INFLUENCE OF INPUT-INTENSIVE MANAGEMENT ON SOFT WINTER WHEAT AND SOYBEAN GRAIN YIELD AND PROFITABILITY

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ABSTRACT

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Increasing grain yields, climatic variability, and commercial marketing has prompted many wheat (*Triticum aestivum* L.) and soybean [*Glycine max* (L.) Merr.] producers to adopt input-intensive management systems for maximum yield. Field studies were conducted in Lansing and Richville, MI from 2015 - 2017 investigating soft winter wheat and soybean grain yield and economic net return in response to commonly marketed agronomic inputs applied to both intensive (i.e., high-input) and traditional (i.e., low-input) management systems. Wheat inputs included greater rates of nitrogen (N) fertilizer, urease inhibitor (UI), nitrification inhibitor (NI), plant growth regulator (PGR), foliar micronutrients, and fungicide. Soybean inputs included poultry litter (PL), potassium thiosulfate (KTS), foliar micronutrients, and fungicide. Wheat yield decreased 0.94 Mg ha^{-1} when N rate was reduced within the intensive system and increased 0.75 Mg ha^{-1} when fungicide was added to the traditional system in 2016. Urease inhibitor removal from the 2017 intensive system decreased wheat yield 0.52 Mg ha^{-1} while UI addition to the traditional system decreased wheat yield 0.51 Mg ha^{-1}. Although wheat yield occasionally increased, no single input increased economic net return. Across all site-years, no single input positively affected soybean grain yield or profitability. In the current study, intensive management systems significantly decreased producer economic net return in 6 of 7 site-years. Results suggest producers should expect few benefits from input-intensive management systems without the presence of yield-limiting factors.

Dedicated to my family and friends whom have expressed their love and support along the way.

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CHAPTER 1

LITERATURE REVIEW

Wheat Classification

Wheat classifications are derived from plant physical factors such as the color of the kernel, described as either red or white, and the hardness of the seed, described as either hard or soft (McFall and Fowler, 2009). Michigan wheat production involves soft red and soft white winter wheat varieties used in products such as cereals, pastries, and baked goods (Brown et al., 2018). Soft white winter wheat has similar flour qualities as soft red winter wheat, but is preferred by local millers due to superior flour extraction rates, color, and flavor in whole-grain products (Brown et al., 2018). A 2011 survey determined 60% of Michigan wheat acreage produces soft red and 40% produces soft white (Nagelkirk and Black, 2012).

The majority of wheat breeding programs dedicate more resources to red wheat (Sherman et al., 2008). The color of the kernel outer layer, described as either red or white is controlled by three homoeologous genes located on chromosomes 3A, 3B, and 3D (Mcintosh et al., 1998; Sherman et al., 2008). Red color is dominant to white, with a single locus containing the dominant allele being sufficient enough to result in a red color (Metzger and Silbaugh, 1970; Sherman et al., 2008). Therefore, breeding for three recessive alleles resulting in a white wheat plant is more difficult. (Metzger and Silbaugh, 1970; Sherman et al., 2008). Kernel color genetics cause white wheat breeding difficulties, thus complicating the ability to introduce desirable traits (Sherman et al., 2008).

Seed coat color may also influence the resistance or susceptibility to pre-harvest sprouting (PHS) (Brown et al., 2018). Pre-harvest sprouting of wheat is defined as grain germination prior to harvest and can result in yield and market losses due to decreased grain weight and quality (Groos et al. 2002). Diminished grain characteristics from PHS is influenced by early alpha-amylase activity, which is designated by low falling number (Groos et al. 2002). Seed coat color is considered an important seed dormancy component and is controlled by the red grain color (R) loci (R-A1, R-B1, and R-D1) located on the group 3 chromosomes (Metzger and Silbaugh, 1970; Bassoi and Flintham, 2005). Dominant R genes producing red grain color are directly related to the promotion of dormancy, resulting in an elevated tolerance to PHS (Bassoi and Flintham, 2005).

Michigan Wheat Production

Wheat area harvested in Michigan equaled 230,670 ha in 2016 and 171,991 ha in 2017, totaling 1,380,644 and 913,761 Mg of wheat grain, respectively (NASS, 2017). Total wheat production in Michigan ranked 12th and 15th in the U.S. during 2016 and 2017, respectively (NASS, 2017). However, Michigan growers consistently produce wheat yields that rank in the top five annually in the U.S., with state record yield averages of 5.44 and 5.98 Mg ha^{-1} observed during the 2015 and 2016 growing seasons, respectively (NASS, 2017; Swoish and Steinke, 2017). Awareness of the local yield potential, in combination with spring (Apr. – Jun.) weather volatility has motivated Michigan producers to invest in additional agronomic input applications as insurance against environmental factors that may threaten the high wheat yield potential (Swoish and Steinke, 2017).

Intensive Management

Intensive management relies on prophylactic applications of multiple agronomic inputs to maximize grain yield, contrasting to a minimal input, traditional management system that justifies applications utilizing university recommended integrated pest management (IPM) (Beuerlein et al., 1989; Risbey et al., 1999; Rosenzweig et al., 2001; Crane et al., 2011; Mourtzinis et al., 2016). Previous literature involving multiple input applications on wheat suggests grain yield increases only occur in the presence of antagonistic environmental conditions (Beuerlein et al., 1989; Harms et al., 1989; Karlen and Gooden, 1990; Mohammed et al., 1990). Beuerlein et al. (1989) concluded positive input responses are often varietal and environment specific. Mohammed et al. (1990) observed no winter wheat yield benefit to increased N fertilizer, plant growth regulator, and fungicide, due to adequate water availability, short-stature of variety used, mild climatic conditions, and absence of disease pressure. Karlen and Gooden (1990) determined selection of disease resistant wheat varieties with good stem strength often negate the proposed benefits of multiple inputs (Karlen and Gooden, 1990). Harms et al. (1989) concluded intensive management practices increase wheat producer economic risk due to unpredictable input responses. Despite often inconsistent and minimal benefits observed from previous intensive wheat management trials, the age (> 20 yrs.) of previous trial results are suggested as non-applicable to modern wheat production due to the availability of new product chemistries and plant genetics. Therefore, further research is needed to understand recently developed wheat genetic responses to new product chemistries routinely applied in modern production.

Urease Inhibitor

Mitigation of potential N losses resulting in improved N fertilizer management is essential for maximizing wheat yield and N-use efficiency (Raun and Johnson, 1999; Thapa et al., 2015; Mohammed et al., 2016). Nitrogen loss caused by gaseous plant emissions, soil denitrification, surface runoff, volatilization, and leaching, can have negative economic and/or environmental impacts for producers (Raun and Johnson, 1999; Thapa et al., 2015; Mohammed et al., 2016). The urease enzyme reacts with urea through the process of hydrolysis to form NH_3-N and CO_2 (Franzen, 2017). Urease is utilized in plants and microorganisms to manage NH_3-N movement and needs, is resistant to decay, and can continue to function within soil systems following the death of an organism (Franzen, 2017). Ammonia released at or near the soil surface on high-residue, high pH, low cation-capacity, and moist to drying soils has the greatest risk of N loss from volatilization (Franzen, 2017). A urease inhibitor (UI) when applied with urea can delay the process of urea hydrolysis, thus inhibiting N loss through NH_3-N volatilization (Manunza et al., 1999; Turner et al., 2010). One commonly used UI is N-(n-butyl)-thiophosphoric triamide (NBPT), which inhibits the urease reaction with urea (Mohammed et al., 2016; Franzen, 2017). NBPT is effective on soils with a high potential for N volatilization (high pH, coarse textured) and/or inadequate moisture to draw the urea away from vulnerable seedlings to reduce damage from seed-placed N (Olson-Rutz et al., 2011). Spring top-dress applications of urea + NBPT on winter wheat have shown a reduction in NH_3-N losses upwards of 66% when compared to urea alone applications (Engel et al., 2011).

Mckenzie et al. (2010) did not observe a significant wheat yield increase from using NBPT, due to the low risk of urea-N volatilization in the region where the study was performed (Mckenzie et al., 2010). Slaton et al. (2011) observed a 3.1% wheat yield increase when using

NBPT treated urea. Slaton et al. (2011) concluded the use of NBPT to minimize N volatilization losses is beneficial when a suboptimal N rate is applied, or when an optimal N rate is applied under conditions that favor N volatilization (Slaton et al., 2011). NBPT application may be most beneficial in a no-till system, due to consistently greater urease activity caused by greater residue accumulation (Barreto and Westerman, 1989). Although positive responses have been observed, the majority of previous trials have determined positive NBPT yield responses in winter wheat production are often lacking and inconsistent, due to cool soils, elevated precipitation risk, and an overall lack of NH_3-N volatilization conditions present during wheat spring top-dress timings (Mckenzie et al., 2010; Slaton et al., 2011; Mohammed et al., 2016; Rajkovich et al., 2017).

Nitrification Inhibitor

Nitrification inhibitors (NI) delay the bacterial oxidation of NH_4-N to NO_3-N through depressing the activity of *Nitrosomonas* bacteria in the soil (Trenkel, 2010). Negatively charged NO_3-N can be lost through leaching and/or denitrification, therefore prolonging NH_4-N availability within the soil can increase plant N-use efficiency (Trenkel, 2010). However, prolonged NH_4-N retention can increase N volatilization risk (Thapa et al., 2015). Nitrification inhibitor applications are effective during conditions where leaching and/or denitrification losses are sufficient to reduce crop yields (e.g. coarse textured soils watered with irrigation) (Olson-Rutz, 2011). Producers should consider using a NI when delayed N applications are unlikely (Warncke et al., 2009). Commonly used NIs include dicyandiamide (DCD) and nitrapyrin. (Mohammed et al., 2016).

Regardless of placement, Rao (1996) observed increased N availability in no-till wheat and yield increases of 26% for urea treated with DCD and 24% for urea treated with nitrapyrin (Rao, 1996). Mohammed et al. (2016) concluded urea containing a UI produced the greatest wheat yield when an NI was added due to the reduction of multiple N-loss risks, and the slow release and synchronization of fertilizer N with crop N demand (Mohammed et al., 2016). Thapa et al. (2015) observed a wheat yield increase with urea treated with nitrapyrin from 3.24 to 3.35 Mg ha^{-1} when 168 kg N ha^{-1} was applied, but only a 3.17 to 3.18 Mg ha^{-1} yield increase when 146 kg N ha^{-1} was applied, suggesting greater N leaching risk occurs when utilizing higher N rates.

In contrast to observed positive responses, non-significant NI responses in the presence of above average rainfall conditions have been observed in recent literature (Barker and Sawyer, 2017; Franzen, 2017). Barker and Sawyer (2017) did not observe an agronomic benefit from NI application on corn (*Zea Mays* L.) across multiple locations and conditions promoting N-loss due to cool soil temperatures delaying bacterial conversion of NH_4-N to NO_3-N (Barker and Sawyer, 2017). Shammas (1986) concluded nitrification rates drop once soil temperatures are < 15°C. In addition to cool soil temperatures, the specific microencapsulation formulation of nitrapyrin products like Instinct® (Dow Agrosciences, Indianapolis, IN) may contribute to a lack of response (Franzen, 2017). Specific formulation may delay release and reduce concentration of nitrapyrin at any one time during N application, thus inhibiting any positive effects from input application (Franzen, 2017).

Plant Growth Regulator

An important component of an intensive wheat management program is the ability to reduce lodging (Khan and Spilde, 1992). Lodging can significantly reduce wheat grain fill by interfering with the water and nutrient source in the plant (Knapp et al., 1987; Van Sanford et al., 1989; Knapp and Harms, 1998). Pumphrey and Rubenthaler (1983) observed a yield decrease of 23% from lodged wheat as well as a 3-10 kg/hl decrease of test weight. Lodging can also decrease yield due to mechanical harvesting difficulties (Knapp et al. 1987). Plant growth regulators (PGR) are labeled to reduce plant height, resulting in the reduction of lodging, and the preserving of crop yield (Van Sanford et al., 1989; Knapp and Harms, 1998; Swoish and Steinke, 2017).

A common PGR utilized in U.S. wheat production is trinexapac-ethyl [4-(cyclopropyl-α-hydroxymethylene)-3, 5-dioxo-cyclohexanecarboxylic acid ethylester] (TE) (Wiersma et al., 2011). Trinexapac-ethyl inhibits the formation of active gibberellins causing decreased stem elongation and strengthened stem tissues (Rademacher, 2000; Matysiak, 2006). As TE rates increased, Wiersma et al. (2011) observed an increase in straw strength, and a decrease in lodging severity. An application of TE at a rate of 125 g a.i. ha^{-1} decreased plant height by 6%, increased plant erectness by 9%, and increased straw strength by 13%, without causing crop injury, delaying maturity, or affecting yield (Wiersma et al., 2011). Matysiak (2006) observed TE applications at rates of 75 g a.i. ha^{-1} and 125 g a.i. ha^{-1} significantly increase the yield of winter wheat in one year but not the other. Yield increased from 6.32 Mg ha^{-1} to 6.78 Mg ha^{-1} and 6.87 Mg ha^{-1} for the TE rates of 75 g a.i. ha^{-1} and 125 g a.i. ha^{-1}, respectively (Matysiak, 2006). Lodging was also decreased when TE was applied and plant heights averaged 26.6% shorter than untreated plots (Matysiak, 2006).

Plant Growth Regulator and Nitrogen Rate

In Michigan, N fertilizer rates have increased along with grain yield, with some producers suggesting yield gains with 25 to 50% more N than recommended (Swoish and Steinke, 2017). Crook and Ennos (1995) determined additional N fertilizer causes a 20% decrease in stem strength and a 17% decrease in root anchorage strength, thus increasing the risk of lodging. Swoish and Steinke (2017) determined PGR application decreased lodging 50 - 83%

compared to untreated plots, however authors determined lodging was not N rate dependent. Producers utilizing a tall, high-yielding, intensely-managed variety, may benefit from using a PGR, rather than basing the decision solely on greater N rates (Swoish and Steinke, 2017). At the current Kentucky wheat N recommendation (112 kg N ha^{-1}) and at high N rates (168 and 224 kg N ha^{-1}), Knott et al. (2016) determined wheat plant height and peduncle diameter were not significantly different following PGR application. Brinkman et al. (2014) observed little evidence of a PGR affecting the yield of wheat when it was applied to treatments with the highest N rate of 170 kg N ha^{-1}. At seven of the nine sites, no yield effects were shown and yield increases of 0.23 and 0.28 Mg ha^{-1} were observed only at two of the sites (Brinkman et al. 2014). Brinkman et al. (2014) concluded if lodging of the wheat does not occur, yield response from a PGR will not occur.

Fungicide

Fungicides are applied to control fungal diseases of wheat, prevent yield loss, and maximize economic return (Wegulo et al., 2012). Prophylactic application of fungicides, regardless of the presence of disease is a common producer decision, however frequently increases production costs and decreases profitability in the absence of disease (Orlowski et al., 2016; Mourtzinis et al., 2017). Response and profitability of foliar fungicide applications depends on weather conditions, pathogens present, level of pathogen intensity, fungicide efficacy, fungicide cost and rate, fungicide application timing, variety resistance, cultural practices, and the grain price of wheat (Paul et al., 2010; Wegulo et al., 2011). Wegulo et al. (2012) determined average net return of a fungicide applied at the Feekes 6 in a minimal disease year was \$14.50 ha^{-1} whereas during a high disease year, average net return was \$166.20 ha^{-1} (Wegulo et al. 2012). Fungicide use is recommended between the period of wheat flag leaf appearance and the milk stage of grain development to adequately control disease (Lorenz and Cothren, 1989). In North America, there are two major classes of fungicides used for wheat production, the strobilurins and triazoles (Wegulo et al. 2012).

Strobiliruns are classified as quinone outside inhibitors and control fungal activity by interfering with the energy production of the fungal cell (Vincelli, 2002; Wegulo et al., 2012). Strobiliruns inhibit spore germination and early infection, and are effective when applied prophylactically (Vincelli, 2002; Wegulo et al., 2012). Strobilurin fungicides have displayed activity against a wide range of fungi species, as well as plant physiological enhancements such as increased leaf greenness, chlorophyll content, and delayed senescence (Grossman and Retzlaff, 1997; Bartlett et al., 2002). Mourtzinis et al. (2017) reported significant wheat yield increases of 7.4, 10.4, and 16.8% following strobilurin fungicide applications at Feekes 9 during years 2013, 2014, and 2015, respectively despite low disease incidence and severity (Mourtzinis et al. 2017). Physiological benefits including photosynthetic electron transport improvement, delayed leaf senescence, and increased photosynthetic activity have contributed to yield increases from strobilurin fungicide applications under low disease conditions (Gooding et al., 2000; Mourtzinis et al. 2017).

In comparison to strobilurin fungicides, triazole fungicides contain curative activity, move through the plant systemically, and control fungal activity through the inhibition of sterol production (Buchenauer, 1987; Wegulo et al., 2012). Triazole compounds are the largest and most important group of systemic compounds developed for control of crop fungal diseases caused by *Fusarium* spp. (Petit et al. 2012). Application of a triazole fungicide at anthesis can significantly decrease deoxynivalenol (DON) contamination in wheat grain, specifically in environments containing high frequencies of Fusarium head blight (FHB) (Blandino and Reyneri, 2009).

Fusarium head blight is one of the most significant disease problems affecting wheat in the Upper Midwest (McMullen et al., 1997; Jones, 2000). Fusarium head blight is caused primarily by the pathogen *Fusarium graminearum* (Parry et al., 1995). Fusarium head blight causes significant reductions of yield, test weight, seed quality, and price reductions due to damaged kernels and DON contamination (McMullen et al., 1997; Jones and Mirocha, 1999; Jones, 2000). Deoxynivalenol contamination causes significant yield losses due to a decrease in the amount of grain produced, reduction in the grain quality due to lower test weight, and reduction in grain market value (Tuite et al., 1990; Bai and Shaner, 1994; McMullen et al., 1997; Parry et al., 1995; Pirgozliev et al., 2003). Methods of control with crop rotation and tillage have been inadequate (Dill-Macky and Jones, 2000). In addition, complete tillage is not always achievable with recently adopted minimum-till and no-till systems (Almeras et al., 1998; Jones, 2000). In order to obtain effective control of FHB, fungicides are applied directly to the grain head of the wheat plant at the time of anthesis (McMullen et al., 1997).

Jones (2000) determined anthesis treatments of triazole fungicides significantly reduce FHB in the field, the incidence of Fusarium spp.- damaged kernels, and DON concentration in harvested grain (Jones, 2000). Jones (2000) observed yield increases from 2.79 Mg ha^{-1} with no fungicide to 3.27 – 3.42 Mg ha^{-1} with fungicide, with propiconazole producing the highest yield. Deoxynivalenol concentrations were also decreased from 3.8 µg g^{-1} with no fungicide to 1.6 - 2.5 µg g^{-1}, with fungicide, with tebuconazole producing the lowest DON concentration (Jones, 2000). A study containing >100 uniform fungicide trials determined every tested triazole fungicide significantly reduced FHB and DON, with metconazole and prothioconazole consistently being the most effective (Paul et al., 2008). Paul et al. (2008) also concluded a wheat variety containing moderate resistance to FHB provided greater control than a susceptible variety receiving a fungicide application. Therefore, varietal resistance can also be an effective tool to minimize FHB incidence (Paul et al., 2008). D'angelo et al. (2014) reported applications of prothioconazole + tebuconazole and metconazole were able to control FHB and DON incidence adequately when applied up to 6 days after 50% early anthesis. Paul et al. (2010) reported triazole-based fungicides applied at anthesis resulted in a 13 to 15% wheat yield increase and a 2.5 to 2.8% test weight increase. However, the magnitude of the yield increase depends on fungicide active ingredient, wheat variety, and FHB background in the specific area (Paul et al. 2010).

In contrast to triazole fungicides, strobilurin fungicide applications have shown poor control of FHB (Simpson et al., 2001; Blandino and Reyneri, 2009). In addition, strobilurin fungicides can increase DON contamination of wheat grain (Simpson et al., 2001; Blandino and Reyneri, 2009). The increase in DON contamination may be attributed to an increased infection from *Fusarium* spp. as a result of a reduction in *Microdochium nivale*, a pathogen involved in the symptomology of FHB, but not the formation of DON (Simpson et al., 2001; Pirogzliev et al., 2003; Blandino and Reyneri, 2009). Blandino and Reyneri (2009) concluded the addition of a strobilurin when compared to a triazole-only fungicide program at anthesis did not delay senescence of the flag leaf or increase grain yield, however did increase DON contamination.

