Fertilizer, Fungicide, and Food: Improving Wheat Yield, Straw, and Quality

2023 Report to the Michigan Wheat Program

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Location: Lansing, MI	**Pre-plant soil** Foll. silage corn: soil pH 7.2, OM 1.8%, 8.2 CEC, 55ppm Bray P, 68ppm K Foll. soybean: soil pH 7.8, OM 1.8%, 16.2 CEC, 142ppm Bray P, 96ppm K
Planting Date Foll. silage corn: 30 Sept. 2022 Foll. soybean: 04 Oct. 2022	**Treatments:** see Table 1
Harvesting Foll. silage corn: 10 July 2023 Foll. soybean: 10 July 2023	**Replications:** 4
Variety and Population: SRWW 'Wharf' at 1.8 million seeds A^{-1}	**Tillage:** Conventional

INTRODUCTION

In Michigan, winter wheat (*Triticum aestivum* L.) is the third most planted annual row crop (*FAOSTAT*, n.d.). Despite Michigan's higher yield of 5.5 Mg ha^{-1} surpassing the U.S. average of 3.12 Mg ha^{-1} (USDA NASS, 2022), planted area decreased by about 24% to 190 thousand ha with production down by nearly 22.5% to 940 thousand MT (USDA NASS, 2022). Grain yield can widely vary in Michigan from year to year, and production practices can play an essential role in mitigating seasonal yield variability. The current state guidelines for winter wheat management include 45-135 kg N ha^{-1} top-dressed at green-up (Warncke & Nagelkirk, 2010) and foliar fungicide 5 to 6 days following early flowering or Feekes [FK] 10.5.1 stage against Fusarium head blight (FHB) (*Fusarium graminearum* Schwabe [telemorph *Giberella zea* (Schweinit) Petz] (Nagelkirk & Chilvers, 2019). Given the rising demand for wheat and climate uncertainties, Michigan growers are increasingly exploring intensive management strategies for greater yield and economic benefits. This study compared current and intensive management (IM) with autumn starter fertilizer, multiple fungicide timing applications, and late-season nitrogen at FK 7.

Intensive management (IM) includes manipulating agronomic inputs to address yield-limiting factors (Harms et al., 1989). Studies indicate intensive management can result in greater grain yield and quality possibly due to synergistic interactions among added inputs. In Michigan, applying foliar fungicide at FK 10.5.1 increased yield by up to 0.75 Mg ha^{-1} (Quinn & Steinke, 2019a). Conversely, omitting fungicide at FK 6 and 10.5.1 in a high-disease environment reduced yield by 1 Mg ha^{-1} in Kansas (De Oliveira Silva et al., 2021). Applying 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 FK 10.4, increased grain yield and aboveground biomass in irrigated Kansas fields (Jaenisch et al., 2022). In Ohio, implementing high seeding rates, split N rates at FK 3-4 and FK 5-6, 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 1.2–1.2 MT ha^{-1} (Roth et al., 2021). While literature suggests IM can boost winter wheat grain yield potential, profitability can be influenced by fluctuating grain prices and input costs (Peterson et al., 2023; Steinke et al., 2021). The absence of yield-limiting factors such as disease susceptibility, pre-plant nutrient deficiencies, and lodging might eliminate the benefits of multiple agronomic inputs (De Oliveira Silva et al., 2021; Karlen & Gooden, 1990; Knott et al., 2016; Mohamed et al., 1990; Quinn & Steinke, 2019b). Therefore careful selection of agronomic inputs is crucial to address production challenges and optimize economic returns.

Applying autumn starter fertilizer is a crucial decision for wheat growers each planting season. Starter fertilizer is applied near the planted seeds to improve the early growth of seedlings. The benefits of starter fertilizer in crop production have been recognized for years (Niehues et al., 2004; Purucker & Steinke, 2020; Winters, 2015). In Midwest states, studies have highlighted the advantages of autumn nutrient application in winter wheat. The use of 280 kg ha^{-1} starter fertilizer containing N, P, S, and Zn increased grain yield by 0.6-1.7 kg ha^{-1}, as well as tiller and head production under low-input management (Steinke et al., 2021). Across different 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} (Maeoka et al., 2020). Planting with 224 kg of mono-ammonium phosphate (11-52-0) alongside 112 kg N ha^{-1} spring N fertilizer improved phytomass and fertile tillers, 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 (Maeoka et al., 2020), ensuring an optimal start for initial yield potential becomes critical to capitalize on the mid-season environment.

