# IMPROVEMENT OF WINTER WHEAT AND SUGARBEET YIELD, GROWTH, AND QUALITY UTILIZING INTEGRATED NUTRIENT MANAGEMENT

By

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**ABSTRACT**

IMPROVEMENT OF WINTER WHEAT AND SUGARBEET YIELD, GROWTH, AND QUALITY UTILIZING INTEGRATED NUTRIENT MANAGEMENT

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The overwintering success of winter wheat (*Triticum aestivum* L.) along with heightened awareness of soil spatial variabilities have growers focusing more on season-long soil nutrient availability. Field trials were initiated in Richville and Lansing, MI to evaluate the effects of autumn starter, spring nitrogen (N), and varietal stature on winter wheat plant growth, grain yield, and expected net return. Application of autumn starter (i.e., mid and high treatments compared to no autumn starter) increased grain and straw yield in all site years. Autumn starter and spring N applications indicate above-recommended spring N did not compensate for the lack of autumn-applied starter during establishment. When fertilizing for straw production, varieties may respond to greater rates of autumn starter, but yield increases did not result in increased profitability.

One of the more severe foliar pathogens capable of causing damage to sugarbeet is *Cercospora beticola*, the causal pathogen of Cercospora leaf spot (CLS). Management strategies including boron (B)-containing compounds have shown to have fungistatic properties with the ability to reduce disease severity in the field. Field studies were established to investigate the effects of foliar applied B on sugarbeet plant health and CLS disease severity. Application of foliar B did not reduce CLS in field environments across site years. Complementary *in vitro* studies were conducted to test B effects on *C. beticola* mycelial growth. *Cercospora beticola* $EC_{50}$ values were 772-876 mg $kg^{-1}$ for sodium tetraborate. Reduced control options, increased CLS resistance, and increase B requirement of sugarbeet enhance the need for further evaluation.

Dedicated to my dad for his impeccable strength, courage, and determination to remain steadfast no matter what obstacles life may bring. Forever in our hearts.

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# CHAPTER 1

# LITERATURE REVIEW

## Wheat Classification

Wheat (*Triticum* spp.) classification is derived from various physical factors including kernel color (red or white), growing season and vernalization period (spring or winter), and seed hardness (hard or soft) (Mcfall & Fowler, 2009). The six classes of wheat grown in the United States include hard red winter, hard red spring, soft red winter, soft white, hard white, and durum (Sherman et al., 2008). Variation in physiological characteristics determine the optimum usage and marketing for wheat classes. Grain standards for marketing wheat were established by the U.S. Grain Standards Act of 1916 and the U.S Grain Quality Improvement Act of 1986 (Slaughter et. al., 1992). The purpose of these acts was to establish official U.S. grain standards used to measure and describe the physical and biological properties of the grain at the time of inspection (Womach, 2005). Wheat cultivars are further classified by protein content, gluten quality for elasticity, and grain color resulting in diversity of carotenoid pigments (Shewry, 2009).

Hard red winter wheat (HRWW) accounts for nearly 40% of the total wheat crop in the U.S. and is primarily grown in the Great Plains and California (USDA, 2020). It has moderately high protein content (i.e., 11–12%), making it well suited for pan bread, rolls, flat breads, and all-purpose flour (Tilley et al., 2012). Hard red spring wheat (HRSW) is grown in the Northern Plains of the upper Midwest, specifically Montana, Minnesota, North Dakota and South Dakota (USDA, 2020). HRSW has a high protein content (i.e., 13-14%) and is predominantly used for croissants, bagels, buns, pizza crust and a blending wheat (Tilley et al., 2012). Soft red winter

(SRWW) is grown in eastern regions of the U.S. and accounts for 18.5% of production (USDA, 2020). SRWW has a soft kernel texture and low protein content making it ideal for pastries, cakes, crackers, and various snack foods (Tilley et al., 2012). Durum wheat is a spring wheat produced primarily in the Northern Plains of the upper Midwest, although a small quantity of winter-sown durum is grown in Arizona and California (USDA, 2020). Durum has the hardest kernel texture and protein content (i.e., >15%) of the wheat classes and is milled for pasta products or specialty breads (Tilley et al., 2012). Soft white wheat (SWW) wheat makes up 10% of U.S. production and is grown in the Pacific Northwest (USDA, 2020). Similar to SRW wheat, its soft texture is ideal for pastries, cakes, biscuits, crackers, snack foods, and flat breads (Tilley et al., 2012). SWW comprises 20% of total US wheat exports with most of it going to Asia and the Middle East. Hard white wheat (HWW) is grown in both spring and winter seasons in the Pacific Northwest (Washington, Oregon and Idaho) and some Great Plains and Northern Plains states (USDA, 2020). HWW has similar baking properties to HRW, ideal for Asian noodles and whole-wheat pan breads (Tilley et al., 2012). HWW makes up 1% of US production with limited export (USDA, 2020).

## Michigan Wheat Production

Michigan produces some of the highest winter wheat yields in the nation. On average, wheat is grown on 202,000 hectares in 75 of Michigan's 83 counties (MDARD, 2018). The top producing counties are Huron, Tuscola, Sanilac, Lenawee, and Shiawassee located on the eastern side of the state (MDARD, 2018). In 2019, Michigan harvested a total of 1,115,889 Mg of wheat with an average yield of 5,111.08 kg ha$^{-1}$ (USDA-NASS, 2019). Michigan wheat growers produced an average of 5,043.83 kg ha$^{-1}$ totaling $180,563,000.00 in production for the 2020 growing season (USDA-NASS, 2020). The national winter wheat average yield was 3604.66 kg ha$^{-1}$ in 2019 (USDA-NASS, 2019). From 2012-2014, Michigan ranked first in the Midwest in grain yield, exceeding the consistent top five placement nationally (USDA-NASS, 2014). In addition, a new state record was established in 2015 of 5447 kg ha$^{-1}$ (USDA-NASS, 2015).

## Management Strategies

With a predicted world population of 9 billion in 2050, the demand for wheat is expected to increase by 60%. To meet this demand, annual wheat yield increase must rise from the current level of below 1% to at least 1.6% (GCARD, 2012). For maximum production, methods of determining nitrogen (N) fertilization rates in winter wheat are based on fixed N removal rates per unit of produced grain and projected yield goals (Lukina et al., 2001). Variation in N usage and yield potential of varieties influence fertilization practices based on estimates of early-season plant N uptake and potential yield (Lukina et al., 2001). Studies to evaluate multiple input applications to prevent plant stress and enhance grain yield potential have been a focus in wheat production (Beuerlein et al., 1989; Karlen & Gooden, 1990). Responses to enhanced input application are often specific to wheat variety and environmental conditions (Beuerlein et al., 1989; Karlen & Gooden, 1990). Similar results were confirmed by Mohammed et. al (1990) as no yield response was observed with increased N application, fungicide, and plant growth regulator usage. Primary yield benefits are attributed to adequate water supply, absence of disease pressure, and the short stature of the variety studied (Mohamed et al., 1990).

Variety selection is an important management strategy to achieve high yielding grain and straw. Variation in plant height correlates to straw production and growth in stressed environments (Pinthus, 1974). Taller varieties are more suitable for stressed environments for successful emergence and combing harvest (Pinthus, 1974). In addition to plant height, selecting varieties that are less susceptible to lodging and shattering is important to both grain and straw production (Klein, 2007). Plant lodging in small grains is caused by failure of roots to anchor the plant or bending of the internodes near the culm base (Pinthus, 1974). Lodging may be enhanced by excessive nitrogen fertilization, incorrect fertilization timing, and environmental conditions. Shorter (semi-dwarf) varieties are less susceptible to lodging while varieties with upright stature incur less hail damage (shattering) (Klein, 2007). While short statured varieties are often overlooked for straw production, semi-dwarf varieties can be top-ranking for economic yield (Annicchiarico et al., 2005). When economic assessment of straw value is expressed in terms of grain-equivalent, (defining an economic yield as: grain yield+(0·30×straw yield)), tall germplasm showed higher grain yield stability, lower straw yield stability and slightly higher economic yield than semi-dwarf varieties measured by Shukla's stability variance (Annicchiarico et al., 2005).

Evaluation of current, mid, and high-level management intensities have highlighted benefits of protecting wheat health and yield potential with utilization of fungicides, growth regulators, and micronutrients (Roth et al. 2021). Increasing management intensity from current strategies to mid- or high levels significantly increased straw yield by 1.2-1.2 Mg ha $^{-1}$, grain yield by 0.81 – 1.22 Mg ha $^{-1}$, and grain test weight by 2.6 -3.2 kg hl $^{-1}$ from 2016 – 2019, respectively (Roth et al. 2020). In addition to manipulation of various inputs, increases in straw production are heavily reliant on early planting date (Donaldson et al., 2001). A three-year study from the Washington State University Dryland Research Station reported straw production more than doubled in August – September planting dates as compared to October seeding (Donaldson et al., 2001). The quantity of straw decreased ≈30% per month, resulting in 71 and 42% of the August amount for September and October, respectively (Donaldson et al., 2001).

## Nitrogen

The response to N application in wheat is more significant than any other nutrient (Nagelkirk, 2016). Studies have shown that there is variation in nitrogen utilization, uptake, and recovery efficiency between wheat varieties (Belete et al., 2018). Nitrogen is responsible for the production of a photosynthetically active plant canopy and is required for grain storage proteins for improved cereal quality (Hawkesford, 2014). Nutritional and milling characteristics of wheat are influenced by amino acid composition and protein content, markedly influenced by nitrogen fertilization (Ruisi et al., 2015). However, the adoption of excessive nitrogen applications has shown to increase lodging, disease pressure, and harmful environmental effects due to N losses through leaching and volatilization (Kanampiu et al., 1997, Warncke et al., 2009). Application timing, rate of N applied, and precipitation has a major influence on plant use efficiency of top-dressed N (Alcoz et al., 1993).

The standard N recommendation for Michigan winter wheat is 0.018 mg N kg grain$^{-1}$ (Nagelkirk, 2014). Single applications are typically applied between mid-late April depending on green-up timing and environmental conditions (Nagelkirk, 2014). Split applications may be necessary when fall establishment is not ideal. To encourage tiller development in the spring, N may be applied on frosted, not frozen field conditions, followed by an additional application at or near jointing (Nagelkirk, 2014). Increase in N rate can promote tiller production and increase the number of stems (Engstrom & Bergkvist, 2009). From stem elongation to anthesis, rapid growth of productive and unproductive tillers greatly increases N requirement of wheat (Lu et al., 2016). Throughout this growth, changes in stem quality can fluctuate resulting in substantial differences between strong and weak tillers (Davidson & Chevalier, 1990). Wheat grain yield is mainly attributed to maintaining optimal stem number, the number of productive stems, and achieving optimal biomass of productive stems (Zhang et. al, 2020).

Nitrogen application timing and rate may vary based on wheat variety and plant height. Lodging is one of the key limitations to wheat yield and quality in both developed and developing countries (Foulkes et al., 2011). Increasing N rates, in combination with high winds and spring weather volatility increase risk and incidence of wheat lodging (Swoish & Steinke, 2017). Reduction of photosynthetic capacity provides a favorable environment for fungal growth, leaf disease, and limitations to harvestability (Piñera-Chavez et al., 2016).

Recommendations for N application first include gaining an understanding of the spatial distribution of N deficiencies in fields (Roth et al. 2020). N fertilization of winter wheat is impacted by residual soil nitrate levels dependent on frequency of crop rotation and preceding crop (Mourtzinis et al., 2017). Soil nitrate levels are higher following grain corn production than soybeans as N removed by legume crops may exceed biological fixation (Katupitiya et al. 1997). To promote autumn tillering and stand establishment, no more than 28.02 kg N $ha^{-1}$ should be utilized in Michigan winter wheat production (Warncke et al., 2009). In four site years, Quinn and Steinke (2019) found no yield response to a 20% N rate increase above Michigan State University recommendations in both soft red winter wheat and soft white winter wheat.

**Sulfur**

The interaction between sulfur and N has shown to have an impact on the physiological attributes to wheat biomass and grain yield, however, it has not been deeply studied on a scale of mass production (Salvagiotti & Miralles, 2008). Research has demonstrated that N use efficiency can be increased when there is no sulfur deficiency of the current crop (Salvagiotti & Miralles, 2008). Nutrient interactions in crop plants occur when the availability of a nutrient is directly impacted by the absorption and utilization of other nutrients (Fageria, 2001). These interactions result in changes at the subcellular level that impact cell division, photosynthesis, respiration rates, and translocation of organic acids and carbohydrates. These alterations determine the final yield of the crop (Fageria, 2001).

Sulfur is a component of two amino acids and occurs in the plant with a ratio of 1 part sulfur to 15 parts N (Camberato & Casteel, 2010). Due to a decrease in atmospheric sulfur, synthetic fertilizers are used to obtain recommended sulfur levels including: ammonium sulfate (21-0-0-24S), ammonium thiosulfate (12-0-0-26S), elemental sulfur (0-0-0-80S), potassium sulfate (0-0-42-18S), and gypsum (0-0-0-18S) (Dick et al., 2008). Additional organic sources of sulfur include: crop residues (0.10-0.22% S), biosolids (0.3-1.2% S), dairy manure (0.22% S), poultry manure (0.5% S), and sheep manure (0.35% S) (Dick et al., 2008). Sulfur exists in the soil profile as sulfate ($SO_4^{2-}$) or elemental sulfur ($S^0$) (Isleib, 2011). Similar to nitrate, sulfate is a water-soluble anion that is readily available for plant uptake (Isleib, 2011). Though plants can absorb sulfate quickly, its solubility causes it to be extremely mobile and prone to leaching out of the root zone (Isleib, 2011). This is enhanced in course textured, well-drained soil types that are low in organic matter (Dick et al., 2008).

Commercial sulfur fertilizer sources include either elemental or sulfate forms of sulfur. Sulfate sulfur forms such as gypsum or ammonium sulfate, contain readily available sulfur, while elemental sulfur must be oxidized for plant uptake (Kaiser, 2019). Elemental sulfur is insoluble in water and works as a slow release S fertilizer due to its low mobility making it a good option for fall fertilization (Bouranis et al., 2019). The demand for fertilizers with higher sulfur use efficiency has intensified over the last decade due to sulfur deficiency in crops becoming more wide spread (Bouranis et al., 2019). Sulfur deficiency in agronomic crops is more prevalent due to a decrease in sulfur deposition into the atmosphere from power plants and industrial sources (Camberato & Casteel, 2017). Purdue University has monitored decreases in soil sulfur concentrations derived from atmospheric sources and have observed changes in levels from 13-18 pounds per acre in 2001 down to < 10 pounds per acre as of 2015 (Camberato & Casteel, 2017). These decreases have resulted in the need for growers to supplement fertilizer sources with sulfur to maintain critical levels for crop production.

## Phosphorous

Phosphorus (P) is the second most important nutrient after N among all vital plant nutrients (Kizilgeci, 2018). Phosphorous is crucial for plant development from seedling to physiological maturity in wheat. It plays a major role in seed formation, grain quality, uniform heading, and overwintering strength as a result of its involvement in cellular energy transfer, respiration, and photosynthesis (Shabnam et al., 2018). Phosphorous is absorbed by plants in the form of orthophosphate ($H_2PO_4^-$ and $HPO_4^{2-}$) (Hinsinger, 2001). P availability is often limited in acidic soils due to minimal inorganic P concentrations in soil solution (Shabnam et al., 2018). Inorganic phosphorous binds strongly to soil surfaces and forms insoluble complexes with soil cations such as Fe and Al (Talboys et al., 2014). Mineralization of organic phosphorous is enhanced by microbial activity for conversion to orthophosphate forms for plant uptake (Hyland et al., 2005). Compared with the other major nutrients, phosphorus is the least mobile and available to plants in most soil conditions; therefore, it is frequently a major limiting factor for plant growth (Hinsinger, 2001).

Phosphorous fertilization can be completed with various commercially available P products. These products include: monoammonium phosphate (11-52-0), diammonium phosphate (18-46-0), polyphosphate (10-34-0 and 11-37-0), various manure sources, and organic rock phosphate (Roberston et al., 2012). Having available soil P and K in the adequate zone provides the opportunity for excellent yields when growing conditions are favorable (Warncke et al., 2009). Applying sufficient P to achieve adequate soil nutrient levels should be based on current soil test levels for optimum crop production (Warncke et al., 2009).

## Zinc

Zinc is a common micronutrient deficiency in wheat growing in diverse climatic regions (Rengel & Graham, 1995). Widespread zinc deficiency in wheat is a result of high $CaCO_3$ and pH paired with low levels of soil moisture and organic matter (Torun et al., 2001). The mobility and availability of zinc sourced from soil and applied fertilizer is limited by these conditions (Torun et al., 2001). Zinc is responsible for driving many metabolic reactions in crops and is a component of various plant enzymes that regulate growth and development (Keiser & Rosen, 2016). When a zinc deficiency is present, carbohydrate, protein, and chlorophyll formation is significantly reduced resulting in a direct impact on wheat yield and straw production (Keiser & Rosen, 2016). In addition to growth and development, high grain zinc is considered a desirable quality factor that contributes to seedling vigor and increased nutritional level of the following generation (Rengel & Graham, 1995).Without adequate zinc fertilization, the growing world population could experience human zinc deficiency due to high dependence on cereal grains for caloric intake (Arif et al., 2017).

