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Integrating multiple inputs for soft red and white winter wheat

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Abstract

Michigan winter wheat (*Triticum aestivum* L.) growers continue to adopt intensive management strategies. However, instead of broadscale implementation of an entire collection of inputs simultaneously, practitioners question which inputs may better contribute to improved production. Studies evaluated soft winter wheat plant growth, grain yield, and expected economic net return for multiple agronomic and nutrient inputsacross varying production intensities. Field trials established in Richville and Lansing, MI, during 2017 and 2018 evaluated six agronomic inputs including: seeding rate, fungicide, plant growth regulator (PGR), autumn starter fertilizer, weekly nitrogen (N) applications, and a high N rate. Autumn-applied starter fertilizer was the only individual input resulting in a consistent grain yield response. Removal of autumn starter fertilizer from high-input (HI) management decreased grain yield an average of 1.6 Mg ha^{-1} while increasing grain yield 1.1 Mg ha^{-1} on average when added to low-input (LI) management. Autumn starter fertilizer accounted for 71% of the grain yield difference between HI and LI. Although greater management intensity increased grain yield compared to LI management in 3 of 4 site-years, expected net return was greater when utilizing LI management. Results suggest producers consider current soil, plant, and climate conditions at the time of application and across variabilities through the field as weather factors may control much of the uncertainty growers encounter when deliberating between individual or multiple input adoption.

1 | INTRODUCTION

Michigan average winter wheat (*Triticum aestivum* L.) grain yields ≥4.8 Mg ha^{-1} since 2015 combined with greater awareness of climate variability and better understanding of input applications including nutrients and fungicides have growers interested in utilizing additional inputs to raise yield yet protect profitability and risks for yield loss (Crane et al., 2011; NASS, 2019; Quinn & Steinke, 2019; Rosenzweig et al., 2001; Roth et al., 2021). Intensive management strategies aim to control yield-limiting factors by including additional production practices to reduce the risk for yield loss but may also add significant costs affecting expected net return (Harms et al., 1989; Mourtzinis et al., 2016). Traditionally many Michigan growers struggled to plant wheat timely due to the inability to get the previous soybean [*Glycine max*. (L.) Merr.] crop harvested. However recent studies indicating a loss of nearly 40 kg grain ha^{-1} day^{-1} with late-planted wheat have many growers opting for earlier-maturing soybean varieties or managing crop rotations for wheat to follow dry edible bean (*Phaseolus vulgaris* L.) or corn (*Zea mays* L.) silage to

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Abbreviations: DON, deoxynivalenol; FHB, fusarium head blight; GDD, growing degree days; HI, high-input; LI, low-input; NDVI, normalized difference vegetation index; PGR, plant growth regulator; SRWW, soft red winter wheat; SWWW, soft white winter wheat.

facilitate earlier wheat planting (Olson et al., 2021). Lower seeding rates have been suggested with earlier-planted wheat (i.e., within 1 wk of the Hessian fly [*Mayetiola destructor*] -free date) in Michigan to avoid overly dense stands, additional disease development, and increased lodging risks that accompany higher seeding rates required for later planting or no-till (Dahlke et al., 1993; Jaenisch et al., 2019; Olson et al., 2021; Staggenborg et al., 2003). Improved plant tillering, light interception, input efficiency, compensation capacities, and comparable grain yields from reduced seeding rates (e.g., 2.2 million seeds ha^{-1}) as compared to greater seeding rates (e.g., 4.4 million seeds ha^{-1}) have piqued grower interest in whether to plant lower population with more inputs (i.e., doing more with less) or greater population with fewer inputs (i.e., doing less with more) for timely planted wheat (Darwinkel et al., 1977; Isidro-Sánchez et al., 2017; Joseph et al., 1985; Lloveras et al., 2004; Park et al., 2003). Appropriate intensified management strategies that investigate multiple inputs across a range of plant populations with timely planted wheat are required to continue successful wheat production in the Great Lakes region.

Intensive wheat management often utilizes fungicide applications to decrease disease incidence and avoid grain yield reductions (Brinkman et al., 2014; Mourtzinis et al., 2017). A problematic disease in soft winter wheat is fusarium head blight (FHB) (*Fusarium graminearum*) as few cultivars offer full resistance to this disease which can decrease grain yield up to 50% through shriveled kernels and mycotoxin (e.g., deoxynivalenol [DON]) presence (Nagelkirk & Chilvers, 2016; Paul et al., 2010; Windels, 2000). Marketability of soft white and red winter wheat decreases when DON concentrations exceed 1 and 2 mg kg^{-1}, respectively (Nagelkirk & Chilvers, 2016). Conditions favoring FHB consist of wet, humid weather during anthesis and grain fill (Paul et al., 2010). Many growers choose to apply fungicide regardless of environmental conditions impacting disease severity as meta-analysis studies have shown anthesis applications may reduce FHB 40–50%, decrease DON contamination, and increase yield nearly 330 kg ha^{-1} (Mourtzinis et al., 2017; Paul et al., 2008). Additionally, foliar disease development can be widespread in Michigan with preventative fungicide applications retaining green leaf area longer into grain fill (Dimmock & Gooding, 2002). However, economic return from fungicide application will depend upon disease severity, varietal characteristics, and environmental conditions (Bhatta et al., 2018).

Core Ideas

- Decreased seeding rates may offer greater opportunity in a high-input compared to low-input management system.
- Autumn starter fertilizer accounted for nearly 71% of the grain yield difference between management systems.
- Soil testing should still be considered prior to making starter fertilizer decisions.
- Weekly N applications beginning at Feekes 4 showed no benefit compared to Feekes 5 single N applications.
- Despite grain yield increases, economic net returns may not offset the cost to attain greater yield.

Increased management intensity may include above recommended N rates which can increase plant height, weaken stem strength, and cause plant lodging (Knott et al., 2016; Swoish & Steinke, 2017). Growers may perceive yield loss from under-applying N a greater risk than the cost of over-application thus resulting in a recent trend of greater N rate applications with simultaneous use of a plant growth regulator (PGR), regardless of plant stature, as assurance to prevent lodging (Quinn & Steinke, 2019; Swoish & Steinke, 2017). Plant lodging affects grain yield and quality by restricting water and nutrient transport from plant roots to developing grain tissues often resulting in non-harvestable grain due to proximity beneath the combine head (Harms et al., 1989; Knapp et al., 1987; Van Sanford et al., 1989). Trinexapac-ethyl is a PGR inhibiting gibberellin biosynthesis which can decrease plant height, increase stem diameter and stalk strength, reduce lodging susceptibility, and has increased chlorophyll concentrations in other plant systems (Knott et al., 2016; Matysiak, 2006; Steinke & Stier, 2003; Swoish & Steinke, 2017). Reduced plant lodging from PGR application can increase yield due to a greater number of harvestable grain heads (Nagelkirk, 2012). In Michigan, PGR application increased grain yield 0.3–0.4 Mg ha^{-1} while also reducing lodging 50–83% compared to no PGR (Swoish & Steinke, 2017). Other studies found PGR application did not consistently affect grain yield due to lack of plant height reduction and lodging susceptibility (Knott et al., 2016; Quinn & Steinke, 2019). Wheat yield response to PGR application may depend on varietal characteristics including plant height and lodging incidence or stem strength during the growing season with benefits more frequent when using a high yielding, taller-statured, and intensively managed variety (e.g., increased N rate) that is susceptible to lodging (Brinkman et al., 2014; Quinn & Steinke, 2019 ; Swoish & Steinke, 2017).