Plant fungal pathogens significantly impact wheat yield and quality (McGrath, 2004) causing 15-20% annual yield losses (Figueroa et al., 2018). Farmers use fungicides to enhance yield and quality, but deciding when and how to apply them is complex. While fungicide benefits are recognized, costs and wheat prices affect spraying decisions. The current recommendations advise applying fungicides from anthesis to six post-anthesis (PAA) to control Fusarium head blight (Bolanos-Carriel et al., 2020; Ransom & McMullen, 2008; Singh et al., 2021). Nonetheless, the potential early and mid-season foliar fungal diseases raise questions about the pre-anthesis fungicide need. Standard pre-anthesis foliar fungicide spraying typically takes place between flag leaf emergence (FK 8) and heading (FK 10.5) to preserve flag leaf health and extend greenness. Previous research explored various fungicide timing programs, from early season (FK 4-7) to anthesis (FK 10.5.1). A split application of propiconazole at FK 4-5 and FK 9 yielded a 13.22% increase in yield compared to untreated 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, consistently reduced disease severity and increased yield (Milus, 1994). Using prothioconazole at FK 6, 9, and 10.5.2 decreased FHB and deoxynivalenol (DON) by 97% and 83%, respectively, compared to untreated plots (Edwards & Godley, 2010). A meta-analysis of Breunig et al., (2022), showed that applying fungicides at FK 5 to 7 and FK 10.5.1 produced the highest mean yield response of 0.71 Mg ha^{-1} compared to non-treated checks in Michigan. These studies highlight the potential for disease control during the early and mid-season stages of winter wheat.

OBJECTIVE AND HYPOTHESES

Although previous studies have shown that additional inputs can individually improve the yield of winter wheat, little research has been done on the combined effects of early nutrient source and late-season N fertilizer with multiple fungicide sprays. Additionally, studies about their influence on grain nutritive quality are limited. Our objectives were: (i) to evaluate soft red winter wheat grain and straw yield response to autumn-applied starter fertilizer, multiple fungicide application timings, and late-season N at FK 7 in fields following silage corn and soybean, (ii) determine the influence of autumn applied starter fertilizer and late season N on the nutritive quality of soft red winter wheat, and (iii) determine whether correlations exist between in-season agronomic components, flag leaf tissue nutrient concentrations, or grain quality with grain yield, protein content, and straw yield.

Materials and Methods

Field studies were established in Lansing, MI on a Conover loam soil (Fine-loamy, mixed, active, mesic Aquic Hapludalfs) following silage corn (SC) and soybean (SB) during the 2022-2023 growing season. Soft red winter wheat 'Wharf', a short-strawed, high-yielding variety

(Michigan Crop Improvement Association, Okemos, MI), was planted following SC (30 September 2022) and SB (04 October 2022). Treatments were arranged in a full factorial, randomized complete block design with three experimental factors across four replications (2×5×2). Experimental factors included two levels of autumn starter (AS) (12-40-0-10-1, N-P-K-S-Zn) (0 and 250 lb AS A^{-1}) applied at planting, five levels of fungicide timing (FT) (none, FK 5-7 and 10.5.1 (early, late), FK 9 and 10.5.1 (mid-season, late), FK 10.5.1 individually (late), and FK 5-7, 9 and 10.5.1 (early, mid-season, late)) and two levels of late-season N (LN) (0 and 30 lb N A^{-1}) applied at FK 7. All treatments received a base green-up N application of 100 and 75 lb N A^{-1} at FK 5 following SC and SB, respectively, except for the non-treated check. The pre-planting and spring soil characteristics of SC and SB are summarized in Table 2.

Preliminary Results (2022-2023)

Environmental Condition. The 2022-2023 weather conditions included a warm, dry autumn followed by a warm, wet winter with increased March 2023 precipitation (+127%). April conditions were wet early followed by reduced May 2023 rainfall (-80%). Dry conditions continued into summer with -76% and -42% below the 30-year average June and July rainfall, respectively (Table 3), resulting in a narrowed grain-filling growth stage.

