guidelines for corn. Publ. PM2015, Iowa State Univ. Ext., Ames, IA.

Sawyer, J. 2018. A late spring – nitrogen considerations. Iowa State Univ. Ext., Ames, IA. https://crops.extension.iastate.edu/cropnews/2018/04/late-spring-nitrogen-considerations (Accessed 21 Oct. 2019).

Stein, D. 2018. 2019 Custom machine and work rate estimates. Michigan State University Extension. https://msu.edu/user/steind/06%2019%20MSU%20Custom%20Work%20Rates.pdf (accessed 17 Apr. 2020).

Swoish, M., and K. Steinke. Plant growth regulator and nitrogen applications for improving wheat production in Michigan. Crop Forage Turfgrass Manage. 3:1-7. doi:10.2134/cftm2016.06.0049

Tinker, P.B., and F.W. Widdowson. 1982. Maximizing wheat yields and some causes of yield variation. 149– 184. Fertilizer Society of London proc. no. 211, London. 10 Dec. Greenhill House London.

Van Sanford, D.A., J. H. Grove, L.J. Grabau, and C.T. MacKown. 1989. Ethephon and nitrogen use in winter wheat. Agron. J. 81:951–954. doi:10.2134/agronj1989.00021962008100060021x

Warncke, D., J. Dahl, and L. Jacobs. 2009. Nutrient recommendations for field crops in Michigan. Ext. Bull. E2904. Michigan State Univ. Ext., East Lansing, MI. https://soil.msu.edu (accessed 20 May 2018).

Warncke, D., and J.R. Brown. 2015. Potassium and other basic cations. In: M.V. Nathan and R. Gelderman, editors, Recommended chemical soil test procedures for the North Central Region. North Central Region Res. Publ. 221 (rev.). SB 1001. Missouri Agric. Exp. Stn, Columbia. p. 7.1-7.3.

Wasson, A.P., Richards, R.A., Chatrath, R., Misra, S.C., Prasad, S.S., Rebetzke, G.J., Kirkegaard, J.A., Christopher, J. and Watt, M., 2012. Traits and selection strategies to improve root systems and water uptake in water-limited wheat crops. Journal of experimental botany, 63(9), p.3485-3498.

Wegulo, S., J. Stevens, M. Zwingman, and P.S. Baenziger. 2012. Yield response to foliar fungicide application in winter wheat. In: D. Dhanasekaran, editor, Plant and animal diseases. Intech Publishing, Rijeka, Croatia. p. 227-244.

Whitney, D.A. 2015. Micronutrients: Zinc, iron, manganese and copper. In: M.V. Nathan and R. Gelderman, editors, Recommended chemical soil test procedures for the North Central Region. North Central Region Res. Publ. 221 (rev.). SB 1001. Missouri Agric. Exp. Stn, Columbia. p. 9.1-9.4.

Wiersma, J. J., J. Dai, and B. R. Durgan. 2011. Optimum Timing and Rate of Trinexapac-ethyl to Reduce Lodging in Spring Wheat. Agron. J. 103:864-870. doi:10.2134/agronj2010.0398

Wise, K., B. Johnson, C. Mansfield, C. Krupke. 2011. Managing wheat growth by stage. Ext. Publ. ID-422. Purdue University Ext., West Lafayette, IN.

Zadoks, J.C., T.T. Chang, and C.F. Zonzak. 1974. A decimal code for the growth stages of cereals. Weed. Res. 14:415-421.

CHATER 3

SUGARBEET RESPONSE TO PLANT POPULATION, NITROGEN RATE, ROW SPACING, AND SUBSURFACE BANDED NITROGEN

Abstract

Michigan sugarbeet (*Beta vulgaris* L.) growers question how intensive management strategies involving greater plant densities, nitrogen (N) rates, and narrower row spacing may improve root yield, quality, and profitability. As row spacings decrease, the use of starter N subsurface banded 5 cm beneath and 5 cm beside the furrow (5x5) has decreased. Two field studies were established to investigate 1) two plant populations (123,552 and 148,260 seeds ha^{-1}), four N rates (0, 89, 179, and 269 kg N ha^{-1}), and with or without 45 kg N ha^{-1} starter N applied in 5x5 at-planting, and 2) two row spacings (56 and 76 cm) both with and without 45 kg N ha^{-1} starter N applied 5x5 at-planting. Across tested N rates, 179 kg N ha^{-1} produced optimal root yield, quality, and expected net return, but peak recoverable sucrose averaged 27 kg N ha^{-1} lower than peak root yield across years. At 179 kg N ha^{-1}, starter N increased root yield and recoverable sucrose 13.4 Mg ha^{-1} and 1680 kg ha^{-1}, respectively, in 2018. Narrower row spacing increased root yield 14.5 and 23.8 Mg ha^{-1} in 2018 and 2019, respectively, with 5x5 starter N increasing root yield 4.3 Mg ha^{-1} compared to PRE N placement in 2018. Greater root yield benefits from 5x5 starter N existed during dry May-June soil conditions. Data suggest 5x5 starter N placement still offers benefits in 56 cm rows and that 5x5 N should not be abandoned in narrow row spacings simply due to less distance between rows.

Introduction

Michigan sugarbeets accounted for 12.9 and 13.7% of total U.S. production in 2018 and 2019, respectively (NASS, 2018, 2019). Production occurred on approximately 59,084 hectares of non-irrigated land located within the Great Lakes watershed basin (NASS, 2019). Since 2009 mean root yields increased 14% across the state, but sucrose concentrations have correspondingly declined 11% (NASS, 2019). Environmental conditions and field variabilities may supersede production practices and decreasing sucrose concentrations from excessive rainfall events near harvest (Märländer et al., 2003; Chatterjee et al., 2018). Greater root yields and fluctuating commodity prices have increased grower interest in adaptive, focused intensive production practices including narrower row spacings (Grove et al., 2005), increased plant populations (Sogut andArioglu, 2004), and variable N rates (DeBruyn et al., 2017), but negative effects on recoverable sucrose may occur from these practices (Yonts and Smith, 1997; Chatterjee et al., 2018).

Water quality concerns and proximity within the Great Lakes watershed basin have prompted growers to consider N fertilizer strategies that promote sugarbeet quality while simultaneously addressing environmental sustainability (Steinke and Bauer, 2017). Below optimal N rates risk reduced root yield and recoverable sucrose per hectare while over applying N may increase root impurities, production costs, and risk environmental contamination (Hergert, 2010; Chatterjee et al., 2018). Nitrogen guidelines for Michigan sugarbeet production following corn (*Zea mays* L.) or wheat (*Triticum aestivum* L.) suggest totals near 179 kg N ha^{-1} with 45 kg N ha^{-1} applied as starter N at planting with the remainder sidedressed near the 2-4 leaf growth stage (Steinke and Chomas, 2018). Steinke and Chomas (2018) found 179 kg N ha^{-1} produced the highest recoverable sucrose per hectare and root yield when comparing N rates between 0 and 269 kg N ha^{-1} following corn. As N rates increase, sucrose concentrations (g kg^{-1}) typically decrease due to increased water retention by the taproot resulting in decreased root dry matter (Draycott, 2006). Excessive N may also reduce the amount of extractable sugar due to increased concentrations of soluble N compounds (Draycott and Christenson, 2003). In the Red River Valley region of North Dakota and Minnesota, Chatterjee et al. (2018) found 213 kg N ha^{-1} reduced sucrose concentration compared to 0 and 112 kg N ha^{-1} likely due to an increase of N compounds associated with greater rates of N application. Since N application rates are positively correlated with root yield but negatively correlated with recoverable sucrose per Mg, optimum N rates should consider both yield and percentage sugar considering that grower payment is calculated from both factors (Van Eerd et al., 2012; DeBruyn et al., 2017).

