OPTIMIZING AGRONOMIC PRACTICES ON MICHIGAN WINTER WHEAT AND SUGARBEET PRODUCTION

By

Christopher Alan Bauer

A THESIS

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

Crop and Soil Sciences – Master of Science

2016

ABSTRACT

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Winter wheat (*Triticum aestivum* L.) yield potential can be impacted by planting date, and nitrogen (N) rate and timing strategies may offer additional opportunities to enhance the production and efficiency of this cropping system. Field experiments were initiated in Lansing, MI to determine the effects of three planting dates, three N rates, and three N timings on winter wheat grain yield potential, lodging incidence, tiller and grain head production, and efficiency of applied N fertilizer and to evaluate the potential of specific plant characteristics used to predict grain yield. In the 2013-2014 growing season, early-planted wheat produced excessive plant tillering and height (102 cm) resulting in significant lodging and a 20% yield reduction compared to the second planting date (91 cm). In both study years, the efficiency of applied N decreased with increasing N rate. In order to optimize yield and N efficiency, N rates and timing may be managed in response to planting date in lieu of static recommendations.

Increased spring weather variability and early planting dates may allow enhanced efficiency fertilizers (EEF) to improve sugarbeet (*Beta vulgaris* L.) N management. Field studies were initiated in Richville, MI to study the effects of EEF in comparison to standard N programs on sugarbeet yield and quality. Nitrogen strategy did not significantly affect root yield or sucrose concentration in 2014 or 2015. However, significant reductions in plant population were observed without EEF in both years and from in-furrow applications in 2015. Nitrogen loss conditions are required to obtain a positive yield response to EEF, but this class of fertilizer products will inhibit the release of N and reduce saltation risks regardless of weather conditions.

ACKNOWLEDGEMENTS

I would like to thank my major advisor, Dr. Kurt Steinke, for giving me the opportunity to attain my goal of receiving a Master's Degree. I would also like to thank Dr. Marty Chilvers and Dr. Chris Difonzo for devoting their time to be on my committee and providing me with their knowledge on writing my thesis.

This work would not have been possible without the assistance of many people who helped with various aspects of the project including: Andy Chomas, Mike Swoish, Jeff Rutan, and Tom Galecka and also the undergraduate student assistants including: Dan Quinn, Quinten Sackett, Cameron Hiscock, Michelle Sondergrath, and Ashley Jackson. I would also like to thank my friends and family for their support and inspiration. Lastly, I would especially like to thank my parents, Mark and Collette Bauer, for their encouragement and support throughout my graduate school experience.

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CHAPTER 1

LITERATURE REVIEW

Introduction

Wheat (*Triticum aestivum* L.) ranks third in Michigan (MI) field crops behind corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) and is one of the most-produced cereal grains in the world. Michigan is the second most diverse agricultural state in the U.S. with a variety of row and specialty crops preceding winter wheat in rotation (Farm Service Agency, 2016). To achieve maximum yields, winter wheat is planted in September and October in MI (Nagelkirk, 2012). In 2015, an estimated 206,000 hectares of wheat was planted in MI, down 16,500 hectares from the previous year. However, high-yield potential along with favorable prices have renewed interest in winter wheat production in MI. Michigan winter wheat yields have ranked in the top five nationally and number one in the Midwest from 2012-2014 (National Agricultural Statistics Service, 2014). The average yield in 2015 was 5.4 Mg ha^{-1}, which set the new state record (National Agricultural Statistics Service, 2015).

Wheat is thought to have evolved from wild grasses and first cultivated between 15,000 and 10,000 BC (White and Edwards, 2008). Wheat is a C3 plant which grows best in cool and wet environments (Curtis et al., 2002). However, spring wheat grows best in environments with increasing temperatures and longer photoperiods (White and Edwards, 2008). Winter and spring wheat are the two types grown. Winter wheat requires a cold period (known as vernalization), while spring wheat does not. Vernalization occurs when plants are exposed to a period of cold temperatures, between 0° and 10°C, which activates a change from vegetative growth to anthesis (flowering). The wheat plant progresses through many growth stages including: germination, emergence, tillering, stem elongation, booting, heading, anthesis, grainfill, and maturity (White and Edwards, 2008). The growth stages of winter wheat are important in assisting a grower on when to apply fertilizer or fungicide applications. Two common scales that are used for determining growth stages of wheat are the Feekes and Zadoks scales (Alley et al., 2009).

Optimal air temperature for germination of wheat ranges from 12-25°C, but germination may occur between 4° and 37°C. During germination, the seminal roots develop first followed by the coleoptile, which encases the first leaf. Once the coleoptile emerges from the soil and stops growing, the first true leaf pushes through its tip (Curtis et al., 2002). The optimum air temperature for leaf growth is 29°C. When the temperature falls below 25°C, leaf growth slows (White and Edwards, 2008).

Aside from the main stem of the wheat plant, additional shoots, known as tillers are produced. Tillering can be important in determining grain yield, and the production of tillers usually starts following the expansion of the third leaf (White and Edwards, 2008). The tillers emerge from the auxiliary buds, which are located at the nodes in the crown. In the early period of a tiller developing, energy is drawn from the main stem. After a tiller has at least three leaves, tillers are no longer dependent on the main stem and develop an individual root system (Lee and Herbek, 2009). Winter wheat tillers may form in the autumn or spring, and a rapid increase in tiller number occurs in the spring due to warmer temperatures. Grain heads are not produced by all tillers because later-formed tillers usually senesce. Thus the main stem and earlier-formed tillers are most likely to produce harvestable grain heads (Simmons, 1987). Tillering ends as the canopy closes due to the competition for light, which is usually at 50-60% light interception (White and Edwards, 2008).

Stem elongation begins once the developing head is at least one cm above the ground. Stem growth occurs due to the elongation of internodes, i.e. the tissue between two nodes. Once the last internode (or peduncle) is fully elongated, the growth of the stem is complete. Then the flag leaf, the last leaf to develop, emerges. The flag leaf is extremely important as it contributes approximately 45% of the carbohydrate for yield. This is why fungicide applications at the emergence of the flag leaf are recommended to protect the wheat plant from disease, unless environmental conditions do not favor disease (Acevedo et al., 2002).

The boot stage of development occurs when the grain head is fully developed and can be seen in the swollen section of the leaf sheath below the flag leaf. Boot stage ends when the head is first visible at the flag leaf collar. Heading stage begins when the tip of the head emerges from the flag leaf sheath, and ends once the head is completely emerged (White and Edwards, 2008). Anthesis (flowering) follows head emergence and is the time when the florets in each grain head are self-pollinated. The pollination process only lasts three to four days, and the end is determined by anthers protruding from the grain head (Acevedo et al., 2002).

After flowering is complete, the grainfill period begins as kernels mature to form grain through a series of stages. The watery ripe stage occurs first, as kernels increase in size. A clear, watery liquid can be squeezed from the developing kernel. The kernel continues to grow in the milk stage, when a white milk-like substance can be squeezed from the kernel. In the soft dough stage, the green color of kernels fades, and a dough-like substance can be squeezed from the grain. Kernels harden and reach physiological maturity in the hard dough stage, and no additional weight will be added to the grain. After this stage, the moisture is still high, around 30%. The grain is ripe and ready for harvest when the moisture content reaches 12-15% (White and Edwards, 2008).

Planting Date and Yield

Planting date is an important determinant in winter wheat yield and varies based on the region. In Nebraska, maximum yield was reached when 400 GDD were accumulated between planting date and 31 Dec. (Blue et al., 1990). In the state of Washington, planting wheat early (early September) versus late (early October) resulted in increased yield due to an increase in tillers, heads, and kernel weight (Thill et al., 1978). In Saskatchewan, Canada, yield decreased 30-40% when wheat was planted in late October versus early September (McLeod et al., 1992). A similar trend was found in New York, where wheat yield declined as planting dates progressed from late August into late October (Knapp and Knapp, 1978). In central Kansas, Thiry et al. (2002) reported that grain yields were greatest for mid-October plantings and lower for early (28 September) and late (13 November) plantings.

Planting date studies attributed yield differences to the number of heads produced m^{-2}. In eastern Washington, early-planted wheat (early September) produced a greater number of tillers than late-planted wheat (early October), resulting in a greater number of heads m^{-2} (Thill et al., 1978). With the early-planting, yield increased from 7.1 to 8.8 Mg ha^{-1} compared to the late-planting. In New York, the number of grain heads m^{-2} decreased, as planting was delayed, reducing grain production (Knapp and Knapp, 1978). Blue et al. (1990) reported that when planting was delayed from mid-September to late October, the number of grain heads m^{-2} decreased by 20% and 46% in the two years of the study. Kansas research reported wheat grain yield reductions near 25% when planting was delayed from October to November. Wheat that headed out earlier had a greater numbers of heads m^{-2} and heads $plant^{-1}$. Earlier heading allowed for an extended grain fill period, resulting in greater yields. When the heading period occurred later due to late-planting, there was a risk of higher temperatures during the grainfill period, resulting in reduced yield (Witt, 1996).

Cultivar selection decisions change based on planting date in order to achieve maximum yields. In South Dakota, optimal planting dates for early and medium maturing cultivars ranged from 7 September to 19 October, and 5-20 October for late maturing cultivars. Data showed similar yields between early, medium, and late maturing cultivars when planted between 15 September and 1 October. In 2005, yields were within 0.5 Mg ha^{-1} between 15 September and 1 October, and in 2006 and 2007, the yields were within 0.1 Mg ha^{-1}. After 15 October, late maturing cultivars had reduced yield potential as compared to early or medium maturing cultivars. Warmer temperatures during grainfill and decreased head density where hypothesized as the mechanisms responsible for yield reduction of late-planted or late-maturing wheat (Nleya and Rickertsen, 2014).

When conditions do not allow for timely planting, adjusting seeding rate may compensate for planting date. In Wisconsin, when wheat was planted on 25 August and 3 September, seeding rates greater than 2.6 seeds m^{-2} did not increase yields. When winter wheat was planted between 12 and 23 September, increasing seeding rates to >2.6 seeds m^{-2} had a positive effect on yield (Dahlke et al., 1993).

Planting Date and Tiller Production

Tiller production is an important factor in assessing how well winter wheat is performing. Research in Wisconsin showed that tiller production decreased as planting was delayed, resulting in lower yields (Dahlke et al., 1993). Late-planted winter wheat decreased tiller production due to slower plant development given the short proximity of optimal temperatures. Under optimal growing conditions, which entails adequate temperature, moisture, fertility, etc., up to 70% of the wheat yield derives from the tillers. When planting during the ideal growing period, which for northwest Kansas is 10-20 September and for southeast Kansas is 5-20 October, wheat is able to form a sufficient number of tillers during autumn and spring. If wheat is planted too early for a given region, an abundance of tillers can form; this in turn results in competition among plants for soil moisture and may result in decreased grain yields. In contrast, if wheat is planted too late, plants have a shorter period to develop tillers, resulting in fewer grain heads m^{-2} and reduced yield (Thiry et al., 2002). However, research showed that early plantings may be beneficial to tiller production. In eastern Washington, early planting (early September) resulted in greater tiller density, averaging five tillers $plant^{-1}$ at the end of autumn. The earlier growth allowed for extraction of moisture to depths of 105 cm into the soil a month before flowering, allowing for greater tiller density. The late-planted wheat (early October) had two to three tillers $plant^{-1}$ at the end of autumn and was unable to extract moisture to depths of 105 cm into the soil until after flowering, in which moisture was extracted as deep as 170 cm (Thill et al., 1978).

Planting Date and Test Weight

Test weight in wheat is an important factor for the quality and value of the crop. In Michigan, the standard test weight is 75 kg/hL (Isleib, 2012). Factors affecting test weight include planting date, moisture stress, and temperature extremes. In Kansas, a late spring freeze in 1990 reduced test weights for the 28 September planting, and in 1995 water-saturated soil conditions reduced test weights for 30 November planted wheat (Kelley, 2001). When above average air temperatures occurred in the late spring in 1991, Kelley (2001) reported a reduction in test weight in the later maturing cultivars when the wheat was sown in November. In another study in Kansas, test weight was reduced an average of 2.96 kg/hL per month of planting delay (Witt, 1996). In Saskatchewan, Canada, test weights were also reduced with delayed planting

(McLeod et al., 1992). A New York study showed that greater test weights (41.9-43.5 kg/hL) came from the intermediate planting date which was the middle of September (Knapp and Knapp, 1978).