Winter wheat autumn starter fertilizer can provide developing roots greater access to soil-supplied nutrients thus affecting grain yield potential (Nkebiwe et al., 2016). Moderate amounts of autumn-applied N (28 kg N ha^{-1}) are often suggested for winter wheat establishment but exceeding 34 kg N ha^{-1} can create excessive autumn growth and increase winter kill (Alley et al., 2009; Warncke et al., 2009). Wheat grain yield responses to autumn-applied N are more probable when pre-plant soil nitrate concentrations (NO_3–N) are <10 mg kg^{-1} soil (Alley et al., 2009). Winter wheat responsiveness to autumn-applied N may be greater following soybean [*Glycine max* (L.) Merr.] as compared to corn due to reduced C/N and less residual soil NO_3–N variability following soybean (Forrestal et al., 2014; Mourtzinis et al., 2017; Roth & Fox, 1990). Since winter wheat growth coincides with cooler spring (i.e., April–May) Michigan air and soil temperatures, sulfur (S) mineralization from organic matter at soil temperatures <10 ˚C may not satisfy early-season S requirements (Lecheta & Lambais, 2012). Soil temperatures in Michigan may not raise above 10 ˚C until early to mid-May. Therefore, autumn fertilizer containing some soluble S may help satisfy early wheat S requirements (Mascagni et al., 2008). Phosphorus (P) fertilizer applications should be based on pre-plant soil test concentrations and not solely based on crop removal as when soil test P concentrations are above critical (i.e., 25 mg kg^{-1} P [Bray-P] for wheat) grain yield response to P application becomes less probable (Culman et al., 2020; Rutan & Steinke, 2021; Warncke et al., 2009).

Split-applied N can reduce environmental N losses (i.e., leaching or denitrification) on medium to fine-textured soils but spring rainfall variability influences the success of split-N applications with few consistent advantages (Alcoz et al., 1993; Bagg et al., 2009; Liu et al., 2018; Olson et al., 2021). Alcoz et al. (1993) reported grain yield increased 0.5 Mg ha^{-1} with four compared to two split N applications at a total N rate of 150 kg N ha^{-1}. European researchers suggest grain yields increase with multiple split N as compared to singular N applications (Dilz, 1971; Dilz et al., 1982; Gravelle et al., 1988; Tinker & Widdowson, 1982). Although split-applied N may reduce N losses during periods of ample moisture, insufficient quantities of soluble N in the rhizosphere during peak growth periods (i.e., Feekes 5–9) may reduce grain yield emphasizing the importance for synchronizing N availability with N uptake (Roberts et al., 2004; Zadoks et al., 1974). Additionally, N applications following peak N uptake may affect grain protein more than biomass or grain yield (Ercoli et al., 2012; Fuertes-Mendizábal et al., 2010). Although split N applications may allow greater flexibility for both N rates and application timings and may at times improve N uptake efficiency, the cumulative costs of multiple split-N applications must be considered in the overall net economic return.

As overall N rates have risen along with increases in grain yield, the assumption that modern (i.e., post-2010) wheat varieties show an improved response to N fertilizer application may be incorrect as modern varieties may also contain poorer rooting systems unable to access as large of a rooting area thus requiring greater N (Brinkman et al., 2014; Wasson et al., 2012). Greater N rates under more intensive rather than traditional management may improve wheat performance (Brinkman et al., 2014). Efficient use of N fertilizer is essential to increasing grain yield and longer-term winter wheat sustainability, but growers often associate reduced risk with over-application of N (Bhatta et al., 2017; Delogu et al., 1998; Gravelle et al., 1988; Mourtzinis et al., 2017). Greater N rates may be required under intensified management systems due to N stimulating the response of other agronomic inputs (e.g., stay-green potential) (Quinn & Steinke, 2019).

With the second highest crop diversity in the United States, Michigan producers can rotate multiple crops prior to wheat to facilitate timely planting. With lower seeding rates suggested for earlier-planted wheat, few data are available investigating timely planted wheat and the removal or addition of individual inputs in lieu of multiple input packages on wheat production or profitability. The objective of this trial was to investigate the grain yield and economic net return of soft red and white winter wheat to seeding rate, fungicide, PGR, autumn starter fertilizer, weekly N applications, and increased N fertilizer across two management intensities. Omission trial designs allow for evaluation of specific management factors and was used in the current study to determine whether the removal of an individual input from high-input (HI) management or the addition of an individual input to low-input (LI) management significantly influenced grain yield or profitability.

2 | MATERIALS AND METHODS

Soft red winter wheat (SRWW) field trials were established at the South Campus Research Farm in Lansing, MI (42˚42′37.0″N, 84˚28′14.6″W) on a Capac loam soil (fine loamy, mixed, active, mesic Aquic Glossudalf). Pre-plant soil characteristics (0–20 cm) included 7.0–7.1 pH (1:1 soil/water) (Peters et al., 2015), 25–28 g kg^{-1} soil organic matter (loss-on-ignition) (Combs & Nathan, 2015), 12–33 mg kg^{-1} P (Bray-P1 or Olsen-P, pH-dependent) (Frank et al., 2015), 80–102 mg kg^{-1} K (ammonium acetate method) (Warncke & Brown, 2015), 8–9 mg kg^{-1} S (monocalcium phosphate extraction) (Combs & Nathan, 2015), and 2.5–3.4 mg kg^{-1} Zn (0.1 M HCl) (Whitney, 2015). Prior to planting, soil samples (0–30 cm) for nitrate-N (NO_3–N) analysis were collected, air-dried, and ground to pass through a 2 mm sieve. Pre-plant soil NO_3–N concentrations were 4.3 mg NO_3–N kg^{-1} soil (nitrate electrode method) in both years (Gelderman & Beegle, 2015). Triple superphosphate (0–45–0 N–P_2O_5–K_2O) was broadcast at a rate of 146 and 73 kg P_2O_5 ha^{-1} in 2018 and 2019, respectively, while muriate of potash (0–0–62 N–P_2O_5–K_2O) was broadcast at a rate of 40 kg K_2O ha^{-1} in 2018 based on soil tests. Preceding crop was silage corn and soybean in 2018 and 2019, respectively, and tilled prior to planting. Soft white winter wheat (SWWW) trials were conducted at the Saginaw Valley Research and Extension Center in Richville, MI (43˚23′57.3″N, 83˚41′49.7″W) on a Tappan-Londo loam soil (fine-loamy, mixed, active, calcareous, mesic Typic Enduaquoll). Pre-plant soil characteristics (0–20 cm) included 7.7–8.0 pH (1:1 soil/water), 20–21 g kg^{-1} soil organic matter (loss-on-ignition), 13–17 mg kg^{-1} P (Bray-P1 equivalent) (Frank et al., 2015), 137–152 mg kg^{-1} K (ammonium acetate method, 6–9 mg kg^{-1} S (monocalcium phosphate extraction), and 5.4–5.7 mg kg^{-1} Zn (0.1 M HCl). Prior to planting, soil samples (0–30 cm) for nitrate-N (NO_3–N) analysis were collected, air-dried, and ground to pass through a 2-mm sieve resulting in concentrations of 9.1 and 4.3 mg NO_3–N kg^{-1} soil in 2018 and 2019, respectively. Triple superphosphate (0–45–0 N–P_2O_5–K_2O) was broadcast at a rate of 73 and 101 kg P_2O_5 ha^{-1} in 2018 and 2019, respectively, based on soil tests. Preceding crop was dry bean (*Phaseolus vulgaris* L.) and soybean in 2018 and 2019, respectively, and tilled prior to planting. All plots received standard weed control (Huskie, pyrasulfotole, 3.3%, {2,5-dimethyl-4-[2-methylsulfonyl-4-(trifluoromethyl)benzoyl]−1H-pyrazol-3-one} Bayer CropScience).

