UNDERSTANDING WINTER WHEAT AND SUGARBEET YIELD, GROWTH, AND QUALITY THROUGH INTENSIVE MANAGEMENT

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ABSTRACT

Increased global demand for small grains emphasizes the need for intensified management strategies and future yield gains. The first study investigated the influence of various fertilizer and fungicide strategies and effects on winter wheat (*Triticum aestivum* L.) growth and development. Treatments were arranged as a full-factorial, randomized complete block design with two rates of autumn starter (AS), five fungicide timings (FT), and two rates of late-season nitrogen (LN) applied at Feekes 7 following both silage corn (SC) and soybean (SB). All treatments received a blanket N application [84 (SB) or 112 (SC) kg ha^{-1}] at Feekes 5, except for check plots. Following SC, AS increased mean grain yield by 2.2 Mg ha^{-1} in 2022. Across FT, AS consistently increased mean grain yield by 1.4 – 2.6 Mg ha^{-1} in SC 2023. Following SB, AS increased mean straw yield by 0.4, and 0.7 MT ha^{-1}, respectively in 2022 and 2023. An interaction between AS and LN significantly influenced straw yield with AS increasing straw yield both with and without LN in SC 2022. Autumn starter increased mean straw yield by 1.3 MT ha^{-1} than no AS in SC 2023. Autumn starter decreased grain protein content when LN was not applied (SC 2023, SB 2022). Late-season N at Feekes 7 occasionally increased mean grain protein content (SC 2022 and SB 2023).

Michigan sugarbeet (*Beta vulgaris* L.) nutrient management recommendations include 157-179 kg N ha^{-1} with an initial 45 kg N ha^{-1} applied at planting to promote canopy closure. While individually added inputs associated with yield gaps were previously investigated, synergistic influences combined with a standard N program (SN) within an intensive management perspective have not been explored. This second study investigated sugarbeet root yield and recoverable sucrose response to different fertilizer strategies along a stepwise increase in management intensity. In 2022, SN treatment averaged 90.1 Mg ha-1, 148.4 kg Mg-1, and 13,327.9 kg ha-1. The addition of in-furrow P negatively impacted root yield and recoverable sugar by -15.5 Mg ha^{-1} and - 2,325.7 kg ha^{-1}, respectively. In 2023, pre-plant broadcast lime, in-furrow P, and intensive management increased root yield by 13.7, 11.9, and 13.2 Mg ha^{-1}, respectively. The intensive management and pre-plant broadcast lime increased recoverable sugar per Mg by +7.1 and +8.4 kg Mg^{-1}, respectively, while also improving recoverable sugar per hectare by +2,329.8 and +2,278.0 kg ha^{-1}, respectively. In-furrow P increased sugar per hectare by 2,186.3 kg ha^{-1}.

Dedicated to my Mama Elsie, Papa Allen, brothers Kuya Paolo and Ryan, and my husband Ryan.

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CHAPTER 1: LITERATURE REVIEW

Intensive Management on Wheat Production

While wheat has historically been cultivated under low-input conditions, wheat producers are increasingly transitioning towards more intensive production management systems. This shift is driven by the unpredictable climate, fluctuations in rainfall patterns, and inherent spatial variability of soils. Intensive management involves manipulating agronomic inputs to mitigate yield-limiting factors through various management practices (Harms et al., 1989). Intensive management primarily focuses on optimizing crop nutrition and disease control. For instance, in Michigan, the application of foliar fungicide at the FK 10.5.1 stage increased yield by up to 0.75 Mg ha^{-1} (Quinn & Steinke, 2019b). Conversely, in a high-disease-pressure context, omitting fungicide applications at FK 6 and 10.5.1 stages reduced yield by 1 Mg ha^{-1} in Kansas (De Oliveira Silva et al., 2021). In a Kansas irrigated setting, 112 kg ha^{-1} of broadcast starter fertilizer containing nitrogen (N), phosphorus (P), sulfur (S), and zinc (Zn), along with 6.7 kg ha^{-1} of spring N and fungicide at the FK 10.4 stage, led to increased grain yield accompanied by higher aboveground biomass and kernel density (Jaenisch et al., 2022). In Ohio, adopting an intensive approach involving high seeding rates, split N application at FK 3-4 and FK 5-6 stages, S fertilizer at FK 5-6 stage, and fungicide sprays at FK 9 and 10.5.1 stages resulted in an average grain yield increase of 0.83 Mg ha^{-1} (Peterson et al., 2023). Similarly, in Wisconsin, an enhanced management strategy incorporating split N fertilizer, plant growth regulators, micronutrient application, and two-spray fungicides at FK 9 and 10.5.1 stages improved mean grain yield by 0.81–1.22 kg ha^{-1} and straw yield by 1.2–1.2 MT ha^{-1} (Roth et al., 2021).

Although the literature suggests that adopting IM for winter wheat holds the potential to elevate grain yield, its profitability is contingent on fluctuating grain prices and variable input costs (Peterson et al., 2023; Steinke et al., 2021). The absence of yield-limiting factors like conducive disease environments, inadequate pre-plant nutrient levels, and lodging may curtail the advantages of employing numerous agronomic inputs (De Oliveira Silva et al., 2021; Karlen & Gooden, 1990; Knott et al., 2016; Mohamed et al., 1990; Quinn & Steinke, 2019a). Therefore, a judicious selection of agronomic inputs is critical to address specific production challenges and achieve improved economic returns.

Starter Fertilizer

Starter fertilizer is applied in a band near the planted seeds to improve the early growth of seedlings. For years, the benefits of starter fertilizer in crop production were acknowledged (Purucker & Steinke, 2020; Winters, 2015). The application of 280 kg ha^{-1} starter fertilizer with N, P, S and Zn increased grain yield by about 0.6-1.7 kg ha^{-1}, tiller production, and head production in low-input management in Michigan (Steinke et al., 2021). In multi-variety trials, the addition of starter fertilizer improved physiological traits leading to enhanced yields regardless of crop phenotype. In Kansas, the addition of 12 kg ha^{-1} in-furrow 12-40-0-10-1 (N-P-K-S-Zn)] improved mean grain yield by 300 kg ha^{-1} (Maeoka et al., 2020). In Indiana, the application of 224 kg of mono-ammonium phosphate (11-52-0) with 112 kg N ha^{-1} spring N fertilizer enhanced phytomass at maturity and fertile tillers leading to higher grain yield by 18% (Russell et al., 2020). Since modern winter wheat varieties have early vegetative and longer grain-filling stages (Maeoka et al., 2020), providing an optimum stage for initial yield potential is necessary for a mid-season environment.

Studies showed that soil texture and pre-planting soil condition influence the effectiveness of starter fertilizer. Kristoffersen et al. (2005) observed a grain yield difference up to 0.37 Mg ha^{-1} and 0.31 Mg ha^{-1} on silty clay loam and silt soils, respectively as compared with untreated plots when initial phosphorous fertilizer was applied. It is possible that fine-textured soils can retain nutrient sources within the root zone during the fall to winter seasons unlike coarse-textured areas; therefore, there is a lower risk of nutrient loss (Forrestal et al., 2014). Meanwhile, the low pre-plant soil nitrate concentration may indicate whether wheat will respond to N starter fertilizer. Low soil nitrate (< 10 NO_3-N kg^{-1} soil) sites responded positively to starter fertilizer with a 0.6 to 1.7 Mg ha^{-1} grain yield increase in Michigan (Steinke et al., 2021). In Kentucky, in-furrow fertilizers did not significantly influence grain yield over control in above-critical phosphorous (P) (> Mehlich-3 P 32.5 ppm) and potassium (K) (> 100 ppm) environment (Finch et al., 2022).

Nitrogen

One of the most essential requirements for profitable wheat production is sufficient crop nutrition. Timing and appropriate amount of nitrogen (N) are vital for maximizing yield and reducing N loss (Anderson, 2008; Forrestal et al., 2014). As a yield-limiting nutrient, insufficient N application risk suboptimal photosynthetic capacity leading to lower grain yield while excessive N fertilizer may result in nitrate leaching (Andraski et al., 2000; Shangguan et al., 2000). Wheat requires N for vegetative growth, photosynthesis and N translocation from vegetative parts to grains (Arregui et al., 2006; Ellen & Spiertz, 1980). Early signs of N deficiency in wheat are poor and late tillering (Forrestal et al., 2014). Insufficiency of N during grain filling and maturation stages reduce yield and total protein content (Wang et al., 2021). In Michigan, the recommended total N rate for soft winter wheat is 78 – 135 kg ha^{-1} with 4.03 – 6.72 Mg ha^{-1} yield goal (Culman et al., 2020). It is commonly applied as spring N on wheat just as the wheat is greening up when there is good potential for spring rains to move the N into the soil and root zone and minimize the potential for volatile N loss (Warncke & Nagelkirk, 2010).

Growers benefit from the application of N fertilizer depending on the wheat crop stage. Early application of N promotes yield component formation while later N fertilization often boosts post-yield parameters such as grain protein content. Application of early N fertilizer at FK 3-4 (GS 25) promotes higher tiller densities at FK 5 (GS 30) and grain yield (Weisz et al., 2001). Top-dressed spring N applications before stem elongation improved fertilizer N recovery, grain yield, and protein content (Sowers et al., 1994; Vaughan et al., 1990). On the other hand, variable findings were reported about the influence of N application in later wheat stages. Nitrogen application at FK 9 increased grain yield as compared to untreated plots in 2014 (Bhatta et al., 2017). The N application at planting provided a minimal increase in grain yield but additional N in FK 3 and 9 increased grain yield, harvest index, and protein content (Ellen and Spiertz, 1980). Dick et al., (2016) reported that late-season N applications at FK 9 and 10.5.4 positively influenced the protein content. It agrees with the findings of Bly and Woodard's (2003) where post-anthesis foliar N provided the highest grain protein while pre-anthesis application reduced grain yield by 5%. Late-season N increased kernel weight and protein content, implying that N is necessary during grain filling stage (Brown and Petrie, 2006). The beginning of reproductive phase initiates the remobilization of N from vegetative organs resulting in diminished canopy photosynthesis and hastening leaf senescence (Bertheloot et al., 2008).

In terms of application frequency, multiple or split N applications generally promote higher grain yield than a single N treatment. Application of N fertilizer at FK 3 and FK 6 increased grain yield compared to a single N treatment (Cox et al., 1989). The splitting of N fertilizer in FK 3, 10, and 10.5 or any of the two combined stages was associated with more grain yield by 3-12% (Gravelle et al., 1988). Multiple applications at FK 2, 7, and 10 showed the highest grain yield as compared with applying 25 or 75% of N at FK 2 (Zebarth & Sheard, 1992). The split applications with 25% of N rate banded below the seed or surface broadcast in fall and the remainder applied in spring at FK 3 (Zadoks 24) increased nitrogen use efficiency (NUE) and grain yield (Mahler et al., 1994).

Determining optimal N applications faces two key challenges: N loss extent and N positioning during high nutrient demand. Woolfolk et al., (2002) contended that while preplant fertilization can counter early growth nutrient deficiencies, it might incur losses or immobilization. In contrast, late application offers flexibility to adapt N rates based on crop status, averting losses like leaching and denitrification (Woolfolk et al., 2002).

Fusarium Head Blight

Fusarium head blight (FHB) of wheat also known as the head scab is caused by *Fusarium graminearum* Schwabe [telemorph *Giberella zea* (Schweinit) Petz] (Goswami & Kistler, 2004). Despite being considered monocyclic with limited secondary spread impact (Wegulo et al., 2015), it inflicts significant economic losses in US wheat production (Lilleboe & Roth, 2011). The primary symptom is spike bleaching, starting at the center and progressing to the whole spike (Wegulo et al., 2015). Affected spikelets, termed "tombstones," are infertile, chalky white, or pink, rendering them unsuitable for food production (Bolanos-Carriel et al., 2020). Wheat susceptibility begins from anthesis initiation (FK 10.5.1) to soft dough kernel development (FK 11.2) (McMullen et al., 2012); thus, FHB fungicide application commonly targets the onset of anthesis (FK 10.5.1). Yield loss stems from spikelet infection and compromised grain quality (Wegulo et al., 2015). Poor grain quality arises from kernel damage and Fusarium damaged kernels (FDK), along with mycotoxins like deoxynivalenol (DON) and zearalenone (Cowger et al., 2009; Haidukowski et al., 2012; Lemmens et al., 2004).

Favorable FHB development is linked to high precipitation, warm temperature, and relative humidity at pre-anthesis to grain-filling stage (Bhatta et al., 2018; Blandino et al., 2006; Hernandez Nopsa et al., 2012). In 2008, elevated precipitation (May-June 371 mm) before and during anthesis led to almost ten-fold higher DON accumulation compared to 2007 (May-June 200 mm) and 2009 (May-June 132 mm) (Hernandez Nopsa et al., 2012). Increased rainfall (+ 37.2%), higher temperatures (+ 3.2%), and elevated relative humidity in 2015 favored FHB and stripe rust, causing nearly double the yield reduction compared to 2014 (Bhatta et al., 2018). Moist, cool conditions with frequent anthesis rainfall resulted in more infected heads and a yield reduction of 0.8 Mg ha^{-1} when fungicide was omitted in intensive management (Steinke et al., 2021).

Foliar Fungal Diseases and Fungicide

Fungal plant pathogens play a crucial role in the yield and quality of wheat (McGrath, 2004). In fact, the plant-fungal disease poses a substantial constraint to wheat production and is responsible for 15-20% annual yield losses (Figueroa et al., 2018). Aside from Fusarium head blight (FHB) (caused by *Fusarium graminearum*), the common wheat foliar fungal diseases are rust (caused by *Puccinia triticina* for leaf rust, *Puccinia striiformis* f.sp. *tritici* for stripe rust, and *Puccinia graminis* Pers. f. sp. *tritici* for stem rust), Septoria tritici blotch (caused by *Zymoseptoria tritici*), Stagonospora leaf and glume blotch (caused by: *Parastagonospora nodorum,* and *Parastagonospora avenae*), tan spot (caused by *Pyrenophora tritici-repentis*), and powdery mildew (caused by *Blumeria graminis* f. sp. *tritici*) (Audsley et al., 2005; Bingham et al., 2009; Cox et al., 1989; Figueroa et al., 2018; Kutcher et al., 2018; Serrago et al., 2009; Smith et al., 2021). Infection of these pathogens negatively influenced the number of ears per unit of land area, number of grains per ear, and average grain weight leading to reduced yield (Bingham et al., 2009). Meanwhile, disease incidence and severity can adversely impact the grain quality (Serrago et al., 2009).

Weather is an important driving factor of foliar fungal disease pressure. Warm temperature and high precipitation are key factors of powdery mildew infection. At 14°C, the conidia increased more than 10 times than at 7°C leading to a higher infection index (Last, 1953). Presence of low temperature, high precipitation, and relative humidity could promote greater disease pressure of Septoria leaf blotch (Fones & Gurr, 2015; McKendry et al., 1995). Another foliar fungal disease influenced by temperature are wheat rust species. Leaf rust favors cool temperatures (5-25 °C) with high relative humidity (Moschini & Pérez, 1999; Naseri & Sasani, 2020). Stripe rust thrives in a cool (7 to 12°C) and high moisture environment, particularly, with prolonged dew leading to a high probability of infection (Chen, 2020). Oppositely, stem rust prevails in warm temperatures with the minimum, optimum and maximum temperatures of 2, 15-24, and 30°C for urediniospore germination (Singh et al., 2008) and high relative humidity (>60%) (Naseri & Sabeti, 2021).

Benefits of fungicide application

Numerous studies consistently demonstrate the benefits of fungicide application for enhancing grain yield, post-harvest indicators, disease severity, and economic returns (Bhatta et al., 2018; Blandino et al., 2006; Cox et al., 1989; Freije & Wise, 2015; Lopez et al., 2015; Mascagni et al., 1997; Milus, 1994; Varga et al., 2005; Wegulo et al., 2011). Fungicide application during anthesis boosts yield and grain quality by mitigating Fusarium head blight (FHB) severity and reducing deoxynivalenol (DON) content. Tebuconazole at FK 10.1 to 10.4 increased 1000-grain weight by 4.6% and yield by 5.6% (Varga et al., 2005). Triadimefon + mancozeb at FK 9 and 10 increased yield with minimal rust and blotch severity (Milus, 1994). Fungicide usage improved 1000-kernel weight during a 2012-2014 study (Freije & Wise, 2015). Bhatta et al., (2018) attributes 7.10–16.13% seed weight increase in 2015 to leaf preservation, enhancing grain-filling. Triazoles at FK 10.5.2 reduce FHB incidence by 52% and DON by 48% (Blandino et al., 2006).

Profitability of fungicides thrives in disease-conducive, high inoculum environments. Higher net returns are seen under wet, disease-severe conditions (Wegulo, et al., 2011) and fungicide impact is pronounced during moderate to high disease pressure (Lopez et al., 2015). Preventive fungicide application is discouraged under low inoculum levels (Cox et al., 1989).

Timing of fungicide application

Proper fungicide application timing significantly impacts efficacy. Literature suggests that an effective window to control FHB spans from the beginning of anthesis up to six post-anthesis (PAA) and had a critical effect on reducing mycotoxin accumulation. (Bolanos-Carriel et al., 2020; Ransom & McMullen, 2008; L. Singh et al., 2021; Yoshida et al., 2012). However, this "narrow window" poses challenges due to unfavorable climate or logistical constraints (Bolanos-Carriel et al., 2020).

Results from previous studies about the efficacy of different fungicide spray timings vary from pre-anthesis to post-anthesis. The protection of flag leaf against foliar diseases encouraged pre-anthesis application. Flag leaf photosynthesis contributes 30-50% of the assimilates for grain filling (Sylvester-Bradley et al., 1990) and greenness longevity of flag leaf associates with accumulation of grain protein (Blake et al., 2007). Therefore, management to protect flag leaf and delaying senescence is vital to promote higher yield and quality. A single FK 9 prothioconazole + tebuconazole spray increased yield by 41.9% (Bhatta et al., 2018). Feekes 9 fungicide yielded higher returns in moderate-high disease pressure than FK 6 (Wegulo et al., 2012). There were also efforts made to determine the efficacy of post-anthesis application. Post-anthesis sprays up to 6 DAA reduced FHB index, FDK, and DON (Bolanos-Carriel et al., 2020;

D'Angelo et al., 2014). Similarly, prothioconazole + tebuconazole sprayed up to 11 DAA was still useful in managing head scabs and reducing DON (Freije & Wise, 2015).

The efficacy of various fungicide timing programs has been explored. Split propiconazole application at FK 4-5 and FK 9 increased yield by 13.22% compared to untreated plots (Kutcher et al., 2018). Multiple fungicide applications – tebuconazole at FK 8-9 and propiconazole at FK 9, followed by triadimefon + mancozeb at FK 10.3-10.5 – consistently reduced disease severity and increased yield (Milus, 1994). Prothioconazole at FK 6, 9, and 10.5.2 significantly reduced FHB and DON by 97% and 83%, respectively, versus untreated plots (Edwards & Godley, 2010). In a multi-state experiment, single applications at FK 8 or 10.5.1 and multiple applications at FK 5 and 8 led to higher grain yield and reduced leaf blotch severity than FK 5 (Willyerd et al., 2015). Breunig et al., (2022), meta-analysis revealed that the combination of FK 5-7 and 10.5.1 applications produced the highest mean yield response of 0.71 Mg ha^{-1} compared to non-treated checks in Michigan. However, in the absence of extreme disease pressure, the two-spray application at green-up (FK 5) with either flag leaf emergence (FK 9) or the beginning of anthesis (FK 10.5.1) might not be profitable (Sylvester et al., 2018).

Fungicide and Nitrogen Fertilizer

The combined influence of N fertilizer and fungicide exhibits advantages in grain yield, post-yield components, and disease indicators, revealing synergistic effects between N fertilizer and disease control. Brinkman et al., (2014) observed that the response of grain yield to various fungicide treatments was contingent upon the applied N rate. Increasing N from 100 to 170 kg ha^{-1} boosted grain yield with fungicide applications at FK 8-9 or FK10.5.1 (Brinkman et al., 2014). In a multi-variety experiment in Kansas, adding 45 kg N ha^{-1} at FK 4-5 alongside fungicide applications at FK 6 and 10 increased mean grain yield by 0.9 Mg ha^{-1} (de Oliveira Silva et al., 2020). Past studies have explored the interplay of N rate, fungicide application, and aboveground biomass. Serrago et al., (2009) noted that high and low N rates combined with disease control improved above-ground biomass by 14.4% and 7.4%, respectively, compared to unprotected plots with similar N rates. Varga et al., (2005) indicated that the N rate and fungicide impact related to current inoculum levels and cultivar susceptibility. In low inoculum settings, susceptible cultivars outperformed, while high inoculum locations displayed linear yield increase with N rate and fungicide application for all cultivars. Conversely, in the absence of fungicide, resistant cultivars demonstrated greater yield increase than susceptible ones.

The enhanced fungicide efficacy at higher N rates promotes denser canopy coverage and increased biomass, potentially heightening disease pressure. Consequently, frequent fungicide application acts preventively in low inoculum settings and curatively in high inoculum environments.

