PLANTING PRACTICES FOR IMPROVED STAND ESTABLISHMENT AND YIELD POTENTIAL IN WINTER WHEAT

By

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ABSTRACT

While planting time is an important factor in determining yield potential in winter wheat (*Triticum aestivum* L.), adverse weather conditions in the US Midwest often pose a challenge for achieving timely planting. In recent years, broadcast incorporation of seed has gained some traction as a faster, cheaper alternative to the traditional grain drill or air seeder, but there are concerns with imprecise seed placement. Precision planting, which results in more precise seed placement but does not have the speed or cost benefits of broadcast incorporation, is also being considered as an alternative planting method. Multiple field trials were conducted across Michigan to examine the influence of planting time, seeding rate, planting method, and seeding depth on stand establishment and yield in winter wheat. A significant reduction in yield was observed when planting occurred after mid-October, with >20% yield decline in all three years. Precision planting exhibited an 8–33% yield increase over drill or air seeder at 4 out of 11 site-years. Broadcast incorporation showed a 63–103% increase in depth variability relative to drill or air seeder but did not consistently result in yield difference. This may have been due to a 50–169% increase in the number of effective tillers plant^{-1}. Yield showed no relation to seeding depth, except in 2022, where shallow seeding depth of 1.3 cm resulted in higher yield, likely due to favorable fall weather allowing for more fall tiller formation. Overall, while precision planting in winter wheat may result in a yield increase compared to a grain drill, broadcast incorporation may be a better choice in situations where its increased speed of operation allows for earlier planting.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
AOSR	Agronomically optimal seeding rate
CEC	Cation exchange capacity
CV	Coefficient of variation
DON	Deoxynivalenol
HSD	Honest significant difference
TKW	Thousand-kernel weight
US	United States

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CHAPTER 1: INTRODUCTION

Changing climatic conditions in recent years have brought about many weather-related challenges when it comes to planting winter wheat (*Triticum aestivum* L.) in Michigan and other Midwestern states. Winter wheat benefits from early planting, yet a wide range of planting dates are still implemented due in part to the large amount and variability of fall rainfall resulting in poor soil conditions. Climatic shift toward a longer growing season in Michigan and other northern US states could be a benefit for winter wheat crops, but a better understanding of how planting decisions influence crop yield potential is necessary to reap this benefit.

The yield gains in agronomic crops since the Green Revolution in the mid-20th century were largely attributed to increases in yield potential resulting from improved genetics and the adoption of better agronomic practices (Evans & Fisher, 1999). Yield potential is a function of light interception, radiation use efficiency, and the partitioning of photosynthetic products into biomass and grain yield (i.e., harvest index). Improvements in stand establishment can have a positive impact on yield potential by increasing canopy cover, improving radiation use efficiency, and improving plant-to-plant uniformity. There are many decisions that go into achieving good stand establishment, including planting date, seeding rate, seed placement, and pre-planting treatment/handling of seeds. This project evaluated planting strategies to improve yield potential and profitability in winter wheat.

Two of the most basic and crucial factors in determining yield potential are planting date and seeding rate. Current MSU recommendations for winter wheat suggest a seeding rate of 2.0–3.5 million seeds ha^{-1} when planting during the optimal window (i.e., mid-September–mid-October) and an increase to 4.4–4.9 million seeds ha^{-1} under delayed planting. However, data on the response of current cultivars to various seeding rates and planting dates are needed to update these recommendations and to determine the current yield penalty resulting from delayed planting. Additionally, quantifying the rates of physiological development—especially the length of the grain filling stage—will be key to understanding the consequences of planting time on wheat development and yield.

Proper placement of seeds in the seedbed is another important aspect of productive and profitable crop production (Koch & Khosla, 2003a). Traditionally, in the United States, wheat is planted using low-precision grain drills. These drills meter seed by means of metering gears in the bottom of the seed box that rotate to allow seed to fall past them at the appropriate rate into the seed tube, which carries the seed into the ground between the disc openers. This results in very imprecise metering, as well as poor depth control and a random distribution of seeds within the row, which can cause poor germination and crown root development, reduced tillering, increased disease incidence, susceptibility to winter injury in winter cereals, and ultimately reduced yields (Hines, 2018a; Hörbe et al., 2016a; Kirby, 1993a). A commonly-used remedy for this in larger-seeded crops is precision planting, where the use of vacuum pressure against a seed plate allows for singulation and regular spacing of seeds. Small-plot research in wheat at Michigan State University showed a 2.4–25.8% yield improvement by combining precision planting with narrow rows. However, this research needs validation under commercial field settings and comparison against other less precise planting methods.

Development of precision planting for wheat can result in more precise seed placement. Yet, adverse weather conditions have resulted in planting delays and increased interest in high-speed planting technologies among Midwest row crop growers. Broadcasting seed then incorporating it with a shallow tillage implement (i.e., “broadcast incorporation”) is one such technique that offers faster planting with low initial investment. Theoretically, this can lead to a more uniform two-dimensional distribution of plants compared to planting in rows, which results in a high density within the row and a low density across rows. A uniform distribution of plants would reduce inter-plant competition, and the technique has shown promise in crops such as soybean (Wilde, 2020a). However, there has not been enough research done to confirm this hypothesis. There are also concerns regarding non-ideal seeding depth, inadequate seed-to-soil contact, and impacts on grain quality. Limited research comparing broadcasting with drill showed either a yield reduction with broadcasted seed (Collins & Fowler, 1992a), due to poorer stand establishment and more prostrate plant growth habit, or no yield difference between methods but greater variability in broadcasted seed (Hines, 2018a).

Precise seed placement can impact plant growth and development—especially root development and tillering potential—in winter wheat. Extremely shallow or deep placement due to poor depth control results in uneven emergence and tillering and hinders establishment of an adequate wheat stand. Shallow seeding results in poor seed coverage by soil, inadequate moisture for germination, and the development of plant crowns near the soil surface, where they are susceptible to heaving and lodging (Roth et al., 1984). Deeper seeding may cause low seedling emergence (especially in semi-dwarf varieties with short coleoptiles), weaker plants, and uneven stands. Most wheat varieties grown in the United States have the Rht-B1b or Rht-D1b dwarfing alleles, which reduce plant height but also lead to coleoptiles up to 50% shorter than in wild types (Guedira et al., 2010). However, the impact of seeding depth on emergence and tillering potential in wheat in Michigan is not well understood and will be critical in determining the ideal planting technologies for wheat production.

1.1 PRIMARY GOALS AND OBJECTIVES

The overall goal of this body of research was to identify and evaluate planting strategies to improve stand establishment and yield in winter wheat.

Objective 1: Evaluate the impact of planting date and seeding rate on stand establishment, phenological development, and grain yield and quality of winter wheat.

Objective 2: Compare seed placement accuracy, yield, and grain quality among conventional drill, broadcast incorporation, and precision planting technologies in winter wheat.

Objective 3: Quantify the effect of seeding depth on stand establishment and tillering potential among diverse winter wheat cultivars at low and high seeding rates.

1.2 EXPERIMENTAL PLAN

1.2.1 Objective 1: Evaluate the impact of planting date and seeding rate on stand establishment, phenological development, and grain yield of winter wheat.

Hypothesis: Optimal seeding rate would increase with delayed planting to minimize yield loss, while a shorter grain fill period under late planting would reduce yield potential.

Trial Design: A small-plot replicated field experiment was conducted at the Michigan State University Mason Farm for three years (2019–20, 2020–21, 2021–22) in randomized complete blocks in a split-plot design. Whole plots consisted of winter wheat planted on each of five separate planting dates (starting mid-September and planting every 11–23 days until mid-November). Subplots included five seeding rates (2.0, 3.0, 4.0, 4.9, and 5.9 million seeds ha^{-1}). Each plot consisted of six rows spaced 19 cm apart and 3.7 m in length, with a 1.8-m alley between plots.

Data collection: Data collection included stand counts at Feekes 1, pre-harvest head counts, yield, TKW, grain protein content (measured using near-infrared spectroscopy), and deoxynivalenol content.

1.2.2 Objective 2: Compare seed placement accuracy, yield, and grain quality among conventional drill, broadcast incorporation, and precision planting technologies in winter wheat.

Hypothesis: Precision planting would result in more accurate seed placement than a conventional grain drill, leading to improved wheat development, yield potential, and quality. Meanwhile, yield and quality would be lower under broadcast incorporation due to increased variability in depth and seed-to-seed spacing. These negative results would be reduced, however, by increasing the seeding rate by about 30%.

Trial Design: Field scale trials were conducted across Michigan farms in a randomized complete block design (RCBD) for three years (2020–21, 2021–22, 2022–23). Plot width was dependent on the equipment used and ranged from 3 m to 34 m, while plot length ranged from 9.1-m to 900-m. Each treatment was replicated four times. Each location included a minimum of three of the following treatments: seed drill (required at all locations), broadcast incorporation (required at all locations), precision planting in 13-cm rows, and broadcast incorporation with 30% higher than standard seeding rate. Other treatments were added, based on grower and researcher interest.

Data collection: Data collection consisted of fall stand counts, spatial uniformity measurements (2–3 spots per plot), seed depth measurements (15 plants per plot), spring tiller counts, pre-harvest tiller and head counts (2–3 spots per plot), yield, TKW, and grain protein content (measured using near-infrared spectroscopy).

1.2.3 Objective 3: Quantify the effect of seeding depth on stand establishment and tillering potential among diverse winter wheat cultivars at low and high seeding rates.

Hypothesis: Optimum seeding depth would improve stand establishment, uniformity, and tillering potential, leading to increased yield and benefits of precision planting.

Trial Design: A small-plot replicated field experiment was conducted at the Michigan State University Mason Farm for three years (2020–21, 2021–22, 2022–23) in a split-plot design with four replications. Whole plots included four seeding depths (1.3, 3.8, 6.4, and 8.9 cm), while sub-plots included a combination of three varieties with different dwarfing genes (Rht-B1b, Rht-D1b, and non-Rht) and two seeding rates (2.0 and 3.5 million seeds ha^{-1}). Each plot consisted of six rows spaced 19 cm apart and 3.7 m in length, with a 1.8 m alley between plots, and were planted using an Almaco research plot planter.

Data collection: Data collection consisted of daily emergence ratings, plant counts at Feekes 1, seeding depth (15 plants per whole plot, taken from alleys between sub-plots), spring stem counts, pre-harvest tiller and head counts, lodging ratings, and yield.

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CHAPTER 2: MAXIMIZING WINTER WHEAT YIELD THROUGH PLANTING DATE AND SEEDING RATE MANAGEMENT

2.1 ABSTRACT

Planting date and seeding rate are two of the most basic and important factors in determining yield potential in winter wheat (*Triticum aestivum* L.) due to their impact on stand establishment. Timely planting of winter wheat (within a few days after the Hessian fly free date) ensures sufficient time for fall growth and tillering, which are critical for maximizing yield, while adequate seeding rate is necessary to optimize the number of heads per unit area. Field experiments were conducted in Mason, Michigan during three growing seasons (2020–2022) utilizing five planting dates, ranging from mid-September to mid-November, and five seeding rates ranging from 2.0–5.9 million seeds ha^{-1}. There was no interaction between planting date and seeding rate in determining yield. Yields declined by 22–48% from the earliest to the latest planting dates in response to a 33–47% reduction in the number of heads ha^{-1}. Seeding rate did not significantly impact yield except at low seeding rates under delayed planting. Maximum yield was achieved with a seeding rate of 2.30, 3.39, 3.63, 3.81, and 4.57 million seeds ha^{-1} during the mid-September, late September, mid-October, late October, and mid-November plantings, respectively. Overall, results demonstrated that timely planting of wheat is critical for maximizing yield, with significant yield reductions occurring when planting is delayed, regardless of seeding rate used. Furthermore, while low seeding rates may be used within the optimal planting window without yield penalty, seeding rates should be progressively increased as planting is delayed to diminish yield loss.

2.2 INTRODUCTION

Planting date and seeding rate are two of the most basic and important factors in determining yield potential in winter wheat (*Triticum aestivum* L.). Yield potential is a function of radiation interception, radiation use efficiency, and the partitioning of photosynthetic products into biomass and grain yield (i.e., harvest index). Improvements in stand establishment positively impact yield potential by improving plant-to-plant uniformity (Hörbe et al., 2016a; Koch & Khosla, 2003a), increasing canopy cover, which improves radiation interception and use efficiency. Stand establishment can be affected by a variety of factors, including seed quality, seed placement (Hörbe et al., 2016a; Kirby, 1993a; Koch & Khosla, 2003a; Loeppky et al., 1989a), planting date, seeding rate, and weather (Lindsey et al., 2020; McGlinch & Lindsey, 2022).

Winter wheat benefits from timely planting since planting too late limits fall growth and tillering, which are critical for maximizing yield. An adequate seeding rate is also necessary to optimize the number of grain-bearing heads (Lindsey et al., 2020; McGlinch & Lindsey, 2022), but higher seeding rates increase seed cost and can reduce net returns if there is not a sufficient corresponding yield benefit. Crop yields are determined by a set of physiological traits known as yield components, which relate to one another hierarchically (Figure 2.1). Determining how a given factor interacts with each yield component improves understanding of how that factor impacts yield. In Wisconsin in the 1990s, winter wheat yields decreased when planting was delayed beyond early October due to reductions in head density and thousand-kernel weight (TKW). Furthermore, tiller production was reduced with delayed seeding, and seeding rate did not influence yield until planting after early October—at which point, increasing seeding rate diminished yield losses (Dahlke et al., 1993).

Seeding Rate per Unit Area
×
Percent Emergence = Plants per Unit Area
×
Heads per Plant = Heads per Unit Area
×
Kernels per Head = Kernels per Unit Area
×
Kernel Weight = Yield

Figure 2.1. Physiological traits that relate to one another hierarchically and interact in determining final grain yield.

Current recommendations in the U.S. Great Lakes Region advise that winter wheat should be planted within a few days following the Hessian fly free date (Lindsey et al., 2017; Nafziger, 2002; Pennington et al., 2022). Hessian fly (*Mayetiola destructor* Say.) is no longer a significant concern for wheat growers, but this date is still considered a good rule of thumb for determining optimal planting date to avoid excessive fall growth and early disease establishment (Lindsey et al., 2017; Pennington et al., 2022). The Hessian fly free date varies with latitude with earlier dates occurring farther north, so wheat should be planted earlier farther north and later farther south. Recommendations also state that seeding rate should increase as planting is delayed to account for potential reductions in fall tillers per plant resulting from late planting (Lindsey et al., 2017; Pennington et al., 2022). In the Great Lakes Region, university extension recommendations typically suggest a seeding rate of 3.0–4.0 million seeds ha^{-1} when planting during the optimal window (i.e., mid-September to mid-October) and an increase to 4.0–4.9 million seeds ha^{-1} when planting is delayed into the latter half of October (Lindsey et al., 2017; Olson et al., 2021; Pennington et al., 2022). However, these recommendations are based primarily on studies conducted decades ago. Since then, there have been changes in climate and wheat genetics that can impact crop response to planting date and seeding rate.