Continued adoption of 4R nutrient stewardship (i.e., right rate, source, placement, and time) has prompted Michigan sugarbeet growers to consider applying a portion of N in a band 5 cm below and 5 cm laterally from the furrow at planting (i.e., starter N) (DeBruyn et al., 2019). Starter N applied in a 5x5 promotes early season plant biomass, quicker canopy closure, and improved root quality compared to pre-plant incorporated N (Clark et al., 2010). Due to sugarbeet sensitivity to fertilizer saltation as compared to other rotational field crops, growers who utilize starter N at planting often apply the remainder of total N as an early-vegetative sidedress application (i.e., 2-4 leaf growth stage) (Steinke and Bauer, 2017). Current university and Michigan Sugar Company (MSC) recommendations suggest starter N should consist of 45-56 kg N ha^{-1} in a 5x5 at planting (Warncke et al., 2009; MSC, 2020; Steinke and Bauer, 2017). Sugarbeet producers that utilize 45 kg N ha^{-1} in a 5x5 starter N application may be able to decrease overall N rates while simultaneously achieving maximum root yield, recoverable sucrose per hectare, and expected net return on investment.

Plant population is an important and controllable factor affecting sugarbeet root yield and quality (Cakmakci et al., 1998). Maintaining increased plant populations (>172,000 seeds ha^{-1}) through field harvest can be difficult when utilizing 76 cm row spacings due to greater inter-plant competition from reduced spacing between individual plants (Yonts and Smith, 1997)and may be more attainable in narrower row spacings than 76 cm (DeBruyn et al., 2017). Michigan Sugar Company recommends a final plant stand of 86,000 seeds ha^{-1}, however not all seeds planted will produce sugarbeet roots due to germination issues, soil crusting, and seedling disease (MSC, 2020). In Michigan, Groulx et al. (2010) found plant population between 99,000 and 124,000 seeds ha^{-1} produced the greatest root yield and recoverable sucrose per hectare when utilizing 76 cm row spacings. In Nebraska, Yonts and Smith (1997) found plant populations between 40,000 and 100,000 seeds ha^{-1} produced the highest recoverable sucrose per ha^{-1}. Plant population typically has a greater impact on recoverable sucrose per hectare rather than root yield which may in turn influence optimal overall N rates needed to achieve maximum expected net return (DeBruyn et al., 2017).

Greater root yield and sucrose concentration in sugarbeets planted to narrower row spacings (i.e., 56 cm) as compared to wider (i.e., 76 cm) row spacings is not new (Dillon and Schmehl, 1971; Yonts and Smith, 1997). In 2010, MSC set a goal to reach 19% mean grower sucrose concentration which prompted more growers to utilize 56 cm row spacings (Flegenheimer, 2010). Recently, MSC set a new goal for Michigan growers to increase average recoverable sucrose per Mg to 150 kg Mg^{-1} while maintaining 67 Mg ha^{-1} root yields which may continue to include 56 cm row spacing (Flegenheimer, 2019). The use of narrower 56 cm row spacings may allow sugarbeet growers to increase plant populations without producing under-sized roots which can occur with greater plant populations in 76 cm rows due to the reduced inter-plant spacing (Grove et al., 2005). Narrower (e.g., 56 cm) row spacing may offer quicker row closure which may be a tool in managing weed pressure (Armstrong and Sprague, 2010). However utilizing 76 cm row spacings may allow greater wind movement between rows resulting in less disease occurrence (Palti, 2012). Growers also question whether benefits from starter fertilizer are needed when utilizing reduced row spacing. Additionally, corn is typically grown in rotation with sugarbeets and utilizes 76 cm row spacing which may allow growers to maintain a standard row width for sharing equipment between crops (Yonts and Smith, 1997).

The objectives of this study were to 1) evaluate plant population, N rate, and starter N on sugarbeet root yield and quality, expected net return, and total N tissue concentration, and 2) determine the effects of sugarbeet row spacing and starter N on root yield and quality, expected net return, and row closure.

Materials and Methods

Field trials were established during the 2018-2019 growing seasons at the Saginaw Valley Research and Extension center near Richville, MI (43°23’57.3”N, 83°41’49.7”W) on a Tappan-Londo loam (fine-loamy, mixed, active, calcareous, mesic Typic Epiaquoll). Located in Northeastern Michigan, the site is non-irrigated, tile-drained, and contains soils representative of sugarbeet production throughout the region. Fields were previously cropped to corn, and autumn moldboard plowed followed by spring field cultivation (0-10 cm depth). Pre-plant soil characteristics (0-20 cm) included 8.0-8.2 pH (1:1 soil/water), 24 g kg^{-1} soil organic matter (loss-on-ignition), 15-34 mg kg^{-1} P (Olsen sodium bicarbonate extraction), and 137-227 mg kg^{-1} K (ammonium acetate method) (Table 3.01). Prior to planting, soil samples (0-30 cm) for nitrate-N (NO3-N) analysis were air-dried and ground to pass through a 2 mm sieve resulting in pre-plant concentrations of 2.2 and 2.6 mg NO3-N kg^{-1} soil (nitrate electrode method) in 2018 and 2019, respectively (Gelderman and Beegle, 1998). Monthly precipitation and temperature data were collected and recorded throughout the growing season from Michigan State University Enviro-weather (http://agweatger.geo.msu.edu/mawn/) Michigan State University, East Lansing, MI).

Experimental Procedures for Population, N Rate, and Starter N Study

Plots measured 4.5 m in width by 10.7 m in length utilizing 76 cm row spacing. Trial consisted of 16 treatments arranged as a randomized complete-block split-plot design with four replications. Main plots consisted of seeding rate while subplots were N rate and starter N. The two seeding rates were one seed every 8.9 cm (148,260 seeds ha^{-1}) or 10.4 cm (123,552 seeds ha^{-1}). Four N rates were 0, 89, 179, and 269 kg N ha^{-1} total N. Starter N included 45 kg N ha^{-1} applied 5 cm below and 5 cm laterally from the seed at planting or no application. Nitrogen source for all treatments was urea ammonium nitrate (UAN, 28N-0P_2O_5-0K_2O). Treatments received remainder of total N (i.e., minus starter N) injected to 12.7 cm depth and halfway between the rows at 2-4 leaf growth stage on 30 May 2018 and 4 June 2019 using UAN.

Trials were planted on 30 April 2018 and 25 April 2019 utilizing variety ‘Crystal G675’ (ACH Seeds, Inc., Eden Prarie, MN) with a Monosem planter (Monosem Inc., Kansas City, KS). Plant emergence was counted 20-30 days after planting to confirm actual plant population equaled targeted plant population. Percent ground coverage was determined utilizing digital images taken every 10-14 days from each plot starting at the 2-4 leaf growth stage and lasting until canopy closure (Patrignani and Ochsner, 2015). The uppermost fully developed and extended leaf and petiole were collected from 10 plants $plot^{-1}$ at the 6-8 leaf growth stage. Plant tissue samples were dried at 60°C, mechanically ground to pass through a 1-mm mesh screen, and analyzed for total N using a micro-Kjeldahl digestion method and colorimetric analysis with a Lachat rapid flow injector autoanalyzer (Nelson and Sommers, 1973; Bremner, 1996). Roots from the center two rows of each plot were harvested on 17 October 2018 and 14 October 2019 with a mechanical plot harvester and weighed. Root subsamples were collected from each plot (10-12 roots plot^{-1}) analyzed for sucrose concentration, extraction percentage, and recoverable sucrose at the Michigan Sugar Co. laboratory (Bay City, MI).