Fungicide and Nitrogen Fertilizer

Previous trials have reported greater individual input responses under intensive management, suggesting synergy among various intensive technologies (Brinkman et al., 2014; Bluck et al., 2015; Ruffo et al., 2015). Disease control and enhanced fertility programs are two main components of an intensive wheat management program (Oplinger et al., 1985; Beuerlein et al., 1989). Previous research has observed synergistic effects between fungicide applications and increased N fertilizer rates (Kelley, 1993; Brinkman et al., 2014). During environmental conditions favoring high wheat yields, Kelley (1993) determined fungicide application only significantly increased grain yield at the high N rate of 140 kg N ha^{-1}. Brinkman (2014) observed a fungicide yield response of 0.67 Mg ha^{-1} at the low N rate of 100 kg ha^{-1} and a fungicide yield response of 0.97 Mg ha^{-1} at the high N rate of 170 kg N ha^{-1}. Results suggest fungicides applications may result in the greatest and most consistent yield responses when accompanied with high rates of N. (Brinkman et al., 2014). However, synergistic effect may depend on specific environment and variety selection (Kelley, 1993; Brinkman et al., 2014).

Micronutrients

Micronutrients are suggested as being reduced in the soil due to the increased dependence on synthetic fertilizer and increased cropping intensity with higher yielding crops (Dewal and Pareek, 2004). Micronutrient deficiency problems have only recently been recognized due to a rise in intensive crop management systems utilizing elevated use of N, P, and K fertilizers, new and higher yielding varieties, liming to adjust soil pH conditions, and increased use of chemicals to control pests and diseases (Alloway, 2008). Zinc, Mn, B, Fe, Cu, and Mo are classified as the most important micronutrients for plants (Welch et al., 1991). Deficiencies of these nutrients are uncommon, but when they occur yield loss can be significant (Alloway, 2008; White and Edwards, 2008).

In Michigan, micronutrient recommendations are based on soil test, soil pH, and likelihood of crop response at low soil nutrient levels (Warncke et al., 2009). Literature states wheat has a low likelihood of response to the micronutrients B and Zn, and a high likelihood to

Cu and Mn (Warncke et al., 2009; Havlin et al., 2014). Michigan B recommendations are based only on the likelihood of crop response at low nutrient availability (Warncke et al., 2009). Boron tends to be deficient in coarse-textured soils due to leaching (Warncke et al., 2009). Zinc recommendations are based on soil test value and soil pH (Warncke et al., 2009). Michigan soils with a pH < 6.5 typically contain an adequate amount of Zn to meet crop needs (Warncke et al., 2009). Zinc deficiency is likely to occur on the alkaline mineral soils of the lake-bed regions of eastern Michigan and on neutral to alkaline organic soils (Warncke et al., 2009). Manganese availability decreases as soil pH increases (Warncke et al., 2009). Wheat is highly responsive to Mn, therefore soils high in pH or soils following a liming application may express a Mn deficiency (Warncke et al., 2009). In Michigan, Cu is typically not deficient on mineral soils with the exception of highly acidic, sandy soils that have been heavily cropped (Warncke et al., 2009). Soil test values containing > 0.5 ppm Cu are considered adequate for wheat growth (Warncke et al., 2009). Mallarino et al. (2015) determined the greatest possibility for a Cu and Mn deficiency in wheat occurs on acidic, organic, or very sandy soils for Cu and calcareous soils (pH >7.0) for Mn.

Different methods are used to apply micronutrients such as seed priming, soil application, and foliar application, with foliar application being the most effective (Zain et al., 2015). Bameri et al. (2012) reported improved root growth in wheat by foliar applying micronutrients which led to an increase in uptake of macro- and micronutrients. Boorboor et al. (2012) observed an increase in the percentage of seed protein and yield components when micronutrients are foliar applied in barley (*Hordeum vulgare*). Zain et al. (2015) determined maximum wheat height and maximum grain yield was produced from a foliar treatment containing Fe and Mn (Zain et al. 2015). Curtin et al. (2008) observed only a significant wheat yield response to Mn and not B and

Zn on soils deficient in all three nutrients. Gupta et al. (1976) did not observe a significant response from B application on yield of barley and wheat. Korzeniowska (2008) reported grain yield increases between 8.6 to 15.2% from foliar applied B on 4 of 10 wheat varieties, suggesting B response may be variety specific.

With micronutrient application there is a fine line between adequate nutrition and toxicity, therefore applying too much of a certain micronutrient can result in toxic effects to the wheat plant (White and Edwards, 2008). Under Mn deficiency, Ohki (1985) observed top dry weight, net photosynthesis, and total chlorophyll reductions in affected wheat plants, yet excessive Mn in solution also caused reductions of the same physiological factors. Mortvedt and Cox (1985) determined foliar applications of Cu can cause leaf burn, however damage can be minimized by keeping application rates at 0.25 to 0.5 kg Cu ha^{-1}. Paull et al. (1988) observed reductions in both wheat grain yield and total dry matter with increasing concentrations of B in the soil (Paull et al., 1988). Gupta et al. (1976) observed applications of 2.24 and 4.48 kg ha^{-1} of B resulted in reduced grain yield and B toxicity symptoms on the leaves of barley and wheat.

Nitrogen Management

Nitrogen supply is important in nearly all processes of a growing wheat plant and must be available throughout the growing season in order to maximize grain yield and quality (White and Edwards, 2008). Nitrogen fertility is a primary factor in limiting the yield of winter wheat (Nielsen and Halvorson, 1991). Nitrogen is required for root growth, tillering, and the production of chlorophyll (White and Edwards, 2008). Nitrogen also allows for deeper rooting of a winter wheat plant, allowing access to water and nutrients stored deeper in the soil (Brown, 1971). In Michigan, N rate recommendations are based on yield potential of the wheat plant (Warncke et al., 2009). However, unrealistic yield goals can result in excess N applied, causing groundwater contamination, delayed maturity, and/or increased plant lodging risk (Warncke et al., 2009). Despite the risks and lack of research support, producers attempting to further increase wheat yields apply N rates exceeding university recommendations, reporting yield increases with upwards of 25 to 50% more N applied (Knott et al., 2016; Swoish and Steinke, 2017).

When N rate was increased from 100 kg ha^{-1} to 170 kg ha^{-1}, Brinkman et al. (2014) observed a grain yield increase of 0.5 Mg ha^{-1}. Brinkman et al. (2014) also determined as N rate was increased from 100 kg ha^{-1} to 170 kg ha^{-1} the average number of heads per square meter increased from 680 to 720 and the number of kernels per head increased from 27.0 to 29.3 (Brinkman et al., 2014). Mascagani et al. (1997) observed yield increases in wheat of 11.5% for 101 kg N ha^{-1} and only 3.8% for 138 kg N ha^{-1}. Wang et al. (2014) concluded increasing the N fertilizer rate from 120 to 240 kg ha^{-1} did not further increase the grain yield of wheat. Staggenborg et al. (2003) determined maximum wheat yield following grain sorghum required 112 kg N ha^{-1} and 94 kg N ha^{-1}, whereas maximum wheat yield following soybean only required 94 kg N ha^{-1} and 70 kg N ha^{-1}, during 1998 and 1999, respectively (Staggenborg et al. 2003). Higher N requirement was likely due to the increased amount of residue following grain sorghum which may result in more N immobilization as compared to soybean residue (Staggenborg et al., 2003).

Greater N fertility increases above-ground biomass, thus increasing transpiration demands of the wheat plant (Ritchie and Johnson, 1990). If water in the soil is not sufficient, water stress can occur in high-N treatments causing decreased yields (Howell, 1990). Excessive N fertilizer will also increase the probability that a crop will lodge before harvest (Brinkman et al. 2014). Crook and Ennos (1995) determined increasing N from a rate of 160 kg N ha^{-1} to 240 kg N ha^{-1} weakened the stems by 20%, lowered the anchorage strength by 17%, and decreased the total bending strength of coronal root systems as compared to the wheat plants grown with the lower N rate. Literature reports lodging can decrease yields by 23%, reduce test weight, increase harvest losses, reduce the efficiency of harvest, and increase both mycotoxins and foliar diseases of the wheat plant (Pinthus, 1973; Pumphrey and Rubenthaler, 1983; Roth et al., 1984; Mascagni et al., 1997; Olesen et al., 2003; Nakajima et al., 2008).

Roth et al. (1984) reported grain yield decreases at N levels above 34 kg ha^{-1}, due to elevated disease pressure. Mascagni et al. (1997) observed an increase in leaf rust severity as N rate increased. Across all cultivars and environments, leaf rust ratings ranged from 5.8% for 67 kg N ha^{-1} rate to 9.4% for 134 kg N ha^{-1} (Mascagni et al., 1997). Increases in disease is often caused by humid microclimates created due to dense canopies formed near the soil surface by the wheat plant (Tompkins et al., 1992). Nielsen and Halvorson (1991) concluded increased levels of N had the ability to increase both above ground biomass and below ground root growth, thus increasing light interception and soil water availability, and ultimately resulting in greater yields during water stress conditions (Nielsen and Halvorson, 1991). However, increased production of biomass may draw on the products of photosynthesis, leaving little to store as water-soluble carbohydrates for translocation during grain fill (White and Edwards, 2008).

Nitrogen level can also effect micronutrient concentrations in a wheat plant (Wang et al. 2014). Wang et al. (2014) indicated fertilizer N increased the Zn, Fe, and Cu concentrations in the grain and shoot of the wheat plant. Manganese concentrations were increased in the shoot of the wheat plant and decreased in the grain with N fertilization due to the slowed translocation of Mn from vegetative tissue to grain following N fertilization (Wang et al. 2014). In both growing seasons, increasing the N rate from 120 kg ha^{-1} to 240 kg ha^{-1} increased the Zn concentration in the grain and shoot by an extra 30% and 45.8%, respectively (Wang et al. 2014). Doubling the N rate had only an effect on wheat Zn concentrations and not Fe, Cu, and Mn (Wang et al. 2014). Nitrogen nutrition in plants may contribute to the activities of transporter proteins which are significant in facilitating micronutrient translocation from vegetative tissues to grain (Curie et al., 2009; Waters and Sankaran, 2011).

LITERATURE CITED

LITERATURE CITED

Alloway, B.J. 1995. Soil processes and the behavior of metals. In: B.J. Alloway, editor, Heavy metals in soils. Chapman & Hall, London. p. 11-37.

Alloway, B.J. 2008. Micronutrients and crop production: An introduction. In: B.J. Alloway, editor, Micronutrient deficiencies in global crop production. Springer, Netherlands. p. 11-37.

Almeras, R.R., D.E. Wilkins, O.C. Burnside, and D.J. Mulla, 1998. Agricultural technology and adoption of conservation tillage practices. p. 99-158. In: F.J. Pierce and W.W. Frye, editor(s), Advances in soil and water conservation. Ann Arbor Press, Chelsea, MI

Bai, G. and G. Shaner. 1994. Scab of wheat: Prospects for control. Plant Dis. 78:760-766.

Bameri, M., R. Abdolshahi, G. Mohammadi-Nejad, K. Yousefi, and S. M. Tabatabaie. 2012. Effect of different microelement treatment on wheat (*Triticum aestivum*) growth and yield. International Research Journal of Basic and Applied Sciences. 3:219-223.

Barker, D., and J. Sawyer. 2017. Evaluation of nitrogen fertilizer additives for enhanced efficiency in corn on Iowa soils. Crop Forage Turfgrass Manage. 3:1-6.

Barreto, H.J. and R.L. Westerman. 1989. Soil urease activity in winter wheat residue management systems. Soil Sci. Soc. Am. J. 53:1455-1458.

Bartlett, D.W., J.M. Clough, J.R. Godwin, A.A. Hall, M. Hamer, and B. Parr-Dobrzanski. 2002. The strobilurin fungicides. Pest Manage. Sci. 58:649-662.

Bassoi M. C. and J. Flintham. 2005. Relationship between grain colour and preharvest sprouting-resistance in wheat. Pesquisa Agropecuária Brasileira, 40:981-988.

Beuerlein, J.E., E.S. Oplinger, and D. Reicosky. 1989. Yield and yield components of winter wheat cultivars as influenced by management – A regional study. J. Prod. Agric. 2:257-261.

Blandino, M., and A. Reyneri. 2009. Effect of fungicide and foliar fertilizer application to winter wheat at anthesis on flag leaf senescence, grain yield, flour bread-making quality, and DON contamination. Europ. J. Agron. 30:275-282.

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

Boorboor, M.R., D. Eradatmand Asli, and M. Tehrani. 2012. The effect of dose and different methods of iron, zinc, manganese and copper application on yield components, morphological traits and grain protein percentage of barley plant (*Hordeum vulgare* L.) in greenhouse conditions. J. Adv. Environ. Biol. 6:740-746.

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

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

Brown, P.L. 1971. Water use and soil water depletion by dryland winter wheat as affected by nitrogen fertilization. Agron. J. 63:43-46.

Buchenauer, H. 1987. Mechanism of action of triazolyl fungicides and related compounds. p. 205-231. In: H. Lyr, editor, Modern selective fungicides: properties, applications, mechanisms of action. Wiley, New York, NY.

Bulman, P. and L.A. Hunt 1988. Relationships among tillering, spike number and grain yield in winter wheat (Triticum aestivum L.) in Ontario. Can. J. Plant Sci. 68:583-596.

Curie, C., G. Cassin, D. Couch, F. Divol, K. Higuchi, and M. L. Jean et al. 2009. Metal movement within the plant: contribution of nicotianamine and yellow stripe 1-like transporters. Ann. Bot. (Lond.) 103:1–11.

Curtin, D., R.J. Martin, and C.L. Scott. 2008. Wheat (Triticum aestivum) response to micronutrients (Mn, Cu, Zn, B) in Canterbury, New Zealand. New Zealand J. Crop Hort. Sci. 36:169-181.

Crook, M.J., and A.R. Ennos. 1995. The effect of nitrogen and growth regulators on stem and root characteristics associated with lodging in two cultivars of winter wheat. J. Exp. Bot. 46:931-938.

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

D’Angelo, D.L., C.A. Bradley, K.A. Ames, K.T. Willyerd, L.V. Madden, and P.A. Paul. 2014. Efficacy of fungicide applications during and after anthesis against Fusarium head blight and deoxynivalenol in soft red winter wheat. Plant Dis. 98:1387-1397.

Dewal, G.S. and R.G. Pareek. 2004. Effect of phosphorus, sulphur and zinc on growth, yield and nutrient uptake of wheat (Triticum aestivum L.). Indian J. Agron. 49:160-162.

Dill-Macky, R. and R.K. Jones. 2000. The effect of previous crop residues and tillage on Fusarium head blight of wheat. Plant Dis. 84:71-76.

Engel R., C. Jones, and R. Wallander. 2011. Ammonia volatilization from urea mitigation by NBPT following surface application to cold soils. Soil Sci. Soc. Am. J. 75:2348-2357.

Franzen, D.W. 2017. Nitrogen extenders and additives for field crops. SF1581. North Dakota State Univ. Ext. Fargo, ND.

Gooding, M.J., J.P.R.E. Dimmock, J. France, and S.A. Jones. 2000. Green leaf area decline of wheat flag leaves: the influence of fungicides and relationships with mean grain weight and grain yield. Ann. Appl. Biol. 136:77-84.

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

Grossman, K., and G. Retzlaff. 1997. Bioregulatory effects of the fungicidal strobilurin kresoxim-methyl in wheat (*Triticum aestivum*). Pestic. Sci. 50:11-20.

Gupta, U.C., J.A. MacLeod, and J.D.E. Sterling. 1976. Effects of boron and nitrogen on grain yield and boron and nitrogen concentrations of barley and wheat. Soil Sci. Soc. Am. J. 40:723-726.

Halvorson, A.D., M.M. Alley, and L.S. Murphy. 1987. Nutrient requirements and fertilizer use. Wheat and wheat improvement. p. 345-383.

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

Havlin, J.L., S.L. Tisdale, J.D. Beaton, and W.L. Nelson. 2014. Soil fertility and fertilizers: An introduction to nutrient management 8^{th} ed. Upper Saddle River, New Jersey, Pearson Prentice Hall.

Himi, E., D.J. Mares, A. Yanagisawa, and K. Noda. 2002. Effect of grain colour gene (R) on grain dormancy and sensitivity of the embryo to abscisic acid (ABA) in wheat. J. Exp. Bot. 53:1569-1574.

Howel, T.A., 1990. Relationships between crop production and transpiration, evapotranspiration, and irrigation. In: B.A. Stewart and D.R. Nielsen, editor(s), Irrigation of agricultural crops. Agron. Monogr. 30. ASA, CSSA, SSSA, Madison, WI. p. 391-434.

Hughes, K.R., C.A. Griffey, D.J. Parrish, W.E. Barbeau, E. Souza, and W.E. Thomason. 2010. Preharvest sprouting tolerance in current soft red winter wheat cultivars. Crop Sci. 50:1449-1457.

Jacobsen, B. J. 1977. Effect of fungicides on Septoria leaf and glume blotch, Fusarium scab, grain yield, and test weight of winter wheat. Phytopathology. 67:1412-1414.

Jones, R. K. 2000. Assessments of Fusarium head blight of wheat and barley in response to fungicide treatment. Plant Dis. 84:1021-1030.

Jones, R. K., and C. J. Mirocha. 1999. Quality parameters in small grains from Minnesota affected by Fusarium head blight. Plant Dis. 83:506-511.

Karlen, D.L., and D.T. Gooden. 1990. Intensive management practices for wheat in the southeastern coastal plains. J. Prod. Agric. 3:558-563.

Kelley, K.W. 1993. Nitrogen and foliar fungicide effects on winter wheats. J. Prod. Agric. 6:53-57.

Kelley, K.W. 2001. Planting date and foliar fungicide effects on yield components and grain traits of winter wheat. Agron. J. 93:380-389.

Khan, A., and L. Spilde. 1992. Response of hard red spring wheat genotypes to management systems. Crop Sci. 32:206–212

Knapp, J.S., and C.L. Harms. 1988. Nitrogen fertilization and plant growth regulator effects on yield and quality of four wheat cultivars. J. Prod. Agric. 1:94–98.

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

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

Korzeniowska, J. 2008. Response of ten winter wheat cultivars to boron foliar application in a temperate climate (South-West Poland). Agron. Res. 6:471-476.

Lorenz, E.J., and J.T. Cothren. 1989. Photosynthesis and yield of wheat (*Triticum aestivum*) treated with fungicides in a disease-free environment. Plant Dis. 73:25-27.

Mallarino, A.P., J.J. Camberato, D.E. Kaiser, C.A.M. Laboski, D.A. Ruiz-Diaz, and T.J. Vyn. 2015. Micronutrient fertilization for corn and soybean: A research update. North-Central Extension-Industry Soil Fertility Conference, Vol. 31. Des Moines, IA.

Manunza, B., S. Deiana, M. Pintore, and C. Gessa. 1999. The binding mechanism of urea, hydroxamic acid and N-(N-butyl)-phosphoric triamide to the urease active site. A comparative molecular dynamics study. Soil Biol. Biochem. 31:89-796.

Mascagni, H.J., Jr., S.A. Harrison, J.S. Russin, H.M. Desta, P.D. Colyer, and R.J. Habetz et al. 1997. Nitrogen and fungicide effects on winter wheat produced in the Louisiana Gulf Coast region. J. Plant Nutr. 20:1375–1390.

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

McKenzie, R.H., A.B. Middleton, P.G. Pfiffner, and E. Bremer. 2010. Evaluation of polymer-coated urea and urease inhibitor for winter wheat in southern Alberta. Agron. J. 102:1210-1216.

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

McFall, K.L., and M.E. Fowler. 2009. Overview of wheat classification and trade. Wheat Sci. Trade. p. 437-454.

McIntosh, R.A., G.E. Hart, K.M. Devos, M.D. Gale, and W. J. Rogers 1998. Catalogue of gene symbols for wheat. In: A.E. Slinkard, editor, Proc. 9th Inter. Wheat Genet. Symp., Vol. 5. University Extension Press, University of Saskatchewan, Canada.

McMullen, M.P., R.K. Jones, and D.J. Gallenberg. 1997. Scab of wheat and barley: A re-emerging disease of devastating impact. Plant Dis. 81:1340-1348.

Mohamed, M.A., J.J. Steiner, S.D. Wright, M.S. Bhangoo, and D.E. Millhouse. 1990. Intensive crop management practices on wheat yield and quality. Agron. J. 82:701–707

Mohammed, Y.A., C. Chen, and T. Jensen. 2016. Urease and nitrification inhibitors impact on winter wheat fertilizer timing, yield, and protein content. Agron. J. 108:905-912.

Mortvedt, J.J. and F.R. Cox. 1985. Production, marketing, and use of calcium, magnesium, and micronutrient fertilizers. In O.P. Engelstad, editor, Fertilizer Technology and Use. SSSA, Madison, WI. p. 455-481.