Preceding Cropping

Wheat yield potential is more strongly influenced by previous crop, fertilizer N rate, and N placement method than tillage system (Kelley & Sweeney, 2005). Crop rotations impact yield potential through Carbon:Nitrogen (C:N) ratios of crop residues and soil residual N from the previous crop (Arcand et al., 2014; Mason & Rowland, 1992). Wheat is often rotated with other crops to diversify cropping systems; therefore, preceding cropping should be considered in determining nutrient applications. The main nitrogen source for wheat is mineralized nitrogen (Soon et al., 2006). Previous literature reported that the wheat benefits from residual soil N from leguminous crops leading to higher grain yield. Winter wheat following soybean yielded 88% of the winter wheat with high-input following oat–pea (Anderson, 2008). The increased soil N availability in the pea-wheat rotation explained 8% of the rotation effect on grain yield (Stevenson & Kessel, 1996). Additionally, the lower C:N ratio of leguminous crops promotes N mineralization resulting to lower N uptake from applied N fertilizers. The apparent in-crop N mineralization (ANM) under no-till wheat was higher in leguminous preceding crops such as field pea, lentil and fava bean; therefore there is a lower crop response to increasing N fertilizer rates of no-till wheat (Luce et al., 2016). These findings coincide with Staggenborg et al., (2003) observation that the wheat following grain sorghum requires 21 kg ha^{-1} more N than following soybean to maximize yield potential; since it produces more crop residue that may lead to N immobilization.

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CHAPTER 2: INTEGRATING AUTUMN STARTER FERTILIZER, FUNGICIDE TIMING, AND LATE-SEASON NITROGEN STRATEGIES IN WINTER WHEAT

ABSTRACT

Increased global demand for small grains emphasizes the need for intensified management strategies and future yield gains. While nutrients and fungicides can individually improve winter wheat (Triticum aestivum L.) yield, the synergism between early and late-season fertilizer with multiple fungicide strategies is less understood. This study investigated the influence of various fertilizer and fungicide strategies and effects on winter wheat growth and development. Treatments were arranged as a full-factorial, randomized complete block design with two rates of autumn starter (AS), five fungicide timings (FT), and two rates of late-season nitrogen (LN) applied at Feekes 7 following both silage corn (SC) and soybean (SB). All treatments received a blanket N application [84 (SB) or 112 (SC) kg ha^{-1}] at Feekes 5, except for check plots. Following SC, AS increased mean grain yield by 2.2 Mg ha^{-1} in 2022. The interaction of AS and FT significantly influenced grain yield following SC in 2023. Across FT, AS consistently increased mean grain yield by 1.4 – 2.6 Mg ha^{-1}. Following SB, AS increased straw yield by 0.4 and 0.7 MT ha^{-1} in 2022 and 2023, respectively. Autumn starter increased straw yield both with and without LN application following SC 2022. Autumn starter fertilizer increased mean straw yield by 1.3 MT ha^{-1} compared to no AS following SC 2023. The interaction of AS and LN significantly influenced grain protein content with AS decreasing grain protein content when LN was not applied (SC 2023, SB 2022). Late-season N at Feekes 7 occasionally increased grain protein content (SC 2022 and SB 2023). Plant height was most correlated with grain yield while headcount and flag leaf S level were moderate modulators of straw production in following SC. Further, grain N was most correlated with grain protein content. Results emphasize the positive impacts that autumn starter fertilizer can have on yield potential but changes in plant growth and development may impact grain quality.

2.1 Introduction

The United States ranks fourth in global wheat (*Triticum aestivum* L.) production behind China, India, and Russia (*FAOSTAT*, 2023). Between 2020 and 2021, U.S. wheat hectares increased from 14.8 to 15 million, but annual production decreased from 50 to 45 million metric tons with average yields per hectare decreasing from 3.34 to 2.98 Mg (*FAOSTAT*, 2023). Fluctuations in yield and variabilities in harvestable hectares threaten wheat grain stocks and ultimately food supply (FAO, 2021). Improving crop yield through input-intensified management is one potential solution that also minimizes the necessity for agricultural land expansion (Cassman & Grassini, 2020).

In Michigan, winter wheat (~170 thousand ha) is the third greatest row crop by area (*FAOSTAT*, 2023). Despite Michigan's mean yield of 5.5 Mg ha^{-1} in 2022, planted hectares decreased from 2021 by 24% (~190 thousand ha) with production also down nearly 23% to 940 thousand MT (NASS, 2022.). Although grain yields will vary year to year, proactive production practices may help mitigate some seasonal yield variability. Current guidelines for winter wheat management include 45-135 kg N ha^{-1} top-dressed at green-up and foliar fungicide applied 5 to 6 days following early flowering or Feekes [FK] 10.5.1 growth stage primarily for Fusarium head blight (FHB) (*Fusarium graminearum* Schwabe) (Nagelkirk & Chilvers, 2019; Warncke & Nagelkirk, 2010). Due to rising demand for wheat amid climate variabilities, Michigan growers are increasingly exploring alternative strategies for greater yield and profitability.

Intensive management (IM) includes manipulating agronomic inputs to address yield gaps or limiting factors, but environmental variabilities often result in site-specific yield responses (Harms et al., 1989). In Michigan, applying foliar fungicide at FK 10.5.1 increased yield up from 0.50 to 0.75 Mg ha^{-1} (Breunig et al., 2022; Quinn & Steinke, 2019). Conversely, omitting fungicide at FK 6 and 10.5.1 in a high-disease pressure environment reduced yield by 1 Mg ha^{-1} in Kansas (De Oliveira Silva et al., 2021). Applying broadcast starter fertilizer containing nitrogen (N), phosphorus (P), sulfur (S), and zinc (Zn) along with spring N and fungicide at FK 10.4 increased grain yield and aboveground biomass in irrigated Kansas fields (Jaenisch et al., 2022). In Ohio, implementing greater seeding rates, split-applied N, S fertilizer at FK 5-6, and fungicide sprays at FK 9 and 10.5.1 enhanced mean grain yield by 0.83 Mg ha^{-1} (Peterson et al., 2023). Similarly, in Wisconsin, an intensified strategy featuring split N fertilizer, plant growth regulators, micronutrient applications, and two fungicide sprays at FK 9 and 10.5.1

improved mean grain yield by 0.81–1.22 kg ha^{-1} and straw yields by 1.2 MT ha^{-1} (Roth et al., 2021). While literature suggests intensive management can boost winter wheat grain yield potential, profitability is influenced by fluctuating grain and input prices (Peterson et al., 2023; Steinke et al., 2021). The absence of yield-limiting factors such as disease susceptibility, pre-plant nutrient deficiencies, and lodging potential may diminish the benefits of multiple agronomic inputs (Karlen & Gooden, 1990; Knott et al., 2016; Mohammed et al., 2013; Quinn & Steinke, 2019). Judicious usage and selection of agronomic inputs is crucial to address production challenges and optimize economic return.

Autumn starter fertilizer application is a decision wheat growers must choose well before planting. Starter fertilizer is applied near the seed to improve early seedling growth. Benefits of starter fertilizer in crop production have long been recognized (Niehues et al., 2004; Purucker & Steinke, 2020). In Midwest states, studies have highlighted the advantages of autumn nutrient application in winter wheat. The use of starter fertilizer containing N, P, S, and Zn increased grain yield by 1.1 Mg ha^{-1} as well as tiller and head production (pre-plant Bray P1 values 23-46 mg kg^{-1}) (Steinke et al., 2021). Across multiple wheat varieties, starter fertilizer enhanced physiological traits leading to increased yields irrespective of crop phenotype. In-furrow application of 12 kg ha^{-1} of 12-40-0-10-1 (N-P-K-S-Zn) raised grain yield by 300 kg ha^{-1} (pre-plant Mehlich-3 P > 25 mg kg^{-1} or Bray P1 > 18 mg kg^{-1}) (Maeoka et al., 2020). Planting with mono-ammonium phosphate alongside spring N fertilizer improved biomass and tiller production resulting in an 18% increase in grain yield (Russell et al., 2020). Given the early vegetative and extended grain-filling stages of modern winter wheat varieties, ensuring an optimal start for yield potential is critical to capitalize on the mid-season growing environment (Maeoka et al., 2020).

Fungal pathogens can significantly reduce wheat yield and quality causing 15-20% yield loss annually (Figueroa et al., 2018). While fungicide benefits are well-recognized, costs and wheat prices affect application decisions. Current recommendations suggest applying fungicides from anthesis to six days after anthesis to control Fusarium head blight and provide late-season protection of the foliage (Bolanos-Carriel et al., 2020; Nagelkirk & Chilvers, 2019). The potential for early and mid-season foliar fungal diseases raises questions about pre-anthesis fungicide requirements.

To preserve flag leaf health and extend greenness, standard pre-anthesis foliar fungicide applications are suggested between flag leaf emergence (FK 8) and heading (FK 10.5) (Bhatta et al., 2018; Wegulo et al., 2012). Comparable to flag leaf fungicide spray (FK 9), a split application of propiconazole at FK 4-5 and FK 9 yielded a 13% increase in yield compared to non-treated plots (Kutcher et al., 2018). Applying tebuconazole at FK 8-9 and propiconazole at FK 9 followed by triadimefon + mancozeb at FK 10.3 to FK 10.5 increased yield (Milus, 1994). A meta-analysis by Breunig et al. (2022) in Michigan showed that applying fungicides at FK 5 to 7 and FK 10.5.1 produced the greatest mean yield response of 0.71 Mg ha^{-1} compared to non-treated control. Decreased FHB severity and reduced mycotoxin levels were also observed from pre-anthesis fungicide spray. Using prothioconazole at FK 6, 9, and 10.5.2 decreased FHB and deoxynivalenol (DON) by 97% and 83%, respectively, compared to non-treated plots (Edwards & Godley, 2010). These studies all highlight the potential of early and mid-season fungicide applications for yield protection.

Adequate crop nutrition is essential for profitable wheat production. Proper timing and rate of N are critical for maximizing yield while minimizing N loss (Anderson, 2008; Forrestal et al., 2014). Insufficient N rates hinder photosynthetic capacity and reduce grain yield while excessive N fertilizer can lead to nitrate leaching, lodging, water and soil acidification, and pollution of surface and groundwater resources (Andraski et al., 2000; Bashir et al., 2013; Li et al., 2022; Shangguan et al., 2000). Wheat relies on N for vegetative growth, photosynthesis, and translocation of N from vegetative biomass to the grain head (Arregui et al., 2006; Ellen & Spiertz, 1980). Early indicators of N deficiency in wheat include poor and delayed tillering while insufficient N during grain fill and maturation reduces yield and total grain protein content (Forrestal et al., 2014; Wang et al., 2021). In Michigan, the total recommended N rates for soft winter wheat are 78 – 135 kg ha^{-1} for a yield goal of 4.0 – 6.7 Mg ha^{-1} (Culman et al., 2020). Spring N application near FK 5 is a common practice and can be adjusted to account for severity and quantity of spring rainfall (Warncke & Nagelkirk, 2010). Early N application (FK 3-7) offers advantages including greater tiller density, improved fertilizer N recovery, and ultimately increased grain yield (Sowers et al., 1994; Vaughan et al., 1990; Weisz et al., 2001). Conversely, late-season N application (i.e., FK 7 and later) inconsistently affects grain yield but often enhances grain protein content. As flowering begins, N translocates from vegetative parts reducing canopy photosynthesis and hastening leaf senescence (Bertheloot et al., 2008). Studies reveal that late-season N applications from FK 9 to post-anthesis can improve grain protein content thus highlighting the importance of N during the grain-filling stage (Bly & Woodard, 2003; Brown & Petrie, 2006; Dick et al., 2016).

Harvesting wheat straw as a secondary product can provide additional income. 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 0.75 – 2 T/A with some states using a straw harvest index value of 80% (i.e., straw yield is 80% of grain yield) (Thomason et al., 2005). The preferred grain protein content in soft winter wheat (SRWW) is 8-11% (Hunter & Stanford, 1973). SRWW is commonly used for specialty products such as sponge cakes, cookies, crackers and other confectionary products (US. Wheat Associates, 2024). Effective fertilizer management is important for enhancing wheat straw production and grain quality.

Although previous studies have shown additional inputs can individually improve winter wheat yield, little research has been done on the effects of autumn nutrient applications and late-season N fertilizer combined with multiple fungicide timings. The objectives of the current study included: (i) to evaluate soft red winter wheat grain yield, straw yield and grain protein content response to autumn-applied starter fertilizer, multiple fungicide application timings, and late-season N at FK 7 in fields following silage corn and soybean and (ii) to determine whether correlations exist between in-season agronomic components, flag leaf tissue nutrient concentrations, or 1000-kernel weight with grain yield, protein content, and straw yield.

2.2 Materials and Methods

Field studies were established at two locations in Lansing, MI (42°41'14.78"N, 84°29'10.15" W) (42°42'12.17"N, 84°28'14.14"W) on a Conover loam soil (Fine-loamy, mixed, active, mesic *Aquic Hapludalfs*). Four site-years of field research were categorized based on the preceding crop: winter wheat following silage corn (SC 2022 and 2023) or following soybean (SB 2022 and 2023).

Plots (SC 2022,2023 and SB 2023) were twelve-rows wide (2.5 m width by 7.6 m length by 19.1 cm row spacing) and planted using a Great Plains 3P600 drill (Great Plains Manufacturing, Salina, KS). The SB 2022 field consisted of eight-row plots (2.0 m in width by 6.4 m in length by 19.1 cm row spacing) but planted with an orbit-air granular applicator with disc furrow opener (Gandy Company Manufacturing, Owatonna, MN). Plant populations were 4.4 million seeds ha^{-1} across all site years. Soft red winter wheat variety 'Wharf', a short-strawed, high-yielding variety (Michigan Crop Improvement Association, Okemos, MI) was planted following SC on 20 Sept. 2021 and 30 Sept. 2022 and following SB on 01 Oct. 2021 and 04 Oct. 2022.

Pre-plant soil characteristics (0–20 cm) included 6.6 to 7.8 pH (1:1 soil/water) (Peters et al., 2015), 14 to 55 mg kg$^{–1}$ P (Bray-P1 or Olsen-P, pH-dependent) (Frank et al., 2015), 68 to 96 mg kg$^{–1}$ K (ammonium acetate method) (Warncke& Brown, 2015), 18 to 29 g kg$^{–1}$ soil organic matter (loss-on-ignition) (Combs & Nathan, 2015), and 2.5-6.1 mg kg$^{–1}$ Zn (0.1 M HCl) (Whitney, 2015). Soil nitrate concentrations (0-30 cm) were collected prior to planting and green-up nitrogen (N) applications and ranged from 4-5 and 1.8-3.8 NO_3-N kg^{-1} soil (nitrate electrode method) (Gelderman & Beegle, 2015) for pre-plant and green up, respectively.

Treatment structure and experimental design

The experiment was designed as a complete factorial, randomized complete block with three experimental factors across four replications (2×5×2) **(Table 2.1)**. Experimental factors included two levels of autumn starter fertilizer (12-40-0-10-1, N-P-K-S-Zn) (0 and 280 kg ha^{-1}) applied at planting, five fungicide strategies (none, FK 5-7 and 10.5.1, FK 9 and 10.5.1, FK 10.5.1 individually, and FK 5-7, 9, and 10.5.1) (Large, 1954) and two rates of late-season N (0 and 34 kg N ha^{-1}) applied at FK 7. All treatments received a base green-up N application rate of 112 or 84 kg N ha^{-1} at FK 5 following SC or SB, respectively, except for the check.

Autumn starter fertilizer (12-40-0-10-1, N-P-K-S-Zn) (MicroEssentials® SZ® (MESZ) (Mosaic CO., Plymouth, MN) was top-dressed at a rate of 280 kg ha^{-1} to supply approximately 33.6 kg N, 112 kg P_2O_5, 28 kg S, and 2.8 kg Zn during planting. To establish varying disease intensity levels, five fungicide programs were implemented either during stem elongation (FK5 – 7), flag leaf emergence (FK 9), or the onset of anthesis (FK 10.5.1). Fungicide application timings included 1) control (no fungicides applied), 2) FK 10.5.1 individually, 3) FK5 – 7 and 10.5.1, 4) FK 9 and 10.5.1, and 5) FK 5 – 7, 9, and 10.5.1. Initial foliar fungicide applications consisted of propiconazole (41.8%) (Tilt; Syngenta Crop Protection, Greensboro, NC) applied at 292.31 ml ha^{-1} during FK 5 – 7. The second foliar fungicide consisted of pyraclostrobin (18.76%) and propiconazole (11.73%) (Nexicor Xemium; BASF Corporation, Research Triangle Park, NC) applied at a rate of 511.54 ml ha^{-1} during FK 9. The third foliar fungicide was pydiflumetofen (13.7%) and propiconazole (11.4%) (Miravis Ace; Syngenta Crop Protection, Greensboro, NC) applied at 1,001.16 ml ha^{-1} during FK 10.5.1. Each application included a non-ionic surfactant and anti-foaming agent at 0.125% v/v for enhanced coverage. Fungicides were applied using a modified LeeAgra Avenger with Kincaid cobra plot sprayer attachment controlled using HarvestMaster (LeeAgra, Inc. Lubbock, TX; Kincaid Equipment Manufacturing Corporation, Haven, KS; Juniper Systems Inc., Logan, UT). For early season (FK 5-7) and mid-season (FK9) fungicide sprays, Wilgeres ER80-015 flat fan nozzles (80 degrees) was used. For late-season (FK 10.5.1) fungicide spray, dual fan nozzles (DGTJ60-110015VS DG TwinJet Drift Guard) were used. All fungicide sprays were implemented at 30 psi applying 140 L ha^{-1} at 4.0 km hour^{-1}. Green-up N applications were applied at the FK 5 growth stage. For SC fields (2022 and 2023)

Table 2.1. Overview of complete three-level (2x5x2) factorial design, treatments, and agronomic inputs to winter wheat, Lansing, MI, 2021-2023.

	Agronomic inputs applied					
Treatment	Green-up N ††	Autumn starter (AS) †	---------Fungicide---------			Late N (LN) #
			Early (E) ‡	Mid (M) §	Late (L) ¶	
GRNUP + L	Y	N	N	N	Y	N
− L	Y	N	N	N	N	N
−L + LN	Y	N	N	N	N	Y
+ LN	Y	N	N	N	Y	Y
+ E	Y	N	Y	N	Y	N
+ E + LN	Y	N	Y	N	Y	Y
+ M	Y	N	N	Y	Y	N
+ M + LN	Y	N	N	Y	Y	Y
+ E + M	Y	N	Y	Y	Y	N
+ E + M + LN	Y	N	Y	Y	Y	Y
−L + AS	Y	Y	N	N	N	N
−L + AS + LN	Y	Y	N	N	N	Y
+ AS + E	Y	Y	Y	N	Y	N
+ AS + E + LN	Y	Y	Y	N	Y	Y
+ AS	Y	Y	N	N	Y	N
+ AS + LN	Y	Y	N	N	Y	Y
+ AS + M	Y	Y	N	Y	Y	N
+ AS + M + LN	Y	Y	N	Y	Y	Y
+ AS + E + M	Y	Y	Y	Y	Y	N
+ AS + E + M + LN	Y	Y	Y	Y	Y	Y
Check	N	N	N	N	N	N

† Autumn starter (12-40-0-10-1, N-P-K-S-Zn) applied at a rate of 280.5 kg ha^{-1} at planting.

‡ Early fungicide spray propiconazole (Tilt) applied at a 292.3 ml ha^{-1} rate at Feekes 5-7 stage.

§ Mid fungicide spray pyraclostrobin (Nexicor Xemium) applied at 511.5 ml ha^{-1} rate at Feekes 9 stage.

¶ Late fungicide spray pydiflumetofen + propiconazole (Miravis Ace) applied at a 1,001.2 ml ha^{-1} rate at Feekes 10.5.1 stage.

Late-season nitrogen was applied at a rate of 33.7 kg ha^{-1} at Feekes 7 stage.

†† All plots except the check plot received blanket spring N or green-up application at a rate of 112.2 kg ha^{-1} in fields following silage corn while 84.1 kg ha^{-1} in following soybean at Feekes 5 stage.

and SB field (2023), urea ammonium nitrate (UAN, 28-0-0) was applied at a rate of 112 or 84 kg N ha^{-1} following SC or SB, respectively with 311 L ha^{-1} and 233 L ha^{-1}, accordingly using a backpack sprayer equipped with streamer bars (Chafer Machinery Ltd, Upton, UK). For SB 2022 field, urea (46-0-0) was applied at a rate of 84 kg ha^{-1} using a Kubota Oscillating Spreader (Kubota Tractor Corporation, Groveport, OH). Late-season N fertilizer was applied at a rate of 33.7 kg N ha^{-1} as UAN at FK 7 at a rate of 93.53 L ha^{-1} in SC and SB fields using a backpack sprayer equipped with streamer bars.