Pre-plant and spring soil characteristics Pre-plant soil test levels can be a reliable indicator for fertilizer recommendations and likelihood for plant response. In SC 2023, pre-plant soil characteristics were 7.2 soil pH, 4 NO_3-N kg^{-1} soil, above-critical Bray P1 (55 ppm) and Zn (2.5 ppm) levels with below critical K level (68 ppm) (Table 2). The 2023 spring nitrate levels were 2.0 and 3.75 NO_3-N kg^{-1} soil in non- and with autumn starter fertilizer plots, respectively (Table 2). In SB 2023, pre-plant soil characteristics were slightly alkaline soil pH (7.8), 5 NO_3-N kg^{-1} soil, above-critical Bray P1 (142 ppm), and Zn (6.1 ppm) levels with below critical K level (96 ppm) (Table 2). The 2023 spring nitrate levels were 1.75 and 2.0 NO_3-N kg^{-1} soil in non- and with autumn starter fertilizer plots, respectively (Table 2). High pre-plant Bray P-1 levels in both sites reduced the likelihood of yield response to P application from the autumn starter fertilizer.

Grain Yield, Nutritive Quality, and Straw Yield. Following SC, grain yield ranged from 33.1 – 115.2 bu. A^{-1} with a mean of 90.0 bu. A^{-1}. An interaction between AS and FT significantly affected SC grain yield (Table 4, $p = 0.0682$). Across FT, AS consistently increased mean grain yield by 20.8 – 38.2 bu. A^{-1}. Conversely, FT only had a significant effect on mean grain yield with no AS and no fungicide (84.7 bu. A^{-1}) as compared to fungicide applications at FK 5-7 and 10.5.1 (67.3 bu. A^{-1}). The interaction between AS and LN significantly influenced grain protein content (Table 6, $p = 0.038$). With AS application, LN increased grain protein content. Straw yield ranged from 0.2 – 1.8 T A^{-1} with a mean of 1.1 T A^{-1}. Only AS had a significant influence on mean straw yield with 0.6 T A^{-1} greater than no AS (Table 5, $p < 0.0001$).

Following SB, grain yield ranged from 57.3 – 134.8 bu. A^{-1} with a mean of 103.3 bu. A^{-1}. Neither AS ($p = 0.1544$), FT ($p = 0.8609$), or LN ($p = 0.7767$) significantly influenced grain yield. Grain protein content was significantly affected by AS and LN main effects. AS and LN improved mean grain protein content by 0.3% ($p = 0.0109$) and 0.8% ($p < 0.0001$), respectively (Table 7). Straw yield ranged from 0.3 – 2.3 T A^{-1} with an average of 1.2 T A^{-1}. Autumn starter increased mean straw yield by 0.3 T A^{-1} when compared to no AS (Table 5, $p < 0.0001$).

Potential Economic Profitability. Traditional treatment is defined as green-up N application of 100 and 75 lb N A^{-1} in SC and SB during FK 5, respectively, and late-season fungicide spray at FK 10.5.1. In SC, the mean grain and grain + straw potential economic profitability (PEP) of traditional treatment (GRNUP + L) were USD 456.49 and USD 566.69, respectively. Without late-fungicide spray at FK 10.5.1, the addition of AS increased mean grain PEP by USD 95.20 ($p = 0.0452$). Meanwhile, incorporating multiple fungicide spray programs and LN decreased grain PEP by USD 98.25 – 156.58 ($p = 0.0014 – 0.0389$). AS increased grain + straw PEP by USD 111.20 – 158.99, regardless of mid-season fungicide spray at FK 9 ($p = 0.0738 – 0.0117$). Incorporating additional early (FK 5-7) and mid-season (FK 9) fungicide spray with LN reduced grain + straw PEP by USD 111.05 – 171.09 ($p = 0.0069 – 0.0742$).