Studies have shown that the effect of Zn application can be significant on the grain yield (q/ha), straw yield (q/ha), and sterility percentage but have no effect on spike length, thousand grain weight and harvest index (Firdous et al., 2018). A field experiment conducted by the Department of Soil Science and Agricultural Chemistry, BAU in 2012-2014, evaluated the effect of zinc (Zn) on the yield and yield contributing factors of wheat to determine the optimum dose and fertilization method for yield maximization (Firdous et al., 2018). The observed increase grain yield was attributed to the improved physiology of plants that enhanced the efficiency of various enzymes, improvement of nitrate conversions to ammonia for plant uptake, and increased chlorophyll content (Abbas et al., 2010; Hacisalihoglu et al., 2003). Increased straw yield was significantly superior with a split application of zinc (Firdous et al., 2018). The harvest index displayed a different partitioning behavior than observed for grain yield; however, the differences in harvest index were non-significant (Firdous et al., 2018). Additional studies have confirmed that the increase in grain and straw yield may be associated with zinc's impact on increasing capacity for water uptake and transport, ultimately reducing the adverse effects of heat stress and soil salt content (Peck & McDonald, 2010).

**Straw Usage**

Straw from small grains is one of the largest potential sources of feed for maintenance of ruminant animals (White et al., 1981). In recent years, the usage of straw in dairy heifer diets has increased due to high fiber content and low crude protein (Anderson & Hoffman, 2006). Straw is commonly added to dilute energy content to prevent over-conditioning. Over conditioned cows are at risk for metabolic issues during calving as a result of low or excessive fat content (Ishler, 2014). Straw is rationed into feed to reduce the nutrient (primarily energy) density of the diet (Anderson & Hoffman, 2006). Low inclusion rates of straw are often implemented for lactating dairy cows to assure fiber adequacy and stimulate rumination (Anderson & Hoffman, 2006). Straw may also be added to increase dry matter content and alter dietary cation to anion ration (Undersander & Kelling, 2001).

Straw inclusion typically ranges from 2.7 – 5.4 kg per cow, per day based on straw availability, cost, and total mixed ration constraints (Shaver & Hoffman, 2010). According to the

Team Forage Division of the University of Wisconsin Extension, wheat straw contains the following nutrient values: 93.6% dry matter, 4.6% crude protein, 78.8% neutral detergent fiber / 39% NDF digestibility, 1.6% fat, and 37.6% total digestible nutrients (Shaver & Hoffman, 2010). Dairy producers wishing to dilute energy-dense diets should test all key lots of straw (Anderson & Hoffman, 2006). Nutrient content of straw can be predicted near-infrared reflectance spectroscopy (NIRS) equations to evaluate dry matter, crude protein, neutral detergent fiber, NDFD, fat and ash. These nutrients are required to calculate an accurate energy estimate for small grain straws to accurately ration into current feeding practices (Anderson & Hoffman, 2006).

**Straw Nutrient Removal and Economic Implications**

Essential elements such as N, potassium (K), and phosphorous (P), directly influence the growth and quality of all field crops (Warncke et al., 2009). In addition to establishing proper nutrition for crop growth, it is important to recognize nutrient removal from the harvested grain and biomass removed from a cropping system (Silva, 2017). From a pure nutrient standpoint, wheat straw contains very little in terms of P and moderate amounts of N and K (Gross, 2016). According to Michigan State University Extension bulletin E-2904, "Nutrient Recommendations for Field Crops in Michigan", one metric ton of wheat straw contains 5.4 kg of N, 1.4 kg of phosphorous, and 9.4 kg of potassium, respectively (Warncke et al., 2009). Variation in nutrient content is based on environmental conditions of the growing season and soil nutrient supply (Gross, 2016).

Average pricing of N, $P_2O_5$, and $K_2O$ costs \$0.42, \$0.50, and \$0.34 per pound (Silva, 2017). Therefore, based on average nutrient removal, a ton of straw will contain approximately \$14.93 worth of nutrients. It is important to consider variation in nutrient pricing and yield to evaluate the cost of removal on a year to year basis (Gross, 2016). When calculating removal, average wheat straw yields are approximately 3.36 Mg $ha^{-1}$ ton per acre and can reach over 4.48 Mg $ha^{-1}$ in exceptional production years (Gross, 2016). Factors such as plant height, cutting height, and moisture directly influence average yields. Market demand for wheat straw is continuing to increase from year to year. Mid-Michigan growers have taken an advantage of an increase in straw pricing from 2017-2020. Average straw pricing, when marketed to large-scale dairy operations, has increased from $85.00 per ton in 2017 to $140 per ton for the 2020 growing season. Factors such as quantity, trucking, grain marketability, and market source directly influence the pricing available for wheat growers throughout the state.

In addition to nutrient removal and straw pricing, harvesting wheat straw has a direct impact on soil carbon levels (Li et al., 2016). Straw incorporation is a widely recognized strategy for increasing soil organic carbon (SOC), sequestration, and improving soil quality and crop productivity (Li et al., 2016). Leaving crop residues on the soil surface, use of no-till, and use of cover crops add organic matter that increase soil respiration and soil microbial activity (Ditzler & Tugel, 2002). Crop residues with a low carbon to nitrogen (C:N) ratio such as soybean residue decompose faster than crop residues with a high C:N ratio such as wheat straw (Ditzler & Tugel, 2002). Crops producing high residue increase decomposition and accrual of soil organic matter (SOM) when coupled with N from any source (Ditzler & Tugel, 2002). C:N ratio, soil moisture, and soil temperature each determine the rate of mineralization of SOM and soil respiration (Lentz & Lindsey, 2017). The USDA reports a C:N ratio of 80:1 for wheat straw indicating that mineralization occurs at a slow rate (Lentz & Lindsey, 2017). A replicated study conducted in 2008-2012 in the Guanzhong Plain determined that despite slow mineralization, straw return was effective in increasing carbon sequestration and grain production, increasing grain yield and sustainable yield index (SYI) value, and a minimum C input of 4.07 Mg $ha^{-1}$ per year was required to maintain SOC level (Li et al., 2016). Aside from providing nutrients, it can be concluded that straw has value as organic matter, but it is challenging to determine the dollar value in various cropping systems (Lentz & Lindsey, 2017). The most accurate analysis for carbon removal, nutrient removal, and economic impact of wheat straw harvest should be done by soil testing for each grower (Lentz & Lindsey, 2017).

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# CHAPTER 2

# WINTER WHEAT GRAIN AND STRAW IMPACTS FROM AUTUMN STARTER AND SPRING NITROGEN FERTILIZER STRATEGIES


## Abstract

The establishment and overwintering success of winter wheat (*Triticum aestivum* L.) are determining yield factors in Michigan. Increased demand for straw production and the economic value has practitioners questioning agronomic strategies to improve wheat yield potential and nutrient efficiency. Previous studies indicate positive response to autumn starter but impacts on straw production have not been widely studied. An eight site-year trial was established in Richville and Lansing, MI to evaluate soft red winter wheat (SRWW) and soft white winter wheat (SWWW) grain and straw yield response to autumn starter fertilizer, spring nitrogen (N), and varietal stature (i.e., short vs. tall varieties). Application of autumn starter (i.e., mid and high treatments compared to no autumn starter) increased grain and straw yield in all site years. Net profitability analysis of grain and straw demonstrated positive increase to application of autumn starer in six of eight site years. Treatments containing autumn starter resulted in lower harvest index (HI) suggesting that plant biomass (i.e. straw yield) was more responsive to autumn starter in short-statured varieties. Overall, autumn starter and spring N applications indicate above recommended spring N did not compensate for the lack of autumn applied starter during establishment. Low pre-plant residual nitrate concentrations, inclusion of sulfur, and timely autumn planting likely resulted in the positive grain and straw yield response to autumn starter fertilizer observed in this study.

## Introduction

The overwintering condition and success of winter wheat (*Triticum aestivum* L.) along with heightened awareness of soil spatial variabilities have growers focusing more on season-long soil nutrient availability. Michigan produces some of the greatest wheat yields in the U.S. averaging 5.04-5.44 Mg $ha^{-1}$ in 2020-2021 (USDA-NASS, 2020-2021). Utilizing agricultural inputs to maximize grain yield has led to an increase in intensively managed wheat systems (Khan and Spilde, 1992; Mohamed et al., 1990). As the demand for wheat grain and straw increases (i.e., livestock bedding, feed, and biofuel), nutrient management strategies that optimize both grain and straw yield are critical to improve the economic return for growers, address climate uncertainties, and ultimately increase production acres.

Studies evaluating wheat yield response to intensive management show variable response to additional fertilizer application in the absence of nutrient-loss conditions or visual deficiencies (Gooden et al., 1990; Quinn & Steinke, 2019; Steinke et al., 2021). Quinn and Steinke (2019) found no yield response to N rates 20% above university recommendations in both SRWW and SWWW. Steinke et al. (2021) found autumn starter fertilizer increased yield 0.6 – 1.7 Mg $ha^{-1}$ while removal of autumn starter fertilizer reduced yield by 1.0-2.5 Mg $ha^{-1}$ resulting in the greatest impact on wheat growth and grain production, even larger than above-recommended or late-applied N. Mohammed et. al (1990) observed similar results, as increased N application, fungicide, and plant growth regulator usage failed to increase yield. Yield increases were attributed to adequate water supply, absence of disease pressure, and the short-stature of the variety studied (Mohamed et al., 1990). While input intensive management continues to gain interest amongst wheat growers, nutrient efficiency and profitability still warrant greater consideration.

Autumn starter fertilizer may help satisfy nutritional needs of seedlings by promoting interception of nutrients within the zone of undeveloped root systems (Abit et al., 2016). Starter fertilizers provide nutrients to developing roots, promote autumn root growth, improve nutrient uptake, increase biomass yield (i.e., straw), and increase grain yield (Nkebiwe et al., 2016). To facilitate plant root uptake and availability longer into the season, pre-plant or at-plant starter fertilizer, including micronutrients, may be a key component within intensive wheat management systems. Application of autumn starter fertilizer provides greater nutrient availability during early crop development, potentially impacting yield (Nkebiwe et al., 2016; Steinke et al., 2021). Response to autumn starter fertilizer may be impacted by residual soil nitrate levels, crop rotational diversity, and planting dates (Donaldson et al., 2001; Mourtzinis et al., 2017). Nitrogen fertilization rates in winter wheat are often based on fixed N removal rates per unit of produced grain and projected yield goals (Arnall et al., 2009; Lukina et al., 2001; Raun et al., 2005). Previous studies indicated a positive correlation between wheat yield and biomass production (Baker, 1982; Donaldson et al., 2001). Nitrogen deficiency during establishment may result in reduced tiller counts and growth rates, limiting both grain yield and biomass production prior to initial stem development (Longnecker et al., 1993; Zhang et al., 2020). To promote autumn plant tillering and stand establishment, 28 – 34 kg $ha^{-1}$ N may be regionally-recommended (Alley et al., 2009; Warncke et al., 2009; Weisz and Heiniger, 2004). Variation in N utilization, uptake, yield potential, and recovery efficiency among wheat varieties may influence nutritional needs based on cultivar selection and early-season plant uptake (Belete et al., 2018; Lukina et al., 2001).

While practitioners often focus on individual nutrient applications and availabilities, synergistic interactions between nutrients may influence plant response. Nutrient interactions in crop plants occur when the availability of a nutrient is directly impacted by the absorption and utilization of other nutrients (Fageria, 2001). For example, N application may increase biomass growth and development, which may require additional P or S to support growth or risk becoming a limiting factor. Nutrient interactions result in changes at the subcellular level that impact cell division, photosynthesis, respiration rates, and translocation of organic acids and carbohydrates (Fageria, 2001). The interaction between S and N impacts physiological attributes to wheat biomass and grain yield, but has not been well-studied (Salvagiotti & Miralles, 2008).

Sulfur (S) has received increased interest over the last decade due to decreased atmospheric deposition (Camberato & Casteel, 2017; Dick et al., 2008; Steinke et al., 2015). Sulfur is a component of two amino acids and occurs within the plant at a ratio of 1 part S to 15 parts N (Camberato & Casteel, 2010). Commercial fertilizer sources include elemental or sulfate forms of S. Sulfate (i.e., gypsum or ammonium sulfate) contains readily available S, while elemental must be oxidized for plant uptake (Kaiser, 2019). Elemental S is insoluble in water and may work as a slow-release S fertilizer due to poor soil mobility, making this source a better option for autumn fertilization (Bouranis et al., 2019). The demand for fertilizers with higher S use efficiency has intensified over the last decade due to S deficiency in crops becoming more wide spread (Bouranis et al., 2019). In Michigan, yield increases ranging from 0 - 0.67 Mg $ha^{-1}$ have been inconsistent with applications of 28 kg $ha^{-1}$ of sulfate S applications. (Olsen et al., 2021) Factors such as previous crop, fertilization history, precipitation volumes, and soil texture and physical properties influence variabilities in yield response. Despite yield discrepancies, most S uptake occurs during grain-fill, not vegetative growth, and thus season-long availability of S may be required (Bender et al., 2013).

Responses to intensive management can be specific to wheat variety and environmental conditions (Beuerlein et al., 1989; Karlen & Gooden, 1990). Variety selection is an important management strategy for achieving high yielding grain and straw (Pinthus, 1974). Tall wheat varieties are better suited for stressed environments due to improved emergence and harvestability, but selecting shorter varieties less susceptible to lodging and shattering reduces risk for harvest loss and yield limitations (Klein, 2007). Semi-dwarf wheat cultivars improve biological efficiency, as shorter cultivars produce less straw per unit of grain than conventional height cultivars (Donaldson et al., 2001a). In comparison to semi-dwarf germplasm, taller cultivars tend to increase straw yield and aboveground biomass with lower grain yield and decreased harvest index (HI) (Annicchiarico et al. 2005). Although, short-statured varieties are often overlooked for straw production, responses to input applications have overcome limitations specific to wheat variety and environmental conditions (Beuerlein et al., 1989; Karlen & Gooden, 1990).

By utilizing inputs aimed at increasing grain yield, wheat straw as a secondary product may enhance grower profitability. While livestock bedding and feed rations continue to drive demand for wheat straw, other uses such as erosion control, biofuel, and growth media for specialty vegetable production are increasing in demand (Battaglia et al., 2021; Olsen et al., 2021; Reiter et al., 2015). Although taller wheat generally produces more straw, greater grain yields often do not translate to increased straw production (Lee and Grove, 2005). Straw production may range between 1.68 – 4.48 Mg $ha^{-1}$ with some states using a straw HI value of 80% (i.e., straw yield is 80% of grain yield) (Thomason et al., 2005). At 2021-2022 commodity and input prices, improving straw harvest may enhance grower profitability and increase acres planted. However, straw nutrient removal values must be considered prior to adoption and implementation of management strategies. Effective fertilizer management is crucial to future efficiency of wheat grain and straw production

The objectives of this study were to 1) determine whether autumn-applied starter fertilizer rate and rate of spring N application influenced wheat grain yield, straw production, and grower profitability in short and tall- statured winter wheat varieties and 2) evaluate whether autumn starter fertilizer or spring N affected straw nutrient removal concentrations necessitating revisions to current guidelines.

## Materials and Methods

Soft red winter wheat (SRWW) field trials were established at the Michigan State University 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) were 28 to 31 g $kg^{-1}$ soil organic matter (loss-on-ignition) (Combs and Nathan, 2015), 6.8 - 7.0 pH (1:1 soil/water) (Peters et al., 2015),  35-42 mg $kg^{-1}$ P (Bray-P1) (Frank et al., 2015), 91 - 99 mg $kg^{-1}$ K (ammonium acetate method) (Warncke and Brown, 2015), 7 - 8 mg $kg^{-1}$ S (monocalcium phosphate extraction) (Combs and Nathan, 2015), and 3.1 - 3.8 mg $kg^{-1}$ Zn (0.1 M HCl) (Whitney, 2015). Prior to planting, soil samples (0-30 cm) for nitrate-N ($NO_3$-N) analysis were collected, air-dried, and ground to pass through a 2 mm sieve. Pre-plant soil $NO_3$-N concentrations were 3.5 - 5.9 mg $NO_3$-N $kg^{-1}$ soil (nitrate electrode method) in both years (Gelderman and Beegle, 1998). Preceding crop was silage corn (*Zea mays* L) in 2019 and 2020with fields tilled prior to planting. Soft white winter wheat (SWWW) trials were conducted at the Michigan State University Saginaw Valley Research and Extension Center in Richville, MI (43°23’57.3”N, 83°41’49.7”W) on a Tappan-Londo loam soil (fine-loamy, mixed, active, calcareous, mesic Typic Enduaquolls). Pre-plant soil characteristics (0-20 cm) included 7.4 – 7.9 pH (1:1 soil/water), 28 to 31 g $kg^{-1}$ soil organic matter (loss-on-ignition), 18-21 mg $kg^{-1}$ P (Olsen sodium bicarbonate extractant) (Frank et al., 2015), 166 - 183 mg $kg^{-1}$ K (ammonium acetate method, 7 - 10 mg $kg^{-1}$ S (monocalcium phosphate extraction), and 7.4 – 7.9 mg $kg^{-1}$ Zn (0.1 M HCl). Prior to planting, soil samples (0-30 cm) for nitrate-N ($NO_3$-N) analysis were collected, air-dried, and ground to pass through a 2 mm sieve resulting in concentrations of 3.3 and 3.7 mg $NO_3$-N $kg^{-1}$ soil in 2020 and 2021, respectively. The preceding crop was soybean (*Glycine max* L.) in 2019 and 2020 with fields tilled prior to planting.