Plots were 12 rows wide (2.5 m width by 7.6 m length by 19.1 cm row spacing) planted with a Great Plains 3P600 drill (Great Plains Manufacturing) at plant populations of 2.2 and 4.4 million seeds ha^{-1}. Spring stand counts occurred prior to Feekes 4 applications to validate plant populations. Trials were arranged in a randomized complete block design with four replications. Soft red winter wheat variety Starburst (Michigan Crop Improvement Assoc.) a shorter strawed, high-yielding variety was planted in Lansing on 20 Sept. 2017 and 9 Oct. 2018 (delayed planting due to wet soil conditions). Soft white winter wheat variety Jupiter (Michigan Crop Improvement Assoc.) a shorter strawed, high-yielding variety was planted in Richville on 22 Sept. 2017 and 24 Sept. 2018.

Nitrogen was applied as UAN (28–0–0) utilizing a backpack sprayer equipped with streamer bars (Chafer Machinery Ltd.) at the Feekes 4 growth stage (5 Apr. 2018 and 6 Apr. 2019, Lansing; 11 Apr, 2018 and 3 Apr. 2019, Richville). Low-input N rates were based on Michigan State University recommendations for Lansing and Richville and included 112.1 kg N ha^{-1} and 145.7 kg N ha^{-1} for SRWW and SWWW, respectively. High-input N rates were 33% greater than LI management (149.1 kg N ha^{-1} and 193.9 kg N ha^{-1} for SRWW and SWWW, respectively). Weekly N applications (18.6 kg N ha^{-1} and 24.2 kg N ha^{-1} per application for SRWW and SWWW, respectively) began at Feekes 4 and included 8 weekly applications (SRWW dates were 5, 11, 17, 24 April and 2, 8, 16, and 24 May in 2018; 6, 10, 15, 25, 30 April and 7, 14, and 21 May in 2019; SWWW dates were 11, 18, 25 April and 1, 9 16, 23, and 30 May in 2018; 3, 10, 16, 24, and 30 April and 7, 14, and 21 May in 2019). Autumn starter (12–40–0–10–1N–P–K–S–Zn) (MicroEssentials SZ (MESZ) (Mosaic CO.) fertilizer was topdressed (3 Oct. 2017 and 12 Nov. 2018, Lansing; 10 Oct. 2017 and 15 Oct. 2018, Richville) at 280 kg ha^{-1}. Plant growth regulator (Palisade EC, trinexapac-ethyl [0.8 L ha^{-1}]; Syngenta Crop Protection) was applied at Feekes 6 (30 Apr. 2018 and 10 May 2019, Lansing; 1 May 2018 and 30 Apr. 2019, Richville) using a backpack sprayer calibrated at 140.3 L ha^{-1} with Teejet XR8002 nozzles (Teejet Technologies, Wheaton, IL). Fungicide (Prosaro 421 SC, prothioconazole {2-[2-(1-chlorocyclopropyl0-3-(2-chlorophenyl)−2-hydroxypropyl]−1, 2-dihydro-3H-1, 2, 4-triazole-3-thione} and tebuconazole {alpha-[2-(4-chlorophenyl)ethyl]-alpha-(1,1-dimethylethyl)−1H-1, 2, 4-triazole-1-ethanol}[0.6 L ha^{-1}]; Bayer CropScience) was applied at Feekes 10.5.1 (29 May 2018 and 11 June 2019, Lansing; 31 May 2018 and 11 June 2019, Richville) using a backpack sprayer calibrated at 140.3 L ha^{-1} with Teejet tt11002 nozzles (Teejet Technologies).

An omission treatment design was utilized to determine individual input responses (Table 1). In addition to an overall non-treated control in the current study, two treatment controls are included in omission trial designs with one containing all inputs (i.e., HI) and one containing no inputs (i.e., LI) (Bluck et al., 2015; Quinn & Steinke, 2019). To evaluate individual input response, inputs removed from the HI management system were compared only with the all-inclusive HI treatment and inputs added to LI management were only compared to the LI treatment containing only a recommended base rate of N. The inputs evaluated in the current study differed from previous wheat investigations (Quinn & Steinke, 2019).

Environmental data were recorded throughout the growing season and obtained from MSU Enviro-weather (https://enviroweather.msu.edu, Michigan State University, East Lansing, MI). Temperature and precipitation 30-yr means were collected from the National Oceanic and Atmospheric Administration (NOAA, 2019). Tiller counts were collected from representative areas within each plot using a 0.10 m^2 quadrat placed outside yield harvest areas at Feekes 4 with similar head count measurements occurring at Feekes 11.2. Percentage of grain heads affected by FHB were taken 3 wk after fungicide application.

Grain yield was harvested from the center 1.2 m of each plot utilizing a small-plot combine (Almaco) on 11 July 2018 and 23 July 2019 in Lansing and 12 July 2018 and 24 July 2019 in Richville and adjusted to 135 g kg^{-1} moisture. Grain subsamples were collected from each plot to evaluate DON concentration and sent to the U.S. Wheat and Barley Scab Initiative mycotoxin testing laboratory (University of Minnesota, St. Paul, MN). Due to pre-harvest sprouting susceptibility of SWWW, additional grain samples were taken from SWWW variety Jupiter (Brown et al., 2017) and evaluated for α-amylase activity and pre-harvest sprouting incidence. Sprout damage and α-amylase activity of SWWW flour was determined using the falling number procedure (Perten Instruments).

TABLE 1 Overview of omission treatment design, treatment names, and inputs applied to winter wheat in 2018–2019. High-input (HI) control included all applied inputs but at a decreased seeding rate while low-input (LI) control included only a base rate of N with no additional applied inputs at an increased seeding rate

		Agronomic input applied					
Treatment	**Treatment name**	**D.S.[a]**	**Fungicide**	**PGR**	**Autumn starter**	**Weekly N**	**High N**
1	HI (+) D.S.[a]	Yes	Yes	Yes	Yes	Yes	Yes
2	HI (–) D.S.	No	Yes	Yes	Yes	Yes	Yes
3	HI (–) Fungicide	Yes	No	Yes	Yes	Yes	Yes
4	HI (–) PGR	Yes	Yes	No	Yes	Yes	Yes
5	HI (–) Autumn starter	Yes	Yes	Yes	No	Yes	Yes
6	HI (–) Weekly N	Yes	Yes	Yes	Yes	No	Yes
7	HI (–) High N	Yes	Yes	Yes	Yes	Yes	No
8	LI (+) I.S.[f]	No	No	No	No	No	No
9	LI (+) D.S.	Yes	No	No	No	No	No
10	LI (+) Fungicide	No	Yes	No	No	No	No
11	LI (+) PGR[g]	No	No	Yes	No	No	No
12	LI (+) Autumn starter	No	No	No	Yes	No	No
13	LI (+) Weekly N	No	No	No	No	Yes	No
14	LI (+) High N	No	No	No	No	No	Yes
15	Check	No	No	No	No	No	No

[a] Decreased seeding (D.S.) rate of SRWW/SWWW at 2,223,900 seeds ha^{-1}.