Nitrogen Rate and Yield

Nitrogen (N) rates vary by region, and N is the most limiting nutrient in wheat production (Stoskopf, 1985). In MI, the current N recommendations for winter wheat are [(1.33 x projected yield) – 13] (Warncke et al., 2009). When applying N several factors should be considered including: autumn or spring N application, fungicide usage, irrigation frequency, and crop rotation. With an autumn application studies have shown that applying N at a greater rate than spring applied N was needed to produce similar yields because an autumn application is subject to leaching or denitrification over the winter. In Colorado, 53.8 kg N ha^{-1} was required in the autumn, compared to 44.8 kg N ha^{-1} in the spring, to produce similar yields (Vaughan et al., 1990). In Ontario, when N rate was increased from 100 to 170 kg ha^{-1}, grain yield increased from 6.09 to 6.57 Mg ha^{-1} (Brinkman et al., 2014). When fungicide applications were added at Feekes growth stages 3, 9, and 10.51, the yield difference between 100 and 170 kg N ha^{-1} was 6.77 and 7.54 Mg ha^{-1}. The combination of fungicide with the greater N rate resulted in a 1.45 Mg ha^{-1} increase as compared to the low rate of N without fungicide. Also the number of heads m^{-2} increased from 680 to 720 by increasing the rate of N from 100 to 170 kg N ha^{-1}, respectively (Brinkman et al., 2014).

Other studies on winter wheat and N rates show that N rate can be significant in determining wheat yields. A study in South Carolina found a 29.7% increase in grain yield when irrigation was coupled with fertilization but only a 7.4% increase in yield for irrigation alone (Frederick and Camberato, 1995). Crop rotation may also affect total N rate application on winter wheat. When winter wheat was planted after grain sorghum (*Sorghum bicolor* (L.) Moench), an additional 21 kg N ha^{-1} was required to maximize yields as compared to following soybean (Staggenborg et al., 2003). Due to soybean producing less residue than grain sorghum, the available N being immobilized was reduced when winter wheat was planted after soybean.

Nitrogen rates vary depending on different soil textures and environmental conditions. In North Dakota a rate of 160 kg N ha^{-1} produced the greatest yield with yields declining greater or less than this N rate (Major et al., 1988). Research in South Carolina showed that grain yields were the greatest at a rate of 67 kg N ha^{-1}, but yields were reduced approximately 500 kg ha^{-1} at a greater rate of 101 kg ha^{-1} (Frederick and Camberato, 1994). Pennsylvania field research has shown that N rates of 67 and 100 kg N ha^{-1} decreased yields in 13 of the 15 locations, and the optimum rates were 0 and 34 kg N ha^{-1} in which the greatest yields were found (Roth et al., 1984).

Effects of Nitrogen Rate on Lodging

Lodging may reduce yield, and the quality of the crop. Determining the optimal application rate of N is critical to reduce the risk of lodging. In North Dakota, 240 kg N ha^{-1} at one of the five locations resulted in lodging that reduced yield by 250-370 kg ha^{-1} (Major et al., 1988). Roth et al. (1984) reported that when a high seeding rate was combined with a high N rate, lodging severity increased. At a higher seeding rate, plants cannot build a strong root system. As the N rate increases, tiller numbers may increase, leading to reduced stem strength (HGCA, 2005).

Nitrogen Application Timing and Yield

Spring split N applications reduce the opportunity for N loss from leaching or denitrification, if an extended wet period occurs early in the spring (Warncke and Nagelkirk, 2010). In Colorado, N applied in the spring resulted in greater grain yields and protein than fall and split-applied (fall and spring) nitrogen applications. To achieve similar grain yield, 1.34 kg N ha^{-1} in the fall was equal to 1.12 kg N ha^{-1} in the spring. If most of the split-applied N was applied in the spring, grain yield increased (Vaughan et al., 1990).

Rainfall may impact how wheat reacts to N application timings. In 2003 and 2005, Mohammed et al. (2013) reported that when applying 50 kg N ha^{-1} pre-plant with 100 kg N ha^{-1} applied in March on the soil surface resulted in the greatest yields. During 2003 and 2005 the amount of rainfall was minimal (< 5 cm) in March and April limiting N mineralization. In 2004 and 2006 the greatest yield resulted from 100 kg N ha^{-1} applied pre-plant. During 2004 and 2006 the amount of rainfall received in the months of March and April exceeded 10 cm, which assists with mineralizing the N during important plant growth stages. (Mohammed et al., 2013).

The different growth stages at which N is applied can be variable depending on the region that wheat is being grown. A Pennsylvania study showed that by applying 100 kg N ha^{-1} at Feekes 3, the wheat yields may be similar when compared to split or delayed N applications at Feekes 5 and 8 (Roth and Marshall, 1987). Research in Virginia has shown that an equal split application of 134 kg N ha^{-1} at Feekes 2-3 and Feekes 10.5 in the first year resulted in the greatest yield at 6.7 Mg ha^{-1}, and in the second year 134 kg N ha^{-1} at Feekes 2-3 and Feekes 10 resulted in the greatest yield at 8.0 Mg ha^{-1}. By applying a single application of 89.6 or 134 kg N ha^{-1} during the tillering process can enhance tiller production which allows for an increase in heads m^{-2} (Gravelle et al., 1988). In Texas, field research has shown that split applications of 75 and 150 kg N ha^{-1} at pre-plant and Feekes 4 or 6 resulted in yield increases versus a single application at pre-plant. The following year a split application at pre-plant and Feekes 10 resulted in greater yields compared to the split application at growth stage 4 or 6 due to environmental conditions (Alcoz et al., 1993). Although, a study in Oklahoma has shown that the timing of N applications to winter wheat had a minimal impact on grain yield (Boman et al., 1995).

Effect of Application Timing on Lodging

Nitrogen application timings may have an effect on lodging but is not as significant compared to the effect of N rates. Split or delayed applications of N between Feekes growth stage 3 and 8 did not result in lodging differences (Roth and Marshall, 1987). In Virginia lodging increased when N was applied at the high rate of 134 kg N ha^{-1} as a single application at Feekes 2-3. When there was a split application of 134 kg N ha^{-1} between Feekes 2-3, Feekes 10, and Feekes 10.5 the lodging rating was minimal (Gravelle et al., 1988).

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CHAPTER 2

MODIFYING NITROGEN APPLICATION RATE AND TIMING IN RESPONSE TO WINTER WHEAT PLANTING DATE

Abstract

Winter wheat (*Triticum aestivum* L.) yield potential starts with planting date, and nitrogen (N) rate and timing strategies may allow for improved production and efficiency of this cropping system. In 2013 and 2014, field experiments were conducted in Lansing, MI to determine the effects of planting date on winter wheat yield potential and to determine N rate and timing requirements across planting dates in Michigan. Three planting dates, three N rates, and three N application timings were arranged in a split-split plot design with four replications. In both growing seasons, autumn and spring tiller counts were significantly ($P < 0.10$) impacted by planting date. Excessive tillering and taller plants in the early planting date (2013-14) resulted in significant lodging and a 1.5 Mg ha^{-1} yield reduction from the mid planting date, and in the 2014-2015 growing season a 16% increase in yield was observed with the early planting date over the two later planting dates but was not significantly different. The 84 kg N ha^{-1} rate resulted in a greater partial factor productivity of applied nitrogen (PFP_N) in both study years thus showing that the efficiency of N is decreased with greater N rates. These data suggest that planting winter wheat at an optimum time to allow for sufficient tillering and applying N at rates to sustain maximum efficiency will allow for the potential to achieve greater yields while improving the efficiency of the N being applied.

Introduction

Favorable prices and high-yield potential have renewed interest in winter wheat production in Michigan (MI). Increases in winter wheat (*Triticum aestivum* L.) prices during 2012/13 led to an increase in total hectares planted in MI from 230,671 to 250,905 (NASS, 2014; NASS, 2015a). Mean grain yields from 2012-2014 were 5.0 Mg ha^{-1} with a new state record of 5.4 Mg ha^{-1} in 2015 (NASS, 2015b). Michigan winter wheat yields have ranked in the top five nationally and number one in the Midwest from 2012-2014 (NASS, 2014). The high-yield potential of winter wheat within the state has renewed interest of when winter wheat should be seeded, and whether nitrogen (N) rate and timing need to be adjusted for a specific planting date.

Michigan is the second most diverse agricultural state in the U.S. with a variety of row and specialty crops preceding winter wheat in rotation, which leads to fluctuating planting dates (Farm Service Agency, 2016). Winter wheat is an autumn-seeded crop in which planting date can impact autumn growth, carbohydrate accumulation, and cold hardiness; all of which are affected by air and soil temperatures prior to winter dormancy (Fowler, 2002). Optimal air temperature for germination and development ranges from 12-25°C (Acevedo et al., 2002), while optimal soil temperature (5 cm) ranges from 15-18°C (Jensen and Lund, 1967). Once air and soil temperatures fall outside of these ranges (i.e., late-October in MI), emergence and germination may be delayed or inhibited (Jensen and Lund, 1967). Plants must be exposed to optimum soil temperatures to germinate and then be exposed to soil temperatures below 9°C to achieve cold hardiness (Larsen, 2013). Cold hardiness allows for the plant to go through many different processes such as cell membrane changes, increasing cell concentrations of solutes (i.e., sugars), and alterations in cell metabolism to sustain photosynthetic capacity (Ruelland et al., 2009).

Planting date has also proven to significantly impact grain yield (Blue et al., 1990; McLeod et al., 1992; Witt, 1996; Ghaffari et al., 2001; Nleya and Rickertsen, 2014.). When cereal crops (barley, oat, spring and winter wheat) were planted outside of optimum planting dates, yield decreases of 74 kg ha^{-1} day^{-1} was reported (Brown, 2009). Planting winter wheat outside of October in Oregon caused a reduction in yield with decreases from the September plantings ranging from 745-1550 kg ha^{-1} (Chen et al., 2003). A 30 to 40% yield decrease was reported in wheat planted in late-October as compared to early-September in Saskatchewan, Canada (McLeod et al., 1992).

Planting date may influence tiller and grain head production in addition to test weight and was reported to affect grain yield (McLeod et al., 1992; Dahlke et al., 1993; Witt, 1996; Thiry et al., 2002; Morgan et al. 2011). September-planted wheat in Washington had $\geq$5 tillers $plant^{-1}$ as compared to 2-3 tillers $plant^{-1}$ for wheat planted in early-October (Thill et al., 1978). Increases in tiller density were shown to increase grain yield (Weisz et al., 2001), while decreases in density from delayed planting resulted in yield reductions (Dahlke et al. 1993). Across Nebraska as planting was delayed from mid-September to late-October, grain head density decreased resulting in decreased yields (Blue et al., 1990). Delayed planting was also reported to negatively affect grain test weight (McLeod et al., 1992; Witt, 1996).

Nitrogen is the most limiting nutrient in wheat production, and optimal N rates vary by region (Stoskopf, 1985). Current N recommendations for MI winter wheat are [(1.33 x projected yield) – 13] (Warncke et al., 2009). In North Dakota and South Carolina, optimum N rates to achieve maximum yield were 160 and 67 kg N ha^{-1}, respectively. (Major et al., 1988; Frederick and Camberato, 1994). When altering N rates in a management regime, lodging is a risk. Increased N rates are associated with plant lodging, causing weaker stems and reducing anchorage strength (Crook and Ennos, 1995). Excessive N rates may also affect other factors including the partial factor productivity of applied nitrogen (PFP_N), tillering, and disease pressure. Partial factor productivity of applied nitrogen, the amount of grain produced per kilogram of N applied, is a nitrogen use efficiency index that can be negatively affected by greater N rates (Dobermann, 2005; Ladha et al., 2005; Almas, 2009; Zhu et al., 2011). Increased N application rates may cause an abundance of leaf growth, which may limit tillering (Stoskopf, 1985). Olesen et al. (2003) reported that the severity of plant diseases, such as powdery mildew and septoria leaf spot, increased as N application rates increased. When N recommendations increased from 100 to 170 kg N ha^{-1}, grain heads m^{-2} increased from 680 to 720, and grain yield increased by 0.48 Mg ha^{-1} (Brinkman et al., 2014). Balkcom and Burmester (2015) reported an 11% increase in grain yield at the recommended rate of 101 kg N ha^{-1} as compared to the low rate of 67 kg N ha^{-1}.