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

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

Nagelkirk, M. 2012. Winter wheat planting recommendations. MSUENews. Michigan State University Ext. http://msue.anr.msu.edu/news/winter_wheat_planting_recommendations (accessed 5 Jan. 2016)

Nagelkirk, M., and R. Black. 2012. Wheat varieties used in Michigan. Michigan State Univ. Ext., East Lansing, MI. http://msue.anr.msu.edu/news/wheat_varieties_used_in_michigan (accessed 11 Nov. 2017).

Nagelkirk, M., and M. Chilvers. 2016. Managing fusarium head blight. Michigan State Univ. Ext., East Lansing, MI. msue.anr.msu.edu/uploads/234/89014/disease/Managing_Fusarium_Head_Blight.pdf (accessed 15 Aug. 2017).

Nakajima, T., M. Yoshida, and K. Tomimura. 2008. Effect of lodging on the level of mycotoxins in wheat, barley, and rice infected with the Fusarium graminearum species complex. J. Gen. Plant Pathol. 74:289–295.

National Agricultural Statistics Service. 2017. USDA-NASS agricultural statistics 2017. USDA-NASS. http://www.nass.usda.gov (accessed 8. April. 2017).

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

Ohki, K. 1985. Manganese deficiency and toxicity effects on photosynthesis, chlorophyll, and transpiration in wheat. Crop Sci. 25:187-191.

Olesen, J.E., L.N. Jørgensen, J. Petersen, and J.V. Mortensen. 2003. Effects of rate and timing of nitrogen fertilizer on disease control by fungicides in winter wheat. 2. Crop growth and disease development. J. Agric. Sci. 140:15–29.

Olson-Rutz, K., C. Jones, and C.P. Dinkins. 2011. Enhanced efficiency fertilizers. EB0188. Montana State University Ext., Bozeman, MT.

Oplinger, E.S., D.W. Wiersma, C.R. Grau, and K.A. Kelling. 1985. Intensive wheat management. A3337. Univ. of Wisconsin Ext., Madison, WI.

Orlowski, J.M., B.J. Haverkamp, R.L. Laurenz, D.A. Marburger, E.W. Wilson, S.N. Casteel, S.P. Conley, S.L. Naeve, E.D. Nafzinger, K.L. Roozeboom, W.J. Ross, K.D. Thelen, and C.D. Lee. 2016. High-input management systems effect on soybean seed yield, yield components, and economic break-even probabilities. Crop Sci. 56:1988-2004.

Parry, D.W., P. Jenkinson, and L. McLeod. 1995. Fusarium ear blight (scab) in small grain cereals–a review. Plant Pathol. 44:207-238.

Paul, P.A., P.E. Lipps, D.E. Hershman, M.P. McMullen, M.A. Draper, and L.V. Madden. 2007. A quantitative review of tebuconazole effect on Fusarium head blight and deoxynivalenol content in wheat. Phytopathology. 97:211-220.

Paul, P.A., P. E. Lipps, D. E. Hershman, M. P. McMullen, M. A. Draper, and L. V. Madden. 2008. Efficacy of triazole-based fungicides for Fusarium head blight and deoxynivalenol control in wheat: A multivariate meta-analysis. Phytopathology. 98:999-1011.

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

Paull, J.G., B. Cartwright, and A.J. Rathjen. 1988. Responses of wheat and barley genotypes to toxic concentrations of soil boron. Euphytica. 39:137-144.

Pennington, D., J. DeDecker, and M. Nagelkirk. Intensive wheat management. Michigan State Univ. Ext., East Lansing, MI http://msue.anr.msu.edu/news/intensive_wheat_management (accessed 15. Aug. 2017).

Petit, A., F. Fontaine, P. Vatsa, C. Clement, and N. Vaillant-Gaveau. 2012. Fungicide impacts on photosynthesis in crop plants. Photosynth. Res. 111:315-326.

Pinthus, M.J. 1973. Lodging in wheat, barley, and oats. The phenomenon, its causes, and preventative measures. Adv. Agron. 25:209–256.

Pirgozliev, S.R., S.G. Edwards, M.C. Hare, and P. Jenkinson. 2003. Strategies for the control of Fusarium head blight in cereals. Eur. J. Plant Pathol. 109:731-742.

Pumphrey, F.V. and G.L. Rubenthaler. 1983. Lodging effects on yield and quality of soft white wheat. Cereal Chem. 60:268-270.

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

Rajkovich, S., D. Osmond, R. Weisz, C. Crozier, D. Israel, and R. Austin. 2017. Evaluation of nitrogen-loss prevention amendments in maize and wheat in North Carolina. Agron. J. 109:1-14.

Rao, S.C. 1996. Evaluation of nitrification inhibitors and urea placement in no-tillage winter wheat. Agron. J. 88:904-908.

Raun, W.R. and G.V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. Agron. J. 91:357-363.

Risbey, J., M. Kandlikar, H. Dowlatabadi, and D. Graetz. 1999. Scale context and decision making in agricultural adaptation to climate variability and change. Mitigation and Adaption Strategies for Global Change. 4:137-165.

Ritchie, J.T. and B.S. Johnson. 1990. Soil and plant factors affecting evaporation. Agron. 30:363-390.

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

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

Ruffo, M.L., L.F. Gentry, A.S. Henninger, J.R. Seebauer, and F.E. Below. 2015. Evaluating management factor contributions to reduce corn yield gaps. Agron. J. 107:495-505.

Shammas, N.K. 1986. Interactions of temperature, pH, and biomass on the nitrification process. Water Pollution Control Federation. 58:52-59.

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

Simpson, D.R., G.E. Weston, J.A. Turner, P. Jennings, and P. Nicholson. 2001. Differential control of head blight pathogens of wheat by fungicides and consequences for mycotoxin contamination of grain. Eur. J. Plant Path. 107:421-431.

Slaton, N.A., R.J. Norman, and J. Kelley. 2011. Winter wheat yield response to a urea amended with a urease inhibitor and fertilization time. Crop Manage. doi:10.1094/CM-2011-0126-01-RS

Staggenborg, S.A., Whitney, D.A., Fjell, D.L., & Shroyer, J.P. 2003. Seeding and nitrogen rates required to optimize winter wheat yields following grain sorghum and soybean. Agron. J. 95:253-259.

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

Thapa, R., A. Chatterjee, J. M. Johnson, and R. Awale. 2015. Stabilized nitrogen fertilizers and application rate influence nitrogen losses under rainfed spring wheat. Agron. J. 107:1885-1894.

Tompkins, D.K., D.B. Fowler, and A.T. Wright. 1992. Influence of agronomic practices on canopy microclimate and septoria development in no-till wheat produced in the Parkland region of Saskatchewan. Can. J. Plant Sci. 72:965–972.

Torada, A., and Y. Amano. Effect of seed coat color on seed dormancy in different environments. Euphytica, 126:99-105.

Trenkel, M.E. 2010. Slow- and controlled-release and stabilized fertilizers: An option for enhancing nutrient use efficiency in agriculture. 2nd ed. Int. Fert. Assoc., Paris.

Tuite, J., G. Shaner, and R.J. Everson. 1990. Wheat scab in soft red winter wheat in Indiana in 1986 and its relation to some quality measures. Plant Dis. 74:959-962.

Turner, D.A., R.B. Edis, D. Chen, J.R. Freney, O.T. Denmead, and R. Christie. 2010. Determination and mitigation of ammonia loss from urea applied to winter wheat with N-(n-butyl) thiophosphorictriamide. Agric. Ecosyst. Environ. 137:261-266.

CHAPTER 2

SOFT RED AND WHITE WINTER WHEAT RESPONSE TO INPUT-INTENSIVE MANAGEMENT

Abstract

Record grain yields and climate variability have increased producer interest for intensive (i.e., high-input) wheat (*Triticum aestivum* L.) management. The objective of this trial was to investigate soft winter wheat response to several agronomic inputs across intensive and traditional (i.e., low-input) management systems. A four site-year trial was established at Richville and Lansing, MI during 2015 and 2016 to evaluate the following inputs: higher rates of nitrogen (N) fertilizer, urease inhibitor (UI), nitrification inhibitor (NI), fungicide, plant growth regulator (PGR), and foliar micronutrients. Across four site-years, intensive management did not increase yield compared to traditional management. In addition, traditional management increased average economic net return by \$221 ha^{-1}. With a reduced N rate, Richville 2016 yield decreased 0.94 Mg ha^{-1} within the intensive system, suggesting greater N demand with intensive management. Due to significant Lansing 2016 stripe rust (*Puccinia striiformis* f. sp. *tritici*), fungicide addition to the traditional system increased yield 0.75 Mg ha^{-1}. Lansing 2017 yield decreased 0.52 Mg ha^{-1} when UI was removed from the intensive system, yet decreased 0.51 Mg ha^{-1} when UI was added to the traditional system. Heavy rainfall, lack of urea hydrolysis, and N rate likely contributed to the inconsistent UI response. The 2016 and 2017 growing seasons produced an overall absence of adverse environmental conditions which influenced negligible input responses. Although yield increases were observed, no single input increased net return.

Results suggest intensive management benefits are unlikely at current wheat prices and without the presence of yield-limiting factors.

Introduction

Interest in maximizing wheat grain yield continues to increase due to consecutive record yield averages of 5.44 and 5.98 Mg ha^{-1} produced during the 2015 and 2016 Michigan growing seasons, respectively (NASS, 2017; Swoish and Steinke, 2017). Additionally, increased awareness of climate variability combined with soil spatial inconsistencies has motivated producers to maximize grain yield by adopting more intensive wheat management systems (Rosenzweig et al., 2001; Kravchenko et al., 2005; Crane et al., 2011; Swoish and Steinke, 2017). Intensive management commonly involves prophylactic applications of multiple inputs as a form of risk insurance (Mourtzinis et al., 2016). In contrast, traditional management involves minimal input applications justified utilizing university recommended integrated pest management (IPM) practices (Marburger et al., 2016; Mourtzinis et al., 2016). Recent studies have examined wheat response to commonly marketed inputs including additional N fertilizer, urease inhibitor, nitrification inhibitor, plant growth regulator, foliar micronutrients, and fungicide (Paul et al., 2010; Wang et al. 2015; Knott et al., 2016; Mohammed et al., 2016; Swoish and Steinke, 2017). However, few studies exist investigating wheat grain yield and profitability in response to multiple inputs applied individually and in combination across intensive and traditional management systems.

Over time, N fertilizer application rates have risen simultaneous with gains in grain yield (Swoish and Steinke, 2017). Michigan growers continue to report significant grain yield increases with 25 to 50% more applied N than recommended despite multiple university trials observing a lack of increased grain yield and N use efficiency from greater N application rates (Kanampiu et al., 1997; Knott et al., 2016; Mourtzinis et al., 2017; Swoish and Steinke, 2017). Nitrogen fertilizer was identified as the single most important input to maximize wheat yield (Nielsen and Halvorson, 1991; White and Edwards, 2008) with growers often perceiving yield loss from under-application as a greater risk than the cost of over-application (Mourtzinis et al., 2017; Rutan and Steinke, 2017). However, excessive N applications have been shown to increase disease pressure, plant lodging, and N leaching causing ground water contamination (Kanampiu et al., 1997; Warncke et al., 2009; Brinkman et al., 2014). Producers continue to increase N rates for maximum wheat yield and in doing so may further increase the need for additional inputs to mitigate otherwise preventable risks from greater N (Knapp and Harms, 1988; Knott et al., 2016; Salgado et al., 2017; Swoish and Steinke, 2017).

Mitigation of potential N losses is essential for maximizing wheat grain yield and nutrient efficiency (Raun and Johnson, 1999; Mohammed et al., 2016). Michigan growers often utilize spring (i.e., March - April) top-dress applications of N using surface-applied urea or urea ammonia nitrate (UAN) which can enhance NH_3-N volatilization losses further inhibiting N availability and uptake (Terman, 1979; Warncke et al., 2009; Warncke and Nagelkirk, 2010). Urease inhibitors (e.g., N-(n-butyl)-thiophosphoric triamide (NBPT)) are often applied with top-dressed urea or UAN applications to delay NH_3-N volatilization and improve the functionality of urea-based fertilizers (Mohammed et al., 2016). Early spring applied urea + NBPT applied to winter wheat has shown nearly a 66% reduction in NH_3-N losses and a 3.1% increase in grain yield when compared to urea without NBPT (Engel et al., 2011; Slaton et al., 2011). However, NBPT can also be detrimental to wheat growth due to increased incidence of urea leaching and

NH_4-N toxicity (Joo et al., 1991; Dawar et al., 2002; Britto and Kronzucker, 2011). Positive NBPT yield responses are often inconsistent and not widely reported due to cool soil temperatures, increased precipitation frequency, or lack of NH_3-N volatilization conditions during winter wheat spring N application timings (Mckenzie et al., 2010; Grant, 2014; Mohammed et al., 2016; Rajkovich et al., 2017).

In addition to N loss from NH_3-N volatilization, soil bacterial oxidation of NH_4-N to NO_3-N can result in leaching and/or denitrification N losses (Mohammed et al., 2016; Franzen, 2017). Winter wheat spring N applications in Michigan have greater risk of leaching and/or denitrification due to spring weather volatility (Warncke et al., 2009; Steinke and Bauer, 2017). Nitrification inhibitors, (e.g., nitrapyrin [2-chloro-6-(trichloromethyl) pyridine]) can be added with urea or UAN to inhibit the conversion of NH_4-N to NO_3-N thereby reducing the risk of leaching and/or denitrification and allowing larger quantities of N to remain higher in the root zone (Warncke et al., 2009; Trenkel, 2010). In Canada, spring urea-based fertilizer applications containing nitrapyrin resulted in larger pools of NH_4-N for at least 8 weeks after treatment and increased total N by 25% as compared to untreated N fertilizer (Degenhardt et al., 2016). Rao (1996) and Mohammed et al. (2016) observed a 7 - 24% and 5 - 17 % increase in wheat yield, respectively, following incorporation of nitrapyrin onto urea-based fertilizers. However like NBPT, yield responses are often inconsistent as yield increases from nitrapyrin applications are only expected in the presence of climatic N loss conditions (Liu et al., 1984; Barker and Sawyer, 2017; Franzen, 2017; Steinke and Bauer, 2017; Sassman et al., 2018).

Greater than recommended N fertilizer rates, often associated with intensive management, combined with high wind speeds and frequency from spring weather volatility can increase the incidence of plant lodging prior to harvest (Brinkman et al., 2014; Knott et al., 2016;

Swoish and Steinke, 2017; Kleczewski and Whaley, 2018). Plant lodging can interfere with plant water and nutrient uptake, increase mechanical harvest difficulties, and reduce grain fill and yield. (Knapp et al., 1987; Knapp and Harms, 1988; Van Sanford et al., 1989). Plant growth regulators have proven successful in the shortening of plant height resulting in reduced lodging incidence and crop loss (Knapp and Harms, 1988; Van Sanford et al., 1989). Trinexapac-ethyl (TE) {ethyl 4-[cyclopropyl (hydroxyl) methylene]-3, 5-dioxocyclohexane-1-carboxylate} is a PGR labelled to decrease plant height and therefore reduce lodging susceptibility caused by wind damage (Rademacher, 2000; Swoish and Steinke, 2017). Trinexapac-ethyl inhibits the formation of active gibberellins resulting in decreased stem elongation and stronger stem tissues (Rademacher, 2000; Matysiak, 2006). In Michigan, TE applications decreased lodging 50 - 83% and increased grain yield by 5% suggesting TE may be a beneficial risk management tool for high yielding, intensively managed wheat (Swoish and Steinke, 2017). In contrast, Kleczewski and Whaley (2018) observed no significant yield response to TE application due to the absence of lodging. Recent literature suggests wheat response to PGR application may be dependent upon lodging occurrence, environmental conditions, and varietal characteristics including plant height and stem strength (Brinkman et al., 2014; Knott et al., 2016; Kleczewski and Whaley, 2018).

Perceived increased occurrence of plant tissue micronutrient deficiencies has raised grower interest in foliar micronutrient applications for intensively managed systems (Sutradhar et al., 2017). The increased use of synthetic fertilizers, new and greater yielding crop genetics, and liming to increase soil pH have all been suggested to decrease soil micronutrient concentrations and availability (Alloway, 2008). Michigan micronutrient recommendations are based on soil test, soil pH, and crop responsiveness at low micronutrient availability (Vitosh et al., 1995; Warncke et al., 2009). Greater emphasis has been placed on B, Mn, and Zn deficiencies throughout Michigan field crops generating grower interest in foliar applications of these specific nutrients to correct perceived deficiencies (Vitosh et al., 1995; Warncke et al., 2009). In B, Mn, and Zn-deficient New Zealand soils, wheat grain yield was increased following Mn application but not Zn or B (Curtin et al., 2015). Wheat grain yield was also not increased in China or Canada following Zn or B application to soils deficient in each nutrient (Gupta et al., 1976; Lu et al., 2012; Wang et al., 2015). University guidelines suggest wheat as responsive to Mn but non-responsive to B and Zn, suggesting that only a Mn application is warranted on deficient soils (Vitosh et al., 1995; Warncke et al., 2009). Local Midwest research documenting wheat response to applications of B, Mn, and Zn is scarce, suggesting further research is needed to understand wheat response to micronutrient applications.

Intensive management practices often incorporate fungicide application to control disease and prevent yield loss (Beuerlein et al., 1989; Mourtzinis et al., 2017). Fusarium head blight (FHB) (*Fusarium graminearum*) affects wheat yield potential and grain quality across both soft red and soft white winter wheat production in Michigan (McMullen et al., 1997; Jones, 2000; Nagelkirk and Chilvers, 2016). Environmental conditions including frequent rainfall, high relative humidity, or heavy dew coinciding with anthesis and grain fill favors disease development (McMullen et al., 1997). Fusarium head blight infection can result in grain yield reductions through discolored and/or shriveled kernels and reduced marketability when deoxynivalenol (DON) mycotoxin concentrations exceed 1 mg kg^{-1} and 2 mg kg^{-1} for Michigan soft white and soft red winter wheat, respectively (McMullen et al., 1997; Jones and Mirocha, 1999; Jones, 2000; Nagelkirk and Chilvers, 2016). Previous research from >100 fungicide efficacy trials determined triazole-based fungicide applications including prothioconazole {2-[2-(1-chlorocyclopropyl0-3-(2-chlorophenyl)-2-hydroxypropyl]-1, 2-dihydro-3H-1, 2, 4-triazole-3-

thione} and tebuconazole {alpha-[2-(4-chlorophenyl)ethyl]-alpha-(1,1-dimethylethyl)-1H-1, 2, 4-triazole-1-ethanol} significantly reduced FHB severity, increased grain yield, and reduced DON contamination when applied directly to the grain head during anthesis (Paul et al., 2008). Deoxynivalenol content reductions upwards of 57% and 18-23% increases in grain yield have been observed following triazole fungicide application (Beyer et al. 2006; Blandino et al. 2006; Paul et al. 2010). However, frequency of positive fungicide response will depend upon varietal resistance, climatic conditions, and pathogen presence during wheat heading through kernel ripening (Blandino et al., 2006; Paul et al., 2010).

The objectives of this trial were to investigate soft red and soft white winter wheat grain yield and economic net return in response to high-N fertilizer, urease inhibitor, nitrification inhibitor, plant growth regulator, fungicide, and foliar micronutrient applications across intensive (i.e. high-input) and traditional (i.e. low-input) production systems. An omission trial design, previously used in Midwest corn (*Zea Mays* L.) and soybean research to evaluate specific intensive management factors (Bluck et al., 2015; Ruffo et al., 2015), was used to determine whether the elimination of a specific input from an intensive management system or the introduction of a specific input into a traditional management system significantly affected grain yield or economic return.

Materials and Methods

Soft Red Winter Wheat (SRWW) field trials were conducted at the South Campus Research Farm in Lansing, MI. (42°42’37.0”N, 84°28’14.6”W) on a Capac loam soil (fine-loamy, mixed, active, mesic Aquic Glossudalfs). Pre-plant soil characteristics (0-20 cm) included 6.4 - 7.0 pH (1:1 soil/water) (Peters et al., 2015), 27 - 47 mg kg^{-1} P (Bray-P1) (Frank et al., 2015), 85 - 94 mg kg^{-1} K (ammonium acetate method) (Warncke and Brown, 2015), 0.6 - 2 mg kg^{-1} B (hot-water extraction) (Watson, 1998), 36 - 37 mg kg^{-1} Mn (0.1 M HCl) (Whitney, 1998) , and 0.4 - 2.1 mg kg^{-1} Zn (0.1 M HCl) (Whitney, 1998). Calcium sulfate (0-0-0-16 N-P-K-S) was broadcast at a rate of 18 kg S ha^{-1} in 2016 and 2017 while muriate of potash (MOP) (0-0-62 N-P-K) was broadcast at a rate of 70 kg K ha^{-1} in 2017 based on soil test. Fields were previously cropped to corn harvested for silage and tilled prior to planting. Soft White Winter Wheat (SWWW) trials were conducted at the Saginaw Valley Research and Extension Center in Richville, MI (43°23’57.3”N, 83°41’49.7”W) on a Tappan-Londo loam soil (fine-loamy, mixed, active, calcareous, mesic Typic Enduaquolls). Pre-plant soil characteristics (0-20 cm) included 6.6 - 7.8 pH, 23 - 46 mg kg^{-1} P, 124 - 150 mg kg^{-1} K, 0.5 - 6 mg kg^{-1} B, 16 - 43 mg kg^{-1} Mn, and 1.2 - 3.6 mg kg^{-1} Zn. Fields received broadcast applied calcium sulfate (0-0-0-16 N-P-K-S) at a rate of 18 kg S ha^{-1} in 2016 and 2017. Fields were previously cropped to dry bean (*Phaseolus vulgaris* L.) and soybean in 2016 and 2017, respectively, and tilled prior to planting. Both Lansing and Richville were non-irrigated and tile-drained.