In SB, the mean grain and grain + straw PEP of traditional treatment (GRNUP + L) were USD 606.69 and USD 768.78, respectively. The addition of AS with LN or multiple fungicide spray at FK 5-7 or 9 reduced grain PEP by USD 129.33 – 188.70 ($p = 0.0075 – 0.0624$). Further, the addition of AS with mid-season fungicide spray at FK 9 decreased grain + straw PEP by USD 185.89 ($p = 0.03$).

Discussion

Impact of weather on the growth and development of winter wheat

The phenological phases of winter wheat are strongly related to temperature trends (Xiao et al., 2015). As winter wheat root systems develop minimally at 5 °C (41 °F) (Equiza et al., 2001), supplying early nutrients near seedlings before dormancy becomes critical. Notably, the impact of autumn starter was more pronounced in the 2022-2023 season, enhancing spring tiller production (Table 8), canopy coverage, and green vegetation for both SC and SB at FK 3 and 5 stages.

The role of precipitation is crucial alongside temperature for later wheat stages. Lower temperatures and adequate moisture from heading to grain-filling phases ensure prolonged growth, robust grain set, and development (Farooq et al., 2014; Xiao et al., 2015). The warm June and July of 2023, with deviations of -76% and -42% from the 30-year average precipitation, respectively (Table 3), resulted in a shortened grain-filling period. This coincides with Shah and Paulsen, (2003) that drought and higher temperature lowered photosynthesis rate, reduced shoot and grain mass, and decreased kernel weight during the grain-filling phase. Similarly, heat stress during anthesis or grain-filling stages decreased the photosynthesis rate by 17-25%, causing 29-44% lower grain yield (Djanaguiraman et al., 2020).

Influence of autumn starter on yield and agronomic components.

Tillering and headcount. One of the benefits of the autumn starter application was increased spring tiller density. In SC, tiller density ranged from 62 – 233 tillers ft^{-2}, with an average of 161 tillers ft^{-2}. In SB, tiller density ranged from 146 – 386 tillers ft^{-2}, with an average of 232 tillers ft^{-2}. Autumn starter increased tiller density in SC and SB by 35% ($p < 0.0001$) and 27% ($p = 0.0002$), respectively (Table 8). However, only in SC, did tiller density have a moderate positive influence on grain yield ($r = 0.60$, Table 10).

Tiller production helps determine the potential headcount. In SC, headcount ranged from 37 – 102 spikes ft^{-2} with a mean of 67 spikes ft^{-2}. In SB, headcount ranged from 48 – 150 spikes ft^{-2} with a mean of 83 spikes ft^{-2}. Autumn starter increased headcount 31% ($p < 0.0001$) and 23% ($p < 0.0001$), following SC and SB, respectively (Table 9). Consequently, headcount exerted a moderate positive influence on grain yield (SC $r = 0.63$, SB $r = 0.42$, Table 10). Results align with Quinn and Steinke (2019) where both tiller and head production were enhanced by the application of autumn starter in a low-input management system. The minimal influence of tiller density on grain yield highlights the significance of tiller survival to develop into productive wheat heads later in the season.

Head length. 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. Autumn starter increased the mean head length at both sites (SC $p < 0.0001$, SB $p < 0.0001$, Table 9). However, only in SC did head length have a moderate positive influence on grain yield ($r = 0.62$, Table 10). According to Broeske et al., (2020), the number of spikes per head is determined at FK 5. Early nutrient application offers the potential for greater stem elongation, especially in unfavorable mid-season environments such as hot and dry May – June 2023 weather conditions that resulted in a shorter grain-filling period.

Plant height and straw yield. Autumn starter increased mean plant height. Autumn starter increased plant height by 14% ($p < 0.0001$) and 1% ($p = 0.0549$) following SC and SB, respectively (Table 9). Consequently, plant height exerted a moderate to strong positive influence on straw yield (SC $r = 0.82$, SB $r = 0.57$, Table 10).

The positive correlation between straw yield and plant height demonstrates the influence of stem elongation during straw accumulation. The active growing stage of wheat starts at FK 5 when leaf sheaths are fully elongated and pseudostems are strongly erect up abd extends until FK 10 when the head is visible in the leaf sheath (Broeske et al., 2020). Rapid N uptake begins at FK 5 to 7 (Waldren & Flowerday, 1979). The early nutrient application promoted N uptake and improved stem elongation translating into enhanced straw production.