In-season measurements

Monthly growing season weather data obtained from MSU Enviro-weather (https://enviroweather.msu.edu/, MSU, East Lansing, MI). A 30-year mean was compiled using National Oceanic and Atmospheric Administration data (NOAA, 2022). weather data were categorized into four distinct phases: Planting through November 30 (establishment and fall season), December 1 through March 31 (winter season), April 1 through May 31 (active growing and flowering), and June 1 through July 15 (grain-fill and harvest). Growing degree days (GDD) were calculated using the average of daily maximum and minimum temperatures from planting to harvest with a subtraction of 32°F as a lower threshold temperature (Karow, 1993). Plant tiller counts were assessed from two linear meters per plot at FK 4. At FK 11.1, plant height, head density per 0.90 m^{-2}, and head length were measured. Plant height was determined from the soil surface to the top of each spike. Head density was calculated by counting the number of head-bearing tillers within 0.90 m^{-2}. Head length was measured using a digital vernier caliper. Fractional green canopy coverage (FGCC) and normalized difference vegetation index (NDVI) were monitored at FK 6, 7, 9, and 10.5.1 using Canopeo (Mathworks, Inc., Natick, MA) and a GreenSeeker® crop sensing system (Trimble Agriculture Division, Westminster, CO), respectively. Flag leaf tissue collection and subsequent nutrient analysis were conducted at FK 9. Forty flag leaf samples were dried at 70°C, mechanically ground to pass through a 1-mm mesh screen, analyzed for total N using Dumas Method (Nitrogen by Combustion or Nitrogen by Thermal Conductance) following AOAC Official Method 972.43 (Horwitz & Latimer, 2000) while digested in an open vessel microwave procedure (SW846-3051A) (US EPA, 2015) and analyzed for total P, K, Ca, Mg, Mn, and B concentrations using Inductively Coupled Argon Plasma (ICAP) run on Thermo iCAP 6500 following AOAC Official Method 980.03 (Horwitz & Latimer, 2000). Incidence and index of Fusarium head blight (FHB) were evaluated 22 June

2022 and 20 June 2023 corresponding to growth stage FK 11.1. One hundred random heads were examined within each plot and rated for disease severity. Disease incidence was calculated by dividing the number of diseased heads by 100. The disease severity equation was utilized with modifications to estimate severity (Paul et al., 2005). The FHB index was derived by multiplying the incidence by mean head severity. Deoxynivalenol (DON) concentration was determined using the same 0.5-kg subsample utilized for measuring vomitoxin levels produced in winter wheat grains infected by FHB. Kernels were ground into a coarse powder with an electric coffee grinder (Hamilton Beach®, Richmond, VA) with cross-contamination between samples prevented by thoroughly vacuuming the coffee grinder between samples. A 20 g subsample was sent to the U.S. Wheat and Barley Scab Initiative mycotoxin testing laboratory (University of Minnesota, St. Paul, MN) for DON quantification using gas chromatography – mass spectrometry as described in Fuentes et al., (2005) and reported in parts per million (ppm) which equated to mg DON kg^{-1} of grain.

On 9 July 2022 and 10 July 2023 in SC plots and 15 July 2022 and 10 July 2023 in SB plots, the outer 1.5 m of plots were mowed prior to harvest. Grain and straw yields were collected from the center 1.5 m by 6.4 m in each plot using a plot combine (Kincaid Equipment Manufacturing, Haven, KS). Grain weight, moisture, and test weight were measured to calculate grain yield expressed as Mg ha^{-1} at 135 g kg^{-1} moisture basis. Grain subsamples were obtained for nutrient concentration and quality analysis. The samples are dried overnight at 100-105°C, ground with a Wiley Mill Grinder and sieved through a 20 mesh screen following AOAC Official Method 922.02 (Horwitz & Latimer, 2000), analyzed for total N using Dumas Method (Nitrogen by Combustion or Nitrogen by Thermal Conductance) following AOAC Official Method 972.43 (Horwitz & Latimer, 2000) while digested in an open vessel microwave procedure (SW846-3051A) (US EPA, 2015) and analyzed for total P, K, Ca, Mg, Mn, and B concentrations using Inductively Coupled Argon Plasma (ICAP) run on Thermo iCAP 6500 following AOAC Official Method 980.03 (Horwitz & Latimer, 2000). Grain nutritive quality included starch, fiber, ash, protein, and fat content determined from a 150 g subsample using near-infrared transmission (NIRS™ DS2500 L; FOSS Analytical, Hillerød, DK). The 1000-kernel weight was assessed by weighing 1000-grain samples from each plot. Straw yield was determined by weighing the total residue from the combine output with the cutting bar set 12.7 cm above soil surface. Total straw yield was adjusted by subtracting the total moisture content from the gross harvest weight.

Partial returns

The partial returns (\$ ha^{-1}) was calculated as follows: Rn = [P (Yt) + S (St)] – (Cf + Cfa + Cfg + Cfga), where P represents the grain price (\$ Mg^{-1}), Yt is the observed grain yield from the treated treatment (with fertilizer and/or fungicide), S is the straw price (\$ MT^{-1}), and St is the observed straw yield from the treated treatment. The abbreviations Cf stands for fertilizer cost (\$ ha^{-1}), Cfa for fertilizer application cost (\$ ha^{-1}), Cfg for fungicide cost (\$ ha^{-1}), and Cfga for fungicide application cost (\$ ha^{-1}). The partial return in this economic analysis excludes specific grower management practices such as direct and fixed costs and focused solely on expenses affected by the treatments. The average local grain price was \$342.03 Mg^{-1} and \$242.84 Mg^{-1} in 2022 and 2023, respectively. Average local straw prices were \$149.91 MT^{-1} and \$145.51 MT^{-1}. Fertilizer and fungicide costs were \$0.89 kg^{-1}, \$37-72 kg^{-1}, \$0.77 kg^{-1}, \$26.95-33.03 L^{-1}, \$64.73-66.31 L^{-1}, and \$52.31-54.16 L^{-1} for 12-40-0-10S-1Zn fertilizer, UAN, urea, propiconazole, pyraclostrobin + propiconazole, and pydiflumetofen + propiconazole, respectively. Application costs were estimated using the Michigan State University Extension Custom Machine and Work Rate Estimates (MSU Extension, 2021) and Purdue University Indiana Farm Custom Rates (Langemeier, 2023) for 2022 and 2023, respectively. Partial returns for grain yield and combined grain and straw yield were assessed using net return from the traditional farmers' treatment (i.e., green-up N application and late-season fungicide spray at FK 10.5.1, GRN-UP + L) and compared using a Dunnet-Hsu Test at $\alpha = 0.10$.

Statistical analyses

Data analyzed using the PROC MIXED procedure in SAS 9.4 (SAS Institute Inc., 2017). The statistical model included fixed effects for autumn starter rates, fungicide application timings, and late-season nitrogen rates with block as a random effect. Normality was assessed through histograms and normal probability plots of the residuals. Unequal variance assumption was evaluated using side-by-side box plots of residuals and Levene's test. In cases where unequal variances were indicated, REPEATED /GROUP= statements were used in PROC MIXED for unequal variance analyses. Homogeneous and heterogeneous variance models were compared using AIC criteria to select the optimal model (Milliken & Johnson, 2009). Significant interactions ($p < 0.10$) between studied factors led to interaction slicing. For non-significant interactions, the Least Significant Difference (LSD) was employed for multiple comparisons among marginal means and main effects. Results were considered statistically significant for p-values < 0.10.

Orthogonal contrasts were used for group comparisons in various treatment combinations including fertilizer application (AS without LN vs. AS with LN), fungicide timing (EML vs. EL, L, ML), and combined fertilizer and fungicide strategies. The abbreviation AS refers to the autumn starter, LN to late-season nitrogen, EL to early-late (FK 5-7 and 10.5.1) fungicide sprays, L to late (FK 10.5.1) fungicide spray, ML to mid-late (FK 9 and 10.5.1) fungicide sprays, and EML to early-mid-late (FK 5-7, 9, and 10.5.1) fungicide sprays. Strategies included 1) AS – EL vs. AS – L, AS – ML, AS – EML to determine if early-fungicide influenced autumn starter application, 2) LN – ML vs. LN – EL, LN – L, LN – EML to determine if mid-season fungicide at FK 9 impacted late-season N at FK 7, and 3) AS – no fungicide – LN vs. AS – EL – LN, AS-L-LN, AS-ML-LN, AS-EML-LN to determine if multiple nutrient applications are influenced by fungicide application.

Pearson correlation was performed in SAS 9.4 using PROC CORR to determine the degree of linear association between grain yield, protein content, and straw yield with in-season measurements (tiller count, headcount, head length, plant height), crop nutrient status at FK 9 (Flag N, P, S, N/S), grain nutrient concentrations (grain N, P, S, N/S) and 1000-kernel weight in each site-year at $\alpha = 0.05$. The check (no fertilizer and fungicide) was excluded from all statistical analyses.

2.3 Results

Environmental Conditions

As compared to 30-year air temperature and precipitation averages growing conditions in 2021-2022 and 2022-2023 had normal air temperatures (avg. 2.8 – 16.7°C) with dry autumns (-10.1 cm (-45%) and -8.6 cm (-59%), respectively). From December to March 2022, there was a cold (-0.8°C) and dry winter (-4.7 cm or -27%), while from December to March 2023, there was a warm (+0.8°C) and wet winter (+1.6 cm or +9%). These conditions created contrasting moderately dry and wet winter seasons. April to May 2022 and 2023 both had cold (-0.6°C and -0.3°C, respectively) and dry springs (-3.6 cm (-18%) and -10.5 cm (-52%), respectively). Furthermore, June to July 2022 and 2023 both had cold (-1.0°C and -0.6°C, respectively) and dry summers (-11.7 cm (-64%) and -11.0 cm (-60%) respectively) **(Table 2.2)**.

Grain Yield and Quality

Grain yields averaged between 2.2-10.6 Mg ha^{-1} across all site years with yields ranging from 2.7-10.6 Mg ha^{-1} in 2022 and from 2.2-9.1 Mg ha^{-1} in 2023.

Following silage corn

Following SC 2022, grain yield ranged from 2.7-9.2 Mg ha^{-1} with a mean of 7.1 Mg ha^{-1}. Grain yield and protein content were significantly affected by main effects of autumn starter fertilizer (AS) and late-season nitrogen applied at FK 7 (LN). Autumn starter fertilizer yielded 2.2 Mg ha^{-1} more than no AS (**Table 2.3,** $P < 0.0001$**)**. Conversely, autumn starter fertilizer reduced grain protein content following SC 2022 (**Table 2.5,** $P < 0.0001$**)**. Late-season N increased grain yield 0.3 Mg ha^{-1} compared to no LN (**Table 2.3**, $P = 0.013$) and increased grain protein content by 0.7% (**Table 2.5,** $P < 0.0001$**)**. Following SC 2023, grain yield ranged from 2.2-7.7 Mg ha^{-1} with a mean of 6.1 Mg ha^{-1} with a significant interaction between AS and fungicide timing (FT) (**Table 2.4,** $P = 0.0682$**)**. Across all fungicide timings, AS consistently increased mean grain yield by 1.4 – 2.6 Mg ha^{-1} (**Table 2.4)**. Fungicide timing only had a significant effect on yield in the absence of AS. In the absence of AS, the fungicide treatments applied at FK 5-7 and 10.5.1

Table 2.2. Mean monthly and 30-year air temperature and precipitation † for the winter wheat growing season, Lansing, MI, 2021-2023.

	Establishment & fall season				Winter season			Active growing & flowering		Grain filling - harvest	
Year	Sept	Oct.	Nov.	Dec.	Jan.	Feb.	Mar	Apr.	May.	Jun.	Jul.
minimum °C											
2021-2022	9.6	9.0	-2.1	-3.0	-12.8	-9.7	-3.4	1.7	10.0	13.1	14.2
2022-2023		3.3	-1.0	-4.4	-3.5	-5.3	-2.9	2.6	6.2	11.5	16.6
30-yr.avg. ‡	11.1	5.3	0.1	-4.8	-8.1	-7.4	-2.7	3.0	9.2	14.3	16.4
average °C											
2021-2022	16.7	13.8	2.8	1.1	-7.9	-4.5	2.1	6.7	16.1	19.8	21.2
2022-2023		10.2	4.6	-1.3	-0.7	-0.6	1.9	9.1	14.2	19.1	22.6
30-yr.avg.	17.8	11.0	4.6	-1.0	-4.1	-3.1	2.3	8.7	15.3	20.4	22.5
maximum °C											
2021-2022	23.8	18.6	7.6	5.2	-3.0	0.6	7.6	11.7	22.2	26.5	28.2
2022-2023		17.2	10.2	1.9	2.1	4.0	6.6	15.6	22.3	26.7	28.6
30-yr.avg.	24.4	16.6	9.1	2.9	-0.1	1.3	7.2	14.4	21.4	26.5	28.6
cm											
2021-2022	0.00	9.68	2.69	3.84	0.10	3.30	5.74	9.78	6.71	6.12	0.36
2022-2023		4.52	1.32	1.42	2.79	5.33	9.73	7.32	2.26	2.29	4.95
30-yr.avg.	8.05	7.92	6.48	4.06	5.28	4.06	4.27	9.02	11.07	9.63	8.56

† 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).

and FK 9 and 10.5.1 reduced grain yield by 1.2 Mg ha^{-1} and by 0.6 Mg ha^{-1}, respectively as compared to FK 10.5.1 **(Table 2.4)**. An interaction between AS and LN significantly influenced grain protein content **(Table 2.6,** $P = 0.038$**)**. With AS application, LN increased protein concentration, but without LN application, AS decreased grain protein concentration.

Following soybean

Following SB 2022, grain yields ranged between 3.9-10.6 Mg ha^{-1} with a mean of 8.9 Mg ha^{-1}. Late-applied N was the only main effect to significantly influence grain yield with LN increasing yield 1.0 Mg ha^{-1} compared to no LN **(Table 2.3,** $P < 0.0001$**)**. An interaction between AS and LN significantly influenced grain protein content **(Table 2.6,** $P = 0.0678$**)**. Late-season N increased protein content both with (10.4%) and without AS (10.9%, **Table 2.6**). Following SB 2023, grain yield ranged from 3.9-9.1 Mg ha^{-1} with an average of 6.9 Mg ha^{-1}. Neither AS ($P = 0.1544$), FT ($P = 0.8609$) or LN ($P = 0.7767$) significantly influenced grain yield **(Table 2.3)**. However, grain protein content was significantly affected by the main effects of AS and LN increasing protein concentration by 0.3% ($P = 0.0109$) and 0.8% ($P < 0.0001$), respectively **(Table 2.3).**

Straw Yield

Across site years, straw yields ranged between 0.1-5.6 MT ha^{-1} with mean straw yield ranging from 0.1-5.6 MT ha^{-1} in 2022 and from 0.4-5.1 MT ha^{-1} in 2023. Following SC 2022, straw yield ranged from 0.1-3.2 MT ha^{-1} with a mean of 1.7 MT ha^{-1}. An interaction between AS and LN significantly influenced straw yield with AS increasing straw yield both with and without LN application (**Table 2.7**, $P = 0.0122$). Late N increased straw yield by 25% when AS was not applied (Table 7). Although there was a significant interaction between FT and LN (**Table 2.8**, $P = 0.0276$), only in a three-FT program did LN increase straw yield by 0.7 MT ha^{-1} **(Table 2.8)**. Following SC 2023, straw yield ranged from 0.4-4.1 MT ha^{-1} with a mean of 2.4 MT ha^{-1}. Autumn starter fertilizer increased mean straw yield by 1.3 MT ha^{-1} compared to no AS (**Table 2.9**, $P < 0.0001$). Following SB 2022, straw yield ranged from 0.4-4.1 MT ha^{-1} with an average of 2.4 MT ha^{-1} with AS increasing mean straw yield by 0.4 MT ha^{-1} over no AS (**Table 2.9**, $P = 0.0046$). Following SB 2023, straw yield ranged from 0.8-5.1 MT ha^{-1} with an average of 2.7 MT ha^{-1} but again AS increased mean straw yield by 0.7 MT ha^{-1} compared to no AS (**Table 2.9**, $P < 0.0001$).

Table 2.3. Mean winter wheat grain yield (Mg ha^{-1}) as influenced by autumn starter (12-40-0-10-1, N-P-K-S-Zn), fungicide timing, and late-season applied nitrogen in following silage corn (SC 2022) or soybean (SB 2022 and SB 2023), Lansing, MI, 2021-2023.

	Grain yield §		
Treatment ††	SC 2022	SB 2022	SB 2023
	Mg ha^{-1}		
Autumn Starter Fertilizer (12-40-0-10-1, N-P-K-S-Zn) †			
0 kg AS ha^{-1}	6.2b	7.5	6.9
280 kg AS ha^{-1}	8.4a	7.5	7.2
$P > F$	***	NS	NS
Fungicide Timing ‡			
No fungicide	7.2	7.6	7.1
Feekes 5-7, 10.5.1	7.2	7.4	7.0
Feekes 10.5.1	7.4	7.6	7.0
Feekes 9, 10.5.1	7.1	7.4	7.0
Feekes 5-7, 9, 10.5.1	7.3	7.4	7.3
$P > F$	NS	NS	NS
Late-season Nitrogen #			
0 kg N ha^{-1}	7.1b	7.0b	7.0
34 kg N ha^{-1}	7.4a	8.0a	7.1
$P > F$	**	***	NS
Check	3.1	5.2	4.4

† Autumn starter (12-40-0-10-1, N-P-K-S-Zn) applied at a rate of 280.5 kg ha^{-1} at planting.

‡ Early fungicide spray propiconazole (Tilt) applied at a 292.3 ml ha^{-1} rate at Feekes 5-7 stage.

§ Mid fungicide spray pyraclostrobin (Nexicor Xemium) applied at 511.5 ml ha^{-1} rate at Feekes 9 stage.

¶ Late fungicide spray pydiflumetofen + propiconazole (Miravis Ace) applied at a 1,001.2 ml ha^{-1} rate at Feekes 10.5.1 stage.

Late-season nitrogen was applied at a rate of 33.7 kg ha^{-1} at Feekes 7 stage.

†† All plots except the check plot received blanket spring N or green-up application at a rate of 112.2 kg ha^{-1} in fields following silage corn while 84.1 kg ha^{-1} in following soybean at Feekes 5 stage.

Table 2.4. Interaction between autumn starter (12-40-0-10-1, N-P-K-S-Zn) and fungicide timing on winter wheat grain yield (Mg ha^{-1}) in following silage corn, Lansing, MI, 2022-2023.

	SC 2023 Grain yield §		
	Autumn Starter		
Treatment ††	0 kg AS ha^{-1}	280 kg AS ha^{-1}	
	——Mg ha^{-1}——		P > F †
Fungicide Timing			
No fungicide	5.7aB	7.3aA	***
Feekes 5-7, 10.5.1	4.5cB	7.1aA	***
Feekes 10.5.1	5.7aB	7.2aA	***
Feekes 9, 10.5.1	5.1bB	7.3aA	***
Feekes 5-7, 9, 10.5.1	5.5abB	6.9aA	***
P > F #	**	NS	
Check	2.6		

§ Treatments were compared at 0.10 probability level, Fisher's least significant difference (LSD). Asterisks indicate thresholds of significance (NS, P > 0.10; *, P < 0.10; **, P < 0.05; ***, P < 0.001). Check is not included in the analysis.

Means within columns followed by the same lower-case letters are not statistically different (LSD, P < 0.10).

† Means within rows followed by the same upper-case letters are not statistically different (LSD, P < 0.10).

†† All plots except the check plot received blanket spring N or green-up application at a rate of 112.2 kg ha^{-1} in fields following silage corn (SC) at Feekes 5 stage.

Table 2.5. Mean winter wheat grain protein content (%) as influenced by autumn starter (12-40-0-10-1, N-P-K-S-Zn) and late-season applied nitrogen in following silage corn 2022 (SC 2022) or soybean 2023 (SB 2023), Lansing, MI, 2021-2023§.

Treatment ††	SC 2022	SB 2023
	——————%——————	
Autumn Starter Fertilizer (12-40-0-10-1, N-P-K-S-Zn) †		
0 kg AS ha^{-1}	11.0a	10.6b
280 kg AS ha^{-1}	9.7b	10.9a
P > F	***	**
Late-season Nitrogen #		
0 kg N ha^{-1}	10.0b	10.4b
34 kg N ha^{-1}	10.7a	11.2a
P > F	***	***
Check	9.7	9.0

† Autumn starter (12-40-0-10-1, N-P-K-S-Zn) applied at a rate of 280.5 kg ha^{-1} at planting.

Late-season nitrogen was applied at a rate of 33.7 kg ha^{-1} at Feekes 7 stage.

†† All plots except the check plot received blanket spring N or green-up application at a rate of 112.2 kg ha^{-1} in fields following silage corn while 84.1 kg ha^{-1} in following soybean at Feekes 5 stage.

Table 2.6. Interaction between autumn starter (12-40-0-10-1, N-P-K-S-Zn) and late-season nitrogen on winter wheat grain protein content (%) in following silage corn 2023 (SC 2023) or soybean 2022 (SB 2022), Lansing, MI, 2021-2023§.

	SC 2023			SB 2022		
	Late-season Nitrogen			Late-season Nitrogen		
Treatment ††	0 kg N ha^{-1}	34 kg N ha^{-1}		0 kg N ha^{-1}	34 kg N ha^{-1}	
	—————%——————			—————%——————		
Autumn Starter Fertilizer (12-40-0-10-1, N-P-K-S-Zn)			P > F †			P > F †
0 kg AS ha^{-1}	10.7aA	10.9aA	ns	9.9aB	10.9aA	***
280 kg AS ha^{-1}	10.0bB	10.7aA	**	9.8aB	10.4bA	**
P > F #	**	ns		ns	**	
Check	8.8			9.6		

§ Treatments were compared at 0.10 probability level, Fisher's least significant difference (LSD). Asterisks indicate thresholds of significance (NS, $P > 0.10$; *, $P < 0.10$; **, $P < 0.05$; ***, $P < 0.001$). Check is not included in the analysis.

Means within columns followed by the same lower-case letters are not statistically different (LSD, $P < 0.10$).

† Means within rows followed by the same upper-case letters are not statistically different (LSD, $P < 0.10$).