Locations included twelve-row plots measuring 2.5 m in width by 7.6 m in length with 19.1 cm row spacing. Plots were planted with a Gandy Orbit-Air Seeder coupled with John Deere double disk openers at a plant population of 4.4 million seeds ha^{-1} and arranged in a randomized complete block design with four replications. Soft red winter wheat variety ‘Sunburst’ (Michigan Crop Improvement Assoc., Okemos, MI), a short strawed, high yielding, variety was planted at Lansing on 29 Sept. 2015 and 23 Sept. 2016. Soft white winter wheat variety ‘Jupiter’ (Michigan Crop Improvement Assoc., Okemos, MI), a short strawed, high yielding, variety was planted at Richville on 1 Oct. 2015 and 10 Oct. 2016.

Nitrogen was applied as UAN (28-0-0) utilizing a backpack sprayer equipped with streamer bars (Chafer Machinery Ltd, Upton, UK) at the Feekes 3 growth stage. Traditional management system N rates were based on Michigan State University recommendations for the Lansing and Richville locations. Traditional N rate treatments consisted of 100.9 kg N ha^{-1} and 134.5 kg N ha^{-1} for SRWW and SWWW, respectively. Intensive N rate treatments consisted of a 20 percent increase from traditional N rates (121.1 kg N ha^{-1} and 161.4 kg N ha^{-1} for SRWW and SWWW, respectively). Urease inhibitor (Agrotain Advanced, N-(n-butyl)-thiophosphoric triamide (NBPT) [1.04 ml kg^{-1} UAN]; Koch Agronomic Services LLC, Wichita, KS) and nitrification inhibitor (Instinct II, nitrapyrin [2-chloro-6-(trichloromethyl) pyridine] [2.7 L ha^{-1}]; Dow Agrosciences, Indianapolis, IN) were applied with UAN at Feekes 3. Foliar micronutrient fertilizer (Max-In Ultra ZMB, 4% Zn (EDTA), 3% Mn (EDTA), 0.1% B (boric acid) [4.7 L ha^{-1}]; Winfield United LLC, St. Paul, MN) and plant growth regulator (Palisade EC, Trinexapac-ethyl [0.8 L ha^{-1}]; Syngenta Crop Protection, Cambridge, UK) were applied at Feekes 6 using a backpack sprayer calibrated at 140.3 L ha^{-1} with Teejet XR8002 nozzles (Teejet Technologies, Wheaton, IL). Fungicide (Prosaro 421 SC, prothioconazole {2-[2-(1-chlorocyclopropyl0-3-(2-chlorophenyl)-2-hydroxypropyl]-1, 2-dihydro-3H-1, 2, 4-triazole-3-thione} and tebuconazole {alpha-[2-(4-chlorophenyl)ethyl]-alpha-(1,1-dimethylethyl)-1H-1, 2, 4-triazole-1-ethanol}[0.6 L ha^{-1}]; Bayer CropScience Research Triangle Park, NC) was applied at Feekes 10.5.1 using a backpack sprayer calibrated at 140.3 L ha^{-1} with Teejet tt11002 nozzles (Teejet Technologies, Wheaton, IL). Inputs applied simultaneously at the same growth stage were tank-mixed.

Omission treatment design was used to determine specific input responses (Table 2.01). The omission design utilized two treatment controls, one containing all applied inputs (i.e., intensive management strategy) and one containing none of the applied inputs (i.e., traditional management strategy) (Bluck et al., 2015; Ruffo et al., 2015). To evaluate individual input effects, inputs removed from the intensive management system were compared only to the intensive management control and inputs added into the traditional management system were only compared with the traditional management control (Bluck et al., 2015; Ruffo et al., 2015).

Average monthly temperature and total cumulative precipitation were recorded throughout the growing season and obtained from Michigan State University Enviro-weather (Michigan State University, East Lansing, MI). Temperature and precipitation 30-year means were obtained from the National Oceanic and Atmospheric Administration (NOAA, 2017). Flag leaf tissue samples for Zn, Mn, and B concentrations and mean plant height were collected at Feekes 9 and Feekes 10.5.4, respectively. Visual estimates of percent flag leaf area affected by foliar disease and/or percent grain heads affected by FHB were taken two and three weeks after fungicide application.

Grain yield was harvested from the center 1.2 m of each plot utilizing a small-plot combine (Almaco, Nevada, IA) on 11 July 2016 and 9 July 2017 at Lansing and 12 July 2016 and 17 July 2017 at Richville and adjusted to 135 g kg^{-1} moisture. Grain sub-samples were collected from each plot and sent to the U.S. Wheat and Barley Scab Initiative mycotoxin testing laboratory (University of Minnesota, St. Paul, MN) and evaluated for DON quantification. Due to the susceptibility of SWWW variety ‘Jupiter’ to pre-harvest sprouting (Brown et al., 2017), additional grain samples were taken from SWWW plots and evaluated for alpha-amylase activity and pre-harvest sprouting incidence. Falling number procedure (Perten Instruments, Springfield, IL) was used to determine alpha-amylase activity of SWWW flour and determine sprout damage.

Economic profitability was assessed using input cost estimates of US\$96.37-153.20, \$13.34-27.70, \$28.91, \$39.14, \$34.60, and \$44.33 ha^{-1} in 2016 and \$90.96-145.55, \$12.60-20.16, \$29.62, \$32.79, \$31.51, and \$43.27 ha^{-1} in 2017 for urease inhibitor, nitrification inhibitor, plant growth regulator, foliar micronutrient, and fungicide, respectively. An additional cost of \$18.53

and \$17.30 ha^{-1} for 2016 and 2017, respectively was incorporated as an application cost for N fertilizer, plant growth regulator, foliar micronutrient, and fungicide. Net returns were calculated by multiplying harvest grain price estimates of \$1.71 and \$1.87 kg^{-1} in 2016 and \$1.86 and \$2.08 kg^{-1} in 2017 for soft red and soft white winter wheat, respectively, by grain yield and subtracting total treatment cost. Product, application, and harvest grain price estimates were taken from local agriculture retailers and grain elevators.

Site years were analyzed separately due to a significant treatment by year interaction. Locations were analyzed separately due to different SRWW and SWWW wheat varieties and locally recommended N rates. Statistical analyses were performed using the GLIMMIX procedure in SAS (SAS Institute, 2012) at $\alpha = 0.10$. Replication was considered a random factor in all experiments with all other factors considered fixed. Single degree of freedom contrasts were used to determine treatment mean separations. Authors could not contrast input responses across both the intensive and traditional management systems due to unequal comparisons regarding treatments containing a specific input and treatments without that input.

Results and Discussion

Environmental Conditions

Growing season (March – July) precipitation differed by -27 and 4% and -9 and 14% from the 30-yr mean during 2016 - 2017 at Richville and Lansing, respectively (Table 2.02). May and June 2016 cumulative rainfall was 68 and 60% below the 30-yr mean for Richville and Lansing, respectively, likely reducing wheat grain yield potential. April 2017 rainfall was 72-82% above 30-yr means at both locations likely resulting in some degree of N loss conditions (e.g., leaching and/or denitrification). March 2016 air temperatures were 3.2 and 4.9°C above average and April 2017 air temperatures were 2.9 and 2.5°C above average at Richville and Lansing, respectively (Table 2.02). May through July mean air temperatures were within 10% of the 30-yr mean across all four site-years. Delayed autumn planting, site-specific soil spatial variability, and winter injury caused by cool February and March air temperatures with minimal snow cover contributed to the below average grain yields observed at Richville during 2017 (Table 2.03).

Intensive vs Traditional Management Systems

Across site-years, locations, and both red and white wheat varieties, grain yield was not significantly different between the intensive management control containing all inputs and the traditional management control containing a recommended rate of N fertilizer (Table 2.03). Intensively-managed wheat resulted in grain yields of 7.02 and 4.34 Mg ha^{-1} at Richville and 5.25 and 6.69 Mg ha^{-1} at Lansing, as compared to 6.85 and 4.34 Mg ha^{-1} at Richville and 5.43 and 6.73 Mg ha^{-1} at Lansing for traditionally-managed wheat during 2016 and 2017, respectively. An overall lack of adverse 2016 – 2017 environmental conditions including N loss, micronutrient deficiency symptoms, plant lodging, and disease pressure resulted in minimal and inconsistent input responses across all site-years. Additionally, SRWW and SWWW grain DON concentration and SWWW falling number is not presented due to a lack of FHB and pre-harvest sprouting incidence across all site-years. Richville 2017 site-specific variability causing a yield coefficient of variation (CV) of 42 % also likely contributed to the lack of significant input responses during the single site-year. However, no additional N loss, micronutrient deficiency symptoms, disease, or plant lodging were observed. Results from the current study are consistent with previous research and support university recommended IPM principles that suggest positive grain yield responses are not associated with specific input applications without the presence of yield-limiting factors (Paul et al., 2010; Wegulo et al., 2012; Knott et al., 2016; Barker and Sawyer, 2017; Rajkovich et al., 2017; Swoish and Steinke, 2017).

Economic Net Return

Across all four site-years, intensive management averaged a \$346 ha^{-1} treatment cost with an average break-even yield of 2.3 Mg ha^{-1} as compared to the \$127 ha^{-1} treatment cost and break-even yield of 0.8 Mg ha^{-1} for traditional management. Traditional management containing only a university recommended N rate significantly increased net return per hectare in three of four site-years compared to intensive management and averaged \$221 ha^{-1} greater across all four site-years (Table 2.04). The 20% greater N rate was the only individual input to significantly increase net return per hectare in 1 of 4 site-years. Positive economic gains were only observed with additional N within the intensive management system. Intensive management containing 20% greater N only produced an average net return of \$686 ha^{-1} compared to \$891 ha^{-1} for the traditional treatment at Richville in 2016 (Table 2.04). Data suggest that although increased N rates positively impacted net return in an intensive system, utilization of a traditional management system was still more profitable. July 2016 and 2017 wheat commodity prices received were the lowest in the last 8 years (NASS, 2017). Producers continue to perceive yield loss as a greater risk than profit loss (Rutan and Steinke, 2017), however at current year wheat prices, results suggest producers should place more emphasis on profitability rather than yield loss protection when choosing to incorporate additional inputs.

Nitrogen Rate

A 20% greater N rate did not significantly affect yield in any site-year within the traditional management system (Table 2.03). Previous research from both Michigan and Wisconsin concluded optimal wheat yields were produced with N rates between 52 – 84 kg N ha^{-1} (Bauer, 2016; Mourtzinis et al., 2017). Results from this trial concur with previous traditional management findings that suggested negligible grain yield increases occur with above-recommended N rates when utilizing minimal input management systems (Vaughan et al., 1990, Bauer, 2016; Knott et al., 2016; Mourtzinis et al., 2017; Swoish and Steinke, 2017).

In contrast to the traditional system, a significant grain yield decrease of 0.94 Mg ha^{-1} occurred at Richville in 2016 when the 20% increased N rate was reduced to the recommended N rate (Table 2.03). A similar albeit non-significant observation occurred at Lansing within the intensive system where yield decreased 0.58 Mg ha^{-1} and 0.15 Mg ha^{-1} in 2016 and 2017, respectively, at the lower N rate. However, the lower SRWW intensive N rate (121.1 kg N ha^{-1}) at Lansing may have been insufficient to produce a significant yield response. Data from this trial suggests potential greater N fertilizer demand with intensive management (Ruffo et al., 2015) or a potential synergistic effect between additional inputs and the greater intensive N rate (161.4 kg N ha^{-1}) associated with SWWW as compared to the lower intensive N rate (121.1 kg N ha^{-1}) associated with SRWW. However, no other input resulted in a significant yield decrease when removed from the Richville 2016 intensive system, causing difficulty in understanding which specific input(s) interacted with the increased N rate. Previous research observed significant interactions between fungicide application and increased N rates (140 kg N ha^{-1} – 240 kg N ha^{-1}) regardless of disease presence presumably due to an extended photosynthetic period associated with fungicide application (Kelley, 1993; Dimmock and Gooding, 2002; Brinkman et al., 2014; Mourtzinis et al., 2017; Salagado et al., 2017). Application of multiple inputs can enhance the green flag leaf area and extend grain fill resulting in increased plant N requirement (Mourtzinis et al., 2017; Salgado et al., 2017).

Previous reports of greater individual input responses using intensive rather than traditional management suggests synergy may exist depending upon the various intensive input technologies utilized (Brinkman et al., 2014; Bluck et al., 2015; Ruffo et al., 2015). University recommended N rates are based off the assumption that N response is independent of agronomic factors other than yield (Warncke et al., 2009; Brinkman et al., 2014). Results suggest recommended N rates proposed by Warncke et al. (2009) have the potential to supply sufficient available N to optimize wheat yield when utilizing a low-input, traditional management system. However, a greater N demand may occasionally be needed for an intensive management system due to sufficient N being the primary source for significant input interactions (Mourtzinis et al., 2017). Significant N rate responses were inconsistent across both site-years at Richville, with site-specific variability potentially hindering a similar 2017 response as observed in 2016. Further research is likely needed to investigate potential synergisms between inputs and N fertilizer as a source for interactions across additional site-years to determine whether recommended wheat N rates require adjustment based upon specific agronomic inputs and management practices.

Urease Inhibitor

Utilizing a urease inhibitor resulted in a significant grain yield response in 1 of 4 site-years across both management systems (Table 2.03). Lansing 2017 grain yield significantly decreased 0.52 Mg ha^{-1} when UI was removed from the intensive system and significantly decreased 0.51 Mg ha^{-1} when UI was added to the traditional system. In all four site-years, UAN was applied to minimal residue, cool spring soils with rainfall occurring within 7 days following N fertilizer application (Table 2.05). Environmental conditions encountered across all site-years of this study suggest a response to UI application should not have been expected due to a lack of volatilization N loss conditions (Warncke et al., 2009; Ma et al., 2010; Franzen, 2017). Urease inhibitor effects may also be less likely when utilizing UAN due to only 50% urea composition (Hendrickson, 1992).

The 2017 growing season produced April rainfall totals 82 and 72% greater than the 30-yr mean in Richville and Lansing, respectively (Table 2.02) with Lansing experiencing the greatest cumulative rainfall (5.3 cm) within 1 week of N application (Table 2.05). Significant rainfall following N application at Lansing in 2017 may suggest that N fertilizer was transported beneath the soil surface, decreasing the risk of volatilization. In addition, although non-significant, the High-N treatment was the only other input to give a negative yield response of 0.15 Mg ha^{-1} when removed from the intensive system at Lansing in 2017 (Table 2.03). Yield reduction observed from UI removal following significant rainfall within the intensive system suggests a potential synergistic effect occurred between application of both UI and the SRWW intensive N rate of 121 kg N ha^{-1}. Urea is an uncharged, mobile form of N that can readily move through the soil profile under high moisture conditions (Fenn and Miyamoto, 1981; Dawar et al., 2011). Adding a UI while also receiving significant rainfall may delay urea hydrolysis and promote leaching through the soil profile beyond the wheat root system (Dawar et al., 2011). However, current results suggest the combination of a UI with the SRWW intensive N rate inhibited N transformation and accounted for potential N loss by supplying additional N to the root zone (Dawar et al., 2011; Mohammed et al., 2016).

In contrast to a positive yield response within the intensive management system, UI application significantly decreased grain yield within the traditional management system at 2017 Lansing (Table 2.03). The traditional system base-N rate of 100.9 kg N ha^{-1} was the lowest among all SRWW and SWWW treatments allowing for smaller N losses to have a greater potential reduction of plant available N. Similar yield reductions from UI additions have been observed in corn where UAN+UI applications were followed with 2.9 cm rainfall within 4 days of N application (Murphy and Ferguson, 1997). Joo et al. (1991) observed decreased recovery of plant and soil urea-derived N in turfgrass with the addition of a UI due to a combination of delayed hydrolysis and 13 cm rainfall within 7 days of N application. Due to the high frequency of Michigan's spring rainfall events often coinciding with wheat N application timings, UI application is unlikely to provide a yield benefit when applied individually under traditional management and may result in additional risk of N loss when fertilizing within recommended N guidelines. However, intensive management practices including a UI application with a 20% greater N rate may enhance N availability and offset some degree of N loss, thus enhancing N-use efficiency (Hou et al., 2006; Dawar et al., 2011; Mohammed et al., 2016).

Nitrification Inhibitor

Nitrification Inhibitor did not significantly impact wheat grain yield across any of the four site-years (Table 2.03). Lack of significant grain yield response in 2016 was likely due to negligible risk of N leaching and/or denitrification from below 30-yr average April rainfall at both locations (Table 2.02). Results were consistent with previous research indicating yield gains from NI application are not expected when below average rainfall follows N application (Nelson and Huber, 1980; Barker and Sawyer, 2017; Franzen, 2017; Steinke and Bauer, 2017).

April 2017 rainfall followed N fertilizer applications and was 82% and 72% greater than the 30-yr average at Richville and Lansing, respectively, suggesting a potential for N-loss conditions (Table 2.02). Lansing received significant rainfall (5.3 cm) within 1 week of N application (Table 2.05). Despite significant rainfall following N application, NI application did not affect grain yield at either 2017 location. In spite of above average rainfall, insignificant responses to NI application following N fertilization have been observed in recent literature (Barker and Sawyer, 2017; Franzen, 2017; Maharjan et al., 2017; Sassman et al., 2018). Barker and Sawyer (2017) observed no soil NO_3-N or corn grain yield benefits from NI application on fine-textured, poorly drained soils receiving 10.7 cm rainfall within 1 week of N application. Authors attributed the lack of NI response to cool soil temperatures following N application, resulting in delayed bacterial conversion of NH_4-N to NO_3-N (Barker and Sawyer, 2017). Nitrification rates significantly decrease at soil temperatures < 15°C (Shammas, 1986). Both Richville and Lansing average soil temperatures 1 week following N application were < 9°C and < 11°C in 2017, respectively (Table 2.05), and may provide evidence that bacterial conversion of NH_4-N to NO_3-N may have been slowed or delayed, thus reducing the risk of N loss.

In addition to cool soil temperatures, the specific formulation of nitrapyrin (Instinct® II; Dow Agrosciences, Indianapolis, IN) used in the current study may have contributed to the lack of response (Ferrel, 2012; Franzen, 2017; Maharjan et al. 2017). Instinct® is a polymer-encapsulated form of nitrapyrin that is ineffective until nitrapyrin is released from the microcapsule (Ferrel, 2012). Ferrel (2012) observed a 300% increase in soil NH_4-N concentration when utilizing the NI dicyandiamide (DCD) as compared to Instinct®. Maharajan et al. (2017) observed no corn yield benefits to Instinct® application despite significant rainfall occurring the day of N application and in the two weeks following N application. Previous research has observed poor Instinct® performance across various cropping systems and environmental conditions (Ferrel, 2012; Franzen, 2017; Maharjan et al. 2017; Sassman et al., 2018), with authors attributing poor performance to inadequate nitrapyrin availability from microencapsulation (Ferrel, 2012; Franzen, 2017; Maharjan et al. 2017). Instinct® has been suggested to delay release and reduce concentration of nitrapyrin during N applications and may require greater application rates than labeled to inhibit nitrification (Ferrel, 2012; Franzen, 2017; Maharjan et al. 2017).

Foliar Zn, Mn, and B

Foliar application of Zn, Mn, and B did not affect grain yield (Table 2.03). Pre-plant soil test data showed B deficiencies (< 0.7 mg kg^{-1}) in 2 of 4 site-years, Zn deficiencies (Zn requirement = [(5.0 x pH) – (0.4 x soil test Zn mg kg^{-1})] – 32) in 3 of 4 site-years, and no Mn deficiencies (Mn requirement = [(6.2 x pH) – (0.35 x soil test Mn mg kg^{-1})] – 36) in any site-year (Table 6) (Warncke et al., 2009). Tissue samples from the uppermost leaf at Feekes 9 showed deficiencies in B (< 6 mg kg^{-1}) in 3 of 4 site-years, Zn deficiency (< 21 mg kg^{-1}) in 4 of 4 site-years, and no Mn deficiency (< 16 mg kg^{-1}) in any site-year (Table 2.07). Soil and tissue nutrient analyses suggested a potential response to foliar application of B and Zn (Vitosh et al., 1995). However, despite soil and tissue deficiencies of B and Zn, plant deficiency symptoms were not observed across any site-year.