Twelve-row plots measured 2.5 m in width by 7.6 m in length with 19.1 cm row spacing and planted using a Great Plains 3P600 drill (Great Plains Manufacturing, Salina, KS) to a population of 4.4 million seeds $ha^{-1}$. Plant emergence was quantified in spring prior to Feekes 4 nutrient applications. Soft red winter wheat varieties 'Flipper' (short-statured) and 'Red Dragon'(tall-statured) (Michigan Crop Improvement Assoc., Okemos, MI) were planted in Lansing on 8 Oct. 2019 and 21 Sept. 2020. Soft white winter wheat varieties 'Jupiter' (short-statured) and 'AC Mountain' (tall-statured) (Michigan Crop Improvement Assoc., Okemos, MI) were planted in Richville on 26 Sept. 2019 and 24 Sept. 2020.

Autumn starter (12-40-0-10-1, N-P-K-S-Zn) (MicroEssentials® SZ® (MESZ) (Mosaic CO., Plymouth, MN) fertilizer was topdressed utilizing a 2.27 kg capacity handheld spreader (Meyer Products LLC, Cleveland, OH) on 8 Oct. 2019 and 21 Sept. 2020 (Lansing) and 26 Sept. 2019 and 24 Sept. 2020 (Richville). Starter fertilizer rates were 0 (no autumn starter), 140 (mid-rate autumn starter), and 280 (high-rate autumn starter) kg $ha^{-1}$. Spring N was applied as UAN (28-0-0) utilizing a backpack sprayer equipped with streamer bars (Chafer Machinery Ltd, Upton, UK) at the Feekes 4 growth stage (20 March 2020 and 23 March 2021, Lansing; 23 March 2020 and 30 March 2021, Richville). Nitrogen rates were based on Michigan State

University recommendations for Lansing and Richville, respectively, and included a low, base, and high treatment. Low N rates were 50 percent below recommendations at 56.0 kg N $ha^{-1}$ and 67.3 kg N $ha^{-1}$ for SRWW and SWWW, respectively. Base (i.e., recommended) N rates were 112.1 kg N $ha^{-1}$ and 134.5 kg N $ha^{-1}$ for SRWW and SWWW, respectively. High N rates were 50 percent greater than recommendations at 168.1 kg N $ha^{-1}$ and 201.8 kg N $ha^{-1}$ for SRWW and SWWW, respectively.

Trials were arranged in a randomized complete block, split-plot design with four replications and established by individual variety (i.e., stature), thus treatment effects cannot be compared between varieties. Main plots consisted of autumn starter fertilizer application with subplots consisting of spring N application rates. A non-treated control with no fertilizer or additional inputs was included in study design and data collection.

Environmental data for the growing season were obtained from MSU Enviro-weather (https://enviroweather.msu.edu, Michigan State University, East Lansing, MI). Temperature and precipitation 30-year means were collected from the National Oceanic and Atmospheric Administration (NOAA, 2020). Prior to spring N application, soil samples (0-30 cm) for nitrate-N ($NO_3$-N) were collected on a per-plot basis to quantify residual N concentrations from autumn starter application. Tiller counts were collected outside yield harvest areas at Feekes 4. Plant height, head counts, and head lengths were collected at Feekes 11.2. Fractional green canopy coverage (FGCC) and normalized difference vegetation index (NDVI) were recorded at Feekes 5, 7, and 9. Flag leaf tissue collection and nutrient analysis occurred at Feekes 9. Harvest index (HI) was calculated as the percentage grain in total plant biomass.

Grain and straw yields were harvested from the center 1.2 m of each plot utilizing a small-plot combine (Kincaid Equipment Manufacturing, Haven, KS) on 13 July 2020 and 14

July 2021 in Lansing and 14 July 2020 and 14 July 2021 in Richville with grain adjusted to 135 g $kg^{-1}$ moisture. Straw yield was determined by weighing total residue from combine output with the cutting bar set 12.7 cm above ground level. Straw yield was adjusted by subtracting total moisture content from gross harvest weight. Straw subsamples were submitted for nutrient analysis to quantify nutrient removal.

Expected net return was estimated using an average local grain price of \$0.17 and \$0.23 $kg^{-1}$ for SRWW and \$0.18 and \$0.24 $kg^{-1}$ for SWWW in 2020 and 2021, respectively. Average local straw price remained consistent at \$0.15 $kg^{-1}$ across treatment years. Input costs were \$0.50 and \$0.55 $kg^{-1}$ for MESZ and \$0.93 and \$1.14 $kg^{-1}$ for UAN in 2020 and 2021, respectively. Harvest costs were obtained from the Michigan State University Extension Custom Machine and Work Rate Estimates (Stein, 2021) at \$74.85 and \$82.63 $ha^{-1}$ for grain harvest and \$30.79 and \$29.60 $ha^{-1}$ for straw baling in 2020 and 2021, respectively. Net economic return was calculated using a partial budget subtracting input and harvest costs from gross revenue (i.e., grain and straw price multiplied by yield).

Data were analyzed in SAS 9.4 (SAS Institute, 2012) using the GLIMMIX procedure at $\alpha = 0.10$. Normality of residuals were examined using the UNIVARIATE procedure ($P \leq 0.05$). Squared and absolute values of residuals were examined with Levene's Test to confirm homogeneity of variances ($P \leq 0.05$). Least square means were separated using the LINES option of the slice statement when ANOVA indicated a significant interaction ($P \leq 0.10$). Each site-year was analyzed individually due to a significant treatment-by-year interaction. Due to different SRWW and SWWW varieties and locally recommended N rates, locations were analyzed individually. Replication was considered a random factor with all other factors considered fixed. Dunnett's test was used to compare the untreated control relative to all treatments receiving N to verify N responsive locations (Dunnett, 1955). Treatment mean separations were calculated utilizing single degree of freedom contrasts.

## Results

### Environmental Conditions

Growing season (March – July) precipitation differed from the 30-yr mean by -10 and -24% at Richville and -6 and -4% at Lansing in 2020 and 2021, respectively (Table 2.01). Dry soil conditions due to rainfall deficits of 55% and 49% from the 30-yr mean at Richville June 2020 and Lansing July 2020 likely reduced yield potential and grain fill. May and June 2021 precipitation was 65-72% below normal and 50 – 127% above normal, respectively, across locations indicating some potential for late-season denitrification N losses on the medium to fine-textured soils. Warm mean March air temperatures (i.e., +105 to +1025% greater than 30-yr mean) across both locations hastened spring plant development and green-up.

### Grain Yield Soft Red Winter Wheat

An autumn starter and spring N interaction increased grain yield in three of four SRWW site years (Table 2.02). In 2020, the mid-rate autumn starter + high N treatment increased yield 1.43-1.48 Mg ha$^{-1}$ across ‘Flipper’ and ‘Red Dragon’, respectively, as compared to the no autumn starter + high N treatment (data not shown). In addition, ‘Red Dragon’ grain yield increased 1.04 Mg ha$^{-1}$ with mid-rate autumn starter + base N exceeding yield from the no autumn starter + high N treatment (data not shown). Increased tiller and head production with high-rate autumn starter application in ‘Flipper’ 2020 may have attributed to the grain yield increase observed (Table 2.03, 2.04). An interaction between autumn starter and spring N increased head count in ‘Red Dragon’ 2020, but tiller count remained unaffected (Table 2.03, 2.04). In ‘Flipper’ 2021, the high-rate autumn starter + low N treatment increased grain yield by

1.51 Mg $ha^{-1}$ as compared to no autumn starter + high N treatment (data not shown). Main effects of mid-rate autumn starter and base spring N increased grain yield in 'Red Dragon' 2021 by 1.16 and 1.85 Mg $ha^{-1}$, respectively.

**Grain Yield Soft White Winter Wheat**

Grain yield was increased by an autumn starter and spring N interaction in one of four SWWW site years (i.e., 'AC Mountain' 2021). The statistically highest grain yield was achieved with high-rate autumn starter + base N, and increased production by 1.13 Mg $ha^{-1}$ as compared to no autumn starter + base N. No differences in grain yield were detected between no, mid, or high-rate autumn starter in combination with high spring N (data not shown). Tiller counts increased with high-rate autumn starter application but increases in head count and head length were increased by base rates of spring N (Table 2.03, 2.05). Main effects of autumn starter and spring N increased grain yield in three of four site-years (Table 2.02). Mid-rate autumn starter increased grain yield 0.62 and 1.31 Mg $ha^{-1}$ in AC Mountain 2020 and 'Jupiter' 2021, respectively. Grain yield of 'Jupiter' 2020 increased 0.62 Mg $ha^{-1}$ with high-rate autumn starter as compared to no autumn starter. In 2020, base N rates increased grain yield 1.09 – 1.13 Mg $ha^{-1}$ across SWWW with no significant increase to above recommended (i.e., high) spring N across any site year (data not shown). In 2021 'Jupiter', base and high spring N increased grain yield by 0.76 - 0.98 Mg $ha^{-1}$ as compared to low spring N.

**Straw Yield Soft Red Winter Wheat**

An interaction between autumn starter and spring N increased straw yield in three of four SRWW site years (Table 2.02). In 2020, mid-rate autumn starter + low N increased 'Flipper' straw yield 1.25 Mg $ha^{-1}$ compared to no autumn starter + high N (data not shown). In 2021, 'Flipper' straw yield increased 1.99 Mg $ha^{-1}$ with high-rate autumn starter + low N as compared to no autumn starter + low N, but no differences occurred across mid- and no autumn starter rates and base or high N rates. No differences in plant height were recorded between mid-rate autumn starter + base N compared to no starter + base N resulting in similar biomass and overall straw yield (data not shown). In 2020 'Red Dragon' straw yield indicated a significant interaction ($P < 0.01$) with mid-rate autumn starter + base N exceeding the yield of no starter + base N by 1.31 Mg $ha^{-1}$. Additionally, mid-rate autumn starter + high N increased yield 1.96 Mg $ha^{-1}$ as compared to no autumn starter + high N. Application of autumn starter increased straw production in 'Red Dragon' 2021 by 0.77 Mg $ha^{-1}$. Low spring N (i.e 50% below recommended) reduced straw yield in 'Red Dragon' 2020-2021 with no difference between base and high N application rates.

**Straw Yield Soft White Winter Wheat**

Main effects of autumn starter increased straw production 0.35-0.72 Mg $ha^{-1}$ across site years for SWWW (Table 2.02). In 2020, mid and high autumn starter increased straw yield in 'AC Mountain' 0.51 and 0.93 Mg $ha^{-1}$ as compared to no autumn starter, respectively (data not shown). Additionally, straw yield increased 0.73 Mg $ha^{-1}$ with high spring N as compared to base spring N in 'Jupiter' 2020. Across varieties, low spring N (i.e 50% below recommended) reduced straw yield 0.35 – 0.62 Mg $ha^{-1}$ with no difference between base and high N in 2021. Plant height increased with application of autumn starter in three of four site years (data not shown) while increases in tiller count occurred across all site years likely contributing to the greater straw yield (Table 2.03).

**Economic Analysis**

An autumn starter and spring N interaction increased net grain profitability in five of eight site years (Table 2.02). When combining both net grain and straw profitability, autumn starter fertilizer and spring N interacted in three of eight site years (Table 2.02). Autumn starter and spring N interactions for grain and straw yield individually paralleled the interaction on combined grain and straw profitability. Orthogonal contrast analysis of net profitability demonstrated no increase, in net grain profit or net grain and straw profit combined, with high-rate autumn starter as compared to mid-rate autumn starter, indicating mid-rate autumn starter was sufficient to attain yield and profit increases (Table 2.06). Application of autumn starter increased net grain profitability in 'Flipper' 2020 but was not effective in offsetting production and treatment costs in any other 2020 site-year. In 2021, both grain profit and grain and straw profit increased in all varieties but 'AC Mountain.' In five of eight site-years, net grain and straw profitability combined resulted in a significant response to autumn starter application thus including straw production in lieu of grain individually enhanced overall net profitability of winter wheat production. Profitability analyses suggest application of autumn starter may promote greater economic return and yield beyond parameters of grain. Contrasts to evaluate base (i.e., recommended) N rates compared to high (i.e., 50% above recommended) N rates indicated no impact on grain or grain plus straw profitability across site years suggesting that base N rates were sufficient for production and may also simultaneously reduce risk for environmental contamination and increase economic return.

**Straw Nutrient Removal**

Straw nutrient removal must be considered when evaluating the economic return of straw production. Mean straw removal nutrient concentrations are generally 5.3-6.7 kg $Mg^{-1}$ N, 1.0-1.4 kg $Mg^{-1}$ $P_2O_5$, 9.5-11.0 kg $Mg^{-1}$ $K_2O$, and 0.3 kg $Mg^{-1}$ sulfur (S) (Culman et al., 2020; Reiter et al., 2015; Warncke et al., 2009). In 2020, straw N removal values were below listed thresholds ranging from 2.96-5.99 kg $Mg^{-1}$ (Table 2.07). In 2021, SRWW N removal values averaged 3.85 – 7.60 kg $Mg^{-1}$. High spring N application rates resulted in the greatest N removal across site years (data not shown). Mean S removal in 2020 was 0.27 – 0.63 kg $Mg^{-1}$ and remained unaffected by spring N in three of four 2020 site years (data not shown). Sulfur removal increased with application of high rates of autumn starter. In 2021 S removal increased ranging from 0.39 – 0.64 kg $Mg^{-1}$ across varieties.

Straw $P_2O_5$ removal values were below listed thresholds for ‘Jupiter’ 2020, ‘Jupiter’ 2021, and ‘AC Mountain’ 2020 but within normal ranges for remaining site years (Table 2.07). Removal of $K_2O$ ranged between 8.72 – 14.23 kg $Mg^{-1}$ in 2020 with highest removal values recorded where high rates of spring N and high autumn starter application occurred (data not shown). Potassium removal was significantly lower in 2021 for SRWW (i.e., 5.20 – 7.15 kg $Mg^{-1}$ $K_2O$) but only slightly below average for SWWW (Table 2.07). Straw removal of $K_2O$ was not affected by autumn starter in 2021.

## Discussion

Orthogonal contrast data assessing grain and straw yield response to application of autumn starter (i.e., all treatments with starter fertilizer as compared to without) was significant across all site years (i.e., 8 of 8 site years total) (Table 2.06). No significant increase in grain yield was observed between mid and high-rate autumn starter indicating similar grain yields were achieved with the mid-rate autumn starter (140 kg $ha^{-1}$) as compared to the high autumn starter rate (280 kg $ha^{-1}$). Application of high-rate autumn starter as compared to mid-rate autumn starter increased straw yield in ‘Flipper’ 2020 and 2021 and in ‘AC Mountain’ 2020. Autumn starter may have a greater potential impact on biomass production in short-statured winter wheat varieties as application increased mean plant height 4.3 and 5.8 cm with mid and high autumn starter, respectively, as compared to no autumn starter in ‘Flipper’ 2020 (data not shown). Additionally, 'Flipper' 2021 HI was the only variety influenced by autumn starter and spring N suggesting fertilizer strategies had a greater impact on short-statured varieties. Treatments containing autumn starter resulted in lower HI suggesting that plant biomass (i.e., straw yield) was more responsive to autumn starter in short-statured varieties. While utilization of short-statured wheat cultivars has shown to increase biological efficiency by producing less straw per unit of grain than tall-statured cultivars (Donaldson et al., 2001), results indicate application of autumn starter may enhance straw yield potential in addition to desired yield goals thus significantly improving potential profitability. Mean HI index value was 67% across site-years. Short-statured 'Flipper' and 'Jupiter' had HI values of 70% while tall-statured 'Red Dragon' and 'AC Mountain' had mean HI values of 65% (data not shown).