†† All plots except the check plot received blanket spring N or green-up application at a rate of 112.2 kg ha^{-1} in fields following silage corn while 84.1 kg ha^{-1} in following soybean at Feekes 5 stage.

Table 2.7. Interaction between autumn starter (12-40-0-10-1, N-P-K-S-Zn) and late-season nitrogen on winter wheat straw yield (MT ha^{-1}) in following silage corn, Lansing, MI, 2021-2022.

	SC 2022 Straw yield § Late-season Nitrogen		
Treatment ††	0 kg N ha^{-1}	34 kg N ha^{-1}	
	——MT ha^{-1}——		
Autumn Starter Fertilizer (12-40-0-10-1, N-P-K-S-Zn)			P > F †
0 kg AS ha^{-1}	1.2bB	1.5bA	**
280 kg AS ha^{-1}	2.3aA	2.0aA	NS
P > F #	***	***	
Check	0.5		

§ Treatments were compared at 0.10 probability level, Fisher's least significant difference (LSD). Asterisks indicate thresholds of significance (NS, P > 0.10; *, P < 0.10; **, P < 0.05; ***, P < 0.001). Check is not included in the analysis.

Means within columns followed by the same lower-case letters are not statistically different (LSD, P < 0.10).

† Means within rows followed by the same upper-case letters are not statistically different (LSD, P < 0.10).

†† All plots except the check plot received blanket spring N or green-up application at a rate of 112.2 kg ha^{-1} in fields following silage corn (SC) at Feekes 5 stage.

Table 2.8. Interaction between fungicide timing and late-season nitrogen on winter wheat straw yield (MT ha^{-1}) in following silage corn, Lansing, MI, 2021-2022.

	SC 2022 Straw yield §		
	Late-season Nitrogen		
Treatment ††	0 kg N ha^{-1}	34 kg N ha^{-1}	
	——MT ha^{-1}——		
Fungicide Timing			P > F †
No fungicide	1.9aA	1.6aA	NS
Feekes 5-7, 10.5.1	1.7aA	1.9aA	NS
Feekes 10.5.1	1.9aA	1.7aA	NS
Feekes 9, 10.5.1	1.8aA	1.6aA	NS
Feekes 5-7, 9, 10.5.1	1.4aB	2.1aA	***
P > F #	NS	NS	
Check	0.5		

§ Treatments were compared at 0.10 probability level, Fisher's least significant difference (LSD). Asterisks indicate thresholds of significance (NS, P > 0.10; *, P < 0.10; **, P < 0.05; ***, P < 0.001). Check is not included in the analysis.

Means within columns followed by the same lower-case letters are not statistically different (LSD, P < 0.10).

† Means within rows followed by the same upper-case letters are not statistically different (LSD, P < 0.10).

†† All plots except the check plot received blanket spring N or green-up application at a rate of 112.2 kg ha^{-1} in fields following silage corn (SC) at Feekes 5 stage.

Table 2.9. Mean winter wheat straw yield (MT ha^{-1}) as influenced by autumn starter (12-40-0-10-1, N-P-K-S-Zn), fungicide timing, and late-season applied nitrogen in following silage corn (SC 2023) or soybean (SB 2022 and SB 2023), Lansing, MI.

	Straw yield §		
Treatment ††	SC 2023	SB 2022	SB 2023
	MT ha^{-1}		
Autumn Starter Fertilizer (12-40-0-10-1, N-P-K-S-Zn) †			
0 kg AS ha^{-1}	1.8b	4.3b	2.4b
280 kg AS ha^{-1}	3.1a	4.7a	3.1a
P > F	***	**	***
Fungicide Timing ‡			
No fungicide	2.4	4.5	2.6
Feekes 5-7, 10.5.1	2.3	4.4	2.9
Feekes 10.5.1	2.5	4.4	2.7
Feekes 9, 10.5.1	2.5	4.8	2.8
Feekes 5-7, 9, 10.5.1	2.4	4.5	2.9
P > F	NS	NS	NS
Late-season Nitrogen #			
0 kg N ha^{-1}	2.4	4.5	2.7
34 kg N ha^{-1}	2.5	4.5	2.8
P > F	NS	NS	NS
Check	0.6	3.8	1.2

§ Treatments were compared at 0.10 probability level, Fisher's least significant difference (LSD). Values followed by the same lowercase letter are not significantly different. Asterisks indicate thresholds of significance (NS, P > 0.10; *, P < 0.10; **, P < 0.05; ***, P < 0.001). Check is not included in the analysis.

† Autumn starter (12-40-0-10-1, N-P-K-S-Zn) applied at a rate of 280.5 kg ha^{-1} at planting.

‡ Early fungicide spray propiconazole (Tilt) applied at a 292.3 ml ha^{-1} rate at Feekes 5-7 stage.

§ Mid fungicide spray pyraclostrobin (Nexicor Xemium) applied at 511.5 ml ha^{-1} rate at Feekes 9 stage.

¶ Late fungicide spray pydiflumetofen + propiconazole (Miravis Ace) applied at a 1,001.2 ml ha^{-1} rate at Feekes 10.5.1 stage.

Late-season nitrogen was applied at a rate of 33.7 kg ha^{-1} at Feekes 7 stage.

†† All plots except the check plot received blanket spring N or green-up application at a rate of 112.2 kg ha^{-1} in fields following silage corn while 84.1 kg ha^{-1} in following soybean at Feekes 5 stage.

Partial returns

Traditional winter wheat management (i.e., GRNUP + L) incorporates a green-up application of 112 and 84 kg N ha^{-1} in SC and SB, respectively, at FK 5 and late-season fungicide applied at FK 10.5.1. In this study, GRNUP + L was used as a primary reference for comparing partial returns across all treatments excluding the check. In general, grain partial returns of GRNUP + L was greater in 2022 by + USD 602.8 and + USD 1,047.9 in SC and SB, respectively than in 2023 due to greater grain price (2022, USD 342.03 Mg^{-1}; 2023, USD 242.84 Mg^{-1}).

Following silage corn

Following SC 2022, mean grain and grain + straw partial returns for GRNUP + L was USD 1,730.8 ha^{-1} and USD 1,974.0 ha^{-1}, respectively **(Table 2.10).** The addition of late-season N or multiple fungicide programs increased grain and grain + straw partial returns only when autumn starter fertilizer was applied. Incorporating autumn starter fertilizer and late-season N without late-season fungicide spray at FK 10.5.1 resulted in the greatest grain and grain + straw partial returns by USD 583.3 ($P < .0001$) and USD 601.0 ($P < .0001$), respectively **(Table 2.10).** Incorporating mid-season fungicide spray at FK 9 with late-season N reduced mean grain partial returns by USD 241.2 ha^{-1} ($P = 0.0872$) and mean grain + straw partial returns by USD 307.7 ha^{-1} ($P = 0.06$). The increase in partial returns resulted from enhanced mean grain yield leading to higher income and offsetting additional fertilizer and fungicide costs.

Following SC 2023, mean grain and grain + straw partial returns for GRNUP + L was USD 1,128.01 ha^{-1} and USD 1,400.32 ha^{-1}, respectively **(Table 2.10).** Without late-fungicide spray at FK 10.5.1, the addition of autumn starter fertilizer only (+ USD 392.9, $P = 0.0017$) or with mid-season fungicide spray at FK 9 (+ USD 274.8, $P = 0.0738$) increased grain + straw partial returns **(Table 2.10).** Meanwhile, implementing multiple fungicide spray programs or late-season N without autumn starter fertilizer decreased grain partial returns by USD 242.78 – 386.92 ha^{-1}.

Following soybean

Following SB 2022, mean grain and grain + straw partial returns for GRNUP + L were USD 2,547.1 ha^{-1} and USD 3,158.5 ha^{-1}, respectively **(Table 2.11).** Across inputs, only late-season N improved mean grain partial returns by USD 293.5 ha^{-1} ($P = 0.0687$). Incorporation of autumn starter with early fungicide spray at FK 5 reduced mean grain partial returns by USD

375.5 – 390.4 ha^{-1}. Further, the addition of mid-season fungicide spray at FK 9 reduced grain + straw partial returns by USD 316.1 ha^{-1} ($P = 0.0166$).

In SB 2023, mean grain and grain + straw partial returns for traditional treatment GRNUP + L was USD 1,499.16 ha^{-1} and USD 1,899.70 ha^{-1}, respectively **(Table 2.11).** The addition of autumn starter fertilizer with late-season N or multiple fungicide sprays at FK 5-7 or 9 reduced grain partial returns by USD 319.58 – 466.29 ha^{-1}. Further, the addition of autumn starter with mid-season fungicide spray at FK 9 decreased grain + straw partial returns by USD 459.34 ha^{-1} ($P = 0.03$).

Table 2.10. Partial returns of winter wheat grain yield and grain plus straw yield following silage corn, Lansing, MI, 2021-2023. Mean partial return of green-up application and Feekes 10.5.1 fungicide spray treatment displayed with all other treatments displaying change in net return from this treatment using Dunnet-Hsu Test at $\alpha = 0.10$. §

Treatment	Grain (USD ha^{-1})		Grain + Straw (USD ha^{-1})	
	SC 2022	SC 2023	SC 2022	SC 2023
GRNUP + L	$1,730.8	$1,128.0	$1,974.0	$1,400.32
−L	-47.7	+17.3	-65.7	+17.8
− L + LN	-16.7	+51.7	-31.7	+77.1
+ E	-3.4	-331.9**	-116.3	-403.6**
+ E + LN	-203.8	-386.9**	-183.8	-422.8**
+ LN	+144.0	-95.4	+120.2	-89.0
+ M	-117.2	-242.8**	-176.8	-275.3*
+ M + LN	-241.2*	-264.9**	-307.7*	-282.5*
+ E + M	-128.1	-244.8**	-253.0	-274.4*
+ E + M + LN	-204.1	-128.8	-200.3	-111.1
+ AS	+351.4**	+54.3	+427.5**	+224.9
+ AS + LN	+440.1**	+51.9	+477.0**	+251.9
+ AS + E	+399.7**	+24.7	+552.3**	+168.7
+ AS + E + LN	+408.7**	-30.3	+475.2**	+204.9
− L + AS	+448.6**	+235.2*	+527.0**	+392.9**
−L + AS + LN	+585.3***	+73.9	+601.0**	+228.2
+ AS + M	+335.0**	+66.4	+437.6**	+274.8*
+ AS + M+ LN	+343.2**	-26.4	+398.5**	+171.2
+ AS + E + M	+410.1**	-52.2	+461.9**	+160.1
+ AS + E + M + LN	+440.1**	-174.5	+573.5**	-49.9
Check	$1,055.4	$635.4	$1,119.1	$722.2

§ Asterisks indicate thresholds of significance (*, $P < 0.10$; **, $P < 0.05$; ***, $P < 0.001$). Check is not included in the analysis.

Abbreviations: GRNUP – blanket green-up N application at Feekes 5 stage except check, AS – autumn starter applied at planting, E – early fungicide spray at Feekes 5-7 stages, M – mid-season fungicide spray at Feekes 9 stage, L – late-season fungicide spray at Feekes 10.5.1 stage, LN – late-season N application at Feekes 7 stage.

Table 2.11. Partial returns of winter wheat of grain yield and grain plus straw yield following soybean, Lansing, MI, 2021-2023. Mean net return of green-up application and Feekes 10.5.1 fungicide spray treatment displayed with all other treatments displaying change in net return from this treatment using Dunnet-Hsu Test at α = 0.10. §

Treatment	Grain (USD ha^{-1})		Grain + Straw (USD ha^{-1})	
	SB 2022	SB 2023	SB 2022	SB 2023
GRNUP + L	$2,547.1	$1,499.2	$3,158.5	$1,899.7
−L	+44.9	+104.5	+104.9	+ 67.5
− L + LN	+244.2	-77.1	+293.1	-158.9
+ E	-4.6	+13.3	-9.3	-28.1
+ E + LN	+121.5	-274.0	+180.8	-332.5
+ LN	+293.5*	-232.7	+292.3	-274.1
+ M	-78.6	-136.0	+7.3	-199.6
+ M + LN	+94.6	-189.5	+169.5	-274.6
+ E + M	-146.0	-151.5	-109.7	-240.3
+ E + M + LN	+67.5	-71.2	+89.4	-16.9
+ AS	-191.0	-278.0	-102.2	-271.0
+ AS + LN	+44.1	-261.3	+130.0	-248.5
+ AS + E	-375.5**	-319.6*	-293.1	-223.3
+ AS + E + LN	+46.2	-350.8**	+106.1	-267.3
− L + AS	-144.5	-148.8	-43.7	-145.1
−L + AS + LN	-19.4	-199.3	+9.4	-171.0
+ AS + M	-236.5	-466.3**	-116.1	-459.3**
+ AS + M+ LN	-148.2	-256.1	-28.9	-110.8
+ AS + E + M	-390.4**	-268.9	-316.1*	-234.4
+ AS + E + M + LN	-54.7	-367.8**	+53.7	-283.6
Check	**$1,783.1**	**$1,068.8**	**$2,345.1**	**$1,239.3**

§ Asterisks indicate thresholds of significance (*, P < 0.10; **, P < 0.05; ***, P < 0.001). Check is not included in the analysis.

Abbreviations: GRNUP – blanket green-up N application at Feekes 5 stage except check, AS – autumn starter applied at planting, E – early fungicide spray at Feekes 5-7 stages, M – mid-season fungicide spray at Feekes 9 stage, L – late-season fungicide spray at Feekes 10.5.1 stage, LN – late-season N application at Feekes 7 stage.

2.4 Discussion

This study aimed to enhance understanding of intensive management on winter wheat grain yield, straw production, and grain quality. Over four site-years, the traditional treatment (i.e., GRNUP + L) yielded on average 6.9 Mg ha^{-1} grain and 2.6 MT ha^{-1} straw while more intensive strategies (i.e., autumn starter, fungicide sprays at FK 5-7, 9, 10.5.1, and late-season N at FK 7) resulted in mean yields of 8.2 Mg ha^{-1} grain and 3.3 MT ha^{-1} straw. Results emphasize the potential for intensive management to effectively narrow yield gaps and are similar to those reported in other studies (Jaenisch et al., 2022; Peterson et al., 2023; Steinke et al., 2021).

Orthogonal contrasts helped evaluate which agronomic inputs impacted yield and grain protein content. Across the four site years, only the 2021-2022 cropping season demonstrated a significant interaction between autumn starter fertilizer (208 kg ha^{-1}) and late-season N (34 kg N ha^{-1}) on grain yield for SC 2022 ($P = 0.01$) and SB 2022 ($P < 0.0001$) **(Table 2.12).** Grain protein content was significantly influenced by autumn starter and late-season N across all site-years (SC 2022 $P = 0.0003$; SC 2023 $P = 0.0002$; SB 2022 $P = 0.001$; SB 2023 $P < 0.0001$) **(Table 2.12).** Combined fertilizer and fungicide strategies had no effect on grain yield, straw yield, or grain protein content across all site-years **(Table 2.12).** The absence of interaction between early (FK 5-7) and mid-season (FK 9) fungicide applications with autumn starter and late-season N underscores the limited impact of fungicide strategy in a low disease environment regardless of multiple fertilizer applications.

Weather

The early phenological phases of winter wheat is strongly related to air temperature (Xiao et al., 2015). As winter wheat root systems minimally develop at 5 °C air temperature, supplying early nutrients near seedlings before dormancy becomes critical due to the reduced osmotic potential of shoots and roots; hence decreasing sugar accumulation (Equiza et al., 2001). Autumn starter fertilizer demonstrated enhanced spring tiller production in three of four sites year (not following SB 2022, data not shown). Precipitation is crucial alongside temperature for later-stage wheat development. Cooler air temperatures and adequate moisture from heading to grain-fill ensure prolonged growth and robust grain set (Farooq et al., 2014; Xiao et al., 2015). Warm May and June 2023 growing conditions combined with deviations of -80% and -76% from the 30-year avg. precipitation, respectively, resulted in a narrowed grain-filling period contributing to a 16% decline in grain yield compared to 2022.

Table 2.12. Winter wheat grain yield, straw yield, and grain protein content treatment response using single degree of freedom contrasts, Lansing, MI. 2021-2023.

	2022		2023	
	SC	SB	SC	SB
Grain Yield				
AS-no LN vs. AS-LN	**0.01**[*]	**<.0001**	0.87	0.25
AS-EL vs. AS-L, ML, EML	0.98	0.86	0.92	0.71
LN-ML vs. LN-EL, L, ML	0.20	0.32	0.99	0.58
EML vs. EL, L, ML	0.62	0.54	0.87	0.29
AS-no fungicide-LN vs. AS-EL, L, ML, EML - LN	0.55	0.44	0.97	0.93
Straw Yield				
AS-no LN vs. AS-LN	0.13	0.58	0.88	0.13
AS-EL vs. AS-L, ML, EML	0.25	0.34	0.90	0.23
LN-ML vs. LN-EL, L, ML	0.12	0.17	0.97	0.82
EML vs. EL, L, ML	0.82	0.86	0.91	0.51
AS-no fungicide-LN vs. AS-EL, L, ML, EML - LN	0.16	0.12	0.42	0.26
Grain Protein Content				
AS-no LN vs. AS-LN	**0.0003**	**0.001**	**0.0002**	**<.0001**
AS-EL vs. AS-L, ML, EML	0.57	0.74	0.94	0.18
LN-ML vs. LN-EL, L, ML	0.22	0.48	0.89	0.93
EML vs. EL, L, ML	0.22	0.34	0.90	0.95
AS-no fungicide-LN vs. AS-EL, L, ML, EML - LN	**0.03**	0.63	0.32	0.43

*Bolded values significantly increased at α=0.10 using single degree of freedom contrasts. Check is not included in the analysis.

Abbreviations: AS – autumn starter applied at planting, E – early fungicide spray at Feekes 5-7 stages, M – mid-season fungicide spray at Feekes 9 stage, L – late-season fungicide spray at Feekes 10.5.1 stage, LN – late-season N application at Feekes 7 stage, no fungicide – no fungicide spray in any Feekes stages.

Shah and Paulsen (2003) similarly found that drought and higher temperature lowered photosynthetic rate, reduced shoot and grain mass, and decreased kernel weight during grain-fill. Likewise, anthesis or grain-filling heat stress decreased photosynthetic rates by 17-25% causing 29-44% grain yield reduction (Djanaguiraman et al., 2020).

Autumn Starter

Grain Yield. Across the four site-years, application of 280 kg ha^{-1} of autumn starter (12-40-0-10-1, N-P-K-S-Zn) only significantly influenced grain yield following silage corn (SC). Autumn starter (AS) increased mean grain yield by 2.2 Mg ha^{-1} (**Table 2.3**, $P < 0.0001$) in SC 2022 and by 1.7 Mg ha^{-1} (**Table 2.4**, $P < 0.0001$) in SC 2023. However, no significant influence of AS was observed following soybean (SB 2022, $P = 0.6427$ and SB 2023, $P = 0.1544$, **Table 2.3**). The potential positive influence of AS on grain yield could be attributed to the previous cropping history via C:N ratios of crop residues and soil residual N (Arcand et al., 2014; Mason & Rowland, 1992). The greater C:N ratio in silage corn (70-75:1) compared to C:N ratio in soybean (20:1 – 40:1) may promote N immobilization thereby increasing wheat N uptake from applied fertilizers (Klinger & Bugeja, 2018; McDivitt, 2021).

Another possible explanation for the lack of autumn starter differences following soybean as compared to following silage corn may center on greater nutrient requirements. To produce an average of 14.4 Mg ha^{-1} (230 bu. A^{-1}) of hybrid corn variety, the crop requires 286.9 kg N ha^{-1} (256 lbs. A^{-1}), 113.2 kg P_2O_5 ha^{-1} (101 lbs. A^{-1}), 201.8 kg K_2O ha^{-1} (180 lbs. A^{-1}) and 25.8 kg S ha^{-1} (23 lbs. A^{-1}) (Bender et al., 2013). Further, if all or portions of aboveground stover were used, an additional 10.4 kg N (20.8 lbs. N T^{-1}), 2.0 kg P_2O_5 (4.0 lbs. P_2O_5 T^{-1}), 11.7 kg K_2O (23.3 lbs. K_2O T^{-1}), and 1.0 kg S (1.9 lbs. S T^{-1}) per Mg^{-1} of dry matter should be considered (Bender et al., 2013). On the other hand, to produce 3,500 kg ha^{-1} of soybean, the crop requires 275 kg N, 48 kg P_2O_5, 207 kg K_2O, and 19 kg S (Bender et al., 2015). Since both biomass and grain are removed when harvesting silage corn, compared to only grain with soybeans, it is possible that the application of autumn starter compensated for the greater nutrient removal in following silage corn.

1000-kernel weight. Autumn starter reduced 1000-kernel weight in all site years except SB 2022 ($P = 0.67$) (data not shown). Following SC, AS reduced 1000-kernel weight by 8.5% ($P < 0.0001$) and 14.8% ($P < 0.0001$) for 2022 and 2023, respectively. Following SB 2023 field showed a 9.4% ($P < 0.0001$) reduction in 1000-kernel weight from AS application. Increased grain production reflected as greater grain yield, may have increased the number of kernels and in turn, at the expense of reduced kernel size and weight. Kernel weight only moderately negatively influenced grain yield in following silage corn (SC 2022 $r = -0.56$; SC 2023 $r = -0.69$; **Table 2.13**).