Despite the importance of timely planting, winter wheat is planted over a wide range of dates in Michigan and the Great Lakes Region (Supplemental Figure S2.1), due in part to the amount and variability of rainfall resulting in poor soil conditions and delayed harvest of preceding crops. In Michigan between 1995 and 2020, the number of days suitable for field work between 15 September and 31 October decreased by 0.3 days per year (Kansas State University, 2023). In 2021, wet weather during the soybean [*Glycine Max* (L.) Merr.] harvest and wheat planting seasons in the state resulted in a 25% reduction in hectares planted compared to 2020 (USDA-NASS, 2022). This necessitates understanding the yield penalty resulting from delayed planting to allow growers to make informed decisions when timely planting is not possible. This study addresses the impact of planting date and seeding rate on winter wheat yields in Michigan with the objectives of 1) quantifying the current yield penalty associated with delayed planting, 2) determining whether increased seeding rate can minimize yield loss from delayed planting, and 3) determining the optimal seeding rate that maximizes winter wheat yield for a given planting time.

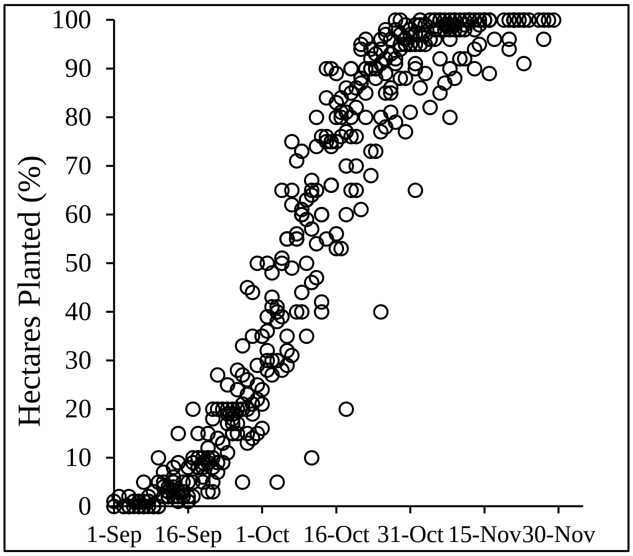

Figure S2.1. Weekly percent winter wheat hectares planted in Michigan for 1982–2022 (USDA-NASS, 2022).

2.3 MATERIALS AND METHODS

2.3.1 Experimental Design

A field experiment was conducted at the Michigan State University Mason Research Farm in Mason, Michigan, during three growing seasons (2019-20, 2020-21, and 2021-22;

hereafter referred to as 2020, 2021, and 2022, respectively). The experimental design was a randomized complete block in a split-plot arrangement with four replications. Main-plots consisted of winter wheat planted on five separate planting dates, the first in mid-September (the optimal planting time based on current university extension recommendations of within a few days after the Hessian fly free date of 17 September for Mason, Michigan) then every 12–18 days until mid-November (Table 2.1). Sub-plots consisted of five seeding rates (2.0, 3.0, 4.0, 4.9, and 5.9 million seeds ha^{-1}). Each plot included six rows spaced 19 cm apart and 5.5 m in length, trimmed to 3.7 m before harvest.

Table 2.1. Locations and planting dates for field trials at Mason, MI for 2019-20, 2020-21, and 2021-22 (referred to as 2020, 2021, and 2022, respectively).

	2020	**2021**	**2022**
Location			
Latitude	42.627931	42.6287805	42.628328
Longitude	-84.427539	-84.4271304	-84.430175
Planting Dates:[a]			
Mid-Sept.	19 Sept.	17 Sept.	19 Sept.
Late Sept.	7 Oct.	29 Sept.	30 Sept.
Mid-Oct.	18 Oct.	14 Oct.	23 Oct.
Late Oct.	29 Oct.	29 Oct.	3 Nov.
Mid-Nov.	15 Nov.	12 Nov.	16 Nov.

[a] Planting date ranges are generalized based on target dates. Hessian fly free date for Mason, MI is 17 September.

In all three growing seasons, the soil type was Conover loam (fine-loamy, mixed, active, mesic Aquic Hapludalf) with a pH range of 6.0–6.7 and cation exchange capacity (CEC) range of 9.8–10.2 meq 100 g^{-1}. Previous crop was soybean in all years, and the winter wheat variety used was “Whitetail.” Plots were planted using a three-point mounted Almaco packet planter and harvested using a research plot combine (Wintersteiger, Ried im Innkreis, Austria for 2020 and 2021 seasons; Kincaid, Haven, Kansas for 2022). Outside of treatment factors, management followed current Michigan State University recommendations, including 170 kg ha^{-1} N (34 kg ha^{-1} at planting, 100 kg ha^{-1} at greenup, and 34 kg ha^{-1} at Feekes 6–7), 22 kg ha^{-1} sulfur at planting, and potassium and phosphorus applications according to soil tests and university recommendations (Culman et al., 2020). Weeds were controlled in fall and spring according to university recommendations (Sprague & Burns, 2021). Fungicide was applied at the flag leaf stage to control leaf diseases and again at the flowering stage to control Fusarium head blight (*Fusarium graminearum*). There was minimal to no Fusarium head blight pressure across all three years of this study. In 2020, all plots were harvested on July 7. In 2021, all plots were harvested on July 9. In 2022, the first two plantings were harvested on July 12, while the last three were harvested on July 21.

2.3.2 Data Collection

In 2020, the only data collected was yield. In 2021 and 2022, more extensive data collection was conducted. Plant counts were conducted at Feekes 1, and tiller and head counts were conducted before harvest, by counting the number of plants, tillers, or heads in a 20.7-in section of two rows near the middle of each plot. These numbers were used to calculate the number of plants, tillers, and heads ha^{-1}, as well as the emergence rate. Each year, harvest weight and moisture were measured by the combine at harvest, and yields were standardized to 13.5% moisture.

Grain quality parameters for 2021 and 2022 were measured on subsamples collected from each plot during harvest. Thousand-kernel weight (TKW) was measured from the grain subsample and standardized to 13.5% moisture. Yield, TKW, and heads ha^{-1} were used to estimate kernels ha^{-1} and kernels $head^{-1}$. Grain protein content was measured for each combine subsample using near infrared spectroscopy (NIRS DS2500, FOSS, Hillerød, Denmark).

2.3.3 Statistical Analyses

Analysis of variance (ANOVA) was conducted to test for interactions among treatment factors and between treatment factors and growing season in determining yield using the GLIMMIX procedure in SAS 9.4 ($\alpha = .10$). Normality and homoskedasticity assumptions were met as determined by the Shapiro-Wilkens test for normality ($\alpha = .05$) and visual inspection of the box plots. Initial analysis used a model where year, planting date, and seeding rate were included as fixed effects and replication was included as a random effect. This analysis showed a significant interaction between year and planting date effects in determining yield ($p < .01$), so a subsequent analysis was run by year with planting date and seeding rate as fixed effects and replication as a random effect. There was no interaction between planting date and seeding rate in determining yield in any year ($p = .81$, .92, and .19 for 2020, 2021, and 2022, respectively).

Regression analysis was used to evaluate planting date and seeding rate as factors for determining yield, heads ha^{-1}, TKW, and grain protein content ($\alpha = .10$). This was done in RStudio 2021.09.0 using the "lm" function for linear and quadratic regression and the "nls" function with self-starter functions from the "nlraa" package (Miguez, 2022). Several models were fit for each comparison (Table 2.2), and Akaike's information criterion was used to determine the best model across years. Due to the interaction between year and planting date in determining yield, analysis involving planting date was conducted separately for each year. Since there was no three-way interaction between year, planting date, and seeding rate ($p = .38$) and no two-way interaction between year and seeding rate ($p = .41$), data was pooled across years for analysis involving seeding rate to increase the power of the analysis.

Table 2.2. Models used for regression analysis in R. Linear and quadratic regression were done using the “lm” function, while all other models were fit using the “nls” function in conjunction with the indicated self-starter function from the “nlraa” package.

Regression Type	R Function	Model
Linear	lm	$y = ax + b$
Quadratic	lm	$y = ax^2 + bx + c$
Asymptotic (through origin)	SSasympOrig	$y = Asym * (1 - exp(-exp(lrc) * x))$
Asymptotic	SSasymp	$y = Asym + (R0 - Asym) * exp(-exp(lrc) * x)$
Linear Plateau	SSlinp	$x < xs: y = a + b * x$ $x \geq xs: y = a + b * xs$
Plateau Linear	SSplin	$x < xs: y = a$ $x \geq xs: y = a + b * (x - xs)$
Quadratic Plateau	SSquadp3	$x \leq -0.5 * b / c: y = a + b * x + c * x^2$ $x > -0.5 * b / c: y = a - b^2 / (4 * c)$
Plateau Quadratic	SSpquad3	$x < -0.5 * b / c: y = a - b^2 / (4 * c)$ $x \geq -0.5 * b / c: y = a + b * x + c * x^2$

Though ANOVA showed no interaction between planting date and seeding rate, ANOVA cannot identify agronomically optimal seeding rates (AOSRs), which often fall between tested seeding rates (Hamman et al., 2021). Therefore, regression analysis was used to calculate an AOSR for each planting date based on maximizing relative yield within that planting date. Relative yield was used to better represent the increased importance of seeding rate under later planting dates with lower yield potential, where a relatively small decrease in actual yield translates to a relatively high percentage yield loss. Relative yield was calculated by dividing yield by the maximum treatment (planting date-seeding rate combination) average for a given planting date. As the best model for representing yield response to seeding rate was an asymptotic mode, AOSRs were calculated as the seeding rate that would achieve yield equal to 99% of the asymptote (Siler & Singh, 2022).

A Pearson’s correlation matrix comparing yield, TKW, kernels acre^{-1}, kernels head^{-1}, heads acre^{-1}, heads plant^{-1}, plants acre^{-1}, seeding rate, and emergence rate was created in Rstudio using the “corrplot” function in the “corrplot” package (Wei & Simko, 2021).

2.4 RESULTS AND DISCUSSION

2.4.1 Weather and Growing Conditions

Daily precipitation and temperature data for the period of 1 September–30 June were obtained for each year of this study from Michigan State University's Enviroweather Automated Weather Station Network (https://enviroweather.msu.edu/), (Figure 2.2). Total precipitation during this period for 2020, 2021, and 2022 was 65.9 cm, 52.2 cm, and 55.4 cm, respectively—slightly lower than the 30-year average of 69.9 cm during the same months from 1991–2020 (NOAA-NCEI, 2020). Annual minimum temperature for 2020, 2021, and 2022 was -29.3°C, --2.8°C, and -30.8°C, respectively—significantly colder than the 30-year average of -8.1°C minimum temperature during the same months from 1991–2020 (NOAA-NCEI, 2020).

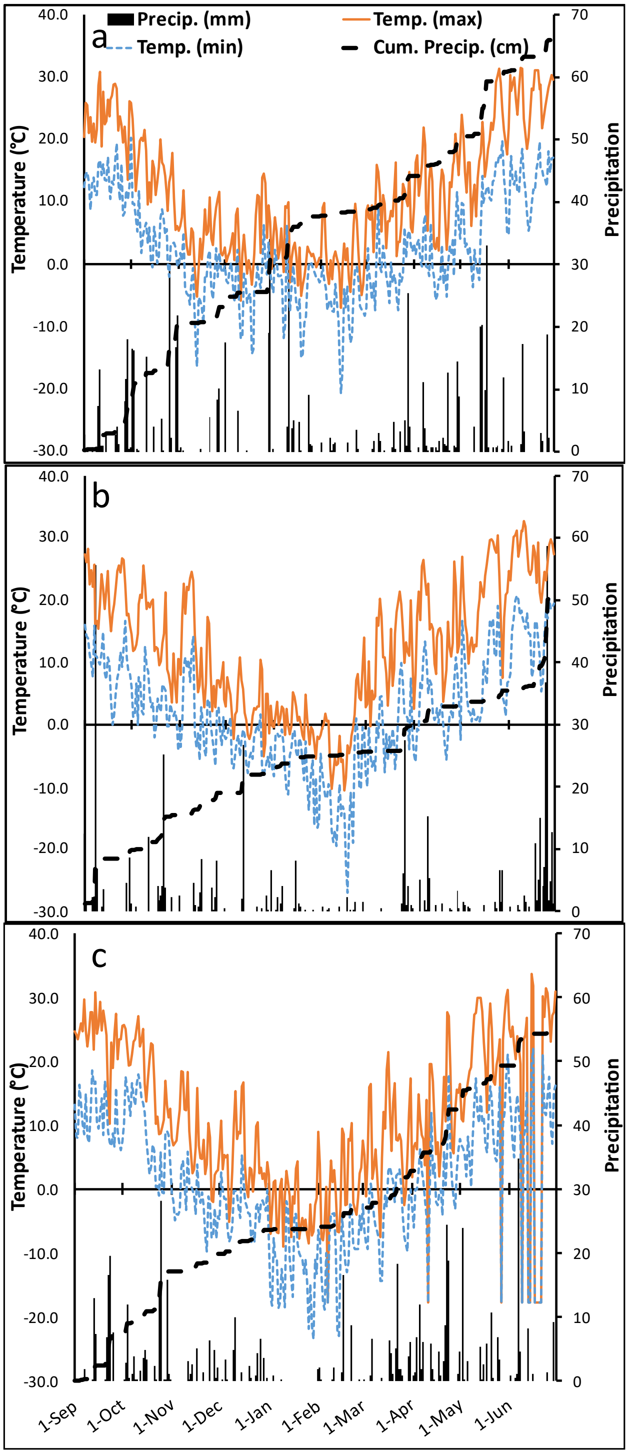

Figure 2.2. Daily precipitation and maximum and minimum temperature for 2020 (a), 2021 (b), and 2022 (c) growing seasons. The horizontal line across middle of plots refers to freezing point of water (0°C). Data were collected from the nearest weather station (within 6 miles of field site) in the Michigan State University Enviroweather network (https://enviroweather.msu.edu/).

2.4.2 Planting Date Effect

There was an interaction between year and planting date in determining yield ($p < .01$), likely due to differences in precipitation during the grain fill period (May-June) each year. Yield declined with delayed planting (Figure 2.3) in every year of the study. This decline became highly variable as planting was delayed into late October and November. Planting on 1 October, 15 October, 30 October, or 12 November resulted in a 7–10%, 17–21%, 24–33%, and 24–47% decline in yield, respectively, compared to planting optimally on 19 September. Heads ha^{-1} decreased by 12–20%, 24–35%, 37–40%, and 35–46% on 1 October, 15 October, 30 October, and 12 November planting dates, respectively, compared to a 19 September planting date (Figure 2.4a–b). Thousand-kernel weight varied by planting date in both 2021 ($p < .01$, $R^2 = .10$) and 2022 ($p < .01$, $R^2 = .25$). However, the relationship was weak, increasing with delayed planting in 2021 (Figure 2.4c) but decreasing with delayed planting in 2022 (Figure 2.4d). In 2021, protein increased under later planting ($p < .01$, Figure 2.4e), but in 2022, it decreased with later planting dates up to early October, after which it began to increase ($p < .01$, Figure 2.4f). The increase in protein content under delayed planting may be due to the smaller amount of grain in which protein could be stored, rather than an actual increase in protein production.