Flag leaf S concentration. Flag leaf tissue S concentrations ranged from 0.15 – 0.42% in 2023. Autumn starter significantly influenced flag leaf S concentration across both sites. AS increased flag leaf S concentrations both in SC ($p <0.0001$) and SB ($p <0.0001$). Previous studies reported a positive relationship between N and S in improving physiological attributes, yield components, nutrient uptake, and nutritional quality (Carciochi et al., 2020; Coolong & Randle, 2003; Randall et al., 1981; Salvagiotti & Miralles, 2008). In this study, the application of autumn starter provided 30 lb N and 25 lb S assisted in developing canopy and leaf area coverage from Feekes 3 to 10.5.1.

During the growing season, a wider-sized flag leaf with horizontal orientation on AS-applied plots was observed. Wider and larger flag leaves might have promoted greater photosynthetic capacity, hence increased grain yield. Previous literature reported that wheat is a more S-responsive crop than corn and sugarbeets. A multi-crop trial of Goyal et al., (2021) reported that spring wheat had a positive response to ATS with 5.44 MT ha^{-1} (5.44 Mg ha^{-1}) grain yield. Also, N and S application improved the 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 concentration exerting a moderate to strong positive influence in grain yield (SC 2023 $r = 0.84$, SB 2023 $r = 0.49$, Table 10).

Influence of late-season N at Feekes 7 on flag leaf N, grain N, and protein content.

As a yield-limiting nutrient, insufficient N application risks suboptimal photosynthetic capacity leading to lower grain yield potential while excessive N fertilizer may result in over-application, environmental contamination, and reduced profitability. Early N application promotes yield component formation while later N fertilization often boosts post-yield parameters such as grain protein content.

In the current study, the main effects of late-season N at FK 7 improved mean grain protein content following soybean ($p < 0.0001$) where autumn starter had less impact on tiller counts. Late-season N interacted with autumn starter ($p = 0.038$) following silage corn where tiller counts were more affected than following soybean. Results may indicate that where autumn starter had greater impacts on tiller counts, LN increased protein due to N dilution across a greater number of spikes. Conversely, where LN was not applied, AS may have decreased protein content also due to growth dilution across a greater number of spikes. Previous studies observed variability regarding the influence of late-season applied N on grain yield, nutrient concentration, and quality (De Oliveira Silva et al., 2021; Sowers et al., 1994). This can be attributed to low N fertilizer recovery of wheat ranging from 30-50% (Raun et al., 2002) and increases at anthesis from 55 to 80% in irrigated wheat (Wuest & Cassman, 1992) which demonstrates that the late N can be supplemented with available soil moisture.

Flag leaf N and grain N concentrations were measured at FK 9 and harvest, respectively. The interaction between late-season N and autumn starter significantly influenced flag leaf N concentration (SC $p = 0.0802$, SB $p = 0.0035$). Late-season N increased flag leaf N when autumn starter was applied. The flag leaf contributes 30-50% of assimilates for grain filling (Sylvester-Bradley et al., 1990), and its longevity correlates with grain protein accumulation (Blake et al., 2007). Flag leaf N content had a moderate positive influence on grain protein content only in SB (SB $r = 0.45$, Table 10). Late-season N also increased grain N content (SC $p < 0.0001$, SB $p <$

0.0001). Further, grain N content had a strong positive influence on grain protein content (SC r = 0.87, SB r = 0.93). This result was supported by Waldren and Flowerday (1979) that the N accumulation peaks at the grain-filling stage with 70% of N uptake going into the grain.

Influence of multiple fungicide applications on foliar fungal disease development

Following silage corn, autumn starter and late-season N had a significant interaction on the FHB index ($p = 0.066$). The absence of autumn starter and late-season N provided the highest FHB index at 0.25. In assessing the FHB index, incidence and severity are necessary in determining FHB infection. Although incidence is easier and quicker to measure, determining severity might be prone to the assessor's subjective observation. Hence quantitative and objective parameters such as Deoxynivalenol (DON) analysis are critical. This study has not detected DON accumulation across any site year (DON < 0.05 ppm) translating to the limited FHB infection.