Tillering and headcount. Autumn starter application increased spring tiller density in following SC 2022, SC 2023, and SB 2023 by 14% ($P = 0.0565$), 34% ($P < 0.0001$), and 27% ($P = 0.0002$), respectively (data not shown). Following SC, tiller density ranged from 334 – 2,831 tillers m^{-2} averaging 1,507 tillers m^{-2} in 2022 with density ranges from 667 – 2,508 tillers m^{-2} and an average of 1,733 tillers m^{-2} in 2023. Following SB, tiller density varied from 1,033 – 5,242 tillers m^{-2} with an average of 1,507 tillers m^{-2} in 2022 while ranging from 1,572 – 4,155 tillers m^{-2} and an average of 2,497 tillers m^{-2} in 2023. However, only following SC 2023, did tiller density have a moderate positive influence on grain yield ($r = 0.60$, **Table 2.13**). Tiller density had a low (SB $r = 0.33$, Table 14) to moderate (SC $r = 0.61$, **Table 2.13**) positive influence on straw yield in 2023.

Tiller production determines potential headcount. Following SC, head counts ranged from 441 – 1,227 spikes m^{-2} with a mean of 797 spikes m^{-2} and from 398 – 1,098 spikes m^{-2} with a mean of 721 spikes m^{-2} in 2022 and 2023, respectively. Following SB, head counts ranged from 452 – 1,023 spikes m^{-2} with a mean of 721 spikes m^{-2} and from 517 – 1,615 spikes m^{-2} with a mean of 893 spikes m^{-2} in 2022 and 2023, respectively. Autumn starter fertilizer increased the mean headcount across all site years (data not shown). Following SC, AS increased wheat spikes by 47% ($P < 0.0001$) and 31% ($P < 0.0001$) in 2022 and 2023, respectively while AS increased wheat spikes by 11% ($P = 0.0032$) and 23% ($P < 0.0001$) following SB in 2022 and 2023, respectively. Consequently, headcount exerted a moderate to strong positive influence on grain yield in three out of four site years (SC 2022 $r = 0.83$; SC 2023 $r = 0.63$; SB 2023 $r = 0.42$; **Tables 2.13 and 2.14**). Results align with Quinn and Steinke (2019) where both tiller and head production were enhanced by applying autumn starter in a low-input management system. The minimal influence of tiller density on grain yield highlights the significance of tiller survivability when developing into productive wheat heads at harvest.

Head length. Autumn starter fertilizer increased the mean head length in three of four site years (SC 2022 $P = 0.0069$; SC 2023 $P < 0.0001$; SB 2023 $P < 0.0001$; data not shown) and had a weak to moderate positive influence on grain yield (SC 2022 $r = 0.41$; SB 2022 $r = 0.26$; SC

2023 $r = 0.62$; **Tables 2.13 and 2.14**). Head lengths ranged between 66.9 – 81.1 mm and 54.6 – 77.7 mm in 2022 and 2023, respectively. Head development is most rapid during stem elongation (FK 5-7). As the wheat stem elongates, the "heading stage" is initiated suggesting that as the stem extends there is a greater opportunity for the head to stretch thereby producing a longer head (Simmons et al., 1985). Longer head length corresponds to more spikelets that can be filled with grain. According to Broeske et al., (2020), the number of spikelets per head is determined at FK 5. The application of an early nutrient source offers the potential for greater stem elongation especially in unfavorable mid-season environments such as the hot and dry May – June 2023 weather conditions which resulted in a shorter grain-fill period.

Plant height and straw yield. Plant height ranged between 47.9 – 80.9 cm in 2022 compared to 40.5 – 75.2 cm in 2023. Autumn starter fertilizer increased mean plant height in all four site years (data not shown). Following SC, AS increased plant height by 7% ($P < 0.0001$) and 15% ($P < 0.0001$) in 2022 and 2023, respectively, while following SB, AS increased plant height by 3% ($P < 0.0001$) and 1% ($P = 0.05$) in 2022 and 2023, respectively. Plant height showed a strong positive influence on grain yield in all site years (SC 2022 r = 0.78; SC 2023 $r = 0.88$; SB 2022 $r = 0.60$; SB 2023 $r = 0.75$). During the growing season, uniform growth with greater plant height was observed in AS-applied plots which promoted enhanced photosynthetic capacity leading to increased grain yield. Plant height also exerted a moderate to strong positive influence on straw yield in three out of four site years (SC 2022 $r = 0.52$; SC 2023 $r = 0.82$; SB 2023 $r = 0.57$; **Tables 2.13 and 2.14**). The positive correlation between straw yield and plant height demonstrates the contribution of stem elongation during straw accumulation. The active growth stage of wheat starts at Feekes 5 when leaf sheaths are fully elongated and pseudostems are strongly erect and proceed up until Feekes 10 when the head is visible in the leaf sheath (Broeske et al., 2020). Since rapid N uptake begins at Feekes 5 to 7, autumn starter provided wheat greater opportunity to uptake N which translated to improved stem elongation and straw production.

Table 2.13. Correlations between winter wheat agronomic components, Feekes 9 flag leaf, and grain nutrient concentrations at harvest with grain yield, straw yield, and grain protein content following silage corn (SC), Lansing, MI, 2021-2023. †

SC 2022													
	Agronomic ‡				Flag leaf				Grain				
	T	PH	HC	HL	N	P	S	N:S ratio	N	P	S	N:S ratio	KW
GY	0.20	0.78***	0.83***	0.41**	0.38**	0.22*	0.67***	-0.61***	-0.62***	-0.43***	0.65***	-0.72***	-0.56***
SY	-0.01	0.52***	0.58***	0.08	0.08	0.01	0.40**	-0.40**	-0.44***	-0.35**	0.32**	-0.41***	-0.48***
GP	-0.12	-0.56***	-0.56***	-0.29*	0.05	0.12	-0.56***	0.71***	0.94***	0.53***	-0.53***	0.83***	0.64***

SC 2023													
	Agronomic				Flag leaf				Grain				
	T	PH	HC	HL	N	P	S	N:S ratio	N	P	S	N:S ratio	KW
GY	0.60***	0.88***	0.63***	0.60***	0.63***	-0.05	0.84***	-0.85***	-0.47***	-0.43***	0.76***	-0.81***	-0.69***
SY	0.61***	0.82***	0.60***	0.41**	0.56***	0.05	0.76***	-0.75***	-0.30*	-0.38**	0.73***	-0.70***	-0.72***
GP	-0.42**	-0.43***	-0.20	-0.47***	-0.07	0.34**	-0.28*	0.44**	0.87***	0.30*	-0.26*	0.57***	0.20

† Pearson correlation coefficient analysis using PROC CORR procedure. Asterisks indicate thresholds of significance (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$). Check is not included in the analysis.

‡ Abbreviations: GY – grain yield; SY – straw yield; GP – grain protein; T – tiller population; PH – plant height; HC – head count; HL – head length; KW – 1000-kernel weight

Flag leaf tissue collection and subsequent nutrient analysis were conducted at Feekes 9. Grains were sampled at harvest and sent to the laboratory for analysis.

Table 2.14. Correlations between winter wheat agronomic components, Feekes 9 flag leaf, and grain nutrient concentrations at harvest with grain yield, straw yield, and grain protein content following soybean (SB), Lansing, MI, 2021-2023. †

SB 2022													
	Agronomic				Flag leaf				Grain				
	T	PH	HC	HL	N	P	S	N:S ratio	N	P	S	N:S ratio	KW
GY ‡	0.13	0.60***	0.21	0.26*	0.60***	0.30**	0.27*	-0.03	nd	nd	nd	nd	-0.08
SY	0.08	0.27*	0.15	-0.10	0.00	0.39**	-0.14	0.16	nd	nd	nd	nd	-0.13
GP	-0.11	0.33**	0.03	0.19	0.61***	-0.09	0.41**	-0.17	nd	nd	nd	nd	-0.12
SB 2023													
	Agronomic				Flag leaf				Grain				
	T	PH	HC	HL	N	P	S	N:S ratio	N	P	S	N:S ratio	KW
GY	-0.05	0.75***	0.42**	0.10	0.34**	0.06	0.49***	-0.53***	-0.15	-0.12	0.20	-0.46***	0.03
SY	0.33**	0.57***	0.44***	0.35**	0.38**	0.37**	0.64***	-0.66***	0.25*	0.13	0.52***	-0.46***	-0.40**
GP	0.41**	-0.05	0.06	0.38**	0.45**	0.39**	0.33**	-0.14	0.93***	0.40**	0.59***	0.12	-0.58***

† Pearson correlation coefficient analysis using PROC CORR procedure. Asterisks indicate thresholds of significance (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$). Check is not included in the analysis.

‡ Abbreviations: GY – grain yield; SY – straw yield; GP – grain protein; T – tiller population; PH – plant height; HC – head count; HL – head length; KW – 1000-kernel weight; nd – no data. Flag leaf tissue collection and subsequent nutrient analysis were conducted at Feekes 9. Grains were sampled at harvest and sent to the laboratory for analysis.

Flag leaf S concentration. Flag leaf S concentrations ranged from 0.25 – 0.70% in 2022 and 0.15 – 0.42% in 2023. The critical range for flag leaf S is 0.20-0.40% (Vitosh et al., 1998). The possible explanation behind the below critical flag leaf S level in 2023 was reduced precipitation by -80% in May 2023 compared to 30-year average leading to decreased soil S uptake. Autumn starter fertilizer significantly influenced flag leaf S concentration in all site-years except SB 2022. Autumn starter fertilizer containing S increased flag leaf S concentrations by 0.06% ($P < 0.0001$), 0.10% ($P < 0.0001$), and 0.10% ($P < 0.0001$) in SC 2022, SC 2023, and SB 2023, respectively (data not shown). Winter wheat undergoes rapid biomass growth in the early spring when the air and soil temperatures are cool with limited soil S mineralization (Camberato et al., 2022). Early S deficiency in non-AS treated plots diminished as the spring air temperatures warmed but yield limitations might still have persisted. Recent research reported a positive relationship between N and S in improving physiological attributes, yield components, nutrient uptake, and grain quality (Carciochi et al., 2020; Salvagiotti & Miralles, 2008). In the current study, AS provided 34 kg N and 28 kg S which assisted in developing canopy and leaf area coverage from Feekes 3 to 10.5.1 (data not shown). During the growing season, a wider-sized flag leaf with horizontal orientation on AS-treated plots was observed. Broader and larger flag leaves may have promoted greater photosynthetic capacity and increased grain yield. Previous research observed wheat to be more S-responsive than corn and sugarbeets. Goyal et al., (2021) reported that spring wheat positively responded to ammonium thiosulfate with 5.44 Mg ha^{-1} grain yield as compared to the no-S control (4.73 MT ha^{-1}). Also, N and S application improved wheat biomass at flowering by 62% along with improved physiological traits such as leaf area index (LAI) and intercepted radiation (IPAR) by 13% and 7%, respectively (Salvagiotti & Miralles, 2008). The advantage of S application from autumn starter was demonstrated with flag leaf S concentrations exerting a moderate to strong positive influence on grain yield in three out of four site-years (SC 2022 $r = 0.67$; SC 2023 $r = 0.84$; SB 2023 $r = 0.49$, **Tables 2.13 and 2.14**).

Fungicide Timing and Disease Assessment

Autumn starter had a significant interaction with late-season N ($P = 0.0448$) and fungicide timing ($P = 0.01$) on the FHB index following SC 2022 and SB 2022, respectively (data not shown). However, following SC 2023, autumn starter and late-season N only had a significant interaction on the FHB index ($P = 0.066$, data now shown). Following SC 2022 and

2023, the absence of autumn starter and late-season N provided the highest FHB index with 0.14 and 0.25, respectively (data not shown). Following SB 2022, autumn-applied starter plots with no fungicide had the highest FHB index (5.72, data not shown). Incidence and severity are necessary in determining FHB index. However both incidence and severity might be prone to the assessor's subjective observation. Meanwhile, deoxynivalenol (DON) analysis determined mycotoxin levels in winter wheat grains infected by FHB. Although FHB infection does not mean presence of mycotoxin levels, high DON levels (> 1 ppm) could exclude grains for human consumption. This study did not detect DON accumulation in any site year (DON < 0.05 ppm).

The inherent susceptibility of the host, the inoculum potential of the parasite, and the impact of the environment on parasitism and pathogenesis are key factors for disease infection (Scholthof, 2007). Favorable FHB development is linked to high precipitation, warm temperature, and relative humidity at the pre-anthesis to grain-filling stage (Bhatta et al., 2018; Blandino et al., 2006; Hernandez Nopsa et al., 2012). Previous literature demonstrated the influence of pre- and during anthesis weather on FHB development. Elevated precipitation (i.e., May-June; 371 mm) before and during anthesis led to an almost ten-fold greater DON accumulation compared to drier spring seasons (i.e., May-June; 200 or 132 mm) (Hernandez Nopsa et al., 2012). Moist, warm conditions with frequent anthesis rainfall resulted in more infected heads and yield reductions of 0.8 Mg ha^{-1} when fungicide was omitted from an intensive management strategy (Steinke et al., 2021). Aside from FHB, mid-season and late-season fungal pathogens may also occur, potentially reducing grain yield. In 2016, due to a significant occurrence of stripe rust (*Puccinia striiformisf. sp. tritici*), yield increased by 0.75 Mg ha^{-1} when fungicide at FK 10.5.1 was applied in Lansing, MI. (Quinn and Steinke, 2018). In 2024, another occurrence of stripe rust was observed as early as FK 9 facilitated by strong winds aiding the spore movement from southern states (i.e. Louisiana) (Wheat Ag. Pest, 2024). Both occurrences demonstrate the potential of pre-anthesis fungicide spray (i.e. FK 9) against mid-season fungal diseases.

In the current study, decreased precipitation during anthesis (-36% and -76% as compared to the 30-year avg. during June 2022 and 2023, respectively) likely reduced opportunities for late-season disease infection. The absence of fungicide's main effects in three of four site years indicated fungicide application at FK 10.5.1 was sufficient for yield protection in a low-disease pressure environment.

Flag leaf disease observations at FK 10.5.4 occurred. Autumn starter fertilizer increased flag leaf disease at FK 10.5.4 (SC 2022 $P < 0.0001$; SC 2023 $P = 0.0009$; SB 2022 $P = 0.013$; data not shown), but late-season N influenced flag leaf disease only in SC and SB 2022 (SC 2022 $P = 0.0486$; SB 2022 $P = 0.0293$, data not shown).

Late-season Nitrogen at Feekes 7

Previous studies observed variability regarding the influence of late-season applied N on grain yield, nutrient concentration, and grain quality (De Oliveira Silva et al., 2021; Sowers et al., 1994). Results could be attributed to low N fertilizer recovery of wheat (e.g., 30-50%) and presence of nutrient limiting conditions (Raun et al., 2002). In 2022, late-season N at FK 7 increased mean grain yield (SC 2022 $P = 0.013$; SB 2022 $P < 0.0001$; Table 3). In March and April 2022, precipitation was 34% and 8%, respectively greater than the 30-year avg. (March 4.27 cm., April 9.02 cm). Greater precipitation resulted in more N-loss conditions after green-up N application thus greater opportunity for enhancing grain yield via FK 7 N application. Late-season N also improved mean grain protein content as a main effect (SC 2022 $P < 0.0001$; SB 2023 $P < 0.0001$; **Table 2.5**) and interacted with autumn starter (SC 2023 $P = 0.038$; SB 2022 $P = 0.0678$; **Table 2.6**). In SC 2023 and SB 2022, late-season N increased mean grain protein content with autumn starter application **(Table 2.6).** Autumn starter may have decreased protein content due to growth dilution across a greater number of tillers; however with late-season N, grain protein content increased.

Flag leaf N and grain N concentrations were measured at FK 9 and harvest, respectively. The interaction between late-season N and autumn starter fertilizer increased flag leaf N across all site years (SC 2022 $P = 0.0769$; SC 2023 $P = 0.0802$; SB 2022 $P = 0.0882$; SB 2023 $P = 0.0035$; data not shown). Late-season N increased flag leaf N when AS was applied (data not shown). The flag leaf contributes 30-50% of assimilates for grain filling and the stay-green potential correlates with grain protein accumulation (Blake et al., 2007; Sylvester-Bradley et al., 1990). Results show that across all site-years, flag leaf N concentrations were sufficient (data not shown) but only had a moderate positive influence on grain protein content following soybean (SB 2022 $r = 0.61$; SB 2023 $r = 0.45$; **Table 2.14**). Late-season N also increased grain N content in three site-years (SC 2022 $P < 0.0001$; SC 2023 $P < 0.0001$; SB 2023 $P < 0.0001$; data not shown). Grain N content had a strong positive influence on grain protein content (SC 2022 $r = 0.94$; SC 2023 $r = 0.87$; SB 2023 $r = 0.93$; **Tables 2.13 and 2.14**). Grain protein concentrations in the current study ranged from 8.9 – 12.5% with a mean of 10.3% in 2022 and 8.5 – 13.1% with an average of 10.6% in 2023. It is important to note that grain protein content affects flour quality. Since SRWW is primarily used for light and airy baked goods (i.e., cakes, pretzels, donuts, and crackers), maintaining grain protein content within the preferred range (8-11%) is essential to avoid undesirable final baking properties (i.e., crumbly and chewy structure) (Hunter & Standford, 1973; Carson and Edwards, 2009). The positive effect of late-season N on grain protein content in all site-years was due to reduced late-season precipitation resulting in greater concentration and less dilution. Decreased June 2022 and 2023 precipitation (-36% and -76%, respectively) resulted in dry soil conditions further concentrating grain protein content. Results coincide with Gauer et al., (1992) in which increased soil moisture reduced grain protein content but increased grain yield and grain N use efficiency.

2.5 Conclusion

The results from this study suggest the potential for intensive management to fulfill yield gaps in grain and straw production. Without adverse conditions such as pre-plant nutrient deficiency or high disease pressure; however, this approach may not be profitable. Autumn starter only increased grain yield following silage corn but enhanced straw production in all site years. Late-season N at Feekes 7 increased grain protein content (SC 2022, SB 2023) or with interaction with autumn starter (SB 2022, SC 2023). Our results support the use of the current Michigan State University fungicide recommendations for Fusarium head blight (FHB) suppression. Field scouting and keeping field history of diseases, crop rotation, planting resistant varieties and integrated pest management (IPM) are important to avoid fungicide resistance. Use of disease outbreak modeling tools such as Wheat Ag Pest Monitor and Fusarium Head Blight Prediction Center for Wheat can also monitor early-season and mid-season fungal diseases. With a few exceptions, correlation analysis confirmed the essential roles of plant height, headcount and flag leaf S levels in maximizing grain yield and straw production. Likewise, grain N increased grain protein content. Our findings highlight the potential of autumn starter fertilizer for enhancing in-season yield components to improve grain yield and nutritive quality as well as straw production.

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CHAPTER 3: SUGAR BEET YIELD AND RECOVERABLE SUCROSE RESPONSE TO INTENSIVE NUTRIENT MANAGEMENT

ABSTRACT

Michigan sugarbeet (*Beta vulgaris* L.) nutrient management recommendations include 157-179 kg N ha^{-1} with an initial 45 kg N ha^{-1} applied at planting to promote canopy closure. While individually added inputs associated with yield gaps were previously investigated, synergistic influences when combined with a standard N program (SN) within an integrated management perspective have not been explored. This study investigated sugarbeet root yield and recoverable sucrose response to different fertilizer strategies along a stepwise increase in management intensity. In 2022, SN treatment averaged 90.1 Mg ha^{-1}, 148.4 kg Mg$^{-1,}$ and 13,327.9 kg ha^{-1} in root yield, recoverable sugar per ton and recoverable sugar per hectare, respectively. The addition of in-furrow P negatively impacted root yield and recoverable sugar by -15.5 Mg ha^{-1} and - 2,325.7 kg ha^{-1}, respectively. In 2023, pre-plant broadcast lime, in-furrow P, and intensive management (combining all individual inputs) increased root yield by 13.7, 11.9, and 13.2 Mg ha^{-1}, respectively. The intensive management and pre-plant broadcast lime increased recoverable sugar per Mg by +7.1 and +8.4 kg Mg^{-1}, respectively, while also improving recoverable sugar per hectare by +2,329.8 and +2,278.0 kg ha^{-1}, respectively$^{.}$ In-furrow P increased sugar per hectare by 2,186.3 kg ha^{-1}. The inconsistent root yield and recoverable sucrose response to marketed inputs accentuate the importance of pre-plant soil analysis, in-season weather monitoring, and the use of disease models for developing a climate-smart agricultural system.

3.1 Introduction

The United States ranks third in global sugarbeet (*Beta vulgaris* L.) production behind Russia and France (*FAOSTAT*, 2023). Between 2021 and 2022, U.S. sugarbeet hectares increased from 450 to 460 thousand, but annual production decreased from 30 to 27 million metric tons with average yields per hectare decreasing from 74 to 64 Mg (*FAOSTAT*, 2023). In 2022, Michigan sugarbeet production decreased 25% from 4.8 million Mg to 3.6 million Mg with an average yield of 64.5 Mg ha^{-1} which was lower than the national average of 70.6 Mg ha^{-1} (NASS, 2022; *NASS*, 2021). To obtain more sugar on equal or fewer hectares while simultaneously addressing climate variability, soil spatial differences, and unpredictability of disease occurrence, growers are increasingly exploring intensive nutrient management strategy combinations including lime (Clark et al., 2015), P applications (Steinke & Bauer, 2017), supplementary potassium (Milford et al., 2000), sulfur (Kastori et al., 2000), and foliar B (Armin & Asgharipour, 2012).