Experimental Procedures for Row Spacing and N Placement Study

Plots measured 4.5 m in width by 10.7 m in length and consisted of four treatments arranged as a randomized complete-block split-plot design with four replications. Main plots consisted of row spacing while subplots were at-plant N strategy. The row spacings were 56 and 76 cm while the two N strategies were 45 kg N ha^{-1} surface applied after planting (PRE) or 45 kg N ha^{-1} applied 5 cm below and 5 cm laterally from the seed (5x5). Nitrogen source for all applications was UAN. The PRE N rate coincided with the 5x5 N rate to measure the impact of starter N and not differences in total N rate or timing. Treatments containing the PRE strategy included a urease inhibitor (UI) (N-(n-butyl)-thiophosphoric triamide (NBPT) [2.09 ml kg-1 urea]; Koch Agronomic Services LLC, Wichita, KS) to prevent surface N volatilization as the 5x5 N was applied subsurface where minimal volatilization occurs. All treatments received 134 kg N ha^{-1} surface banded immediately adjacent to the sugarbeet row using urea (46-0-0 N-P-K) with a UI at the 2-4 leaf growth stage on 30 May 2018 and 4 June 2019.

Trials were planted on 30 April 2018 and 25 April 2019 utilizing variety ‘Crystal G675’ (ACH Seeds, Inc., Eden Prarie, MN) with a Monosem planter (Monosem Inc., Kansas City, KS) at a rate of one seed every 14.4 cm for 56 cm rows and every 10.4 cm for 76 cm rows (123,552 seeds ha^{-1}). Plant emergence was counted 20-30 days after planting to validate plant populations. Percent ground coverage was determined utilizing digital images taken every 10-14 days from each plot starting at the 2-4 leaf growth stage and lasting until canopy closure using the software Canopeo (Patrignani and Ochsner, 2015). Roots from the center two rows of each plot were harvested on 17 October 2018 and 14 October 2019 with a mechanical plot harvester and weighed. Root subsamples were collected from each plot (10-12 roots plot^{-1}) and analyzed for sucrose concentration, extraction percentage, and recoverable sucrose at the Michigan Sugar Co.laboratory (Bay City, MI).

Expected economic net return was calculated using both root yield and recoverable sucrose (kg Mg^{-1}) in addition to MSC's average payment standard (2018-2019) (Michigan Sugar Company, Bay City, MI) for 2018. Expected net return was based on US$45.1 Mg^{-1} (fresh weight) for sugarbeet roots which was later adjusted based on a ratio of observed recoverable sucrose (kg Mg^{-1}) to average Michigan Sugar Company's recoverable sucrose (kg Mg^{-1}) value of 119 kg Mg^{-1}. Michigan Sugar Company 2019 payment standards were calculated using adjustment factors based on harvest date to determine amount of sugar delivered (kg ha^{-1}). Adjustment factors used were 1.07 for root yield and recoverable sucrose (kg ha^{-1}) and then multiplied by US$0.08 kg^{-1} to equal total payment ha^{-1}. Variable costs of N fertilizer (US$0.97 kg^{-1}) and trucking (US$4.13 Mg^{-1}) were subtracted from expected net return across years.

Data were analyzed in SAS 9.4 (SAS Institute, 2012) using the GLIMMIX procedure (SAS Institute, 2012). Year, population, N rate, and starter N were considered fixed effects and replication as random for the population, N rate, and starter N study. Year, row spacing, and N placement were considered fixed effects and replication as random for the row spacing study. Data were analyzed separately after being determined to be significantly different by year for both studies ($P \leq 0.10$). Dunnett's test was used to compare the untreated control relative to all treatments receiving N to verify N responsive locations (Dunnett, 1955). The UNIVARIATE procedure in SAS was used to examine the normality of residuals ($P \leq 0.05$). Squared and absolute values of residuals were examined with Levene's Test to confirm homogeneity of variances ($P \leq 0.05$). Least square means were separated using the LINES option of the slice statement when ANOVA indicated a significant interaction ($P \leq 0.10$). A linear plateau model was developed to investigate the response of root yield and recoverable sucrose per hectare to N rate for the population, N rate, and starter N study. Pearson product-moment correlations were generated using the REG procedure of SAS to investigate the relationships between root yield and recoverable sucrose per ha^{-1} with 6-8 leaf tissue N concentration.

Results and Discussion

Environmental Conditions

Total growing season (April-September) precipitation deviated -4% and +13% from the 30-yr mean during 2018 and 2019, respectively (Table 3.02). However, May-June total precipitation was 43% below and 88% above the 30-yr mean in 2018 and 2019, respectively, while August precipitation was 140% above and 68% below the 30-yr mean in 2018 and 2019, respectively. This precipitation pattern created contrasting dry early/wet late and wet early/dry late seasons between 2018 and 2019, respectively. Dry August 2019 soil conditions from deficit precipitation likely limited sugarbeet bulking and concomitantly decreased overall root yield. Except for April 2018, monthly growing season air temperatures were near the 30-yr mean. A late April 2018 planting date resulted in little impact on sugarbeet emergence or growth from cool air temperatures.

Effect of Population, N Rate, and Starter N on Root Yield, Quality, and Expected Net Return

An interaction between total N rate and starter N fertilizer influenced root yield ($P < 0.01$) and recoverable sucrose per hectare ($P < 0.01$) in 2018 (Table 3.03). Utilizing starter N, 179 kg N ha^{-1} produced the greatest root yield of 80.7 Mg ha^{-1} as compared to the 269 kg N ha^{-1} required to achieve a similar root yield without starter N application. At the 179 kg N ha^{-1} rate, starter N increased root yield 13.4 Mg ha^{-1} compared to no starter N. Total N rate of 179 kg N ha^{-1} also produced maximum recoverable sucrose per hectare (8691-10371 kg ha^{-1}) with and without starter N. Starter N increased recoverable sucrose per hectare 10 and 20% at 89 and 179 kg N ha^{-1}, respectively, compared to no starter N. Limited May-June precipitation in combination with cool April air temperatures leading into plant emergence may have limited early season (May-June) vegetative growth where starter N was absent thus providing opportunities for starter N to increase root yield and recoverable sucrose per hectare. Starter N increased canopy coverage 10-17% (data not shown) throughout the growing season which may have translated into increased light interception, root yield, and recoverable sucrose per hectare as compared to no starter N at the 179 kg N ha^{-1}. Starter N may promote quicker vegetative growth compared to no starter N during dry soil conditions by providing N in close proximity to developing roots from the seed which may increase light interception and translate into season-long vigor and greater root sucrose (Hergert, 2011; Gehl and Boring, 2011). The primary purpose of starter N is to accelerate early season sugarbeet growth rates to achieve maximum development at an earlier point in the season (Clark et al., 2010; Overstreet and Cattanach, 2010). Results agree with Clark et al. (2010) who found 56 kg N ha^{-1} in a starter N application increased root yield and recoverable sucrose per hectare 13.5 Mg ha^{-1} and 910 kg ha^{-1}, respectively, compared to no starter N. Current data also suggest application of starter N may provide opportunities for growers to produce optimal root yield and recoverable sucrose per hectare at decreased N rates.

Nitrogen rate influenced root yield ($P < 0.01$) and recoverable sucrose per hectare ($P < 0.01$) in 2019 (Table 3.04). A linear plateau model was best fit across all treatments and suggested maximum root yield occurred at 145 and 170 kg N ha^{-1} while recoverable sucrose per hectare was maximum at 115 and 146 kg N ha^{-1} in 2018 and 2019, respectively. Across 2019 tested N rates, a total of 179 kg N ha^{-1} produced optimal root yield and recoverable sucrose per hectare. Peak sucrose per hectare averaged 27 kg N ha^{-1} lower than peak root yield across years. Optimal N rates required to achieve maximum root yield and recoverable sucrose were greater in 2019 than 2018 likely due to an 88% increase in May-June 2019 rainfall from 30-year means (Table 3.02). Data from this study provides support to both the university and MSC's total N recommendation for sugarbeet following corn in Michigan (Warncke et al., 2009; MSC, 2020). Previous research from both Michigan and Ontario found optimal root yields with N rates between 157 and 168 kg N ha^{-1} following corn (Clark et al., 2010; DeBruyn et al., 2017). Clark et al. (2010) suggested greater amounts of N may be needed to satisfy sugarbeet N requirements when heavy corn residues are present, however application of a 5x5 starter N at planting may negate needs for greater N rates due to N placement beneath the residue layer. Nitrogen can become immobilized in high C:N ratio residue (e.g., corn) decomposition resulting in period of N unavailability until decomposition is complete (Green and Blackmer, 1995). Michigan Sugar Company N rate recommendations following corn are typically greater compared to soybean (*Glycine max* L. Merr.) or dry bean (*Phaseolus vulgaris* L.) due to greater C:N ratios from corn residue compared to leguminous crops (MSC, 2020). Optimal N rates should account for both economic net return and reducing potential N losses rather than solely relying upon root yield

(DeBruyn et al., 2017). Root yield was not influenced by starter N in 2019 likely due to excessive May-June rainfall which may have hindered root establishment limiting root access to starter N (Finch et al., 2014). Results suggest starter N may provide a greater benefit under dry early season (i.e., May-June) conditions by promoting early season root and above ground growth which may translate into longer-term root and sucrose yield gains.