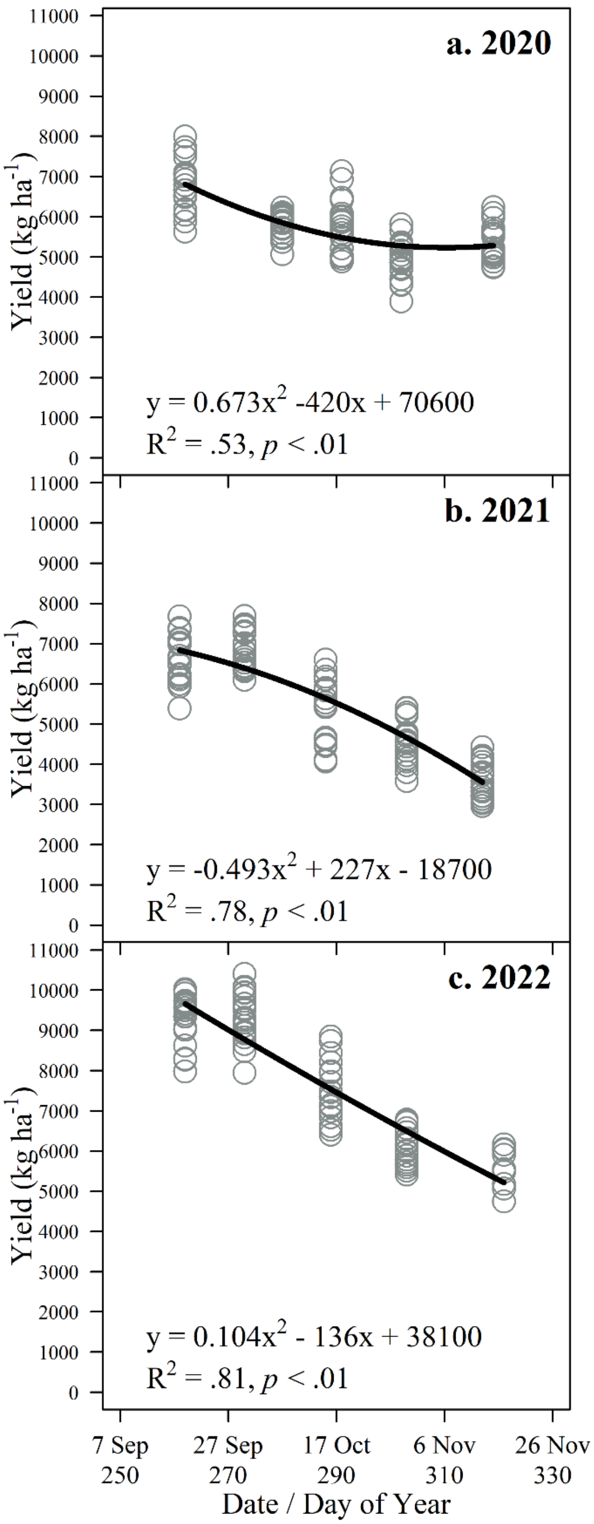

Figure 2.3. Regression models with least square trend lines for winter wheat yield as a function of planting date for the 2020 (a), 2021 (b), and 2022 (c) growing seasons in Mason, Michigan. The Hessian fly free date for Mason, Michigan is September 17.

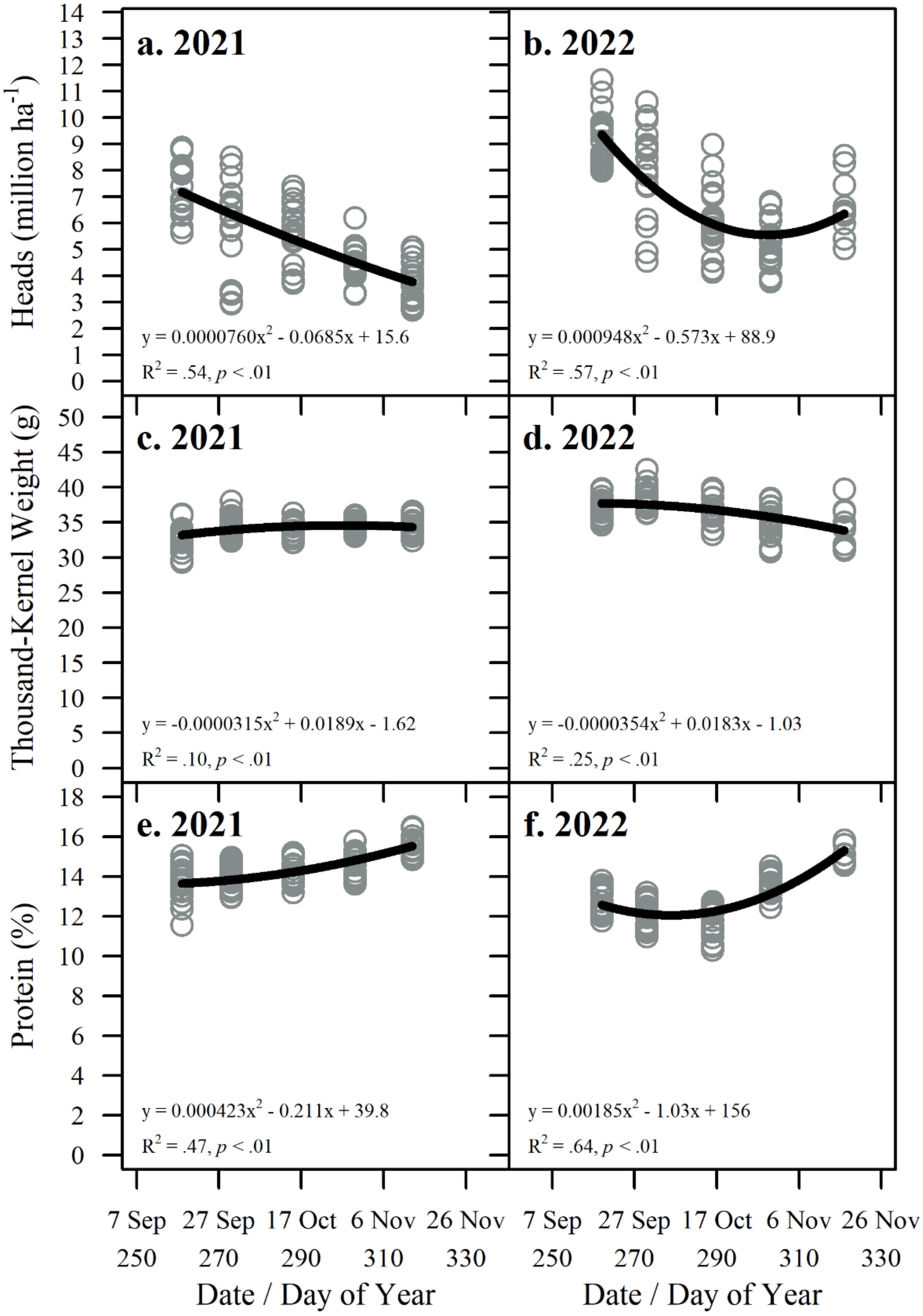

Figure 2.4. Regression models with least square quadratic trendlines for winter wheat heads ha^{-1} as a function of planting date for 2021 (a) and 2022 (b) growing seasons, thousand-kernel weight (TKW) as a function of planting date for 2021 (c) and 2022 (d) growing seasons, and grain protein content as a function of planting date for 2021 (e) and 2022 (f) growing seasons in Mason, Michigan. The Hessian fly free date for Mason, Michigan is September 17.

Our results demonstrate the value of avoiding late planting, as well as the increased uncertainty resulting from planting delays. This is consistent with the current recommendations to plant within a few days after the Hessian fly free date, suggesting that, though no longer relevant for its original purpose, the Hessian fly free date is still a useful reference for determining optimal planting time (Lindsey et al., 2017; Nafziger, 2002; Olson et al., 2021; Pennington et al., 2022). The reduction in yield appears to be resulting primarily from a decrease in heads ha^{-1} (Figure 2.5; 2021: r = .66; 2022: r = .66). This is consistent with at least one previous study conducted in Wisconsin, which also showed a reduction in yield due to delayed planting resulting primarily from a decrease in the number of heads ha^{-1} (Dahlke et al., 1993). We saw no consistent response of quality factors (protein and TKW) to planting date.

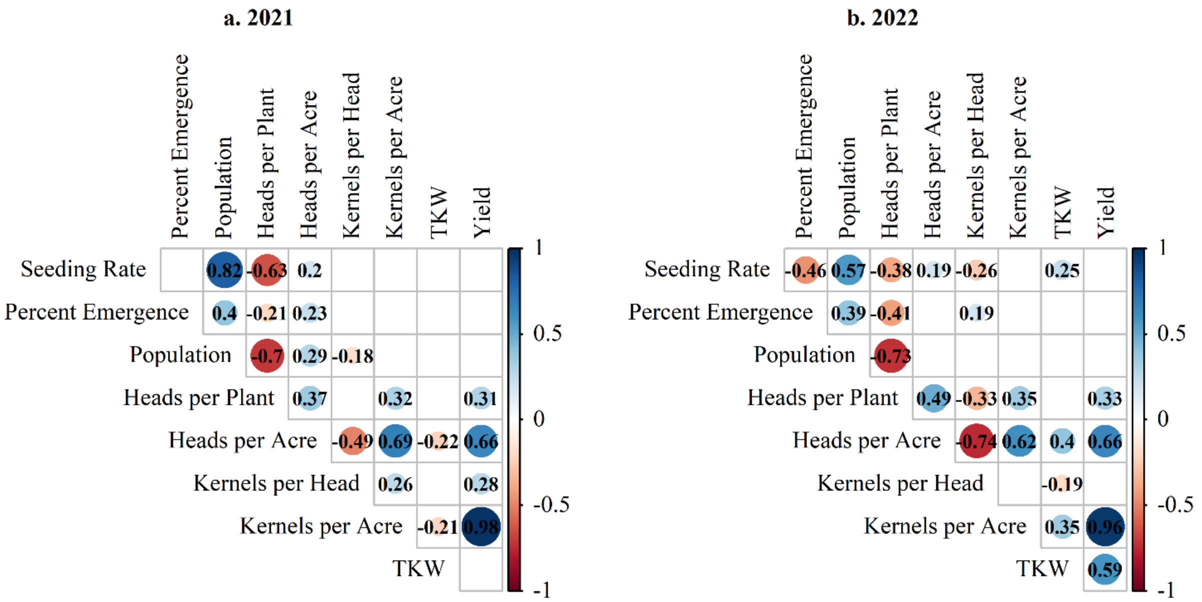

Figure 2.5. Pearson's correlation matrices for winter wheat yield components in 2021 (a) and 2022 (b) growing seasons in Mason, Michigan. Only significant correlations are plotted (α = 0.10). Colors represent the r values as indicated by the color legend, and circles are sized according to the magnitude of the r value. Yield components are physiological traits that are related to one another hierarchically and interact in determining crop yield. TKW: thousand-kernel weight.

2.4.3 Seeding Rate Effect

Regression analysis using relative yield for a given planting date showed a consistent trend toward higher optimal seeding rates and greater yield penalties under low seeding rates and delayed planting (Figure 2.6). The AOSRs for the five planting dates were 2.30 million seeds ha^{-1} for mid-September planting, 3.39 million seeds ha^{-1} for late September planting, 3.63 million seeds ha^{-1} for mid-October planting, 3.81 million seeds ha^{-1} for late October planting, and 4.57 million seeds ha^{-1} for mid-November planting.

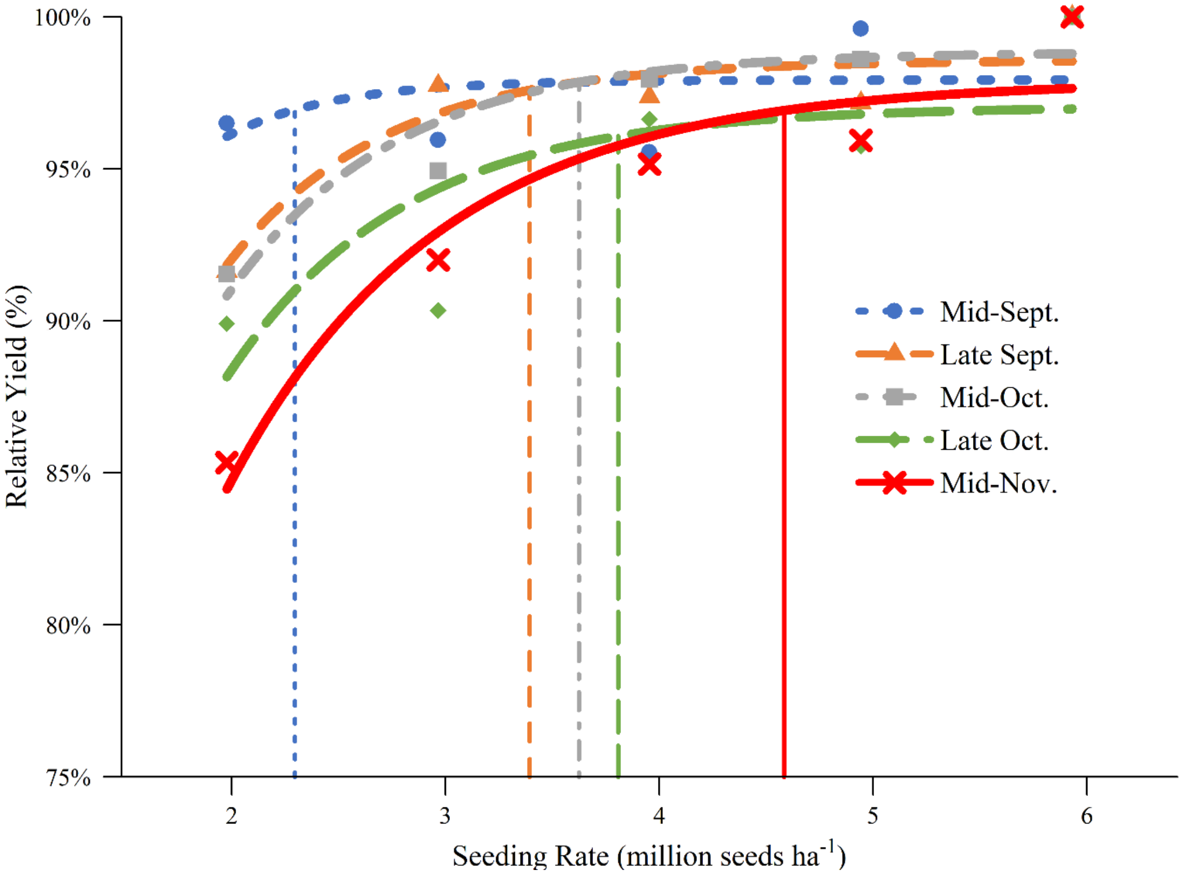

Figure 2.6. Regression models with least square asymptotic trendlines for winter wheat relative yield for a given planting date as a function of seeding rate across 2020–22 growing seasons in Mason, Michigan. Relative yield is defined as percentage of maximum treatment (combination of planting date and seeding rate) average within a given planting date. Vertical lines indicate agronomically optimal seeding rate (AOSR, 99% of asymptote) for the respective planting dates.