Lime has direct and indirect positive benefits to the soil–crop system. Direct benefits include neutralizing soil acidity, enhancing soil nutrient availability (i.e. N, P, K, Ca, Mg, S, B, Mo) and reducing heavy metal solubility (Hati et al., 2008; Holland et al., 2018; Nichol et al., 1993; Olego et al., 2021; Olsson et al., 2019; Windels et al., 2007a). Indirect benefits will depend on initial soil and plant characteristics but may include increased crop yield, improved soil physical properties, and enhanced soil biological activity (DeSutter & Godsey, 2010; Hossain, 2021; Valzano et al., 2001). In the current study, pre-plant broadcast agricultural lime was substituted for precipitated calcium carbonate (PPC) which is a byproduct from sucrose extraction during sugarbeet processing due to logistical limitations. Precipitated calcium carbonate, also known as beet lime, has an annual application rate in Michigan of nearly 220,000 tons PCC (Clark et al., 2015). Precipitated calcium carbonate is formed when combining calcium oxide and carbon dioxide which are added to the juice stream for impurity removal during the purification of sucrose (Clark et al., 2015). Due to the high Ca content (35%) and calcium carbonate equivalence (CCE) (84.3%) relative to 100% calcium carbonate, PCC serves as an excellent source of Ca and may function as a liming material (Clark et al., 2015). Due to neutral to alkaline soil conditions within the Michigan sugarbeet growing region, liming materials are often not required to neutralize soil acidity, but sugarbeet growers may apply PCC to prevent accumulation at the processing plant, to provide nutrients such as Ca, Mg, and K or to reduce the pressure of seedling damping off diseases like *Aphanomyces cochlioides* (= A. cochlioides) which causes sugarbeet root damage (Sims et al., 2010; Windels et al., 2007a). Previous studies reported the benefits of PCC application on crop production and disease control under slightly alkaline soil conditions. In Michigan (i.e., soil pH 7.4), sugarbeet root yield and recoverable sucrose by hectare increased 4.9 Mg ha^{-1} and 694.9 kg ha^{-1}, respectively after the application of 27 Mg PPC ha^{-1} (Clark et al., 2015). In Idaho (i.e., soil pH 7.9-8.1, silt loam soil), bicarbonate soil P concentrations increased 25% and 73% for the final PCC application amounts of 27 and 90 Mg ha^{-1} due to high P concentration of PCC (6,559 mg kg^{-1}) (Tarkalson & Bjorneberg, 2024). In North Dakota (i.e, soil pH 7.6), Aphanomyces soil index values decreased as rates of lime increased at 34 and 45 Mg lime ha^{-1} compared to control due to antagonistic microorganisms present in the sugarbeet rhizosphere against *A. cochlioides* (Windels et al., 2007b). However, concerns do exist regarding potential adverse effects from PCC application including imbalanced soil pH and micronutrient deficiencies. At pH values near or above neutral, the precipitation of insoluble calcium phosphates can decrease phosphate availability (Haynes, 1982). Liming also decreases the solubility and concentration of many micronutrients in soil solution (Fageria & Baligar, 2008). Therefore risks of P and micronutrient deficiencies resulting from heavy lime applications must be considered.

Nitrogen nutrition is critical in sugarbeet production. In Michigan, the recommended N rate is around 157-179 kg N ha^{-1} with an initial 45 kg N ha^{-1} applied at planting to promote canopy closure (Purucker & Steinke, 2022; Warncke et al., 2009). Sub-optimal N rates reduce root yield and recoverable sucrose while excessive N application exacerbates impurities in sugarbeet roots (Blumenthal et al., 2008; Carter & Traveller, 1981; Draycott & Christenson, 2003). Aside from N rate, placement and timing of application are vital for N absorption. The total 179 kg N ha^{-1} with 5 cm × 5 cm N application at planting with 45 kg N ha^{-1} provided greater root yield and recoverable sugar by +13.4 Mg ha^{-1} and + 1,680 kg ha^{-1}, respectively, compared with no 5 × 5-cm band placement (Purucker & Steinke, 2022). Meanwhile, late N application has been found to increase the N concentration in plants and canopy size but had little effect on beet and sugar yield. The application of 60 kg N ha^{-1} with 85% canopy coverage increased foliage dry weight but did not affect sugar yield (Malnou et al., 2008). Similarly, Wiesler et al. (2002) concluded that split N applications at planting and 16 weeks after planting did not affect beet yield or quality. Limited information concerning late N fertilizer effects on beet yield and sugar content encouraged the incorporation of late-applied N in the current study.

Phosphorus, considered one of the most unavailable nutrients in the soil, functions primarily for root establishment, hastened germination, and rapid early plant development (Grant et al., 2001; Lynch & Brown, 2008; Nadeem et al., 2013). Previous studies reported a positive response on root yield and sugar production with individual and combined effects of P with other nutrients under various soil textures. Application from 15 to 30 kg P_2O_5 increased the sugar content and improved root yield with applied foliar B and Mg in sandy soils (i.e., soil pH 8.1, soil P 4.8-6.1 mg kg^{-1}) (Makhlouf et al., 2020). The P rate at 30 kg P_2O_5 produced greatest root biomass, sugar, and improved sugar quality in clay soils (i.e., soil pH 8.1-8.5, soil P 9.2 mg kg^{-1}) (Mahmoud et al., 2014). Another significant aspect of optimizing P efficiency is the method of application. In-furrow application of ammonium polyphosphate (10-34-0) enhanced spring stand count and canopy development but little influence on root yield (i.e., soil pH 7.8-8.0, soil Bray P1 32-41 mg kg^{-1}) (Steinke & Bauer, 2017). The placement of N and P in a single starter band (5 cm x 5 cm) was comparable to placing a band on each side of the row in sorghum (i.e., soil pH 6.9, soil Bray P1 12 mg kg^{-1}) (Gordon & Whitney, 2000). The annual seed placed application of 10 and 20 kg P ha^{-1} increased the yield and P uptake of wheat similar to the broadcast application of 40 kg P ha^{-1} (i.e, soil pH = 7.3, soil Bicarbonate P < 3 mg kg^{-1}) (Wagar et al., 1986).The possible explanation behind the positive response of localized P fertilizer was deficient pre-plant soil P levels and increased P availability promoting plant P uptake.

Potassium (K) is an essential nutrient for plant growth and development, and importance of K fertilizer in agriculture is comprehensively documented (Römheld & Kirkby, 2010; Sardans & Peñuelas, 2021). Field studies show K fertilizer plays an essential role in the transport of photosynthates and nutrients thus having a significant influence on greater root yield and sugar production (Hadir et al., 2020; Jákli et al., 2018). In Michigan, recommended K rates are near 74 kg K_2O ha^{-1} for 44.8 Mg ha^{-1} yield potential (Warncke et al., 2009). The influence of K on active phloem loading has been identified in numerous species with decreased sugar translocation as a primary effect of K deficiency (Doman & Geiger, 1979; Zhao et al., 2001). Cakmak et al. (1994) investigated the influence of varied P, K, and magnesium (Mg) supply on the translocation of phyto-assimilates and found sucrose export decreased from K deficiency. Potassium deficiency also results in the accumulation of sucrose in leaves due to reduced entry of sucrose in the transport pool for translocation (Zhao et al., 2001). Due to the crucial role of K in sugar translocation, K-fertilizer application occurred closer to mid-season in the current study, near to the onset of root bulking and sugar translocation from aboveground biomass.

Due to decreased atmospheric deposition, sulfur (S) has received increased interest over the last decade (Steinke et al., 2015). As a structural component of cysteine (Cys) and methionine (Met), S occurs within the plant at an average ratio of one part S to about 15 parts N and stimulates seed and root growth along with supporting a “dark green color” favorable for photosynthesis (Crusciol et al., 2013; Droux, 2004; Szulc et al., 2021). The sulfate anion (SO_4^{2-}) ion serves as the primary S source for plants and is typically found in minimal quantities in the soil (Narayan et al., 2022). Since $SO4^{-2}$ is water-soluble and may readily leach from the soil profile, application of S-containing fertilizers might be necessary (Camberato et al., 2022). Most inorganic S fertilizers contain S either as $SO4^{-2}$ or as elemental S with sulfate-S being immediately available but highly mobile in most soils (Camberato et al., 2022). Soil texture and organic matter influence sugarbeet response to S fertilizer. In a multi-location study, S application did not positively impact root yield on heavier textured soils (80% loam, 5% clay) across 33 sites (Hoffmann et al., 2004). In a multi-crop trial, Goyal et al. (2021) reported corn and sugarbeet did not respond to the addition of S fertilizer. A likely explanation was soil organic matter (12-31 g kg^{-1}) concentrations were great enough to mineralize sufficient S to corn and sugarbeet. Previous research presented a positive association between S and N in improving physiological attributes, yield components, nutrient uptake, and grain quality (Carciochi et al., 2020; Coolong & Randle, 2003; Randall et al., 1981; Salvagiotti & Miralles, 2008). The synergistic relationship between N and S suggests both nutrients may be required in lieu of individual nutrient applications.

Boron (B) is taken up by plants primarily as undissociated H_3BO_3 (boric acid) and $H_2BO_3^-$ (borate) with availability impacted by soil pH (Rehman et al., 2018). As soil pH increases (> 6.5), the availability of B decreases (Rehman et al., 2018). In high pH soils (> 7.5), the borate anion (HBO_4^-) prevails and is subject to leaching (Dhassi et al., 2019). When deficient, B may impact root yield and quality but also may affect plant metabolic functions including cell wall and membrane structure, metabolite transfer, and enzyme activation (Song et al., 2023; Wu et al., 2021).

Cercospora leaf spot (CLS), caused by the foliar fungus *Cercospora beticola*, is a devastating foliar sugarbeet disease (Tedford et al., 2019). The progressive increase of necrotic leaf spots and loss of producing new leaves can affect the photosynthetic capacity and adversely influence yield and sugar content (Rossi et al., 2000; Weiland & Koch, 2004). Effective control of CLS requires an integrated and intensive approach. Fungicide application, planting resistant varieties, and crop rotation with non-host crops are common disease control strategies (Skaracis et al., 2010). More recently, B-containing products have been reported to contain fungistatic properties showing reduced CLS severity with boron application. Multiple B spray at 60, 90, and 120 DAP with boric acid provided lower CLS severity (13.56%) as compared to zinc sulfate (16.62%) and potassium bicarbonate (23.4%) (El-Shazly et al., 2018). Currently, there is limited data on the direct impact of B application in managing CLS in sugarbeet fields.

While individual added fertilizers and soil amendments associated with sugarbeet yield gaps were previously investigated, synergistic influences when combined with a standard N management (179 kg N ha^{-1}) program have been poorly explored. The objective of the current study was to investigate the sugarbeet root yield and recoverable sucrose response to multiple fertilizer strategies reflecting a stepwise increase in management intensity compared to a baseline standard N management program.

3.2 Materials and Methods

Sugarbeet trials were established in the 2022 and 2023 growing seasons at the Saginaw Valley Research and Extension Center near Richville, MI (43°23’57.3” N, 83°41’49.7” W) on a Tappan-Londo loam (fine-loamy, mixed, active, calcareous, mesic *Typic Epiaquoll*) soil. The site was non-irrigated and tile-drained on 5.2 m spacings representative of production areas in northeastern MI. Thirty-year mean annual temperature and precipitation were 9.0 ºC and 86.3 cm, respectively. Fields were autumn chisel plowed (20-cm) following corn and field cultivated (10-cm) in the spring before planting. Pre-plant soil characteristics (0-20 cm) included 7.7-7.8 soil pH (1:1 soil/water) (Peters et al., 2015), 21-28 g kg^{-1} soil organic matter (loss-on-ignition) (Combs and Nathan, 2015), 20 mg kg^{-1} P (Olsen sodium bicarbonate extraction) (Frank et al., 2015), and 152-171 mg kg^{-1} K (ammonium acetate method) (Brown, 2015) across two cropping years. Prior to planting, soil samples (0-30 cm) for nitrate-N (NO_3-N) analysis were air-dried and ground to pass through a 2-mm sieve resulting in concentrations of 5.7 and 7.0 mg NO_3-N kg^{-1} soil (nitrate electrode method) in 2022 and 2023, respectively (Gelderman and Beegle, 1998). Monthly precipitation, air and soil temperature data were collected and recorded throughout the growing season from Michigan State University Enviro-weather (http://mawn.geo.msu.edu)

(Michigan State University, East Lansing, MI). The 30-year average of temperature and precipitation was obtained from the National Oceanic and Atmosphere Administration (NOAA, 2022).

Treatment Structure and Experimental Design

Field experiments were planted on 11 May 2022 and 27 April 2023 with a Monosem planter (Monosem Inc., Kansas City, KS). Plots measured 4.6 m in width by 10.7 m in length containing 6 rows with 76-cm spacing. Sugarbeet 'Crystal G049' (ACH Seeds, Inc., Eden Prairie, MN), a high tonnage, moderate sugar-producing variety with excellent Cercospora and good Rhizoctonia resistance (Michigan Sugarbeet Research Education Advisory Council, 2022) was planted both seasons. Experiment included eight treatments plus a check arranged in a randomized complete block design with four replications. Treatments represented stepwise increases in management intensity from 1) a standard N baseline of 179 kg N ha^{-1} (SN) with 45 kg N ha^{-1} applied 5 cm below and 5 cm laterally from the seed at planting as urea ammonium nitrate (UAN, 28-0-0) (5×5 N) and remaining 135 kg N ha^{-1} (UAN) as sidedressed at 2-4 leaf growth stage (LF) (1 June 2022 and 31 May 2023), 2) SN + P, 7.2 kg N and 22.3 kg P_2O_5 ha^{-1} were applied in-furrow during planting using liquid ammonium polyphosphate (APP, 10-34-0), 3) SN + Lime, 4.5 MT ha^{-1} of agricultural lime (32% Ca) broadcast before planting, 4) SN + S, 44.8 kg N ha^{-1} from UAN at planting (5×5) with 126.1 kg N ha^{-1} (UAN), 8.2 kg N ha^{-1} and 17.8 kg S ha^{-1} from ammonium thiosulfate (ATS, 12-0-0-26S) at 2-4 LF, 5) SN + B, with 0.56 kg ha^{-1} of sodium tetraborate (16.5% B) diluted and applied weekly in July 2022 (08, 14, 19, and 22 July) and July 2023 (07, 14, 19 and 27 July), 6) SN + K, 112 kg K2O ha^{-1} from Monty's® LiquidK2O® (Monty's Plant Food, Louisville, KY) surface banded at 20 LF (05 July 2022 and 07 July 2023), 7) SN + Late N, 44.8 kg N ha^{-1} was applied 2 weeks after the initial side-dress of 89.6 kg N ha^{-1} (UAN) at 2-4 LF (14 June 2022 and 14 June 2023), 8) intensive management including all treatment combinations, and 9) check. Foliar boron was sprayed using a CO_2-powered backpack sprayer equipped with four TJ 8002XR nozzles (76-cm spacing) calibrated at 140 L ha^{-1}. Side-dress N applications were made using a tractor-mounted coulter injection cart placing fertilizer 10 cm below ground directly between sugarbeet rows. Surface band applications of liquid K_2O were made using a backpack sprayer equipped with orifice body nozzles and short drop hoses to place fertilizer 5-10 cm laterally from sugarbeet rows. Rates of applied fertilizer, placements, and timings are summarized in **Table 3.1.**

Table 3.1. Overview of treatment names, fertilizer source, grade, rate, placement, and timings applied to sugarbeet, Richville, MI. 2022-2023.

Treatment Name	Fertilizer	Fertilizer grade	Amount —ha^{-1}— (A^{-1})	Placement	Timing
Standard N (SN)	Urea ammonium nitrate (UAN)	28-0-0	124.4 L. (13.3 gal)	5cm. × 5 cm.	Planting
	UAN	28-0-0	374.2 L. (40 gal)	Side-dress (SD)	2-4 leaf (LF)
SN + P	Ammonium polyphosphate	10-34-0	46.8 L. (5 gal)	In-furrow	Planting
SN + Lime	Agricultural lime	32% Ca	4.5 MT. (2 T)	Broadcast	Pre-planting
SN + S	UAN	28-0-0	124.4 L. (13.3 gal)	5cm. × 5 cm.	Planting
	UAN	28-0-0	350.8 L. (37.5 gal)	SD	2-4 LF
	ATS	12-0-0-26S	52.4 L. (5.6 gal)	SD	2-4 LF
SN + B	Sodium tetraborate	16.5% B	0.6 kg. (0.5 lb.)	Foliar	Weekly in July
SN + K	K_2O Liquid	0-0-28	288.1 L. (30.8 gal)	Band	Early July
SN + Late N	UAN	28-0-0	249.8 L. (26.7 gal)	SD	2-4 LF
	UAN	28-0-0	124.4 L. (13.3 gal)	SD	2WASD
Intensive (all treatments)	Agricultural lime	32% Ca	4.5 MT (2 T)	Broadcast	Pre-planting
	UAN	28-0-0	124.4 L. (13.3 gal)	5cm. × 5 cm.	Planting
	liquid ammonium phosphate	10-34-0	46.8 L. (5 gal)	In-furrow	Planting
	UAN	28-0-0	226.4 L. (24.2 gal)	SD	2-4 LF
	ATS	12-0-0-26S	52.4 L. (5.6 gal)	SD	2-4 LF
	UAN	28-0-0	124.4 L.	SD	2WASD
	Sodium tetraborate	16.5% B	0.6 kg. (0.5 lb.)	Foliar	Weekly in July
	K_2O Liquid	0-0-28	288.1 L. (30.8 gal)	Band	Early July
Check	No fertilizer added	NA †	NA	NA	NA

† NA – not applicable

Measurements

Plant emergence was recorded from two linear meters per plot 20-30 days after planting (DAP). Fractional green canopy coverage (FGCC) and normalized difference vegetation index (NDVI) were recorded at 10-14 day intervals using Canopeo (Mathworks, Inc., Natick, MA) and GreenSeeker® crop sensing system (Trimble Agriculture Division, Westminster, CO), respectively, starting at 2-4 leaf stage until full canopy closure (Patrignani & Ochsner, 2015). The uppermost fully developed and extended leaf and petiole were collected from 20 plants per plot at the 6-8 and 20+ LF growth stages. Plant tissue samples were dried at 60°C, mechanically ground to pass through a 1-mm mesh screen, digested in an open vessel microwave procedure (SW846-3051A) (US EPA, 2015) and analyzed for total N using Dumas Method (Nitrogen by Combustion or Nitrogen by Thermal Conductance) following AOAC Official Method 972.43 (Horwitz & Latimer, 2000) and total P, K, Ca, Mg, Mn, and B concentrations using Inductively Coupled Argon Plasma (ICAP) run on Thermo iCAP 6500 following AOAC Official Method 980.03 (Horwitz & Latimer, 2000). Final stand counts were recorded prior to harvest from two linear meters per plot. Sugarbeets from the center two rows were harvested 24 October 2022 and 24 October 2023 using a mechanical plot harvester and weighed. Ten sugarbeet root samples per plot were collected and analyzed for sucrose concentration, extraction percentage, and recoverable sucrose at the Michigan Sugar Co. (MSC) Laboratory (Bay City, MI).

Partial Returns

Partial returns were calculated using Michigan Sugar Company's average payment standard (2022-2023) which considers root yield (Mg ha^{-1}) and recoverable sucrose (kg Mg^{-1}). The expected net return (USD ha^{-1}) was calculated from each treatment as follows: $Rn = [(Y \times S \times St \times A)] – [(Cf + Cfa) + (Y \times T)]$, where Y is the observed root yield (Mg ha^{-1}) from the treated treatment, S is the recoverable sucrose (kg Mg^{-1}), St is the price of sugar (USD kg^{-1}), and A is the adjustment factor for root yield and recoverable sugar. The abbreviations Cf stands for fertilizer cost (USD ha^{-1}), Cfa for fertilizer application cost (USD ha^{-1}), and T for trucking cost. Net return in this economic analysis excludes specific grower management practices such as direct and fixed costs and focused solely on expenses affected by treatments. In 2022, gross economic return was based on USD 0.40 kg^{-1} sugar delivered while in 2023 the price was USD 0.55 kg^{-1} sugar delivered. Fertilizer costs were obtained from local elevators while application costs were estimated using the Michigan State University Extension Custom Machine and Work

Rate Estimates for 2022 and 2023, respectively. Trucking from field to processor was \$4.13 Mg^{-1} for both years. The prices of sugar and agronomic inputs applied are summarized in Table 2.

Statistical Analysis

Analyses for in-season measurements (plant emergence, pre-harvest stand count, percent canopy coverage, and NDVI) and leaf tissue nutrient concentrations (6-8 and 20-22 leaf stages) were conducted using the PROC MIXED procedure in SAS (SAS 9.4) (SAS Institute Inc., 2017). Each site year was analyzed individually due to significant treatment-by-year interactions. Fertilizer treatment was considered a fixed effect while block was a random effect. The normality assumption was checked by examining the residuals' histogram and normal probability plots. Unequal variance assumption was assessed by visual inspection of the side-by-side box plots of the residuals followed by Levene's test for unequal variances. Since Levene's test results indicated that the equal variance assumption might be violated, unequal variance analyses were conducted using the REPEATED /GROUP= statement of PROC MIXED. Models with homogeneous and heterogeneous variances were compared using AIC criteria (Milliken & Johnson, 2009) The model that resulted in the lowest AIC and BIC values was selected for further analysis. These were analyzed using Analysis of Variance and compared using Least Significant Difference (LSD) at $\alpha = 0.10$. Root yield, recoverable sugar (RSWT and RSWA), and partial returns were analyzed using the single degrees of freedom at $\alpha = 0.10$ with SN (Treatment 1) compared to remaining fertilizer treatments (Treatment 2 – 8) to evaluate the individual input effects. Unpaired T-test was performed to compare SN + Lime and intensive management to the SN for determining the impact of agricultural lime applications in 2023.