**Tiller Response**

Tiller production relies upon multiple factors including climate, seeding rate, fertilizer management, and cultivar selection (Bauer et al., 1984; Gooding et al., 2002; Tilley et al., 2019). While often overlooked in variety selection, cultivars with good tillering capacity may achieve greater yield due to increased spike number. However, yield of low-tillering cultivars relies largely on spike size and fertile floret (Zhang et al., 2020). Differences in plant stature (i.e. short vs. tall) correlated with differences in tiller production. In 2020, 'Flipper' and 'Jupiter' (i.e., short-statured) produced more tillers than 'Red Dragon' and 'AC Mountain' (i.e., tall-statured) but had comparable tillers in 2021 (Table 2.03). Inclusion of autumn starter may have a greater impact on tiller production of short-statured varieties by increasing tiller count and straw yield potential. Despite reductions in plant height, increased tiller production promotes biomass accumulation allowing short-statured varieties to be managed for straw. In addition to straw production, studies have shown tiller production (i.e. spikes per area) has the greatest impact on wheat grain followed by grains per spike or total grain weight (Iftikhar et al., 2012; Lynch et al., 2017). Proper fertilizer management during plant establishment can promote tiller production and development of spikes per area (i.e. productive stems at harvest) resulting in greater yield potential and efficiency (Engstrom & Bergkvist, 2009, Slafer et al., 2015, Zhang et al., 2020). Tiller response to autumn starter translated to grain and straw yield response in seven of eight site-years.

**Soil Test and Autumn Starter Response**

Pre-plant soil test levels can be a reliable indicator for fertilizer recommendations and likelihood for plant response. High pre-plant Bray P-1 (35-42 mg $kg^{-1}$ P in Lansing) and Olsen-P concentrations (18-21 mg $kg^{-1}$ P in Richville) reduced the likelihood of grain yield response to P application from the autumn starter fertilizer (Table 2.08). Addition of N and S within the autumn starter fertilizer application may have contributed to observed yield responses. Autumn application of 28 kg $ha^{-1}$ N is recommended for Michigan wheat production (Warncke et al., 2009). Mid-rate and high-rate autumn starter application included 16.8 – 33.6 kg N $ha^{-1}$, respectively, indicating that the high rate of autumn starter was above the recommended response threshold. When pre-plant soil nitrate concentrations (0-30 cm) are < 10 mg $NO_3$-N $kg^{-1}$, positive yield response to autumn N application are probable (Alley et. al., 2009; Steinke et. al., 2021). Pre-plant soil nitrate concentrations in the current study were 3.3 – 5.7 mg $NO_3$-N $kg^{-1}$ across site years indicating a positive response to autumn N was possible if timely planted. Decreased atmospheric deposition of sulfur (S) has resulted in applications of 28 kg $ha^{-1}$ S beneficial for winter wheat growth, development, and yield potential (Dhillon et al., 2019; Steinke et. al., 2021; Warncke et al., 2009). Application rates of 14 - 28 kg $ha^{-1}$ S with mid and high autumn treatments likely contributed to autumn tiller development, winter hardiness, and successful establishment. Adequate $SO_4$-S and N at plant establishment is essential for biosynthesis of amino acids, proteins, and chlorophyll, while also aiding N metabolism (Wilson et al., 2020). Results agree with Steinke et al. (2021) who observed a grain yield decrease of 1.26 - 2.52 Mg $ha^{-1}$ when autumn starter fertilizer was removed from enhanced management and a grain yield increase of 1.17 - 1.74 Mg $ha^{-1}$ when autumn starter fertilizer was added to traditional management cross both SRWW and SWWW production.

**Economic Analysis**

Nutrient management strategies must minimize environmental losses and improve nutrient use efficiency (i.e., yield per unit of fertilizer applied) for long-term sustainability (Silva et al., 2021). High-rate autumn starter did not increase profit across any site year. Volatile fertilizer costs increase the importance of site-specific nutrient management and application efficiency. Intense energy requirements of ammonia synthesis and decreases in quantity and quality of phosphate rock reserves continue to elevate N and P prices (Cordell et al., 2009; Mohammadi Aframehr & Pfromm, 2021). October 2021 mean price per pound of N, $K_2O$, and $P_2O_5$ increased 25-110% as compared to October 2019 values (Table 2.09). Continued increase in fertilizer pricing combined with decreased availability may drive the economic importance for precise, timely, and soil-test based application of autumn starter and spring N fertilizer to maximize net profitability

**N:S Ratios and Straw Nutrient Removal**

Interactions between N and S have shown to impact physiological attributes including wheat biomass and grain yield (Salvagiotti & Miralles, 2008). Research has shown that N use efficiency can be increased with S sufficiency (Salvagiotti & Miralles, 2008). Although pre-plant soil S concentrations were 7 - 10 mg S $kg^{-1}$ across site years, soil S testing has not been a reliable indicator for S response. The autumn starter utilized in the current study contained 50% readily available sulfate – S ($SO_4$-S) and 50% elemental S (ES) that must be oxidized for plant uptake, dependent on soil pH and organic matter (Degryse et al., 2021; Mahler & Maples, 2008). Recent studies have discovered greater plant S uptake from autumn-applied ES as compared to $SO_4$-S primarily due to leaching potential of soluble S sources in rainfed environments (Degryse et al., 2021). Mean N:S ratios at maturity ranged from 8-12.5:1 in SWWW varieties indicating sufficient S levels across treatments (Table 2.10, 2.11). Interactions between autumn starter and spring N influenced N:S ratio in SRWW 2020 with possible deficiencies (i.e., N:S > 13-23:1) where no autumn starter was applied. In 2021, mid-rate autumn starter + base N and no autumn starter + high N also exceeded N:S ratio for sufficient S levels in 'Red Dragon.' Camberato & Casteel (2010) determined S concentrations > 20:1 may indicate S deficiency with plant tissue > 0.20% and N:S ratio < 12:1 indicating S sufficiency in winter wheat. Reductions in grain and straw yield may be linked to S deficiency. Grain and straw yield reductions with treatments containing no autumn starter also contained N:S ratios > 12:1. Flag leaf tissue nutrient concentrations were all ≥ 0.20% S with no visual S deficiencies (data not shown). Treatments excluding autumn starter had the lowest S concentrations across site years. Lack of information for critical S dilution curves may require further examination to validate S sufficiency levels in winter wheat varieties (De Oliveira Silva et al., 2021).

Straw K removal is an important factor affecting profitability and fertilizer application for crops following winter wheat. Pre-plant K was 99-166 mg K $kg^{-1}$, exceeding critical levels for both Lansing and Richville. The K uptake rate increases during the period between Feekes 4 and Feekes 10.0 with peak uptake at full to end of flowering (Ali et al., 2019 & Malhi et al., 2011). May cumulative rainfall differed from the 30 yr mean by -72% and -65% in Lansing and

Richville, respectively in 2021. Lack of soil moisture throughout vegetative and flowering stages likely reduced K accessibility for uptake resulting in no change of $K_2O$ removal by treatment. After spring green up (i.e., Feekes 4), water use increases and plateaus at Feekes 10.0 (boot stage) as carbohydrates are utilized for grain production (Yonts et al., 2009). Feekes 10.0 was recorded on May 19 and 23 for Lansing and Richville, respectively, in 2021 indicating that the lack of soil moisture contributed to the overall reduction in grain yield in 2021 thus impacting nutrient removal. In 2020 HI was reduced with application of autumn starter in all varieties (data not shown). In 2021, HI remained unaffected by autumn starter and spring N treatments in three of four varieties suggesting that dry soil conditions negatively impacted both grain yield and biomass. An overall increase in nutrient removal was consistent with above recommended N rates. Differences in N and S uptake may be affected by nutrient availability (i.e. fertilizer application, specifically N) while changes in uptake of P and K may be attributed to changes in total shoot biomass (De Oliveira Silva et al., 2021).

## Conclusions

Current results from autumn starter and spring N applications indicate above recommended spring N did not compensate for the lack of autumn applied starter during establishment. Low pre-plant residual soil nitrate concentrations, including S with autumn starter fertilizer, and timely autumn planting likely resulted in the positive grain and straw yield response to autumn starter fertilizer in this study. Secondary responses such as tiller count, head count, head length, and plant height directly impacted both grain and straw yield. Mid-rate autumn starter was the most economical option under the current environmental conditions to maximize grain and straw yield in soft red and white winter wheat. When fertilizing for straw production, varieties may respond to greater rates of autumn starter, but yield increases did not result in increased profitability. Despite physiological limitations, proper nutrient management can allow short-statured varieties to be managed for straw production. Autumn starter may be one component to accelerate plant growth and yield potential while simultaneously addressing soil variabilities, but producers must also consider pre-plant soil nutrient concentrations and plant winter wheat early enough in autumn to allow plants to uptake nutrient applications. While autumn starter can facilitate plant establishment for optimal grain and straw production, responses will be field and site-specific.


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# APPENDIX

*Table 2.01*. Mean monthly and 30-yr temperature and precipitation† for the winter wheat growing season, Richville and Lansing, MI, 2020 – 2021.

| Site | Year | Mar. | Apr. | May | Jun. | Jul. | Total |
|---|---|---|---|---|---|---|---|
| | | ---------- | ---------- | ---------- cm | ---------- | ---------- | ---------- |
| Richville | 2020 | 5.3 | 5.3 | 9.5 | 3.4 | 8.2 | 31.7 |
| | 2021 | 3.3 | 1.8 | 3.0 | 11.4 | 7.3 | 26.8 |
| | 30-yr‡ | 5.2 | 7.3 | 8.6 | 7.6 | 6.6 | 35.3 |
| | | | | | | | |
| Lansing | 2020 | 5.3 | 7.3 | 11.0 | 7.4 | 4.2 | 35.2 |
| | 2021 | 4.5 | 3.8 | 2.4 | 20.2 | 5.2 | 36.1 |
| | 30-yr avg. | 4.5 | 7.3 | 8.5 | 8.9 | 8.3 | 37.5 |
| | | ---------- | ---------- | ---------- °C | ---------- | ---------- | ---------- |
| Richville | 2020 | 3.4 | 6.2 | 13.8 | 20.6 | 23.7 | -- |
| | 2021 | 4.5 | 9.3 | 14.1 | 21.8 | 21.3 | -- |
| | 30-yr avg. | 0.4 | 7.4 | 13.2 | 18.7 | 20.9 | -- |
| | | | | | | | |
| Lansing | 2020 | 3.9 | 6.6 | 13.8 | 20.2 | 23.5 | -- |
| | 2021 | 5.2 | 8.9 | 13.7 | 21.2 | 21.5 | -- |
| | 30-yr avg. | 1.9 | 8.7 | 14.7 | 20.0 | 22.9 | -- |

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

*Table 2.02.* Analysis of variance results for grain yield, straw yield, net grain profitability (G), and net grain and straw (G+S) combined profitability as affected by autumn starter and spring N in Lansing and Richville 2020-2021.

| **Site** | **Wheat** | **Variety‡** | | **Autumn Starter x Spring N** | **Autumn Starter** | **Spring N** |
|---|---|---|---|---|---|---|
| Lansing 20 | SRWW | FL | Grain Yield | **0.06*** | **< 0.01** | **< 0.01** |
| | | | Straw Yield | **< 0.01** | **< 0.01** | **< 0.01** |
| | | | G Net Profit | **0.06** | **0.04** | **< 0.01** |
| | | | G+S Net Profit | **< 0.01** | **< 0.01** | **< 0.01** |
| Lansing 20 | SRWW | RD | Grain Yield | **0.07** | **0.04** | **< 0.01** |
| | | | Straw Yield | **< 0.01** | **0.02** | **< 0.01** |
| | | | G Net Profit | **0.07** | 0.51 | **< 0.01** |
| | | | G+S Net Profit | **< 0.01** | 0.11 | **< 0.01** |
| Lansing 21 | SRWW | FL | Grain Yield | **0.04** | **0.01** | 0.27 |
| | | | Straw Yield | **0.07** | **0.02** | 0.43 |
| | | | G Net Profit | **0.04** | **0.10** | 0.24 |
| | | | G+S Net Profit | **0.05** | **0.04** | 0.68 |
| Lansing 21 | SRWW | RD | Grain Yield | 0.12 | **< 0.01** | **< 0.01** |
| | | | Straw Yield | 0.18 | **< 0.01** | **< 0.01** |
| | | | G Net Profit | **0.09** | **0.05** | **< 0.01** |
| | | | G+S Net Profit | 0.20 | **0.02** | **< 0.01** |
| Richville 20 | SWWW | JU | Grain Yield | 0.78 | 0.53 | **< 0.01** |
| | | | Straw Yield | 0.99 | **0.06** | **< 0.01** |
| | | | G Net Profit | 0.62 | **< 0.01** | **< 0.01** |
| | | | G+S Net Profit | 0.82 | **< 0.01** | **< 0.01** |
| Richville 20 | SWWW | AC | Grain Yield | 0.93 | **0.04** | **< 0.01** |
| | | | Straw Yield | 0.14 | **0.01** | **< 0.01** |
| | | | G Net Profit | 0.81 | 0.88 | **0.05** |
| | | | G+S Net Profit | 0.54 | 0.15 | **< 0.01** |
| Richville 21 | SWWW | JU | Grain Yield | 0.60 | **< 0.01** | **< 0.01** |
| | | | Straw Yield | 0.43 | **< 0.01** | **< 0.01** |
| | | | G Net Profit | 0.62 | **< 0.01** | **< 0.01** |
| | | | G+S Net Profit | 0.81 | **< 0.01** | **< 0.01** |
| Richville 21 | SWWW | AC | Grain Yield | **0.06** | **< 0.01** | **< 0.01** |
| | | | Straw Yield | 0.69 | **0.03** | **< 0.01** |
| | | | G Net Profit | **0.09** | 0.90 | **< 0.01** |
| | | | G+S Net Profit | 0.29 | 0.18 | **< 0.01** |

* Bolded values significant α=0.10 probability level by GLIMMIX-SAS procedure.
‡ Flipper (FL), Red Dragon (RD), Jupiter (JU), AC Mountain (AC).

*Table 2.03.* Influence of autumn starter fertilizer (12-40-0-10S-1Zn) on Feekes 4 mean tiller production, 2020-2021.

| Variety | Location | 2020 No | 2020 Mid | 2020 High | 2020 $P_r > F$ | 2021 No | 2021 Mid | 2021 High | 2021 $P_r > F$ |
|---|---|---|---|---|---|---|---|---|---|
| | | ----------tillers $m^2$------------ | | | | -----------tillers $m^2$----------- | | | |
| RD§ | Lansing | 997† | 1019 | 1149 | NS | 671 b | 773 a | 782 a | = 0.08 |
| FL | Lansing | 1010 b | 1111 b | 1319 a | < 0.01 | 1739 | 1772 | 1845 | NS |
| AC | Richville | 813 b | 962 a | 1074 a | = 0.03 | 1526 b | 1689 b | 2016 a | =0.03 |
| JU | Richville | 853 c | 1366 b | 1733 a | < 0.01 | 1144 b | 1596 a | 1703 a | < 0.01 |

† Values followed by the same lowercase letter within row, year, and variety are not significantly different at α=0.1
‡ Non-treated check containing no fertilizer or additional inputs was not included in statistical analysis.
§ Flipper (FL), Red Dragon (RD), Jupiter (JU), AC Mountain (AC).

*Table 2.04.* Impact of autumn starter and spring nitrogen on winter wheat grain head production. Mean 2020 head production displayed for varieties.

| Treatment | -Red Dragon- | Treatment | -Flipper- | -Jupiter- | -AC Mountain- |
|---|---|---|---|---|---|
| | ---heads $m^{-2}$--- | | ---------------------heads $m^{-2}$--------------------- | | |
| No Starter, Low N | 759 bcd † | No Starter | 769 b | 763 | 726 |
| No Starter, Base N | 775 abcd | Mid Starter | 829 b | 832 | 762 |
| No Starter, High N | 646 d | High Starter | 955 a | 763 | 794 |
| Mid Starter, Low N | 840 abc | *Pr > F* | = 0.02 | NS | NS |
| Mid Starter, Base N | 700 cd | | | | |
| Mid Starter, High N | 936 a | Low N | 719 c | 718 b | 722 |
| High Starter, Low N | 667 d | Base N | 852 b | 946 a | 738 |
| High Starter, Base N | 834 abc | High N | 982 a | 819 b | 821 |
| High Starter, High N | 858 abc | *Pr > F* | < 0.01 | = 0.01 | NS |
| Check‡ | 613 | | | | |
| $P_r > F$ | = 0.03 | Check‡ | 689 | 320 | 234 |

† Values followed by the same lowercase letter are not significantly different at α=0.1
‡ Non-treated check containing no fertilizer or additional inputs was not included in statistical analysis.