University micronutrient recommendations are not solely based on soil or tissue test levels but also incorporate crop sensitivity to low micronutrient availability (Vitosh et al., 1995; Warncke et al., 2009). Crops categorized as sensitive to specific micronutrients have a high likelihood of response to application once soil and tissue nutrient levels drop below sufficiency ranges, while crops categorized as non-sensitive may not respond (Vitosh et al., 1995; Warncke et al., 2009). Previous literature and university guidelines suggest wheat as non-sensitive to B and Zn, yet highly sensitive to Mn (Vitosh et al., 1995; Warncke et al., 2009; Havlin et al., 2014). Therefore, yield increases from a combined foliar application of Zn, Mn, and B to wheat may only occur in the presence of a Mn deficiency, which was not present in any site-year. Results are supported by Curtin et al. (2008) who only observed a significant wheat yield response to Mn and not B or Zn on soils identified as deficient in all three nutrients. Additionally in Chinese and Canadian soils deficient in Zn (0.5 – 0.7 mg kg^{-1}) and B (0.6 mg kg^{-1}), respectively, wheat grain yield was not increased following Zn or B application (Gupta et al., 1976; Lu et al., 2012; Wang et al., 2015). Current results suggest micronutrient applications may only be warranted once crop-sensitive micronutrients decrease below sufficiency ranges, stressing not only the importance of soil and tissue testing, but also the use of university fertilizer guidelines before incorporating a micronutrient application.

Plant Growth Regulator

Plant growth regulator application did not affect grain yield in any site-year (Table 2.03). Plant height reductions were inconsistent when PGR was applied individually in the traditional system, resulting in one significant height reduction (5.8 cm) at Lansing in 2017 (Table 2.08). Inconsistent height reductions following PGR application has also been reported by Knott et al. (2016). Results contradict Matysiak (2006) and Wiersma et al. (2011) who observed 27 and 6% height reductions, respectively, following PGR application. When the PGR was removed from the intensive system, significant plant height increases were observed in two of four site-years. Additionally, when the foliar micronutrient was removed from the intensive system, significant plant height increases were observed in three of four site-years, suggesting a potential synergism between the tank-mixed application of the PGR and foliar micronutrient. Foliar micronutrient

(Max-IN® ZMB; Winfield United, St. Paul, MN) used in this trial contains a monosaccharide adjuvant utilized to increase plant uptake of foliar-applied Zn, Mn, and B (Boring, 2013). Results suggest the addition of this specific adjuvant may have allowed for an elevated and more consistent plant uptake of the PGR resulting in a greater PGR-induced plant height reduction.

Plant lodging did not occur in any of the four site-years across both soft red and soft white winter wheat varieties and management systems including N rates of up to 161.4 kg N ha^{-1}. Both SWWW and SRWW varieties used in this study consisted of short-strawed, high stem strength physical characteristics (Siler et al., 2017; Michigan Crop Improvement Assoc., Okemos, MI) which likely contributed to the lack of lodging and grain yield response to PGR application. Results corresponded with recent research by Swoish and Steinke (2017) who observed yield increases from PGR application only in the presence of lodging, which was more consistent of a taller, weaker structured cultivar rather than adoption of greater N rates. Results suggest motives for applying a PGR may depend more upon cultivar structure, susceptibility to lodging, and average plant height data which are evaluated and accessible through university variety trials (Siler et al., 2017), rather than management intensification (Knott et al., 2016; Swoish and Steinke, 2017).

Fungicide

Adding a fungicide to the traditional management system increased yield 0.75 Mg ha^{-1} in 1 of 4 site-years (Table 2.03). Fungicide removal from the intensive system did not significantly affect grain yield at either location in 2016 or 2017. Fusarium head blight did not occur in any of the four site-years. Below average May rainfall occurred across all site-years (Table 2.02). When rainfall is deficient during the period of wheat anthesis or growth stage F10.5.1 (i.e., May), decreased risks of FHB infection and subsequent DON accumulation occur. Lansing 2016 was the only site-year to experience significant foliar disease pressure predominantly caused by stripe rust (Table 2.09). Stripe rust, rarely prevalent in Michigan, was identified as the most significant wheat yield reducing factor in 2016 due to strong winds out of the western and southern U.S. aiding fungal spore dispersal and local areas receiving adequate temperature, rainfall, and humidity for disease growth (Chen, 2005; Siler et al., 2016). Lansing received 5.6 cm greater April – June rainfall than Richville in 2016 likely creating an advantageous environment for stripe rust development.

Visual assessment of flag leaf infection showed removal of fungicide from the intensive system at Lansing 2016 increased disease presence 11.3% (Table 2.09). Addition of the fungicide to the traditional management system reduced flag leaf disease presence 15%. Data are supported by Chen (2014) who reported controlling wheat stripe rust incidence 42 - 100% with triazole fungicide applications, resulting in 22 – 878% grain yield increases compared to non-fungicide plots. Additionally, Salgado et al. (2017) observed triazole fungicide treatments applied at Feekes 10 or 10.5.1 reduced wheat leaf rust (*Puccinia triticina*) in Ohio from 72 – 99%. Explanation for the non-significant yield response to fungicide in the presence of disease despite significant visual control within the intensive system at Lansing remains unclear. Disease suppression from inputs other than fungicide including foliar applied Mn and B have occurred and been shown to decrease rust (*Puccinia* spp.) incidence in wheat (Huber and Wilhelm, 1988; Datnoff et al., 2007). Results support previous findings by Paul et al. (2010) and Wegulo et al. (2012), suggesting greatest fungicide impact occurred only in a high disease, minimal input environment.

Conclusions

Trial results demonstrated little evidence that an intensive management system utilizing prophylactic applications of multiple inputs benefits wheat yield and/or producer economic profitability without the presence of yield-limiting factors (e.g., disease presence, nutrient-loss conditions, and variety-specific characteristics). The 2016 and 2017 growing seasons produced negligible and inconsistent responses from applications of urease inhibitor, nitrification inhibitor, plant growth regulator, foliar micronutrients, fungicide, and high N management on soft red and soft white winter wheat grain yield. Although positive yield responses from an increase in N rate, urease inhibitor, and fungicide were observed, economic net return was not greater than a traditional management system utilizing only a university recommended N rate at current wheat grain prices. Results appear to provide continued support for the use of university IPM programs which emphasize both grain yield and profitability. Producers should look to incorporate a management system that utilizes specific techniques (i.e. crop scouting, prediction models, varietal resistance, nutrient recommendations) to minimize and justify input applications for specific crop requirements and maximize profitability, rather than applying a suite of inputs as risk insurance.

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APPENDIX

Table 2.01. Overview of omission treatment design, treatment names, and inputs applied, 2016-17.

Treatment	Treatment Name	Agronomic Inputs Applied					
		UI†	NI‡	PGR§	Fungicide¶	Micro#	High-N††
1	Intensive (I)	Yes	Yes	Yes	Yes	Yes	Yes
2	I - UI	No	Yes	Yes	Yes	Yes	Yes
3	I - NI	Yes	No	Yes	Yes	Yes	Yes
4	I - PGR	Yes	Yes	No	Yes	Yes	Yes
5	I - Fungicide	Yes	Yes	Yes	No	Yes	Yes
6	I - Micro	Yes	Yes	Yes	Yes	No	Yes
7	I - High-N	Yes	Yes	Yes	Yes	Yes	No
8	Traditional (T)	No	No	No	No	No	No
9	T + UI	Yes	No	No	No	No	No
10	T + NI	No	Yes	No	No	No	No
11	T + PGR	No	No	Yes	No	No	No
12	T + Fungicide	No	No	No	Yes	No	No
13	T + Micro	No	No	No	No	Yes	No
14	T + High-N	No	No	No	No	No	Yes
15	Check	No	No	No	No	No	No

† N-(n-butyl)-thiophosphoric triamide urease inhibitor (UI) applied at a rate of 1.04 ml kg^{-1} UAN at F3 growth stage.

‡ Nitrapyrin nitrification inhibitor (NI) applied at a rate of 7.71 L ha^{-1} at F3 growth stage.

§ Trinexapac-ethyl plant growth regulator (PGR) applied at a rate of 0.8 L ha^{-1} at F6 growth stage.

¶ Prothioconazole + tebuconazole fungicide applied at a rate of 0.6 L ha^{-1} at F10.5.1 growth stage.

Foliar micronutrient fertilizer containing Zn, Mn, B applied at a rate of 4.68 L ha^{-1} at F6 growth stage.

†† High-nitrogen applied at a rate of 121.1 and 161.4 kg ha^{-1} for Lansing and Richville locations, respectively.

Table 2.02. Mean monthly temperature and precipitation† for the winter wheat growing season, Richville and Lansing, MI, 2016-17.

Site	Year	Mar.	Apr.	May	Jun.	Jul.	Total
		-- cm --					
Richville	2016	10.1	3.3	1.6	4.0	8.8	27.9
	2017	4.8	14.7	5.0	12.3	2.8	39.6
	30-yr‡	4.9	8.1	8.4	9.0	7.9	38.2
Lansing	2016	10.1	7.5	5.2	1.8	9.6	34.2
	2017	7.6	13.2	6.5	8.4	6.7	42.5
	30-yr	5.2	7.7	8.5	8.8	7.2	37.4
		-- °C --					
Richville	2016	3.6	5.6	14.8	19.7	22.6	--
	2017	0.7	10.3	13.7	20.4	21.1	--
	30-yr	0.4	7.4	13.2	18.7	20.9	--
Lansing	2016	5.6	7.5	14.8	20.3	23.0	--
	2017	1.1	11.1	13.5	19.9	21.8	--
	30-yr	1.7	8.6	14.3	19.8	21.9	--

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

Table 2.03. Wheat grain yield for Richville and Lansing, MI, 2016-17. Mean grain yield of intensive and traditional control treatments displayed. All other treatments display change in grain yield from respective intensive or traditional control using single degree of freedom contrasts.

	2016		2017	
Treatment†	Richville	Lansing	Richville	Lansing
	---------- Mg ha^{-1} ----------			
Intensive (I)	7.02	5.25	4.34	6.69
I - UI‡	-0.39	+0.40	+1.09	-0.52*
I - NI	-0.32	+0.15	+1.54	+0.35
I - PGR	-0.57	-0.08	+1.11	+0.32
I - Fungicide	-0.56	0.0	-0.63	+0.05
I - Micro	-0.17	+0.65	+1.01	+0.20
I - High-N	-0.94*	-0.58	+1.16	-0.15
Traditional (T)	6.85	5.43	4.34	6.73
T + UI§	+0.40	-0.18	+0.03	-0.51*
T + NI	-0.32	+0.23	+0.10	-0.20
T + PGR	+0.30	+0.10	-1.22	-0.29
T + Fungicide	-0.05	+0.75*	+0.18	+0.07
T + Micro	0.0	+0.50	+0.13	-0.41
T + High-N	-0.05	+0.23	-0.67	+0.06
Check#	4.25	4.52	2.79	3.21
I vs. T	ns¶	ns	ns	ns
CV %	11.25	17.51	42.25	10.19

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

† N-(n-butyl)-thiophosphoric triamide urease inhibitor (UI), nitrapyrin nitrification inhibitor (NI), trinexapac-ethyl plant growth regulator (PGR), 20% increase in nitrogen fertilizer rate (High-N).

‡Values in I w/o input rows indicate a yield (Mg ha^{-1}) change from respective intensive (I) treatment.

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

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

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

Table 2.04. Economic net return for Richville and Lansing, MI, 2016-17. Mean net return of intensive and traditional control treatments displayed. All other treatments display change in net return from respective intensive or traditional control using single degree of freedom contrasts.

	2016		2017	
Treatment†	Richville	Lansing	Richville	Lansing
	---------------------------------- US$ ha^{-1}	----------------------------------		
Intensive (I)	686.14	385.31	374.74	694.06
I - UI‡	-38.88	+68.63	+203.79	-63.98
I - NI	-24.79	+49.99	+289.65	+81.96*
I - PGR	-46.13	+35.20	+220.09	+80.51*
I - Fungicide	-38.05	+67.39	-43.69	+69.53
I - Micro	+4.81	+124.35*	+200.83	+59.55
I - High-N	-118.48*	-55.83	+222.57	-1.40
Traditional (T)	891.41	635.91	592.25	905.86
T + UI§	+45.85	-39.98	-11.99	-88.79*
T + NI	-81.60	+2.13	-45.76	-60.33
T + PGR	-15.44	-48.77	-255.94	-94.68*
T + Fungicide	-73.57	+35.70	-31.57	-51.68
T + Micro	-54.91	+13.82	-27.02	-110.12*
T + High-N	-31.08	+17.76	-136.59	-8.69
Check#	643.16	620.38	469.67	483.49
I vs. T	*	*	ns¶	*
CV %	14.99	10.20	61.11	12.84

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

† N-(n-butyl)-thiophosphoric triamide urease inhibitor (UI), nitrapyrin nitrification inhibitor (NI), trinexapac-ethyl plant growth regulator (PGR), 20% increase in nitrogen fertilizer rate (High-N).

‡Values in I w/o input rows indicate a net return (US$ ha^{-1}) change from respective intensive (I) treatment.

§Values in T w/ input rows indicate a net return (US$ ha^{-1}) change from respective traditional (T) treatment.

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

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

Table 2.05. Mean weekly soil temperature and precipitation† following wheat N fertilizer application, Richville and Lansing, MI, 2016-17.

Site	Year	Day 1-7	Day 8-14	Day 15-21	Day 22-28
		---------------------------------- cm ------------------------------------			
Richville	2016	2.8	0.7	0.0	1.5
	2017	2.5	3.2	0.0	1.9
Lansing	2016	2.5	3.2	0.0	1.9
	2017	5.3	0.5	2.9	3.9
		-----------------------------------°C ------------------------------------			
Richville	2016	3.4	3.3	9.6	9.8
	2017	10.2	11.0	8.9	10.0
Lansing	2016	7.3	4.5	10.0	12.3
	2017	8.9	13.3	14.8	12.7

† Precipitation and soil temperature (0-5 cm) data were collected from Michigan State University Enviro-weather (https://enviroweather.msu.edu/).

Table 2.06. Site year and soil descriptions, soil chemical properties, and mean P, K, B, Mn, and Zn soil test (0 – 15 cm) nutrient concentrations obtained prior to winter wheat planting, Richville and Lansing, MI, 2016-17.

		Soil	Soil Test†						
Site	Year	Description	P	K	B	Mn	Zn	pH	CEC
			--------------mg kg^{-1}------------						cmolc kg^{-1}
Richville	2016	Tappan-Londo Loam	23	150	6	43	1.2	7.8	16.7
	2017	Tappan-Londo Loam	46	124	0.5	16	3.6	6.6	5.6
Lansing	2016	Capac Loam	27	94	2	35.	0.4	6.4	9.1
	2017	Capac Loam	47	85	0.6	37	2.1	7.0	10.4

†P phosphorus (Bray–P1); K potassium (ammonium acetate extractable K); Zn zinc (0.1 M HCl); Mn manganese (0.1 M HCl); B boron (hot-water extraction).

Table 2.07. Winter wheat flag leaf B, Mn, and Zn tissue nutrient concentrations taken from non-treated plots at Feekes 9 growth stage, Richville and Lansing, MI, 2016-17.

		Tissue Micronutrient Concentration†		
Site	Year	B	Mn	Zn
		---------------------------------- mg kg^{-1} ---------------------------------		
Richville	2016	2	20	16.5
	2017	3.3	21.8	19.8
Lansing	2016	5	44	19.5
	2017	9.3	22	15

† B boron (ICP mass spectroscopy); Mn manganese (ICP mass spectroscopy); Zn zinc (ICP mass spectroscopy).

Table 2.08. Plant growth regulator (PGR) and foliar micronutrient effects on Feekes 10.5.4 mean winter wheat plant height, Richville and Lansing, MI, 2016-17.

		Treatment					
Site	Year	Intensive (I)	I - PGR†	I - Micro	Traditional (T)	T + PGR‡	T + Micro
		-- cm	--				
Richville	2016	71.9	+1.3	+1.2	73.8	+3.8	+1.6
	2017	63.9	+11.6*	+8.8*	70.1	-4.3	+3.5
Lansing	2016	70.5	+4.6	+8.7*	77.4	-1.3	+0.6
	2017	71.8	+10.5*	+7.1*	81.2	-5.8*	+0.3

* Significantly different at α=0.1 using single degree of freedom contrasts.
† Values in w/o input column indicate a plant height (cm) change from respective intensive (I) treatment.
‡ Values in w/input column indicate a plant height (cm) change from respective traditional (T) treatment.

Table 2.09. Effect of Feekes 10.5.1 fungicide on wheat foliar disease presence three weeks after application, Richville and Lansing, MI, 2016-17.

		Treatment			
Site	Year	Intensive (I)	I - Fungicide†	Traditional (T)	T + Fungicide‡
		------------------------------ % leaf area affected --------------------------------			
Richville	2016	0.0§	0.0	0.0	0.0
	2017	0.0	0.0	0.0	0.0
Lansing	2016	6.8	+11.3*	21.8	-15.0*
	2017	0.0	0.0	0.0	0.0

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

† Values in I w/o fungicide column indicate a leaf area affected (%) change from respective intensive (I) treatment.

‡ Values in T w/ fungicide column indicate a leaf area affected (%) change from respective traditional (T) treatment.

§ Years and locations containing all values of 0.0 indicate years and locations that did not receive foliar disease pressure.

LITERATURE CITED

LITERATURE CITED

Alloway, B.J., 2008. Micronutrients and crop production: An introduction. In: B.J. Alloway, editor, Micronutrient deficiencies in global crop production. Springer Science and Business Media, BV, Dordrecht. p. 1-39.

Barker, D., and J. Sawyer. 2017. Evaluation of nitrogen fertilizer additives for enhanced efficiency in corn on Iowa soils. Crop Forage Turfgrass Manage. 3:1-6.

Bauer, C.A. 2016. Optimizing agronomic practices on Michigan winter wheat and sugarbeet production. M.S. Thesis. ProQuest Diss. Publ. UMI 10108870. Michigan State Univ.

Beyer, M., M.B. Klix, H. Klink, and J.A. Verreet. 2006. Quantifying the effects of previous crop, tillage, cultivar and triazole fungicides on the deoxynivalenol content of wheat grain - a review. J. Plant Dis. Prot. 113:241-246.

Beuerlein, J.E., E.S. Oplinger, and D. Reicosky. 1989. Yield and yield components of winter wheat cultivars as influenced by management – A regional study. J. Prod. Agric. 2:257-261.

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

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

Boring, T.J. 2013. Field investigations of foliar fertilizer strategies of soybean Mn deficiency in Michigan and phosphorus and potassium fertilizer application strategies in corn-soybean rotations in the United States. Ph.D. dissertation. ProQuest Diss. Publ. UMI 3601052. Michigan State Univ.

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

Britto, D.T., and H.J. Kronzucker. 2002. NH_4^+ toxicity in higher plants: a critical review. J. Plant. Physiol. 159:567-584.

Brown, L.K., M.L. Nagelkirk, A.T. Wiersma, L.F. Siler, and E.L. Olson. 2017. Wheat variety comments. Michigan State Univ. Ext., East Lansing, MI. http://fieldcrop.msu.edu/uploads/files/Wheat/Wheat_Variety_Comments_2017_Field_Day_Handout.pdf (accessed 1. Aug. 2017).

Chen, X.M. 2005. Epidemiology and control of stripe rust [*Puccinia striiformis* f. sp. *tritici*] on wheat. Can. J. Plant Pathol. 27:314-337.

Chen, X.M. 2014. Integration of cultivar resistance and fungicide application for control of wheat stripe rust. Can. J. Plant Pathol. 36:311-316.

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

Curtin, D., R.J. Martin, and C.L. Scott. 2008. Wheat (*Triticum aestivum*) response to micronutrients (Mn, Cu, Zn, B) in Canterbury, New Zealand. New Zealand J. Crop Hort. Sci. 36:169-181.

Datnoff, L.E., W.H. Elmer, and D.M. Huber. 2007. Mineral nutrition and plant disease. APS Press, St. Paul, MN.

Dawar, K., M. Zaman, J.S. Rowarth, J. Blennerhasset, and M.H. Turnbull. 2011. Urea hydrolysis and lateral and vertical movement in the soil: effects of urease inhibitor and irrigation. Biol. Fertil. Soils 47:139-146.