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 of 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 demonstrates the influence of pre- and during anthesis weather in FHB development. Moist, warm 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). In this research, the lower precipitation during anthesis (June 2023, -76% as compared to the 30-year average) is a likely explanation for the reduced opportunity for FHB infection.

The presence of flag leaf disease at FK 10.5.4 was also measured. Autumn starter increased the flag leaf disease presence at FK 10.5.4 except in the field following soybean (SC 2023 $p = 0.0009$). In the 2021-2023 cropping seasons, viral cereal diseases such as wheat streak mosaic and barley yellow dwarf were confirmed. Wheat streak mosaic virus (WSMV) causes wheat streak mosaic to be transmitted by wheat curl mites (*Aceria tosichella*) (Singh et al., 2018) while Barley yellow dwarf virus (BYDV) is persistently transmitted by grass-feeding aphids (Walls III et al., 2019). In this study, viral diseases were not included in the scope of disease assessment. Nonetheless, the unforeseen occurrence of foliar viral diseases underlined the importance of field scouting for appropriate disease control.

Table 1. Overview of the complete three-level (2x5x2) factorial structure, treatment names, and inputs to winter wheat, Lansing, MI, 2022-2023.

		Agronomic inputs applied				
Treatment	Treatment name ††	Autumn starter (AS) †	Fungicide			Late N (LN) #
			Early (E) ‡	Mid (M) §	Late (L) ¶	
1	GRNUP	No	No	No	No	No
2	GRNUP + LN	No	No	No	No	Yes
3	GRNUP + E + L	No	Yes	No	Yes	No
4	GRNUP + E + L + LN	No	Yes	No	Yes	Yes
5	GRNUP + L	No	No	No	Yes	No
6	GRNUP + L + LN	No	No	No	Yes	Yes
7	GRNUP + M + L	No	No	Yes	Yes	No
8	GRNUP + M + L	No	No	Yes	Yes	Yes
9	GRNUP + E + M + L	No	Yes	Yes	Yes	No
10	GRNUP + E + M + L + LN	No	Yes	Yes	Yes	Yes
11	AS + GRNUP	Yes	No	No	No	No
12	AS+ GRNUP + LN	Yes	No	No	No	Yes
13	AS + GRNUP + E + L	Yes	Yes	No	Yes	No
14	AS + GRNUP + E + L + LN	Yes	Yes	No	Yes	Yes
15	AS + GRNUP + L	Yes	No	No	Yes	No
16	AS + GRNUP + L + LN	Yes	No	No	Yes	Yes
17	AS + GRNUP + M + L	Yes	No	Yes	Yes	No
18	AS + GRNUP + M + L	Yes	No	Yes	Yes	Yes
19	AS + GRNUP + E + M + L	Yes	Yes	Yes	Yes	No
20	AS + GRNUP + E + M + L + LN	Yes	Yes	Yes	Yes	Yes
21	Non-treated check	No	No	No	No	No

† Autumn starter (12-40-0-10-1, N-P-K-S-Zn) applied at a rate of 250 lbs A^{-1} at F1 – F2 stages.

‡ Early fungicide spray (propiconazole) applied at a rate of 4 fl oz A^{-1} at F5-7 stage.

§ Mid fungicide spray (pyraclostrobin) applied at a rate of 7 fl oz A^{-1} at F9 stage.

¶ Late fungicide spray (pydiflumetofen + propiconazole) applied at a rate of 13.7 fl oz A^{-1} at F10.5.1 stage.

Late-season nitrogen was applied at a rate of 30 lb A^{-1} at the F7 stage.

†† All plots except the nontreated check plot received spring N or green-up application at a rate of 75 and 100 lbs A^{-1} in fields following soybean and silage corn, respectively at the F5 stage.

Table 2. Site description, soil chemical properties and mean P, K, S, and Zn nutrient concentrations (0 – 8 inches) obtained before winter wheat planting and spring soil nitrate levels (0 – 12 inches) before green-up application at Feekes 5, fields following silage corn and soybean, Lansing, MI, 2022-2023.