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

[c] Autumn starter fertilizer (12–40–0–10–1 N–P–K–S–Zn) at a rate of 280 kg ha^{-1} autumn applied.

[d] Weekly applications of UAN (28%) starting at Feekes 4 growth stage applied at a rate of 18.6 and 24.2 kg N ha^{-1} for Lansing and Richville locations, respectively.

[e] High nitrogen applied at F4 growth stage at a rate of 149 and 194 kg N ha^{-1} for Lansing and Richville locations, respectively.

[f] Increased seeding (I.S.) rate of SRWW/SWWW at 4,447,800 seeds ha^{-1}.

[g] Trinexapac-ethyl plant growth regulator (PGR) applied at a rate of 0.88 L ha^{-1} at F6 growth stage.

2.1 | Data analysis

Expected net return wasassessed using input cost estimates from Star of the West Milling Company, Jorgenson Farm Elevator, and Nutrien Ag Solutions and consisted of US$0.90 kg^{-1}, $0.64 kg^{-1}, $34.18, $45.91 ha^{-1} in 2018 and $1.02 kg^{-1}, $0.65 kg^{-1}, $34.83, $45.91 ha^{-1} in 2019 for N fertilizer, autumn starter fertilizer, plant growth regulator, and fungicide, respectively (Table 2). Seed costs were $0.59 and $0.51 kg^{-1} for SRWW and $0.53 and $0.47 kg^{-1} for SWWW in 2018 and 2019, respectively. Application costs were estimated from the Michigan State University Extension Custom Machine and Work Rate Estimates and included $19.15 ha^{-1} for N fertilizer, plant growth regulator, and fungicide (Stein, 2018). Weekly N applications added $19.15 ha^{-1} per N application. An additional cost of $16.16 ha^{-1} was utilized for the application of autumn starter fertilizer. Net returns were calculated by multiplying mean harvest grain price estimates received from Star of the West Milling Company, Jorgenson Farm Elevator, and Michigan Agricultural Commodities which consisted of $0.16 and $0.18 kg^{-1} in 2018, $0.17 and $0.18 kg^{-1} in 2019 for SRWW and SWWW, respectively, by grain yield and subtracting total treatment costs.

Data were analyzed in SAS 9.4 (SAS Institute, 2012) using the GLIMMIX procedure at $\alpha = .10$. Each site-year was analyzed individually due to a significant treatment × year interaction. Due to different SRWW and SWWW varieties and site-specific N rates, locations were analyzed individually. Replication was considered a random factor with all other factors considered fixed. Treatment mean separations were calculated utilizing single degree of freedom contrasts. Due to unequal comparisons concerning treatments incorporating an individual input and treatments excluding that input, authors cannot contrast input responses across both management systems.

3 | RESULTS AND DISCUSSION

3.1 | Environmental conditions

Total precipitation during March–July differed from the 30-yr mean by −41 and +20% and −26 and +20% in 2018 and 2019 at Richville and Lansing, respectively (Table 3). June 2018 precipitation was 57 and 58% below the 30-yr mean for Richville and Lansing, respectively, which likely impacted grain fill and decreased yield potential due to dry soil

TABLE 2 Estimates of winter wheat prices received and input costs per hectare used for expected net return analysis, Richville and Lansing, MI, 2018–2019

Investments	Returns	2018 Richville	2018 Lansing	2019 Richville	2019 Lansing
		US$ kg^{-1}			
Price received	Wheat	0.59	0.51	0.53	0.47
	Costs	US$ ha^{-1}			
Inputs applied	Decreased seeding rate[a]	59	53	47	51
	Increased seeding rate[b]	118	106	94	102
	Fungicide	46	46	46	46
	Plant growth regulator	34	34	34	34
	Autumn starter fertilizer	181	181	181	181
	Weekly N applications	132	101	132	101
	Base N rate[c]	132	101	132	101
	High N rate[d]	175	135	175	135
Application[e]	Spray application[f]	19	19	19	19
	Weekly N application[g]	153	153	153	153
	Dry fertilizer application[h]	16	16	16	16

[a] Decreased seeding (D.S.) rate of SRWW/SWWW at 2,223,900 seeds ha^{-1}.

[b] Increased seeding (I.S.) rate of SRWW/SWWW at 4,447,800 seeds ha^{-1}.

[c] Base-nitrogen applied at a rate of 112 and 146 kg N ha^{-1} for Lansing and Richville locations, respectively.

[d] High-nitrogen applied at a rate of 149 and 194 kg N ha^{-1} for Lansing and Richville locations, respectively.

[e] Application cost estimates obtained from Michigan State University Extension custom machine and work rate.

[f] Application spray cost estimates for fungicide, plant growth regulator, base N rate, and high N rate.

[g] Application spray cost total estimate for all weekly N applications.

[h] Application cost estimate for autumn starter fertilizer.

conditions. May and June cumulative 2019 rainfall was 55–75% above 30-yr means at both locations increasing the potential for leaching and denitrification N losses on these medium to fine-textured soils. Except for Richville May 2018 which was 33% above the 30-yr mean, May through July mean air temperatures did not deviate more than 10% from the 30-yr mean across site-years.

3.2 | High-input vs. low-input management

High-input management containing all inputs (i.e., decreased seeding rate, fungicide, PGR, autumn starter fertilizer, weekly N applications, and high N management) increased grain yield compared to LI management containing only a recommended base rate of N fertilizer in 3 of 4 site-years (Table 4). Richville 2018 was the only site-year where grain yield did not significantly differ between HI and LI management. Lack of additional yield-limiting conditions (e.g., N loss, pest pressure, plant lodging) combined with deficit precipitation in Richville 2018 may have contributed to the lack of yield response to additional inputs. Compared to LI wheat management, HI increased SWWW grain yield from 6.7 to 8.4 Mg ha^{-1} in Richville 2019 while also increasing SRWW grain yield from 5.8 to 7.0 and 5.4 to 7.7 Mg ha^{-1} in Lansing 2018 and 2019, respectively. Averaged across the three responsive site-years, HI management increased yield 1.7 Mg ha^{-1} compared to traditional management. Autumn starter fertilizer accounted for nearly 71% or 1.2 Mg ha^{-1} of the grain yield difference between HI and LI management within the three significant site-years. Soft white winter wheat falling number data are not presented due to lack of pre-harvest sprouting incidence across both years. Results agree with previous research that show positive grainyield responses to specific input applications (e.g., fungicide, PGR, weekly N applications, high-N) are unlikely without the presence of yield-limiting factors (i.e., disease occurrence, plant lodging, leaching, denitrification, or deficient soil nutrient concentrations) (Jaenisch et al., 2019; Knott et al., 2016; Paul et al., 2010; Quinn & Steinke, 2019; Swoish & Steinke, 2017; Wegulo et al., 2012).