Degenhardt R.F., L.T. Juras, L.R.A. Smith, A.W. MacRae, J. Ashigh, and W.R. McGregor. 2016. Application of nitrapyrin with banded urea, urea nitrate, and ammonia delays nitrification and reduces nitrogen loss in Canadian soils. Crop Forage Turfgrass Manage. 2:1-11.

Enderson, J.T., A.P. Mallarino, and M.U. Haq. 2015. Soybean yield response to foliar-applied micronutrients and relationships among soil and tissue tests. Agron. J. 107:2143-2161.

Engel, R., C. Jones, and R. Wallander. 2011. Ammonia volatilization from urea mitigation by NBPT following surface application to cold soils. Soil Sci. Soc. Am. J. 75:2348-2357.

Fenn, L.B., and S. Miyamoto. 1981. Ammonia loss and associated reactions of urea in calcareous soils. Soil Sci. Soc. Am. J. 45:537-540.

Ferrel, A.D. 2012. Effect of time and moisture on the efficacy of an encapsulated nitrification inhibitor. M.S. thesis. ProQuest Diss. Publ. UMI 1529640. Purdue Univ.

Frank, K., D. Beegle, and J. Denning. 2015. Phosphorus. In: M.V. Nathan and R. Gelderman, editors, Recommended soil test procedures for the North Central Region. North Central Regional Publ. No. 221 (Rev.). Missouri Agric. Exp. Stn., Columbia. p. 6.1-6.6.

Franzen, D.W. 2017. Nitrogen extenders and additives for field crops. Bull. SF1581. North Dakota State Univ. Ext. Fargo, ND.

Grant, C.A. 2014. Use of NBPT and ammonium thiosulphate as urease inhibitors with varying surface placement of urea and urea ammonium nitrate in production of hard red spring wheat under reduced tillage management. Can. J. Plant Sci. 94:329-335.

Gupta, U.C., J.A. MacLeod, and J.D.E. Sterling. 1976. Effects of boron and nitrogen on grain yield and boron and nitrogen concentrations of barley and wheat. Soil Sci. Soc. Am. J. 40:723-726.

Havlin, J.L., S.L. Tisdale, J.D. Beaton, and W.L. Nelson. 2014. Soil fertility and fertilizers: An introduction to nutrient management 8th ed. Upper Saddle River, New Jersey, Pearson Prentice Hall.

Hendrickson, L.L. 1992. Corn yield response to urease inhibitor NBPT: five-year summary. J. Prod. Agric. 5:131-137.

Hou, X., J. Hua, W. Liang, and D. Yang. 2006. Effect of combined application of urease and nitrification inhibitors on yield and quality of wheat. Agric. J. 1:109-112.

Huber, D.M., and Wilhelm, N.S. 1988. The role of manganese in resistance to plant diseases. In: R.D. Graham et al, editor(s), Manganese in soil and plants. Kluwer Acadmic Publishers, Dordrecht, Netherlands. p. 155-173.

Jones, R. K., and C. J. Mirocha. 1999. Quality parameters in small grains from Minnesota affected by Fusarium head blight. Plant Dis. 83:506-511.

Jones, R.K. 2000. Assessments of Fusarium head blight of wheat and barley in response to fungicide treatment. Plant Dis. 84:1021-1030.

Joo, Y.K., N.E. Christians, and A.M. Blackmer. 1991. Kentucky bluegrass recovery of urea-derived nitrogen-15 amended with urease inhibitor. Soil Sci. Soc. Am. J. 55:528-530.

Kanampiu, F.K., W.R. Raun, and G.V. Johnson. 1997. Effect of nitrogen rate on plant nitrogen loss in winter wheat varieties. J. Plant Nutr. 20:2-3, 389-404.

Kelley, K.W. 1993. Nitrogen and foliar fungicide effects on winter wheats. J. Prod. Agric. 6:53-57.

Kleczewski, N.M., and C. Whaley. 2018. Assessing the utility of growth regulator trinexapac-ethyl and fungicides in mid-Atlantic soft red winter wheat productions systems. Crop Prot. 104:60-64.

Knapp, J. S., and C. L. Harms. 1988. Nitrogen fertilization and plant growth regulator effects on yield and quality of four wheat cultivars. J. Prod. Agric. 1:94–98.

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

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

Kravchenko, A.N., G.P. Robertson, K.D. Thelen, and R.R. Harwood. 2005. Management, topographical, and weather effects on spatial variability of crop grain yields. Agron. J. 97:514-523.

Liu, S.L., E.C. Varsa, G. Kapusta, and D.N. Mburu. 1984. Effect of etridiazol and nitrapyrin treated N fertilizers on soil mineral N status and wheat yields. Agron. J. 76:265-270.

Lu, X., J. Cui, X. Tian, J.E. Ogunniyi, W.J. Gale, and A. Zhao. 2012. Effects of zinc fertilization on zinc dynamics in potentially zinc-deficient calcareous soil. Agron. J. 104:963-969.

Ma, B.L., T.Y. Wu, N. Tremblay, W. Deen, N.B. McLaughlin, M.J. Morrison, and G. Stewart. 2010. On-farm assessment of the amount and timing of nitrogen fertilizer on ammonia volatilization. Agron. J. 102:134-144

Maharjan, B., R.B. Ferguson, and G.P. Slater. 2017. Irrigated corn productivity as influenced by nitrogen source, rate, and climatic conditions. Agron. J. 109:2957-2965.

Marburger, D.A., B.J. Haverkamp, R.G. Laurenz, J.M. Orlowski, E.W. Wilson, S.N. Casteel, C.D. Lee, S.L. Naeve, E.D. Nafzinger, K.L. Roozeboom, W.J. Ross, K.D. Thelen, and S.P. Conley. 2016. Characterizing genotype x management interactions on soybean seed yield. Crop Sci. 56:786-796.

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

McKenzie, R. H., A. B. Middleton, P. G. Pfiffner, and E. Bremer. 2010. Evaluation of polymer-coated urea and urease inhibitor for winter wheat in southern Alberta. Agron. J., 102:1210-1216.

McMullen, M. P., R. K. Jones, and D. J. Gallenberg. 1997. Scab of wheat and barley-A re-emerging disease of devastating impact. Plant Dis. 81:1340-1348.

Mohammed, Y.A., C. Chen, and T. Jensen. 2016. Urease and nitrification inhibitors impact on winter wheat fertilizer timing, yield, and protein content. Agron. J. 108:905-912.

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

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

Murphy, T.L., and R.B. Ferguson. Ridge-till corn and urea hydrolysis response to NBPT. 1997. J. Prod. Agric. 10:271-282.

Nagelkirk, M., and M. Chilvers. 2016. Managing fusarium head blight. Michigan State Univ. Ext., East Lansing, MI. msue.anr.msu.edu/uploads/234/89014/disease/Managing_Fusarium_Head_Blight.pdf (accessed 15 Aug. 2017).

National Agricultural Statistics Service. 2017. USDA-NASS agricultural statistics 2017. USDA-NASS. http://www.nass.usda.gov (accessed 21. Aug. 2017).

Nelson, D.W., and D.M. Huber. 1980. Performance of nitrification inhibitors in the Midwest (east). In: J.J. Meisinger et al., editor(s), Nitrification inhibitors: Potentials and limitations. ASA Spec. Publ. 38. ASA and SSSA, Madison, WI. p. 75-88.

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

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

Paul, P.A., P. E. Lipps, D. E. Hershman, M. P. McMullen, M. A. Draper, and L. V. Madden. 2008. Efficacy of triazole-based fungicides for Fusarium head blight and deoxynivalenol control in wheat: A multivariate meta-analysis. Phytopathology. 98:999-1011.

Pierce, F.J., D.D. Warncke, and M.W. Everett. 1995. Yield and nutrient variability in glacial soils of Michigan. In: P.C. Robert et al., editor(s), Proc. 2nd Int. Conf. on Site-Specific Management for Agricultural Systems, Minneapolis, MN. 27-30 Mar. 1994. ASA, SSSA, CSSA, Madison, WI. p. 133-150.

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

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

Rajkovich, S., D. Osmond, R. Weisz, C. Crozier, D. Israel, and R. Austin. 2017. Evaluation of nitrogen-loss prevention amendments in maize and wheat in North Carolina. Agron. J. 109:1-14.

Rao, S.C. 1996. Evaluation of nitrification inhibitors and urea placement in no-tillage winter wheat. Agron. J. 88:904-908.

Raun, W.R., and G.V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. Agron. J. 91:357-363.

Risbey, J., M. Kandlikar, H. Dowlatabadi, and D. Graetz. 1999. Scale context and decision making in agricultural adaptation to climate variability and change. Mitigation and Adaption Strategies for Global Change. 4:137-165.

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

Ruffo, M.L., L.F. Gentry, A.S. Henninger, J.R. Seebauer, and F.E. Below. 2015. Evaluating management factor contributions to reduce corn yield gaps. Agron. J. 107:495-505.

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

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

Sassman, A.M., D.W. Barker, and J.E. Sawyer. 2018. Corn response to urea-ammonium nitrate solution treated with encapsulated nitrapyrin. Agron. J. 110:1-10.

Shammas, N.K. 1986. Interactions of temperature, pH, and biomass on the nitrification process. Water Pollut. Cont. Fed. 58:52-59.

Siler, L., M. Graham, A. Hoffstetter, A. Wiersma, L. Brown, K. McCarthy, J. Kovach, J. Turkus, T. Watkins, and E. Olson. 2017. Michigan state wheat performance trials. http://www.varietytrials.msu.edu/wheat (accessed 18 Oct. 2017).

Siler, L., M. Graham, A. Wiersma, L. Brown, K. McCarthy, A. Hoffstetter, J. Kovach, D. Pennington, and E. Olson. 2016. Michigan state wheat performance trials. http://www.varietytrials.msu.edu/wheat (accessed 18 Oct. 2017).

Slaton, N. A., R. J. Norman, and J. Kelley. 2011. Winter wheat yield response to a urea amended with a urease inhibitor and fertilization time. Crop Manage. 10:1.

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

Sutradhar, A.K., D.E. Kaiser, L.M. Behnken. 2017. Soybean response to broadcast application of boron, chlorine, manganese, and zinc. Agron. J. 109:1-12.

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

Terman, G.L. 1979. Volatilization losses of nitrogen as ammonia from surface applied fertilizers, organic amendments, and crop residues. Adv. Agron. 31:189-223.

Trenkel, M.E. 2010. Slow- and controlled-release and stabilized fertilizers: An option for enhancing nutrient use efficiency in agriculture. Int. Fert. Ind. Assoc., Paris, France.

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

Vaughan, B., D.G. Westfall, and K.A. Barbarick. 1990. Nitrogen rate and timing effects on winter wheat grain yield, grain protein, and economics. J. Prod. Agric. 3:324-328.

Vitosh, M.L., J.W. Johnson, and D.B. Mengel. 1995. Tri-state fertilizer recommendations for corn, soybeans, wheat, and alfalfa. Bull. E2567. Michigan State Univ. Ext., East Lansing, MI.

Wang, S., M. Li, X Tian, J. Li, H. Li, Y. Ni, J. Zhao, Y. Chen, C. Guo, and A. Zhao. 2015. Foliar zinc, nitrogen, and phosphorus application effects on micronutrient concentrations in winter wheat. Agron. J. 107:61-70.

Warncke, D., and J.R. Brown. 1998. Potassium and other basic cations. In: J.L. Brown, editor, Recommended soil test procedures for the North Central Region. North Central Regional Publ. No. 221 (Rev.). Missouri Agric. Exp. Stn., Columbia. p. 7.1-7.3.

Warncke, D., and M. Nagelkirk. 2010. Spring nitrogen management for winter wheat. Michigan State Univ. Ext., East Lansing, MI. http://msue.anr.msu.edu/news/spring_nitrogen_management_for_winter_wheat (accessed 21 Aug. 2017).

Warncke, D., J. Dahl, and L. Jacobs. 2009. Nutrient Recommendations for field crops in Michigan. E2904. Michigan State Univ. Ext., East Lansing, MI.

Watson, M.E. 1998. Boron. In: Recommended chemical soil test procedurs for the Nort Central Region. North Central Regional Publ. No. 221 (Rev.) Missouri Agric. Exp. Stn., Columbia. p. 10.1-10.4.

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

White, J., and J. Edwards. 2008. Wheat growth and development. NSW Department of Primary Industries, New South Wales.

Whitney, D.A. 1998. Micronutrients: Zinc, iron, manganese and copper. In: Recommended chemical soil test procedures for the North Central Region. North Central Regional Publ. No. 221 (Rev.) Missouri Agric. Exp. Stn., Columbia. p. 9.1-9.4.

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

CHAPTER 3

SOYBEAN RESPONSE TO POULTRY LITTER, POTASSIUM THIOSULFATE, FOLIAR MICRONUTRIENTS, AND FUNGICIDE

Abstract

Increased commodity price, greater acres planted, and commercial marketing has encouraged soybean [*Glycine max* (L.) Merr.] producers to adopt high-input management systems for maximum grain yield. A three site-year trial was established in Michigan to investigate soybean grain yield and profitability in response to poultry litter (PL), potassium thiosulfate (KTS), foliar micronutrient, and fungicide applications across intensive (i.e. high-input) and traditional (i.e. low-input) management systems. Poultry litter was broadcast and incorporated prior to planting, KTS and foliar micronutrient were surface-banded and foliar applied, respectively, at R1, and fungicide was foliar applied at R3. Across all site-years, intensive management did not significantly increase soybean grain yield compared to traditional management. Due to non-observable nutrient deficiencies and lack of significant plant disease pressure during 2016 and 2017, no single input applied significantly increased grain yield. In addition, traditional management significantly increased producer economic net return by an average of \$501 ha^{-1}. Potassium thiosulfate significantly decreased net return in 1 of 3 site-years and PL significantly decreased net return in all three site-years due to a lack of positive yield response and high individual input cost. Data suggest limited potential for intensive management systems to increase soybean grain yield and profitability without the presence of yield-limiting factors.

Introduction

Since 2007, soybean commodity prices increased 21% compared to a 1% decrease for corn (*Zea mays* L.) (NASS, 2017). During the same time period, soybean yield and total acres planted in Michigan increased by 8 and 28%, respectively (NASS, 2017). Increased price paid, production, and commercial marketing has encouraged soybean producers to adopt high-input management in which a greater number of agronomic inputs are applied to maximize yield and profitability (Gregg et al., 2015; Marburger et al., 2016; Orlowski et al., 2016). Additionally, increased adoption of input-intensive soybean systems combined with the introduction of new genetics have some individuals questioning older (> 20 yrs.) university nutrient recommendation guidelines (Vitosh et al., 1995; Brooker et al., 2017). Unrealized yield potential due to perceived nutrient deficiencies caused by elevated crop nutrient removal via greater grain yield is another concern (Nelson et al., 2005; Bender et al., 2015; Bluck et al., 2015; Brooker et al., 2017). However, many of the inputs being applied to combat producer concerns contain limited, unbiased information validating the proposed benefits (Marburger et al., 2016).

Poultry litter is one input that has garnered interest due to purported soil quality and grain yield benefits compared to commercial N, P, and K fertilizers (Adeli et al., 2005; Watts and Torbert, 2011). Adeli et al. (2005) observed 8-10% yield increases from at-plant PL applications compared to commercial fertilizer due to added availability of secondary and micronutrients. Direct manure application to soybean enhanced plant biomass, nutrient uptake, nutritional status, and seed composition of P, K, secondary, and micronutrients (Adeli et al., 2005; Slaton et al., 2013). In addition, continuous applications of PL may increase concentrations of soil macro- and micronutrients, soil organic matter (SOM), soil cation exchange capacity, and decrease risk from soybean cyst nematode (Wood et al., 1996; Morant et al., 1997; Adeli et al., 2005; Watts et al., 2010).

Increased acreage and grain yield, more frequent weather volatility, and soil compaction have allowed greater opportunity for potassium (K) deficiencies to develop in soybean (Nelson et al. 2005; Nelson and Motavelli, 2007; Nelson et al., 2010). In addition, soybean grain K removal is greater than other grain crops causing the perception of additional K need beyond recommended guidelines (Warncke et al., 2009; Clover and Mallarino, 2013). Inadequate soybean K levels can decrease pods per plant, seeds per pod, seed weight, photosynthetic assimilates, and increase soybean aphid populations (Nelson et al. 1945; Bharati et al., 1986; Walter and Difonzo, 2007; Pettigrew, 2008). In-season K applications are marketed to provide additional K at peak soybean uptake (Bender et al., 2015; Gaspar et al., 2017) and minimize potential K deficiencies caused by variable soil properties, management practices, and environmental conditions (Nelson et al. 2005). However, positive results from in-season K fertilizer applications are often dependent on soil test K levels and the environmental conditions present (Haq and Mallarino, 2000; Nelson et al., 2005). During drought conditions that inhibited soybean K uptake, Nelson et al. (2005) observed increased soybean yield (0.73-0.83 Mg ha^{-1}) from foliar K applications at the V4 and R1-R2 growth stages. In contrast, Haq and Mallarino (2000) observed inconsistent response to in-season K fertilization due to above critical soil test K concentrations and optimal environmental conditions allowing for adequate nutrient uptake.

Lack of atmospheric sulfur (S) deposition and increased S response in corn have growers considering S applications to soybean (Dick et al., 2008; Kaiser and Kim, 2013). Soybean yield response to S may be site-specific depending upon SOM content, cropping history, and environmental factors affecting S mineralization (Kaiser and Kim, 2013). Bluck et al. (2015) did not observe a positive soybean yield response to S fertilization across 10 Ohio locations due to uppermost R1 trifoliate S tissue concentrations within the sufficiency range of 2.1 to 4.0 g kg^{-1} (Vitosh et al. 1995) and no visual S deficiency symptoms. Kaiser and Kim (2013) observed a positive soybean grain yield response to S when SOM concentrations were < 20 g kg^{-1}. In Michigan, Thurgood (2014) did not observe a positive yield response to S fertilization and concluded residual soil S and mineralized S from SOM were sufficient for optimal plant growth. Previous trials concluded that consideration of all potential S sources (i.e. SOM, residual soil S, and S-deposition) is critical when determining soybean S needs. (Kaiser and Kim, 2013; Thurgood, 2014).

Decreased soil micronutrient availabilities has been suggested due to more intensive cropping systems, greater yielding varieties, and increased concentration and purity of synthetic fertilizers (Alloway, 2004; Dewal and Pareek, 2004). In Ohio, Bluck et al. (2015) observed a significant 0.54 Mg ha^{-1} yield increase from Mn application due to reduced plant availability on a dry, sandy soil. Enderson et al. (2015) and Sutradhar et al. (2017) concluded foliar or soil applied B, Mn, and Zn individually and in combination did not significantly increase yield across 54 locations. Mallarino et al. (2017) summarized 88 – 99 field trials from Iowa, Kansas, and Minnesota and observed one significant yield response to Mn application and no significant responses to applied Zn and B. In Michigan, micronutrient recommendations are based on soil micronutrient concentration, soil pH, and crop responsiveness with soybean classified as moderate and highly responsive to Zn and Mn, respectively (Vitosh et al., 1995; Warncke et al., 2009). Soybean Mn and Zn tissue concentrations are considered below sufficiency at $\leq$ 21 g kg^{-1} when sampled from the uppermost trifoliate at R1 (Vitosh et al., 1995; Bluck et al., 2015), with both deficiencies likely to occur on high pH, calcareous soils (> 7.0) (Warncke et al., 2009; Mallarino et al., 2017)

Despite below threshold levels of disease, growers are increasingly adopting prophylactic fungicide applications to enhance soybean yield (Swoboda and Pedersen, 2009; Henry et al., 2011; Mourtzinis et al., 2016). Strobilurin-based fungicides have displayed a wide range of effectiveness against varying types of fungi and plant physiological enhancements including increased leaf greenness, water use efficiency, chlorophyll content, and delayed senescence (Grossman and Retzlaff, 1997; Bartlett et al., 2002). However, positive responses to fungicide application in more recent literature have been inconsistent. Mourtzinis et al. (2017) observed a 3.6 and 5.4% soybean yield increase with low disease incidence in 2014 and 2015, respectively. Similarly, Henry et al. (2011) and Orlowski et al. (2016) observed soybean yield increases of 3.5 and 4.6% from pyraclostrobin applications, respectively, in the absence of disease. In contrast, Swoboda and Pedersen (2009), Gregg et al. (2015), and Ng et al. (2018) found no differences in soybean grain yield and yield components (i.e., pods per plant, seeds per pod) from fungicide applications within an environment lacking disease presence.