Nitrogen rate significantly affected recoverable sucrose per Mg ($P < 0.01$) and sucrose concentration ($P < 0.01$) in 2018 and 2019, while only affecting extraction percentage in 2019 ($P < 0.01$) (Table 3.04, 3.05). Starter N affected sucrose concentration ($P < 0.02$) in 2019. Among N treatments, recoverable sucrose per Mg was optimal at 89 kg N ha^{-1} while N rates $\geq$ 179 kg N ha^{-1} reduced recoverable sucrose per Mg and sucrose concentration similarly in 2018 and 2019. Extraction percentages decreased at 179 and 269 kg N ha^{-1} in 2019, however differences were minimal and likely did not affect recoverable sucrose or sucrose concentration. Starter N increased sucrose concentration 0.3% compared to no starter in 2019. Nitrogen fertilizer application often has an inverse relationship with recoverable sucrose per Mg and sucrose concentration due to increased water retention by the taproot associated with increased growth rates from applied N (Draycott and Christenson, 2003; Draycott, 2006). In 2019, higher N rates were required to decrease recoverable sucrose per Mg than 2018 due to August precipitation being 68% below the 30-yr mean which likely limited overall water absorption and therefore N. In 2019, starter N increased canopy coverage 6.8% at 60 days after planting (DAP) (data not shown) compared to no starter which likely translocated more sucrose into the root due to greater light interception from increased above ground leaf biomass (Draycott, 2006). Despite the inverse relationship between N rate and both recoverable sucrose per Mg and sucrose concentration, the direct relationship between N rate and root yield requires both yield and quality consideration when contemplating overall changes in expected net return (DeBruyn et al., 2017).

An interaction between N rate and starter N fertilizer influenced expected net return ($P < 0.02$), expected net return minus N costs ($P < 0.03$), and expected net return minus N and trucking costs ($P < 0.01$) in 2018 (Table 3.06). The 179 kg N ha^{-1} rate produced the greatest expected net return with or without starter N (US$ ha^{-1}) in 2018. However when N or trucking costs were taken into consideration, 89 kg N ha^{-1} maximized expected net return with and without starter N. Starter N provided a 20-21% increase in expected net return, expected net return minus N costs, and expected net return minus N and trucking costs at the 179 kg N ha^{-1} rate compared to no starter N in 2018. Main effects of N rate influenced expected net return, expected net return minus N costs, and expected net return minus N and trucking costs ($P < 0.10$) in 2019 (Table 3.07). In 2019, total N rates of 179 kg N ha^{-1} maximized expected net return across all economic variables. Data did not show yield or profitability benefits when applying above university recommended N rates (179 kg N ha^{-1}). Yield loss from underapplication of N is often perceived as a greater risk than reductions in sucrose concentration and recoverable sucrose from overapplying N, but greater root yields may not offset increased production costs resulting in greater expected net returns at lower yield potentials (Mourtzinis et al., 2017; Rutan and Steinke, 2017; Chatterjee et al., 2018). Results suggest that starter N improved overall 2018 profit by promoting plant growth during dry early season soil conditions (i.e. May-June precipitation deficits) which correspondingly decreased the overall N rate required to achieve maximum root yield. No benefit from starter N on 2019 economic net return was likely due to a lack of root yield and recoverable sucrose per hectare increases from hindered root establishment under dry conditions near and after planting. Greater emphasis upon optimal recoverable sucrose per hectare should be the main objective when implementing management practices to maximize expected net return as the current payment structure rewards growers based solely off recoverable sucrose per hectare rather than previous payment structures (e.g., pre-2019) which rewarded growers based upon root yield and recoverable sucrose per Mg incentives.

Effect of Population, N Rate, and Starter N on Tissue N Concentration

An interaction between N rate and starter N influenced 6-8 leaf total N concentration ($P <$ 0.01) in 2018 (Table 3.08), while only main effects of plant population ($P < 0.09$), N rate ($P <$ 0.01) and starter N ($P < 0.02$) influenced 6-8 leaf tissue N concentration in 2019 (Table 3.09). Six to eight leaf total N concentration was maximized at 179 kg N ha^{-1} in 2018 and 2019. At 89 and 179 kg N ha^{-1}, 6-8 leaf total N concentration increased 0.4-0.5%, respectively, with starter N application in 2018. In 2019, 6-8 leaf total N concentration increased 0.3% in the low seeding rate (123,552 seeds ha^{-1}) compared to the high seeding rate (148,260 seeds ha^{-1}). Six-eight leaf total N concentration increased 0.3% with no starter N compared to when starter N was included in 2019. With dry May-June conditions, starter N was likely accessed by the root soon after root emergence which facilitated sufficient early canopy growth and is suggested for optimal N management in rainfed sugarbeet production systems (Hergert, 2011; Steinke and Bauer, 2017). At the low seeding rate, each plant was likely able to uptake more applied N due to less interplant competition (Suhre et al., 2014) resulting in an increase in 6-8 leaf total N concentration. Increase in 6-8 leaf total N concentration from no starter N was likely due to less higher proportion of N applied being closer to data collection in 2019 when wet conditions limited root growth to uptake starter N. Although differences occurred between treatments in both years, all 6-8 leaf tissue N concentrations exceeded the minimum N sufficiency range (i.e., 3.0%) for sugarbeet (Vitosh et al., 1988) suggesting differences did not affect root yield or quality. Pearson product-moment correlations suggested a weak positive relationship between 6-8 leaf tissue N concentration and root yield (r = 0.49, P < 0.01) or recoverable sucrose per ha^{-1} (r = 0.49, P < 0.01). Although optimal N rates were similar for tissue concentration and root yield, tissue N may be an unreliable predictor for overall optimum N rate due to variable precipitation throughout the growing season (Sharma and Bali, 2018) and the inverse effects of N on quality (Hergert et al., 2011).

Effect of Row Spacing and N placement on Root Yield, Quality, and Expected Net Return

Nitrogen placement significantly affected root yield in 2018 (P < 0.08) while row spacing significantly affected root yield in 2018 (P < 0.09) and 2019 (P < 0.02) (Table 3.10). Row spacing at 56 cm increased root yield 14.5 and 23.8 Mg ha^{-1} compared to 76 cm rows in 2018 and 2019, respectively. Roots grown in narrower rows have greater intra-plant spacing and able to utilize nutrients and moisture more efficiently due to less interplant competition (Yonts and Smith, 1997; Grove et al., 2005). Total August 2019 rainfall was 68% below the 30-yr mean (Table 3.02), and the larger yield increase from 56 cm rows, compared to 2018, suggests dry soil conditions had a greater impact with the wider row spacing perhaps due to evaporative moisture losses in uncovered soil from greater distances and less shading between rows (Bhattacharya, 2018).