3.3 | Expected economic net return

Product and application costs for HI management across all 4 site-years averaged \$694 ha^{-1} with a break-even yield of 3.9 Mg ha^{-1}, while LI management costs and break-even yield were \$249 ha^{-1} and 1.4 Mg ha^{-1}, respectively. Low-input SWWW and SRWW management containing only a university recommended base N rate increased expected

TABLE 3 Mean monthly and 30-yr temperature and precipitation[a] for the winter wheat growing season, Richville and Lansing, MI, 2018–2019

Site	Year	Mar.	Apr.	May	June	July	Total
		cm					
Richville	2018	1.4	7.1	5.4	3.8	5.0	22.7
	2019	3.4	5.8	12.8	17.7	6.0	45.7
	30-yr[b] avg.	4.9	8.1	8.4	9.0	7.9	38.2
Lansing	2018	2.5	6.0	12.6	3.7	2.7	27.5
	2019	5.0	7.2	8.5	18.3	5.8	44.8
	30-yr avg.	5.2	7.7	8.5	8.8	7.2	37.4
		˚C					
Richville	2018	–0.6	3.6	17.6	19.7	22.1	–
	2019	–0.8	7.4	12.8	18.4	22.6	–
	30-yr avg.	0.4	7.4	13.2	18.7	20.9	–
Lansing	2018	0.7	4.4	17.7	20.0	21.8	–
	2019	–0.3	8.0	14.1	18.3	23.1	–
	30-yr avg.	1.7	8.6	14.3	19.8	21.9	–

[a] Precipitation and air temperature data were collected from MSU Enviro-weather (https://enviroweather.msu.edu/).

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

TABLE 4 Winter wheat grain yield for Richville and Lansing, MI, 2018–2019. Mean grain yield of high-input (HI) control (all inputs applied at decreased seed rate) and low-input (LI) control (base rate of N with no inputs) treatments displayed. All other treatments display change in grain yield from respective HI or LI control using single degree of freedom contrasts

Treatment[a]	2018		2019	
	Richville	Lansing	Richville	Lansing
	Mg ha^{-1}			
HI (+) D.S.	6.2	7.0	8.4	7.7
HI (–) D.S[b]	+0.3	+0.3	–0.1	+0.4
HI (–) Fungicide	+0.0	-0.8[c]	–0.6	–0.6
HI (–) PGR	+0.2	+0.2	–0.2	+0.3
HI (–) Autumn starter	–0.2	–1.0[c]	–1.3[c]	–2.5[c]
HI (–) Weekly N	+0.5 [c]	+0.2	+0.3	+0.4
HI (–) High-N	+0.3	+0.2	+0.2	+0.0
LI (+) I.S.	6.1	5.8	6.7	5.4
LI (+) D.S.[d]	–0.3	–1.1 [c]	–0.3	–0.3
LI (+) Fungicide	–0.1	–0.1	+0.6	+0.8 [c]
LI (+) PGR	–0.3	–0.9 [c]	+0.6	+0.5
LI (+) Autumn starter	+0.6 [c]	+0.7 [c]	+1.2 [c]	+1.7 [c]
LI (+) Weekly N	–0.1	–0.3	+0.1	+0.4
LI (+) High N	+0.0	–0.2	+0.6	+0.4
Check[e]	4.2	2.9	3.2	3.5
HI vs. LI[f]	ns[g]	[c]	[c]	[c]
CV, %	5.1	10.5	8.0	11.3

[a] Decreased seeding rate (D.S.), trinexapac-ethyl plant growth regulator (PGR), weekly N applications (Weekly N), 33% increase in nitrogen fertilizer rate (High N), increased seeding rate (I.S.).

[b] Values in HI(–) input rows indicate a yield (Mg ha^{-1}) change from respective HI treatment.

[c] Significantly different at $\alpha = .10$ using single degree of freedom contrasts.

[d] Values in LI (+) input rows indicate a yield (Mg ha^{-1}) change from respective LI treatment.

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

[f] Comparison between the HI and LI control treatment utilizing single degree of freedom contrasts.

[g] Non-significant $\alpha = .10$ using single degree of freedom contrasts.

TABLE 5 Expected economic net return for winter wheat, Richville and Lansing, MI, 2018–2019. Mean expected net return for high-input (HI) control (all inputs applied at decreased seed rate) and low-input (LI) control (base rate of N with no inputs)treatments displayed. All other treatments display change in expected net return from respective HI or LI control using single degree of freedom contrasts

Treatment[a]	2018 Richville	2018 Lansing	2019 Richville	2019 Lansing
	US$ ha^{-1}			
HI (+) D.S.	426.50	500.70	819.16	656.52
HI (–) D.S.[b]	–6.75	–3.51	–62.15	+24.71
HI (–) Fungicide	+76.45[c]	–65.23	–44.03	–41.96
HI (–) PGR	+92.42[c]	+96.22	+28.42	+107.96
HI (–) Autumn starter	+152.31[c]	+39.07	–32.30	–239.24[c]
HI (–) Weekly N	+228.77[c]	+165.04[c]	+181.12[c]	+210.97[c]
HI (–) High-N	+92.86[c]	+61.53	+85.82	+38.40
LI (+) I.S.	848.86	740.29	955.96	693.36
LI (+) D.S.[d]	+6.62	–123.33[c]	–9.34	–3.85
LI (+) Fungicide	–87.13[c]	–81.86	+40.92	+74.77
LI (+) PGR	–104.38[c]	–199.83[c]	+43.71	+33.41
LI (+) Autumn starter	–85.13[c]	–84.43	+16.58	+103.26
LI (+) Weekly N	–198.55[c]	–230.08[c]	–163.68[c]	–107.09
LI (+) High-N	+46.50	–64.25	+65.23	+25.67
Check[e]	649.68	365.24	482.14	499.09
HI vs. LI[f]	[c]	[c]	[c]	ns[g]
CV, %	8.9	18.3	12.3	18.5

[a] Decreased seeding rate (D.S.), trinexapac-ethyl plant growth regulator (PGR), weekly N applications (Weekly N), 33% increase in nitrogen fertilizer rate (High-N), increased seeding rate (I.S.).

[b] Values in HI (-) input rows indicate an expected return (US$ ha^{-1}) change from respective HI treatment.

[c] Significantly different at α = .10 using single degree of freedom contrasts.

[d] Values in LI (+) input rows indicate an expected return (US$ ha^{-1}) change from respective LI treatment.

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

[f] Comparison between the HI and LI control treatment utilizing single degree of freedom contrasts.

[g] Non-significant α = .1 using single degree of freedom contrasts.

net return $136.8–422.36 ha^{-1} compared to the HI treatment containing all inputs in 3 of 4 site-years (Table 5). Results agree with Quinn and Steinke (2019) where LI management containing only a university recommended base N rate increased expected net return $221 ha^{-1} compared to another HI intensified management system. Due to application costs exceeding grain yield increases, weekly N applications decreased expected net return when added to LI management in 3 of 4 site-years and increased net returns when removed from HI management in all 4 site-years. Averaged across site-years, removing weekly N application from HI management increased expected net return $196 ha^{-1} and decreased returns by $175 ha^{-1} when added to LI management (Table 5). Despite some yield gains, no individual input increased expected net return across all 4 site-years. Producers may often consider potential yield loss a greater liability than losing net return (Mourtzinis et al., 2017; Rutan & Steinke, 2017). However, results from this study were consistent with previous research indicating that both grain yield and profitability must be integrated for optimal wheat management (Jaenisch et al., 2019; Quinn & Steinke, 2019). At listed wheat prices and input costs, producers may benefit from greater emphasis upon expected net returns in lieu of protecting yield losses which may or may not occur (Quinn & Steinke, 2019). Despite wheat grain yield increases from many of the inputs within the environments tested, the economic net returns may not be sufficient to offset the costs to attain greater yield.

