Fertilizer, Fungicide, and Food: Improving Wheat Yield, Straw, and Quality
2022 Report to the Michigan Wheat Program

Participating PI's/Co PI's:
Kurt Steinke, Ph.D., Associate Professor, Dept. of Plant, Soil, and Microbial Sciences
Martin Chilvers, Ph.D. Associate Professor, Dept. of Plant, Soil, and Microbial Sciences
Maria Kenneth Lane Suplito, Graduate Research Assistant
Andrew Chomas, Research Specialist
Bill Widdicombe, Research Specialist

Location: Lansing, MI	**Pre-plant soil:** soil pH 6.9, OM 2.1%, 10.3 CEC, 32ppm Bray P, 88ppm K
Planting Date: 20 Sept. 2021	**Treatments:** see Table 3
Harvesting: 9 July 2022	**Replications:** 4
Variety and Population: Soft Red Winter Wheat 'Wharf' at 1.8 million seeds A^{-1}	**Tillage:** Conventional

INTRODUCTION

Wheat (*Triticum aestivum* L.) is cultivated on more than 200 million hectares of world agricultural land, accounting for 8% of the global food production behind sugarcane (21%), maize (12%), and rice (8%) (FAO, 2022; FAO, 2021). Wheat flour is an essential nutritive component due to its agronomic adaptability, health benefits, easy storage, and versatility as an ingredient (Uthayakumaran & Wrigley, 2017). According to the U.S. NASS (2021a), wheat acres planted increased 5% between 2020 to 2021, but annual production declined 10% with mean grain yields decreasing from 44.6 bu. A^{-1} to 40.2 bu A^{-1}. Fluctuations in yield and harvestable acres pose threats to sustaining future food demand (FAO, 2022). Improving crop yield through input-intensified management has been identified as a potential solution while minimizing the necessity for agricultural land expansion (Cassman & Grassini, 2020).

Although wheat can be grown quite well utilizing conventional management, producers have interest in more intensive production practices. Several studies have shown that traditional nitrogen (N) applications combined with specific inputs can result in greater grain yield (De Oliveira Silva et al., 2021; Quinn & Steinke, 2019; Steinke et al., 2021). A likely reason for this behavior is the synergistic effects between added inputs. For instance, improved fertility management and disease control including the application of autumn-applied starter fertilizer, increased N applications, and micronutrient foliar fertilizers with fungicide have been positively associated with increased yield (Jaenisch et al., 2022; Anderson, 2008; Blandino & Reyneri, 2009).

Starter fertilizer is typically applied in a band near the planted seed to improve the early growth of seedlings (Marschner, 1995). Several studies have demonstrated the capacity of starter fertilizer to improve yield. Steinke et al., (2021) reported increased grain yields of 0.6-1.7 kg ha^{-1}, increased tiller production, and increased head production following autumn starter fertilizer applications. Similarly, Jaenisch et al., (2022) found that the application of autumn-applied starter fertilizer with greater spring N fertilizer improved the grain yield at three out of four locations.

Fungicide is another essential input used in intensive wheat management (Harms et al., 1989). Numerous studies have shown advantages with fungicide usage in grain yield, post-harvest indicators, disease severity, and economic profit (Bhatta et al., 2018; Blandino et al., 2006; Wegulo et al., 2011). Proper application timing is crucial for improving fungicide efficacy. The beginning of anthesis (Feekes 10.5.1) is most common fungicide timing for control of Fusarium head blight (FHB) (Yoshida et al., 2012). Nonetheless, previous studies showed the efficacy of pre- to post-anthesis spray timings. Pre-anthesis application is most advantageous for protection of flag leaves against foliar diseases. Bhatta et al., (2018) observed increased yields from single application of prothioconazole + tebuconazole at Feekes 9. Wegulo et al. (2012) found that fungicide use at Feekes 9 has a higher yield and net return than at Feekes 6. The effectiveness of post-anthesis applications has also been evaluated. In a high disease-pressure environment, prothioconazole + tebuconazole spray at Feekes 10.5.1 was comparable to those made 2 to 7 days after anthesis (DAA) (Paul et al., 2019). Post-anthesis applications made up to 6 DAA can provide lower FHB index, Fusarium damaged kernels (FDK), and deoxynivalenol (DON) accumulation (Bolanos-Carriel et al., 2020; D'Angelo et al., 2014). Similarly, prothioconazole + tebuconazole spray made up to 11 DAA was still useful in managing head scab and reducing DON (Freije & Wise, 2015). In a meta-analysis study (Breunig et al., 2022), researchers found that the combination of fungicide applications at Feekes 5-7 and 10.5.1 had the highest mean yield response of 10.5 bu A^{-1} while Feekes 10.5.1 alone provided 7.4 bu A^{-1} as compared to nontreated control suggesting potential benefits of disease control during early and late wheat growth stages.

Nitrogen management is essential in maximizing yield and reducing nutrient loss (Anderson, 2008; Forrestal et al., 2014). Aside from vegetative growth and photosynthesis (White, 2021), wheat requires N for translocation from vegetative parts to grain (Arregui et al., 2006; Ellen & Spiertz, 1980). Increased N rates often boost grain protein content but do not influence yield in enhanced input management or low-input production systems (Davis et al., 2009; Farrer et al., 2006; Quinn & Steinke, 2019; Steinke et al., 2021) which may be an indicator of luxury consumption (De Oliveira Silva et al., 2021). Grain yield and quality are also influenced by N timing. Topdressed spring N applications before stem elongation can improve fertilizer N recovery, grain yield, and protein content (Sowers et al., 1994; Vaughan et al., 1990), while late-season N applications (Feekes 9 and Feekes 10.5.4) can affect protein content (Dick et al., 2016). Bly and Woodard (2003) found post-anthesis foliar N increased grain protein by 70% while pre-anthesis application reduced grain yield by 5%. Also, late-season applied N improved kernel weight and protein content, implying that N was necessary during the grain-filling stage (Brown and Petrie, 2006).