Greater yield with narrower row spacing has been documented previously with similar row spacing comparisons (Cattanach and Schroeder, 1980; Dillon and Schmehl, 1971; Yonts and Smith, 1997, Groulx et al., 2010). However, the question many growers ask is whether starter N still benefits at the narrower row spacing. In 2018, 5x5 N placement increased root yield 4.3 Mg ha^{-1} compared to PRE N placement. Nitrogen placed closer to the seed using 5x5 applications allows the plant easier access to soluble N especially in sugarbeet where limited ability for lateral seedling root movement exists (Weaver, 1926; Stevens et al., 2007). During soil moisture stress, N is more readily available from subsurface (5x5) placement as compared to surface (PRE) placement (Stevens et al., 2007). Data indicate that dry May-June 2018 soil conditions likely limited N movement from PRE placement into the rhizosphere providing opportunities for root yield increases from 5x5 N placement due to closer N proximity. Results highlight one of the risk factors to surface-applied N applications which is greater potential for positional unavailability during dry soil conditions. No differences were observed between N placements in 2019 likely due to excessive May-June rainfall inhibiting root establishment and restricting benefits of N placed closer to the seed (Finch et al., 2014). Benefits of PRE placement include ease and quickness of application but potential for volatilization and surface-runoff N losses may exist. Additionally, disadvantages of 5x5 placement (i.e., soil disturbance, slower planting speeds, delayed planting dates due to moist soils) may be outweighed by the consistency of increased vegetative and root growth offered from subsurface N placement but results will depend upon season long climatic conditions.

Row spacing significantly affected recoverable sucrose per Mg ($P < 0.07$), sucrose concentration ($P < 0.07$) and extraction ($P < 0.07$) in 2018 but only recoverable sucrose per Mg ($P < 0.01$) and recoverable sucrose per hectare ($P < 0.05$) in 2019 (Table 3.10). Sucrose concentration and extraction increased 0.9 and 0.7%, respectively, with 76 cm rows in 2018. Recoverable sucrose increased 6 and 14 kg Mg^{-1} with 76 cm rows in 2018 and 2019, respectively. Although recoverable sucrose per Mg was greater from 76 rows, recoverable sucrose per hectare increased 28% with 56 cm rows in 2019 likely due to the large observed root yield increase. Sugarbeets grown in 56 cm rows may have produced larger individual roots that absorbed more moisture due to less inter-plant competition within a row which lowered the concentration of sucrose in 2018 (Hills, 1972; Alford et al., 2003). Data suggests increases in sucrose concentration and extraction percentage likely translated into an increase in recoverable sucrose per Mg from 76 cm rows in 2018, as recoverable sucrose per Mg is calculated using the two parameters (Tarkalson et al., 2012). In 2019, dry August conditions may have limited moisture availability within 76 cm rows due to greater evapotranspiration from greater space between plants and rows which likely decreased sugarbeet root water tissue thus concentrating recoverable sucrose per Mg. An advantage of utilizing 56 cm rows is the ability to increase intra-row spacing to reduce interplant competition. However 76 cm rows may produce comparable root and sucrose yields with sufficient August rainfall while also allowing more room for air movement between rows to reduce risk of disease (Clark et al., 2010; Palti, 2012).

Row spacing significantly affected expected net return ($P < 0.05$) and expected net return minus trucking costs ($P < 0.05$) in 2019 (Table 3.11). Expected net return and expected net return minus trucking costs increased 27-28% with 56 cm rows. Before 2019, MSC awarded grower payment based upon a base payment with volume and quality incentives, however current payment structure emphasizes the importance of maximizing recoverable sucrose per hectare instead of root yield or recoverable sucrose per Mg individually. Greater expected net return in 2019 from 56 cm rows was directly influenced by the increase of recoverable sucrose per hectare observed. This study did not reflect other factors, such as equipment, which may impact overall farm efficiency and profitability. Growers should be cognizant of associated costs when considering row spacings and the impact of changing to a narrow or wide row spacing on other rotational crops, such as corn or soybean, when sharing planting equipment between cropping systems.

Effect of Row Spacing and N Placement on Row Closure

An interaction between row spacing and N placement influenced canopy coverage 37 and 51 DAP ($P < 0.01$) in 2018 (Table 3.12). Within 56 cm rows, 5x5 N placement increased canopy coverage 3.0 and 15.1% at 37 and 51 DAP compared to PRE N with no differences observed at the wider row spacing. At both 37 and 51 DAP however, PRE N placement resulted in a 1.5 and 7.2% increase in canopy coverage with 76 cm rows as compared to the narrower 56 cm rows while 5x5 placement appeared to have a greater impact on the 56 cm rows at 51 DAP. Limited May-June 2018 precipitation likely hindered N movement from PRE placement into the root zone and canopy coverage differences at 37 and 51 DAP between row spacings was likely due to plants in 76 cm rows utilizing greater area between rows for canopy growth (Stebbing et al., 2000). Nitrogen within the 5x5 N placement was likely accessed by the plant soon after root emergence which promoted above ground growth and resulted in an increase in canopy coverage (Hergert, 2011; Steinke and Bauer, 2017). Increase in row closure at 51 DAP with 5x5 N was likely due to less distance between rows in 56 cm rows compared to 76 cm. Sugarbeet growth rates are slower at 37-51 DAP compared to 90-100 DAP (De et al., 2019), and starter N applications may promote early season above ground biomass and provide an advantage for the remainder of the growing season (Stevens et al., 2007). As the growing season progressed (e.g., 70-90 DAP), differences in canopy coverage diminished between row spacing and N placement (data not shown) and both row spacings completed maximum row closure near the same day across years. Lack of canopy coverage differences at complete row closure indicate that despite having greater distance between rows, 76 cm rows can complete row closure near similar dates as 56 cm rows. Data suggest 5x5 N placement still offers canopy coverage benefits in 56 cm rows and that 5x5 N should not be abandoned in row spacings narrower than 76 cm simply due to less distance between rows.

Conclusions

In the environments tested, plant population did not affect root yield or quality in either year. Optimal N rates should incorporate maximizing expected net return, root yield, and sugar quality and not one component individually. Across tested N rates, 179 kg N ha^{-1} resulted in the best combination among root yield, quality, and expected net return further supporting university and MSC recommended N rates when following high residue crops such as corn or wheat. A linear plateau model suggested peak recoverable sucrose per hectare averaged 27 kg N ha^{-1} lower than peak root yield across years. Limited May-June precipitation may have limited early season plant growth where starter N was absent thus providing opportunities for 5x5 starter N to increase root yield and recoverable sucrose per hectare. Although excessive May-June 2019 precipitation hindered root development and reduced benefits from starter N, root yield or quality was not decreased by this fertilizer strategy. Advantages of starter N fertilizer may outweigh potential disadvantages by providing opportunities to increase N efficiency and decrease overall N rates by addressing early-season variable weather patterns.

Row closure was completed near the same date with both row spacings and data suggest 5x5 starter N placement still offers row closure benefits in 56 cm row, and this fertilizer strategy should not be abandoned in row spacings narrower than 76 cm simply due to less distance between rows. Narrow (56 cm) rows increased root yield while wide (76 cm) rows increased recoverable sucrose per Mg across both years with narrow row spacing increased recoverable sucrose per hectare in 2019. Due to current (2019) MSC payment structure, recoverable sucrose per hectare should be a primary factor for sugarbeet growers when making agronomic management decisions such as population, 5x5 starter N, overall N rate, and row spacing to increase expected net return. Growers should also take into consideration the cost of planting and harvest equipment when considering alternative row spacings. Growers may want to consider field conditions, soil texture, harvest date, sugar prices, and input costs prior to adopting widely implemented management strategies such as plant population, N management, and row spacing.

Acknowledgements

The authors would like to thank the USDA National Institute of Food and Agriculture, Michigan Sugar Company, Michigan State University College of Agriculture and Natural Resources, and Michigan State University AgBioResearch for partial funding and support of this research. In addition, the authors would like to thank Andrew Chomas, undergraduate research assistants, graduate research assistants, and research farm staff for their support and assistance.