Our results differed somewhat from what was reported in a recent study in the Great Lakes Region (Lindsey et al., 2020) that showed a benefit of increasing seeding rates in Ohio up to 6.8 million seeds ha^{-1} beyond the current university recommendations. Our results showed that there is potential to reduce seeding rates below 2.5 million seeds ha^{-1} when planting in September but that they should be progressively increased as planting is delayed into October and November, although at a lower magnitude than the current university recommendations ranging from 3.0 to 4.0 million seeds ha^{-1} under early planting and 4.0 to 5.4 million seeds ha^{-1} when planting late (Lindsey et al., 2017; Nafziger, 2002; Olson et al., 2021). The reason for the lower AOSR under early planting may be because earlier planting allows more time for fall tiller production, facilitating production of more heads $plant^{-1}$ under lower seeding rates and maintaining similar heads ha^{-1} as under higher seeding rates. Under delayed planting, the time for fall tillering is diminished, reducing the ability of lower seeding rates to achieve the same heads $acre^{-1}$ as higher seeding rates.

Agronomically optimal plant density in Kansas was lower under high yield environments (Bastos et al., 2020), typical of optimal planting time in our study and can further explain lower AOSR under these conditions. Ma et al. (2018) concluded that competition among wheat plants, due to higher seeding rates and/or tiller production, can result in “growth redundancy,” which refers to excessive growth of certain resource-foraging organs. This can lead to ineffective tillers, excessive plant height, higher lodging potential, and potentially lower yields under higher seeding rates or ultra-early plantings. Moreover, an examination of actual yield by planting date (Supplemental Figure S2.2) showed that increasing seeding rate is not effective at reducing yield loss resulting from delayed planting. Increasing seeding rate did compensate for yield under slightly delayed planting in a recent study in China (Shah et al., 2020), but its compensatory effect diminished as planting was further delayed. Our results (Figure 2.6) showed AOSR ranged from 3.5-4.0 million seeds ha^{-1} for moderately delayed plantings (mid- to late October), while >4.4 million seeds ha^{-1} were required under November plantings.

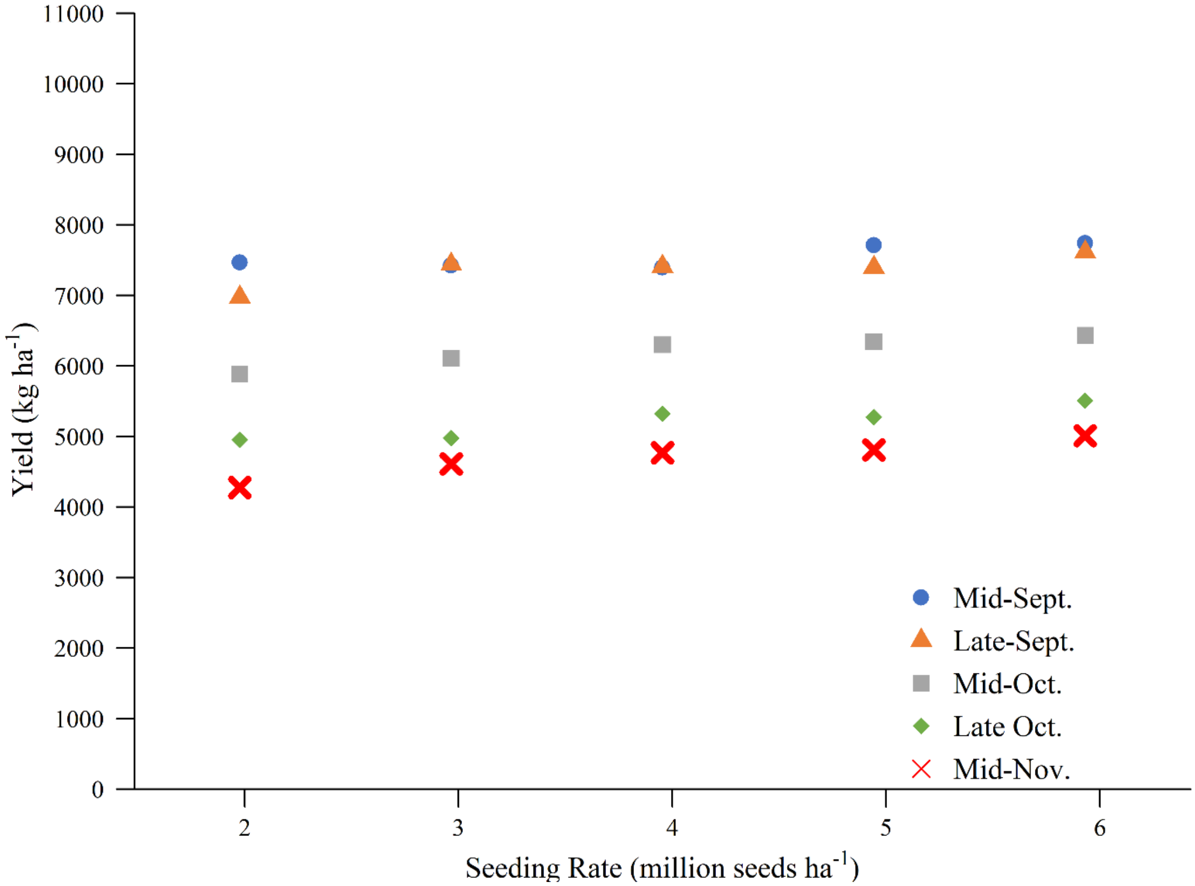

Figure S2.2. Winter wheat yields for a given planting date as a function of seeding rate across 2020–22 growing seasons in Mason, Michigan. Regressions were not significant for any planting date (α = .10).

2.5 CONCLUSIONS

In this study, we saw that timely planting of wheat (within a few days after the Hessian fly free date) is critical for maximizing yield, with significant yield reductions occurring when planting is delayed beyond the optimal planting window. Therefore, efforts should be made to identify strategies that will enable farmers to achieve early planting in the face of the realities of weather variability. We also saw that increasing seeding rates will not make up for yield potential lost due to delayed planting. However, seeding rates should be progressively increased as planting is delayed beyond the recommended planting window, and planting within the optimal window provides potential to reduce seeding rates even below 2.5 million seeds ha^{-1} due to the reduced yield response to seeding rate under earlier planting.

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CHAPTER 3: COMPARING WINTER WHEAT PLANTING METHODS FOR SEED PLACEMENT ACCURACY, GRAIN YIELD, AND QUALITY

3.1 ABSTRACT

Good stand establishment is critical for maximizing yield in winter wheat (*Triticum aestivum* L.) and can be affected by a variety of factors, including seed placement and planting date. Traditionally, small grains such as winter wheat are planted using low-precision grain drills or air seeders, but precision planters, which provide more precise metering and seed placement and have proven valuable in certain larger-seeded crops, are not common in small grains. Meanwhile, adverse weather conditions have resulted in planting delays and increased interest in high-speed planting technologies, such as broadcast incorporation. To compare each of these planting methods and their impact on winter wheat growth and yield, field-scale trials were conducted on several Michigan farms during 2021–2023 in a randomized complete block design. Precision planting exhibited an 8–33% yield increase over grain drill or air seeder at 4 out of 11 site-years, likely due to more precise seed placement leading to more heads ha^{-1}. On the other hand, broadcast incorporation yielded similarly to grain drill or air seeder at 14 out of 17 site-years, despite 61–117% more variability in seed depth. This is likely the result of 50–169% increased tillering resulting from more uniformly spaced plants in the absence of a row pattern. Finally, increasing seeding rate under broadcast incorporation had only a marginal impact on yield. Overall, results showed that precision planting can increase yields compared to grain drills or air seeders, while broadcast incorporation can be used to achieve faster planting without sacrificing yields compared to grain drills or air seeders, even while using the same seeding rate.

3.2 INTRODUCTION

Good stand establishment is critical for maximizing yield in winter wheat (*Triticum aestivum* L.). By improving plant-to-plant uniformity (Hörbe et al., 2016b; Koch & Khosla, 2003b), increasing canopy cover, and improving radiation use efficiency (Sylvester-Bradley et al., 2000), good stand establishment enables the plants to make the best possible use of available resources. Stand establishment can be affected by a variety of factors, including seed quality, seeding rate (Copeland et al., 2023; L. E. Lindsey et al., 2020b; McGlinch & Lindsey, 2022b), seed placement (Hörbe et al., 2016b; Kirby, 1993b; Koch & Khosla, 2003b; Loeppky et al., 1989b), and planting date (Copeland et al., 2023), and environmental conditions before and after planting.

Proper placement of seeds in a seedbed is an important aspect of optimizing crop production (Koch & Khosla, 2003b). Poor depth control and an imprecise distribution of seeds can cause poor germination and crown root development, reduced tillering, increased disease incidence, susceptibility to winter injury (in winter cereals), and ultimately reduced yield (Hörbe et al., 2016b; Kirby, 1993b; Loeppky et al., 1989b).

Traditionally, in the United States (US), small grains are planted using low-precision grain drills. Grain drills meter seed by means of a series of rotating gears in the bottom of the seed box that rotate, allowing seed to fall past them at the appropriate rate into the seed tubes, which carry the seed into the ground between the disc openers. This results in imprecise metering, as well as poor depth control and a random distribution of seeds within the row (Figure 3.1a). In recent years, air seeders replaced grain drills on many larger farms. Air seeders provide higher capacities and better depth control, but their metering systems function similarly to those of traditional drills and suffer from the same weaknesses.

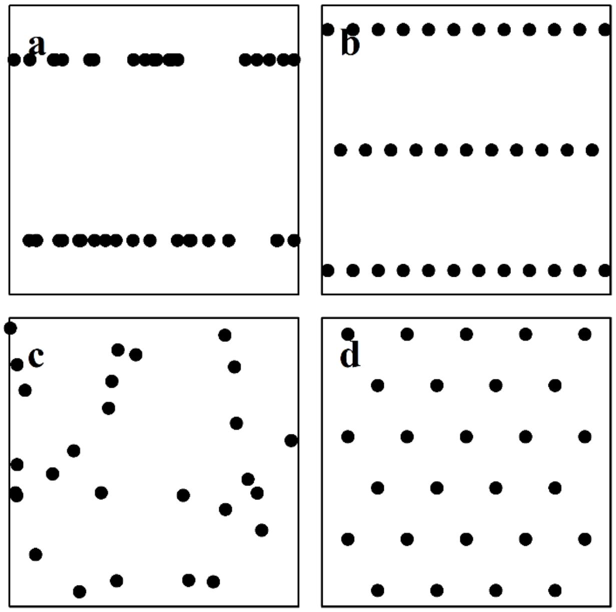

Figure 3.1. Theoretical differences in seed distribution achieved by traditional grain drill on 19-cm row spacing (a), precision planter on 13-cm row spacing (b), and broadcast incorporation (c), compared to an optimal, uniform distribution (d).

A solution for the problem of imprecise seed placement used in larger-seeded crops is precision planting, where the use of a seed plate with vacuum pressure against the back side allows for singulation and regular spacing of seeds (Figure 3.1b). Precision planting has proven crucial for maximizing yield in crops such as corn (*Zea mays*, L.; Hörbe et al., 2016b). Development of precision planters for small grains could result in more precise seed placement, particularly when combined with narrower row spacings (Canfield et al., 2020). Small plot research in winter wheat showed ~10% yield improvements by combining precision planting with narrow rows (Canfield et al., 2020), but this research needs validation under commercial field settings and comparison against other technologies.

Another factor that is critical for achieving good stand establishment is planting date. Most U.S. states advise that winter wheat should be planted within a few days after the Hessian fly-free date (L. Lindsey et al., 2017b; Nafziger, 2002; Pennington et al., 2022b). Timely planting is important for avoiding early establishment of disease (Lindsey et al., 2017b; Pennington et al., 2022b) and to avoid yield reductions of up to 21%, which can result from delaying planting four weeks beyond the Hessian fly-free date (Copeland et al., 2023). However, adverse weather conditions have resulted in planting delays and increased interest in high-speed planting technologies among US row crop growers. Broadcasting and incorporating seed with a shallow tillage implement (i.e., "broadcast incorporation") is one technique that offers faster planting with low initial investment. Theoretically, this can lead to a more uniform two-dimensional distribution of plants compared to planting in rows with a high density of plants within the row and a low density between rows (Figure 3.1c). A uniform distribution of plants reduces inter-plant competition (Figure 3.1d), and broadcast incorporation has shown some promise in certain crops, such as soybean (*Glycine max*, L. Merr.; Wilde, 2020b). There are also concerns that non-ideal seeding depth and inadequate seed-to-soil contact will negatively impact yield and grain quality. Limited research comparing broadcast incorporation with grain drill showed either a yield reduction with broadcast incorporation due to poorer stand establishment and more prostrate plant growth (Collins & Fowler, 1992b) or no yield difference between planting methods but greater variability in broadcasted seed (Hines, 2018b).

One aspect of comparing planting methods is quantifying the resulting spatial distribution of plants. This requires selection of a proper method of quantifying variability, which can be challenging. One approach is to calculate coefficient of variation (CV), which measures the variability of plant-to-plant spacing within the row (Kovács & Casteel, 2023). However, CV is not well suited for comparing distributions that vary in two dimensions, such as when row spacing is changed, and cannot be readily applied to broadcasted seed. Another way to quantify spatial uniformity of a point pattern is to use Ripley's K statistic (Ripley, 1976). This statistic is calculated by determining the total number of points that fall within a given radius of each point.

This is done for many different radii to determine the spatial uniformity at various different scales. Ripley's K statistic is typically used to determine whether a geographic phenomenon is spatially random, uniform, or clustered. When the statistic falls along a theoretical line representing a completely spatially random pattern, it is considered to be spatially random at the evaluated scale. When it falls above or below the completely spatially random line, it is considered clustered or uniform, respectively. An alternative way to use Ripley's K statistic is to compare the distribution of two or more point patterns (Hahn, 2012), such as those resulting from different planting methods.

To properly evaluate how new planting methods perform in a grower's field, it is important to conduct field-scale trials under a range of environmental conditions that would be encountered in commercial farming. Small-plot research may not adequately represent the within-field variability encountered by a commercial grower, resulting in a disconnect between what researchers find in small-plot research and what growers see in their fields. Field-scale experiments on commercial farms allow a researcher to measure results under real-world conditions and draw conclusions that can be better relied upon by growers.

To compare each of the planting methods discussed above and their impact on plant growth and yield in winter wheat at the commercial field scale, this research was conducted in Michigan across 17 site-years in three growing seasons. We hypothesized that (i) precision planting would result in more accurate seed placement than a grain drill, leading to improved wheat development, yield potential and quality; (ii) yield and quality would be lower under broadcast incorporation due to increased variability in depth and seed-to-seed spacing; and (iii) these negative results in broadcast incorporation can be reduced, however, by increasing the seeding rate by in broadcast incorporation.