OBJECTIVE AND HYPOTHESES

Objective 1: Evaluate soft red winter wheat grain and straw yield response to autumn-applied starter fertilizer, multiple fungicide application timings, and late-season applied nitrogen.

- ❖ Working hypothesis: Autumn-applied starter fertilizer will serve as an early season nutrient source on plots with low soil nitrate concentration and will result in more tillers and enhanced canopy closure. The additional biomass will be positively impacted by early season (Feekes 5-7) fungicide spray. Additionally, the late-season applied N will serve as a late-season nutrient source and will improve grain and straw yield which will be positively influenced by mid (Feekes 9) and late-season (Feekes 10.5.1) fungicide sprays.

Objective 2: Determine the influence of autumn-applied starter fertilizer and late-season applied nitrogen on the nutritive quality of soft red winter wheat grains.

- ❖ Working hypothesis: Autumn-applied starter fertilizer will reduce grain nutritive quality due to increased tiller population, diluting the accumulated N, while late-season applied N will increase the protein content—indicating that N is necessary during the grain-filling stage.

METHODOLOGY

Soft red winter wheat (SRWW) field trials were established in Lansing, MI, on non-irrigated, Conover loam soils (Fine-loamy, mixed, active, mesic *Aquic Hapludalfs*) following silage corn (*Zea mays* L.). The experimental site had a neutral soil pH with above-average soil P and slightly deficient soil K levels (Table 1).

Experimental site included twelve-row plots measuring 8 ft in width by 25 ft in length with 7.5 inches row spacing. Plots were planted with an Orbit-Air Granular Applicator with Disc Furrow Opener (Gandy Company Manufacturing, Owatonna, MN) at a rate of 1.8 million seeds A^{-1}. A short-statured, high-yielding variety of soft red winter wheat was planted 20 September 2021. Average yields of 'Wharf' (Michigan Crop Improvement Association, Okemos, MI), ranged from 95.6 – 104.6 bu A^{-1}, adjusted to 13.5% moisture (Pennington et al., 2020; Pennington et al., 2021). In 2021 multi-location trials, the FHB severity, incidence, index, and DON ppm of 'Wharf' were 48.2, 94.3, 45.5, and 9.5, respectively (Pennington et al., 2021).

Treatments were arranged in a complete factorial, randomized complete block design, with three experimental factors in four replications (2×5×2) (Table 3). Experimental factors included two levels of autumn starter (12-40-0-10-1, N-P-K-S-Zn) (0 and 250 lbs A^{-1}), five levels of fungicide application timing (none, Feekes 7 and 10.5.1, Feekes 9 and 10.5.1, Feekes 10.5.1

individually, and Feekes 7, 9 and 10.5.1) and two levels of late-season applied nitrogen (0 and 30 lbs A^{-1}) applied at Feekes 7. All treatments received a base rate of N (100 lbs N A^{-1}) at Feekes 5. Experimental sites consisted of 20 treatments and a non-treated control (no fertilizer or fungicide) with a total of 84 plots.

PRELIMINARY RESULTS (YEAR 1, 2021-2022)

Weather. Cumulative May and June 2022 rainfall for was 35% and 56% below average, respectively (Table 2). April 2022 temperatures were also 5% lower than the 30-yr mean which delayed spring plant development and green-up. The continuous cold and dry early- and mid-spring season months (March-May) were not conducive for foliar fungal disease development. Despite greater relative humidity in May 2022, conditions were not sufficient to increase the disease pressure in the later season (June-July).

Grain yield, straw production, and yield components. Main effects of autumn starter (AS) and late-season applied nitrogen (LN) significantly influenced grain production (Table 4), 1000-seed weight and grain protein content, tillers ft^{-2}, head count ft^{-2}, and plant height (Table 7). AS increased mean grain yield 33.0 bu A^{-1} providing an additional US$ 262.56 potential profitability. Meanwhile, LN improved mean grain yield 5.0 bu A^{-1} with an additional US$ 28.90 potential profitability.

AS provided the highest mean straw yield when LN was not applied (1 ton A^{-1}) (Fig. 1). Conversely, the absence of AS resulted in reduced straw yield, regardless of LN. Grain + straw (G+S) potential profitability was affected by autumn starter and late-season N. AS and LN increased the G + S net profitability by 41% and 4%, respectively.

When autumn starter was applied, tillers ft^{-2}, head count ft^{-2}, and plant height increased 13.7%, 46.7% and 9.8%, respectively (Table 7). Late-season applied N also improved head count ft^{-2} (Table 7). Head length was most influenced by AS, as it was comparable with or without LN application (Fig. 2). Autumn starter reduced 1000-seed weight and grain protein content but were increased by application of LN. Fungicide timing had minimal effect on grain weight and protein content.

Disease Assessment. Disease incidence was unaffected by any main effects. Highest disease severity and index were observed where neither AS nor LN were applied (Table 8). The combination of autumn starter or late-season applied N reduced both FHB severity and index with the lowest 1.26% and 0.07 in no AS × LN interaction.

DISCUSSION

Influence of weather on fungal disease development and fungicide effectivity.

The continuous cold and dry early- and mid-season months (March-May) eliminated the favorable environment for fungal disease development. Moist, cool conditions are most conducive for early fungal diseases including Septoria leaf spot (*Zymoseptoria tritici*) and powdery mildew

(*Blumeria graminis f. sp. tritici*) (Kelley, 2001). The absence of significant differences in grain yield (Table 4) and straw production (Fig. 1) across fungicide treatments indicates disease control was not necessary in a low-disease pressure environment.