*Table 2.05.* Impact of autumn starter and spring nitrogen on winter wheat grain head production. Mean 2021 head production displayed for varieties.

| **Treatment** | **-Flipper-** | **-Red Dragon-** | **-Jupiter-** | **-AC Mountain-** |
|---|---|---|---|---|
| | ---------------------------------- | heads $m^{-2}$ | ---------------------------------- | |
| No Starter | 767 b † | 671 b | 627 b | 675 |
| Mid Starter | 940 a | 773 a | 669 ab | 712 |
| High Starter | 921 a | 782 a | 746 a | 760 |
| $P_r > F$ | = 0.04 | = 0.08 | = 0.08 | NS |
| | | | | |
| Low N | 834 | 674 b | 640 | 617 b |
| Base N | 875 | 799 a | 701 | 757 a |
| High N | 919 | 753 a | 701 | 617 a |
| $P_r > F$ | NS | = 0.04 | NS | < 0.01 |
| Check‡ | 573 | 549 | 584 | 541 |

† Values followed by the same lowercase letter are not significantly different at α=0.1

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

*Table 2.06.* Winter wheat grain yield, straw yield, net grain profitability, and net grain + straw profitability treatment response using single degree of freedom contrasts.

| | Variety¶ | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2020 | | | | 2021 | | | |
| | FL | RD | JU | AC | FL | RD | JU | AC |
| **Grain Yield** | | | | | | | | |
| Starter vs. No Starter † | **< 0.01***  | **0.02** | **0.05** | **0.02** | **< 0.01** | **< 0.01** | **< 0.01** | **< 0.01** |
| Mid Starter vs. High Starter‡ | 0.30 | 0.61 | 0.63 | 0.23 | 0.47 | 0.42 | 0.20 | 0.13 |
| Base N vs. High N§ | 0.17 | 0.74 | 0.12 | 0.23 | 0.21 | 0.50 | 0.12 | 0.76 |
| **Straw Yield** | | | | | | | | |
| Starter vs. No Starter | **< 0.01** | **< 0.01** | **0.02** | **< 0.01** | **0.01** | **< 0.01** | **< 0.01** | **0.01** |
| Mid Starter vs. High Starter | **0.01** | 0.35 | 0.57 | **0.08** | **0.09** | 0.28 | 0.87 | 0.17 |
| Base N vs. High N | 0.16 | 0.12 | 0.18 | 0.30 | 0.31 | 0.79 | 0.32 | 0.79 |
| **Grain Net Profit** | | | | | | | | |
| Starter vs. No Starter | **0.01** | 0.48 | 0.88 | 0.71 | **0.04** | **0.02** | **< 0.01** | 0.66 |
| Mid Starter vs. High Starter | 0.97 | 0.38 | 0.29 | 0.82 | 0.73 | 0.78 | 0.91 | 0.83 |
| Base N vs. High N | 0.81 | 0.23 | 0.81 | 0.86 | 0.99 | 0.67 | 0.49 | 0.14 |
| **G+S Net Profit** | | | | | | | | |
| Starter vs. No Starter | **< 0.01** | **0.04** | 0.22 | **0.07** | **0.01** | **< 0.01** | **< 0.01** | 0.12 |
| Mid Starter vs. High Starter | 0.45 | 0.88 | 0.71 | 0.55 | 0.53 | 0.94 | 0.97 | 0.58 |
| Base N vs. High N | 0.79 | 0.74 | 0.11 | 0.92 | 0.59 | 0.98 | 0.92 | 0.20 |

*Bolded values significantly increased at $\alpha$=0.10 using single degree of freedom contrasts

† Comparison between all treatments containing autumn starter (i.e 140 kg $ha^{-1}$ and 280 kg $ha^{-1}$) to no autumn starter

‡ Comparison between all treatments containing mid-rate autumn starter to all treatments containing high-rate autumn starter

§ Comparison between all treatments containing base spring nitrogen (i.e 112 and 135 kg $ha^{-1}$) to all treatments high spring nitrogen (i.e 168 and 202 kg $ha^{-1}$) in SRWW and SWWW, respectively.

¶ Flipper (FL), Red Dragon (RD), Jupiter (JU), AC Mountain (AC).

*Table 2.07. Mean* winter wheat straw nutrient removal vales across treatment for each variety and site year, 2020-21.

| **Variety** | **Year** | **N** | **$P_2O_5$** | **$K_2O$** | **S** |
|---|---|---|---|---|---|
| | | ----------------------------------- kg $Mg^{-1}$ | ----------------------------------- | ----------------------------------- | ----------------------------------- |
| | | ***5.30-6.70†*** | ***1.00-1.40*** | ***9.50-11.00*** | ***0.30*** |
| Flipper | 2020 | 4.00-5.99‡ | 1.27-2.20 | 10.06-11.58 | 0.30-0.63 |
| | 2021 | 4.88-7.60 | 1.09-2.24 | 6.64-7.15 | 0.51-0.64 |
| Red Dragon | 2020 | 2.98-5.48 | 0.81-1.28 | 8.72-10.01 | 0.27-0.43 |
| | 2021 | 3.85-7.24 | 1.09-2.63 | 5.20-6.06 | 0.39-0.53 |
| Jupiter | 2020 | 2.96-3.47 | 0.74-0.98 | 12.18-14.23 | 0.29-0.40 |
| | 2021 | 4.23-5.63 | 0.58-0.92 | 8.57-10.41 | 0.42-0.58 |
| AC Mountain | 2020 | 3.10-3.78 | 0.53-0.81 | 9.46-13.44 | 0.31-0.44 |
| | 2021 | 3.93-5.75 | 0.92-1.28 | 8.36-11.13 | 0.42-0.63 |
| All Varieties | | **4.39**§ | **1.19** | **9.34** | **0.45** |

†Mean straw nutrient concentrations (Culman et al., 2020; Reiter et al., 2015; Warncke et al., 2009).
‡Removal ranges across treatments for each variety.
§ Average removal value across all site-years.

*Table 2.08.* Site year and soil descriptions including soil chemical properties and mean P, K, S, and Zn soil test (0 – 20 cm) nutrient concentrations obtained prior to winter wheat planting, Richville and Lansing, MI, 2020-2021.

| | | Soil | Soil test† | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Site | Year | description | P | K | S | Zn | pH | OM | CEC |
| | | | ----------mg $kg^{-1}$--------- | | | | | g $kg^{-1}$ | cmolc $kg^{-1}$ |
| Richville† | 2020 | Tappan-Londo loam | 18 | 183 | 10 | 7.1 | 7.9 | 23 | 15.6 |
| | 2021 | Tappan-Londo loam | 21 | 166 | 7 | 3.1 | 7.4 | 24 | 15.8 |
| Lansing | 2020 | Conover loam | 42 | 91 | 7 | 3.8 | 7.0 | 28 | 9.2 |
| | 2021 | Conover loam | 35 | 99 | 8 | 3.1 | 6.8 | 31 | 12.3 |

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

*Table 2.09***.** Mean fertilizer pricing comparison between October 2019 and 2021.

| Product | 2019 | 2021 | Nutrient | 2019 | 2021 |
|---|---|---|---|---|---|
| | ------------- **$/Mg$^{-1}$** | -------------- | | ----------- **$/kg$^{-1}$** | ------------- |
| Urea 46-0-0 | $440† | $735 | Nitrogen | $0.24 | $0.40 |
| UAN 28-0-0 | $349 | $431 | Nitrogen | $0.31 | $0.39 |
| MAP 11-52-0 | $388 | $803 | $P_2O_5$ | $0.18 | $0.39 |
| MOP 0-0-60 | $336 | $704 | $K_2O$ | $0.14 | $0.29 |

† Mean fertilizer price obtained from USDA Illinois Department of Agriculture Market News Report Oct. 2019 and 2021 (https://mymarketnews.ams.usda.gov/filerepo/sites/default/files/3195/2021-10-21/518047/ams_3195_00044.txt).

*Table 2.10.* Effects of autumn starter fertilizer and spring N applications on mean winter wheat N:S ratios across varieties, 2020**.**

| **Treatment** | **-Flipper-** | **-Red Dragon-** | **Treatment** | **-Jupiter-** | **-AC Mountain-** |
|---|---|---|---|---|---|
| No Starter, Low N | 14.1 bc † | 12.1 c | No Starter | 10.3 | 10.5 a |
| No Starter, Base N | 15.0 b | 14.8 b | Mid Starter | 10.0 | 9.4 a |
| No Starter, High N | 23.4 a | 20.1 a | High Starter | 8.1 | 8.0 b |
| Mid Starter, Low N | 10.1 def | 10.5 cde | $P_r > F$ | NS | = 0.02 |
| Mid Starter, Base N | 12.0 cde | 9.5 de | | | |
| Mid Starter, High N | 13.0 bcd | 12.4 c | Low N | 9.3 | 8.9 |
| High Starter, Low N | 8.1 f | 8.4 e | Base N | 9.9 | 9.4 |
| High Starter, Base N | 10.1 ef | 9.4 de | High N | 9.2 | 9.6 |
| High Starter, High N | 9.0 f | 10.8 cd | $P_r > F$ | NS | NS |
| Check‡ | 7.6 | 9.6 | | | |
| $P_r > F$ | < 0.01 | = 0.03 | Check‡ | 5.9 | 4.9 |

† Values followed by the same lowercase letter are not significantly different at α=0.1
‡ Non-treated check containing no fertilizer or additional inputs was not included in statistical analysis.

*Table 2.11***.** Effects of autumn starter fertilizer and spring N applications on mean winter wheat N:S ratios across varieties, 2021**.**

| **Treatment** | **-Red Dragon-** | **Treatment** | **-Flipper-** | **-Jupiter-** | **-AC Mountain-** |
|---|---|---|---|---|---|
| No Starter, Low N | 10.3 cd † | No Starter | 12.0 a | 12.5 a | 11.1 a |
| No Starter, Base N | 12.4 b | Mid Starter | 10.2 b | 9.3 b | 8.5 b |
| No Starter, High N | 17.4 a | High Starter | 8.8 c | 8.8 b | 7.7 b |
| Mid Starter, Low N | 8.6 de | $P_r > F$ | < 0.01 | < 0.01 | < 0.01 |
| Mid Starter, Base N | 20.8 bc | | | | |
| Mid Starter, High N | 10.1 cde | Low N | 10.5 | 9.9 | 9.5 |
| High Starter, Low N | 8.3 e | Base N | 10.0 | 10.6 | 8.7 |
| High Starter, Base N | 9.2 cde | High N | 10.5 | 10.1 | 9.6 |
| High Starter, High N | 9.4 cde | $P_r > F$ | NS | NS | NS |
| Check‡ | 7.9 | | | | |
| $P_r > F$ | < 0.01 | Check‡ | 9.1 | 9.3 | 7.4 |

† Values followed by the same lowercase letter are not significantly different at α=0.1
‡ Non-treated check containing no fertilizer or additional inputs was not included in statistical analysis.

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# CHAPTER 3

# UTILIZING BORON TO IMPROVE SUGARBEET YIELD, QUALITY, AND RESISTANCE TO CERCOSPORA BETICOLA


## Abstract

One of the more severe foliar pathogens capable of causing damage to sugarbeet is *Cercospora beticola*, the causal pathogen of Cercospora leaf spot (CLS). When not managed appropriately, CLS can reduce sugarbeet yield 40%. Although plant defoliation caused by the disease directly impacts root size and sugar quality, other factors including leaf regrowth and impurities within the root affect plant health and crop quality. Management strategies including boron-containing compounds have shown to have fungistatic properties with potential to reduce disease severity in the field. Field studies were established to investigate the effects of foliar applied boron (B) on sugarbeet plant health and CLS disease severity. Treatments included a standard fungicide program, three foliar boron treatments (0.11, 0.28, or 0.56 kg sodium tetraborate $ha^{-1}$) applied at 10-14 day intervals without a standard fungicide program, three foliar boron treatments (0.11, 0.28, or 0.56 kg sodium tetraborate $ha^{-1}$) applied at 10-14 day intervals in conjunction with a standard fungicide program, and a nontreated check for a total of eight treatments. Application of foliar B did not reduce CLS in field environments across site years. *In vitro* analysis of *C. beticola* response to B demonstrated lower $EC_{50}$ values with sodium tetraborate than boric acid. Reduced control options, increased CLS resistance, and increased B requirement of sugarbeet enhance the need for further evaluation of alternative control. In-field evaluation of various B timing, increased B concentration, and addition of B-containing compounds may contribute to future CLS control.

## Introduction

Cercospora leaf spot is one of the most destructive foliar pathogens impacting sugarbeet *(Beta vulgaris* L.) production worldwide (Weiland & Koch, 2004). The causal fungus, *Cercospora beticola,* reduces root yield and recoverable sucrose while increasing sugar impurity concentrations resulting in revenue losses up to 40% (Shane & Teng, 1992; Lamey et al., 1996). Current management strategies rely heavily on fungicide application, host plant resistance, and tillage for inoculum reduction (Khan & Smith, 2005; Miller et al., 1994). Reduced fungicide efficacy and increased resistance to current control mechanisms have been attributed to the high genetic variability, prolific sporulation, and polycyclic life cycle of *C. beticola* (Rosenzweig et al., 2015; Shrestha et al., 2020). Alternative control measures utilizing foliar applied micronutrients have shown to be effective across a range of plant diseases (Farahat et al., 2018; Pérez et al., 2020; M. Reuveni et al., 1997; R. Reuveni & Reuveni, 1998). New CLS management strategies may need to integrate a balanced plant nutrition program, fungicide rotation, resistant germplasm, and cultural practices to enhance sugarbeet plant health and grower profitability.

Primary inoculum of *C. beticola* in sugarbeet is distributed from asexual conidia on plant residue through wind dispersal of spores, or long distance transfer by sugarbeet seed (Spanner et al., 2021; Weiland & Koch, 2004). After conidiation, water-splash, wind, and insects aid in spore transfer to leaf surface where hyphae elongation takes place and infects via stomates (Weiland & Koch, 2004). Optimal conditions for CLS development are relative humidity > 60%, prolonged leaf wetness, and air temperatures > 16°C (Shane & Teng, 1992; Tedford et al., 2018). Following hyphal establishment, toxins are produced within leaf tissue and necrotize cells in close proximity (Rathaiah, 1977; Steinkamp et al.,1979). Symptoms include grey-tan circular lesions with distinct borders that coalesce forming large necrotic areas and death of older leaves (Rangel et al., 2020). Protection of newly emerged leaves is vital to suppress CLS disease progression and reduce plant stress. Cercospora leaf spot is characterized as a polycyclic disease in which *C. beticola* produces phytotoxins cercosporin and beticolin known to debilitate cells and enhance fungal growth throughout the growing season (Weiland & Koch, 2004; Windels et al., 1998). Multiple application timings of foliar protection agents are often required to mitigate quality reduction until harvest. Conidia persistence and spore dispersal require a combination of contact and systemic protection via fungicides and foliar nutrition. While disease control is heavily reliant on fungicide rotation, addition of foliar boron may aid in leaf surface protection from CLS.

A knowledge gap exists regarding the use of B-containing compounds and the potential to aid in CLS management. While sugarbeet response to B application has decreased in Michigan, B-containing products have been reported to contain fungistatic properties. Recent studies in Egypt identified reduced *in vitro* growth of *C. beticola* and decreased in-field disease severity of CLS when including sodium tetraborate and boric acid applications (El-fawy, 2016). Researchers suggested reductions in mycelial growth were related to cell membrane disruption of the pathogen leading to cytoplasmic leakage and death. Additionally, B may stimulate reactive oxygen species accumulation in fungal spores leading to mitochondrial damage and thus antifungal properties (Qin et al., 2010; Shi et al., 2010). Fungistatic properties combined with the role of B in plant defense warrant further CLS management studies.

In addition to root yield and quality, foliar B affects plant metabolism including cell wall and membrane structure, ion, hormone, and metabolite transfer (Brdar & Jokanovi´c, 2020; Brown & Shelp, 1997; Camacho-cristóbal et al., 2008). Micronutrients such as B function as cofactors or activators of enzyme systems which are pivotal to disease resistance and the production of defense barriers (Datnoff et al., 2007). Key roles of B in cell wall structure and plasma membrane integrity are directly impacted by *C. beticola* colonization and necrotrophic disruption. Deficiency of B may decrease root yield, sugar quality, and root quality by inducing ‘heart rot’ symptoms and the subsequent ‘dry rot’ within the root (Armin & Asgharipour, 2012; Cox, 1940). Previously, B applications were utilized for preventative management of ‘heart rot’ disease which increased frequency of B application. The demand for B in sugarbeet as an essential nutrient is greater than other field crops. Sufficient leaf tissue concentrations range from 26-80 ppm with observed deficiency symptoms at < 20 ppm (Voth et al., 1979; Robertson and Lucas, 1981; Christenson et al., 1991). Current soil test B recommendations suggest < 0.7 ppm as deficient and > 1.0 ppm as sufficient with marginal likelihood for deficiency between these values. Sufficient B concentrations may aid in disease resistance by supporting protective barriers in leaf tissue.

Boron fertilizer application practices have evolved over time. Previously, bulk fertilizers (i.e., urea, monoammonium phosphate, muriate of potash) contained B as an impurity which decreased need for supplemental B application (Nelson, 1965). As fertilizer processing and manufacturing improved to produce more highly concentrated fertilizers, the indirect B inclusion in bulk fertilizers was no longer the case. In high pH soils (>7.5) the borate anion ($HBO_4^-$) prevails and is subject to leaching. Field crops grown in rotation with sugarbeet in Michigan (i.e., small grains, dry beans (*Phaseolus vulgaris* L.), and soybeans (*Glycine max* L.) are sensitive to excess soil B, which may limit B application and accumulation within these crop rotations. Additionally, varietal response of sugarbeet to supplemental B has decreased in modern varieties (i.e., 2000 and later) on fine-textured Michigan soils (Voth et al., 1979; Christenson et al., 1991;

Warncke et al., 2009). The role of improved plant genetics on nutrient demand has not been determined.