3.4 | Seeding rate

Decreased seeding rate (i.e., 2.2 million vs. 4.4 million seeds ha^{-1}) within LI management reduced grain yield 1.1 Mg ha^{-1} in 1 of 4 site-years (i.e., Lansing 2018), while removing the decreased seeding rate component (i.e., utilizing a recommended seed rate) from the HI managed system had little impact on grain yield at either location in 2018 or 2019 (Table 4). Fewer plants per unit area may allow for greater light interception, reduced interplant competition for moisture and nutrients, and overall more efficient utilization of

TABLE 6 Winter wheat seeding rate and autumn starter fertilizer effects on Feekes 4 tiller production, Richville and Lansing, MI, 2018–2019. Mean tiller production displayed for high-input (HI) control (all inputs applied at decreased seed rate) and low-input (LI) control (base rate of N with no inputs) with other treatments displaying change in tiller counts from respective HI or LI treatment

		Treatment					
Site	Year	HI (+) D.S.[a]	HI (+) I.S.	HI (–) Autumn starter	LI (+) I.S.	LI (+) D.S.[d]	LI (+) Autumn starter
		tillers m^2	——% change	——	tillers m^2	——% change	——
Richville	2018	1,049	+16	–24[e]	885	+19	+0
	2019	607	+14	–1	651	+13	+42[e]
Lansing	2018	829	+25	–21	671	+31	+116[e]
	2019	581	+59[e]	–15	547	+19	+42[e]

[a] Decreased seeding (D.S.) rate of SRWW/SWWW (Starburst/Jupiter) at 2,223,900 seeds ha^{-1}.

[b] Increased seeding (I.S.) rate of SRWW/SWWW (Starburst/Jupiter) at 4,447,800 seeds ha^{-1}.

[c] Values in column indicate percent tiller production (m^{-2}) change from respective HI treatment control.

[d] Values in column indicate percent tiller production (m^{-2}) change from respective LI treatment control.

[e] Significantly different at α = .10 using single degree of freedom contrasts.

individual inputs as compared to greater seeding rates and still produce comparable grain yield (Chen et al., 2008; Darwinkel et al., 1977; Joseph et al., 1985). Lansing 2018 deficit June through July precipitation (i.e., 60% below the 30-yr mean) combined with 52% of June daytime temperatures >24 ˚C likely produced dry soil conditions during grain fill contributing to grain yield reductions (Table 3). During grain fill, wheat reproductive development is optimal under cooler (<24˚C) daytime air temperatures as temperatures >24 ˚C may reduce kernel size and grain yield (Prasad & Djanaguiraman, 2014 ; Akter & Rafiqul Islam, 2017). Results correspond with Geleta et al. (2002) who found lower than recommended seeding rates reduced yield 0.8 Mg ha^{-1}, but results were influenced by environmental conditions rather than decreased seeding rate alone. Current data suggest decreased seeding rates may offer greater opportunity in a HI as compared to LI management system while still achieving similar grain yield and expected net return.

Plant growth measurements showed tiller density increased 59% utilizing HI management with the greater seeding rate at Lansing 2019 (Table 6). Growing degree days (GDD) from planting to Feekes 4 totaled 758 in 2019 which were 54% fewer than 2018. Winter wheat tiller development begins at 720 GDDs producing an additional tiller every 180 GDDs (Klepper et al., 2014). Lansing 2019 wheat was planted 19 d later than 2018 resulting in less tiller development due to fewer GDDs. Plant development with the decreased seeding rate at Lansing 2019 was limited to an average of two tillers per plant as compared to an average of four tillers per plant in 2018. Compared to greater seeding rates, reduced seeding rates may better utilize May–June GDDs to produce additional tillers per plant resulting in an equivalent heads per unit area and thus result in comparable grain yield (Darwinkel, 1978; Klepper et al., 2014; Masle, 1985). Results from this study suggest that delayed winter wheat planting dates (i.e., after 5 October) may increase the risk for reduced yield potential when utilizing decreased seeding rates as variable autumn weather and spring GDD accumulation are difficult to forecast ahead of time. Recent variable winter precipitation patterns including more frequent freeze/thaw cycling and ice sheeting from winter rainfall over frozen soils in combination with already variable spring precipitation may add additional risks including reduced plant hardiness and spring plant survival when choosing to reduce winter wheat seeding rates.

3.5 | Fungicide

Adding or removing fungicide application each affected grain yield in 1 of 4 site-years (Table 4). Dry soil conditions at Richville 2018 provided low FHB risk with little foliar disease pressure resulting in no response to fungicide. Lansing 2018 fungicide removal from HI management reduced grain yield 0.8 Mg ha^{-1} while fungicide addition to LI management increased grain yield 0.8 Mg ha^{-1} at Lansing 2019 (Table 4). Lansing received 7.2 cm greater May rainfall than Richville in 2018 likely creating a more favorable environment for FHB development (Table 3). Despite Richville May 2019 receiving above average rainfall, dry April soil conditions may have absorbed some of the excess May rainfall leading to a less humid microenvironment and reduced disease development. Moist, cool conditions and frequent rainfall during wheat anthesis (Feekes 10.5.1) increase risk for FHB infection and DON accumulation. Local areas within Michigan experienced warm temperatures and increased humidity levels during anthesis that promoted 2019 FHB development (Pennington et al., 2019). Growers should implement routine field

TABLE 7 Effect of Feekes 10.5.1 fungicide on winter wheat Fusarium head blight occurrence (infected heads) 3 wk after fungicide application, Richville and Lansing, MI, 2018–2019

Site	Year	Treatment HI	HI (–) Fungicide	Change[a]	LI	LI (+) Fungicide	Change
		% infected heads m^{-2}		%	% infected heads m^{-2}		%
Richville	2018	0.0	0.0	g0.0	0.0	0.0	+0.0
	2019	6.6	17.5	+10.9[c]	15.9	10.7	–5.2
Lansing	2018	9.3	17.5	+8.2[c]	16.9	12.1	–4.8
	2019	0.3	2.7	+2.4[c]	4.5	1.6	–2.9[c]

[a] Values indicate percent change in heads affected (%) between 'HI' and 'HI (-) Fungicide' treatment.

[b] Values indicate percent change in heads affected (%) between 'LI' and 'LI (+) Fungicide' treatment.

[c] Significantly different at α = .10 using single degree of freedom contrasts.

TABLE 8 Impact of high-input (HI) or low-input (LI) management and autumn starter fertilizer on winter wheat grain head production, Richville and Lansing, MI, 2018–2019. Mean head production displayed for HI control (all inputs applied at decreased seed rate) and low-input (LI) control (base rate of N with no inputs) treatments. All other treatments display change in head production from respective HI or LI control treatments using single degree of freedom contrasts

Site	Year	Treatment HI	HI (–) Autumn starter	Change	LI	LI (+) Autumn starter	Change[b]
		heads m^{-2}		%	heads m^{-2}		%
Richville	2018	700	762	+9	786	756	–4
	2019	823	699	–15	671	789	+18[c]
Lansing	2018	832	741	–11	780	912	+17[c]
	2019	1,074	681	–37[c]	681	1,160	+70[c]

[a] Values indicate percent change in head production (%) between 'HI' and 'HI (-) Autumn Starter treatment.

[b] Values indicate percent change in head production (%) between 'LI' and 'LI (+) Autumn Starter treatment.

[c] Significantly different at α = .10 using single degree of freedom contrasts.

scouting and utilize disease development prediction models as FHB protecting fungicides are mostly applied prior to infection and may not increase yield or profit without disease pressure.