Effects of autumn starter on grain yield, nutritive quality, and straw production.

The application of 250 lbs. A^{-1} of autumn starter (12-40-0-10-1, N-P-K-S-Zn) increased average grain yield 33 bu A^{-1}. The positive correlation between grain yield, plant height, head count, and head length offers evidence for how autumn starter positively influenced grain production (Table 10). Increased yield through plant height, head count, and head length in response to autumn starter applications may be due to autumn N allowing sufficient biomass growth and tiller initiation especially at low pre-plant soil nitrate levels (Zhang et al., 2020). Tiller population, a component of yield, determines potential headcount. Results align with Quinn and Steinke (2019) where both tiller and head production increased from the application of autumn starter in a low-input management system.

Head development is most rapid during stem elongation. As the wheat stem elongates, the “heading stage” is initiated suggesting that as the stem extends, there is greater opportunity for the head to stretch—producing a longer head (Simmons et al., 1985). With longer head length comes more spikelets that will be filled with grain. According to Broeske et al. (2018), the number of spikes per head is determined at Feekes 5. Since starter fertilizer was applied in the autumn, there was greater opportunity to provide more elongated stems relative to plants that did not receive autumn starter.

Grain yield was negatively correlated with grain nutrient concentrations (Table 10). Waldren and Flowerday (1979) found the translocation of dry matter from leaves to grain starts at the beginning of anthesis (Feekes 10.5.1) up to the grain-filling stage (Feekes 10.5.4). This aligns with the sufficient ranges of flag leaf nutrient concentrations at Feekes 9 since translocation has not yet begun (data not shown). Except for grain K and Ca, autumn starter reduced grain N, P, and Mg by 13.1%, 5.0%, and 5.1%, respectively, and increased grain S by 9.6% (Table 9). At maturity, Waldren and Flowerday (1979) added that 70-75% of N and P are translocated when only 15% of K is present in grains. In this study, grain N, P, and Mg were reduced in autumn starter-treated plots (Table 9) suggesting that translocated grain N, P, and Mg were diluted from higher grain yield.

The application of autumn starter provided the highest mean straw yield when late-season N was not applied (1 ton A^{-1}) (Fig. 1). Conversely, the absence of autumn starter resulted in reduced straw yields, regardless of late-season applied N. The positive correlation between straw yield with plant height demonstrates the contribution of stem elongation during straw accumulation (Table 8). The active growing stage of wheat starts at Feekes 5 when leaf sheaths are fully elongated and pseudostems are strongly erect up to Feekes 10 when head is visible in the leaf sheath (Broeske et al., 2020). Rapid N uptake begins at Feekes 5 to 7 (Waldren & Flowerday, 1979). Since starter fertilizer was applied in the autumn, plants had greater opportunity to uptake N which translated to improved stem elongation. Autumn starter increased plant height by 9.8% (Table 7). Increase plant height demonstrates the potential for autumn starter to provide an advantageous start heading into the mid-growing season and later translating into improved straw production (Fig. 1).

Effects of late-season applied N on grain yield, nutrients, and protein content.
Late-season N at Feekes 7 increased grain yield (Table 4), grain nutrient concentration (Table 9), and protein content (Table 7). Late-season applied N improved grain yield by 5.0 bu. A^{-1}, as well as protein content, grain N, and P. Grain protein content was positively correlated with grain N (0.94) (Table 10). Previous studies have variable observations about the influence of late-season applied N on grain yield, nutrient concentration and quality. Topdressed spring N applications before stem elongation (Feekes 4 – 9) improved fertilizer N recovery, grain yield, and protein content (Sowers et al., 1994). This conflicts with De Oliveira Silva et al., (2021) observation that N application at beginning of stem elongation (Feekes 5) did not increase the yield and nutrient uptake but enhanced the grain and vegetative components—an indicator of luxury consumption. According to Waldren and Flowerday (1979), N accumulation peaks at grain filling stage with 70% of N uptake going into grain. It is possible that the cool spring growing conditions and delayed plant development and greenup resulted in a greater response to late-applied N especially given the dry soil conditions (i.e., poor N use efficiency) observed throughout the winter wheat growing season.

Table 1. Site description, soil chemical properties and mean P, K, S, and Zn nutrient concentrations (0 – 8 inches) obtained prior to winter wheat planting, non-irrigated following silage corn, Lansing, MI, 2021-2022.

	Soil Test							
Site Description	**NO_3^-**	**pH**	**OM**	**P**	**K**	**S**	**Zn**	**CEC**
	–mg kg^{-1}–		**-%-**	**——ppm——**				**–meq 100g^{-1}–**
Fine-loamy, mixed, active, mesic *Aquic Hapludalfs*	3.11	6.9	2.1	32	88	8	3.6	10.3
Mehlich-3 †				43				
		Neutral		(30) ‡	(120)		(2)	

† 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)

‡ Culman, et al., 2020. Bulletin 974. Tri-State Fertilizer Recommendations For Corn, Soybean, Wheat, And Alfalfa. https://www.canr.msu.edu/soilfertility/Files/Main-page/FINAL%20PRINT.pdf. (Accessed 09 Dec. 2022)

Table 2. Mean monthly and 30-yr. precipitation, temperature, and 15-yr relative humidity for the winter wheat growing season. Lansing, MI, 2021-2022. †

Year	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Total**
			inches			
2022	2.10	3.01	2.39	1.66	0.53	9.69
30-yr. Ave‡	2.13	3.26	3.66	3.76	2.94	15.75
			°F			
2022	36.31	44.52	61.19	68.29	71.60	
30-yr. Ave‡	35.20	47.00	58.40	68.00	71.80	-
			%			
2022	48.09	43.25	42.18	37.41	42.48	-
15-yr. Ave§	56.03	44.09	38.31	39.55	42.12	-

†Precipitation, air temperature, and relative humidity data were collected from MSU Enviro-weather (https://mawn.geo.msu.edu/).