Lack of previous response to B application, limited B accumulation in the soil profile, changes in the soil microenvironment (i.e., warmer soil temperatures longer into autumn), and fungicide efficacy may contribute to increases in CLS prevalence. Source of B and application timing may impact CLS reduction and sugarbeet response to B utilization. Approximately 96% of B uptake is in the form of uncharged boric acid molecules with little from borate anions (Bolaños et al., 2004). Application timing is most effective at 80-100 days after planting, with sodium tetraborate and boric acid contributing to increases in yield and quality (Armin & Asgharipour, 2012; Gobarah & Mekki, 2005; Mekdad et al., 2015). Integrating foliar B to improve sugarbeet fertility and reduce CLS may result in synergistic improvements to sugarbeet quality, plant defense mechanisms, and reduced *C. beticola* growth and sporulation.

The objectives of the current study were to 1) evaluate in-field applications of sodium tetraborate on CLS growth and development and 2) evaluate *in vitro* growth of *C. beticola* isolates in response to a concentration gradient of sodium tetraborate and boric acid.

## Materials and Methods

Field trials were established in the 2020-2021 growing seasons at the Michigan State University Saginaw Valley Research and Extension center near Richville, MI (43°23’57.3”N, 83°41’49.7”W) on a Tappan-Londo loam (fine-loamy, mixed, active, calcareous, mesic Typic Epiaquoll). Located in Northeastern Michigan, the site was non-irrigated, tile-drained, and representative of sugarbeet production throughout the state. Fields were previously cropped to corn and autumn plowed followed by spring field cultivation (0-10 cm depth). Pre-plant soil characteristics (0-20 cm) were 6.2-7.2 pH (1:1 soil/water), 22-28 g $kg^{-1}$ soil organic matter (loss-on-ignition), 22-24 mg $kg^{-1}$ P (Olsen sodium bicarbonate extraction), and 138-178 mg $kg^{-1}$ K (ammonium acetate method) (Table 3.01). Monthly precipitation and temperature data were collected and recorded throughout the growing season from Michigan State University Enviro-weather (http://agweatger.geo.msu.edu/mawn/) Michigan State University, East Lansing, MI) (Table 3.02).

**Experimental Procedures Field Trial**

Trials were planted on 7 April 2020 to variety ‘Crystal G332NT’ (ACH Seeds, Inc., Eden Prarie, MN) with a John Deere planter (Deere & Company., Moline, IL). Trials were planted on 5 April 2021 to variety ‘Crystal G932NT’ and replanted 7 May 2021 due to a freezing event 23-24 April 2021. Plots measured 3.05 m in width by 10.7 m in length with 76 cm row spacing. Trial consisted of eight treatments arranged as a randomized complete-block design with four replications. Treatments consisted of an untreated check containing no fungicide or boron, grower standard fungicide program (GS), three rates of sodium tetraborate in combination with a grower standard fungicide program (GS+ FBL, GS+FBM, GS+FBH), and three rates of sodium tetraborate individually excluding fungicide (FBL, FBM, FBH) (Table 3.03, 3.04). A $CO_2$ powered backpack sprayer equipped with four TJ 8002XR nozzles (76-cm spacing) calibrated at 140 L $ha^{-1}$ was utilized for application every 10-14 days starting 6 July and 28 June in 2020 and 2021, respectively. Fungicides were applied 6, 16, 27 July, 11, 24 August, and 4, 14 September in 2020. Fungicides were applied 28 June, 12, 26, July, 5, 16, 25 August, 9, and 27 September in 2021. All treatments received 101 kg N $ha^{-1}$ as pre-plant urea. Sidedress 67 kg N $ha^{-1}$ injected to 12.7 cm depth halfway between the rows as 28% UAN was applied at the 4-6 leaf stage on 9 June 2020 and 1 June 2021.

Inoculation of *C. beticola* (100 spores/mL) was applied at 140 L $ha^{-1}$ using a tractor mounted sprayer on 9 and 23 July 2020 and 12 July 2021. A precipitation event reduced inoculation efficacy in 2020 resulting in an additional application. Bi-weekly disease ratings were collected starting 9 and 26 July and continued to 6 October and 27 September in 2020 and 2021, respectively. Plots were assigned a severity rating using the following scale based on infected leaf area: 1=0.1% (1-5 spots/leaf), 2=0.35% (6-12 spots/leaf), 3=0.75% (13-25 spots/leaf), 4=1.5% (26-50 spots/leaf), 5=2.5% (51-75 spots/leaf), 6=3%, 7=6%, 8=12% 9=25%, 10=50%. Incidence and severity ratings were utilized to calculate disease index (DI) and quantify differences in CLS development among treatments. Disease incidence was recorded to represent the frequency of new lesion activity and ratings were used to calculate area under the disease progress curve for disease severity (AUDPC).

Plant emergence was counted 20-30 days after planting to confirm plant population. Fractional green canopy coverage (FGCC) and normalized difference vegetation index (NDVI) were collected every 10-14 days coinciding with fungicide application (Patrignani and Ochsner, 2015). The uppermost fully developed and extended leaf and petiole were collected from 25 plants $plot^{-1}$ at the 12-14 leaf growth stage in 2020. Additional tissue samples were collected at 6-8 leaf, 12-14 leaf, and 18-20 leaf in 2021 to monitor B uptake throughout the growing season. Plant tissue samples were dried at 60°C, mechanically ground to pass through a 1-mm mesh screen and analyzed for total N using a micro-Kjeldahl digestion method and colorimetric analysis with a Lachat rapid flow injector autoanalyzer (Nelson and Sommers, 1973; Bremner, 1996). Beets from the center two rows of each plot were harvested on 14 October 2020 and 20 October 2021 with a mechanical plot harvester and weighed. Root subsamples were collected

(10-12 roots plot$^{-1}$) analyzed for sucrose concentration, extraction percentage, and recoverable sucrose at the Michigan Sugar Co. (MSC) Laboratory (Bay City, MI).

Expected economic net return was calculated using both root yield and recoverable sucrose (kg Mg$^{-1}$) in addition to MSC's average payment standard (2020-2021) (Michigan Sugar Company, Bay City, MI). Expected net return was based on US$48.58 Mg$^{-1}$ and US$24.25 Mg$^{-1}$ (fresh weight) for sugarbeets in 2020 and 2021, respectively which was later adjusted based on a ratio of observed recoverable sucrose (kg Mg$^{-1}$) to average MSC recoverable sucrose (kg Mg$^{-1}$) value. Michigan Sugar Company payment standards were calculated using adjustment factors based on harvest date to determine amount of sugar delivered (kg ha$^{-1}$). Adjustment factors used were 1.00 and 1.04 for root yield and recoverable sucrose (kg ha$^{-1}$) and then multiplied by US$0.16 kg$^{-1}$ and US$0.10 kg$^{-1}$ to equal total payment ha$^{-1}$ in 2020 and 2021, respectively. Variable costs including trucking (US$4.13 Mg$^{-1}$) were subtracted from expected net return across years.

Data were analyzed in SAS 9.4 (SAS Institute, 2012) using the GLIMMIX procedure (SAS Institute, 2012). Year and treatment were considered fixed effects and replication as random. The UNIVARIATE procedure in SAS was used to examine the normality of residuals ($P \leq 0.05$). Squared and absolute values of residuals were examined with Levene's Test to confirm homogeneity of variances ($P \leq 0.05$). Least square means were separated using the LINES option when ANOVA indicated significance ($P \leq 0.10$).

**Experimental Procedures for *In Vitro* Sensitivity of *Cercospora beticola***

Sensitivity of *C. beticola* isolates to B containing compounds was evaluated using a conidial germination assay. Trials were arranged in a randomized complete block design with four replications and repeated twice for each isolate and concentration. Treatments consisted of a concentration gradient of 0, 1, 10, 50, 100, 500, and 1000 μg $ml^{-1}$ sodium tetraborate, boric acid, and thiophanate-methyl. Thiophanate-methyl was selected as a positive control due to higher $EC_{50}$ value to achieve closest comparison to B compounds. Technical-grade thiophanate-methyl (Millapore Sigma, Burlington, MA) was dissolved in methanol to prepare a stock solution of 7,500 μg $ml^{-1}$. Technical grade boric acid (Fisher Scientific, Waltham, MA) and sodium tetraborate (20 Mule Team, Borax) were weighed and added to test media to achieve desired concentration. The test medium was prepared by mixing potato dextrose agar (PDA) 39 g $L^{-1}$ for 15 minutes, autoclaving at 121°C for 30 minutes, and cooling to 60°C prior adding appropriate dry boron product or thiophanate-methyl stock quantities to achieve the desired concentrations. Once products were added, media was mixed for 10 minutes (until homogenous) and maintained at 60°C for plate transfer. Agar plates were prepared by transferring 20 mL of amended-agar solution to 100 mm x 20 mm Petri dishes. Nonamended control plates consisted of PDA.

Isolates Blum 1-2 and Range A were obtained from the United States Department of Agriculture- ARS Sugar Beet Research Unit (SBRU) fungal collection. Blum 1-2 was obtained from symptomatic sugarbeet leaf lesions in Saginaw County, MI in 2017. ‘Range A’ was collected from a symptomatic sugarbeet leaf in Ingham County, MI in 2008. Single spore transfer protocols were utilized to obtain pure cultures with fungal ball storage at -20 °C. To produce inoculum, isolates were cultured on clarified V8 (CV8) agar medium and incubated at room temperature (21-24°C) for 30 days. Five-mm agar discs were excised from the actively growing margin of the colony. Agar disks were inverted, and a single disk was placed in the center of each amended PDA plate and incubated at room temperature for 21 days. *Cercospora beticola* radial growth diameter was collected every seven days. Diameters were corrected for the 5 mm agar disk. Diameters were calculated relative to the control and $EC_{50}$ values were generated using R version 4.1.2 (R Core Team 2022) with the three-parameter log-logistic (LL.3) function in package ‘drc’ (Ritz et al. 2015). Mean $EC_{50}$ values were obtained from each experimental repetition. Means were further analyzed in a generalized linear mixed model (GLIMMIX) ANOVA in SAS v. 9.4 (SAS, Cary, NC). Isolate and compound were considered fixed effects while experimental repetition was considered a random effect.

## Results and Discussion

### Environmental Conditions

April through September growing season precipitation was 12.5% and 8.3% below the 30-yr mean during 2020 and 2021, respectively (Table 3.02). Cool April soil temperatures combined with deficit June 2020 precipitation (i.e., 55% below the 30-yr mean) slowed plant emergence and development. In 2021, April and May rainfall was 75% and 65% below the 30-yr mean, respectively, resulting in delayed emergence. June precipitation, however, was 50% above the 30-yr mean, contributing to favorable conditions for disease. Except for April 2020, monthly growing season air temperatures were near or above the 30-yr mean. Above average April 2021 soil temperatures resulted on 5 April planting date but a frost on 21 April resulted in replanting the field trial on 5 May.  The 2021 replanting resulted in minimal impact on sugar beet emergence and early season growth.

### Effect of Sodium Tetraborate and Boric Acid on *In Vitro* Growth of *Cercospora beticola*

Relative radial growth of *C. beticola* grown *in vitro* decreased with inclusion of sodium tetraborate and boric acid (Table 3.05). Radial growth decreased 14-19% with sodium tetraborate in Blum 1-2 and Range A as compared to the control. Inclusion of boric acid reduced mean radial growth 5-10% in Range A and Blum 1-2. Thiophanate-methyl (i.e., positive control for both isolates) demonstrated 8 and 86% growth reductions in Range A and Blum 1-2, respectively. A PCR-RFLP analysis confirmed benzimidazole resistance in the Range A isolate resulting in minimal effectiveness by thiophanate-methyl as compared to Blum 1-2.

Benzimidazole resistance was previously identified in Michigan *C. beticola* isolates in the 1990s which contributes to current CLS control challenges (Rosenzweig et al., 2015). In addition to reduced relative radial growth, estimated $EC_{50}$ values (i.e., value of half maximal concentration) for control of *C. beticola* were significantly lower with sodium tetraborate ranging from 772-876 mg $kg^{-1}$ in Blum 1-2 and Range A, indicating greater effectiveness (Table 3.06). Estimated $EC_{50}$ values for boric acid exceeded 1,000 mg $kg^{-1}$ for Range A and Blum 1-2. Response of *C. beticola* may be impacted by pH as the pH of boric acid and sodium tetraborate are 5.1 and 9.3, respectively, indicating that growth of *C. beticola* was reduced at higher pH. Iamandei et al. (2013) evaluated the influence of pH on *in vitro* development of *C. beticola* colonies. Fungus development covered a wide pH spectrum in which vegetative mass and condia growth began with a pH of three with optimal values falling between four and seven. As pH increased, *C. beticola* vegetative growth declined but continued to produce numerous conidia.

Examination of labeled rates of current B-containing products indicate that $EC_{50}$ values can be achieved in field applications. Labeled rates of a boric acid derived product, utilized for foliar application of B in sugarbeet, would be equivalent to 2,000-9,000 mg $kg^{-1}$ B based on recommended product use and carrier rate as a function of solution concentration in a single application. In addition to marketed boric acid products, labeled rates of 100% sodium tetraborate (i.e., borax) are equivalent to 200-900 mg $kg^{-1}$ B in recommended solution concentrations for a single in-field application. Variation in product use rate, active ingredient, and concentration of B strongly influence concentration ranges. Current B-containing products are formulated to correct B deficiency in a wide range of crops. With minimal concentrations needed to correct soil fertility deficiencies, current products are not equally sufficient for disease management. Implementation of higher B concentrations may aid in CLS control, but secondary impacts of greater concentrations would require further examination.

Environmental fate of foliar B is a determining factor in both disease and nutritional response. Plant response is species-specific and highly dependent on method of application, soil characteristics, temperature, and humidity leading to discrepancies in environmental fate and plant B utilization (Brdar-Jokanović, 2020). Soil pH and trace element interaction are known to affect B availability and ion reactions in soil (Ibekwe et al., 2010) In arid and semiarid irrigated areas, high soil B concentrations are often associated with high salt concentrations and can be a limiting factor to plant growth (Ayars et al., 1993; Grieve & Poss, 2008; Shouse et al., 2006). El-Fawy, (2016) reported significant CLS reduction, increase in root yield, and recoverable sucrose with application of B containing compounds in El-Behera Governorate, Egypt. Yield reductions up to 60% have been attributed to salinity levels in similar regions of Egypt as compared to soils with reduced salinity levels (Ahmed Bakry et al., 2014). While *C. beticola* response was attributed to application of foliar B, soil salinity levels of this region may have increased plant nutritional response for improved sugar beet quality thus ultimately improving response to CLS.

**Effect of Foliar Boron and Fungicide on Root Yield, Quality, and Expected Net Return**

Increased air temperatures combined with adequate precipitation resulted root yields ranging between 44.8-89.3 Mg ha$^{-1}$ in 2021 compared to 40.0-60.9 Mg ha$^{-1}$ in 2020. Replanting did not reduce yield in 2021. Across site years, application of foliar B did not increase root yield when compared to the GS treatment (Table 3.07, 3.08). In 2020, the FBH treatment reduced root yield while FBL and FBM yielded similar to GS. In 2021, of GS reduced root yield > 22.2 Mg ha$^{-1}$ across treatments. Gobarah & Mekki (2005) observed application of up to 3.71 kg B ha$^{-1}$ applied as sodium borate increased root length, diameter, and root yield with highest recoverable sucrose at rates of 4.9 kg ha$^{-1}$ in saline soils. In Michigan, current soil test B recommendations suggest < 0.7 mg kg$^{-1}$ as deficient and > 1.0 mg kg$^{-1}$ as sufficient with marginal deficiency conditions in-between these values (Warncke et al., 2009). Current B recommendations indicate 1.1 kg B ha$^{-1}$ may be beneficial with 2.2 kg B ha$^{-1}$ in coarse-textured soils (Vitosh et al., 2006). Soil B concentrations of 1.2 and 0.8 mg kg$^{-1}$ in 2020 and 2021, respectively, indicate sufficiency (Table 3.01) and therefore less probability of a positive impact from foliar B applications on root yield across site years.