Table 3.2. Estimates of sugarbeet input costs per kilogram and sugar prices received used for potential economic profitability, Richville, MI. 2022-2023. †

	Prices (USD)	
Yield	2022	2023
Sugar [a]	0.40 kg^{-1}	0.55 kg^{-1}
Fertilizer	Unit Price (USD kg^{-1})	
UAN (28-0-0) [b]	0.74	0.37
Ammonium polyphosphate (10-34-0) [c]	1.16	0.90
Agricultural lime (32% Ca) [d]	0.003	0.003
Ammonium thiosulfate (12-0-0-26S) [e]	0.74	0.39
Sodium tetraborate (16.5% B) [f]	0.81	0.81
	Unit Price (USD L^{-1})	
Liquid K_2O (0-0-28) [g]	4.40	4.40

[a] Michigan Sugar Company

[b] 675 USD ton^{-1}, 3.61 USD gal^{-1} (2022) 340 USD ton^{-1}, 1.82 USD gal^{-1} (2023)

[c] 1,050 USD ton^{-1}, 6.14 USD gal^{-1} (2022) 818 USD ton^{-1}, 4.78 USD gal^{-1} (2023)

[d] 13 USD ton^{-1} including trucking cost

[e] 670 USD ton^{-1}, 3.64 USD gal^{-1} (2022) 350 USD ton^{-1}, 1.91 USD gal^{-1} (2023)

[f] 739 USD ton^{-1}

[g] 16.65 USD gallon^{-1}

† 5 cm by 5 cm application USD ha^{-1} 7.36 (2022) and 7.36 (2023). Liquid side-dress USD ha^{-1} 27.92. Foliar spray USD ha^{-1} 18.56. MSU Extension Farm Business (2021) https://www.canr.msu.edu/farm_management/uploads/files/MSU%20Custom%20Work%20Rates%202021.pdf.

3.3 Results

Environmental Conditions

Growing season precipitation decreased -28% and -19% from the 30-year mean for 2022 (May – October) and 2023 (April – October), respectively **(Table 3.3).** However, June 2022 and 2023 rainfall decreased -36% and -55%, respectively, compared to 30-year means slowing early vegetative growth and root establishment. Mid- to late-summer growing conditions differed between years with July and August 2022 rainfall decreasing -19% and -18%, respectively, as compared to July and August 2023 rainfall increasing +93% and +55%, respectively, all compared to 30-year means. Excess precipitation during July and August 2023 created moist soil conditions for the remainder of the growing season reducing root yield, sugar percentage, and total sugar production as compared to the 2022 season. Normal to above normal soil temperatures during establishment (+2% and +29%) during May 2022 and April 2023, respectively) hastened seed emergence **(Tables 3.4 and 3.5).**

Sugarbeet Root Yield and Recoverable Sugar

Root yields ranged from 39.9 – 101.6 Mg ha^{-1} across site years with yields ranging from 41.8 – 101.6 Mg ha^{-1} in 2022 and from 39.9 – 97.9 Mg ha^{-1} in 2023. In 2022, the mean root yield from the SN treatment was 90.1 Mg ha^{-1} with in-furrow P the only treatment to significantly impact root yield (-15.5 Mg ha^{-1}) **(Table 3.6).** All fertilizer treatments yielded above the 2022 state root yield average of 82.9 Mg ha^{-1} except for in-furrow P treatment (74.6 Mg ha^{-1}). In 2023, the mean root yield from SN was 78.0 Mg ha^{-1} with pre-plant broadcast lime, in-furrow P, and intensive treatments all significantly increasing root yield by 13.7, 11.9, and 13.2 Mg ha^{-1}, respectively **(Table 3.6).** All fertilizer strategies except for the check surpassed the 2023 state root yield average of 64.6 Mg ha^{-1}. Across all treatments, average recoverable sucrose in 2022 was 148.4 kg Mg^{-1} and 12,433.4 kg ha^{-1} as compared to 134.2 kg Mg^{-1} and 10,536.4 kg ha^{-1} in 2023. The SN treatment in 2022 averaged 148.4 kg Mg^{-1} and 13,327.9 kg ha^{-1} **(Table 3.6).** No treatments impacted recoverable sugar per Mg, but in-furrow P reduced recoverable sugar per hectare by -2,325.7 kg ha^{-1} **(Table 3.6).** In 2023, the average recoverable sucrose from SN was 130.1 kg Mg^{-1} and 10,160.4 kg ha^{-1} **(Table 3.6).** The all-inclusive intensive management treatment and pre-plant broadcast lime increased recoverable sugar per Mg by +7.1 and +8.4 kg Mg^{-1}, respectively, while also improving recoverable sugar per hectare by +2,329.8 and +2,278.0 kg ha^{-1}, respectively (Table 6). In-furrow P increased sugar per hectare by 2,186.3 kg ha^{-1} but had

Table 3.3. Mean monthly † and 30-yr temperature and precipitation for the sugarbeet growing season, Richville, MI, 2022-2023.

Year	April	May	Jun.	Jul.	Aug.	Sept.	Oct.
air min. °C							
2022		10.7	13.6	15.0	15.0	11.5	3.8
2023	4.8	6.5	12.9	16.2	13.5	12.2	7.6
30-yr.avg. ‡	2.0	8.6	14.2	16.3	15.3	11.0	5.3
air avg. °C							
2022		16.6	20.4	21.9	21.2	17.3	10.3
2023	8.9	14.3	19.9	21.9	19.2	17.5	12.0
30-yr.avg.	7.7	14.6	20.2	22.2	21.1	17.1	10.6
air max. °C							
2022		22.5	27.2	28.7	27.5	23.2	16.9
2023	12.9	22.1	26.8	27.7	25.0	22.7	16.4
30-yr.avg.	13.3	20.5	26.1	28.1	26.9	23.2	15.9
cm.							
2022		4.2	5.5	5.9	7.9	6.5	5.0
2023	1.4	2.5	3.8	13.9	15.0	3.4	5.5
30-yr.avg.	7.6	8.5	8.5	7.2	9.7	7.4	7.4

† 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 3.4. Mean monthly and 15-yr soil temperature data for the sugarbeet growing season, Richville, MI, 2022-2023. †

Year	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.
				soil min. °C			
2022		13.1	19.1	21.6	21.4	18.4	10.7
2023	8.3	12.0	18.2	21.1	19.0	ND‡	ND
15-yr.avg.	5.0	11.8	17.8	21.2	20.6	17.1	11.0
				soil avg. °C			
2022		14.7	21.1	23.7	23.3	19.8	12.2
2023	9.5	14.8	21.1	24.0	21.8	ND	ND
15-yr.avg.	7.4	14.3	20.3	23.9	23.1	19.3	12.7
				soil max. °C			
2022		16.3	23.0	25.8	25.2	21.3	13.6
2023	10.7	17.7	24.0	26.9	24.7	ND	ND
15-yr.avg.	9.8	16.8	22.8	26.6	25.6	21.5	14.4

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

‡ ND – no available data

Table 3.5. Sugarbeet emergence and harvest stand counts in response to fertilizer strategy, Richville, MI., 2022-2023. §

	2022		2023	
	Emergence	Pre-harvest	Emergence	Pre-harvest
Treatment	%		%	
Standard N (SN)	75.2a	75.4	66.3	65.4
SN + P	56.0c	60.2	61.9	59.4
SN + Lime	77.3a	74.5	65.5	66.1
SN + S	75.0a	74.0	67.0	66.5
SN + B	75.6a	74.0	70.5	68.0
SN + K	76.4a	76.0	67.3	65.4
SN + Late N	75.6a	71.1	64.2	60.0
Intensive	63.7b	68.1	65.8	68.6
P > F	**	NS	NS	NS
Check	77.6	78.1	64.8	58.1

§ Asterisks indicate thresholds of significance (NS, P> 0.10, *, P < 0.10; **, P < 0.05; ***, P < 0.001). Check is not included in the analysis.

Table 3.6. Fertilizer strategy impacts on sugarbeet root yield (Mg ha^{-1} or T A^{-1}) and recoverable sucrose (kg ha^{-1} or lbs. A^{-1}, kg Mg^{-1} or lbs. T^{-1}), Richville, MI, 2022 - 2023. Mean sugarbeet yield and recoverable sucrose of standard nitrogen treatment (SN) displayed. All other treatments display change in sugarbeet yield recoverable sugar using a single degree of freedom contrasts §.

	——Root yield——		————Recoverable sucrose†————			
Treatment	2022	2023	2022	2023	2022	2023
	——Mg ha^{-1}—— (T A^{-1})		——kg ha^{-1}—— (RSWA)		——kg Mg^{-1}—— (RSWT)	
Standard N (SN)	90.1	78.0	13,327.9	10,160.4	148.4	130.1
	(40.0)	(34.8)	(11,890.9)	(9,064.9)	(296.8)	(260.20)
SN + P	-15.5**	+13.7**	-2,325.7**	+2,186.3**	-0.8	+4.7
	(-6.9)	(+6.1)	(-2,074.9)	(+1,950.6)	(-1.7)	(+9.4)
SN + Lime	+4.0	+11.9**	+438.8	+2,278.0**	-1.8	+8.4**
	(+1.8)	(+5.3)	(+391.5)	(+2,032.4)	(-3.6)	(+16.8)
SN + S	+1.8	+4.3	+465.4	+849.0	+1.7	+3.8
	(+0.8)	(+1.9)	(+415.2)	(+757.5)	(+3.4)	(+7.7)
SN + B	-4.0	-3.8	-474.6	-136.1	+0.9	+5.2
	(-1.8)	(-1.7)	(-423.4)	(-121.4)	(+1.8)	(+10.5)
SN + K	-2.2	-5.2	-105.1	-511.7	+1.6	+2.0
	(-1.0)	(-2.3)	(-93.8)	(-456.5)	(+3.3)	(+4.1)
SN + Late N	-2.0	-2.5	-81.9	-35.2	+2.3	+4.1
	(-0.9)	(-1.1)	(-73.1)	(-31.4)	(+4.6)	(+8.2)
Intensive	-3.8	+13.2**	-750.7	+2,329.8**	-2.8	+7.1*
	(-1.7)	(+5.9)	(-669.8)	(+2,078.6)	(-5.6)	(+14.2)
Check	55.1	49.5	8,111.0	6,584.7	147.8	131.6
	(24.6)	(22.1)	(7,236.5)	(5,874.7)	(295.6)	(263.3)

§ Asterisks indicate thresholds of significance (*, $P < 0.10$; **, $P < 0.05$; ***, $P < 0.001$). Check is not included in the analysis.

† RWSA – recoverable white sugar per acre; RWST – recoverable white sugar per ton

Table 3.7. Fertilizer strategy effects on sugarbeet sucrose percentage and purity extraction, Richville, MI., 2022-2023. §

	2022		2023	
	Sugar	Purity	Sugar	Purity
Treatment	———%	———	———%	———
Standard N (SN)	19.5	95.8	17.5d	96.1
SN + P	19.4	95.8	18.0abc	95.9
SN + Lime	19.3	95.9	18.5a	95.9
SN + S	19.7	95.9	17.9bc	96.0
SN + B	19.6	95.7	18.1abc	95.9
SN + K	19.6	95.9	17.8cd	96.0
SN + Late N	19.8	95.9	18.0bc	95.9
Intensive	19.2	95.9	18.3ab	95.9
$P > F$	NS	NS	**	NS
Check	19.4	95.7	17.6	95.9

§ Asterisks indicate thresholds of significance (NS, P> 0.10, *, P < 0.10; **, P < 0.05; ***, P < 0.001). Check is not included in the analysis.

Table 3.8. Fertilizer treatment costs and partial returns, Richville, MI, 2022- 2023. Mean treatment costs and partial returns of standard nitrogen treatment (SN) displayed. All other treatments display change using single degree of freedom contrasts §.

	2022		2023	
	Treatment Cost	Partial returns	Treatment Cost	Partial returns
Treatment †	USD ha^{-1}		USD ha^{-1}	
Standard N (SN)	510.8	4,380.9	274.8	4,981.7
SN + In-furrow P	+83.2***	-937.9**	+66.5***	+1,078.2**
SN + PPI Ag. lime	+93.9***	+62.7	+93.9***	+1,109.1**
SN + SD ATS	+78.4***	+98.6	+43.2***	+405.7
SN + Foliar B	+74.3***	-244.8	+74.3***	-132.4
SN + Band K	+1,673.6***	-1,705.8***	+1,295.1***	-1,554.7**
SN + Late N	+146.6***	-169.8	+27.9***	-36.3
Intensive	+2,150.0***	-2,431.3***	+1,1671.8***	-445.9
Check	0.0	2,975.4	0.0	1,380.3

§ Asterisks indicate thresholds of significance (*, $P < 0.10$; **, $P < 0.05$; ***, $P < 0.001$). Check is not included in the analysis.

no impact on sugar per Mg (Table 6).

Sugar percentage (*P* = 0.6009) and purity extraction (*P* = 0.8402) were not affected by 2022 fertilizer strategies **(Table 3.7).** In 2023, all treatments other than banded K (SN + K) significantly increased sugar percentage (*P* = 0.0354) but had no effect on purity (*P* = 0.8634) **(Table 3.7).**

Partial Returns

In the current study, the SN treatment was used as a primary reference to gauge potential economic profitability across all treatments excluding the check. In 2022, mean treatment costs (fertilizer and application) and partial returns of SN were USD 510.8 ha^{-1} and USD 4,380.9 ha^{-1}, respectively **(Table 3.8).** All fertilizer treatments significantly increased the treatment costs (USD 83.2 – 2,150.0 ha^{-1}) as expected with intensive management having the highest additional cost (USD 2,150.0 ha^{-1}) followed by banded K (SN + K) (USD 1,673.6 ha^{-1}). Consequently, intensive management and SN + K significantly reduced the partial returns by USD -2,431.3 ha^{-1} and USD -1,705.8 ha^{-1}, respectively. In-furrow P (SN + P) had the lowest treatment cost (USD 83.2 ha^{-1}) but due to a significant decrease in root yield and recoverable sugar per hectare also reduced partial returns by USD -937.9 ha^{-1} **(Table 3.8).**

In 2023, SN treatment costs and partial returns were USD 274.8 ha^{-1} and USD 4,981.7 ha^{-1}, respectively **(Table 3.8).** All fertilizer treatments significantly increased treatment costs by USD 66.5 – 1,1671.8 ha^{-1} with both intensive management and SN + K again having the highest additional costs at USD 1,1671.8 ha^{-1} and USD 1,295.1 ha^{-1}, respectively. Banded K was the only treatment significantly reducing partial returns by USD -1,554.7 ha^{-1}. Across fertilizer strategies, early-season treatment applications including agricultural lime and in-furrow P increased partial returns by USD +1,109.1 ha^{-1} and USD +1,078.2 ha^{-1}, respectively.

Aboveground indices and post-harvest soil chemical properties

In 2022, canopy coverage was significantly influenced by fertilizer treatments at 2-4 leaf (*P* = 0.0405) and 6-8 leaf (*P* = 0.0129) stages **(Table 3.9).** Among individually added inputs, only pre-plant broadcast lime increased canopy coverage than SN by 0.9% and 6.5% at 2-4 LF and 6-8 LF, respectively. However, as vegetative growth progressed to 12-14 LF and 20-22 LF, fertilizer strategies had no impact on canopy development. All fertilizer treatments at 6-8 and 12-14 LF had similar NDVI values. In 2023, intensive management and early-season treatments (i.e., pre-plant broadcast lime and in-furrow P) improved row closure more than SN in all leaf growth stages except 2-4 LF (**Table 3.10**, *P* = 0.8984). Additionally, intensive management and pre-plant broadcast lime had greater NDVI values up until 22-24 LF. At the 22-24 leaf growth stage, only intensive management (0.86) had a greater NDVI value than SN (0.75). Meanwhile, SN had a comparable NDVI value with pre-plant broadcast lime (0.82) and in-furrow P (0.77). In 2023, the addition of pre-plant broadcast lime had no effect on post-harvest soil chemical analyses (data not shown).

Table 3.9. Percent green ground cover and normalized difference vegetation index (NDVI) as influenced by fertilizer strategy, Richville, MI., 2022. §

	Percent canopy coverage			
Treatment	2-4 leaf	6-8 leaf	12-14 leaf	20-22 leaf
Standard N (SN)	3.7b	15.9b	24.5	55.7
SN + P	3.6b	13.9b	24.8	49.4
SN + Lime	4.6a	22.4a	28.1	60.4
SN + S	2.9b	12.1b	26.0	58.0
SN + B	NA †	NA	NA	54.9
SN + K	NA	NA	NA	51.0
SN + Late N	NA	NA	25.5	53.0
Intensive	3.2b	13.7b	21.8	51.8
P > F	**	**	NS	NS
Check	3.3	12.7	20.0	39.5

	Normalized Difference Vegetation Index	
Treatment	6-8 leaf	12-14 leaf
Standard N (SN)	0.75	0.82
SN + P	0.72	0.85
SN + Lime	0.80	0.88
SN + S	0.75	0.87
SN + Late N	0.76	0.88
Intensive	0.74	0.83
P > F	NS	NS
Check	0.70	0.87

§ Asterisks indicate thresholds of significance (NS, P> 0.10, *, P < 0.10; **, P < 0.05; ***, P < 0.001). Check is not included in the analysis.

† Not applicable

Table 3.10. Percent green ground cover and normalized difference vegetation index (NDVI) as influenced by fertilizer strategy, Richville, MI., 2023. §

	Percent canopy coverage				
Treatment	2-4 leaf	6-8 leaf	12-14 leaf	20-22 leaf	22-24 leaf
Standard N (SN)	1.2	1.2c	3.0c	3.1d	31.2b
SN + P	1.4	3.1b	5.8b	5.5bc	44.0a
SN + Lime	1.1	3.7ab	8.1a	7.1b	44.5a
SN + S	0.8	1.2c	3.1c	3.0d	28.1b
SN + B	NA †	NA	NA	NA	27.0b
SN + K	NA	NA	NA	NA	30.4b
SN + Late N	NA	NA	2.4c	4.1cd	27.7b
Intensive	1.2	4.6a	9.4a	10.1a	41.8a
P > F	NS	**	***	**	**
Check	1.2	2.3	3.8	5.4	27.7

	Normalized Difference Vegetation Index			
Treatment	6-8 leaf	12-14 leaf	20-22 leaf	22-24 leaf
Standard N (SN)	0.36c	0.49c	0.45c	0.75bc
SN + P	0.38c	0.57b	0.55b	0.77bc
SN + Lime	0.45b	0.60b	0.58ab	0.82ab
SN + S	0.35c	0.46c	0.47c	0.77bc
SN + B	NA	NA	NA	0.73c
SN + K	NA	NA	NA	0.72c
SN + Late N	NA	0.48c	0.44c	0.73c
Intensive	0.50a	0.70a	0.65a	0.86a
P > F	***	***	**	*
Check	0.36	0.50	0.50	0.76

§ Asterisks indicate thresholds of significance (NS, $P > 0.10$, *, $P < 0.10$; **, $P < 0.05$; ***, $P < 0.001$). Check is not included in the analysis.

† Not applicable

3.4 Discussion

Across two growing seasons, the SN treatment with a nitrogen total of 179 kg N ha^{-1} split at planting and at 2-4 leaf stage yielded an average of 84 Mg ha^{-1}, 139 kg Mg^{-1}, and 11,744 kg ha^{-1}. Conversely, the all-inclusive intensive management treatment which included 194 kg N ha^{-1}, 22 kg P_2O_5 ha^{-1}, 112 kg K_2O_5 ha^{-1}, 1,440 kg Ca ha^{-1}, 18 kg S ha^{-1} and 0.15 kg B ha^{-1} resulted in 89 Mg ha^{-1}, 141 kg Mg^{-1}, and 12,534 kg ha^{-1}. Intensive management only significantly increased root yield and recoverable sucrose in 2023 by +13 Mg ha^{-1}, +7 kg Mg^{-1}, and +2,330 kg ha^{-1}, respectively, compared to SN **(Table 3.6).** The inconsistent influence of what may turn out to be prophylactic inputs on root yield and recoverable sucrose highlights the importance of pre-plant soil analysis and close weather monitoring during the cropping season for disease development.

Weather

Temperature and precipitation affect biomass production and plant development. De et al. (2019) suggested peak sugarbeet dry matter accumulation occurred at 75 DAP with 936 kg ha^{-1} day^{-1} with 93% of accumulation happening in the root under moderately alkaline, silt loam soil, irrigated conditions. Warmer air temperatures and greater precipitation at 75 DAP in 2022 (25 July) as compared to 2023 (11 July) **(Table 3.3)** likely supported additional biomass accumulation. Further, in 2022, there was a 6% greater total solar flux from June to August as compared to similar months in 2023 (data not shown). Greater 2022 biomass accumulation resulted in an improved capacity of sugarbeet leaves to capture solar radiation and when combined with greater total solar flux likely explains the comparable root yield and recoverable sucrose across fertilizer strategies except for the in-furrow P treatment which reduced stand count. Current observations are supported by a simulation model of Kenter et al. (2006) in which increasing temperature and greater radiation between planting through June increased dry matter accumulation.