3.3 MATERIALS AND METHODS

3.3.1 Experimental Sites and Design

Field-scale trials were conducted on multiple Michigan farms with diverse soil types and microclimates during three growing seasons (2021–21, 2021–22, and 2022–23, hereafter referred to as 2021, 2022, and 2023, respectively) for a total of 17 site-years (Table 3.1). Plot width (3–34 m) and length (9.1–900 m) varied based on the field size and the equipment used. The trials were set up in a randomized complete block design. Each treatment was replicated four times at each site year, with the exception of Jackson 2021, which had three replications. Each site-year had a minimum of three of the following treatments (except for Jackson 2021, which only had two treatments): grain drill or air seeder, 13-cm precision planter, broadcast incorporation, and broadcast incorporation with 30% higher than standard seeding rate (Table 3.1). Precision planting was achieved using a custom-built Monosem 4 NG (Monosem Inc., Edwardsville, KS) precision planter with row units spaced 26-cm apart. To achieve a 13-cm spacing, each plot was planted in two passes offset by 13-cm to achieve 13-cm row spacing—desired spacing for precision planted wheat-based research by Canfield et al. (2020). All other treatments were planted using grower-owned equipment. Seeding rate was increased (Table 3.1) for site-years where planting was delayed, to minimize yield losses based on Copeland et al. (2023). Management for each site-year (such as variety, fertility, pest control) followed grower’s standard practices.

Table 3.1. Location details, planting dates, planting method, seeding rate, and row spacing used for each site-year.

Site-year (County Year)	Soil Texture	Planting Date	Planting Method	Seeding Rate (million seeds ha^{-1})	Row Spacing (cm)
Huron 2021	clay loam[b]	16 Sep	precision	3.0	13
			air seeder	3.0	13
			drill	3.0	19
			broadcast	3.0	-[a]
Genesee 2021	clay loam	16 Sep	precision	3.5	13
			air seeder	3.5	19
			broadcast	3.5	-
Tuscola 2021	clay loam	23 Sep	precision	3.0	13
			drill	3.0	19
			broadcast	3.0	3
			broadcast	4.0	-
Jackson 2021	clay loam	9 Oct	air seeder	4.2	12
			broadcast	4.2	-
Clinton 2021	clay loam	9 Oct	drill	3.5	19
			broadcast	3.5	-
			broadcast	4.4	-
Clinton 2022	clay loam	29 Sep	drill	3.0	19
			broadcast	3.0	-
			broadcast	4.0	-
Tuscola 2022	clay loam	30 Sep	precision	3.0	13
			drill	3.0	19
			broadcast	3.0	-
			broadcast	4.0	-
Jackson 2022	sandy clay loam	12 Oct	air seeder	3.5	12
			broadcast	3.5	-
			broadcast	4.4	-
Kalamazoo 2022	sandy clay loam	20 Oct	precision	3.5	13
			drill	3.5	19
			broadcast	3.5	-

Table 3.1 (cont’d)

			broadcast	4.4	-
Ingham 2022	silty clay loam	5 Nov	precision	3.5	13
			drill	3.5	19
			broadcast	3.5	-
			broadcast	4.4	-
Jackson 2023	sandy loam		air seeder	3.0	12
			broadcast	3.0	-
			broadcast	4.0	-
Kalamazoo 2023	sandy clay loam	3 Oct	precision	3.0	13
			drill	3.0	19
			broadcast	3.0	-
			broadcast	4.0	-
Tuscola 2023	clay loam	4 Oct	precision	3.0	13
			drill	3.0	19
			broadcast	3.0	19
			broadcast	4.0	19
Clinton 2023	clay loam	10 Oct	drill	3.0	19
			broadcast	3.0	-
			broadcast	4.0	-
Huron 2023	clay loam	10 Oct	precision	3.0	13
			air seeder	3.0	13
			drill	3.0	19
			broadcast	3.0	-
Genesee 2023	loam	11 Oct	precision	3.0	13
			air seeder	3.0	19
			broadcast	3.0	-
Ingham 2023	clay loam	4 Nov	precision	3.5	13
			drill	3.5	19
			broadcast	3.5	-
			broadcast	4.4	-

[a] Broadcast incorporation plots did not follow specific row spacing.

[b] Soil textures were obtained from Web Soil Survey (https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx).

3.3.2 Data Collection

Plant counts were conducted at Feekes 1, and head counts were conducted before harvest by counting the number of plants or heads in a 0.5-m section of two rows (for plots planted in rows) or a 0.3-m x 0.3-m section (for broadcast incorporated plots) from two or three spots per plot chosen randomly at about ⅓ and ⅔ of the way through the plot (or ¼, ½, and ¾ of the way through if using three spots). These data were used to calculate the number of plants and heads ha^{-1}, as well as heads plant^{-1} and the emergence rate, dividing plant count by seeding rate. Some of these calculated emergence values were outside of the biologically possible range (e.g., above 100%), likely due to a combination of inaccuracies in plant counts due to tillering and imprecision in equipment calibration and actual number of seeds planted. However, the relative differences between treatments should still be meaningful, as all counts for a given site-year were conducted on the same day. Seed depth was measured in either fall or spring by digging up 15 plants per plot from two to three spots per plot, selected in the same manner as for plant, tiller, and head counts, and measuring the distance from the soil line to the top of the seed. In Tuscola 2022 seed depth was measured on a total of 45 plants per plot to facilitate the creation of a visual representation of seed depth distributions for each planting method using actual data. Due to the intensive nature of seed depth data collection, this higher sampling rate was not practical to replicate at all site-years. Coefficients of variation were calculated from these seed depth measurements for each plot by dividing the standard deviation of the measurements by the mean.

To determine the spatial distribution of plants resulting from a given planting method, pictures were taken at a subset of locations in the 2022 and 2023 growing seasons. These pictures were taken using a monopod at a height of about 1.1 m looking straight down at the ground while the plants were small enough to distinguish between them in a picture (around Feekes 1).

Two or three pictures were taken in each plot, depending on the length of the plots at a given location. Picture locations were chosen in the same manner as for other sampling described above. Each picture was inserted into PowerPoint, where a small x was placed at the base of each plant. The coordinates for each x (representing the coordinates of each plant) were exported using virtual basics for applications and transferred into comma-separated values files. To determine the scale of the pictures, pictures were taken of a yardstick using the same setup as was used to take pictures of the plants. These pictures of the yardstick were also inserted into PowerPoint, where the ends of the yardstick were marked and the coordinates exported in the same way as for the field pictures, and the ratio of the distance between the ends of the yardstick in the picture and the distance between the ends of the yardstick in real life were used to scale the coordinates from the field pictures to real-life distances (Figure 3.2).

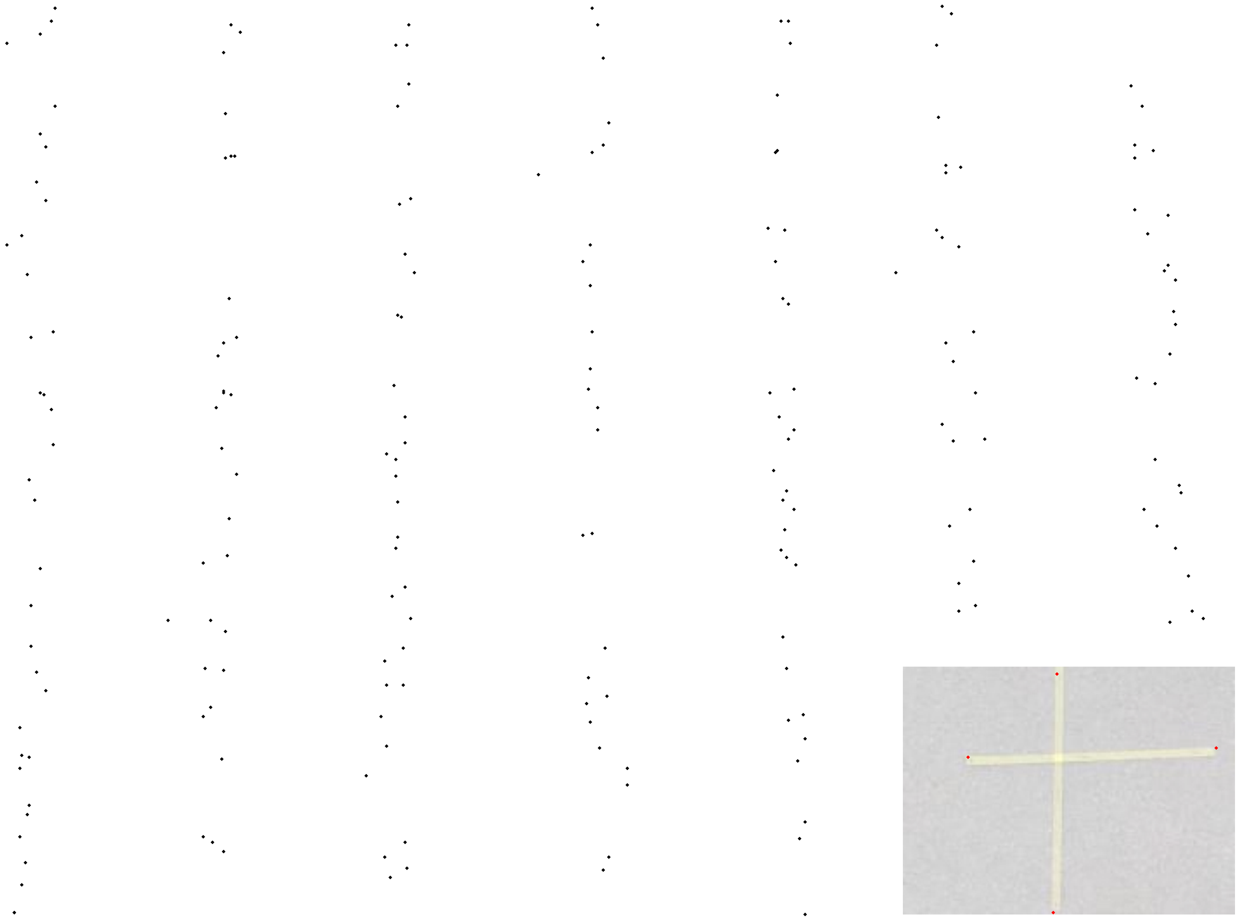

Figure 3.2. Pictures taken to determine spatial uniformity of wheat plants were inserted into PowerPoint, where a small x was placed at the base of each plant. The coordinates for each x (representing the coordinates of the plant) were exported using virtual basics for applications and transferred into comma-separated values files. To determine the scale of the pictures, pictures were taken of a yardstick using the same setup as was used to take pictures of the plants. These pictures of the yardstick were also inserted into the PowerPoint, where the ends of the yardstick were marked and the coordinates exported in the same way as for the field pictures (see inset), and the ratio of the distance between the ends of the yardstick in the picture and the distance between the ends of the yardstick in real life were used to scale the coordinates from the field pictures to real-life distances.

Harvest weight and moisture were measured by the combine at harvest, and yield was standardized to 13.5% moisture. Grain samples from a subset of site-years were analyzed for measuring various grain quality parameters. Deoxynivalenol (DON) was quantified at the University of Minnesota (St. Paul, MN) using gas chromatography and mass spectroscopy (GC-MS) following protocols developed by Fuentes et al., (2005). Thousand-kernel weight (TKW) was measured from the grain subsamples and standardized to 13.5% moisture, yield, TKW, and heads ha^{-1} were used to estimate kernels ha^{-1} and kernels head^{-1}. Grain protein content was measured for each subsample using near infrared spectroscopy (NIRS DS2500, FOSS, Hillerød, Denmark).

3.3.3 Data Analyses

Due to the differences in treatments and equipment used to plant each site-year, statistical analysis was initially conducted separately for each site-year and each objective. Site-years without significant yield differences within an objective were pooled and reanalyzed, according to the approach used by Kaur et al. (2023). Planting method (or seeding rate within a planting method) was included as a fixed effect while replication and site-year x replication (when data were pooled) were included as random effects in the model. Analysis of variance and mean separation using Tukey’s honestly significant difference (HSD) were conducted using the GLIMMIX procedure in SAS 9.4 using level of significance (α) of .10. Normality and homoskedasticity assumptions were met for all variables as determined by visual examination of the histograms, residual plots, and boxplots, with the exception of seed depth, which was transformed using a natural log transformation to achieve normality. Estimates from transformed values were back-transformed for reporting purposes. Treatment was tested as a determinant of seed depth, seed depth variability, plants ha^{-1}, emergence rate, heads ha^{-1}, heads plant^{-1}, yield, and kernels ha^{-1}, kernels head^{-1}, thousand-kernel weight, grain protein content, and grain deoxynivalenol content ($\alpha = .10$).

Spatial uniformity was compared using a methodology derived from Hahn (2012), in RStudio 2021.09.1, using functions in the “spatstat” library (Baddeley et al., 2015). Coordinates derived from the pictures described above were imported into R and converted to a spatial points data frame using the “ppp” function. Ripley’s K statistics (Ripley, 1976) were computed for each picture using the “Kest” function. Since each picture represented a subsample from a plot, the K statistics for all pictures within a given plot were averaged at each radius of the K function to obtain K statistics for each plot. For each treatment, the mean K statistic at each radius of the K function were calculated across plots, and Tukey’s HSD was used to conduct mean separation for each radius of the K function. If two treatments were found to be different at a given radius, the one with the smaller K statistic was concluded to be more spatially uniform than the other treatment at that scale.

3.4 RESULTS

3.4.1 Comparing Precision Planting to Grain Drill or Air Seeder

Precision-planted plots exhibited an 8–33% yield increase over plots planted using an air seeder at three out of four site-years (Genesee 2021, Huron 2021, and Huron 2023) and a 13–17% yield increase over those where a grain drill was used at three out of nine site-years (Huron 2021, Huron 2023, and Ingham 2022; Figure 3.3). These differences corresponded to a 9–29% increase in kernels ha^{-1} when using precision planting compared to when an air seeder was used or an 8–12% increase compared to using a drill for the same site-years (Table 3.2). Thousand-kernel weight was similar across treatments, except for in Huron 2021, where precision planting resulted in a 2% higher TKW than using an air seeder. Precision planting also resulted in a 46% lower CV for depth compared to an air seeder in Genesee 2021 and a 46% lower CV for depth compared to a grain drill in Huron 2021 (Table 3.2). Emergence rate was 30–98% higher when a precision planter was used than when a drill was used in Huron 2021, Huron 2023, and Ingham 2022 (Table 3.2). Plots planted using a precision planter had 10% more heads ha^{-1} than those planted with an air seeder in Genesee 2021 and 61% more heads ha^{-1} than drill in Huron 2023, though kernels head^{-1} was 28–39% lower in precision planted plots in Huron 2023 and pooled site-years. They also had numerically more heads ha^{-1} than those planted with a drill or air seeder across all site years and 36% more heads ha^{-1} than those where a drill was used and 41% more heads ha^{-1} than those planted using an air seeder across the site-years without a significant yield difference (Table 3.2).