Visual assessment of disease presence showed removal of fungicide from HI management increased FHB incidence 10.9% at Richville 2019 (Table 7). Fungicide removal from HI management at Lansing increased FHB incidence 8.2 and 2.4% in 2018 and 2019, respectively. Adding fungicide to LI management reduced FHB occurrence 2.9% at Lansing 2019 with no effects in other site-years (Table 7). Data support Blandino et al. (2006) who reported a 52% reduction of FHB incidence from a triazole fungicide applied during anthesis which resulted in a 20% yield increase. Additionally, McMullen et al. (2008) observed triazole fungicide application applied during anthesis reduced FHB incidence 8.9% compared to no fungicide application. Fungicide application appeared to offer greater consistency in reducing FHB incidence when applied to HI compared to LI management. In years FHB was present, HI management produced on average 28% more heads than LI management (Table 8) likely creating a favorable disease environment due to greater density of heads limiting wind movement. Results suggest greater wheat head production may offer opportunities for a fungicide application to reduce FHB or lessen foliar disease incidence. Aside from grain yield benefits, greater advantages from fungicide application may exist in SWWW as critical DON concentrations are lower compared to SRWW due to SWWW usage within the milling and cereal industries. Producers should consider incorporating a disease resistant variety along with utilizing integrated pest management practices to improve fungicide efficacy and response (Quinn & Steinke, 2019; Wegulo et al., 2012).

3.6 | Plant growth regulator

Adding plant growth regulator to LI management reduced grain yield 0.9 Mg ha^{-1} at Lansing 2018, while removing

TABLE 9 Site year and soil descriptions including soil chemical properties and mean P, K, S, and Zn soil test (0–20 cm) nutrient concentrations obtained prior to winter wheat planting, Richville and Lansing, MI, 2018–2019

			Soil test						
Site	Year	Soildescription	P	K	S	Zn	pH	OM	CEC
			mg kg^{-1}					g kg^{-1}	$cmol_c$ kg^{-1}
Richville	2018	Tappan-Londo loam	17	152	9	5.4	7.7	21	16.0
	2019	Tappan-Londo loam	13	137	6	5.7	8.0	20	20.3
Lansing	2018	Capac loam	12	80	8	2.5	7.0	25	12.1
	2019	Capac loam	33	102	8	3.4	7.1	28	12.0

Note. P, phosphorus (Bray -P1 equivalent or Bray-P1 depending on soil pH); K, potassium (ammonium acetate extractable K); S, sulfur (monocalcium phosphate extraction); Zn, zinc (0.1 M HCl); OM, organic matter; CEC, cation exchange capacity.

PGR from HI management did not significantly influence grain yield across any site-year (Table 4). Grain yield reductions at Lansing 2018 may have been due to an 11% decrease in number of kernels per head when PGR was added to LI management (data now shown). Dry June conditions at Lansing 2018 may have contributed to reduced kernel development and grain yield by limiting nutrient uptake during the grain-fill period. A combination of the PGR application that inhibited gibberellins to promote growth (Matysiak, 2006) and dry soil conditions likely resulted in the grain yield and kernels per head decrease at Lansing 2018. Results agree with Karlen and Gooden (1990) who found grain yield decreased 0.2 Mg ha^{-1} with PGR application compared to no PGR application. Multiple researchers have reported inconsistent grain yield responses from PGR application without plant lodging (Quinn & Steinke, 2019; Swoish & Steinke, 2017; Wiersma et al., 2011). However, Matysiak (2006) reported PGR application increased kernels per head 5.4% which lead to a 7% grain yield increase in the absence of lodging.

Plant height reductions were inconsistent when PGR was added individually to the LI system. No plant lodging occurred across either location or management intensity when utilizing N rates up to 194 kg N ha^{-1}. Results agree with Swoish and Steinke (2017) who determined grain yield increases from a PGR application were more likely in taller-statured varieties with weak-stem strength to increase lodging potential. Both varieties (Jupiter and Starburst) utilized in this study contain short-strawed, high stem-strength physical characteristics (Michigan Crop Improvement Assoc.) which likely explains the lack of response to PGR application. As yield potential continues to increase from shorter plant size and greater harvest index (Evans & Fisher, 1999), positive responses from PGR application may depend more upon varietal characteristics including cultivar structure and lodging susceptibility rather than applying a PGR to account for greater than recommended N rates.

3.7 | Autumn starter fertilizer

Removal of autumn starter fertilizer from HI management decreased grain yield 1.0–2.5 Mg ha^{-1} in 3 of 4 site-years while including autumn starter fertilizer to LI management significantly increased grain yield 0.6−1.7 kg ha^{-1} in all 4 site-years (Table 4). Wheat grain yield responses to P fertilizer applications are less probable when soil test P concentrations are above critical (i.e., 25 mg P kg^{-1} (Bray-P) (Warncke et al., 2009). Soil test P concentrations from this study consisted of 12–33 mg P kg^{-1} across site-years (Table 9). Despite some below critical soil P concentrations for wheat, broadcast applied P to all plots across locations reduced the likelihood of a singular P_2O_5 response from within the autumn starter fertilizer. Wheat is classified as low in responsiveness to zinc applications in Michigan (Warncke et al., 2009). However, positive grain yield responses to autumn starter fertilizer may have been due to the N and or S components.

Pre-plant soil nitrate concentrations (0–30 cm) were <10 mg NO_3–N kg^{-1} across all site-years. Low soil nitrate concentrations increase the likelihood for a positive winter wheat yield response to autumn N-containing starter fertilizer (Alley et al., 2009). Results corroborate with Forrestal et al. (2014) who found no grain yield response to 34 kg N ha^{-1} autumn applied when soil test nitrate concentrations were ≥16 mg NO_3–N kg^{-1} thus the need to consider residual soil N concentrations. At both locations, autumn starter fertilizer had a greater impact on 2019 grain yield when removed from HI management and added to LI management when compared to 2018 (Table 4). Richville soil nitrate concentrations were 9.1 and 4.3 mg NO_3–N kg^{-1} in 2018 and 2019, respectively, suggesting the lower pre-plant nitrate concentration in 2019 increased potential for a positive response to autumn starter fertilizer. Lansing 2018 and 2019 pre-plant soil nitrate concentrations were similar (4.3 mg NO_3–N kg^{-1}), but preceding crops were silage corn and soybean in 2018 and 2019, respectively, likely contributing to the degree of responsiveness between the 2 yr. Response to autumn applied N may be greater for wheat following soybean rather than following corn as corn often leaves greater, more variable residual pre-plant N concentrations for wheat due to a lower N removal rate from the soil combined with N fertilizer applications (Forrestal et al., 2014; Mourtzinis et al., 2017). Soil testing for predicting an S response has been shown to be unreliable (Franzen, 2018; Kaiser et al., 2019). Reduced atmospheric deposition since the 1980s has increased winter wheat yield responses to applied S (Dhillon et al., 2019; Girma et al., 2005). The S component within the autumn starter fertilizer consisted of 50% sulfate-S and 50% elemental S. Sulfate-S is immediately available to the winter wheat crop for uptake while elemental S is oxidized to sulfate-S to later become plant available (Mahler & Maples, 1987). In this study, sulfate-S was immediately available in autumn for the winter wheat while the elemental S may oxidize to become available at a later time the following season. Results from this study correlate with McKay (1996) who found 20 kg S ha^{-1} increased wheat grain yield 0.4 Mg ha^{-1} across 3 site-years. Site-specific field conditions, S source, soil texture, crop rotation, and local environmental factors (e.g., winter precipitation) may influence grain yield responses to winter wheat S applications.