Variability in spring rainfall patterns has resulted in minimal adoption of split N applications. With above average spring rainfall, split N applications minimize leaching and denitrification losses, while dry conditions following the second application may inhibit the N from being used efficiently (Vitosh, 1994). Soft red winter wheat peak N uptake occurs near Feekes 5 (Waldren and Flowerday, 1979; Baethgen and Alley, 1989), which allows for delayed or split N applications to avoid saturated soil conditions that often occur during the March/April snowmelt and intense spring rainfall events. Split N applications may be most effective on non- or poorly-tiled silt and clay loam soils of south-central and northeastern Michigan where denitrification N losses can occur during saturated soil conditions. Split N applications may increase grain protein since N is required later in plant development to enhance protein levels (Brown, 2009). However, greater grain protein concentration is not a factor in soft red pastry wheat production in MI (Souza et al., 2012).

To refine N management in relation to wheat grain yield, tissue N concentrations, tiller counts m^{-2}, grain heads m^{-2}, and chlorophyll meters have all been investigated. Increasing N rate was reported to increase plant tissue N concentrations at different growth stages with Feekes 5 identified as critical, due to the beginning of rapid N uptake (Waldren and Flowerday, 1979; Hargrove et al., 1983; Baethgen and Alley, 1989; Ishaq et al., 2001; Staggenborg et al., 2003; Balkcom and Burmester, 2015). Feekes 5 critical N levels for optimal yield have been reported to range from 32-42 g kg^{-1} (Engel and Zubrishi, 1982; Roth et al., 1989; Vaughan et al., 1990), while flag leaf N concentrations have ranged from 35-40 g kg^{-1} (Hargrove et al., 1983).

Individual plant tiller production may influence N timing and yield as early spring N applications promote tillering, while excessive spring N may result in excessive leaf growth and restrict tillering (Stoskopf, 1985). If tillers exceed 800 m^{-2}, applying N at Feekes 5 based on tissue concentrations was more economical compared to a Feekes 2-3 application timing (Scharf and Alley, 1993). Other research showed that with fewer than 550 tillers m^{-2} at Feekes 2-3 N application increased yield, but delaying N applications until Feekes 5 increased yield with Feekes 2-3 tiller densities greater than 550 tillers m^{-2} (Weisz et al., 2001). Nitrogen application during stem elongation (i.e., Feekes 4-7) promotes adequate leaf growth to ensure sufficient carbohydrates are available during anthesis (i.e., flowering) and grain fill (Stoskopf, 1985). Research in Pennsylvania showed similar yields between Feekes 3 and split or delayed N applications at Feekes 5 or 8 (Roth and Marshall, 1987). Boman et al. (1995) reported N application timing had minimal impact on wheat grain yield, but N timing effects on yield are often influenced by the presence or lack of N loss conditions following application. Research conducted using chlorophyll meters on wheat showed high correlations with grain yield, but the accuracy of the meters is dependent on the ambient sunlight and the angle of the sun (Murdock et al., 2004). Chlorophyll meters may allow for the opportunity to determine N status of wheat more quickly than a tissue test. With an excess of 8,000 wheat growers across the state of Michigan, planting date, N rate, and N timing will be affected by previous crop rotation and individual grower infrastructure. Determining N rate and timing across multiple planting dates will influence a broad continuum of growers. The objectives of this study were to (i) determine the effects of planting date, N rate, and N timing on winter wheat grain yield potential, lodging incidence, tiller and grain head production, and PFP_N and (ii) evaluate whether autumn and spring tiller production, grain head counts, and tissue N concentrations may affect wheat grain yield.

Materials and Methods

Winter wheat field experiments were conducted in 2013 and 2014 at the Michigan State University Farm in East Lansing, MI, on a Capac loam soil (fine-loamy, mixed, active, mesic Aquic Glossudalfs). The 12-row plots were 2.4 m wide by 7.6 m long with 19 cm row spacing. The soft red winter wheat cultivar used for this experiment was ‘Red Dragon’ (Michigan Crop Improvement Association, Okemos, MI). The experimental design was a split-split plot arranged as a 3x3x3 factorial experiment with four replications. Planting date was the main plot factor consisting of an early, mid, and late planting timing, and the dates consisted of the following: 17 September (early), 11 October (mid), and 28 October (late) in 2013 and 29 September (early), 10 October (mid), and 23 October (late) in 2014. Subplots consisted of three N rates (84, 118, and 151 kg ha^{-1}) while sub-subplots consisted of three N application timings (green-up, 50% green-up and 50% Feekes 5, and Feekes 5). The plots were sown at a seeding rate of 4,448,000 seeds ha^{-1}. Nitrogen sources were granular urea (46-0-0) broadcast applied at green-up (11 April 2014 and 6 April 2015) and urea ammonium nitrate (28-0-0) applied at Feekes 5 with a backpack sprayer using 51 cm Chafer MR Fertilizer Stream Bars with 12 nozzles (Agrimart, Owensboro, KY).

Soybean (*Glycine max* [L.] Merr.) was the previous crop in both study years. Fields were disked following harvest and cultipacked prior to planting wheat. Prior to wheat planting in 2014, 157 kg K ha^{-1} (0-0-62) was applied. Soil samples were taken to a depth of 20-cm at pre-plant in 2013 and 2014, and soil samples were also taken in the spring of 2014 and 2015 prior to green-up N applications. Soil samples were dried and ground to pass through a 2-mm sieve, then tested for P, K, and pH. In 2013 and 2014, pre-plant soil samples had levels of 54 to 70 mg kg^{-1} P (Bray P1) (Frank et al., 1998), 115 to 116 mg kg^{-1} K (ammonium acetate extractable K) (Warncke and Brown, 1998), and 5.9 to 6.1 pH (1:1 soil/water) (Watson and Brown, 1998). Spring soil samples from 2014 and 2015 resulted in 57 to 71 mg kg^{-1} P (Bray P1) (Frank et al., 1998), 119 to 148 mg kg^{-1} K (ammonium acetate extractable K) (Warncke and Brown, 1998), and 6.0 to 6.8 pH (1:1 soil/water) (Watson and Brown, 1998).

Affinity BroadSpec (methyl 3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylate and methyl 2-[[[[N-[4-methoxy-6-methyl-1,3,5-triazin-2-yl)methylamino]carbonyl]amino] sulfonyl]benzoate) (7 May 2014) was broadcast applied at a rate of 22 ml ha^{-1} to 5-cm weeds for weed control, and Harmony Extra (methyl 3-[[[[[4-methoxy-6-methyl-1,3,5-triazin-2-yl) amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylate and methyl 2-[[[[N-[4-methoxy-6-methyl-1,3,5-triazin-2-yl)methylamino]carbonyl]amino] sulfonyl]benzoate]) (27 April 2015) was broadcast applied at a rate of 18 ml ha^{-1} (DuPont, Wilmington, DE). Fungicide applications consisted of Quilt (Azoxystrobin, Methyl (2E)-2-(2-{[6-(2-cyanophenoxy)pyrimidin-4-yl]oxy}phenyl)-3-methoxyacrylate; Propiconazole, 1-[[2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-

yl]methyl]-1,2,4-triazole) broadcast applied at Feekes 9 at a rate of 325 ml ha^{-1} (29 May 2014 and 14 May 2015), and Prosaro (Prothioconazole, 2-[2-(1-Chlorocyclopropyl)-3-(2-chlorophenyl)-2-hydroxypropyl]-1, 2-dihydro-3H-1, 2,4-triazole-3-thione; Tebuconazole, alpha-[2-(4-chlorophenyl)ethyl]-alpha-(1, 1-dimethylethyl)-1H-1, 2,4-triazole-1-ethanol) broadcast applied at Feekes 10.5.1 at a rate of 237 ml ha^{-1} (6 June 2014 and 2 June 2015). The Michigan Automated Weather Network and the National Oceanic and Atmospheric Administration (NOAA) were used to acquire and record weather data throughout the growing season (http://www.agweather.geo.msu.edu/mawn/, Michigan State University, East Lansing, MI; http://www.ncdc.noaa.gov/cdo-web/datatools/normals, Asheville, NC).

Tillers $plant^{-1}$ were calculated from one square meter within each plot prior to winter dormancy and prior to spring green-up N applications in both study years, and tillers were counted using a destructive sampling method from border rows within the plot. Plant greenness was measured weekly from green-up through maturity using a FieldScout Chlorophyll Meter 1000® (Spectrum Technologies, Aurora, IL). Three measurements were taken from each plot and averaged to give a final plant greenness reading per plot. Plant tissue samples were taken at Feekes 5 (10 whole plants $plot^{-1}$) and Feekes 9 (30 flag leaves $plot^{-1}$), dried, mechanically ground to make it through a 1-mm mesh screen, and analyzed for total N (Dumas method) (Bremner, 1996). Lodging was evaluated on individual plots using the Belgian lodging scale following lodging incidence (Szoke et al., 1979). Prior to harvest, grain heads m^{-2} were counted within each plot.

The partial factor productivity of applied N (PFP_N), an index of N-use efficiency, was calculated to measure the amount of grain produced kg^{-1} of N being applied (Dobermann, 2005). The PFP_N was calculated by dividing the kg grain ha^{-1} by the kg N ha^{-1} applied. The center 1.2 m of each plot was harvested on 21 July 2014 and 16 July 2015 with a small plot combine (Almaco, Nevada, Iowa). Plot ends were trimmed by 61 cm before harvest to eliminate border effects. Grain yields, moisture, and test weight were determined using a grain analysis computer (Model GAC 2100, DICKEY-john, Auburn, IL). Winter wheat grain yields were adjusted to 135 g kg^{-1} moisture.

Data were analyzed using the PROC GLIMMIX procedure in SAS (SAS Institute, 2012) to determine the significance of planting date, N rate, N timing, and their interaction. When an analysis of variance resulted in a significant F value ($P \leq 0.10$), treatment means were compared using Fisher's protected LSD. Correlations were analyzed using PROC CORR in SAS to determine significance among correlations of grain yields with autumn and spring tillers, Feekes 5 and flag leaf total N concentration, grain heads m^{-2}, and Feekes 5 and 9 chlorophyll readings. A correlation of spring tillers with flag leaf total N concentration was analyzed using the same procedure. First-order (linear) regression was analyzed using SigmaPlot to evaluate the effects of flag leaf total N concentration on grain yield (SigmaPlot 13.0, Systat Software Inc., Chicago, IL). The data were determined to be significantly different by year ($P \leq 0.10$) and were analyzed separately.

Results and Discussion

Environmental Conditions

Mean air and soil (5 cm) temperatures during September and October planting dates were within 1-2°C and 1°C of the 30-yr and 15-yr mean, respectively. Both air and soil temperatures were within the suggested range for germination and uniform plant emergence (Table 2.1) (Acevedo et al., 2002; White and Edwards, 2008). Despite January-March air temperatures being 2-9ºC below the 30-yr mean over both study years, wheat stand loss to winterkill did not occur since the plants had time to achieve cold hardiness. Monthly mean air temperatures (April-July) over both study years were within 1-3°C of the 30-yr mean but below 25°C, the temperature at which heat stress may begin to decrease grain yield (Acevedo et al., 2002). Dry soil conditions were prevalent March through April of 2014 and 2015 as precipitation totals were 61% and 70% below the 30-year mean, respectively (Table 2.2). The below average rainfall in combination with the cooler air and soil temperatures likely limited opportunities for denitrification and leaching N losses.