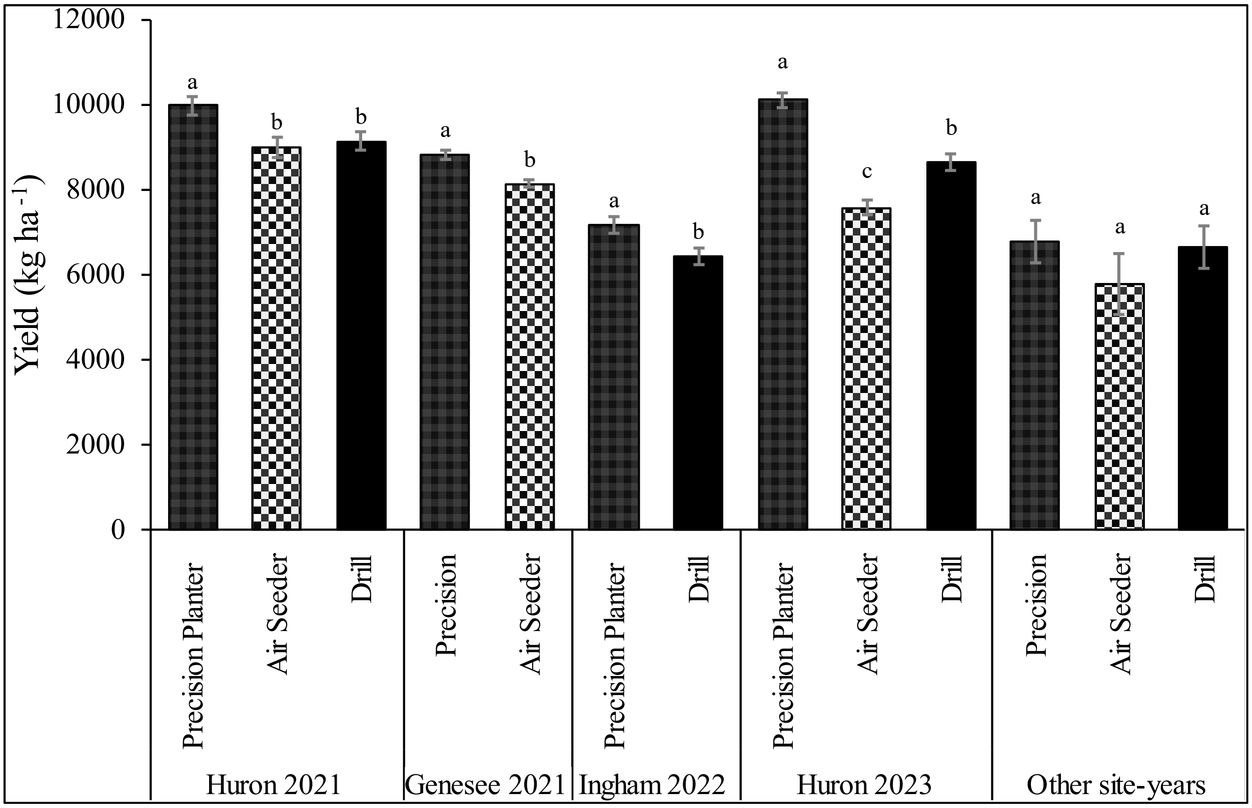

Figure 3.3. Winter wheat yield in plots planted using a precision planter vs a traditional grain drill or air seeder at various site-years in Michigan. Bars with the same letter within a site-year are not significantly different (α = .10). Other site-years represents data pooled from seven site-years where significant differences were not observed among the tested treatments. Vertical lines on each bar represent ± 1 standard error of the mean.

Table 3.2. Average values for yield components (TKW, thousand-kernel weight), as well as depth and depth variability measured as coefficient of variation (CV) for winter wheat planted using a precision planter, conventional grain drill, or air seeder across various site-years in Michigan. Other site-years represents data pooled from seven site-years where significant yield differences were not observed among the tested treatments.

Site-year	**TKW (g)**	**Kernels (million ha^{-1})**	**Kernels (head^{-1})**	**Heads (million ha^{-1})**	**Heads (plant^{-1})**	**Plants (million ha^{-1})**	**Emergence (%)**	**Depth (cm)**	**Depth CV**	**Protein (%)**
Huron 2021										
Precision Planter	28.5 a	351 a	24.3 a	14.7 a	5.46 b	2.72 a	91.6 a	3.07 a	19.9 b	12.4 a
Air Seeder	28.0 b	321 b	22.4 a	14.5 a	5.25 b	2.82 a	95.3 a	2.87 a	25.4 ab	12.1 a
Drill	28.6 a	319 b	23.4 a	13.6 a	7.70 a	1.81 b	61.1 b	3.10 a	26.0 a	12.3 a
Genesee 2021										
Precision Planter	37.1 a	238 a	13.8 a	17.4 a	5.44 a	3.20 a	92.5 a	2.71 a	20.2 b	10.6 a
Air Seeder	37.4 a	218 b	13.8 a	15.8 b	4.91 a	3.28 a	94.8 a	2.46 a	37.4 a	10.8 a
Ingham 2022										
Precision Planter	32.5 a	221 a	40.2 a	5.5 a	1.21 a	4.60 a	132.9 a	1.37 b	36.0 a	10.0 a
Drill	32.6 a	198 b	39.1 a	5.2 a	1.49 a	3.53 b	102.0 b	2.72 a	29.9 a	10.1 a
Huron 2023										
Precision Planter	31.8 a	318 a	37.2 b	8.7 a	3.37 a	2.60 a	87.6 a	1.49 a	33.4 a	12.2 a
Air Seeder	30.8 a	246 c	29.6 b	8.5 a	3.01 a	2.96 a	99.9 a	1.97 a	26.2 a	12.0 a
Drill	30.5 a	295 b	60.8 a	5.4 b	3.37 a	1.66 b	56.0 b	1.59 a	41.6 a	12.4 a
Other site-years										
Precision Planter	32.7 a	209 a	21.3 b[a]	9.9 a	4.52 a	2.59 a	83.7 a	2.43 a	26.2 a	11.1 a
Air Seeder	31.3 a	190 a	33.3 a	7.0 b	2.97 a	2.90 a	95.5 a	1.79 a	38.7 a	11.4 a
Drill	32.8 a	206 a	29.4 a	7.3 b	4.02 a	2.28 a	74.7 a	2.16 a	38.3 a	11.1 a

[a] Stand counts, used to determine kernels head^{-1}, heads plant^{-1}, plants ha^{-1}, and emergence, were not collected for Ingham 2023.

Note: Values followed by the same letter within a site-year and yield component are not significantly different ($\alpha = .10$).

In Tuscola 2022, the precision planting resulted in lower Ripley's K statistics than planting with a drill at scales of 3 cm–9 cm and 20 cm–30 cm, but at scales of 16 cm–18 cm, the K statistics for drill were lower than those for precision planting (Figure 3.4a). In Kalamazoo 2022, precision planting had lower K statistics than drill at scales of 0 cm–7 cm and 23 cm–27 cm, but the K statistics for drill were lower beginning at a scale of 30 cm (Figure 3.4b).

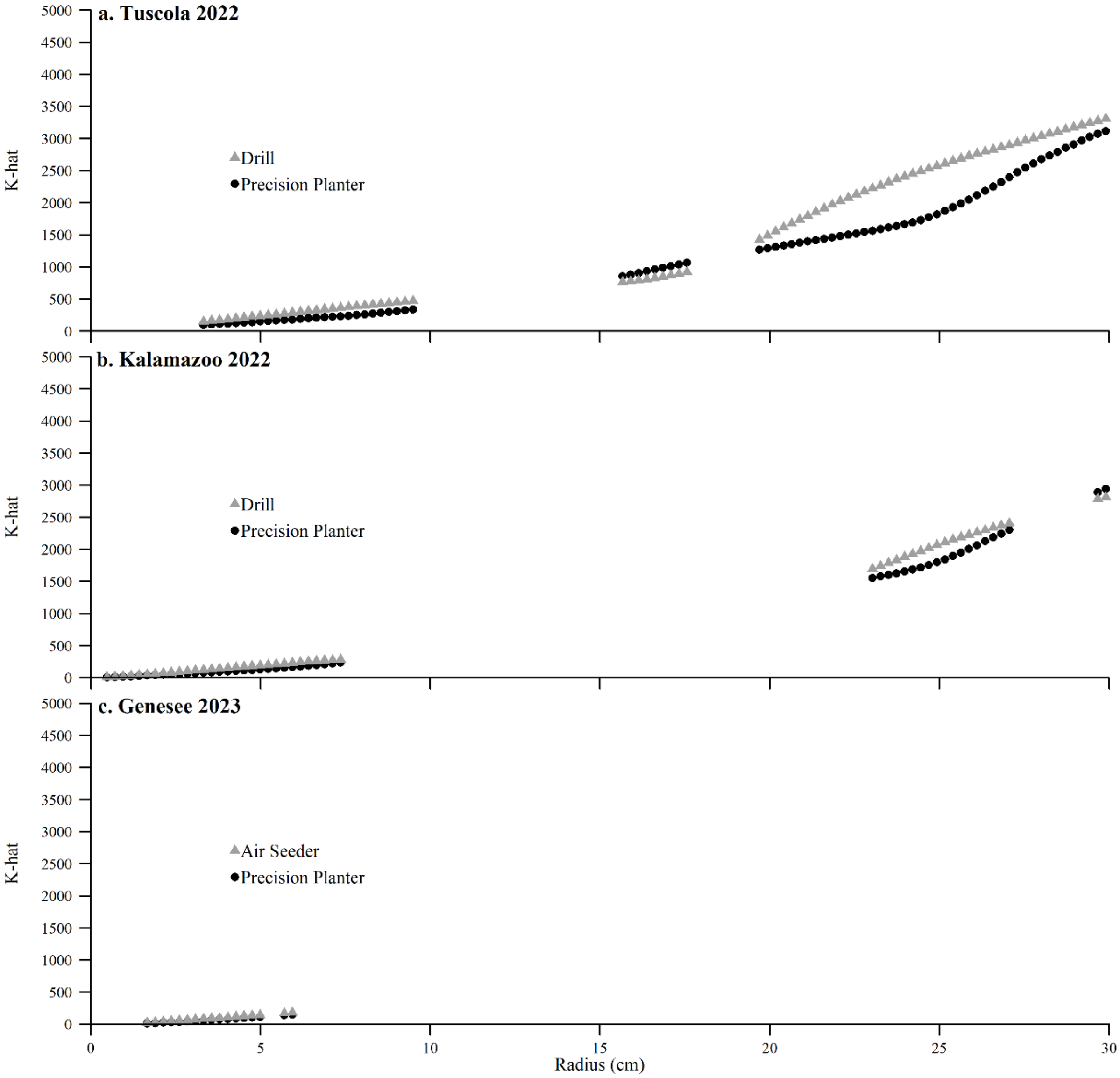

Figure 3.4. Ripley's K statistics estimated for the spatial distribution of winter wheat planted using a precision planter vs a traditional grain drill at various site-years. Statistics are plotted only at scales where Tukey's mean separation concluded a significant difference between

Figure 3.4 (cont'd)
planting methods ($\alpha = .10$). Higher K statistics indicate more clustering, while lower K statistics indicate greater uniformity.

Protein was similar among treatments for all site-years, and DON was not detected in any of the samples that were tested (data not shown).

3.4.2 Comparing Broadcast Incorporation and Grain Drill

Yield was similar under broadcast incorporation compared to planting with a drill or air seeder at 14 out of 17 site-years. In Clinton 2021, broadcast incorporated plots outyielded drilled plots by 4%, but in Jackson 2023 and Huron 2023, plots planted with an air seeder or drill outyielded broadcast incorporated plots by 17% and 22%, respectively (Figure 3.5). Thousand-kernel weight was similar among treatments across site-years (Table 3.3). Clinton 2021 had 24% more heads ha^{-1}, 63% more heads plant^{-1} and 4% more kernels ha^{-1} in broadcast incorporated plots than in drill-planted plots (Table 3.3). However, it also had a 22% lower emergence rate and 64% higher depth CV under broadcast incorporation than when planting with a drill (Table 3.3). In Jackson 2023, plots planted with an air seeder and those planted using broadcast incorporation had similar heads ha^{-1}, heads plant^{-1}, and depth CV, but emergence rate was 47% lower where broadcast incorporation was used than in plots planted with an air seeder. In Huron 2023, broadcast incorporation resulted in 43% more heads ha^{-1} and 22% fewer kernels ha^{-1} than drill and 67% more heads plant^{-1}, 6% fewer kernels ha^{-1}, and 5% lower emergence rate than planting with an air seeder.

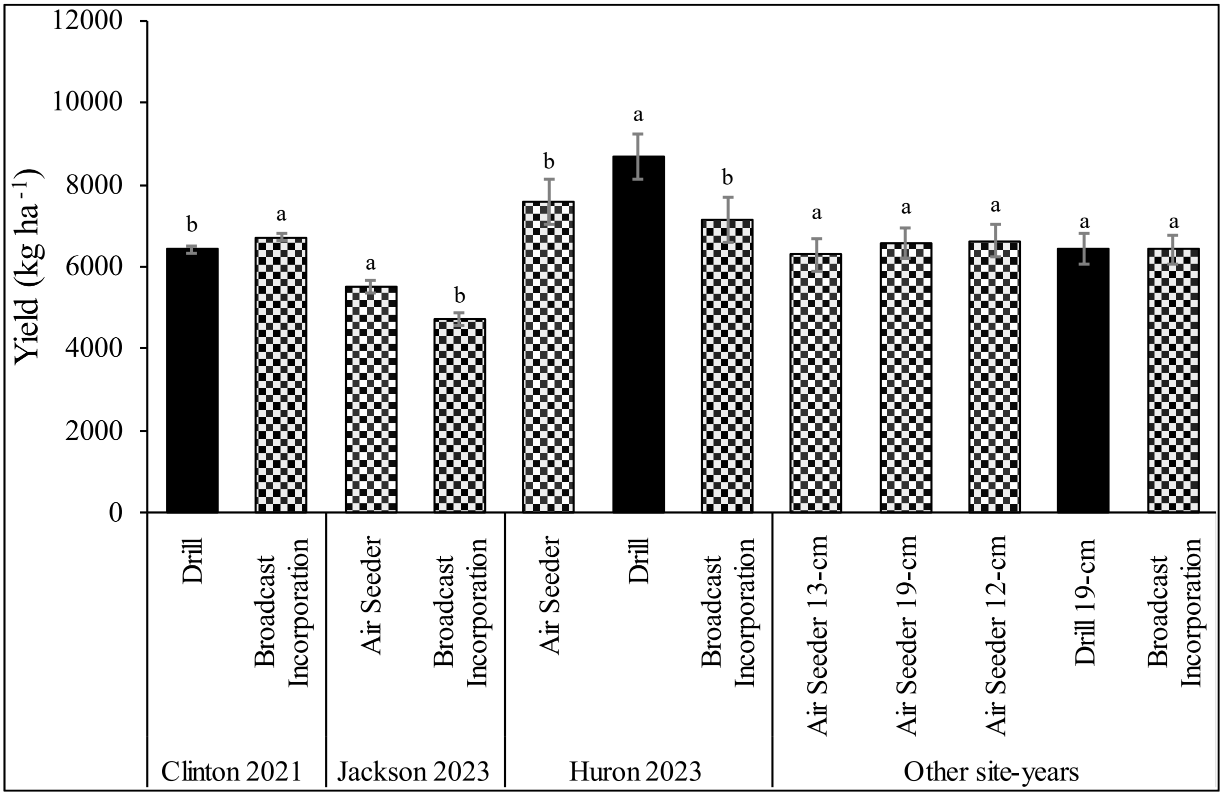

Figure 3.5. Comparing yield for winter wheat planted using a traditional grain drill or air seeder vs broadcast incorporation at various site-years in Michigan. Bars with the same letter within a site-year are not significantly different (α = .10). Other site-years represent data pooled from 14 site-years where significant differences were not observed among the tested treatments. Vertical lines on each bar represent ± 1 standard error of the mean.