APPENDIX

Table 3.01. Soil physical and chemical properties including mean NO_3-N (0-30cm), P (0 – 20 cm), and K soil test (0 – 20 cm) nutrient concentrations obtained prior to sugarbeet planting, Richville, MI, 2018-2019.

Year	**Soil description**	**Soil test**†				
		NO_3-N	P	K	pH	OM
		----------mg kg^{-1}------------				g kg^{-1}
2018	Tappan-Londo Loam	2.2	34	227	8.0	24
2019	Tappan-Londo Loam	2.6	15	137	8.2	24

†P phosphorus (Olsen sodium bicarbonate extraction); K potassium (ammonium acetate extractable K).

Table 3.02. Mean monthly and 30-yr precipitation† and temperature for the sugarbeet growing season, Richville, MI, 2018 - 2019.

Year	Apr.	May	Jun.	Jul.	Aug.	Sept.	Total
				-----cm-----			
2018	7.1	5.4	3.8	5.0	20.1	4.9	46.3
2019	5.8	12.8	17.7	6.0	2.7	9.6	54.6
30-yr‡	7.3	8.6	7.6	6.6	8.4	9.7	48.2
				-----°C-----			
2018	3.6	17.6	19.7	22.1	21.8	17.8	--
2019	7.4	12.8	18.4	22.6	19.9	17.9	--
30-yr	7.8	14.1	19.6	21.7	20.4	16.3	--

†Precipitation and air temperature data were collected from Michigan State University Enviro-weather (https://enviroweather.msu.edu/).

‡30-yr means were obtained from the National Oceanic and Atmospheric Administration (https://www.ncdc.noaa.gov/cdo-web/datatools/normals).

*Table 3.03***.** Starter N fertilizer and nitrogen rate interaction on sugarbeet root yield (Mg ha^{-1}) and recoverable sucrose (kg ha^{-1}), Richville, MI, 2018.

	Root yield			**Recoverable sucrose**		
N Rate	Starter	No Starter	***P > F***	Starter	No Starter	***P > F***
	--------Mg ha^{-1}--------			--------kg ha^{-1}--------		
0	51.6 c†A‡	53.8 bA	0.74	6777 cA	7073 cA	0.55
89	69.5 bA	62.8 bA	0.12	9253 bA	8440 bB	0.06
179	80.7 aA	67.3 bB	<0.01	10371 aA	8691 abB	<0.01
269	76.2 aA	76.2 aA	0.86	9398 bA	9249 aA	0.74
P > F	<0.01	<0.01		<0.01	<0.01	

†Means in the same column following by the same lowercase letter are not significantly different at $P \leq 0.10$.
‡Means in the same row following by the same uppercase letter are not significantly different at $P \leq 0.10$.

*Table 3.04***.** Population, nitrogen rate, and starter N fertilizer effects on sugarbeet root yield, recoverable sucrose (kg ha^{-1} and kg Mg^{-1}), sucrose concentration, and extraction, Richville, MI, 2019.

Treatment	**Root yield**	**Recoverable sucrose**		**Sucrose**	**Extraction**
	--Mg ha^{-1}--	--kg ha^{-1}--	--kg Mg^{-1}--	--%--	--%--
Population, seeds ha^{-1}					
123552	57.4a	8095a	141a	20.6a	97.0a
148260	57.8a	8264a	141a	20.5a	97.1a
P > F	0.92	0.68	0.79	0.74	0.17
N Rate, kg N ha^{-1}					
0	41.9c	5898c	140b	20.2b	97.2a
89	54.2b	8030b	145a	20.8a	97.2a
179	66.4a	9473a	143ab	21.0a	97.0b
269	67.9a	9317a	137c	20.2b	96.8b
P > F	<0.01	<0.01	<0.01	<0.01	<0.01
Starter N					
Starter	58.5a	8297a	142a	20.7a	97.1a
No Starter	56.5a	8062a	141a	20.4b	97.0a
P > F	0.27	0.36	0.65	0.02	0.72

[†]Means in the same column following by the same lowercase letter are not significantly different at $P \leq 0.10$.

*Table 3.05***.** Planting population, nitrogen rate, and starter N fertilizer effects on sugarbeet recoverable sucrose (kg Mg^{-1}), sucrose concentration, and extraction, Richville, MI, 2018.

Treatment	**Recoverable sucrose**	**Sucrose**	**Extraction**
	---kg Mg^{-1}---	---%---	---%---
Population, seeds ha^{-1}			
123552	129a†	19.8a	96.3a
148260	130a	19.9a	96.3a
P > F	0.42	0.48	0.75
N Rate, kg N ha^{-1}			
0	133a	20.2a	96.4a
89	134a	20.4a	96.5a
179	130b	19.8b	96.4a
269	123c	18.8c	96.2a
P > F	<0.01	<0.01	0.21
Starter N			
Starter	130a	19.9a	96.3a
No Starter	129a	19.8a	96.4a
P > F	0.51	0.47	0.26

†Means in the same column following by the same lowercase letter are not significantly different at $P \leq 0.10$.

Table 3.06. Starter N fertilizer and nitrogen rate interaction on sugarbeet expected net return, expected net return minus N costs, and expected net return minus N and trucking costs, Richville, MI, 2018.

	Expected net return §			**Expected net return minus N costs**			**Expected net return minus N and trucking costs**		
N Rate	Starter	No Starter	***P > F***	Starter	No Starter	***P > F***	Starter	No Starter	***P > F***
	---US$ ha^{-1}---								
0	2572c†A‡	2654cA	0.64	2575cA	2654bA	0.64	2360cA	2436bA	0.63
89	3499bA	3193bA	0.23	3413abA	3106aA	0.23	3128abA	2841aA	0.22
179	3929aA	3287abB	<0.01	3756aA	3114aB	<0.01	3425aA	2834aB	<0.01
269	3553bA	3511aA	0.69	3294bA	3252aA	0.69	2980bA	2933aA	0.62
P > F	<0.01	<0.01		<0.01	<0.01		<0.01	<0.01	

†Means in the same column following by the same lowercase letter are not significantly different at P ≤ 0.10.
‡Means in the same row following by the same uppercase letter are not significantly different at P ≤ 0.10.
§Expected net returns based upon US\$45.1 Mg^{-1} base payment with volume and quality incentives, an N price of \$0.97 kg^{-1}, and trucking costs of \$US\$4.13 Mg^{-1}.

*Table 3.07***.** Population, nitrogen rate, and starter N fertilizer effects on sugarbeet expected net return, expected net return minus N costs, and expected net return minus N and trucking costs, Richville, MI, 2019.

Treatment	**Expected net return** [‡]	**Expected net return minus N costs**	**Expected net return minus N and trucking costs**
	-----------------------------US$ ha^{-1}-----------------------------		
Population, seeds ha^{-1}			
123552	3496a	3366a	3128a
148260	3569a	3439a	3197a
P* > *F	0.68	0.68	0.68
N Rate, kg N ha^{-1}			
0	2547c	2547c	2374c
89	3468b	3381b	3152b
179	4091a	3917a	3643a
269	4021a	3763a	3482a
P* > *F	<0.01	<0.01	<0.01
Starter N			
Starter	3584a	3453a	3211a
No Starter	3482a	3351a	3115a
P* > *F	0.36	0.36	0.36

[†]Means in the same column following by the same lowercase letter are not significantly different at $P \leq 0.10$.
[‡]Expected net returns based upon harvest date adjustment factor for recoverable sucrose (kg ha^{-1}) and then multiplied by US$0.08 to determine final payment, an N price of $0.97 kg^{-1}., and trucking costs of US$4.13 Mg^{-1}.

*Table 3.08***.** Nitrogen rate and starter N fertilizer interaction on sugarbeet 6-8 leaf growth stage tissue total N concentration, Richville, MI 2018.