									Soil Nitrate	
		Soil pH	OM	P	K	S	Zn	CEC	Pre-plant	Spring
Site	Soil Description		g kg^{-1}	————ppm———				meq 100g^{-1}	—NO_3-N kg^{-1} soil—	
Foll. silage corn	Fine-loamy, mixed, active, mesic *Aquic Hapludalfs*	7.2	18	55	68	12	2.5	8.2	4	No AS: 2.0 AS †: 3.75
Mehlich-3 ≠		neutral		74 (30)	(120)		(2)			
Foll. soybean	Fine-loamy, mixed, active, mesic *Aquic Hapludalfs*	7.8	18	142	96	9	6.1	16.2	5	No AS: 1.75 AS: 2.0
Mehlich-3 ≠		slightly alkaline		192 (30)	(120)		(2)			

† Autumn starter (12-40-0-10-1, N-P-K-S-Zn) applied at a rate of 250 lb A^{-1} at planting.

≠ Conversions of soil analyses into Mehlich-3 values: Culman, et al., 2019. Converting between Mehlich-3, Bray P, and Ammonium Acetate Soil Test Values. https://www.canr.msu.edu/soilfertility/Files/Bulletins/Bray%20to%20Mehlich%20conversion.pdf. (Accessed 09 Dec. 2022). Soil test values in parentheses represent critical values. Bulletin 974: Tri-State Fertilizer Recommendations, pp. 28, 41

Table 3. Monthly minimum and maximum air temperature as well as precipitation data from environwether.msu.edu observed at MSU Horticulture Teaching and Research Center station (2022-2023) and 30-year minimum air temperature avg compiled from NOAA data observed 1991-2020 at East Lansing, MI.

	Establishment & Fall Season		Winter Season				Active Growing & Flowering		Grain Filling - Harvest	
Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar	Apr.	May.	Jun.	Jul.
	———	———	———	———	minimum °F	———	———	———	———	———
2022-2023	37.9	30.2	24.1	25.8	22.6	26.8	36.6	43.0	52.6	61.7
30-yr.avg.	41.5	32.2	23.5	17.5	18.8	27.2	37.3	48.4	57.6	61.2
	———	———	———	———	maximum °F	———	———	———	———	———
2022-2023	62.6	50.2	35.4	35.8	39.2	43.9	59.9	71.7	79.7	83.1
30-yr.avg.	61.6	48.2	37.1	31.8	34.4	44.9	57.7	70.2	79.4	83.0
	———	———	———	———	inches	———	———	———	———	———
2022-2023	1.78	0.52	0.56	1.10	2.10	3.83	2.88	0.89	0.90	1.95
30-yr.avg.	3.12	2.55	1.60	2.08	1.60	1.68	3.55	4.36	3.79	3.37

Table 4. Interaction of autumn starter (12-40-0-10-1, N-P-K-S-Zn) and fungicide timing on grain yield (bu A^{-1}) in the field following silage corn, Lansing, MI., 2022-2023.

	Grain Yield §		
	Autumn Starter		
Treatment	0 lb AS A^{-1}	250 lb AS A^{-1}	
Fungicide Timing	——bu A^{-1}——		P > F †
No fungicide	84.7aB	108.5aA	***
Feekes 5-7, 10.5.1	67.3cB	105.5aA	***
Feekes 10.5.1	84.5aB	107.0aA	***
Feekes 9, 10.5.1	75.4bcB	108.5aA	***
Feekes 5-7, 9, 10.5.1	81.4abB	102.3aA	***
P > F #	**	ns	
Nontreated check	38.9		

§ Treatments were compared at 0.10 probability level, Fisher's least significant difference (LSD). Asterisks indicate thresholds of significance (ns, $P > 0.10$; *, $P < 0.10$; **, $P < 0.05$; ***, $P < 0.001$). Nontreated 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, $P < 0.10$).

Table 5. Mean straw yield (T A^{-1}) as influenced by autumn starter (12-40-0-10-1, N-P-K-S-Zn) in fields following silage corn (SC) and following soybean (SB), Lansing, MI., 2022-2023.