‡ 30-yr means obtained from the National Oceanic and Atmospheric Administration (https://www.ncdc.noaa.gov/cdo-web/datatools/normals).

§ 15-yr means (2007-2022) gathered from the MSU Enviro-weather (https://mawn.geo.msu.edu/).

Table 3. Overview of the complete three-level (2x5x2) factorial structure, treatment names and inputs to winter wheat, Lansing, MI, 2021.

Treatment	Treatment name ††	Agronomic inputs applied				
		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 (Tilt) applied at a rate of 4 fl oz A^{-1} at F5-7 stage.

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

¶ Late fungicide (Miravis ace) applied at a rate of 13.7 fl oz A^{-1} at F10.5.1 stage.

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

†† All plots except the check plot received spring N or green-up application at a rate of 100 lbs A^{-1} in non-irrigated following silage corn at F5 stage.

Table 4. Mean grain yield and net profitability analysis as influenced by autumn starter (12-40-0-10-1, N-P-K-S-Zn), fungicide timing, and late-season applied nitrogen in non-irrigated following silage corn, Lansing, MI, 2021-2022. †

			Net profitability	
Treatment§		**Grain yield**	**G**	**G + S**
		—bu A^{-1}—	**—US$ A^{-1}—**	
Autumn Starter (12-40-0-10-1, N-P-K-S-Zn)				
0 lb AS A^{-1}		91.6 b	667.31 b	749.69 b
250 lbs AS A^{-1}		124.6 a	929.87 a	1,060.07 a
	p-value ≤ 0.10	*0.0001*	*0.0001*	0.0001
Fungicide Timing				
No fungicide		107.4	775.02	881.26
Feekes 5-7, 10.5.1		107.8	805.25	916.42
Feekes 10.5.1		110.2	839.07	946.51
Feekes 9, 10.5.1		105.8	776.77	878.42
Feekes 5-7, 9, 10.5.1		109.2	796.83	901.74
	p-value ≤ 0.10	*0.64*	*0.71*	0.68
Late-season Nitrogen				
0 lb N A^{-1}		105.5 b	784.14	889.13 b
30 lbs N A^{-1}		110.6 a	813.04	920.62 a
	p-value ≤ 0.10	*0.009*	*0.37*	0.34
Nontreated check ††		**45.9**	**427.09**	456.95

† Treatments were compared at 0.10 probability level, Tukey's HSD. Values followed by the same lowercase letter are not significantly different.

§ All treatments received a base rate of N (100 lbs N A^{-1}) at Feekes 5.

†† Nontreated check, no fertilizer or fungicide applied.

Table 5. Wheat fertilizer costs A^{-1}, Lansing, MI, 2021-2022. §

Fertilizer §	No Autumn Starter	Autumn Starter (12-40-0-10-1, N-P-K-S-Zn), 250 lbs A^{-1} †
No Late N	$116.55 d	$128.55 c
Late-applied N (28-0-0), 30 lbs N A^{-1} #	$151.59 b	$163.59 a

§ All treatments received a base rate of N (100 lbs N A^{-1}) at Feekes 5. (UAN - $655 T^{-1})

† 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. (AS - $12 lb^{-1}) https://www.cropnutrition.com/microessentials/value-calculator

Late-season applied nitrogen applied at a rate of 30 lb A^{-1} at F7 stage. (UAN - $655 T^{-1})

Table 6. Wheat fungicide costs A^{-1}, Lansing, MI, 2021-2022.

	Fungicide† and Application Costs‡ (Cost A^{-1})				
Fungicide Spray Timings	No fungicide	F5-7, 10.5.1	F10.5.1	F9, 10.5.1	F5-7, 9, 10.5.1
	None	$40.11 c	$28.70 d	$49.61 b	$61.03 a

† Early fungicide (Tilt) applied at a rate of 4 fl oz A^{-1} at F5-7 stage. (Tilt - $125 gal^{-1})
Mid fungicide (Nexicor) applied at a rate of 7 fl oz A^{-1} at F9 stage. (Nexicor - $245 gal^{-1})
Late fungicide (Miravis ace) applied at a rate of 13.7 fl oz A^{-1} at F10.5.1 stage. (Miravis Ace - $198 gal^{-1})

† Per application spray - $ 7.5

Table 7. Influence of autumn starter (12-40-0-10-1, N-P-K-S-Zn), fungicide timings and late-season applied nitrogen on 1000-seed weight, nutritive quality and agronomic characteristics in non-irrigated following silage corn, Lansing, MI, 2021-2022. †

Treatment§	**1000-seed weight**	**Grain protein**	**Tillers**	**Plant height**	**Head count**	**Belgian Lodging Scale ¶**
	—g—	—%—	—ft^2—	—cm—	—ft^2—	
Autumn Starter (12-40-0-10-1, N-P-K-S-Zn)						
0 lb AS A^{-1}	35.77 a	10.98 a	131 b	66.80 b	60 b	0.20 b
250 lbs AS A^{-1}	32.96 b	9.70 b	149 a	73.35 a	88 a	0.63 a
p-value ≤ 0.10	*0.0001*	*0.0001*	*0.06*	*0.0001*	*0.0001*	*0.006*
Fungicide Timing						
No fungicide	34.67 ab	10.59 a	141	71.09	76	0.59
Feekes 5-7, 10.5.1	33.73 b	10.15 ab	134	71.44	72	0.38
Feekes 10.5.1	33.83 b	10.11 b	138	70.54	73	0.39
Feekes 9, 10.5.1	34.48 ab	10.44 ab	143	70.68	77	0.44
Feekes 5-7, 9, 10.5.1	35.12 a	10.42 ab	145	71.61	72	0.29
p-value ≤ 0.10	*0.03*	*0.07*	*0.95*	*0.41*	*0.62*	*0.79*
Late-season Nitrogen						
0 lb N A^{-1}	34.09 b	9.98 b	137	70.93	72 b	0.47
30 lbs N A^{-1}	34.64 a	10.71 a	143	71.21	76 a	0.36
p-value ≤ 0.10	*0.83*	*0.19*	*0.54*	*0.51*	*0.09*	*0.47*
Nontreated check ††	**33.65**	**9.66**	**129**	**50.85**	**47**	**0.20**