	Total N		
N Rate	Starter	No Starter	***P > F***
	-----------%-----------		
0	3.7c†B‡	3.9bA	0.07
89	4.3bA	3.9bB	<0.01
179	4.5aA	4.0aB	<0.01
269	4.4aA	4.1aA	<0.01
P > F	<0.01	0.07	

†Means in the same column following by the same lowercase letter are not significantly different at $P \leq 0.10$.
‡Means in the same row following by the same uppercase letter are not significantly different at $P \leq 0.10$.

Table 3.09. Population, nitrogen rate, and starter N fertilizer main effects on sugarbeet 6-8 leaf growth stage tissue total N concentration, Richville, MI 2019.

Treatment	Total N[†]
	---%---
Population, seeds ha^{-1}	
123552	4.4a[‡]
148260	4.1b
P* > *F	0.09
N Rate, kg N ha^{-1}	
0	3.6c
89	4.2b
179	4.7a
269	4.6a
P* > *F	<0.01
Starter N	
Starter	4.1b
No Starter	4.4a
P* > *F	0.02

[†]Uppermost fully developed and extended leaf and petiole samples from 10 plants per plot.
[‡]Means in the same column following by the same lowercase letter are not significantly different at P ≤ 0.10.

Table 3.10. Main effects of row spacing and starter nitrogen (N) fertilizer placement on sugarbeet root yield, recoverable sucrose (kg ha^{-1} and kg Mg^{-1}), sucrose concentration, and extraction, Richville, MI, 2018-2019.

Treatment	**Root yield**	**Recoverable sucrose**		**Sucrose**	**Extraction**
			2018		
	--Mg ha^{-1}--	--kg ha^{-1}--	--kg Mg^{-1}--	---%---	---%---
Row Spacing					
56 cm	75.8a	8759a	116b	18.2b	95.2b
76 cm	61.3b	7516a	122a	19.1a	95.9a
P* > *F	0.09	0.16	0.07	0.07	0.07
N Placement					
5x5	70.7a	8413a	119a	18.7a	95.6a
PRE	66.4b	7862a	119a	18.6a	95.5a
P* > *F	0.08	0.16	0.84	0.82	0.95
			2019		
	--Mg ha^{-1}--	--kg ha^{-1}--	--kg Mg^{-1}--	----%----	----%----
Row Spacing					
56 cm	80.7a	9980a	123b	19.4a	96.2a
76 cm	56.9b	7801b	137a	19.9a	96.5a
P* > *F	0.02	0.05	<0.01	0.14	0.50
N Placement					
5x5	69.2a	8843a	129a	19.6a	96.4a
PRE	68.4a	8938a	132a	19.7a	96.3a
P* > *F	0.85	0.89	0.18	0.48	0.70

†Means in the same column following by the same lowercase letter for each year are not significantly different at P ≤ 0.10.

*Table 3.11***.** Row spacing and starter N fertilizer placement effects on sugarbeet expected net return and expected net return minus trucking costs, Richville, MI, 2018-19.

Treatment	**Expected Net Return** ‡	**Expected Net Return Minus trucking costs**
	2018‡	
	--------------------US$ ha^{-1}--------------------	
Row Spacing		
56 cm	3312a†	2999a
76 cm	2842a	2589a
P* > *F	0.16	0.17
N Placement		
5x5	3182a	2889a
PRE	2973a	2543a
P* > *F	0.16	0.17
	2019§	
	--------------------US$ ha^{-1}--------------------	
Row Spacing		
56 cm	4310a	3976a
76 cm	3369b	3134b
P* > *F	0.05	0.05
N Placement		
5x5	3819a	3533a
PRE	3860a	3578a
P* > *F	0.89	0.87

†Means in the same column following by the same lowercase letter are not significantly different at $P \leq 0.10$.
‡Expected net returns based upon US$45.1 Mg^{-1} base payment with volume and quality incentives and trucking costs of US4.13 Mg^{-1}.
§Expected net returns based upon harvest date adjustment factor for recoverable sucrose (kg ha^{-1}) and then multiplied by US$0.08 to determine final payment, an N price of $0.97 kg^{-1}., and trucking costs of US$4.13 Mg^{-1}.

*Table 3.12***.** Sugarbeet percent canopy coverage as affected by nitrogen rate and starter N fertilizer interaction at 37 and 51 days after planting (DAP), Richville, MI 2018.

Row Spacing	**37 DAP** 5x5	**37 DAP** PRE	***P > F***	**51 DAP** 5x5	**51 DAP** PRE	***P > F***
	-----------% canopy---------			-----------% canopy-----------		
56 cm	6.1a†A‡	3.1bB	<0.01	42.2aA	27.1bB	<0.01
76 cm	4.6aA	4.6aA	0.99	37.3bA	34.3aA	0.24
P > F	0.11	0.08		0.07	0.02	

†Means in the same column following by the same lowercase letter are not significantly different at $P \leq 0.10$.
‡Means in the same row following by the same uppercase letter are not significantly different at $P \leq 0.10$.

LITERATURE CITED

LITERATURE CITED

Alford, C.M., K.K. Nelson, and S.D. Miller. 2003. Plant population, row spacing, and herbicide effects on weeds and yield in sugarbeets. Int. Sugar. J. 105:283-285.

Armstrong, J., and C. Sprague. 2010. Weed management in wide- and narrow-row glyphosate-resistant sugarbeet. Weed Technology, 24(4), 523-528. doi:10.1614/WT-D-10-00033.1

Bhattacharya, A., 2018. Changing Climate and Resource Use Efficiency in Plants. Academic Press.

Bremner, J.M. 1996. Nitrogen-total. p. 1085-1121. In: D.L. Sparks, et. al. (ed.) Methods of Soil Analysis. Part 3. 3rd ed. SSSA Series 5. SSSA, Madison, WI.

Cakmakci, R., E. Oral, and F. Kantar. 1998. Root yield and quality of sugar beet (Beta vulgaris L.) in relation to plant population. *Journal of Agronomy and Crop Science, 180*(1), 45-52.

Cattanach, A. and G. Schroeder. 1980. A comparison of 22 versus 30-inch row spacing at equal plant population in 1976-77. 1979 Sugarbeet Res. and Extension Rep. 11: 198-203.

Chatterjee, A., K. Subedi, D.W. Franzen, H. Mickelson, and N. Cattanach. 2018. Nitrogen fertilizer optimization for sugarbeet in the Red River Valley of North Dakota and Minnesota. Agron. J. 110:1554-1560. doi:10.2134/agronj2017.12.0694

Clark, G.M., J.F. Stewart, L.A. Hubbell, and B.J. Groulx. 2010. Evaluating nitrogen rates, application timings, and application methods for sugarbeets in Michigan. Michigan Sugar Company Grower Records. https://www.bsdf-assbt.org/wp-content/uploads /2018/01/ Clark (accessed 16 Jan. 2020)

De, M., A.D. Moore, and R.L. Mikkelsen. 2019. In-season accumulation and partitioning of macronutrients and micronutrients in irrigated sugarbeet production. J. Sugarbeet Res. 56:54-78.

DeBruyn, A.H., I.P. O'Halloran, J.D. Lauzon, and L.L. Van Eerd. 2017. Effect of sugarbeet density and harvest date on most profitable nitrogen rate. Agron. J. 109:2343–2357. doi:10.2134/agronj2017.03.0141

DeBruyn, A.H., I.P. O'Halloran, J.D. Lauzon, and L.L. Van Eerd. 2019. Nitrogen and Phosphorous Fertilizer Timing, Source, and Placement in Sugarbeet. Agron. J. 111:859-866. doi:10.2134/agronj2018.06.0404

Dillon, M.A., and W.R. Schmehl. 1971. Sugarbeet as influenced by row width, nitrogen fertilization, and planting date. J. Sugar Beet Res. 16:585–595. doi:10.5274/jsbr.16.7.585

Draycott, A.P., D.R. Christenson. 2003. Nutrients for sugarbeet production. CABI Publishing, Cambridge, MA.