Table 3.3. Average values for various yield components (TKW, thousand-kernel weight), as well as depth and depth variability measured as coefficient of variation (CV) for winter wheat planted using a conventional grain drill, air seeder, or broadcast incorporation across various site-years in Michigan. Other site-years represent data pooled from 14 site-years where significant yield differences were not observed among the tested treatments.

	TKW (g)	Kernels (million ha^{-1})	Kernels (head^{-1})	Heads (million ha^{-1})	Heads (plant^{-1})	Plants (million ha^{-1})	Emergence (%)	Depth (cm)	Depth CV	Protein (%)
Clinton 2021										
Drill	35.7 a	180 b	16.4 a	11.2 b	2.79 b	4.06 a	117.4 a	1.83 a	42.7 b	11.7 a
Broadcast Incorporation	35.7 a	188 a	13.5 b	13.9 a	4.56 a	3.17 b	91.6 b	2.26 a	70.1 a	11.6 a
Jackson 2023										
Air Seeder	-[a]	-	-	7.6 a	2.28 a	3.38 a	114.1 a	1.29 a	56.3 a	-
Broadcast Incorporation	-	-	-	5.0 a	2.76 a	1.81 b	61.0 b	0.96 a	54.0 a	-
Huron 2023										
Air Seeder	30.8 a	246	29.6 b	8.5 a	3.01 b	2.96 a	99.9 a	1.97 a	26.2 a	12.0 b
Drill	30.5 a	296	61.3 a	5.4 b	3.37 b	1.66 b	56.0 b	1.59 a	41.6 a	12.4 ab
Broadcast Incorporation	30.9 a	231	30.6 b	7.7 a	5.04 a	1.58 b	53.3 b	1.93 a	44.5 a	12.7 a
Other site-years										
Air Seeder 13-cm	33.3 a	194 a	25.2 ab[b]	8.9 ab	1.52 c	3.43 a	109.0 a	1.39 b	40.8 ab	11.0 a
Air Seeder 19-cm	33.8 a	200 a	22.1 b	9.8 a	2.63 bc	3.46 a	107.2 a	2.63 a	29.5 b	11.2 a
Air Seeder 12-cm	33.7 a	201 a	24.1 ab	9.3 ab	3.59 ab	2.93 ab	86.7 ab	4.16 a	25.7 b	11.7 a
Drill 19-cm	33.7 a	196 a	27.2 a	8.2 b	3.84 ab	2.61 b	81.8 b	1.72 b	42.0 ab	11.1 a
Broadcast Incorporation	33.5 a	197 a	23.5 b	9.4 a	4.09 a	2.47 b	76.8 b	1.63 b	59.9 a	11.1 a

[a] Combine subsamples, used to determine TKW, kernels ha^{-1}, kernels head^{-1}, and protein, were not collected for Jackson 2023.

[b] Stand counts, used to determine kernels head^{-1}, heads plant^{-1}, plants ha^{-1}, and emergence, were not collected for Ingham 2023.

Note: Values followed by the same letter within a site-year and yield component are not significantly different ($\alpha = .10$).

In Tuscola 2022, broadcast incorporation resulted in lower Ripley's K statistics than drill at scales of 3 cm–9 cm and 20 cm–30 cm, but at scales of 16 cm–18 cm, the K statistics for drill were lower than those for precision planting (Figure 3.6a). In Kalamazoo 2022, precision planting had lower K statistics than drill at scales of 0–7 cm, but the K statistics for drill were lower beginning at a scale of 30 cm (Figure 3.6b).

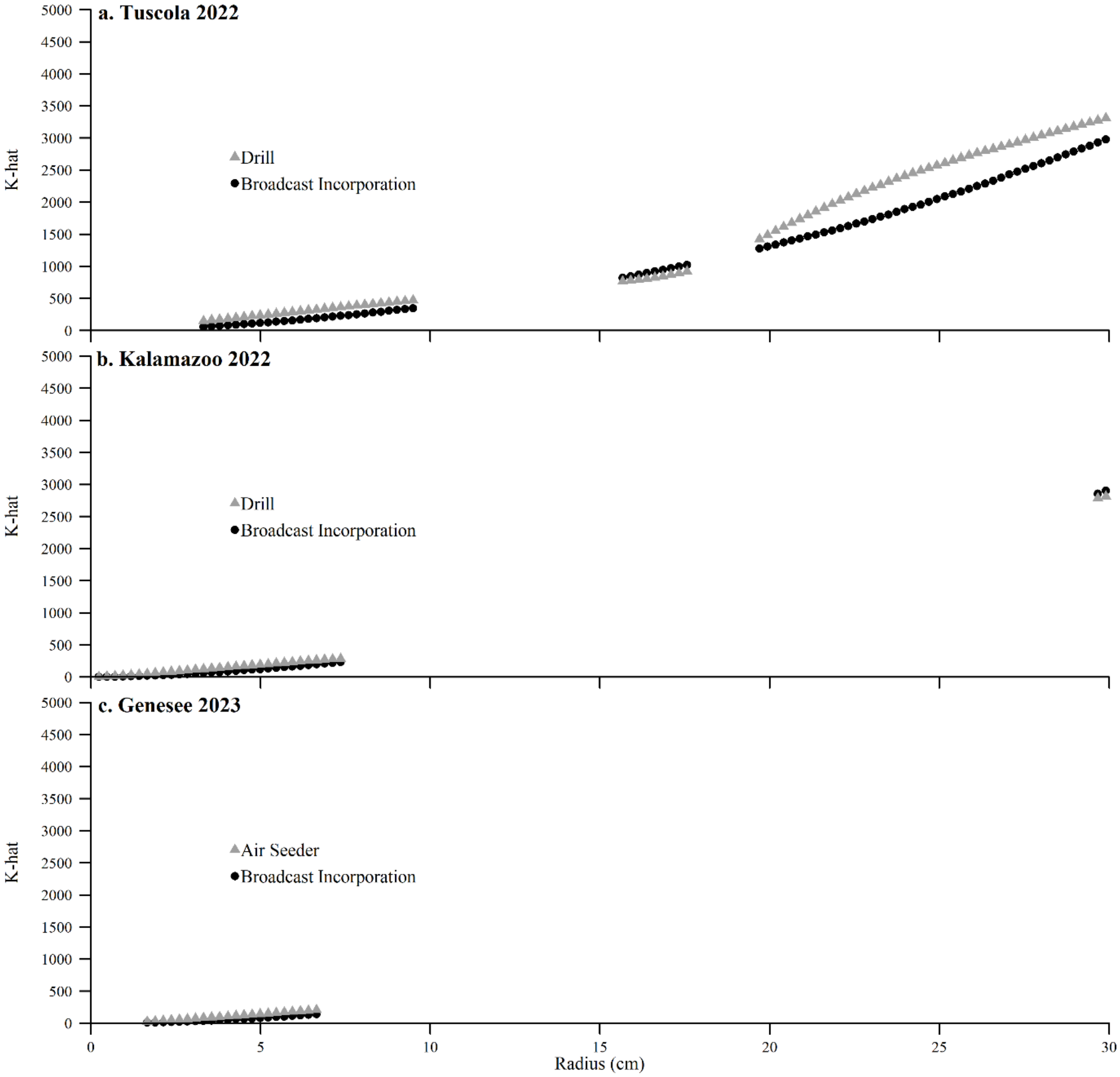

Figure 3.6. Ripley's K statistics estimated for the spatial distribution of winter wheat plants planted using broadcast incorporation vs a traditional grain drill at various site-years. Statistics are plotted only for radii where Tukey's mean separation concluded a significant difference between planting methods (α = .10). Higher K statistics indicate more clustering, while lower K statistics indicate greater uniformity.

Protein was similar among treatments for all site-years, and no DON was detected in any of the samples that were tested (data not shown).

3.4.3 Comparing Broadcast Incorporation at Higher and Lower Seeding Rates

While increasing seeding rate in broadcast incorporation did not show a significant yield benefit at any individual site-year, it did show a small yield benefit of 2% when data was pooled across all site-years (Figure 3.7). TKW and heads ha^{-1} were not affected by increased seeding rate; but kernels ha^{-1} was 2% higher under the higher seeding rate, while heads plant^{-1} and emergence rate were 16% and 6% lower, respectively, under the higher seeding rate (Table 3.4). Protein was similar among treatments for all site-years, and DON was not detected in any of the samples that were tested.

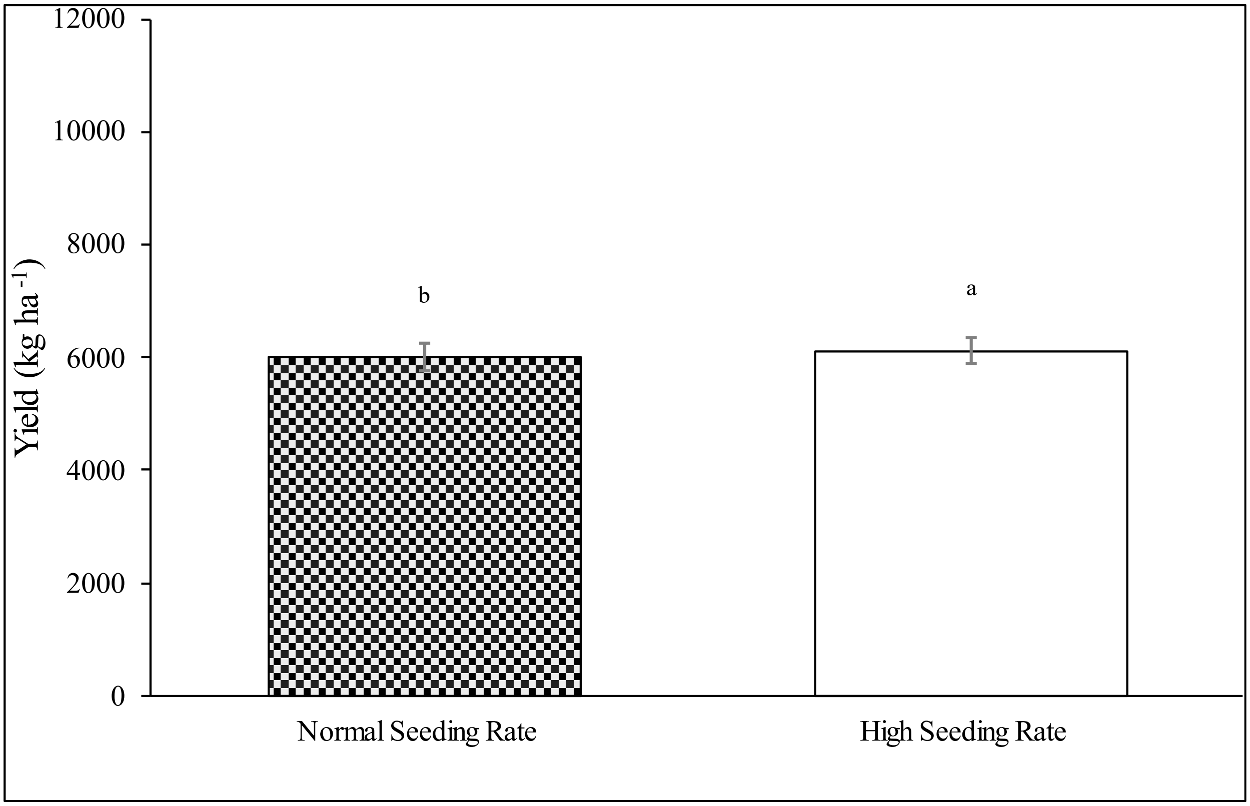

Figure 3.7. Comparing yield for winter wheat planted using broadcast incorporation at normal and 30% higher seeding rates from data pooled across 12 site-years in Michigan. Bars with different letters indicate that yields are significantly different ($\alpha = .10$). Vertical lines on each bar represent ± 1 standard error of the mean.

Table 3.4. Average values for yield components (TKW, thousand-kernel weight) for winter wheat planted using broadcast incorporation at normal seeding rate (Normal) and 30% higher seeding rate (Higher) from data pooled across 12 site-years in Michigan.

Broadcast Seeding Rate	**TKW (g)[a]**	**Kernels (million ha^{-1})**	**Kernels (head^{-1})**	**Heads (million ha^{-1})**	**Heads (plant^{-1})**	**Plants (million ha^{-1})**	**Emergence (%)**	**Protein (%)**
Normal	34.5 a	182 b	23.5 a[b]	8.2 a	3.45 a	2.49 b	79.3 a	11.1 a
Higher	34.4 a	186 a	23.7 a	8.4 a	2.91 b	3.08 a	74.6 b	11.0 a

[a] Combine subsamples, used to determine TKW, kernels ha^{-1}, kernels head^{-1}, and protein, were not collected for Jackson 2023.

[b] Stand counts, used to determine kernels head^{-1}, heads plant^{-1}, plants ha^{-1}, and emergence, were not collected for Ingham 2023.

Note: Values followed by the same letter within a yield components are not significantly different ($\alpha = .10$).

3.5 DISCUSSION

Three planting methods for winter wheat, including precision planter, grain drill or air seeder, and broadcast incorporation, were evaluated for their impact on yield. Precision planting resulted in 8–33% higher yield than planting with an air seeder at three out of four site-years and 13–17% higher yield than planting with a drill at three out of nine site-years. Furthermore, there was no consistent difference in yield between plots planted using broadcast incorporation and those planted using a drill or air seeder, and increasing seeding rate for broadcast incorporation resulted in only a marginal (2%) increase in yield, which likely does not justify the additional seed cost.

The yield increase from precision planting is most directly connected to an increase in kernels ha^{-1} (Table 3.2). This may be driven by increased tillering resulting from a more uniform distribution of plants. The Ripley's K statistics showed that precision planting resulted in a more uniform distribution of plants compared to a grain drill at certain scales and did not generally result in less uniformity (Figure 3.4). This improved uniformity is likely a combination of more uniform spacing within the rows and narrower row spacing. This arrangement allows for increased seed spacing within the rows and reduced spacing between rows, bringing the two measurements closer together (as demonstrated in Figure 3.1). The idea that a combination of precision planting and narrow rows will improve yield is supported by Canfield (2020), which showed similar results in a small-plot study.

The instances where Ripley's K statistic did show more uniformity at certain scales when planting with a drill than with a precision planter were sporadic and likely the result of using a small sample size and imprecision of data translation from pictures to coordinates, though this cannot be proven without more extensive sampling. Each picture used for this analysis represented an area of only about 1.1 m^2. The small sample size and imprecision of data translation were limitations of the equipment and methods available. In order to achieve more robust measurements, a less labor-intensive methodology would need to be developed and more precise equipment used.