	Straw Yield §	
Treatment	SC	SB
Autumn Starter Fertilizer	——T A^{-1}——	
0 lb AS A^{-1}	0.8b	1.1b
250 lb AS A^{-1}	1.4a	1.4a
P > F	***	***
Nontreated check	0.3	0.5

§ 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, $P > 0.10$; *, $P < 0.10$; **, $P < 0.05$; ***, $P < 0.001$). Nontreated check is not included in the analysis.

Table 6. Interaction of autumn starter (12-40-0-10-1, N-P-K-S-Zn) and late-season nitrogen on grain protein content (%) in the field following silage corn, Lansing, MI., 2022-2023.

	Grain Protein §		
	Late-season Nitrogen		
Treatment	0 lb N A^{-1}	30 lb N A^{-1}	
Autumn Starter Fertilizer	%		P > F †
0 lb AS A^{-1}	10.7aA	10.9aA	ns
250 lb AS A^{-1}	10.0bB	10.7aA	**
P > F #	**	ns	
Nontreated check	8.8		

§ Treatments were compared at 0.10 probability level, Fisher's least significant difference (LSD). Asterisks indicate thresholds of significance (ns, $P > 0.10$; *, $P < 0.10$; **, $P < 0.05$; ***, $P < 0.001$). Nontreated 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, $P < 0.10$).

Table 7. Mean grain protein content (%) as influenced by autumn starter (12-40-0-10-1, N-P-K-S-Zn) and late-season applied nitrogen in the field following soybean, Lansing, MI, 2022-2023§.

Treatment	Grain Protein §
Autumn Starter Fertilizer	%
0 lb AS A^{-1}	10.6b
250 lb AS A^{-1}	10.9a
P > F	**
Late-season Nitrogen	
0 lb N A^{-1}	10.4b
30 lb N A^{-1}	11.2a
P > F	***
Nontreated check	9.0

§ 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, $P > 0.10$; *, $P < 0.10$; **, $P < 0.05$; ***, $P < 0.001$). Nontreated check is not included in the analysis

Table 8. Influence of autumn starter fertilizer (12-40-0-10S-1Zn) on Feekes 4 mean tiller production (tillers ft^{-2}), in fields following silage corn and following soybean, Lansing, MI., 2022-2023. §

Treatment	SC 2023	SB 2023
Autumn Starter Fertilizer	tillers ft^{-2}	
0 lb AS A^{-1}	137b	204b
250 lb AS A^{-1}	185a	260a
P > F	***	**
Non-treated check	123	216

§ 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). Nontreated check is not included in the analysis.

Table 9. Mean head count, head length, plant height after Feekes 10 stage, and 1000-kernel weight at harvest as influenced by autumn starter (12-40-0-10-1, N-P-K-S-Zn) and late-season applied nitrogen in fields following silage corn and following soybean, Lansing, MI, 2022-2023.

	SC				SB			
Treatment	Headcount	Head length	Plant height	1000-kernel wt.	Headcount	Head length	Plant height	1000-kernel wt.
Autumn Starter Fertilizer	heads ft^{-2}	mm.	cm.	g.	heads ft^{-2}	mm	cm	g.
0 lb AS A^{-1}	58b	64.8b	60.2b	28.6b	75b	68.3b	68.3b	30.8a
250 lb AS A^{-1}	76a	68.9a	68.9a	32.9a	92a	71.1a	69.3a	28.2b
P > F	***	***	***	***	***	***	*	***
Late-season N								
0 lb N A^{-1}	65	66.5	64.1	31.3a	83	69.2	69.0	29.8
30 lb N A^{-1}	69	67.2	65.0	30.3b	84	70.2	68.6	29.2
P > F	ns	ns	ns	**	ns	ns	ns	ns
Non-treated Check	45	54.4	45.5	31.9	60	66.3	62.0	33.2

§ 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). Nontreated check is not included in the analysis.

Table 10. Correlations between agronomic components, flag leaf during Feekes 9 and grain nutrient concentrations at harvest with grain yield, straw yield, and grain protein content in fields following silage corn (SC) and soybean (SB), Lansing, MI, 2022-2023. †

Following silage corn (SC)													
	Agronomic				Flag leaf at Feekes 9				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
Following soybean (SB)													
	Agronomic				Flag leaf at Feekes 9				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 (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$). Nontreated 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

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