† Treatments were compared at 0.10 probability level, Tukey's HSD. Values followed by the same lowercase letter are not significantly different.

§ All treatments received a base rate of N (100 lbs N A^{-1}) at Feekes 5.

¶ Belgium lodging scores ranged from 0.2 to 9.0, where 0.2 = no lodging and 9.0 = complete lodging.

†† Nontreated check, no fertilizer or fungicide applied.

Table 8. Interaction of autumn starter (12-40-0-10-1, N-P-K-S-Zn) and late-season applied nitrogen on Fusarium head blight (FHB) incidence, severity and index in non-irrigated following silage corn, Lansing, MI, 2021-2022. †

Treatment§	**Incidence**	**Severity**	**Index**
No starter, no Late N	0.07	2.69 a	0.14 a
No starter, w/ Late N	0.06	1.26 b	0.07 b
Starter, no Late N	0.07	1.38 b	0.09 b
Starter, w/ Late N	0.07	1.28 b	0.08 b
p-value ≤ 0.10	*0.96*	*0.01*	*0.04*
Nontreated check ††	**0.11**	**2.22**	**0.24**

† Treatments were compared at 0.10 probability level, Tukey's HSD. Values followed by the same lowercase letter are not significantly different.

§ All treatments received a base rate of N (100 lbs N A^{-1}) at Feekes 5.

†† Nontreated check, no fertilizer or fungicide applied.

Table 9. Influence of autumn starter (12-40-0-10-1, N-P-K-S-Zn), fungicide timings and late-season applied nitrogen grain nutrient concentration at harvest in non-irrigated following silage corn, Lansing, MI, 2021-2022. †

	Grain nutrient concentration					
Treatment§	**N**	**P**	**K**	**Ca**	**Mg**	**S**
	%					
Autumn Starter (12-40-0-10-1, N-P-K-S-Zn)						
0 lb AS A^{-1}	1.780 a	0.354 a	0.425	0.028	0.143 a	0.114 b
250 lbs AS A^{-1}	1.574 b	0.337 b	0.421	0.029	0.136 b	0.125 a
p-value ≤ 0.10	*0.0001*	*0.0001*	*0.31*	*0.21*	*0.0001*	*0.0001*
Fungicide Timing						
No fungicide	1.712	0.343	0.417	0.028	0.138 ab	0.115
Feekes 5-7, 10.5.1	1.653	0.345	0.420	0.028	0.138 ab	0.121
Feekes 10.5.1	1.631	0.339	0.419	0.029	0.136 b	0.119
Feekes 9, 10.5.1	1.684	0.346	0.429	0.029	0.139 ab	0.120
Feekes 5-7, 9, 10.5.1	1.704	0.354	0.430	0.029	0.144 a	0.122
p-value ≤ 0.10	*0.21*	*0.10*	*0.15*	*0.90*	*0.03*	*0.30*
Late-season Nitrogen						
0 lb N A^{-1}	1.608 b	0.342 b	0.422	0.028	0.138	0.119
30 lbs N A^{-1}	1.745 a	0.349 a	0.424	0.029	0.141	0.120
p-value ≤ 0.10	*0.0001*	*0.02*	*0.78*	*0.41*	*0.14*	*0.55*
Nontreated check ††	**1.505**	**0.36**	**0.453**	**0.03**	**0.145**	**0.123**

† Treatments were compared at 0.10 probability level, Tukey's HSD. Values followed by the same lowercase letter are not significantly different.

§ All treatments received a base rate of N (100 lbs N A^{-1}) at Feekes 5.

†† Nontreated check, no fertilizer or fungicide applied.

Table 10. Correlations between agronomic and nutrient concentration with yield components and grain protein content in non-irrigated following silage corn (SC), Lansing, MI, 2021-2022. †

	Agronomic ‡				Grain nutrient concentration					
	T	**PH**	**HC**	**HL**	**N**	**P**	**K**	**Ca**	**Mg**	**S**
Yield	0.19	0.84 ***	0.83 ***	0.67 ***	-0.34 **	-0.44 ***	-0.33 **	-0.06	-0.44 ***	0.48 ***
Straw	0.02	0.63 ***	0.6 ***	0.37 **	-0.28 *	-0.39 **	-0.16	0.06	-0.4 **	0.27
Grain Protein	-0.1	-0.16	-0.47 ***	-0.005	0.94 ***	0.46 ***	-0.04	-0.05	0.46 ***	-0.49 ***

† Peason correlation coefficient analysis using PROC CORR procedure, α = 0.05, where significant values * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001.

‡ Agronomic parameters: T – tiller population, PH – plant height, HC – head count, HL – head length.