Table 2.1. Monthly mean air and soil temperatures, Lansing, MI, 2013-2015.

	Air Temperatures†			**Soil Temperatures**		
Month	2013-14	2014-15	30-yr avg.‡	2013-14	2014-15	15-yr avg.§
	----------°C ----------			----------°C----------		
Sept.	15.8	15.4	17.1	17.3	17.4	18.5
Oct.	10.7	9.1	10.5	12.4	11.4	11.5
Nov.	2.2	0.7	4.6	5.5	4.1	5.9
Dec.	-4.4	-0.5	-1.9	1.1	2.0	1.6
Jan.	-9.9	-6.9	-4.6	0.6	0.2	0.5
Feb.	-9.2	-12.3	-3.2	0.5	-0.0	0.2
Mar.	-3.7	-0.1	2.0	0.8	1.7	3.4
Apr.	8.0	8.1	8.8	8.5	8.4	9.8
May	14.4	16.5	14.8	14.2	17.1	15.7
Jun.	20.0	19.2	20.2	19.1	20.9	21.5
Jul.	18.8	20.9	22.2	19.9	22.5	24.0

†Air and soil temperatures were collected from Michigan Automated Weather Network (http://www.agweather.geo.msu.edu/mawn/). Soil temperatures were recorded from the top 5 cm.
‡30-yr means for air temperatures came from NOAA (http://www.ncdc.noaa.gov/cdo-web/datatools/normals).
§15-yr means for soil temperatures came from Michigan Automated Weather Network (http://www.agweather.geo.msu.edu/mawn/).

Table 2.2. Monthly mean precipitation and growing degree day accumulation, Lansing, MI, 2013-2015.

Month	Precipitation†			Growing Degree Days		
	2013-14	2014-15	30-yr avg.‡	2013-14	2014-15	15-yr avg.§
		----------cm----------			----------base 0 °C----------	
Sept.	2.1	8.5	9.2	474.7	463.4	497.7
Oct.	12.6	5.2	7.0	334.3	267.4	314.8
Nov.	5.8	3.7	7.1	112.7	89.3	150.9
Dec.	3.2	3.5	4.2	27.4	52.1	45.0
Jan.	1.5	1.5	4.6	9.8	5.0	25.7
Feb.	1.5	0.1	3.8	9.1	2.4	24.9
Mar.	2.4	1.4	4.5	45.8	85.6	117.9
Apr.	2.2	2.1	7.3	248.5	241.3	264.8
May	8.3	8.6	8.5	445.8	460.8	443.1
Jun.	12.3	19.2	8.9	599.1	574.6	585.8
Jul.	6.1	6.2	8.3	582.6	646.3	663.1
Total	58.0	60.0	73.4	2889.8	2888.2	3134.0

†Precipitation and growing degree days data were collected from Michigan Automated Weather Network (http://www.agweather.geo.msu.edu/mawn/).
‡30-yr means for precipitation came from NOAA (http://www.ncdc.noaa.gov/cdo-web/datatools/normals).
§15-yr means for growing degree days came from Michigan Automated Weather Network (http://www.agweather.geo.msu.edu/mawn/).

Tiller and Grain Development

Planting date significantly influenced plant tiller production over both growing seasons. In 2013, prior to winter dormancy the early planting had 2 and 4 more tillers than the mid and late plantings, and prior to green-up applications in 2014 the early planting had 5 more tillers than the mid and late plantings (Table 2.3). Prior to winter dormancy in 2014 the early planting had 1 more tiller plant^{-1} than the two later plantings, and prior to green-up applications in 2015 the early planting had 1 and 2 more tillers plant^{-1} than the mid and late plantings (Table 2.3). Studies of winter wheat and winter triticale (*Triticosecale* Wittm.) have also shown reductions in tiller production with later planting dates (Thiry et al., 2002; Schwarte et al., 2006; Morgan et al., 2011). Increases in plant tillering may have been attributed to longer time periods to encounter optimal air temperatures (12-25°C) that promote tiller development (White and Edwards, 2008).

October air temperatures decreased below optimum levels in both study years inhibiting tiller development with later planting dates. In 2013, the early-planted wheat was seeded 12 days earlier than in 2014. A 53% increase in growing degree days from planting until 31 December 2013 accounted for the increase in tillers in the early-planted wheat in 2013 as compared to 2014. In the 2013-14 growing season, the decrease in tillers in the mid-planting from autumn to spring was likely due to the plant's main stem pulling energy from the tillers to withstand the below-average winter air temperatures with minimal snow cover. In the 2014-15 growing season, greater amounts of snow protected the plants from below-average winter air temperatures, which allowed for the main stem to have sufficient energy to withstand the winter temperatures. Thiry et al. (2002) reported that fall tillers account for 69% of the total grain yield with the other 31% coming from spring tillers when winter wheat was planted in mid-October. Late-formed tillers (spring tillers) use more energy formed during photosynthesis, which accounts for fewer carbohydrates to be translocated during grain fill (White and Edwards, 2008). These data suggest that planting winter wheat during optimal conditions allows for sufficient autumn tiller production, consequently allowing energy reserves to be used more efficiently in the spring.

Table 2.3. Influence of planting date on winter wheat autumn and spring plant tiller production, Lansing, MI, 2013-2015.

	Tillers plant^{-1}			
Planting Date	3 Dec. 2013	11 Apr. 2014	26 Nov. 2014	6 Apr. 2015
early‡	4.1 a†	5.3 a	1.2 a	2.2 a
mid§	1.8 b	0.1 b	<0.1 b	1.3 b
late¶	<0.1 c	<0.1 b	<0.1 b	<0.1 c
Significance *P*>*F*	<0.01	<0.01	<0.01	<0.01

†Means followed by the same letters within a column are not significantly different at $P \leq 0.10$.
‡early: Sept. 17, 2013 & Sept. 29, 2014.
§mid: Oct. 11, 2013 & Oct. 10, 2014.
¶late: Oct. 28, 2013 & Oct. 23, 2014.

Planting date significantly affected the number of grain heads m^{-2} in 2014 but not in 2015. Early-planted wheat resulted in 915 grain heads m^{-2} as compared to 776 and 627 for the mid and late-planting dates, respectively (Table 2.4). Plant tiller development directly influences grain head production, as individual tillers will form an inflorescence if given sufficient time to surpass juvenile growth requirements and respond to longer photoperiods. The five spring tiller difference between early and mid or late-planted wheat in 2014 likely resulted in the greater grain head production, as the 2015 spring tiller discrepancy between planting dates was only one or two tillers plant^{-1}. Spring developed tillers may not necessarily produce grain heads if plants are stressed, shaded from earlier developed tillers, or carbohydrate allocation to earlier formed tillers reduces resources available for developing tillers (Robson, 1968; Ong, 1978). The results from the current study agree with previous work documenting decreased grain head production from delaying winter wheat (Blue et al., 1990; Nleya and Rickertsen, 2014) and winter triticale planting dates (Schwarte et al., 2006).

Table 2.4. Planting date effects on winter wheat grain head density, Lansing, MI, 2014-2015. Grain head counts were averaged across three N rates and three N application timings.

	Grain Heads	
Planting Date	**2014**	**2015**
	----------heads m^{-2}----------	
early‡	915 a†	720 a
mid§	776 b	684 a
late¶	627 c	669 a
Significance *P*>*F*	0.01	0.54

†Means followed by the same letters within a column are not significantly different at $P \leq 0.10$.
‡early: Sept. 17, 2013 & Sept. 29, 2014.
§mid: Oct. 11, 2013 & Oct. 10, 2014.
¶late: Oct. 28, 2013 & Oct. 23, 2014.

Plant Lodging and Wheat Grain Yield

Significant plant lodging first occurred on 11 June 2014 (40 days prior to harvest) and increased in severity until 14 July (Table 2.5). Lodging ratings (0.2-9) (Szoke et al., 1979) increased from 0.3 to 7.9 for early-planted wheat during this time period and increased with N rate (Table 2.5). On 18 June 2014, early, mid, and late-planted wheat was 102, 91, and 81 cm tall, respectively. Lodging severity was reduced for the two later planting dates as plant heights were $\leq$ 91 cm, the mean height for this cultivar over the last four years (Olson et al., 2015). Lodging data confirm the increased risk of lodging when utilizing taller cultivars and early planting dates. Increased N supply in combination with warm temperatures can cause excessive shoot growth and increased length between the basal culm internodes resulting in lodged plants (Pinthus, 1973). Crook and Ennos (1995) also have reported increased lodging with increased N application rate as greater N rates reduced stem and anchorage strength by 20% and 17%, respectively. If excessive growth occurs in wheat, the use of a plant growth regulator (PGR), such as trinexapac-ethyl, to decrease plant height and reduce lodging may be a viable option. Wiersma et al. (2011) reported decreased heights and lodging of wheat with the use of trinexapac-ethyl. With this option, a grower may be able to plant a taller cultivar early without lodging becoming a factor. Lodging was not a factor in 2015 as the mean height of all planting dates was $\leq$ 91 cm. Excessive top growth did not occur in the early planting in 2015 because the wheat was planted 12 days later as compared to 2014 thus accumulating fewer growing degree days to stimulate growth.

Table 2.5. Influence of planting date and nitrogen rate on severity of winter wheat plant lodging, Lansing, MI, 2014. Lodging severity was averaged across three N application timings.

	11 Jun.			14 Jul.		
	N Rate (kg ha^{-1})					
Planting Date	**84**	**118**	**151**	**84**	**118**	**151**
	--------------------lodging rating (0.2 - 9)--------------------					
17 Sept. 2013	0.3 bA†	1.2 bA	2.8 aA	4.9 bA	6.3 bA	7.9 aA
11 Oct. 2013	0.2 aA	0.2 aA	0.2 aB	0.4 aB	0.7 aB	0.6 aB
28 Oct. 2013	0.2 aA	0.2 aA	0.2 aB	1.2 aB	0.2 aB	0.8 aB
Significance *P>F*						
Planting date		0.05			<0.01	
N rate		0.06			0.22	
Planting date x N rate		0.04			0.10	

†Means in a row for each date followed by the same lowercase letters are not significantly different at $P \leq 0.10$. Means in a column for each date followed by the same uppercase letter are not significantly different at $P \leq 0.10$.

Winter wheat 2014 grain yields ranged from 3.4 to 8.6 Mg ha^{-1} (averaging 6.4 Mg ha^{-1}), while 2015 grain yields ranged from 3.8 to 9.5 Mg ha^{-1} (averaging 6.6 Mg ha^{-1}). A planting date x N rate interaction ($P < 0.10$) affected grain yield in 2014 (Table 2.6). Early-planted wheat with 84 kg N ha^{-1} resulted in a 0.7 and 0.5 Mg ha^{-1} yield increase over the 118 and 151 kg N ha^{-1} rates, respectively. Nitrogen rate did not influence the mid planting date, but late-October planted wheat produced greater yield at 118 kg N ha^{-1} as compared to 84 and 151 kg N ha^{-1}. With minimal lodging and reduced N loss conditions throughout the growing season, N rate was not a factor in increasing yields within the mid-planting date. However, in the early-planted wheat a reduction in grain yield occurred with increasing N rates due to an increase in lodging severity. Greater N rates reduce stem and anchorage strength thus increasing the severity of plant lodging (Crook and Ennos, 1995). Grain yield was maximized at the 118 kg N ha^{-1} in the late-planted wheat, which indicates that late-planted wheat requires greater N rates to promote leaf development, tiller production, and root growth to support stem and spring tiller development to enhance grain yields (Stoskopf, 1985). Increased grain yield from greater N application rates may be due to increased tillering or increased whole plant root growth from greater N application rates (Nibau et al., 2008). These data suggest that with late-planted winter wheat additional N was required to stimulate tillering and root growth, which coincided with increased yield.