Nitrogen

Except for the in-furrow P treatment, applying the university and MSC recommended N program including 45 kg N ha^{-1} at planting with the remaining N applied at the 2-4 leaf stage provided comparable root yield and recoverable sucrose across fertilizer strategies in 2022 with 90.1 Mg ha^{-1}, 13,327.9 kg ha^{-1} and 148.4 kg Mg^{-1}, respectively **(Table 3.6).** However in 2023, the SN treatment root yield and recoverable sucrose at 78.0 Mg ha^{-1}, 10,160.4 kg ha^{-1} and 130.1 kg Mg^{-1}, respectively, was significantly less than the intensive management, in-furrow P, and pre-plant broadcast lime treatments **(Table 3.6).**

In 2022, the leaf N tissue concentrations at 6-8 (*P* = 0.6985) and 20-22 (*P* = 0.2731) leaf stages were not significantly influenced by fertilizer strategy **(Table 3.11).** All plots obtained sufficient tissue N concentrations at both 6-8 and 20-22 leaf stages. Deficient leaf N concentrations from check plots began to appear at the 20-22 leaf stage (4.1%). In 2023, fertilizer treatments did not significantly influence the 6-8 leaf N concentration (*P* = 0.3703, **Table 3.12**) but was likely deficient due to early-season rainfall deficits. Alternatively, fertilizer treatments significantly impacted leaf N concentrations in 22-24 leaf stage (*P* = 0.0329). Sufficient tissue N levels occurred from all treatments at 22-24 leaf stage, but check plots were N insufficient across all 2023 sampling dates.

More rainfall in May (+68%) and June (+45%) 2022 as compared to May and June 2023 may cause the downward movement of N to the developing roots leading to sufficient tissue N concentrations in 2022. In this study, the urea-ammonium-nitrate fertilizer contained 50% urea, 25% ammonium (NH_4^+), and 25% nitrate (NO_3^-), where NH_4^+ and NO_3^- can be adsorbed by soil particles or transported by mass flow, respectively (Giehl & von Wirén, 2014). In an N-fertilized environment, the presence of precipitation and developing roots are vital since sugarbeet primarily absorbs the nitrate (NO_3^-) (Varga et al., 2022). Decreased May and June 2023 precipitation may have caused limited early root development and hindered N uptake causing tissue N deficiency at 6-8 leaf stage. Early-season drought conditions can affect developing fibrous roots leading to severely limited canopy expansion and radiation interception (Brown et al., 1987). Oppositely, July 2023, increased precipitation (+93% compared to 30-year avg.) may have caused later movement of N to the developing root resulting in sufficient tissue N levels at 22-24 leaf stage.

For the late-applied N treatment, 45 kg N ha^{-1} was applied at-plant with the remaining N split into 90 kg N and 45 kg N applied at the 2-4 leaf stage and two weeks after the initial sidedress, respectively. Due to potential negative impacts on sugar quality, the timing of N application and partitioning of sugarbeet N must be considered. De et al. (2019) reported that irrigated sugarbeet had three distinct N accumulation phases: 1) 85% of accumulated N was in aboveground biomass through 50 DAP, 2) 49% of N partitioned to the root through 84 DAP, and 3) 58% of N accumulation in aboveground biomass at 84-114 DAP. In the current study, late-season N (14 June 2022, 34 DAP and 14 June 2023, 48 DAP) was applied during the growth phase where sugarbeet was still developing canopy coverage. Few data are available for Michigan regarding later N application timings as growers fear reductions in recoverable sucrose and do not want to interfere with the possibility of early harvest which is a Michigan-centric issue. Across both years, late applied N did not significantly influence root yield or recoverable sugar **(Table 3.6).**

Phosphorus

Peak sugarbeet aboveground biomass P accumulation rates occur at 50 and 84 DAP, respectively, under irrigated moderately alkaline silt loam soil conditions (De et al., 2019). Precipitation soon after planting had a distinct impact on root yield and recoverable sucrose with APP application (7 kg N and 22 kg P_2O_5 ha^{-1}). In 2022, root yield and recoverable sugar per hectare decreased -15.5 Mg ha^{-1} and -2,325.7 kg ha^{-1}, respectively **(Table 3.6).** Lack of May 2022 precipitation decreased emergence and harvest stand counts by -19% and -15%, respectively, thus decreasing yield potential **(Table 3.5).** In-furrow P is typically applied at low rates, but the proximity to the seed increases the risk of injury regardless of application rates due to minimal opportunity for root extension beyond the concentrated zone of fertilizer salts. Sufficient rainfall and moist soil conditions heading into May 2023 (1.4 cm.) prevented early season seed damage resulting in comparable stand counts **(Table 3.5)** and greater root yield and recoverable sucrose per hectare for in-furrow P by +13.7 Mg ha^{-1} and +2,186.3 kg ha^{-1}, respectively compared to SN **(Table 3.6).** Pre-plant soil test P concentrations impact P fertilizer strategies. Sugarbeet is less likely to respond to P fertilizer application when pre-plant soil Bray P1 concentrations exceed 25 ppm (Warncke et al., 2009). Across years, pre-plant soil P concentrations were slightly above critical thresholds nearing 30 ppm Bray P1. As soil pH increases, phosphate availability decreases increasing the likelihood of sugarbeet response to P fertilizer. In 2022, fertilizer treatments did not significantly influence tissue P at 6-8 ($P = 0.742$) and 20-22 ($P = 0.1493$) leaf stages **(Table 3.11).** However, it was only at the 6-8 leaf stage that all plots, including check, exhibited sufficient tissue P levels. In 2023, although fertilizer strategy significantly influenced leaf P concentrations at 22-24 leaf stage ($P = 0.0448$) **(Table 3.12)**, tissue P values for all fertilizer strategies including check were deficient across sampling dates. Among individual added inputs, only in-furrow P increased tissue P concentrations by 0.05% compared to SN at the 22-24 leaf stage. Examples of deficient tissue P in both 2022 and 2023 cropping years highlight the impact that soil pH can have on soil P availability and plant P uptake. In soil pH > 7.5, base cations become more soluble increasing availability in the solution and cation exchange sites thus providing more opportunities for soil labile P interaction leading to the precipitation of Ca phosphates (Penn & Camberato, 2019).

Potassium

Pre-plant soil critical K concentrations are 100 and 120 ppm for coarse and fine-textured soils, respectively (Culman et al., 2020). In both 2022 and 2023, the pre-plant soil K levels were above critical thresholds (> 120 mg kg^{-1} K) thus little reason to expect a positive yield or sugar response to applied K_2O fertilizer **(Table 3.6).** Further, tissue K levels were sufficient throughout all sampling stages across both the 2022 and 2023 cropping seasons **(Tables 3.11 and 3.12).** Previous studies demonstrated that sugarbeet had a higher K demand per unit root length and was more effective in removing available soil K. Sugarbeet absorbs more K as compared to small grains. De et al. (2019) found that the K had the highest mean total accumulation at harvest with 529 kg ha^{-1} as compared to N and P with 268 and 69 kg ha^{-1}, respectively. El Dessougi et al. (2002) also reported that sugarbeet had 7-10 times higher K influx than the small grains.

Agricultural Lime

Broadcast applying agricultural lime at 4.5 MT ha^{-1} before planting significantly increased root yield (+11.9 Mg ha^{-1}) and recoverable sucrose (+8.4 kg Mg^{-1} and +2,278.0 kg Mg^{-1}) in 2023 **(Table 3.6).** Across both years, pre-plant soil pH was 7.7-7.8, a common characteristic for the highly calcareous soils of this region. Reports vary on the impacts of sugarbeet lime application on alkaline soils. Christenson et al. (2000) reported no negative effects on root or sugar yield by lime application on a silty clay to loam soil with a pH of 7.7, but Mn and Zn tissue concentrations decreased with increasing lime rate as expected. Similarly, Hubbell et al. (2001) found that recoverable sugar and quality were not significantly affected by the multiple lime rates at a soil pH of 8.0. Both Christenson et al. (2000) and Hubbell et al. (2001) were Michigan-focused studies concluding that lime may be applied up to 5 Mg ha^{-1} once every three years on alkaline soils without adverse effects on sugarbeet. At 2-4 LF, although there was a reduction in 2022 seedling emergence **(Table 3.5)** under intensive management (-11.5%) compared to SN due to the addition of in-furrow P, the incorporation of pre-plant agricultural lime promoted the precipitation of Ca phosphates, reducing the potential for greater salt damage as compared to in-furrow P individually (-19.2%). In 2022, leaf Ca, Mg, and Mn concentrations were not statistically different across fertilizer strategies for all sampling stages and were sufficient including check **(Table 3.11).** In

2023, leaf Ca, Mg, and Mn levels remained sufficient across sampling stages **(Table 3.12).** Leaf Ca level was significantly different across fertilizer treatments at the 6-8 leaf stage ($P = 0.0965$). Leaf Mg and Mn levels were comparable at 6-8 leaf stage. At 20-22 leaf stage, leaf Ca ($P = 0.0507$) and Mg ($P = 0.0927$) were significantly influenced by fertilizer treatments. Calcium is absorbed primarily by young root tips while other cations are absorbed along the entire length of the root (Clarkson et al., 1968). Further, basic cations (i.e. Na^+, K^+ and Mg^{2+}) and $CaCO_3$ dominate in the pH range 7.0–8.5 (Tavakkoli et al., 2015). Since the pre-plant soil pH is slightly alkaline (i.e. 7.7-7.8), it is possible that developing young root tips have absorbed exchangeable Ca^{2+} by mass flow due to May 2022 precipitation (4.2 cm). On the other hand, the reduced rainfall in May 2023 (-71% compared to 30-yr. May avg.) likely reduced the Ca uptake from soil exchangeable Ca pool and acquired Ca from applied pre-plant broadcast lime resulting in increased root yield and recoverable sucrose. Pre-plant broadcast lime also had more canopy development and greater NDVI values until 22-24 leaf stage in 2023, which may demonstrate the benefits of liming being carried longer into the growing season **(Table 3.10).**

Sulfur

Ammonium thiosulfate (ATS, 12-0-0-26S) was applied to supply 8.2 kg N and 17.8 kg S with the S treatment. In both 2022 and 2023 cropping seasons, the addition of sidedress ATS did not significantly influence root yield or recoverable sucrose **(Table 3.6).** Tissue S levels were sufficient in all plots including the check during 2022 **(Table 3.11).** Fertilizer treatments impacted leaf S concentrations at the 6-8 leaf stage ($P = 0.0246$), but leaf S concentrations were comparable at 20-22 leaf stage. In 2023, fertilizer treatments significantly influenced leaf S concentrations across all sampling stages **(Table 3.12).** At 6-8 leaf stage ($P < 0.0001$), intensive management and pre-plant broadcast lime increased leaf S levels by 15% and 13% respectively, compared to SN resulting in the only treatments with sufficient leaf S concentrations. The likely explanation behind sufficient tissue S levels of intensive management and pre-plant broadcast lime at 6-8 leaf stage is enhanced initial canopy and root growth promoting more uptake of available soil S. At 22-24 leaf stage ($P = 0.009$), fertilizer treatments increased leaf S concentrations except for foliar B, banded K, and late-season N. All plots including check had adequate leaf S concentrations at 22-24 leaf stage. In the current study, ATS was applied at sidedress during 2-4 leaf stage. Although ATS has been found as a reliable source of S, ATS needs to be broken down first to tetrathionate (Camberato et al., 2022).

Table 3.11. Sugarbeet tissue nutrient concentrations at 6-8 and 20-22 leaf growth stage as influenced by fertilizer strategy, Richville, MI., 2022. §

Treatment	N	P	K	Ca	Mg	S	Mn	B
	%						ppm	
	6-8 sugarbeet leaf							
Standard N (SN)	5.52	0.63	5.93	1.10	1.17	0.28c	72	26
SN + P	5.69	0.64	5.59	1.16	1.12	0.29bc	77	27
SN + Lime	6.06	0.68	4.99	0.92	0.87	0.34a	59	23
SN + S	5.89	0.72	5.67	0.90	0.90	0.33ab	72	26
Intensive	5.40	0.69	6.10	1.42	1.32	0.36a	80	29
P > F	NS	NS	NS	NS	NS	**	NS	NS
Check	4.64	0.67	6.44	1.24	0.97	0.34	67	29
Treatment	20-22 sugarbeet leaf							
SN	5.40	0.44	4.13	0.74	0.81	0.47	84	40
SN + P	5.31	0.42	4.39	0.85	0.95	0.43	87	41
SN + Lime	5.14	0.37	4.13	0.82	0.82	0.44	97	40
SN + S	5.26	0.42	4.48	0.89	1.00	0.49	102	46
SN + B	5.44	0.43	4.13	0.76	0.86	0.45	90	42
SN + K	5.42	0.44	3.94	0.69	0.74	0.45	77	39
SN + Late N	5.30	0.42	4.16	0.81	0.90	0.44	107	43
Intensive	4.99	0.38	4.58	0.87	0.91	0.47	104	45
P > F	NS	NS	NS	NS	NS	NS	NS	NS
Check	4.12	0.45	5.26	0.77	0.64	0.42	112	49
Critical Nutrient ranges	4.30-5.00¶	0.45-1.10	2.00-6.00	0.50-1.50	0.25-1.00	0.21-0.50 ‡	21-150	26-80

§ Asterisks indicate thresholds of significance (NS, P> 0.10, *, P < 0.10; **, P < 0.05; ***, P < 0.001). Check is not included in the analysis.

† Analyzed using T-tests compared with a non-treated check (NS, P> 0.10, *, P < 0.10; **, P < 0.05; ***, P < 0.001). ND – no data

¶ Mills, H. A., & Jones Jr, J. B. (1996). Plant Analysis Handbook II. Jefferson City. MO: Micro Macro Publishing Inc.

‡ Vitosh, M.L., Warncke, D.D., Lucas, R.E. (2006). E.486. Secondary and Micronutrients for Vegetables and Field Crops. Michigan State University.

Table 3.12. Nutrient concentration at 6-8 and 22-24 sugarbeet leaf tissue as influenced by the multiple fertilizer strategy, Richville, MI., 2023. §

	N	P	K	Ca	Mg	S	Mn	B
	%						ppm	
Treatment	6-8 sugarbeet leaf							
Standard N (SN)	3.86	0.21	5.37a	1.51b	1.78	0.18b	79	40ab
SN + P	4.13	0.24	3.98b	1.60b	1.74	0.20b	101	42a
SN + Lime	4.10	0.16	4.84a	1.82ab	1.85	0.31a	85	37c
SN + S	3.84	0.22	5.37a	1.54b	1.72	0.18b	86	39bc
Intensive	4.23	0.20	4.02b	1.95a	1.94	0.33a	86	40ab
P > F	NS	NS	**	*	NS	***	NS	*
Check	3.51	0.27	6.31	1.55	1.44	0.27	109	40.50
Treatment	22-24 sugarbeet leaf							
SN	4.57bcd	0.26b	5.29a	1.61bc	1.75a	0.36d	174	37c
SN + P	4.76a	0.31a	4.77c	1.70abc	1.54abc	0.39bc	205	38c
SN + Lime	4.51cd	0.25b	5.06ab	1.76ab	1.57ab	0.40b	190	36c
SN + S	4.70ab	0.26b	5.01abc	1.52c	1.68ab	0.39bc	177	37c
SN + B	4.69ab	0.25b	5.02abc	1.58bc	1.44bc	0.38bcd	182	45b
SN + K	4.48d	0.26b	4.80bc	1.48c	1.29c	037cd	182	37c
SN + Late N	4.68abc	0.28ab	5.07ab	1.51c	1.50abc	0.38bcd	170	37c
Intensive	4.82a	0.30a	4.48d	1.92a	1.74a	0.43a	192	57a
P > F	**	**	**	*	*	***	NS	***
Check	4.18	0.33	5.67	1.31	0.96	0.42	194	42
Critical nutrient ranges ¶	4.30-5.00	0.45-1.10	2.00-6.00	0.50-1.50	0.25-1.00	0.21-0.50 ‡	21-150	26-80

§ Asterisks indicate thresholds of significance (NS, P> 0.10, *, P < 0.10; **, P < 0.05; ***, P < 0.001). Check is not included in the analysis.

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‡ Vitosh, M.L., Warncke, D.D., Lucas, R.E. (2006). E.486. Secondary and Micronutrients for Vegetables and Field Crops. Michigan State University.

The conversion of tetrathionate to sulfate is critical for plant S absorption (Camberato et al., 2022). Deficit precipitation in May (-71%) and June (-55%) 2023, compared to 30-yr. avg., may have delayed the conversion of tetrathionate to sulfate. This delay could potentially explain the lack of influence of sidedress ATS application (31 May 2023) at 6-8 leaf stage. Alternatively, precipitation in July 2023 (+93%) could accelerate tetrathionate to sulfate conversion leading to increased 22-24 leaf S concentrations on ATS-applied plots.

Sugarbeet also has deep rooting characteristics that may better exploit soil resources. According to Czaban et al. (2023), intercropping of sugarbeet and chicory *(Cichorium intybus var. foliosum)* resulted in the greatest root growth, extending from 98 ± 48 to 304 ± 28 cm depth and enhanced the N, Mg, Mn, Zn, and Na uptake of sugarbeet. Michigan has a diverse cropping system including rotation of sugarbeet with corn and winter wheat both of which tend to be S responsive. Corn and winter wheat require 17 and 28 kg SO_4^{2-} ha, respectively (Camberato et al., 2022). Hence, continuous S application may result in S accumulation at deeper soil depths with later absorption by more deeply rooted sugarbeet. Although each cropping year was analyzed individually, 13% greater root yield in 2022 accentuated the scavenging ability of sugarbeet demonstrated by sufficient tissue S levels compared to 2023. Taken together, observations suggest that a more developed rooting system offers more opportunity for nutrient scavenging thereby promoting root yield.

Boron

Pre-plant critical soil B concentration is 0.7 ppm (Warncke et al., 2009). In 2022, the pre-plant soil B concentration was above critical at 0.8 ppm. In Michigan, modern sugar beet varieties may not require supplemental B under fine-textured soils eliminating the need for B fertilizer (Warncke et al., 2009). However, Warncke et al. (2009) recommended 1.1 kg ha^{-1} and 2.2 kg ha^{-1} B rates on fine-textured and coarse-textured soils where sugarbeet exhibited B deficiency. Sodium borate (16.5% B, 0.15 kg B ha^{-1}) was applied as a weekly foliar spray application in July 2022 and July 2023 as a B source. In both 2022 and 2023 cropping seasons, the application of foliar B did not significantly influence root yield or recoverable sucrose **(Table 3.6).** Across years, tissue B concentrations remained > 26 ppm indicating sufficiency **(Tables 3.11 and 3.12).**

Cercospora leaf spot is one of the most destructive foliar pathogens impacting sugarbeet production worldwide (Weiland & Koch, 2004). Primary inoculum of *C. beticola* in sugarbeet is distributed from asexual conidia on plant residue through wind dispersal of spores where spores transfer to the leaf surface, hyphae elongate and infect via stomates (Khan et al., 2009; Weiland & Koch, 2004). CLS is a polycyclic disease, with several rounds of infection occurring in a single growing season when weather permits (Franc, 2010). Therefore, farmers should use integrated pest management practices to minimize fungicide resistance. In this study, prevention of CLS heavily relied on weekly standard fungicide applications while foliar B was applied to complement and possibly enhance fungicide leaf protection. Since key roles of B in cell wall structure and plasma membrane integrity are directly impacted by *C. beticola* colonization and necrotrophic disruption, foliar B application may protect newly emerged leaves against CLS infection. Aside from the presence of *C. beticola* spores, relative humidity is vital to CLS infection. Relative humidity above 87% worsens the CLS infection (Khan et al., 2007). In both 2022 and 2023 cropping seasons, monthly relative humidity was below 87% (data not shown) thus reducing CLS infection rates and limiting the potential influence of foliar B on root yield and recoverable sugar.

3.5 Conclusion

Our results demonstrate the inconsistent influence of intensive management for improved sugarbeet root yield, recoverable sucrose, and economic benefit to the producer. Root yield and recoverable sugar were only increased by intensive management in 2023 but would be considered not profitable due to high treatment costs. Conversely, the early-season added fertilizers (in-furrow P or pre-plant agricultural lime) increased root yield and recoverable sugar; thereby improving the potential profitability. Spring weather and pre-plant soil conditions played significant roles in successful early season added fertilization. The presence of precipitation (1.4 cm) and critical soil P level (Olsen P 20 mg kg^{-1}) due to pre-plant soil alkaline conditions had a positive influence on the effects of in-furrow P. Oppositely, 2022 lacked rainfall after the in-furrow P application which may have reduced stand count emergence and therefore, decreased root yield and recoverable sugar. Under slightly alkaline soil conditions, the limited influence of pre-plant broadcast agricultural lime on root yield and recoverable sugar with leaf P deficiency demonstrates the variable impacts of continuous liming leading to nutrient imbalance. Results also appear to provide continued support for the use of the university’s N recommendation, crop scouting, and planting CR+ resistant varieties. Disease outbreak modeling tools such as the BEETcast™ can be used to monitor Disease Severity Values (DSV’s) and help determine the risk factor of sugarbeet fields for CLS.

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