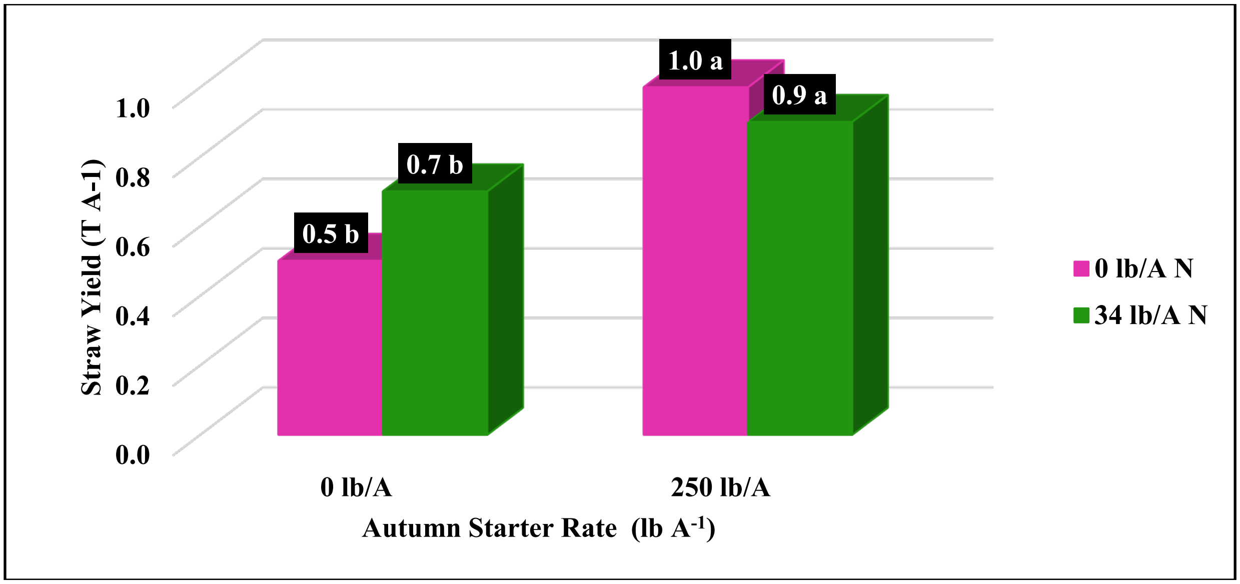

Figure 1. Interaction of autumn starter and late-season applied nitrogen on straw yield (T A^{-1}) in non-irrigated following silage corn, Lansing, MI, 2021-2022. †§

† Treatments were compared at 0.10 probability level, Tukey's HSD. Values followed by the same lowercase letter are not significantly different.

§ All treatments received a base rate of N (100 lbs N A^{-1}) at Feekes 5.

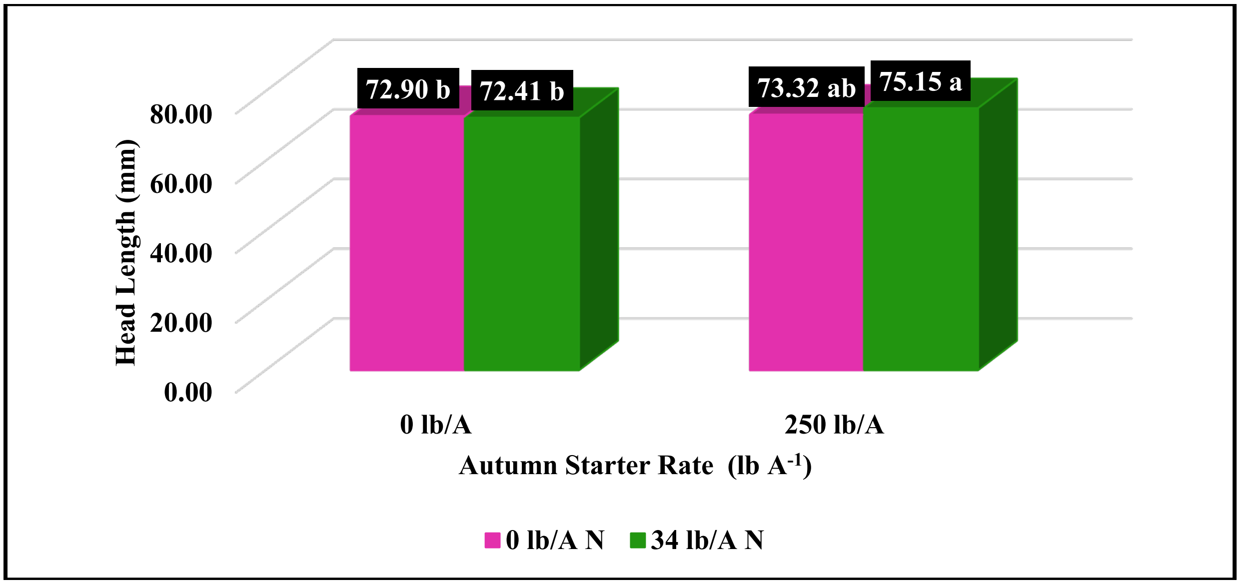

Figure 2. Interaction of autumn starter and late-season applied nitrogen on head length (mm) in non-irrigated following silage corn, Lansing, MI, 2021-2022. †§

† Treatments were compared at 0.10 probability level, Tukey's HSD. Values followed by the same lowercase letter are not significantly different.

§ All treatments received a base rate of N (100 lbs N A^{-1}) at Feekes 5.