Similar to root yield, sugar beet quality parameters indicated lack of response to foliar B. The addition of foliar B did not improve recoverable sucrose in 2020 with FBH individually decreasing recoverable sucrose per hectare (Table 3.07). In 2021, recoverable sucrose per hectare was reduced > 48-57% with treatments excluding the GS program (Table 3.08). Plant response to foliar B is dependent upon soil physical and chemical properties (i.e. nutrient solubility, solution pH, surface tension, retention, and molecular structure of B source), environmental conditions, and leaf characteristics which may help determine the efficacy, uptake, and usage of foliar nutrient solutions (Fernández & Brown, 2013; Fernandez & Eichert, 2009). Application of sodium borate and boric acid have been linked to increases in recoverable sucrose and improved juice purity by decreasing Na and K uptake (Abdallah & Mekdad, 2015; Armin & Asgharipour, 2012; Dordas et al., 2007). Tissue nutrient concentration of B remained sufficient (i.e., 32-46 ppm) throughout the growing season for all treatments (data not shown) indicating foliar B was not limiting and not likely to affect sugar beet yield and quality. Root yield and recoverable sucrose results indicate foliar B applications did not provide or enhance protection from CLS.

Root yield and quality responses to foliar B were also reflected in economic return across site years. Expected net return was similar or reduced with the inclusion of foliar B individually or when combined with a GS program (Table 3.09). Profitability was similar between the GS, GS+FBL, and GS+FBH treatments with reductions > \$973.00 $ha^{-1}$ when removing fungicide applications in 2021. Increases in recoverable sucrose and root yield did not translate to profitability when considering both volume and quality parameters (Table 3.09).

**Effect of Foliar Boron and Fungicide on CLS Development**

Disease development was delayed in 2020 with first symptoms recorded on 20 Aug. Despite inoculation, CLS did not develop until late in the season resulting in a smaller window for treatment effectiveness. Absence of disease during the first half of the growing season allowed increased canopy development thus reducing risk for production losses in treatments excluding fungicide. Decreased June precipitation and sporadic rainfall events in July likely extended the symptomless biotrophic phase of *C. beticola* colonization in 2020 (Table 3.02). Lesion development occurs as the fungus transitions to a necrotrophic phase (Ebert et al., 2021). Without adequate moisture, relative humidity below 90-95%, and overnight temperatures remaining < 16 °C, sporulation was reduced between June – August 2020 resulting in delayed infection. Positive performance of the FBL treatment may be attributed to infection timing and presence of B on the leaf surface during extended periods without precipitation. June 2021 precipitation was frequent with rainfall events taking place on 19 of 30 days resulting in improved conditions for early-season infection.

In 2020, no significant DI differences were detected between foliar B rates for the entire growing season (Table 3.10). All treatments containing fungicide reduced DI values with no impact of foliar B. Similar results were recorded through 9 Sept. 2021. However, a final DI rating on 27 Sept. 2021 demonstrated reduced DI with FBM as compared to FBL. No differences in green canopy coverage (FGCC) or normalized difference vegetation index (NDVI) occurred throughout 2020 (Table 3.11, 3.12). Area under the disease progress curve (AUDPC) values indicate reduced CLS control with treatments excluding fungicide in 2020 (Table 3.13). In 2021, AUDPC of FBL was greater than the GSP while FBM and FBH did not differ.

In 2021, including fungicide increased near-infrared (NIR) and green light reflectance towards the end of the growing season indicating greener plant tissue and lower CLS occurrence. Due to coalescing lesions and loss of older leaves, CLS can be difficult to measure accurately (Steddom et al., 2007). Vegetative indices are largely impacted by percentage of photosynthetically active tissue resulting in difficulty monitoring treatment differences in canopy reflectance as affected by foliar B. Rating variability and physiological response of sugarbeet to *C. beticola* induce challenges to quantify differences among treatments without severe levels of infection. Early CLS pressure in 2021 had a greater impact on measurable response.

**Effect of Foliar Boron and Fungicide on Tissue B Concentration**

Across site years, tissue B concentrations remained > 32 ppm at the 14-16 leaf stage indicating sufficiency (data not shown). In 2021, an additional sample timing was included to evaluate foliar B uptake throughout the growing season. Late season tissue samples demonstrated increased B tissue concentrations with inclusion of fungicide. Tissue B concentrations ranged 43-46 mg $kg^{-1}$ with fungicide and 38-40 mg $kg^{-1}$ in treatments excluding fungicide. Sugarbeet has one of the larger B requirements among field crops with reported sufficient leaf tissue concentrations ranging from 26-80 mg $kg^{-1}$ and observed deficiency symptoms at < 20 mg $kg^{-1}$ (Voth et al., 1979; Robertson and Lucas, 1981; Christenson et al., 1991). Despite statistical differences, B tissue concentrations fell within sufficiency levels for all treatments. Sufficient (i.e. > 0.7 mg $kg^{-1}$) B soil test levels, tissue B concentration (i.e. > 20 mg $kg^{-1}$), and application of B in the form of sodium tetraborate reduced the likelihood of plant response by means of foliar uptake. Frequent application of sodium tetraborate likely had a greater impact on leaf surface physical and chemical properties than internal plant response.

Physical and chemical leaf surface conditions are fundamental to parasitic microorganism development that initiate at the leaf boundary and may also affect the efficiency and persistence of foliar applied pesticides (Oertli et al., 1977). Possible buffering of leaf surface pH may impact effectiveness of foliar B on CLS control. Hutchinson et al. (1986) examined neutralizing abilities of sugarbeet, radish (*Raphanus sativus* L.), sunflower (*Helianthus* L.), and wormwood (*Artemisia tilesii* L) to acid rain ranging in pH from 2.4-4.7. Radish, sunflower, and wormwood significantly increased pH in all droplets while sugarbeet resulted in little to no change. The mechanism behind acid rain neutralization is facilitated by leaching and exchange of base cations (e.g., $Ca^{2+}$, $K^{+}$, $Mg^{+}$ and $Na^{+}$ for $H^{+}$) on leaf surface induced by cell membrane and cuticle damage (Tukey et. al., 1971; Tukey et. al., 1980). Lack of acidic droplet neutralization by sugarbeet was attributed to absence of leaf injury as compared to other species examined (Hutchinson et al., 1986). The sodium tetraborate product used in this study has a pH range of 6-7 reducing the direct impact on leaf surface pH. However, a combination of cuticle injury due to necrotic lesions of CLS may influence sugarbeet leaf ion exchange resulting in neutralization of alternative B containing compounds (i.e., boric acid).

In addition to chemical alteration of leaf microenvironment, parasitic spore germination may be prevented or reduced by synthesis of substances such as phytoalexins (Oertli et al., 1977). Researchers suggest foliar application of B, Mn, and Cu result in exchange of $Ca^{2+}$ cations from cell walls and interact with salicylic acid (involved with phytoalexin response) to activate resistance mechanisms in the host plant (Reuveni et al., 1997; R. Reuveni & Reuveni, 1998). While application of foliar B may support natural plant resistance, it is unlikely to overcome rapid development of CLS. Intact cuticles of sugarbeet, slow rates of ion exchange, low susceptibility of inorganic ion leaching, and limited sodium borate uptake indicate that application of foliar B may not be an effective strategy for CLS management (Bolaños et al., 2004; Tukey & Tukey, 1962). Lack of disease response, reductions in root yield, and decreased quality suggest foliar B failed to provide disease suppression in field environments.

**Toxin Role in *Cercospora beticola* Development and Pathogenicity**

The pathogenicity of *C. beticola* is driven by cercosporin, a photoactivated polyketide toxin that acts as a cell membrane sensitizer and producer of singlet oxygen (Daub & Briggs, 1983; Mitchell et al., 2002). Peroxidation of membrane lipids leads to membrane breakdown, cell death, and leakage of nutrients into leaf intercellular spaces allowing for fungal growth and sporulation (Daub & Briggs, 1983). In addition to cercosporin, beticolins are non-host-specific phytotoxins of *C. beticola* that induce loss of electrolytes, amino acids, and betacyanin via ion channel formation and permeabilization of host cell membranes (Goudet et al., 2000; Macrì & Vianello, 1979). Physiological parameters, including pH, nutrient conditions, temperature, and C:N ratios all influence toxin production (Daub & Ehrenshaft, 2000). Toxin production in culture is highly variable among and within species. *C. beticola* isolates are capable of producing cercosporin, beticolin, or both (Daub & Chung, 2007). While cercosporin and beticolin aid in host pathogenicity of *C. beticola*, auto resistance (AR) is essential for self-protection (Rangel et al., 2020). Cercospora AR is facilitated by toxin export and reductive detoxification of the cercosporin molecule (Margaret E. Daub et al., 1992; Leisman & Daub, 1992; Sollod et al., 1992). Cercosporin derivatives absorb less light and generate significantly less singlet oxygen

($^1O_2$) when stably methylated and acetylated reduced compared to wild-type cercosporin (Leisman and Daub, 1992). Herrero et al., (2007) conducted cercosporin toxicity assays to evaluate isolate strain AR sensitivity to pH and discovered the *crg1*-null strain of C. *nicotianae* to cercosporin was strongly impacted by pH. In the presence of cercosporin on media at pH levels < 6, observation included almost complete lack of growth in the presence of cercosporin suggesting certain isolates lack detection of acidic environments and adjustment of intracellular pH creating cercosporin susceptibility (Herrero et al., 2007). Environmental conditions including changes in pH and ion concentration may influence methylation and acetylation of cercosporin or reduction in isolate AR resulting in altered pathogenicity.

Cercosporin and beticolin levels were not quantified in this study. However, notable differences in isolate color were consistent with varying concentrations of sodium tetraborate and boric acid (Figs. 3.01, 3.02). Cercosporin is characterized by red pigments that turn green in alkaline conditions, while beticolins are yellow in color and turn orange with pH increase (Goodwin & Dunkle, 2010; C. Goudet et al., 1998). Changes in isolate color suggest that cercosporin and beticolin production may be influenced by presence of B containing compounds and altered growth media pH. You et al., (2008) reported changing pH values to 4.0–7.0 reduced cercosporin and isolate radial growth compared to nonbuffered medium. However, addition of citrate or phosphate buffers caused cercosporin reduction regardless of the pH values indicating solution buffer directly impacts cercosporin production. Further examination of metal ions ($Zn^{2+}$, $Fe^{3+}$, $Co^{2+}$, $Mn^{2+}$, $Cu^{2+}$, and $Mg^{2+}$) slightly enhanced or had no effect on cercosporin production unlike high quantities of $Na^+$ or $K^+$ which inhibited cercosporin production (You et al., 2008). The role of cercosporin and beticolin in cell membrane disruption, nutrient leakage, and alteration of ion concentration suggests that leaf surface microenvironment directly impacts cercosporin and beticolin production in sugarbeet. Visual differences in isolate color indicate change in toxin production and suggest altered pathogenicity of *C. beticola* and potential for enhanced host defense by means of ion exchange.

## Conclusions

Application of foliar B did not reduce CLS in field environments across site years. GS practice increased root yield, recoverable sucrose, and canopy coverage with minimal differences detected among foliar B rates. Plant health indicators such as NDVI, fractional green canopy coverage (FGCC), and DI did not support improvement in CLS protection with foliar B. Radial growth of *C. beticola* decreased with increasing concentrations of B *in vitro.* Sodium tetraborate more effectively inhibited growth than boric acid. Differences in growth response and estimated $EC_{50}$ values were attributed to secondary physiological effects based on increasing pH. Boron-compounds were not as effective as the most effective fungicide, but also no effective as the least effective fungicide. Previous findings of reduced CLS with B application in sugarbeet may be due to increased plant health and nutritional improvement. Evaluation of soil test levels, sugarbeet characteristics, environmental conditions, and disease conditions are necessary to make proper B recommendations. Reduced control options, increased CLS resistance, and increase B requirement of sugarbeet enhance the need for further evaluation of alternative control measures. In-field evaluation of various B timing, increased B concentrations, and addition of B-containing compounds may contribute to future CLS control.

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# APPENDIX

*Table 3.01.* Soil physical and chemical properties including mean $NO_3$-N (0-30cm), P (0 – 20 cm), and K soil test (0 – 20 cm) nutrient concentrations obtained prior to sugarbeet planting, Richville, MI, 2020-2021.

| **Year** | **Soil description** | **Soil test†** | | | | |
|---|---|---|---|---|---|---|
| | | P | K | B | pH | OM |
| | | ----------------mg $kg^{-1}$---------------- | | | | g $kg^{-1}$ |
| 2020 | Tappan-Londo Loam | 24 | 138 | 1.2 | 7.2 | 22 |
| 2021 | Tappan-Londo Loam | 22 | 178 | 0.8 | 6.2 | 28 |

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

*Table 3.02.* Mean monthly and 30-yr precipitation† and temperature for the sugarbeet growing season, Richville, MI, 2020 - 2021.

| Year | Apr. | May | Jun. | Jul. | Aug. | Sept. | Total |
|---|---|---|---|---|---|---|---|
| | -------------------------------------cm------------------------------------- | | | | | | |
| 2020 | 5.3 | 9.5 | 3.4 | 8.2 | 8.6 | 7.1 | 42.1 |
| 2021 | 1.8 | 3.0 | 11.4 | 7.3 | 7.8 | 12.8 | 44.1 |
| 30-yr‡ | 7.3 | 8.6 | 7.6 | 6.6 | 8.1 | 9.9 | 48.1 |
| | -------------------------------------°C------------------------------------- | | | | | | |
| 2020 | 6.2 | 13.8 | 20.6 | 23.7 | 21.4 | 15.8 | -- |
| 2021 | 9.3 | 14.1 | 21.8 | 21.3 | 22.8 | 17.6 | -- |
| 30-yr | 7.4 | 13.2 | 18.7 | 20.9 | 19.7 | 15.8 | -- |

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

*Table 3.03.* Sugarbeet treatment design and application timing, Richville, MI, 2020.

| **Treatment** | **Product Rate† and Timing‡** |
|---|---|
| Grower Standard Fungicide | Manzate Max (1.6 qt) ABCDEF + Inspire XT (7 fl oz) ADF + Super Tin (8 fl oz) BE + Priaxor (8 fl oz) C, Topsin (20 fl oz) C + Badge (2 pt) G |
| Foliar Boron – Low No Fungicide | SprayBor (0.1 lb) ABCDEFG |
| Foliar Boron – Medium No Fungicide | SprayBor (0.25 lb) ABCDEFG |
| Foliar Boron – High No Fungicide | SprayBor (0.5 lb) ABCDEFG |
| Grower Standard + Foliar Boron Low | SprayBor (0.1 lb) ABCDEFG +Manzate Max (1.6 qt) ABCDEF + Inspire XT (7 fl oz) ADF + Super Tin (8 fl oz) BE + Priaxor (8 fl oz) C, Topsin (20 fl oz) C + Badge (2 pt) G |
| Grower Standard + Foliar Boron Medium | SprayBor (0.25 lb) ABCDEFG +Manzate Max (1.6 qt) ABCDEF + Inspire XT (7 fl oz) ADF + Super Tin (8 fl oz) BE + Priaxor (8 fl oz) C, Topsin (20 fl oz) C + Badge (2 pt) G |
| Grower Standard + Foliar Boron High | SprayBor (0.5 lb) ABCDEFG +Manzate Max (1.6 qt) ABCDEF + Inspire XT (7 fl oz) ADF + Super Tin (8 fl oz) BE + Priaxor (8 fl oz) C, Topsin (20 fl oz) C + Badge (2 pt) G |
| Check | No Fungicide, No Foliar Boron |

†All rates, unless otherwise specified, are listed as a measure of product per acre.
‡Application letters code for the following dates: A=6 Jul, B=16 Jul, C=27 Jul, D=11 Aug, E= 24 Aug, F= 4 Sept, G= 14 Sept.

*Table 3.04.* Sugarbeet treatment design and application timing, Richville, MI, 2021.

| **Treatment** | **Product Rate† and Timing‡** |
|---|---|
| Grower Standard Fungicide | Manzate Max (1.6 qt) ABCDEFG + Inspire XT (7 fl oz) BEG + Super Tin (8 fl oz) CF + Priaxor (8 fl oz), Topsin (20 fl oz) D + Badge (2 pt) H |
| Foliar Boron – Low No Fungicide | SprayBor (0.1 lb) ABCDEFGH |
| Foliar Boron – Medium No Fungicide | SprayBor (0.25 lb) ABCDEFGH |
| Foliar Boron – High No Fungicide | SprayBor (0.5 lb) ABCDEFGH |
| Grower Standard + Foliar Boron Low | SprayBor (0.1 lb) ABCDEFGH +Manzate Max (1.6 qt) ABCDEFG + Inspire XT (7 fl oz) BEG + Super Tin (8 fl oz) CF + Priaxor (8 fl oz) D, Topsin (20 fl oz) D + Badge (2 pt) H |
| Grower Standard + Foliar Boron Medium | SprayBor (0.25 lb) ABCDEFGH +Manzate Max (1.6 qt) ABCDEF + Inspire XT (7 fl oz) BEG + Super Tin (8 fl oz) CF + Priaxor (8 fl oz) D, Topsin (20 fl oz) D + Badge (2 pt) H |
| Grower Standard + Foliar Boron High | SprayBor (0.5 lb) ABCDEFGH +Manzate Max (1.6 qt) ABCDEF + Inspire XT (7 fl oz) BEG + Super Tin (8 fl oz) CF + Priaxor (8 fl oz) D, Topsin (20 fl oz) D + Badge (2 pt) H |
| Check | No Fungicide, No Foliar Boron |

†All rates, unless otherwise specified, are listed as a measure of product per acre.