Table 2.6. Interaction between planting date and nitrogen rate on winter wheat grain yield, Lansing, MI, 2014. Winter wheat grain yield was averaged across three N application timings.

	N Rate (kg ha^{-1})		
Planting Date	**84**	**118**	**151**
	------------Mg ha^{-1}------------		
17 Sept. 2013	6.4 aB†	5.7 bB	5.9 abB
11 Oct. 2013	7.4 aA	7.5 aA	7.5 aA
28 Oct. 2013	5.1 aC	5.7 aB	5.4 aB
Significance *P>F*			
Planting date		<0.01	
N rate		0.98	
Planting date x N rate		0.07	

†Means in a row followed by the same lowercase letters are not significantly different at $P \leq 0.10$. Means in a column followed by the same uppercase letter are not significantly different at $P \leq 0.1$.

No yield differences were observed among planting dates, N rate, or N timing in 2015. However, the 16% increase in grain yield with the early planting, as compared to the two later planting dates, suggests opportunities do exist to increase wheat productivity through management practices in lieu of solely an input-based approach to grain yield improvement. Nitrogen rate and timing did not influence grain yield in either study year indicating 84 kg ha^{-1} was sufficient for optimal yield and in agreement with University recommendations (Warncke et al., 2009). The lack of plant yield response to greater rates of N and N timing were not surprising as both factors exert greater influence on plant development for yield with above average precipitation conditions during the rapid wheat growth months of March-May (Vitosh, 1994). A lack of excessive rainfall events from March-May over both study years resulted in 36-40% less precipitation as compared to 30-yr means and likely limited opportunities for grain yield increases from split N applications. The greatest potential for N loss in rain-fed agroecosystems in the Upper Midwest occur through denitrification during wet, warm conditions and leaching large quantities of residual soil nitrate without active crop growth (Karlen et al., 1998; Vetsch and Randall, 2004). Dry soil conditions following N application have resulted in the poor use of N due to restricted mass flow and reduced N movement limiting N losses and grain yield (Jokela and Randall, 1997). These data showed that differences in grain yield from split N applications was not observed due to dry soil conditions occurring, thus reducing N loss through leaching or denitrification.

Tissue N Concentration

Planting date and N timing significantly influenced Feekes 5 total N concentrations over both study years (Table 2.7). The time of rapid N uptake in wheat begins at Feekes 5, and previous research has indicated critical levels of 20, 35, and 42 g N kg^{-1} based on the region the wheat is grown (Waldren and Flowerday, 1979; Engel and Zubrishi, 1982; Roth et al., 1989; Brown 2009). In 2014, mid and late-planted wheat increased Feekes 5 N concentrations 38-50% compared to early-planted wheat. However, N concentrations were near or above critical levels (20-30 g kg^{-1}) for all planting dates but below the sufficiency range (40-50 g kg^{-1}) for the early planting date (Alley et al., 2009). Second-year planting date data indicated 23% greater Feekes 5 tissue N with early-planted wheat and no differences between the two subsequent dates. Due to the lack of complete N application by Feekes 5, differences in tissue N due to N timing decreased in the following order over both study years: green-up > 50/50 split > Feekes 5. The >5 tillers $plant^{-1}$ with early-planted wheat in 2014 likely diluted N concentrations from additional tiller biomass and parental tiller support of several juvenile tillers simultaneously (Greenwood et al., 1990). Late-planted wheat tends to have minimal top growth and a decreased rooting mass, thus resulting in fewer opportunities to extract nutrients from the soil profile and decreased tissue N concentrations as observed in year two (Thill et al., 1978; Stoskopf, 1985). Given the similar rainfall totals between green-up and Feekes 5 across years, the decline in overall Feekes 5 tissue concentrations from 2014 to 2015 may have been due to a smaller timeframe of plant N uptake in 2015 with plants reaching the Feekes 5 growth stage 7-10 days sooner in 2014.

Planting date, N rate, and N timing significantly affected flag leaf total N concentrations over both study years (Table 2.7). All N application rates resulted in tissue concentrations above the critical range of 20-30 g kg^{-1} (Brown, 2009). Flag leaf tissue N increased with increasing N rate, which concurs with previous studies (Hargrove et al., 1983; Staggenborg et al., 2003). Late-planted wheat resulted in an 18-22% (2014) and 22-31% (2015) increase in flag leaf total N concentrations as compared to the early and mid-planting dates. Later-planted wheat produced fewer tillers suggesting that as tiller production increased plant available N was distributed into multiple tillers and reduced flag leaf N concentrations. Nitrogen timing affected Feekes 9 N concentrations similarly over both years as N concentration increased with later N timing. Second-year flag leaf tissue N concentrations were 8-10% lower than previous year results likely due to wheat attaining the Feekes 9 growth stage 9-13 days earlier in 2015 than 2014. Kaiser and Rubin (2013) have suggested that using tissue concentration data can be misleading when deciding upon application rates since concentration increases may be due to reduced biomass rather than enhanced uptake in the plant. Our results agree and demonstrated that tissue testing was not infallible as greater N concentration variability occurred due to planting date and N timing as compared to overall N rate. Solely relying on N rate as an indicator of N sufficiency can lead to unnecessary N application as planting date individually accounted for a mean difference of 10.5 g kg^{-1} in flag leaf N concentrations across both study years as compared to a 1.6 g kg^{-1} difference due to N rate.

Table 2.7. Winter wheat Feekes 5 and 9 total N concentrations as affected by planting date, N rate, and N timing, Lansing, MI, 2014-2015.

	2014		2015	
Treatment	**Feekes 5**	**Feekes 9**	**Feekes 5**	**Feekes 9**
	----g kg^{-1}----	-----g kg^{-1}-----	-----g kg^{-1}-----	-----g kg^{-1}-----
Planting Date (PD)				
early‡	30.2 c†	42.7 c	35.9 a	37.3 c
mid§	41.7 b	44.1 b	29.0 b	39.9 b
late¶	45.6 a	52.2 a	29.0 b	48.8 a
N Rate (NR) (kg ha^{-1})				
84	39.4 a	45.7 b	30.8 b	41.1 b
118	39.2 a	46.5 a	30.3 b	41.7 b
151	38.9 a	46.8 a	32.7 a	43.1 a
N Timing (NT)				
Green-up	41.1 a	45.8 b	33.7 a	41.4 c
50% green-up; 50% Feekes 5	39.2 b	46.5 a	31.7 b	42.0 b
Feekes 5	37.2 c	46.8 a	28.4 c	42.6 a
Significance (*P*>*F*)				
PD	0.04	<0.01	0.02	<0.01
NR	0.87	0.02	<0.01	<0.01
NT	<0.01	0.03	<0.01	<0.01
PD x NR	0.51	0.14	0.53	0.19
PD x NT	<0.01	0.10	0.21	0.61
NR x NT	0.05	0.75	0.73	0.70
PD x NR x NT	0.11	0.18	0.93	0.16

†Means followed by the same letters within a column for individual main effects are not significantly different at $P \leq 0.10$.
‡early: Sept. 17, 2013 & Sept. 29, 2014.
§mid: Oct. 11, 2013 & Oct. 10, 2014.
¶late: Oct. 28, 2013 & Oct. 23, 2014.

Partial Factor Productivity of Applied Nitrogen

A planting date x N rate interaction ($P < 0.01$) affected partial factor productivity of applied nitrogen (PFP_N) in 2014 (Table 2.8). Within the three planting dates, the PFP_N decreased as N rate increased. The mid-planting within each N rate had a greater efficiency than the early and late-planted wheat. Since the early-planted wheat lodged, the N was not used as efficiently due to the inability to effectively translocate through the stem. Partial factor productivity of applied nitrogen decreased with increasing N rate alone ($P < 0.01$) over both study years. As N application rate increased from 84 to 151 kg N ha^{-1}, the grain yield produced per kg of N fertilizer applied decreased from 74.8 to 41.6 in 2014 and 78.4 to 44.5 in 2015 (data not shown). Results indicated N timing PFP_N had little influence on plant N utilization for grain production. Previous studies on cereal crops concluded that greater N rates resulted in a decline in the PFP_N (Ladha et al., 2005; Almas, 2009; Zhu et al., 2011). Below average rainfall during spring N application timings in 2014 and 2015 may have limited the movement of N through the soil solution minimizing N losses and impacts from application timing, which resulted in decreased N application rates to maximize PFP_N. Data indicate that in years of below normal spring rainfall, less emphasis on when to apply N and greater attention to having a critical but not excessive N concentration for sufficient grain production will allow greater opportunities for growers to improve N fertilizer efficiency (Ladha et al., 2005).

Table 2.8. Planting date and nitrogen rate interaction on partial factor productivity of applied N on winter wheat averaged across three N application timings, Lansing, MI, 2014.

	N Rate (kg ha^{-1})		
Planting Date	**84**	**118**	**151**
	----------kg grain kg^{-1} N----------		
17 Sept. 2013	76.5 aB†	48.4 bB	39.2 cB
11 Oct. 2013	87.6 aA	63.8 bA	49.8 cA
28 Oct. 2013	60.2 aC	47.9 bB	35.8 cB
Significance *P>F*			
Planting date		<0.01	
N rate		<0.01	
Planting date x N rate		<0.01	

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

Relationships Among Various Wheat Characteristics

Correlation coefficients for autumn and spring tiller production, Feekes 5 and 9 tissue N, grain head density, and Feekes 5 and 9 chlorophyll meter readings in relation to grain yield are listed in Table 2.9. Given the close proximity of grain head production and harvest date (48 days), this variable was expected to have a high correlation (r=0.27 in 2014; r=0.59 in 2015). However, despite the usefulness of grain head density as a yield prediction tool, this variable could not be utilized by a grower as a management tool for improving grain yields due to the immediacy in time between these measurements. Autumn tiller counts were significantly correlated to grain yield over both study years and appeared to be the next best overall indicator that still allowed opportunities for a grower to adjust management regimes or make decisions on stand suitability for production. Weisz et al. (2001) also reported the correlation between tiller production and grain yield. Previous research conducted in MI observed a significant positive correlation with fall tillers and yield indicating the importance of a sufficiently tillered winter wheat stand in the autumn (Kinra et al., 1963). The use of a chlorophyll meter (FieldScout CM

1000®) to assess chlorophyll content at Feekes 5 resulted in a positive correlation with grain yield in one of two years (Table 2.9). Feekes 9 chlorophyll readings resulted in positive correlations in both years of the study, but N applied at this growth stage will not have an effect on grain yield. Previous research using chlorophyll meters on wheat reported high correlations with grain yields (Murdock et al., 2004). However, the accuracy of chlorophyll meters is highly dependent on ambient sunlight, the angle of the sun, and the angle at which the readings are taken. These data suggest that the use of a chlorophyll meter may result in inaccurate N recommendations due to the variability in the readings.

Table 2.9. Correlation coefficients (*r*) of autumn and spring tiller production, Feekes 5 and 9 total tissue N, grain head production, and Feekes 5 and 9 chlorophyll readings with grain yield in winter wheat, Lansing, MI, 2013-2015.

Variables		**2013-14**	**2014-15**
Grain yield x	autumn tillers	0.20*	0.42**
	spring tillers	-0.16	0.37**
	Feekes 5 N	-0.05	0.43**
	Feekes 9 N	-0.48**	-0.03
	grain heads	0.27**	0.59**
	Feekes 5 C†	-0.06	0.42**
	Feekes 9 C	0.33**	0.56**

*Significant at P <0.05.
**Significant at P <0.01.
†Chlorophyll meter reading (C).

Total N tissue testing at Feekes 5 and 9 was minimally correlated with grain yield on two of four dates with a negative relationship on three of four dates. Previous research testing winter wheat has indicated Feekes 5 (hard red) and 9 (soft red) total N correlated positively with yield (Hargrove et al., 1983; Cossey et al., 2002). However, soft red wheat production is primarily grown for yield, which requires N earlier in plant development rather than grain protein production which requires N later in development (Brown, 2009). This may also further explain the negative relationship between Feekes 9 total N and grain yield observed in 2014 (R^2 = 0.19).