Until recently, few studies have examined soybean grain yield and economics in response to specific inputs applied individually or in combination across various management systems (Bluck et al., 2015; Marburger et al., 2016; Orlowski et al., 2016). To the authors' knowledge, no peer-reviewed research has examined individual and combined applications of poultry litter, potassium thiosulfate, foliar micronutrients, and fungicide to soybean. The objective of this trial was to investigate soybean grain yield and economic net return in response to poultry litter, potassium thiosulfate, micronutrient, and fungicide applications across intensive (i.e. high-input) and traditional (i.e. low-input) production systems. An omission trial design, previously used in Midwest corn and soybean research to evaluate intensive management factors (Bluck et al., 2015; Ruffo et al., 2015), was used to determine whether the elimination of a specific input from an intensive management system or the introduction of a specific input into a traditional management system significantly affected grain yield or economic profitability.

Materials and Methods

Soybean trials were initiated at the Saginaw Valley Research and Extension Center (SVREC) near Richville, MI (43°23'57.3"N, 83°41'49.7"W) on a non-irrigated, tile-drained Tappan-Londo loam soil (fine-loamy, mixed, active, calcareous, mesic Typic Enduaquolls) in 2016 and at two locations including SVREC and the Michigan State University South Campus Field Research Farm in Lansing, MI (42°42'37.0"N, 84°28'14.6"W) on a non-irrigated, tile-drained Capac loam soil (fine-loamy, mixed, active, mesic Aquic Glossudalfs) in 2017. Fields were previously cropped to corn (*Zea mays* L.) and cultivated prior to planting. Soil samples were collected prior to planting at a 20 cm depth and analyzed for soil chemical properties (Table 3.01).

Trials were arranged in a randomized complete block design with four replications and utilized an omission treatment design (Table 3.02) to evaluate the effects of poultry litter, potassium thiosulfate, foliar micronutrients, and fungicide. Omission treatment designs utilize two treatment controls, one containing all applied inputs (i.e., intensive management) and another containing no applied inputs (i.e., traditional management) (Bluck et al., 2015; Ruffo et al., 2015). To evaluate treatment effects, inputs are individually removed from the intensive system and compared only to the intensive management control and individually added to the traditional system and only compared to the traditional management control (Bluck et al., 2015; Ruffo et al., 2015).

Individual six-row plots measured 4.6 m x 12.2 m with a 76 cm row spacing. Plots were planted with a six-row Monosem planter (Monosem Inc., Edwardsville, KS) on 9 May 2016 at Richville and on 28 Apr. 2017 and 12 May 2017 at Richville and Lansing, respectively. Soybean variety 'Asgrow 2433' (Monsanto Co., St. Louis, MO), was seeded in all site-years to a plant population of 331,121 seeds ha^{-1}. Poultry litter (4-3-2 N-P-K) was broadcast and incorporated prior to planting at a rate of 2,242 kg ha^{-1}. Potassium thiosulfate fertilizer (0-0-25-17 N-P-K-S) was surface-banded at R1 at a rate of 28 L ha^{-1}. Foliar Zn, Mn, and B (Max-In Ultra ZMB, 4% Zn (EDTA), 3% Mn (EDTA), 0.1% B (boric acid); Winfield United LLC., St. Paul, MN) and fungicide (Stratego YLD; prothioconazole {2-[2-(1-chlorocyclopropyl)-3-(2-chlorophenyl)-2-hydroxypropyl]-1, 2-dihydro-3H-1, 2, 4-triazole-3-thione} and trifloxystrobin {(E,E)-alpha-(methoxyimino)-2-[[[[1-3-(trifluoromethyl)phenyl]ethylidene]amino]oxy]methyl]-methylester}; Bayer CropScience Research Triangle Park, NC) were applied at labelled rates at R1 (4.67 L ha^{-1}) and R3 (0.34 L ha^{-1}), respectively, utilizing a backpack sprayer calibrated at 140 L ha^{-1} with Teejet XR8002 nozzles (Teejet Technologies, Wheaton, IL).

Leaf nutrient analysis was collected from the uppermost, fully developed trifoliate of 20 plants per plot. Average monthly temperature and total cumulative precipitation were recorded throughout the growing season and obtained from Enviro-weather (http://www.agweather.geo.msu.edu/mawn/, Michigan State University, East Lansing, MI). Grain yield was harvested from the center 1.5 m of each plot using a small-plot combine (Almaco, Nevada, IA) on 11 Oct. 2016 at Richville and 2 Oct. 2017 at Richville and Lansing and adjusted to 135 g kg^{-1} moisture.

Economic analysis was performed using local product cost estimates of \$355.83, \$34.60, \$34.60, and \$42.63 ha^{-1} in 2016 and \$331.12, \$34.60, \$31.51, and \$42.28 ha^{-1} in 2017 for poultry litter, potassium thiosulfate, foliar micronutrients, and fungicide, respectively. Application costs were \$18.53 and \$17.30 ha^{-1} in 2016 and 2017, respectively. Application cost of \$34.60 ha^{-1} was estimated for surface band applications of KTS in 2016 and 2017. Net returns were calculated by subtracting total treatment cost from gross revenue (soybean cash price estimates of \$0.35 kg^{-1} in 2016 and \$0.32 and \$0.33 kg^{-1} in 2017 for Richville and Lansing, respectively x grain yield). Product, application, and harvest grain price estimates were received from local agriculture retailers and grain elevators.

Results were determined significantly different between years ($P \geq 0.10$) and analyzed separately. Replication was considered a random factor with all other factors considered fixed. Data analysis was performed in SAS Version 9.4 (SAS Institute Inc., Cary, NC) using the GLIMMIX procedure at $\alpha = 0.10$. Single degree of freedom contrasts were used to assess differences between treatment means. Within an omission treatment design, factors removed from the intensive management system are contrasted only to the intensive management control containing all inputs and factors added to the traditional management system are contrasted only to the traditional management control containing none of the inputs (Bluck et al., 2015).

Results and Discussion

Environmental Conditions

Total growing season (May-Sept) rainfall was 13.6, 16.6, and 14.8 cm below the 30-year mean at 2016 and 2017 Richville and 2017 Lansing, respectively (Table 3.03). May and June 2016 rainfall was 7 and 6 cm below the 30-year mean, respectively, at Richville. However, July rainfall was within 0.5 cm of normal and August was 4.5 cm above the 30-year mean likely providing sufficient moisture for late soybean reproductive stages and grain fill. July and August 2017 rainfall was 6.5 cm and 3 cm below the 30-year mean, respectively, at Richville and 1.5 and 5 cm below the 30-year mean, respectively at Lansing. Dry mid-summer 2017 soil conditions likely contributed to moderate yield reductions when compared to 2016. Air temperatures ranged 1.1 – 3.6°C higher in every month of the growing season in 2016, while 2017 air temperatures were within two degrees of the 30-year mean at both locations.

Intensive vs. Traditional Management Systems

No significant yield differences were observed between the intensive management system (i.e., containing all applied inputs) and the traditional management system (i.e., containing no applied inputs) (Table 3.04). Each site-year had below average rainfall, minimal foliar disease incidence, and a corn-soybean rotation averaging 30 g kg^{-1} SOM with the capacity to supply sufficient macro- and micronutrients. Environmental conditions in the current study contributed to the overall lack of input responses since adverse conditions (e.g., disease pressure, nutrient deficiencies) warranting specific input responses were not present. Results from the current study are supported by recent research from Ohio, Kentucky, and Wisconsin which observed inconsistent and overall non-significant soybean yield increases from multiple prophylactic input applications without the presence of adverse environmental conditions including disease, insects, and nutrient deficiencies (Bluck et al., 2015; Gregg et al., 2016; Mourtzinis et al., 2016).

Economic Net Return

Intensive soybean management containing all applied inputs required additional product and application costs totaling \$557.85 ha^{-1} and \$526.01 ha^{-1} in 2016 and 2017, respectively, compared to traditional management without the applied inputs. In addition, intensive management resulted in a break-even yield of 1.63 Mg ha^{-1} in 2016 and 2017 based on the at-harvest soybean sale price of \$0.34 kg^{-1} in 2016 and \$0.32 kg^{-1} for both 2017 locations. Traditional management was significantly more profitable across all three site-years (Table 3.05), with an average increased economic net return of \$501.44 ha^{-1} over intensive management. Potassium thiosulfate significantly decreased net return in one of three site-years while PL significantly decreased net return in all 3 site-years within both intensive and traditional management systems. Significantly decreased net return was likely due to the lack of positive yield response to input application and input costs. Poultry litter had the greatest cost of all the applied inputs and was on average 8 times greater than the next expensive input (i.e., fungicide).

This study did not observe significant increases in economic net return from individual or multiple input applications to soybean (Table 3.05). Without adverse environmental conditions and/or nutrient deficiencies, producer profitability decreased. Trial results expose the associated economic risks from applying multiple prophylactic applications of agronomic inputs and fertilizer on soybean. In addition, trial results demonstrate the importance of utilizing university recommended integrative pest management (IPM) principles and nutrient recommendation guidelines to justify input applications and consider economic return (Marburger et al., 2016; Mourtzinis et al., 2016). Economic results from this trial are supported by two recently published soybean studies that total 117 site-years across nine states, including multiple yield environments and grain sale prices (Marburger et al., 2016; Orlowski et al., 2016). Authors determined that a high-input soybean system (e.g. seed treatments, foliar fungicides, foliar insecticides, and foliar fertilizers) resulted in a 0% chance to break-even financially at current commodity prices (Marburger et al., 2016; Orlowski et al., 2016).

Poultry Litter

Poultry litter did not impact grain yield when removed from the intensive management system or when added to the traditional system across all site-years (Table 3.04). Due to atmospheric N_2 fixation, yield benefits from PL application are most likely to occur from nutrient additions other than N (Watts and Torbert, 2011; Slaton et al., 2013). Soil P and K concentrations were above critical across all site-years (Warncke et al., 2009) (Table 3.01). Results correspond to Swoish (2016) who did not observe a significant yield benefit to PL application in Michigan during 2013 and 2014 on soils sufficient in P and K. Slaton et al. (2013) observed significant soybean yield responses to PL application on sites defined as having below critical P and K concentrations. Authors concluded from 12 locations that grain yield benefits from PL application were strictly due to P and K fertilization and not added micronutrients or organic components (Slaton et al., 2013). In contrast, Watts and Torbert (2011) observed significant soybean yield increases from PL application on a fine sandy loam soil due to addition of micronutrients from PL. Low soil Zn and B concentrations were observed in two of three and one of three site-years, respectively (Table 3.01). However, across all site-years of this trial no deficiency symptoms or plant tissue micronutrient deficiencies were observed (Table 3.06), indicating plant micronutrient concentrations were sufficient (Vitosh et al., 1995; Warncke et al., 2009).

Current results suggest limited soybean grain yield benefit from PL application on soils with sufficient macro- and micronutrient concentrations (i.e., higher fertility sites). Despite an overall lack of soybean yield response to PL application in this trial, PL may provide a benefit to less productive (i.e. infertile, eroded, low SOM, low CEC) soils. In addition to macro- and micronutrient concentrations, previous literature has shown PL to increase SOM levels, CEC, C and N mineralization, and soil respiration (Watts et al., 2010; Swoish, 2016), suggesting further research may be needed to understand the potential effects of PL application on longer-term nutrient mineralization rates and the soil microbiome.

Potassium Thiosulfate

Application of KTS did not significantly impact grain yield within either the intensive or traditional management systems during this trial (Table 3.04). Pre-plant soil test data indicated soil K concentrations were above critical across site-years indicating no expected response to in-season K applications (Warncke et al., 2009) (Table 3.01). Results are supported by Mallarino et al. (2001) who observed little to no response from in-season foliar K application with above critical soil K concentrations. Michigan fertilizer guidelines recommend 20.1 to 25 g kg^{-1} of K within the uppermost fully developed trifoliate at the R1 growth stage (Vitosh et al., 1995). Plant trifoliate samples collected at R1 prior to K fertilization were within the recommended sufficiency range in 2 of 3 site-years (Table 3.06). Although R1 tissue samples indicated a K deficiency at Richville in 2017, no yield response to K fertilization occurred nor were K deficiency symptoms observed from non-treated plots. The sufficiency range for soybean K tissue levels in Michigan was developed over two decades ago (Vitosh et al., 1995). Therefore due to new germplasm and greater yields, the sufficiency range may need to be adjusted, but not necessarily upwards as some practitioners' postulate (Stammer and Mallarino, 2018). Recent research by Clover and Mallarino (2013) and Stammer and Mallarino (2018) in Iowa determined soybean reproductive tissue K sufficiency ranges were 17.6 to 20.0 g kg^{-1} and 15.6 to 22.6 g kg^{-1}, respectively, providing additional evidence that Michigan K tissue sufficiency ranges may be too high. In combination with previous literature, results suggest growers should expect to see little or no response to in-season K fertilization when soil and tissue K concentrations exceed critical thresholds (Vitosh et al., 1995; Warncke et al., 2009; Clover and Mallarino, 2013; Stammer and Mallarino, 2018).

Although soil test S concentrations are presented (Table 3.01), no sufficiency ranges for soil S level are available in Michigan fertilizer recommendation guidelines (Vitosh et al., 1995; Warncke et al., 2009). Soil S sufficiency concentrations are difficult to assess due to SO_4-S variability, leaching, soil texture, and organic matter S contributions (Hitsuda et al., 2004; Kaiser and Kim, 2013; Franzen, 2015). Previous literature determined soybean tissue S concentrations and SOM content were better predictors of soybean S response rather than soil S (Hitsuda et al., 2008; Kaiser and Kim, 2013). Michigan fertilizer guidelines recommend 2.1 to 4.0 g kg^{-1} of S within the uppermost fully developed trifoliate at the R1 growth stage (Vitosh et al., 1995). All plant trifoliate samples collected at R1 prior to fertilization were within the recommended S sufficiency range (Table 3.06), likely influencing the lack of a yield response to S fertilization. In comparison, Bluck et al. (2015) did not observe a significant yield response to calcium sulfate application on soybean across 16 site-years in Ohio where R1 soybean tissue analysis was within the current recommended S sufficiency range (2.1 to 4.0 g kg^{-1}). Sandy soils with low SOM (< 20 g kg^{-1}) are the most prone to sulfur deficiencies (Barker et al., 2005; Warncke et al., 2009; Kaiser and Kim, 2013). Soil OM content was 30 g kg^{-1} at Richville in 2016 and 28 and 32 g kg^{-1} at Richville and Lansing, respectively, in 2017 (Table 3.01). Tissue R1 analysis and SOM content suggest adequate S was available for soybean growth across site-years.

Authors are not aware of other trials examining the use of an in-season, surface-band application of KTS applied directly at the base of the soybean plant at the R1 growth stage to enhance K and S fertilization. However, data suggest an additional yield benefit from utilizing an in-season, surface-banded K and S application is negligible when adequate nutrient levels and/or environmental conditions were present.

Foliar Zn, Mn, and B

Foliar application of fertilizer containing Zn, Mn, and B did not significantly impact grain yield in any site-year (Table 3.04). Non-significant yield responses were consistent with tissue samples taken from the uppermost R1 soybean trifoliate prior to fertilization which exhibited sufficient Zn (> 21 mg kg^{-1}), Mn (> 21 mg kg^{-1}), and B (> 21 mg kg^{-1}) concentrations in all site-years (Vitosh et al., 1995) (Table 3.06). Tissue concentrations indicated soybean Zn, Mn, and B requirements were sufficient and supplemental fertilization was not needed to maximize yield (Vitosh et al., 1995). In contrast to tissue concentrations, pre-plant soil test data indicated low soil levels of B (< 0.7 mg kg^{-1}) in one site-year and low Zn (i.e., deficiency defined utilizing function [(5.0 x pH) – (0.4 x soil test Zn mg kg^{-1})] – 32) in two site-years (Warncke et al., 2009) (Table 3.01). However, no visual deficiency symptoms were observed suggesting that soil critical levels may be too high.

Due to the overall absence and inconsistency of micronutrient deficiencies in Midwestern U.S. soils, developing soil and tissue test interpretations for micronutrients are difficult (Enderson et al., 2015; Sutradhar et al., 2017; Mallarino et al., 2017). Recent research by Enderson et al. (2015) in Iowa and Sutradhar et al. (2017) in Minnesota were unsuccessful in developing reliable soil and tissue test sufficiency ranges for specific soybean micronutrient concentrations as no significant responses to micronutrient fertilization occurred across 77 locations. Growers should not justify micronutrient fertilizer applications from a soil test or plant tissue analysis alone but simultaneous use of both tools can aid in soybean micronutrient deficiency diagnosis (Vitosh et al., 1994; Mallarino et al., 2017).

University recommendations also define specific crop species sensitivities to low micronutrient availability (Vitosh et al., 1994; Warncke et al., 2009). Over the last 70 years, soybean has been classified as having a moderate to low sensitivity to Zn and B, respectively, at low nutrient concentrations (Berger, 1949; Robertson and Lucas, 1976; Robertson et al., 1981; Vitosh et al., 1994; Warncke et al., 2009; Mallarino et al., 2017). Therefore, soybean response to Zn and B fertilization at low soil and/or tissue concentrations is unlikely (Vitosh et al., 1994; Warncke et al., 2009; Mallarino et al., 2017). In support, a recent bulletin published by Mallarino et al. (2017) summarized 99 soybean Zn trials and 88 soybean B trials from Minnesota, Iowa, and Kansas in which no soybean yield responses were observed from Zn and B fertilization at soil test levels as low as 0.3 and 0.2 mg kg^{-1} in Zn and B, respectively, and tissue test levels as low as 16 and 22 mg kg^{-1} in Zn and B, respectively (Enderson et al., 2015; Sutradhar et al., 2017).

In contrast to Zn and B, Mn is the most common micronutrient deficiency in Michigan (Vitosh et al., 1994; Warncke et al., 2009). Soybeans are highly sensitive to yield loss at low Mn concentrations with deficiencies likely to occur on high pH (> 6.5) soils, (e.g. lake beds, glacial outwashes, peats, and muck) (Vitosh et al., 1994; Warncke et al., 2009; Mallarino et al., 2017). In the current study, Mn soil concentrations were sufficient in all site-years (Table 3.01) (i.e., deficiency defined utilizing function [(6.2 x pH) – (0.35 x soil test Mn mg kg^{-1})] – 36) and tissue concentrations exceeded $\geq$ 21 mg kg^{-1} (Table 3.06) (Warncke et al., 2009). Soil and plant diagnostic results indicated supplemental Mn fertilization was not required and supported the non-significant yield response to foliar Mn applications. Growers should consider the likelihood of soybean responding to micronutrient applications (high, moderate, and low for Mn, Zn, and B, respectively) when choosing to apply a foliar micronutrient application placing greater emphasis on Mn, followed by Zn and B in Michigan production soils (Vitosh et al., 1994; Warncke et al., 2009).

In addition to soil and plant diagnostics and soybean micronutrient sensitivity, emphasis on specific soil properties and/or environmental conditions where deficiencies are likely to occur warrants consideration (Moraghan and Mascagni, 1991; Mallarino et al., 2017). For instance, Zn, Mn, and B are influenced by soil pH with the availability of all 3 nutrients decreasing at a soil pH > 6.5 (Moraghan and Mascagni, 1991; Vitosh et al., 1994; Alloway, 2008; Warncke et al., 2009; Mallarino et al., 2017). Additionally, cool temperatures and soil moisture content can inhibit microbial decomposition of SOM and plant root growth enhancing micronutrient deficiencies (Moraghan and Mascagni, 1991; Vitosh et al., 1994; Alloway, 2008; Warncke et al., 2009; Mallarino et al., 2017). Previous literature observed soil N and P supply, root exudates, pathogen pressure, soil compaction, and crop rotations all influence plant micronutrient availability (Sims, 1986; Moraghan and Mascagni, 1991; Vitosh et al., 1994; Alloway, 2008; Warncke et al., 2009). Due to difficulties associated with predicting crop micronutrient deficiencies, growers should utilize multiple diagnostic tools and techniques in combination with understanding soil physical and chemical properties and site-specific environmental conditions before adopting a micronutrient spray program (Moraghan and Mascagni, 1991; Vitosh et al., 1994; Alloway, 2008; Warncke et al., 2009; Mallarino et al., 2017).

Fungicide

Fungicide did not significantly impact grain yield in any site-year (Table 3.04). Minimal disease pressure due to dry weather conditions and lower relative humidities occurred across site-years (Table 3.03). Growing season (May – Sept.) rainfall averaged 30% and 35% below the 30-yr mean at Richville in 2016 and at both locations in 2017, respectively (Table 3.03). Below average total growing season rainfall and below average July rainfall during soybean R1-R3 growth stages in all site-years (Table 3.03), likely caused a reduction in specific soybean pathogen risks prevalent to Michigan (i.e., Septoria brown spot (*Septoria glycines*) and Sclerotinia stem rot (*Sclerotinia sclerotium*)) (Cruz et al., 2010; Fall et al., 2018). In addition to dry soil conditions, soybeans were planted in 76 cm rows which likely decreased canopy closure, increased air movement between plants, and reduced potential humid microclimates that encourage pathogen growth (Grau and Radke, 1984; Boland and Hall, 1988). Fungicide application may provide greater benefits in narrow-row (≤ 38 cm) soybean systems which often experience greater canopy coverage and humidity levels (Mahoney et al., 2015). The lack of soybean response to fungicide application in the current study is supported by several other reports which also failed to realize benefits from fungicide applications during below threshold levels of disease (Swoboda and Pedersen, 2009; Nelson et al., 2010; Gregg et al., 2015; Ng et al., 2018).