‡ Application letters code for the following dates: A=28 Jun, B=12 Jul, C=26 Jul, D=5 Aug, E= 16 Aug, F= 25 Aug, G= 9 Sept, H= 27 Sept.

*Table 3.05.* Relative radial growth for Blum 1-2 and Range A as affected by isolate and compound.

| Isolate | Compound | Relative Growth |
|---|---|---|
| Blum 1-2 | Boric Acid | 0.90 ab |
| Blum 1-2 | Sodium Tetraborate | 0.86 bc |
| Blum 1-2 | Thiophanate-Methyl | 0.14 d |
| Range A | Boric Acid | 0.95 a |
| Range A | Sodium Tetraborate | 0.81 c |
| Range A | Thiophanate-Methyl | 0.92 ab |
| ***$P_r > F$*** | | < 0.01 |

†Means followed by the same lowercase letter are not significantly different at ($\alpha$=0.1).

‡ Relative growth calculated as compared to control.

*Table 3.06.* Estimated $EC_{50}$ values for Blum 1-2 and Range A as affected by compound.

| Isolate | Compound | $EC_{50}$† Estimate mg $kg^{-1}$ |
|---|---|---|
| Blum 1-2 | Boric Acid | >1000 |
| Blum 1-2 | Sodium Tetraborate | 772 |
| Blum 1-2 | Thiophanate-Methyl | 0.35 |
| Range A | Boric Acid | >1000 |
| Range A | Sodium Tetraborate | 876 |
| Range A | Thiophanate-Methyl | >1000 |

†Value of half maximal effective concentration i.e., 50% growth reduction as compared to control.

*Table 3.07.* Fungicide and foliar boron effects on sugarbeet root yield, recoverable sucrose (kg ha$^{-1}$ and kg Mg$^{-1}$), sucrose concentration, and extraction, Richville, MI, 2020.

| **Treatment** | **Root Yield** | **Recoverable Sucrose** | | **Sucrose** | **Extraction** |
|---|---|---|---|---|---|
| | -Mg ha$^{-1}$- | -kg ha$^{-1}$- | -kg Mg$^{-1}$- | --%-- | --%-- |
| Grower Standard Fungicide | 55.2 abc† | 7389 ab | 134 a | 17.9 a | 95.9 |
| Foliar Boron – Low (FBL), No Fungicide | 59.5 ab | 7561 ab | 127 b | 17.1 b | 95.5 |
| Foliar Boron – Medium (FBM), No Fungicide | 46.6 cd | 5900 bc | 126 b | 16.9 b | 95.6 |
| Foliar Boron – High (FBH), No Fungicide | 40.0 d | 5107 c | 126 b | 17.0 b | 95.7 |
| Grower Standard + FBL | 52.5 abc | 7109 ab | 135 a | 18.0 a | 95.9 |
| Grower Standard + FBM | 55.0 abc | 7361 ab | 133 a | 17.7 a | 95.8 |
| Grower Standard + FBH | 60.9 a | 8172 a | 134 a | 17.9 a | 95.8 |
| Check - No Fungicide, No Boron | 47.2 bcd | 5878 bc | 124 b | 16.7 b | 95.7 |
| ***$P_r$ > F*** | = 0.09 | <0.01 | = 0.06 | < 0.01 | NS |

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

*Table 3.08.* Fungicide and foliar boron effects on sugarbeet root yield, recoverable sucrose (kg ha$^{-1}$ and kg Mg$^{-1}$), sucrose concentration, and extraction, Richville, MI, 2021.

| **Treatment** | **Root Yield** | **Recoverable Sucrose** | | **Sucrose** | **Extraction** |
|---|---|---|---|---|---|
| | -Mg ha$^{-1}$- | -kg ha$^{-1}$- | -kg Mg$^{-1}$- | --%-- | --%-- |
| Grower Standard Fungicide | 89.3 a† | 10759 a | 241 a | 16.4 a | 94.9 |
| Foliar Boron – Low (FBL), No Fungicide | 54.3 c | 5577 c | 205 b | 14.2 b | 94.5 |
| Foliar Boron – Medium (FBM), No Fungicide | 44.8 d | 4571 c | 202 b | 14.0 b | 94.2 |
| Foliar Boron – High (FBH), No Fungicide | 52.2 cd | 5331 c | 204 b | 14.2 b | 94.7 |
| Grower Standard + FBL | 82.7 ab | 10045 ab | 243 a | 16.4 a | 94.5 |
| Grower Standard + FBM | 77.4 b | 8962 b | 232 a | 15.8 a | 94.7 |
| Grower Standard + FBH | 76.5 b | 9797 ab | 241 a | 16.3 a | 95.0 |
| Check - No Fungicide, No Boron | 54.0 cd | 5526 c | 205 b | 14.2 b | 94.5 |
| ***$P_r$ > F*** | <0.01 | <0.01 | <0.01 | < 0.01 | NS |

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

*Table 3.09***.** Fungicide and foliar boron effects on sugarbeet expected net return, expected net return minus N costs, and expected net return minus N and trucking costs, Richville, MI, 2020-21.

| **Treatment** | **Expected Net Return** ‡ | | **Expected Net Return Minus trucking costs** | |
|---|---|---|---|---|
| | ----------------------------US$ $ha^{-1}$ | | ---------------------------- | |
| | **2020** | **2021** | **2020** | **2021** |
| Grower Standard Fungicide | 2929 ab† | 2481 a | 2701 ab | 2112 a |
| Foliar Boron – Low (FBL), No Fungicide | 2999 ab | 1286 c | 2753 ab | 1061 c |
| Foliar Boron – Medium (FBM), No Fungicide | 2338 bc | 1054 c | 2146 bc | 868 c |
| Foliar Boron – High (FBH), No Fungicide | 2024 c | 1229 c | 1859 c | 1013 c |
| Grower Standard + FBL | 2818 ab | 2316 ab | 2601 ab | 1975 ab |
| Grower Standard + FBM | 2917 ab | 2066 b | 2690 ab | 1746 b |
| Grower Standard + FBH | 3196 a | 2259 ab | 2945 a | 1923 ab |
| Check - No Fungicide, No Boron | 2330 bc | 1274 c | 2134 bc | 1051c |
| ***$P_r > F$*** | = 0.08 | < 0.01 | = 0.08 | < 0.01 |

†Means in the same column following by the same lowercase letter are not significantly different at $P \leq 0.10$.
‡Expected net returns based upon MSC payment adjustment with volume and quality incentives and trucking costs of USD $4.13 $Mg^{-1}$.

*Table 3.10.* Sugarbeet final disease index ratings Richville, MI 2020-21.

| **Treatment** | -----------**2020**----------- | | -----------**2021**----------- | |
|---|---|---|---|---|
| | **Sept. 14** | **Oct. 6** | **Sept. 9** | **Sept. 27** |
| Grower Standard Fungicide | 0.88 b | 1.8 b | 17.3 b | 41.5 c |
| Foliar Boron – Low (FBL), No Fungicide | 73.5 a | 90.3 a | 89.0 a | 73.8 a |
| Foliar Boron – Medium (FBM), No Fungicide | 70.4 a | 85.3 a | 87.5 a | 61.3 b |
| Foliar Boron – High (FBH), No Fungicide | 71.5 a | 83.5 a | 88.8 a | 71.3 ab |
| Grower Standard + FBL | 2.1 b | 4.0 b | 21.3 b | 30.0 cd |
| Grower Standard + FBM | 1.0 b | 2.5 b | 20.3 b | 31.3 cd |
| Grower Standard + FBH | 1.3 b | 2.1 b | 12.5 b | 28.0 d |
| Check - No Fungicide, No Boron | 77.5 a | 87.5 a | 90.0 a | 80.0 a |
| ***$P_r > F$*** | <0.01 | <0.01 | <0.01 | <0.01 |

†Means followed by the same lowercase letter are not significantly different at ($\alpha$=0.1).
‡ Disease index calculated from disease incidence and severity ratings recorded every 10-14 days post infection.

*Table 3.11.* Sugarbeet fractional green canopy coverage as affected by fungicide and foliar boron Richville, MI 2020-21.

| **Treatment** | **-----------2020-----------** | | **-----------2021-----------** | |
|---|---|---|---|---|
| | **Sept. 14** | **Oct. 6** | **Sept. 9** | **Sept. 27** |
| | ----------------------% canopy------------------------ | | | |
| Grower Standard Fungicide | 75.4 a | 77.3 a | 87.0 a | 87.0 a |
| Foliar Boron – Low (FBL), No Fungicide | 49.7 b | 37.4 c | 35.1 c | 29.0 c |
| Foliar Boron – Medium (FBM), No Fungicide | 54.5 b | 39.5 c | 33.7 c | 30.0 c |
| Foliar Boron – High (FBH), No Fungicide | 48.7 b | 37.0 c | 35.6 c | 32.0 c |
| Grower Standard + FBL | 70.9 a | 67.5 b | 82.6 ab | 82.0 ab |
| Grower Standard + FBM | 72.2 a | 68.5 ab | 80.0 b | 79.0 b |
| Grower Standard + FBH | 70.9 a | 71.9 ab | 82.6 ab | 79.0 b |
| Check - No Fungicide, No Boron | 55.3 b | 38.7 c | 34.6 c | 33.0 c |
| ***$P_r$ > F*** | < 0.01 | < 0.01 | <0.01 | <0.01 |

†Means followed by the same lowercase letter are not significantly different at (α=0.1).

*Table 3.12.* Sugarbeet normalized difference vegetation index as affected by fungicide and foliar boron Richville, MI 2020-21.

| **Treatment** | **-----------2020-----------** | | **-----------2021-----------** | |
|---|---|---|---|---|
| | **Sept. 14** | **Oct. 6** | **Sept. 9** | **Sept. 27** |
| Grower Standard Fungicide | 0.80 | 0.74 | 0.85 a | 0.89 a |
| Foliar Boron – Low (FBL), No Fungicide | 0.73 | 0.63 | 0.62 b | 0.74 b |
| Foliar Boron – Medium (FBM), No Fungicide | 0.82 | 0.72 | 0.61 b | 0.77 b |
| Foliar Boron – High (FBH), No Fungicide | 0.71 | 0.61 | 0.56 b | 0.74 b |
| Grower Standard + FBL | 0.83 | 0.72 | 0.81 a | 0.86 a |
| Grower Standard + FBM | 0.82 | 0.77 | 0.82 a | 0.86 a |
| Grower Standard + FBH | 0.76 | 0.68 | 0.81 a | 0.87 a |
| Check - No Fungicide, No Boron | 0.80 | 0.68 | 0.57 b | 0.73 b |
| ***$P_r$ > F*** | NS | NS | <0.01 | <0.01 |

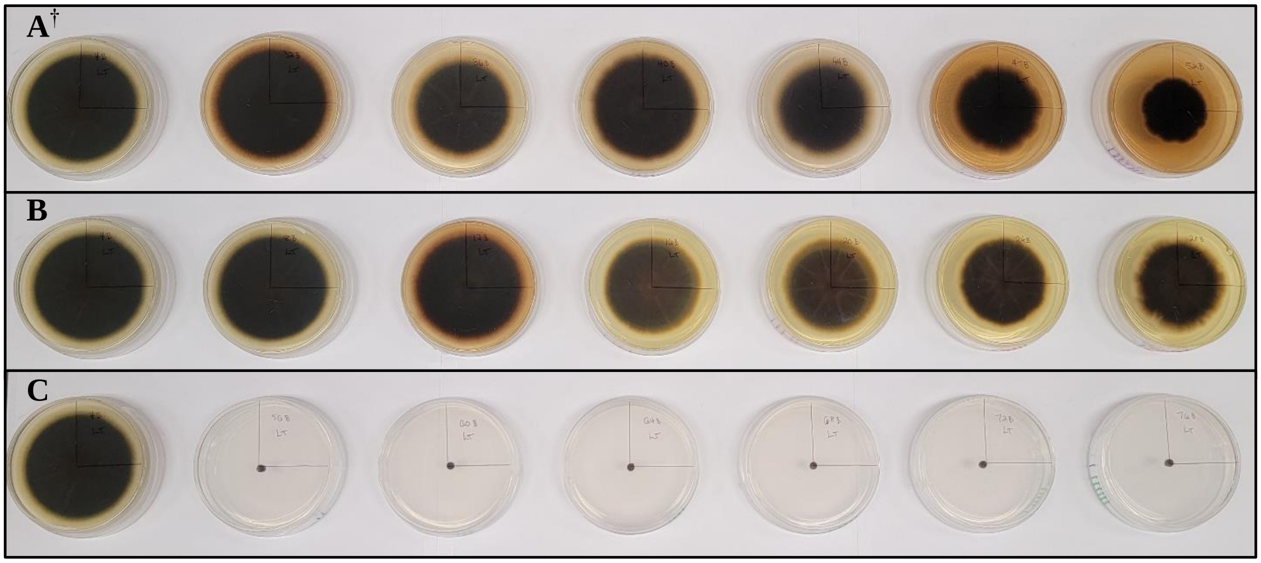
†Means followed by the same lowercase letter are not significantly different at (α=0.1).

*Table 3.13.* Area under the disease progress curve (AUDPC) as affected by fungicide and foliar boron Richville, MI 2020-21.

| **Treatment** | **2020** | **2021** |
|---|---|---|
| Grower Standard Fungicide | 62.4 c | 285.1 bc |
| Foliar Boron – Low (FBL), No Fungicide | 356.8 b | 371.6 a |
| Foliar Boron – Medium (FBM), No Fungicide | 550.0 a | 339.0 ab |
| Foliar Boron – High (FBH), No Fungicide | 337.8 b | 343.4 ab |
| Grower Standard + FBL | 57.9 c | 201.3 d |
| Grower Standard + FBM | 37.9 c | 280.4 bc |
| Grower Standard + FBH | 41.4 c | 223.1 cd |
| Check **-** No Fungicide, No Boron | 355.6 b | 337.4 a |
| $P_r > F$ | < 0.01 | < 0.01 |

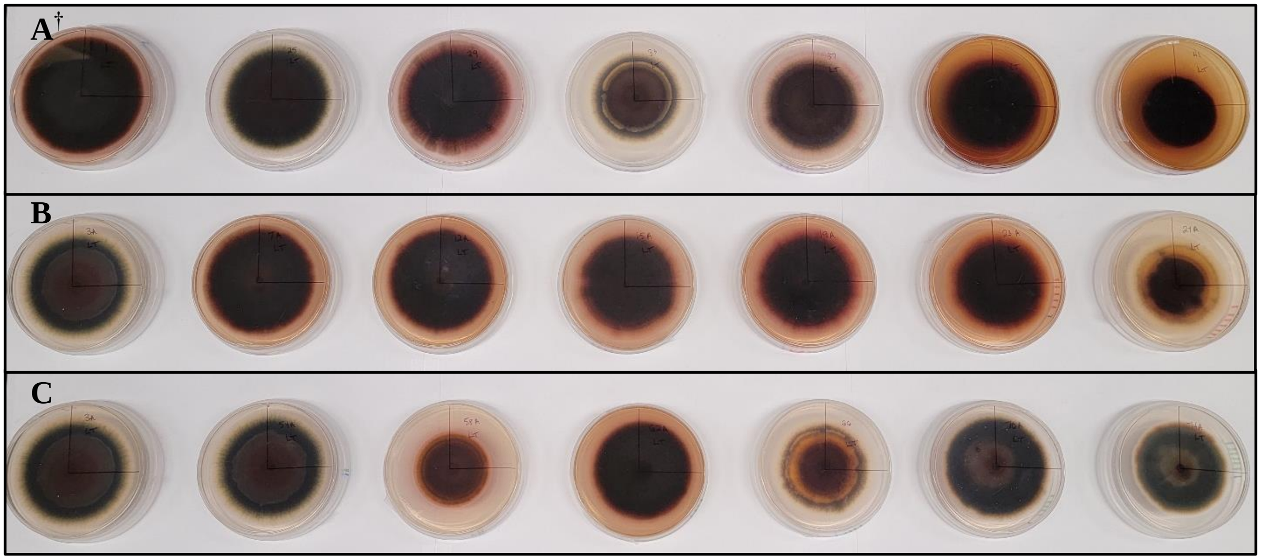
†Means followed by the same lowercase letter are not significantly different at (α=0.1).

*Figure 3.01***.** Day 21 radial growth of *Cercospora beticola* isolate 'Blum 1-2.'




†Sodium tetraborate (1A), boric acid (1B), thiophanate-methyl (1C) concentrations displayed left to right (0, 1, 10, 50, 100, 300, 500 ppm).

*Figure 3.02***.** Day 21 radial growth of *Cercospora beticola* isolate ‘Range A.’




†Sodium tetraborate (2A), boric acid (2B), thiophanate-methyl (2C) concentrations displayed left to right (0, 1, 10, 50, 100, 300, 500 ppm).

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