Of the options investigated in this study, autumn tillers were the best tool to gauge grain yield potential that still allowed for changes in management programs (i.e., N rate, timing, source) to assist in improving yields. While tissue testing may still serve as a valuable tool to gauge plant nutrient status at a specific point in time, greater concentration variability was observed by planting date as compared to N rate or timing. These data indicate that low tissue N concentrations should not be solely based on N availability but rather plant development and greater tiller or biomass dilution (Steenbjerg, 1951).

Conclusions

Nitrogen rate and N timing had minimal impacts over both study years due to below average spring rainfall resulting in fewer opportunities for N loss. Planting date was a dominant factor in increasing MI winter wheat yield potential with late-October planting dates offering fewer opportunities to optimize yields because of decreased tiller production. With late-planting dates, greater N rates may be required to stimulate tillering in the spring and allow for sufficient N to be available to the plant. These data suggest that the optimal time to plant in MI ranges from end of September through mid-October, which allows for tillers to form prior to winter dormancy. However, if a taller wheat cultivar is planted early, the risk of lodging must be considered. With minimal N loss conditions, yields were maximized with 84 kg N ha^{-1} in the early and mid-planting dates in 2014, thus suggesting that additional N will not always result in greater yields. Relying on tissue N concentrations to decide on N applications can be misleading, so by assessing the amount of tillers $plant^{-1}$, N management decisions can be more accurately determined.

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CHAPTER 3

ASSESSING THE USE OF ENHANCED EFFICIENCY FERTILIZERS ON SUGARBEET YIELD AND QUALITY

Abstract

Increased spring weather variability in combination with early planting dates may allow enhanced efficiency fertilizers (EEF) to improve sugarbeet (*Beta vulgaris* L.) nitrogen (N) management programs. A field study was initiated in Richville, MI to study the effects of EEF in comparison to standard N programs on sugarbeet yield and quality. The study was arranged as an eight treatment randomized complete block design with four replications. All treatments received 45 kilograms N ha^{-1} as urea ammonium nitrate applied as a 5x5 (cm) at planting with total N applications at 179 kilograms N ha^{-1}. Significant reductions in plant population were observed with pre-emergence urea in both years and in-furrow applications in 2015 under dry conditions, but N stabilizers appeared to control reductions in plant stand. The ammonium polyphosphate in-furrow application positioned fertilizer in direct contact with the seed, and phosphorus appeared to be a critical addition by contributing to the increase in leaf growth as significant differences were observed in 2014 in the canopy coverage. With the use of EEF the opportunity for a one-pass system is a viable option since N stabilizers will delay the release of N and allow for N to be available longer into the growing season.

Introduction

Nitrogen management is an essential component in sugarbeet production. Michigan sugarbeet production occurs on 61,155 hectares of non-irrigated land in the Great Lakes Bay region of the state (NASS, 2015a). The yield potential in MI increased over the past 25 years; in 2015, a new record of 71.0 Mg ha^{-1} was reached. Average sugarbeet yield was 38.5 Mg ha^{-1} from 1990-95 and 62.0 Mg ha^{-1} from 2010-15 (NASS, 2015b). In 2010, Michigan Sugar Company to increase the quality of sugarbeets, with a goal of 19% sugar (Flegenheimer et al., 2010). This program requires improved management practices, including refined N management strategies and the use of enhanced efficiency N fertilizers. Sugarbeet production in the state of MI is focused in the northeastern portion of the state, within the Lake Huron and Lake Erie watersheds (Michigan Sugar, 2015). Most fields in this region are tile drained. Given the proximity to the Great Lakes, N fertilizer strategies that improve beet quality and promote environmental stewardship are required.

Sufficient, but not excessive, amounts of N are required to optimize sugarbeet root yield and sugar components. Sub-optimal N application reduces root yield, but over-application decreases sucrose concentration, increases impurities, and increases environmental concerns (Draycott, 1993; Hergert, 2010). As sugarbeet N application rates increase, root cell volume also increases, but the sucrose accumulation becomes diluted leading to decreased quantities of sucrose in dry matter (Milford and Watson, 1971). To achieve greater root yields while maintaining or increasing sucrose concentrations, a balanced approach to N management is required emphasizing both yield and quality (Draycott, 1993).

Increased variability in spring and summer weather, concerns about Great Lakes water quality, and increasing interest in a spring stale seed bed may create opportunities for EEF. Enhanced efficiency fertilizers are fertilizer products that may allow growers to decrease nutrient losses and increase nutrient availability throughout the growing season (TFI, 2016). Enhanced efficiency fertilizers include slow and controlled release nitrogen, N stabilizers, and phosphate management products. A urease inhibitor (UI) is a N stabilizer used to delay the conversion of amide-N in urea to ammonium to reduce the risk of losing N as ammonia gas (Upadhyay, 2012). Research conducted on corn (*Zea mays* L.) in Indiana showed urease inhibitors were most effective when added to urea and broadcast on the soil surface (Schlegel et al., 1986). Urease inhibitors begin to lose effectiveness 10-14 days after application (Watson, 2005). To reduce the risk of volatilization, adequate precipitation (>1.3 cm) is needed following application to incorporate the N into the soil (Olson-Rutz et al., 2009). Nitrification inhibitors are N stabilizers used to slow the conversion of ammonium to nitrate by disrupting the activity of nitrifying bacteria in the soil (Draycott and Christenson, 2003). Once the conversion from ammonium to nitrate occurs, the nitrate is prone to leaching due to its negative charge preventing it from attaching to soil particles which are also negatively charged. Keeping N in the ammonium form reduces the risk of leaching and groundwater contamination while sustaining adequate levels of available N in the soil (Frame and Reiter, 2013). Depending on the soil pH, soil moisture, and soil temperature, nitrification inhibitors can delay the conversion of ammonium to nitrate for 4-10 weeks with warmer temperatures speeding up the conversion process (Nelson and Huber, 2001). A controlled release fertilizer is made up of a fertilizer coated with some form of a chemical coating to delay the release of the nutrient. Polymer-coated urea (PCU) is a controlled release fertilizer, and the N release is affected by the moisture and temperature permeability of the polymer coating (Trenkel, 2010). Increases in soil moisture and temperature increase the rate of degradation of the coating material to allow for the slow release of the nutrient. Controlled release fertilizers reduce the risk of nutrient loss in various ways such as leaching, denitrification, and volatilization (Olson-Rutz et al., 2009). Previous research conducted on potatoes (*Solanum tuberosum*) have found that the use of PCUs can result in yields similar or greater in comparison to soluble N fertilizer (Hopkins et al., 2008; Wilson et. al, 2009). Although much research has been conducted on the effects of enhanced efficiency fertilizers in other crops, little research is available on sugarbeet production (Nelson et al., 2009; McKenzie et al., 2010).

Pre-plant N applications using granular N sources have been reported to decrease sugarbeet plant populations due to saltation issues (Last et al., 1983; Blumenthal, 2001). With the use of EEF, N release can be delayed to avoid a decrease in plant populations. To maximize N uptake and reduce the risk of stand loss, pre-plant N applications allow for some early plant growth while allowing for the remainder of N to be applied at later plant growth stages (Carter and Traveller, 1981; Draycott, 1993; Draycott and Christenson, 2003). Previous sugarbeet studies have shown that pre-plant N application increased top growth and maximized light interception early in the growing season (Eckhoff, 1995) allowing for the storage of leaf protein (Armstrong et al., 1986). Sugarbeet plants are able to capitalize on early spring growth by maximizing photosynthesis and light interception to increase sucrose production (Carter, 1987). Although greater amounts of N are required early, sufficient but not excessive N availability later in the season is critical for maintaining canopy and root growth but excessive availability may increase sugar impurities. (Scott and Jaggard, 1993).

Greater yields and increased sugarbeet quality in combination with increasing weather variability offer opportunities for growers to improve N fertilizer management with the aid of EEF. The objective of this field study was to evaluate the use of enhanced efficiency fertilizers as compared to standard grower N practices on sugarbeet root yield, root quality, plant population, canopy coverage, and N partitioning within the plant.

Materials and Methods

Field experiments with sugarbeets were conducted in 2014 and 2015 at the Saginaw Valley Research and Extension Center in Richville, MI, on a Tappan-Londo loam complex (fine-loamy, mixed, active, calcareous, mesic Typic Endoaquolls and fine-loamy, mixed, semiactive, mesic Aeric Glossaqualfs). The design of the experiment was a randomized complete block design with four replications. All treatments received 45 kilograms N ha^{-1} as urea ammonium nitrate (UAN, 28-0-0) applied as a 5x5 (cm) subsurface band at planting with total N applications at 179 kilograms N ha^{-1}. Treatments consisted of urea (46-0-0) sidedressed with light cultivation, N applied pre-emergence with a urease and nitrification inhibitor [($CO(NH_2)_2$) + (N-(n-butyl)-thiophosphoric triamide) + (dicyandiamide) + (N-Methyl-2-pyrrolidone)], urea applied pre-emergence with and without a urease inhibitor [$CO(NH_2)_2$ + N-(n-butyl)-thiophosphoric triamide], UAN banded sidedress with and without a urease inhibitor with no cultivation [(CH4N2O + NH4NO3 + H2O) + (N-methyl-2-pyrrolidone) + (N-(n-butyl) thiophosphoric triamide)] (Koch Agronomic Services, LLC, Wichita, Kansas), ammonium polyphosphate (10-34-0) applied as a pop-up with remaining N as urea sidedressed with light cultivation, and a 75:25 ratio of polymer-coated urea (44-0-0):urea applied pre-emergence (Agrium Inc., Denver, CO).

The plots consisted of six rows spaced at 76 cm and were 4.5 m wide by 10.7 m long. The sugarbeet variety used over both study years was ‘Crystal RR059’ (ACH Seeds Inc., Eden Prairie, MN). Plots were planted on 6 May 2014 and 17 April 2015 at a seeding rate of 123,500 seeds ha^{-1}. Soil samples to a 20-cm depth were collected prior to planting and prior to nitrogen (N) fertilization to determine pH, P, and K levels and to a 30-cm depth at harvest within each plot to determine nitrate-N (NO_3-N) and ammonium-N (NH_4-N) concentrations in both study years. The soil samples were dried at 60°C and ground to go through a 2-mm sieve. The 20-cm soil sample results in 2014 and 2015 included 159 to 162 mg kg^{-1} K (ammonium acetate extractable K) (Warncke and Brown, 1998), 32 to 41 mg kg^{-1} P (Bray P1) (Frank et al., 1998), and 7.8 to 8.0 pH (1:1 soil/water) (Watson and Brown, 1998). In 2014 and 2015 the crop preceding the sugarbeet experiment was corn (Zea mays L.). The fields were autumn moldboard plowed after corn harvest and tilled in the spring with two passes using a field cultivator.

Weed control consisted of two applications of glyphosate [N (phosphonomethyl)glycine] at a rate of 0.6 L ha^{-1} with the first being in the end of May and the second in the end of June of both study years, and an application of Dual Magnum (S-metolachlor) at a rate of 0.5 L ha^{-1} applied in mid-June of both years. The following fungicides were applied in both study years: Quadris (Azoxystrobin) at a rate of 0.9 L ha^{-1} in early June, Inspire XT (Difenoconazole + Propiconazole) at a rate of 0.2 L ha^{-1} in early July and end of July, Super Tin (Triphenyltin Hydroxide) at a rate of 0.1 L ha^{-1} in the end of July, and Manzate (Manganese + Zinc + Ethylenebisdithiocarbamate ion) at a rate of 0.9 kg ha^{-1} in mid-August. Throughout the duration of the growing season weather data were recorded and acquired from the Michigan Automated Weather Network (http://www.agweather.geo.msu.edu/mawn/, Michigan State University, East Lansing, MI).