REFERENCES

Anderson, R. L. (2008). Growth and Yield of Winter Wheat as Affected by Preceding Crop and Crop Management. *Agronomy Journal*, *100*(4), 977–980. https://doi.org/10.2134/agronj2007.0203

Arregui, L. M., Lasa, B., Lafarga, A., Irañeta, I., Baroja, E., & Quemada, M. (2006). Evaluation of chlorophyll meters as tools for N fertilization in winter wheat under humid Mediterranean conditions. *European Journal of Agronomy*, *24*(2), 140–148. https://doi.org/10.1016/j.eja.2005.05.005

Bhatta, M., Regassa, T., Wegulo, S. N., & Baenziger, P. S. (2018). Foliar Fungicide Effects on Disease Severity, Yield, and Agronomic Characteristics of Modern Winter Wheat Genotypes. *Agronomy Journal*, *110*(2), 602–610. https://doi.org/10.2134/agronj2017.07.0383

Blandino, M., Minelli, L., & Reyneri, A. (2006). Strategies for the chemical control of Fusarium head blight: Effect on yield, alveographic parameters and deoxynivalenol contamination in winter wheat grain. *European Journal of Agronomy*, *25*(3), 193–201. https://doi.org/10.1016/j.eja.2006.05.001

Blandino, M., & Reyneri, A. (2009). Effect of fungicide and foliar fertilizer application to winter wheat at anthesis on flag leaf senescence, grain yield, flour bread-making quality and DON contamination. *European Journal of Agronomy*, *30*(4), 275–282. https://doi.org/10.1016/j.eja.2008.12.005

Bly, A. G., & Woodard, H. J. (2003). Foliar Nitrogen Application Timing Influence on Grain Yield and Protein Concentration of Hard Red Winter and Spring Wheat. *Agronomy Journal*, *95*(2), 335–338. https://doi.org/10.2134/agronj2003.3350

Bolanos-Carriel, C., Wegulo, S. N., Baenziger, P. S., Funnell-Harris, D., Hallen-Adams, H. E., & Eskridge, K. M. (2020). Effects of fungicide chemical class, fungicide application timing, and environment on Fusarium head blight in winter wheat. *European Journal of Plant Pathology*, *158*(3), 667–679. https://doi.org/10.1007/s10658-020-02109-3

Breunig, M., Nagelkirk, M., Byrne, A. M., Wilbur, J. F., Steinke, K., & Chilvers, M. I. (2022). Meta-Analysis of Yield Response to Applications of Fungicides Made at Different Crop Growth Stages in Michigan Winter Wheat. *Plant Health Progress*, PHP-09-21-0118-RS.

Broeske, M., Gaska, J., & Roth, A. (2020). *Winter Wheat—Development and Growth Staging*. https://ipcm.wisc.edu/download/pubsGuides/UW_WheatGrowthStages.pdf

Brown, B. D., & Petrie, S. (2006). Irrigated hard winter wheat response to fall, spring, and late season applied nitrogen. *Field Crops Research*, *96*(2–3), 260–268. https://doi.org/10.1016/j.fcr.2005.07.011

Cassman, K. G., & Grassini, P. (2020). A global perspective on sustainable intensification research. *Nature Sustainability*, *3*(4), 262–268.

Culman, S., Mann, M., Sharma, S., Saeed, M., Fulford, A., Lindsey, L., Brooker, A., Dayton, L., Eugene, B., Warden, R., Steinke, K., Camberato, J., Joern, B. (2019). Conversions of soil analyses into Mehlich-3 values. 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)

Culman, S., Fulford, A., Camberato, J., and Steinke, K. 2020. Bulletin 974. Tri-State Fertilizer Recommendations For Corn, Soybean, Wheat, And Alfalfa. https://www.canr.msu.edu/soilfertility/Files/Main-page/FINAL%20PRINT.pdf. (Accessed 09 Dec. 2022)

D'Angelo, D. L., Bradley, C. A., Ames, K. A., Willyerd, K. T., Madden, L. V., & Paul, P. A. (2014). Efficacy of Fungicide Applications During and After Anthesis Against Fusarium Head Blight and Deoxynivalenol in Soft Red Winter Wheat. *Plant Disease*, *98*(10), 1387–1397. https://doi.org/10.1094/PDIS-01-14-0091-RE

Davis, J. G., Westfall, D. G., Mortvedt, J. J., & Shanahan, J. F. (2009). Fertilizing winter wheat. *Crop Series. Soil; No. 0.544*.

De Oliveira Silva, A., Jaenisch, B. R., Ciampitti, I. A., & Lollato, R. P. (2021). Wheat nitrogen, phosphorus, potassium, and sulfur uptake dynamics under different management practices. *Agronomy Journal*, *113*(3), 2752–2769.

Dick, C. D., Thompson, N. M., Epplin, F. M., & Arnall, D. B. (2016). Managing Late-Season Foliar Nitrogen Fertilization to Increase Grain Protein for Winter Wheat. *Agronomy Journal*, *108*(6), 2329–2338. https://doi.org/10.2134/agronj2016.02.0106

Ellen, J., & Spiertz, J. H. J. (1980). Effects of rate and timing of nitrogen dressings on grain yield formation of winter wheat (T. aestivum L.). *Fertilizer Research*, *1*(3), 177–190. https://doi.org/10.1007/BF01053130

Farrer, D. C., Weisz, R., Heiniger, R., Murphy, J. P., & White, J. G. (2006). Minimizing Protein Variability in Soft Red Winter Wheat: Impact of Nitrogen Application Timing and Rate. *Agronomy Journal*, *98*(4), 1137–1145. https://doi.org/10.2134/agronj2006.0039

Forrestal, P., Meisinger, J., & Kratochvil, R. (2014). Winter Wheat Starter Nitrogen Management: A Preplant Soil Nitrate Test and Site-Specific Nitrogen Loss Potential. *Soil Science Society of America Journal*, *78*(3), 1021–1034. https://doi.org/10.2136/sssaj2013.07.0282

Food and Agriculture Organization (FAO). (2021). World Food and Agriculture - Statistical Yearbook 2021. Rome. https://doi.org/10.4060/cb4477en. (Accessed 8 September 2022).

Food and Agriculture Organization (FAO). (2022). Crops and livestock products. https://www.fao.org/faostat/en/#data/QCL. (Accessed 8 September 2022).