Although previous trials observed soybean physiological enhancements and yield increases following strobilurin fungicide applications, (Grossman and Retzlaff, 1997; Bartlett et al., 2002; Mahoney et al., 2015; Orlowski et al., 2016; Mourtzinis et al., 2017), results were inconsistent across treatments and site-years (Swoboda and Pedersen, 2009; Nelson et al., 2010; Gregg et al., 2015; Mourtzinis et al., 2016). Due to inconsistent strobilurin fungicide plant health and yield benefits and the greater risk for strobilurin resistance development (Henry et al., 2011), growers should be cautious when prophylactically applying fungicides, and may want to consider university recommended IPM resources to justify fungicide applications (Henry et al., 2011; Mahoney et al., 2015; Marburger et al., 2016; Mourtzinis et al., 2016).

Conclusions

Application of poultry litter, potassium thiosulfate, foliar micronutrients, and fungicide did not significantly increase soybean grain yield or producer economic net return across any site-year of this trial. A traditional management system was significantly more profitable than the intensive management system resulting in an average economic net return increase of \$501 ha^{-1}. Due to a lack of yield increase in this trial and high individual application and input costs, potassium thiosulfate and poultry litter significantly decreased net returns in one and all three site-years, respectively, within both the intensive and traditional management systems. Soybean plants did not express any obvious nutrient deficiencies or stress from pathogen infection during 2016 and 2017. Results support the continued use of university recommended IPM programs which stress the justification of input applications to match specific crop needs and optimize both grain yield and profitability. Soybean producers should look to incorporate a management system that utilizes various tools and techniques (i.e. crop scouting, disease prediction models, varietal selection, nutrient recommendations) to minimize and justify input applications rather than relying on prophylactic input applications as insurance against yield-limiting factors that may or may not occur.

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APPENDIX

Table 3.01. Soil descriptions, chemical properties, and mean nutrient concentrations (sample depth 0 – 20 cm) obtained prior to soybean planting, Richville and Lansing, MI, 2016-17.

Site	Year	Soil Description	Soil Test†							
			P	K	S	B	Mn	Zn	pH	OM
			---------------------mg kg^{-1} ---------------							g kg^{-1}
Richville	2016	Tappan-Londo Loam	48	182	8	1.6	44	6	7.1	30
	2017	Tappan-Londo Loam	30	191	7	1.7	40	5.8	7.7	28
Lansing	2017	Capac Loam	39	117	7	0.6	34	2.9	6.5	32

†P phosphorus (Bray–P1); K potassium (ammonium acetate extractable K); Zn zinc (0.1 M HCl extraction); Mn manganese (0.1 M HCl extraction); B boron (hot-water extraction).

Table 3.02. Overview of omission trial design, treatment names, and inputs applied, 2016-17.

Treatment	Treatment Name	Agronomic Input Applied			
		Litter†	KTS‡	Micro§	Fungicide¶
1	Intensive (I) #	Yes	Yes	Yes	Yes
2	I - Litter	No	Yes	Yes	Yes
3	I - KTS	Yes	No	Yes	Yes
4	I - Micro	Yes	Yes	No	Yes
5	I - Fungicide	Yes	Yes	Yes	No
6	Traditional (T)††	No	No	No	No
7	T + Litter	Yes	No	No	No
8	T + KTS	No	Yes	No	No
9	T + Micro	No	No	Yes	No
10	T + Fungicide	No	No	No	Yes

† Poultry Litter (litter) pre-plant incorporated at a rate of 0.9 Mg ha^{-1}.
‡ Potassium thiosulfate (KTS) surface-banded at a rate of 11.4 L ha^{-1} at R1.
§ Foliar micronutrients (micro) containing Zn, Mn, and B applied at a rate of 1.9 L ha^{-1} at R1.
¶ Prothioconazole + trifloxystrobin fungicide applied at a rate of 0.14 L ha^{-1} at R3.
# Intensive system containing all agronomic inputs.
†† Traditional system containing no fertilizer or additional inputs.

Table 3.03. Monthly cumulative precipitation† and mean daily temperature for the soybean growing season, Richville and Lansing, MI, 2016-17.

Site	Year	May	Jun.	Jul.	Aug.	Sept.	Total
		-----	-----	-----cm-----	-----	-----	-----
Richville	2016	1.59	4.04	8.81	13.08	5.16	32.68
	2017	5.00	12.27	2.79	5.71	3.96	29.73
	30-yr‡	8.68	10.01	9.32	8.55	9.75	46.31
Lansing	2017	6.58	8.36	6.73	3.48	3.28	28.43
	30-yr	8.45	8.89	8.28	8.38	9.22	43.22
		-----	-----	----- °C -----	-----	-----	-----
Richville	2016	14.8	19.7	22.6	22.4	19.3	--
	2017	13.7	20.4	21.2	18.2	17.9	--
	30-yr	13.1	18.6	20.5	19.5	15.7	--
Lansing	2017	13.5	19.9	21.8	19.3	17.9	--
	30-yr	14.7	20.0	22.1	21.3	16.9	--

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

Table 3.04. Mean soybean grain yield (Mg ha^{-1}) of intensive and traditional control treatments displayed. All other treatments represent change in grain yield from respective intensive or traditional control, Richville and Lansing, MI, 2016-17.

Treatment†	2016 Richville	2017 Richville	2017 Lansing
	---------- Mg ha^{-1} ----------		
Intensive (I)‡	4.31	3.73	3.92
I - Litter¶	+0.25	-0.31	-0.45
I - KTS	+0.28	-0.21	-0.29
I - Micro	+0.04	-0.16	-0.11
I - Fungicide	+0.10	+0.11	-0.05
Traditional (T)§	4.46	3.58	3.59
T + Litter#	-0.25	-0.01	+0.14
T + KTS	-0.19	+0.07	-0.12
T + Micro	-0.01	+0.14	-0.07
T + Fungicide	+0.05	+0.27	-0.06
I vs. T	ns††	ns	ns

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

† Poultry litter (litter), potassium thiosulfate (KTS), foliar applied Zn, Mn, and B (micro), and prothioconazole + trifloxystrobin fungicide.

‡ Intensive system containing all agronomic inputs.

§ Traditional system containing no fertilizer or additional inputs

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

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

†† Non-significant.

Table 3.05. Soybean net economic return (US$ ha^{-1}) in Richville and Lansing, MI, 2016-17.

Treatment†	2016 Richville	2017 Richville	2017 Lansing
		US$ ha^{-1}	
Intensive (I)‡	924.45	675.39	745.19
I - Litter¶	+458.60*	+247.22*	+200.21*
I - KTS	+165.55*	+1.54	-23.44
I - Micro	-65.82	-3.69	+14.48
I - Fungicide	-98.66	+96.38	+43.78
Traditional (T)§	1531.33	1152.67	1165.35
T + Litter#	-460.34*	-348.96*	-303.62*
T + KTS	-134.97*	-46.46	-108.30
T + Micro	-56.01	-3.89	-72.12
T + Fungicide	-44.43	+27.01	-78.53
I vs. T	*	*	*

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

† Poultry litter (litter), potassium thiosulfate (KTS), foliar applied Zn, Mn, and B (micro), and prothioconazole + trifloxystrobin fungicide.

‡ Intensive system containing all agronomic inputs.

§ Traditional system containing no fertilizer or additional inputs.

¶ Values in I - input rows indicate a net return (US$ ha^{-1}) change from respective intensive (I) treatment.

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

Table 3.06. Summary of soybean uppermost trifoliate K, S, B, Mn, and Zn concentrations taken prior to fertilization at the R1 growth stage, Richville and Lansing, MI, 2016-17.

		Tissue Nutrient Concentration†				
Site	Year	K	S	B	Mn	Zn
		-------------g kg^{-1}------------		---------------------mg kg^{-1}--------------------		
Richville	2016	25.5	3.0	45.0	44.8	48.3
	2017	18.4	3.6	41.3	43.8	30.0
Lansing	2017	21.3	2.8	40.3	58.0	36.3

† K potassium (ICP mass spectroscopy); S Sulfur (ICP mass spectroscopy); B boron (ICP mass spectroscopy); Mn manganese (ICP mass spectroscopy); Zn zinc (ICP mass spectroscopy).

LITERATURE CITED

LITERATURE CITED

Adeli, A., K.R. Sistani, D.E. Rowe, and H. Tewolde 2005. Effects of broiler litter on soybean production and soil nitrogen and phosphorus concentrations. Agron. J. 97:314-321.

Alloway, B.J., 2008. Micronutrients and crop production: An introduction. In: B.J. Alloway, editor, Micronutrient deficiencies in global crop production. Springer Science and Business Media, BV, Dordrecht. pp. 1-39.

Barker, D., J. Beuerlein, A. Dorrance, D. Eckert, B. Eisley, R. Hammond et al. 2005. Ohio agronomy guide. 14th ed. The Ohio State Univ. Ext. Columbus, OH.

Bartlett, D.W., J.M. Clough, J.R. Godwin, A.A. Hall, M. Hamer, and B. Parr-Dobrzanski 2002. The strobilurin fungicides. Pest Manage. Sci. 58:649-662.

Bender, R.R., J.W. Haegele, and F.E. 2015. Nutrient uptake, partitioning, and remobilization in modern soybean varieties. Agron. J. 107:563-573.

Berger, K.C. 1949. Boron in soils and crops. In: A.G. Norman, editor, Advances in Agronomy. Vol. 1. Academic Press, New York.

Bharati, M.P., D.K. Whigham, and R.D. Voss. 1986. Soybean response to tillage and nitrogen, phosphorus, and potassium fertilization. Agron. J. 78:947-950.

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

Boland, G.J., and R. Hall. 1988. Epidemiology of Sclerotinia stem rot of soybean in Ontario. Phytopathology. 78:1241-1245.

Brooker, A.P., L.E. Lindsey, S.W. Culman, S.K. Subburayalu, and P.R. Thomison. 2017. Low soil phosphorus and potassium limit soybean grain yield in Ohio. Crop, Forage, Turfgrass Manage. 1(1).

Clover, M.W., and A.P. Mallarino. 2013. Corn and soybean tissue potassium content responses to potassium fertilization and relationships with grain yield. Soil Sci. Soc. Am. J. 77:630-642.

Cruz, C.D., D. Mills, P.A. Paul, and A.E. Dorrance. 2010. Impact of brown spot caused by Septoria glycines on soybean in Ohio. Plant Dis. 94:820-826.

Dewal, G.S. and R.G. Pareek. 2004. Effect of phosphorus, sulphur and zinc on growth, yield and nutrient uptake of wheat (*Triticum aestivum* L.). Indian J. of Agron. 49:160-162.

Dick, W.A., D. Kost. And L. Chen. 2008. Availability of sulfur to crops from soil and other sources. In: J. Jex, editor, Sulfur: A missing link between soils, crops, and nutrition. Agron. Monogr. 50. ASA, CSSA, and SSSA, Madison, WI. p. 59-82.

Enderson, J.T., A.P. Mallarino, and M.U. Haq. 2015. Soybean yield response to foliar-applied micronutrients and relationships among soil and tissue tests. Agron. J. 107:2143-2161.

Fall, M.L., J.F. Boyse, D. Wang, J.F. Willbur, D.L. Smith, and M.I. Chilvers. 2018. Case study of an epidemiological approach dissecting historical soybean Sclerotinia stem rot observations and identifying environmental predictors of epidemics and yield loss. Phytopathology. 108:469-478.

Franzen, D.W. 2015. Sulfate-sulfur. In: M.V. Nathan and R. Gelderman, editors, Recommended chemical soil test procedures for the North Central Region. North Central Regional Publ. 221 (Rev. Aug. 2015). Publ. SB 1001. Univ. of Missouri Exp. Stn., Columbia. p. 35-40.

Gaspar, A.P., C.A.M. Laboski, S.L. Naeve, and S.P. Conley. 2017. Phosphorus and potassium uptake, partitioning, and removal across a wide range of soybean seed yield levels. Crop Sci. 57:2139-2204.

Grau, C.R., and V.L. Radke. 1984. Effects of cultivars and cultural practices on *Sclerotinia* stem rot of soybean. Plant Dis. 68:56-58.

Gregg, G.L., J.M. Orlowski, and C.D. Lee. 2015. Input-based stress management fails to increase soybean yield in Kentucky. Crop, Forage, Turfgrass Manage. 1(1).

Grossmann, K., and G. Retzlaff 1997. Bioregulatory effects of the fungicidal strobilurin kresoxim-methyl in wheat (*Triticum aestivum*). Pestic. Sci. 50:11-20.

Haq, M.U., and A.P. Mallarino. 2000. Soybean yield and nutrient composition as affected by early season foliar fertilization. Agron. J. 92:16-24.

Henry, R.S., W.G. Johnson, and K.A. Wise 2011. The impact of a fungicide and an insecticide on soybean growth, yield, and profitability. Crop Prot. 30:1629-1634.

Hitsuda, K. G.J. Sfredo, and D. Klepker. 2004. Diagnosis of sulfur deficiency in soybean using seeds. Soil Sci. Soc. Am. J. 68:1445-1451.

Hitsuda, K., K. Toriyama, G.V. Subbarao, and O. Ito. 2008. Sulfur management for soybean production. In: J. Jex, editor, Sulfur: A missing link between soils, crops, and nutrition. Agron. Monograph 50. ASA, CSSA, and SSSA, Madison, WI. p. 117-142.

Kaiser, D.E., and K.I. Kim 2013. Soybean response to sulfur fertilizer applied as a broadcast or starter using replicated strip trials. Agron. J. 105:1189-1198.

Mahoney, K.J., R.J. Vyn, and C.L Gillard. 2015. The effect of pyraclostrobin on soybean plant health, yield, and profitability in Ontario. Can. J. Plant Sci. 95:285-292.

Mallarino, A.P., D.E. Kaiser, D.A. Ruiz-Diaz, C.A.M. Laboski, J.J. Camberato, and T.J. Vyn. 2017. Micronutrients for soybean production in the north central region. Bull. 3145. Iowa State Univ. Ext., Ames, IA.

Mallarino, A.P., M.U. Haq, D. Wittry, and M. Bermudez. 2001. Variation in soybean response to early season foliar fertilization among and within fields. Agron. J. 93:1220-1226.

Marburger, D.A., B.J. Haverkamp, R.G. Laurenz, J.M. Orlowski, E.W. Wilson, S.N. Casteel, C.D. Lee, S.L. Naeve, E.D. Nafzinger, K.L. Roozeboom, W.J. Ross, K.D. Thelen, and S.P. Conley. 2016. Characterizing genotype x management interactions on soybean seed yield. Crop Sci. 56:786-796.

Moraghan, J.T., and H.J. Mascagni. 1991. Environmental and soil factors affecting micronutrient deficiencies and toxicities. In: J.J. Mortvedt et al., editor, Micronutrients in agriculture. 2nd ed. SSSA Book Ser. 4. Madison, WI. p. 371-425.

Morant, M.A., J.L. Casasola, C.B. Brooks, E.T. Philip, V.G. Mitchell, and C.R. Orr. 1997. Poultry litter enhances soybean productivity in field infested with soybean cyst nematode. J. Sustain. Agric. 11:39-51.

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

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

Nelson, K.A., and P.P. Motavalli. 2007. Foliar potassium fertilizer sources affect weed control in soybean with glyphosate. Crop Manage. doi:10.1094/CM-2007-0724-01-RS

Nelson, K.A., P.P. Motavalli, and M. Nathan. 2005. Response of no-till soybean [*Glycine max* (L.) Merr.] to timing of preplant and foliar potassium applications in a claypan soil. Agron. J. 97:832-838

Nelson, K.A., P.P. Motavalli, W.E. Stevens, D. Dunn, and C.G. Meinhardt. 2010. Soybean response to preplant and foliar-applied potassium chloride and strobilurin fungicides. Agron. J. 102:1657-1663.

Nelson, W.L., L. Burkhart, and W.E. Colwell. 1945. Fruit development, seed quality, chemical composition, and yield of soybeans as affected by potassium and magnesium. Soil Sci. Soc. Am. Proc. 10:224-229.

Ng, S.J., L.E. Lindsey, A.P. Michel, and A.E. Dorrance. 2018. Effect of mid-season foliar fungicide and foliar insecticide applied alone and in-combination on soybean yield. Crop Forage Turfgrass Manage. 4:1-6.

Orlowski, J.M., B.J. Haverkamp. R.G. Laurenz, D.A. Marburger, E.W. Wilson, S.N. Casteel, S.P. Conley, S.L. Naeve, E.D. Nafzinger, K.L Roozeboom, W.J. Ross, K.D. Thelen, and C.D. Lee. 2016. High-input management systems effect on soybean seed yield, yield components, and economic break-even probabilities. Crop Sci. 56:1988-2004.

Pettigrew, W.T. 2008. Potassium influences on yield and quality production for maize, wheat, soybean, and cotton. Physiologia Plantarum. 133:670-681.

Robertson, L.S., and R.E. Lucas. 1976. Essential micronutrients: Zinc. Bull. E1012. Michigan State Univ. Ext., East Lansing, MI.

Robertson, L.S., R.E. Lucas, and D.R. Christenson. 1981. Boron: An essential plant micronutrient. Bull. E1037. Michigan State Univ. Ext., East Lansing, MI.

Ruffo, M.L., L.F. Gentry, A.S. Henninger, J.R. Seebauer, and F.E. Below. 2015. Evaluating management factor contributions to reduce corn yield gaps. Agron. J. 107:495-505.

Sims, J.T. 1986. Soil pH effects on the distribution and plant availability of manganese, copper, and zinc. Soil Sci. Soc. Am. J. 50:367-373.

Slaton, N.A., T.L Roberts, B.R. Golden, W.J. Ross, and R.J. Norman. 2013. Soybean response to phosphorus and potassium supplied as inorganic fertilizer or poultry litter. Agron. J. 105:812-820.

Stammer, A.J., and A.P. Mallarino. 2018. Plant tissue analysis to assess phosphorus and potassium nutritional status of corn and soybean. Soil Sci. Soc. Am. J. 82:260-270.

Sutradhar, A.K., D.E. Kaiser, L.M. Behnken. 2017. Soybean response to broadcast application of boron, chlorine, manganese, and zinc. Agron. J. 109:1-12.

Swoboda, C., P. Pedersen 2009. Effect of fungicide on soybean growth and yield. Agron. J. 101:352-356.

Swoish, M.J. 2016. Identifying biotic and abiotic factors influencing soybean soil health and winter wheat production. M.S. Thesis. ProQuest Diss. Publ. UMI 10142549. Michigan State Univ.

Thurgood, L.L. 2014. Sulfur management in corn and soybean cropping systems. M.S. Thesis. ProQuest. Diss. Publ. UMI 1555157. Michigan State Univ.

Vitosh, M.L., D.D. Warncke, and R.E. Lucas. 1994. Secondary and micronutrients for vegetables and field crops. Bull. E486. Michigan State Univ. Ext., East Lansing, MI.

Vitosh, M.L., J.W. Johnson, and D.B. Mengel. 1995. Tri-state fertilizer recommendations for corn, soybeans, wheat, and alfalfa. Bull. E2567. Michigan State University Ext., East Lansing, MI.

Walter, A.J., and C.D. Difonzo. 2007. Soil potassium deficiency affects soybean phloem nitrogen and soybean aphid populations. Environ. Entomol. 36:26-33.

Warncke, D., J. Dahl, and L. Jacobs. 2009. Nutrient Recommendations for field crops in Michigan. Bull. E2904. Michigan State Univ. Ext., East Lansing, MI.

Watts, D.B., and H.A. Torbert. 2011. Long-term tillage and poultry litter impacts on soybean and corn grain yield. Agron. J. 103:1479-1486.

Watts, D.B., H.A. Torbert, S.A. Prior, and G. Huluka. 2010. Long-term tillage and poultry litter impacts soil carbon and nitrogen mineralization and fertility. Soil Sci. Soc. Am. J. 74:1239-1247.

Wood, B.H., C.W. Wood, K.H. Yoo, K.S. Yoon, and D.P. Delaney 1996. Nutrient accumulation and nitrate leaching under broiler litter amended corn fields. Commun. Soil Sci. Plant Anal. 27:2875-2894.