Plants 16.3 m^{-2} were counted at 10-20 days after planting, 20-30 days after planting, and prior to harvest in both study years. Chlorophyll readings were collected with a Minolta SPAD (soil plant analysis development) 502 chlorophyll meter to determine sugarbeet leaf greenness in June of both years (Spectrum Technologies, Inc., Aurora, IL). Plant tissue samples were sampled in June and July (25 leaves and petioles $plot^{-1}$), dried at 60°C, mechanically ground to be passed through a 1-mm mesh screen, and analyzed for total N. Digital images were taken from the 2-4 leaf stage until canopy closure on a weekly basis to determine ground coverage. The pictures were cropped and resized in Adobe Photoshop CC 2015 (Adobe Systems, Inc., San Jose, CA) and ran through Sigma Scan Pro 5 using the macro "Turf Analysis" to measure ground coverage (Systat Software, Inc., San Jose, CA). At harvest beet tops were collected from 3 m of row, and the fresh weight was recorded. A fresh homogenous subsample was collected from the whole sample, and the fresh weight was again recorded. The subsample dry weight was recorded after being dried at 60°C, and the sample was ground to pass through a 1-mm mesh screen and analyzed for total N. Four beet roots were collected at harvest, washed, and weighed. A saw was used to collect beet pulp from the four sugarbeets, and a pulp fresh weight was recorded. The pulp samples were frozen, put into a freeze dryer, and dry weights were recorded. The total N in the dry beet pulp samples were analyzed by using a micro-Kjeldahl digestion method (Bremner, 1996) and colorimetric analysis through a Lachat rapid flow injector autoanalyzer (Lachat Instruments, Milwaukee, WI).

The sugarbeet roots from the center two rows of each plot were harvested on 6 October 2014 and 8 October 2015 with a mechanical harvester and weighed. A root subsample (10 roots plot^{-1}) was collected from each plot to be analyzed for sugar and purity components including recoverable white sucrose Mg^{-1} (RWSMg), recoverable white sucrose ha^{-1} (RWSH), percent sucrose, percent clear juice purity, NH_2, and amino-N at the Michigan Sugar Company laboratory (Michigan Sugar Company, Bay City, MI).

The data were analyzed using the PROC GLIMMIX procedure in SAS (SAS Institute, 2012) to determine the significance of treatment. Treatment means were compared using Fisher's protected LSD when ANOVA resulted in a significant *F* value ($P \leq 0.1$). Correlations of sucrose concentrations and recoverable white sucrose ha^{-1} with root yield were analyzed using PROC

CORR in SAS. The data were analyzed separately after being determined to be significantly different by year ($P \leq 0.05$).

Results and Discussion

Growing Conditions

Total precipitation in the 2014 growing season (April-September) was near the 30-yr mean but 23% less than the 30-yr mean in 2015 (Table 3.1). Differences between 2014 and 2015 precipitation totals were driven primarily by a drier April and July 2015 in which 50% less rainfall was received as compared to April and July 2014. Monthly growing season air temperatures were within 1-3°C of the 30-yr mean in both study years (Table 3.1). Monthly soil temperatures (5 cm depth) were below the 7-yr mean every month of the 2014 growing season and at or below the 7-year mean 5 of 6 months in 2015 (Table 3.1). April soil temperatures in 2014 and 2015 were 1.7 and 1.2 °C cooler, respectively, which may have limited early season plant emergence and growth. Near or below average precipitation in conjunction with cooler soil temperatures over both study years may have limited sugarbeet growth.

Table 3.1. Monthly mean precipitation and soil temperatures, Richville, MI, 2014-2015.

Month	Precipitation†			Soil Temperatures			Air Temperatures		
	2014	2015	30-yr avg.‡	2014	2015	7-yr avg.§	2014	2015	30-yr avg.
	cm			°C			°C		
Apr.	10.1	5.0	7.5	6.2	6.7	7.9	7.4	7.4	7.5
May	7.8	7.3	8.7	13.9	15.2	15.2	14.3	15.5	13.3
Jun.	7.0	6.8	10.0	19.6	19.7	20.7	20.2	18.5	18.9
Jul.	10.6	5.6	9.3	21.0	22.2	24.1	19.0	20.9	21.1
Aug.	9.9	10.0	8.6	21.4	20.8	22.5	19.7	20.0	19.8
Sept.	7.7	6.7	9.8	17.4	19.1	18.4	15.5	18.5	16.0
Total	53.1	41.4	53.9						

†Precipitation, soil temperatures, and air temperatures were collected from Michigan Automated Weather Network (http://www.agweather.geo.msu.edu/mawn/). Soil temperatures were recorded from the top 5 cm.
‡30-yr means for precipitation and air temperatures came from NOAA (http://www.ncdc.noaa.gov/cdo-web/datatools/normals).
§7-yr means for soil temperatures (5 cm) came from Michigan Automated Weather Network (http://www.agweather.geo.msu.edu/mawn/). This location only had weather data from Dec. 2008-present.

Root Yield and Quality

Sugarbeet root yields ranged from 77.3 to 86.2 Mg ha^{-1} and from 51.7 to 69.8 Mg ha^{-1} in 2014 and 2015, respectively. Nitrogen strategy did not significantly affect root yield in 2014 or 2015 (Table 3.2). Mean root yields in 2014 were 23% greater than 2015 likely due to a 30% reduction in precipitation from April-July 2015 limiting root growth and bulking. Previous research showed that changes in water status affected root yield to a greater degree than changes in dry matter (Alexander, 1971; Carter, 1987). Enhanced efficiency fertilizers were intended to reduce the risk of N loss which may occur under wet or dry conditions depending on N application method (Olson-Rutz et al., 2009). Total accumulated rainfall in the 14 days following pre-emergence N applications in 2014 and 2015 was neither excessively wet nor dry at 7.4 and 1.1 cm, respectively. Due to drier soil moisture conditions following 2015 pre-emergence N applications, an 18-24% yield increase was observed for urea coated with a UI or urease and nitrification inhibitor (UI+NI) as compared to pre-emergence urea without a stabilizer (Table

3.2). The potential for greater productivity with the UI and UI + NI may have been due to N volatilization from the non-stabilized urea. Urease inhibitors can delay the conversion of amide-N in urea to ammonium for up to 14 days under dry soil conditions by inhibiting the hydrolytic action of the enzyme urease (Trenkel, 2010). Similar to Norton (2011), sufficient (>1.3 cm) precipitation was received in both study years following sidedress N application and resulted in no differences in root yield among sidedress treatments. These data suggest that growers experiencing drought or dry soil conditions around planting time may want to consider the use of a UI when surface applying N, but the amount of precipitation received after planting may dictate sugarbeet yield response.

Root quality as indicated by sucrose concentration and extraction was not impacted by N strategy and similar observations have been documented (Table 3.2) (Norton, 2011). Sucrose concentrations ranged from 18.3 to 18.9% (averaging 18.6%) in 2014 and from 17.4 to 18.7% (averaging 18.2%) in 2015. Data suggest that although EEF products did not increase root quality, these products also did not interfere with N release or plant uptake and reduce sugar quality. The addition of a UI to urea resulted in a 0.9% increase in sucrose concentration as compared to urea individually suggesting that opportunities may exist to increase sugarbeet root quality with a UI under reduced moisture conditions.

The recoverable white sucrose ha^{-1} (RWSH) ranged from 10,918 to 12,142 kg ha^{-1} in 2014 and from 6,740 to 9,719 kg ha^{-1} in 2015 (Table 3.2). Decreased moisture in 2015 likely had a negative impact on sugarbeet production as evidenced by a 25% mean sucrose yield reduction as compared to 2014 (Table 3.2). Urea applied pre-emergence significantly decreased RWSH in 2015 driven in part by lower root yields (Campbell and Kern, 1983; Spangler et al., 2014). When RWSH was correlated with root yield, a significant positive correlation resulted with a Pearson correlation coefficient (r) of 0.94 and 0.97 in 2014 and 2015, respectively (data not shown). These data correspond to previous research showing that as root yield increased RWSH also increased (Campbell and Kern, 1983; Spangler et al., 2014).

Table 3.2. Sugarbeet nitrogen strategy effects on recoverable white sucrose Mg^{-1} (RWSMg), recoverable white sucrose ha^{-1} (RWSH), root yield, percent sucrose, and percent extraction, Richville, MI, 2014-2015.

Treatment[†]	**RWSMg**	**RWSH**	**Root Yield**	**Sucrose**	**Extraction**
			2014		
	kg Mg^{-1}	kg ha^{-1}	Mg ha^{-1}	%	%
Urea pre-emergence	143 a[‡]	11243 a	78.8 a	18.7 a	96.6 a
Urea with UI[§] pre-emergence	144 a	11897 a	82.7 a	18.8 a	96.6 a
Urea with UI & NI[¶] pre-emergence	140 a	10918 a	77.9 a	18.4 a	96.4 a
PCU:urea pre-emergence (75:25 ratio)	143 a	10992 a	77.3 a	18.8 a	96.2 a
In-furrow followed by urea SD[††]	141 a	11624 a	82.7 a	18.5 a	96.4 a
Urea SD	139 a	11936 a	86.2 a	18.3 a	96.3 a
UAN[‡‡] SD	144 a	12142 a	84.2 a	18.9 a	96.5 a
UAN SD with UI	144 a	11807 a	82.2 a	18.7 a	96.8 a
Significance (P>F)	0.69	0.62	0.76	0.75	0.26
			2015		
	kg Mg^{-1}	kg ha^{-1}	Mg ha^{-1}	%	%
Urea pre-emergence	130 a	6740 b	51.7 a	17.4 a	95.6 a
Urea with UI pre-emergence	139 a	8443 a	61.0 a	18.3 a	96.2 a
Urea with UI & NI pre-emergence	140 a	8970 a	64.1 a	18.4 a	96.3 a
PCU:urea pre-emergence (75:25 ratio)	140 a	8999 a	64.3 a	18.4 a	96.3 a
In-furrow followed by urea SD	136 a	8213 ab	60.0 a	18.1 a	95.9 a
Urea SD	139 a	9719 a	69.8 a	18.4 a	96.2 a
UAN SD	143 a	9373 a	65.8 a	18.7 a	96.3 a
UAN SD with UI	139 a	9330 a	66.8 a	18.2 a	96.4 a
Significance P>F	0.19	0.08	0.13	0.20	0.28

[†]All treatments received 45 kg N ha^{-1} applied as a 5x5 (cm) subsurface band at planting.
[‡]Values followed by the same lower case letter are not significantly different at $P \leq 0.1$.
[§]Urease inhibitor (UI)
[¶]Nitrification inhibitor (NI)
[††]Sidedressed (SD) at the 2-4 LS on 29 May 2014 & 20 May 2015.
[‡‡]Urea ammonium nitrate (UAN)

Population and Canopy Coverage

Significant reductions in plant population were observed with pre-emergence urea and in-furrow applications, but N stabilizers appeared to moderate reductions in plant stand (Table 3.3). Plant populations were noted prior to sidedress N application timings causing these treatments to remain unaffected by pre-plant N applications. The pre-emergence urea reduced plant stands by 16 and 40% 25 days after planting as compared to pre-emergence urea with a UI in 2014 and 2015, respectively. Limited rainfall (1.1 cm) within the first 14 days following the pre-emergence N application in 2015 may have limited N dilution and distribution within the upper soil profile contributing to the reduction in plant population. The in-furrow treatment followed by sidedressed urea reduced plant population by 16-21% in 2015, as compared to the other sidedress timings, due to the close proximity of the in-furrow fertilizer to the sugarbeet seed and minimal rainfall. Lack of sufficient rainfall following in-furrow nutrient applications can increase the osmotic pressure of the soil solution surrounding the seed and reduce water imbibition by the seed (Last et al., 1983). These data indicate that urea treatments with a UI, UI+NI, and PCU may have slowed N release early in the growing season when precipitation was limited preventing seed saltation and reductions in plant population. Previous research has shown that spring applying N (granular N or ammonium nitrate) prior to planting resulted in a reduction of plant populations when rainfall was limited (Last et al., 1983; Blumenthal, 2001). The difference between applying N fertilizer prior to planting and applying N pre-emergence at planting could range from one day to several weeks as was demonstrated by Last et al. (1983) where N application dates ranged from 1-14 days prior to planting. Last et al. (1983) also reported that N application prior to planting had no effect on stand establishment when 2.8-4.0 cm rainfall occurred after planting. These data suggest that a one pass fertilizer regimen with 134 kg N ha^{-1} applied pre-emergence using a UI, UI+NI, or PCU and 45 kg N ha^{-1} applied as a 5x5 (cm) at planting is a viable option to mitigate the risk of stand loss.