Freije, A. N., & Wise, K. A. (2015). Impact of Fusarium graminearum inoculum availability and fungicide application timing on Fusarium head blight in wheat. *Crop Protection*, *77*, 139–147. https://doi.org/10.1016/j.cropro.2015.07.016

Harms, C. L., Beuerlein, J. E., & Oplinger, E. S. (1989). Effects of Intensive and Current Recommended Management Systems on Soft Winter Wheat in the U.S. Corn Belt. *Journal of Production Agriculture*, *2*(4), 325–332. https://doi.org/10.2134/jpa1989.0325

Jaenisch, B. R., Munaro, L. B., Jagadish, S. V. K., & Lollato, R. P. (2022). Modulation of Wheat Yield Components in Response to Management Intensification to Reduce Yield Gaps. *Frontiers in Plant Science*, *13*, 772232. https://doi.org/10.3389/fpls.2022.772232

Kelley, K. W. (2001). Planting Date and Foliar Fungicide Effects on Yield Components and Grain Traits of Winter Wheat. *Agronomy Journal*, *93*(2), 380–389. https://doi.org/10.2134/agronj2001.932380x

Marschner, H. (1995). Mineral nutrition of higher plants. Academic Press, London, 889 pp.

Paul, P. A., Salgado, J. D., Bergstrom, G., Bradley, C. A., Byamukama, E., Byrne, A. M., Chapara, V., Cummings, J. A., Chilvers, M. I., Dill-Macky, R., Friskop, A., Kleczewski, N., Madden, L. V., Nagelkirk, M., Stevens, J., Smith, M., Wegulo, S. N., Wise, K., & Yabwalo, D. (2019). Integrated Effects of Genetic Resistance and Prothioconazole + Tebuconazole Application Timing on Fusarium Head Blight in Wheat. *Plant Disease*, *103*(2), 223–237. https://doi.org/10.1094/PDIS-04-18-0565-RE

Pennington, D., Olson, E., Martin, S. & Noble, A. (2020). 2020 Michigan State Wheat Performance Trials. http://miwheat.org/mysite/wp-content/uploads/2020-Report-Final-Revised.pdf. (Retrieved 18 July 2022).

Pennington, D., Olson, E., Martin, S., Noble, A., & Or, A. (2021). 2021 Michigan State Wheat Performance Trials. http://miwheat.org/mysite/wp-content/uploads/2021-Report-Final.pdf. (Retrieved 18 July 2022).

Purucker, T., & Steinke, K. (2020). Soybean seeding rate and fertilizer effects on growth, partitioning, and yield. *Agronomy Journal*, *112*(3), 2288–2301.

Quinn, D., & Steinke, K. (2019). Soft Red and White Winter Wheat Response to Input-Intensive Management. *Agronomy Journal*, *111*(1), 428–439. https://doi.org/10.2134/agronj2018.06.0368

Simmons, S. R., Oelke, E. A., & Anderson, P. M. (1985). *Growth and development guide for spring wheat*.

Sowers, K. E., Miller, B. C., & Pan, W. L. (1994). Optimizing Yield and Grain Protein in Soft White Winter Wheat with Split Nitrogen Applications. *Agronomy Journal*, *86*(6), 1020–1025. https://doi.org/10.2134/agronj1994.00021962008600060017x

Steinke, K., Purucker, S., & Chilvers, M. (2021). Integrating multiple inputs for soft red and white winter wheat. *Agronomy Journal*, *113*(5), 4306–4322. https://doi.org/10.1002/agj2.20790

Uthayakumaran, S., & Wrigley, C. (2017). Wheat: Grain-quality characteristics and management of quality requirements. In *Cereal grains* (pp. 91–134). Elsevier.

US National Agricultural Statistics Service (US NASS). (2021a). Wheat Acreage by Year. https://www.nass.usda.gov/Charts_and_Maps/graphics/awac.pdf. (Accessed 14 February 2022).

Vaughan, B., Westfall, D. G., & Barbarick, K. A. (1990). Nitrogen Rate and Timing Effects on Winter Wheat Grain Yield, Grain Protein, and Economics. *Journal of Production Agriculture*, *3*(3), 324–328. https://doi.org/10.2134/jpa1990.0324

Waldren, R. P., & Flowerday, A. D. (1979). Growth Stages and Distribution of Dry Matter, N, P, and K in Winter Wheat 1. *Agronomy Journal*, *71*(3), 391–397.

Wegulo, S. N., Zwingman, M. V., Breathnach, J. A., & Baenziger, P. S. (2011). Economic returns from fungicide application to control foliar fungal diseases in winter wheat. *Crop Protection*, *30*(6), 685–692. https://doi.org/10.1016/j.cropro.2011.02.002

Wegulo, S., Stevens, J., Zwingman, M., & Stephen, P. (2012). Yield Response to Foliar Fungicide Application in Winter Wheat. In D. Dhanasekaran (Ed.), *Fungicides for Plant and Animal Diseases*. InTech. https://doi.org/10.5772/25716

Winters, M. R. (2015). *Optimization of nitrogen and phosphorus fertilizer timing and placement in coulter-based strip-till corn systems*.

Yoshida, M., Nakajima, T., Tomimura, K., Suzuki, F., Arai, M., & Miyasaka, A. (2012). Effect of the Timing of Fungicide Application on Fusarium Head Blight and Mycotoxin Contamination in Wheat. *Plant Disease*, *96*(6), 845–851. https://doi.org/10.1094/PDIS-10-11-0819

Zhang, L., He, X., Liang, Z., Zhang, W., Zou, C., & Chen, X. (2020). Tiller development affected by nitrogen fertilization in a high-yielding wheat production system. *Crop Science*, *60*(2), 1034–1047.