Draycott, A.P., 2006. Sugarbeet. Blackwell Publishing Professionals, Ames, IA.

Dillon, M.A., and W.R. Schmehl. 1971. Sugarbeet as influenced by row width, nitrogen fertilization, and planting date. J. Sugar Beet Res. 16:585–595. doi:10.5274/jsbr.16.7.585

Dunnett, C.W. 1955. A multiple comparison procedure for comparing several treatments with a control. J. Am. Stat. Assoc. 50:1096-1121.

Finch, S., A. Samuel, and G.P. Lane. 2014. Lockhart and wiseman's crop husbandry including grassland. Root Crops. Elsevier. 15: 362-386.

Flegenheimer, M. 2010. The road to change. The Newsbeet: 23:3.

Flegenheimer, M. 2019. Looking back and planning for the future. The Newsbeet: 33:2.

Gelderman, R.H., and D. Beegle. 2015. Nitrate-nitrogen. In: M.V. Nathan and R. Gelderman, editors, Recommended chemical soil test procedures for the North Central Region. North Central Region Res. Publ. 221 (rev.). SB 1001. Missouri Agric. Exp. Stn, Columbia. p. 5.1-7.4.

Gehl, R. J., and T.J. Boring. 2011. In-season prediction of sugarbeet yield, quality and nitrogen status using an active sensor. Agron. J. 103:1012-1018. doi:10.2134/agronj2011.0040

Green, C. J., and A. M. Blackmer. 1995. Residue decomposition effects on nitrogen availability to corn following corn or soybean. Soil Sci. Soc. Am. J. 59:1065-1070. doi:10.2136/sssaj1995.03615995005900040016x

Groulx, B.J., J.F. Stewart, L. A. Hubbell, and G. Clark. 2010. Effect of row spacing width and population on sugarbeet yield and quality. Michigan Sugar Company Grower Records. https://www.bsdf-assbt.org/wp-content/uploads/2018/01/Groulx (accessed 19 Dec. 2019).

Grove, T., M. Holy, A. Cattanach, J. Christenson. 2005. Narrow row sugarbeet production. Sugarbeet Research and Education Board Records. https://www.sbreb.org/wp-content/uploads/2018/09/NarrowRowSugarbeet (accessed 2 April 2020).

Hergert, G.W. 2010. Sugar beet fertilization. Sugar Tech. 12:256-266.

Hills, F.J. 1973. Effects of spacing on sugar beets in 30 inch and 14-26 inch rows. J. Am. Soc. Sugar Beet Technol, 17(4), 300-308.

Märländer, B., C. Hoffmann, H.J. Koch, E. Ladewig, R. Merkes, J. Petersen, and N. Stockfish. 2003. Environmental situation and yield performance of the sugar beet crop in Germany: Heading for sustainable development. J. Agron. Crop Sci. 189:201-226. doi:10.1046/j.1439-037X.2003.00035.x

Mourtzinis, S., D. Marburger, J. Gaska, T. Diallo, J.G. Lauer, and S. Conley. 2017. Corn, soybean, and wheat yield response to crop rotation, nitrogen rates, and foliar fungicide application. Crop Sci. 57:983– 992. doi:10.2135/cropsci2016.10.0876

MSC. 2020. Fertility. In: Growers' guide for producing quality sugarbeets. Michigan Sugar Company Inc. https://www.michigansugar.com/wp-content/uploads/2016/04/2016-Grower-Guide.pdf (accessed 15 Jan. 2020).

National Agricultural Statistics Service. 2018. USDA-NASS agricultural statistics 2018. USDA-NASS. http://www.nass.usda.gov (accessed 18 Dec. 2019).

National Agricultural Statistics Service. 2019. USDA-NASS agricultural statistics 2019. USDA-NASS. http://www.nass.usda.gov (accessed 18 Dec. 2019).

Nelson, D.W., and L.E. Sommers. 1973. Determination of total nitrogen in plant material. Agron. J. 65:109-112.

Overstreet, L.F., and N.R. Cattanach. 2010. Nitrogen Fertility in strip tillage. Sugarbeet Research & Education Board. https://www.sbreb.org/wp-content/uploads/2018/03/OverstreetNFert2010.pdf (accessed 4 Apr. 2020).

Palti, J. 2012. Cultural practices and infectious crop diseases (Vol. 9). Springer Science & Business Media.

Patrignani, A., and T. E. Ochsner. 2015. Canopeo: A powerful new tool for measuring fractional green canopy Cover. Agron. J. 107:2312-2320. doi:10.2134/agronj15.0150

Rutan, J., and K. Steinke. 2017. Determining corn nitrogen rates using multiple prediction models. J. Crop Improv. 31:780–800. doi:10.10 80/15427528.2017.1359715

SAS Institute. 2012. The SAS system for Windows. Release 9.4. SAS Inst., Cary, NC.

Sharma, L.K., and S.K. Bali. 2018. A review of methods to improve nitrogen use efficiency in agriculture. Sustainability, 10(1), 51.

Sogut, T., and H. Arioglu. 2004. Plant density and sowing date effects on sugarbeet yield and quality. Journal of Agronomy, 3:215-218.

Stebbing, J.A., R.G. Wilson, A.R. Martin, and J.A. Smith. 2000. Row spacing, redroot pigweed (Amaranthus retroflexus) density, and sugarbeet (Beta vulgaris) cultivar effects on sugarbeet development. Journal of sugar beet research, 37(2), 11-31.

Steinke, K., and C. Bauer. 2017. Enhanced efficiency fertilizer effects in Michigan sugarbeet production. J. Sugarbeet Res. 54:2-19.

Steinke, K., and A. Chomas. 2018. Sugarbeet nitrogen response following corn. 2018 Research Results. Michigan Sugarbeet Research and Education Advisory Council. p. 128.

Stevens, W. B., Blaylock, A. D., Krall, J. M., Hopkins, B. G., & Ellsworth, J. W. 2007. Sugarbeet yield and nitrogen use efficiency with preplant broadcast, banded, or point-injected nitrogen application. Agronomy journal, 99(5), 1252-1259.

Suhre, J.J., N.H. Weidenbenner, S.C. Rowntree, E.W. Wilson, S.L. Naeve, S.P. Conley, S.N. Casteel, B.W. Diers, P.D. Esker, J.E. Specht, and V.M. Davis. 2014. Soybean yield partitioning changes revealed by genetic gain and seeding rate interactions. Agron. J. 106:1631-1642.

Tarkalson, D.D., D.L. Bjorneberg, and A. Moore. 2012. Effects of tillage system and nitrogen supply on sugarbeet production.

Van Eerd, L.L., K.A. Congreves, and J.W. Zandstra. 2012. Sugar beet (Beta vulgaris L.) storage quality in large outdoor piles is impacted by pile management but not nitrogen fertilizer or cultivar. Can. J. Plant Sci. 92:129–139. doi:10.4141/cjps2011-054

Van Tassell, L.W., B. Yang, and A.D. Blaylock. 1996. An Economic Analysis of Alternative Nitrogen Fertilization Methods for Sugarbeets. J. Prod. Agric. 9:390-394. doi:10.2134/jpa1996.0390

Vitosh, M. L., Warncke, D. D., & Lucas, R. E. 1998. Secondary and Micronutrients for. Bulletin E-486, Michigan State University Extension Service, East Lansing, Michigan.

Warncke, D., J. Dahl, and L. Jacobs. 2009. Nutrient recommendations for field crops in Michigan. Ext. Bull. E2904. Michigan State Univ. Ext., East Lansing, MI. https://soil.msu.edu (accessed 20 Apr. 2020).

Weaver, J.E. 1926. Root development of field crops. McGraw-Hill, New York.

Yonts, D., and J. Smith. 1997. Effects of plant population and row width on yield of sugarbeet. J. Sugar Beet Res. 34:21–30. doi:10.5274/jsbr.34.1.21