Table 3.3. Impact of N strategy on sugarbeet plant population (plants 16.3 m^{-2}) at 15, 25, or 35 days after planting, Richville, MI, 2014-2015.

	Plants 16.3 m^{-2}			
	2014		**2015**	
Treatment[†]	15 DAP	25 DAP	25 DAP	35 DAP
Urea pre-emergence	127 d[‡]	127 c	83 c	85 c
Urea with UI[§] pre-emergence	152 c	145 b	139 ab	137 ab
Urea with UI & NI[¶] pre-emergence	168 ab	160 ab	149 ab	144 ab
PCU:urea pre-emergence (75:25 ratio)	165 abc	159 ab	153 ab	158 a
In-furrow followed by urea SD[††]	159 bc	157 ab	125 b	123 b
Urea SD	174 a	168 a	159 a	153 ab
UAN[‡‡] SD	167 ab	160 ab	154 a	151 ab
UAN SD with UI	174 a	164 a	150 ab	149 ab
Significance P>F	<0.01	<0.01	<0.01	0.01

[†]All treatments received 45 kg N ha^{-1} applied as a 5x5 (cm) subsurface band at planting.
[‡]Values followed by the same lower case letter are not significantly different at $P \leq 0.1$.
[§]Urease inhibitor (UI)
[¶]Nitrification inhibitor (NI)
[††]Sidedressed (SD) at the 2-4 LS on 29 May 2014 & 20 May 2015.
[‡‡]Urea ammonium nitrate (UAN)

Percent canopy coverage was significant on 3 of 7 rating dates in 2014 with ammonium polyphosphate applied in-furrow resulting in the greatest ground coverage (Table 3.4). No significant canopy coverage differences were observed in 2015. On 29 May 2014 the in-furrow application followed by sidedressed urea increased canopy coverage >100% relative to all N strategies with the exception of urea sidedressed alone. As the growing season progressed, differences in canopy coverage among N strategies was reduced but still significant. The > 100% difference in canopy coverage between the in-furrow sidedressed urea treatment and sidedressed UAN strategy on May 29 was reduced to only a 20% difference in canopy coverage on June 26. Although N is important for stimulating leaf and root growth (Malnou et al., 2006), the 13.5 kg ha^{-1} P_2O_5 from the in-furrow application may have enhanced growth and canopy coverage given the wet, cool soil conditions in April 2014. Early canopy development and row closure can enhance light interception and photosynthesis maximizing sucrose production and yield (Carter, 1987). Despite the potential for greater early season canopy coverage, in-furrow nutrient applications did not result in sugarbeet yield or quality improvements and increased the potential for stand loss when dry soil conditions persisted after planting as observed in 2015.

Table 3.4. Percent canopy coverage of sugarbeets as affected by different N management strategies, Richville, MI, 2014.

Treatment†	**May 29**	**June 12**	**June 26**
	%		
Urea pre-emergence	1.5 cd‡	20.5 bc	73.1 abc
Urea with UI§ pre-emergence	1.6 cd	21.4 bc	72.3 bc
Urea with UI & NI¶ pre-emergence	1.4 d	19.4 c	67.1 c
PCU:urea pre-emergence (75:25 ratio)	1.8 c	20.3 c	76.4 ab
In-furrow followed by urea SD††	3.8 a	26.0 a	79.9 a
Urea SD	3.0 b	23.6 ab	78.1 ab
UAN‡‡ SD	1.6 cd	19.3 c	66.4 c
UAN SD with UI	1.8 c	20.6 bc	68.6 c
Significance P>F	<0.01	0.03	0.03

†All treatments received 45 kg N ha^{-1} applied as a 5x5 (cm) subsurface band at planting.
‡Values followed by the same lower case letter are not significantly different at $P \leq 0.1$.
§Urease inhibitor (UI)
¶Nitrification inhibitor (NI)
††Sidedressed (SD) at the 2-4 LS on 29 May 2014.
‡‡Urea ammonium nitrate (UAN)

Tissue N Concentration

Tissue N concentrations were affected by N strategy on 1 of 2 dates in both study years (Table 3.5). In 2014, 6-8 leaf N concentrations ranged from 46.3 to 50.7 g kg^{-1} (Table 3.5). Three of the four N strategies having the greatest N concentrations were applied pre-emergence. The EEF products did not interfere with N uptake as the N applications containing N stabilizers were not statistically different from each other. Pre-emergence strategies may have increased early N availability and opportunity for N uptake which subsequently increased leaf tissue N concentration. Rapid N uptake begins at the 4-5 leaf stage (LS) (Scott and Jaggard, 1993). Plants receiving N fertilizer at the 2-4 LS may have been limited to N as compared to the plants with N applied at pre-emergence as evidenced by a decrease in N concentrations in the sidedress treatments. A reduction in plant population was observed when urea was applied pre-emergence thus reducing competition among plants for nutrients. The reduction in competition likely resulted in greater N concentrations in the plants.

Total N concentrations observed at the 12-14 LS in 2015 were significantly different among treatments and ranged from 33.2 to 46.2 g kg^{-1} (Table 3.5). The use of EEF products with urea did not affect tissue N concentrations among urea N strategies with the exception of PCU. Similar observations were noted with the use of UAN strategies. Treatments containing urea resulted in greater N concentrations than treatments containing UAN or PCU. Reduced rainfall conditions (16.3 cm) from planting until the tissue sampling period (53 days) likely reduced the release and movement of N from the PCU resulting in less available N for the plant to uptake. Total accumulated rainfall was 5.2 cm 14 days following sidedress N applications, which likely resulted in N movement into the soil profile and increased N availability. However, other unknown factors must have attributed to the decrease in tissue N in the UAN applications as rainfall accumulation was sufficient. Previous research conducted on corn using a UI has shown that urea compared to UAN without a UI resulted in greater leaf N content in one of two years (Schlegel et al., 1986). Schlegel et al. (1986) also observed an increase in tissue N content when urea treated with a UI was applied to no-till corn in one of two years. These data suggest that urea applications with or without N stabilizers may allow for greater N uptake as compared to UAN and PCU applications.

Table 3.5. Effect of N practices on total N concentration in the leaves and petioles of sugarbeets at the 6-8 and 12-14 leaf stage (LS), Richville, MI, 2014 & 2015.

	2014		2015	
Treatment†	**6-8 LS**	**12-14 LS**	**6-8 LS**	**12-14 LS**
	g kg^{-1}			
Urea pre-emergence	50.7 a‡	34.4 a	48.8 a	43.0 a
Urea with UI§ pre-emergence	49.7 ab	31.7 a	48.2 a	40.6 ab
Urea with UI & NI¶ pre-emergence	49.9 ab	34.3 a	49.7 a	46.2 a
PCU:urea pre-emergence (75:25 ratio)	48.2 bcd	30.6 a	47.0 a	35.7 bc
In-furrow followed by urea SD††	46.3 d	30.7 a	50.2 a	43.1 a
Urea SD	47.0 cd	30.1 a	48.1 a	39.8 abc
UAN‡‡ SD	46.4 cd	34.8 a	47.9 a	35.2 bc
UAN SD with UI	48.6 abc	34.2 a	47.7 a	33.2 c
Significance P>F	0.01	0.66	0.33	0.04

†All treatments received 45 kg N ha^{-1} applied as a 5x5 (cm) subsurface band at planting.
‡Values followed by the same lower case letter are not significantly different at $P \leq 0.1$.
§Urease inhibitor (UI)
¶Nitrification inhibitor (NI)
††Sidedressed (SD) at the 2-4 LS on 29 May 2014 & 20 May 2015.
‡‡Urea ammonium nitrate (UAN)

Accumulation of Nitrogen in the Sugarbeet Roots and Tops

Total N uptake was not significant in the roots or in the tops plus roots in 2014 and 2015 but was significant in 2014 tops (Table 3.6). The use of EEF products in 2014 resulted in greater N accumulation in the tops as compared to the N strategies without EEF. The treatment differences in N accumulation in the tops in 2014 corresponded to biomass differences as treatments with less biomass ha^{-1} resulted in less accumulated N in the tops (data not shown). A 46% decrease in biomass ha^{-1} in 2015 corresponded to a similar decrease in N accumulation in the tops as compared to 2014 (data not shown). Dry soil conditions in 2015 from 22% less rainfall may have reduced root bulking and limited N movement reducing N concentrations from 2014 levels. The N accumulation in the tops and roots combined in 2015 was on average 28% lower than in 2014. Leaf area index has been shown to have a direct relationship with N uptake (Scott and Jaggard, 1993). Despite increased sugarbeet top N accumulation at harvest in 1 of 2 years when using EEF, yield differences were not apparent limiting the usefulness of this indicator. Dry conditions during the 2015 growing season likely reduced soil N movement resulting in similar N accumulation among different strategies.

Table 3.6. Total N accumulation of sugarbeets in the beet tops, roots, and tops and roots (T&R) combined as influenced by different N strategies, Richville, MI, 2014 & 2015.

	2014			2015		
Treatment†	**Tops**	**Roots**	**T&R**	**Tops**	**Roots**	**T&R**
	kg N ha^{-1}					
Urea pre-emergence	101 c‡	94 a	195 a	62 a	83 a	145 a
Urea with UI§ pre-emergence	137 a	104 a	241 a	68 a	91 a	159 a
Urea with UI & NI¶ pre-emergence	123 ab	99 a	222 a	57 a	92 a	149 a
PCU:urea pre-emergence (75:25 ratio)	118 abc	98 a	216 a	68 a	99 a	167 a
In-furrow followed by urea SD††	99 c	104 a	203 a	58 a	92 a	150 a
Urea SD	128 a	99 a	227 a	69 a	104 a	173 a
UAN‡‡ SD	104 bc	103 a	207 a	60 a	94 a	154 a
UAN SD with UI	136 a	110 a	246 a	63 a	96 a	159 a
Significance P>F	0.01	0.91	0.22	0.80	0.91	0.80

†All treatments received 45 kg N ha^{-1} applied as a 5x5 (cm) subsurface band at planting.
‡Values followed by the same lower case letter are not significantly different at $P \leq 0.1$.
§Urease inhibitor (UI)
¶Nitrification inhibitor (NI)
††Sidedressed (SD) at the 2-4 LS on 29 May 2014 & 20 May 2015.
‡‡Urea ammonium nitrate (UAN)

Residual Soil Nitrate

Residual soil nitrate levels (0-30 cm) after harvest were not affected in either study year. Nitrate levels ranged from 4.9 to 7.1 kg N ha^{-1} and from 4.6 to 6.7 kg N ha^{-1} in 2014 and 2015, respectively (data not shown). Sugarbeet roots can scavenge nutrients to great depths and have been recorded to depths of 210 cm (Peterson et al., 1979). Due to precipitation exceeding evapotranspiration in the MI sugarbeet production area, residual soil nitrate is often leached or denitrified during the wet, winter season limiting the usefulness of this measureable as compared to production regions west of the Mississippi River.

Conclusions

Although EEF did not improve nor inhibit sugarbeet root yield and sucrose response in this study, weather conditions were not excessively wet nor dry likely limiting volatilization, leaching, and denitrification pathways of N loss. When surface applying N pre-emergence, the use of EEF products allowed for the opportunity to apply N in a one-pass system while mitigating the risk of reducing plant populations by slowing the release of N into the soil. In-furrow nutrient application of ammonium polyphosphate stimulated early growth and canopy development. However, the in-furrow nutrient application failed to elicit a root yield or sugar quality response and increased stand losses when compared to sidedress N application. Fertilizer technologies designed to reduce N losses and improve plant production may require greater N loss conditions beyond those encountered in this study to maximize yield and sugar quality benefits.

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