Removal of autumn starter fertilizer from HI management decreased tiller production in 1 site-year while addition of autumn starter fertilizer to LI management increased tiller production in 3 site-years (Table 6). Increases in tiller production from autumn starter fertilizer were likely due to the N component within the starter fertilizer. University recommendations suggest 34 kg N ha^{-1} autumn applied can promote additional autumn tillering in winter wheat (Alley et al., 2009). Tiller production at Feekes 4 may not always equate to final head production as wheat forms additional grain-producing tillers until Feekes 5 (Wise et al., 2011). Tiller production and head production showed similar increases from addition of autumn starter fertilizer to LI management across site-years (Tables 6 and 8). In 1 of 4 site-years, removal of autumn starter fertilizer from HI management decreased head production 37% while head numbers increased 17–70% in 3 of 4 site-years with addition of autumn starter fertilizer to LI management (Table 8). Similar to grain yield, tiller and head production both showed significant increases from addition of autumn starter fertilizer to LI management in 3 of 4 site-years (Tables 4, 6, and 8). Results suggest pre-plant soil test concentrations and tiller production may both indicate whether a wheat crop will respond to autumn starter fertilizer. Autumn fertilizer applications may be one component to accelerate plant growth and grain yield potential, but producers should base the analysis of an autumn starter fertilizer upon pre-plant soil test concentrations and the likelihood of a positive grain yield response to specific nutrients.

3.8 | Weekly N applications

Removal of weekly N applications from the HI increased grain yield 0.5 Mg ha^{-1} in 1 of 4 site-years, while the addition of weekly N to LI had no effect across any site-year (Table 4). No visual N deficiency symptoms occurred within fertilized plots at any location throughout the study. Minimal rainfall (<0.65 cm) occurred 17 d following the 2nd and 3rd weekly N application at Richville 2018 which coincided with accelerated N uptake (i.e., Feekes 7) (Table 10). Precipitation events ≥0.65 cm may be needed within 2 d of surface N application to eliminate or reduce volatilization potential (Sawyer, 2018). Lack of rainfall between the 2nd and 3rd weekly N applications likely limited N movement into the rhizosphere during the accelerated N uptake period leading to the grain yield increase when removing weekly N at Richville 2018. Results coincide with Roberts et al. (2004) who suggested insufficient amounts of available N during accelerated N uptake and plant growth (May–April) can reduce wheat grain yield. Volatilization likely also occurred to surface applied weekly N during the period of absent rainfall between the second and third application, as canopy coverage was merely 34% (data not shown) indicating lack of dense ground cover. Results are supported by Bacon et al. (1986) who found surface applied N volatilized 35% within 5 d after application when rainfall was <0.65 cm. Although May through June total rainfall during 2019 was 75 and 55% greater compared to the 30-yr mean in Richville and Lansing, respectively, a longer duration of N loss conditions (i.e., leaching and denitrification) on the medium to fine textured soils of this study may be needed to realize benefits from weekly N applications (Gravelle et al., 1988). Compared to one-pass N applications between Feekes 4 and 5, weekly N applications showed no benefit in the current study but may benefit in situations where greater rainfall intensities promote N loss by transporting soluble N out of the rhizosphere. Data from this study suggest excessive rainfall to create N loss conditions throughout the growing season may be required to substantiate a grain yield benefit from weekly N application in Michigan winter wheat growing conditions. Although weekly N applications may minimize risks for N loss in some situations, application costs continued to offset any grain yield increase.

3.9 | High N rate

Applying 33% more N did not influence grain yield in HI or LI systems (Table 4). The 2019 growing season produced excessive (+20%) total growing season rainfall for both locations (Table 3) which likely provided potential for N loss conditions (i.e., denitrification and leaching). However, minimal grain

TABLE 10 Precipitation[a] volumes the week following weekly winter wheat N applications in Richville and Lansing, MI, 2018–2019

Site	Year	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8[b]	Total
		cm								
Richville	2018	5.18	0.05	0.03	1.75	1.88	1.14	0.20	0.74	10.97
	2019	0.36	2.97	8.97	1.07	2.97	0.71	0.79	8.23	26.07
Lansing	2018	0.25	4.50	0.10	0.07	1.40	6.76	2.34	2.11	17.53
	2019	0.02	2.24	1.75	3.02	2.72	1.83	1.70	1.63	14.91

[a] Precipitation data were collected from Michigan State University Enviro-weather (https://enviroweather.msu.edu/).

[b] Volume precipitation totals represent the seven consecutive days following previous weekly N application.

yield responses suggest the LI base N rate was sufficient to optimize wheat grain yield at current production levels within the environments tested. Bauer (2016) concluded an N rate of 84 kg N ha^{-1} produced optimal SRWW grain yield in Michigan. Data from this study correspond with university recommended N rates suggested by Warncke et al. (2009) but recommendations are based off the expectation that yield response to applied N is independent from agronomic factors (e.g., cultivar, seeding rate) (Brinkman et al., 2014). Applying multiple inputs may increase the flag leaf stay-green potential and prolong grain fill resulting in greater N requirements to support greater grain yield potential (Mourtzinis et al., 2017; Quinn & Steinke, 2019; Salgado et al., 2017). No differences in green canopy cover or normalized difference vegetation index (NDVI) occurred at any location throughout the study (data not shown). Previous studies from Quinn and Steinke (2019) and Jaenisch et al. (2019) both suggested enhanced management systems may require additional N to influence grain yield responses from other agronomic inputs. Further research may be needed to explore possible relationships between multiple agronomic inputs and N fertilizer across additional wheat varieties and environmental conditions to determine whether recommended wheat N rates require modification but data from the current study do not support this concept.

4 | CONCLUSIONS

In the environments tested for this study, minimal SRWW and SWWW grain yield responses occurred from applications of fungicide, PGR, weekly N, and high N management. However, benefits from these inputs may occur when utilizing disease susceptible or tall statured varieties or when greater rainfall intensities promote N loss conditions. Decreased seeding rate (i.e., 2,223,900 seeds ha^{-1}) produced comparable grain yield to the increased seeding rate (i.e., 4,447,800 seeds ha^{-1}) under HI management across all site-years. Harsh winter conditions and increased spring weather variability may add additional risk to reducing winter wheat seeding rates with timely planted wheat. Autumn-applied starter fertilizer was the only individual agronomic input to consistently provide grain yield responses across site-years which accounted for 71% of the grain yield difference between HI and LI intensities. Although HI SWWW and SRWW management increased grain yield, LI management containing only a base rate of N increased expected net return in 3 of 4 site-years. Results emphasize that producers should be mindful of pre-plant soil nutrient concentrations (i.e., P and nitrate levels) as responses to autumn fertilizer are unlikely when nutrient concentrations are at or above critical levels. Wheat producers should utilize multiple production strategies (i.e., disease prediction models, crop scouting, varietal resistance, nutrient recommendations) to justify input applications and take advantage of proven benefits identified with many of the agronomic inputs used in this trial. Producers should consider commodity prices, fertilizer cost, and potential yield response prior to adopting widely implemented HI management strategies. Site-specific considerations including soil and plant characteristics, attainable yield potentials, and economics must still be considered within an integrated management program. Despite grain yield increases to input additions, greater expected net return may still be achieved at reduced grain yields if specific inputs turn out to protect or insure against yield losses that may or may not occur.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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