Another weakness of our evaluation of precision planting is that we were using a planter with only five row units on 25-cm spacing. This presented two separate challenges. First, the 25-cm spacing meant that we had to plant each plot twice to achieve the desired row spacing of 13 cm. This was done with varying degrees of success, depending on the accuracy of the tractor's auto-steer system, sometimes resulting in a twin row pattern. The other challenge was that the planter passes (127 cm) were narrower than the combine header (~152 cm), which may have biased the yield results (if the combine was taking in slightly more or less than the presumed 1.524 m operating width in other treatments) and did result in border rows between passes that had to be removed prior to harvest. To address these problems, future research should be conducted using a wider planter with row units on 13-cm spacings.

As we hypothesized, broadcast incorporation resulted in more variable seed depth than the other planting methods. For a visual example of the difference in variability, extra data points on seed depth for each planting method were collected in Tuscola 2022 (see Figure 3.8). Despite this greater variability in seed depth and lower emergence, broadcast incorporation generally yielded similarly to conventional grain drill. This is likely due to increased tillering of plants when broadcast incorporation is used (Table 3.3), resulting from a more uniform distribution of plants, which made up for yield potential lost due to variable seed depth and low emergence. Our hypothesis that broadcast incorporation would result in greater spatial uniformity was supported by the Ripley's K statistics (Figure 3.6). A common concern among growers is that even if broadcast incorporation performs adequately when planting within the optimal window, the lack of seed placement accuracy might exacerbate the yield penalty associated with delayed planting (Copeland et al., 2023). This is particularly of interest since growers are more likely to resort to broadcast incorporation to speed up planting when planting is delayed. However, we did not see a difference in yield between broadcast incorporation and conventional drill even in the three site-years that were planted after October 15, where Copeland et al. (2023) saw a >20% yield loss compared to optimal planting time.

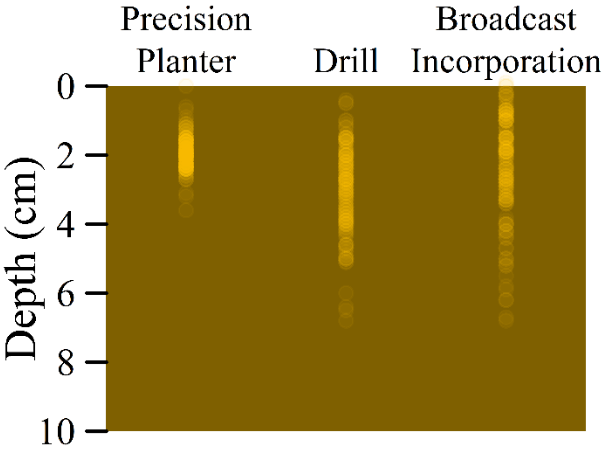

Figure 3.8. Seed depths measured in Tuscola 2022 for precision planting, conventional grain drill, and broadcast incorporation, illustrating the differences in depth variability for each planting method.

Growers who utilize broadcast incorporation generally use a higher seeding rate than when planting with a drill due to the concerns related to lack of seed placement accuracy, adding to production costs. While we did see a marginal yield increase from increasing seeding rate, the difference was likely not sufficient to justify the additional cost of increasing seeding rate, although growers may still choose to increase seeding rates as an insurance policy against stand-reducing factors. This is consistent with what was found by Copeland et al. (2023).

In conclusion, precision planting in narrow rows has potential to improve yield in winter wheat compared to traditional grain drills and air seeders. However, consideration should be given to the cost of precision planting equipment when making the decision to switch from less expensive conventional technologies. Also, further research using more suitable equipment is needed to better determine the extent of the benefits associated with precision planting in wheat. For those who are looking for faster or cheaper ways to plant winter wheat, broadcast incorporation is a viable option, resulting in similar yields to a grain drill or air seeder at similar seeding rates. However, growers should be aware that this planting method does result in variable seed depth and reduced emergence, which could negatively impact yield under certain soil, climatic, or management conditions not encountered in this study.

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CHAPTER 4: EVALUATING THE IMPACT OF SEEDING DEPTH ON WINTER WHEAT EMERGENCE AND YIELD

4.1 INTRODUCTION

Changing climatic conditions in recent years have introduced many weather-related challenges for planting winter wheat (*Triticum aestivum* L.) in the Midwestern US. Winter wheat benefits from early planting, yet a wide range of planting times are implemented due in part to an increased amount and variability of rainfall resulting in a limited and variable planting window where field conditions are suitable for field work. This has led to increased interest in high-speed planting technologies among Midwest row crop growers. Broadcast incorporation, where seed is broadcast over the surface and incorporated using a shallow tillage implement, is one such technology that offers faster planting with low initial investment. However, there are concerns with this approach related to the lack of control over seed placement, and in particular a lack of depth control, as well as the potential for poor seed-to-soil contact and possible negative impacts on grain quality. On the other hand, there is also some interest in switching from grain drills to precision planters, which provide more uniform seed distribution and more consistent seeding depth (Copeland et al., 2022; Figure 3.8). To understand the benefits and risks associated with each of these planting methods it is necessary to evaluate the importance of seeding depth in determining yield.

Proper seed placement is important for productive and profitable crop production (Hörbe et al., 2016a; Koch & Khosla, 2003a). Poor depth control can result in poor germination and crown root development, reduced tillering, increased disease incidence, susceptibility to winter injury in winter cereals, and ultimately reduced yields (Kirby, 1993a; Loeppky et al., 1989a). Shallow planting can result in poor seed coverage, inadequate moisture for germination, and the development of plant crowns near the soil surface, where they are susceptible to heaving and lodging (Roth et al., 1984). Deeper planting may lead to reduced seedling emergence (especially in semi-dwarf varieties with short coleoptiles), weaker plants, and uneven stands. Most wheat varieties grown in the United States have the Rht-B1b or Rht-D1b dwarfing alleles, which reduce plant height but also lead to coleoptiles up to 50% shorter than in wild types (Guedira et al., 2010). These shorter coleoptiles may contribute to poor emergence under deeper planting, as they may not be able to penetrate the thicker layer of soil. However, increasing seeding rate may compensate for reduced emergence at deeper or shallower depth and minimize any yield penalty. Therefore, this research was conducted to evaluate the impact of seeding depth on emergence and yield of winter wheat, as well as to examine the potential interaction between seeding depth, coleoptile length, and seeding rate.

4.2 FIELD TRIALS AND DATA COLLECTION

A field trial was conducted at the Michigan State University Mason Research Farm in Mason, Michigan during three growing seasons (2020–21, 2021–22, and 2022–23; hereafter referred to as 2021, 2022, and 2023, respectively). The experimental design was a randomized complete block in a split-plot arrangement with four replications. Main plots consisted of four seeding depths (1.3, 3.8, 6.4, and 8.9 cm), and sub-plots consisted of a completely randomized combination of three varieties with different dwarfing alleles (DynaGro 9242W with Rht1 dwarfing allele, Whitetail with Rht2 dwarfing allele, and MI16R1172 in 2021 or MO080104 in 2022 and 2023 with a non-Rht1 dwarfing allele) and two seeding rates (2.0 and 3.5 million seeds ha^{-1}). In 2021, the seeding rate factor was not included., and all plots were seeded at 4.4 million seeds ha^{-1}.

In all three growing seasons, the soil type was Conover loam (fine-loamy, mixed, active, mesic Aquic Hapludalf) with a pH range of 6.0–6.7 and cation exchange capacity range of 9.8–

10.2 meq 100 g-1. The previous crop was soybean [*Glycine max* (L.) Merr.] in all years. Plots were planted using a three-point mounted Almaco packet planter, with depth adjustment achieved by manipulating the height of the closing wheels, and harvested using a research plot combine (Wintersteiger Ried im Innkreis, Austria for 2021 season; Kincaid, Haven, Kansas for 2022 and 2023). Management of plots followed current Michigan State University recommendations, including 170 kg ha^{-1} N (34 kg ha^{-1} at planting, 100 kg ha^{-1} at greenup, and 34 kg ha^{-1} at Feekes 6–7), 22 kg ha^{-1} sulfur at planting, and potassium and phosphorus applications according to soil tests and university recommendations (Culman et al., 2020). Weeds were controlled in fall and spring according to university recommendations (Sprague & Burns, 2021). Fungicide was applied at the flag leaf stage to prevent leaf diseases and again at the flowering stage to prevent Fusarium head blight (*Fusarium graminearum*, L). There was minimal to no Fusarium head blight pressure across all three years of this study. Planting and harvest dates are presented in Table 4.1. Data collection included daily visual estimates of percent emergence during the first 5–8 weeks after planting (2022 and 2023 only), plant counts at Feekes 1 (divided by seeding rate to calculate emergence rate), spring stem counts at greenup (2022 and 2023 only), lodging ratings, and harvest weight and moisture measured by the combine at harvest. Yields were standardized to 13.5% moisture prior to analysis.

Table 4.1. Locations, planting dates, and harvest dates for seeding depth field trials in Mason, MI for 2020–21, 2021–22, and 2022–23 (referred to as 2021, 2022, and 2023, respectively).

	2021	**2022**	**2023**
Location			
Latitude	42.6287805	42.628328	42.627931
Longitude	-84.4271304	-84.430175	-84.427539
Planting Date	17 Sep	19 Sep	5 Oct
Harvest Date	9 Jul	14 Jul	11 Jul

Analysis of variance (ANOVA) was conducted to test for interactions among treatment factors in determining yield using the GLIMMIX procedure in SAS 9.4 ($\alpha = .05$). Normality and homoskedasticity assumptions were met as determined by the Shapiro-Wilkens test for normality ($\alpha = .05$) and visual inspection of the box plots. This analysis showed no interactions between treatment factors (Table 4.2), so further analysis focused on the main effect of seeding depth. Using the "lm" function in RStudio 2021.09.1 to conduct quadratic regression analysis, seeding depth was evaluated as a determinant of yield, emergence rate, and spring stems ha^{-1}. Emergence for each seeding depth was evaluated as a function of days after planting using the "SSlogis" function in the "nls" package in R to evaluate the impact of seeding depth on time to emergence.

Table 4.2. *P*-values obtained from ANOVA for main effects and interactions between treatment factors in field trials in Mason, MI for 2020–21, 2021–22, and 2022–23 (referred to as 2021, 2022, and 2023, respectively).

Source	**2021**	**2022**	**2023**
Depth	.592	.125	.990
Variety	<.001	.816	.001
Seeding Rate	-[a]	.859	.011
Depth x Variety	.090	.795	.884
Depth x Seeding Rate	-	.138	.671
Variety x Seeding Rate	-	.727	.849
Depth x Variety x Seeding Rate	-	.455	.921

[a] Seeding rate factor was not included in 2021.

4.3 RESULTS AND DISCUSSION

There were no significant interactions ($\alpha = .05$) between any of the treatment factors in determine yield for any of the three growing seasons (Table 4.2), suggesting that coleoptile length and seeding rate did not have an impact on how seeding depth influenced yield. Therefore, further analysis focused on the main effect seeding depth. In 2022, regression analysis showed a significant, but relatively weak ($R^2 = .424$), relationship between seeding depth and yield (Figure 4.1), with maximum yield of 9870 kg ha^{-1} being achieved at the shallowest depth (1.3 cm). In 2021 and 2023, there was no significant relationship between seeding depth and yield. Similarly, we saw higher emergence rates at shallower depths (though again with a low R2 of .396) in 2022 but not in 2021 or 2023 (Figure 4.2). An examination of the daily emergence data also shows faster emergence with shallower seeding depths in 2022 but no discernible trend in 2023 (Figure 4.3). It should be noted that the low emergence numbers in Figure 4.3 are based on visual estimates of emergence and are not necessarily accurate in absolute terms; yet the relative comparisons should be relevant, since all ratings were conducted by the same person.

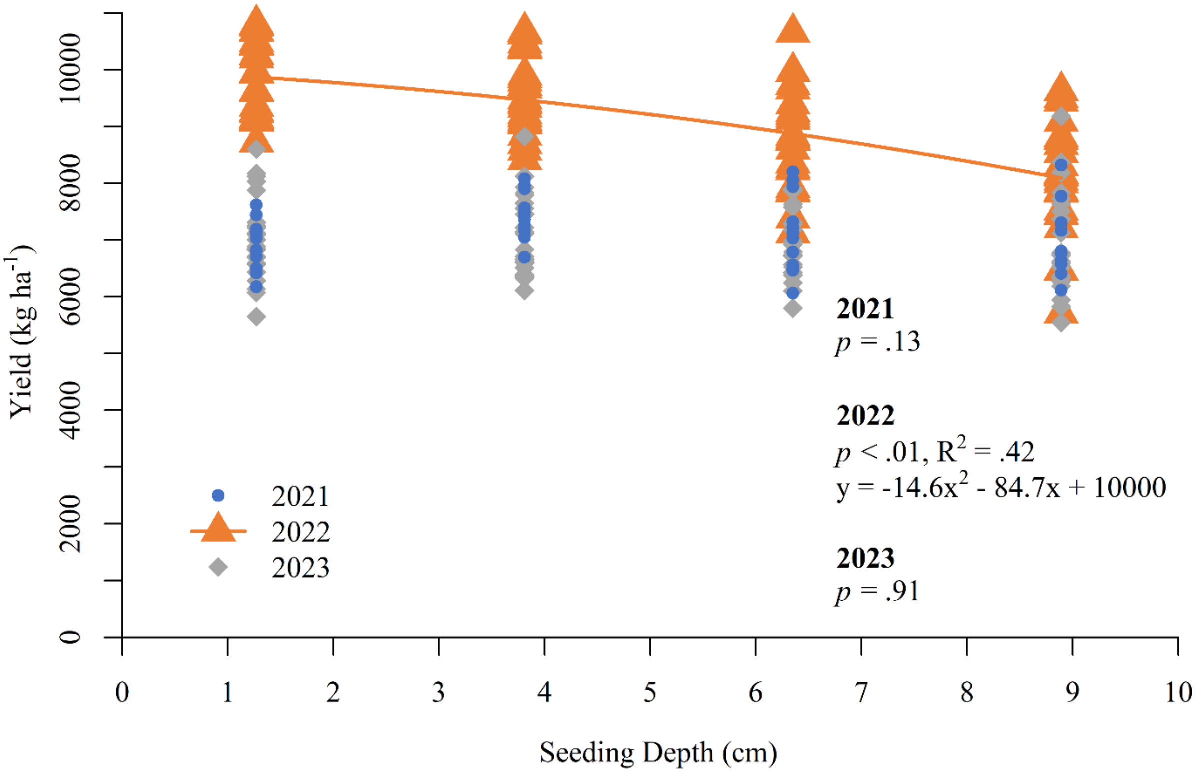

Figure 4.1. Yield as function of seeding depth, using quadratic regression, in field trials in Mason, MI in 2020–21, 2021–22, and 2022–23 (referred to as 2021, 2022, and 2023, respectively).

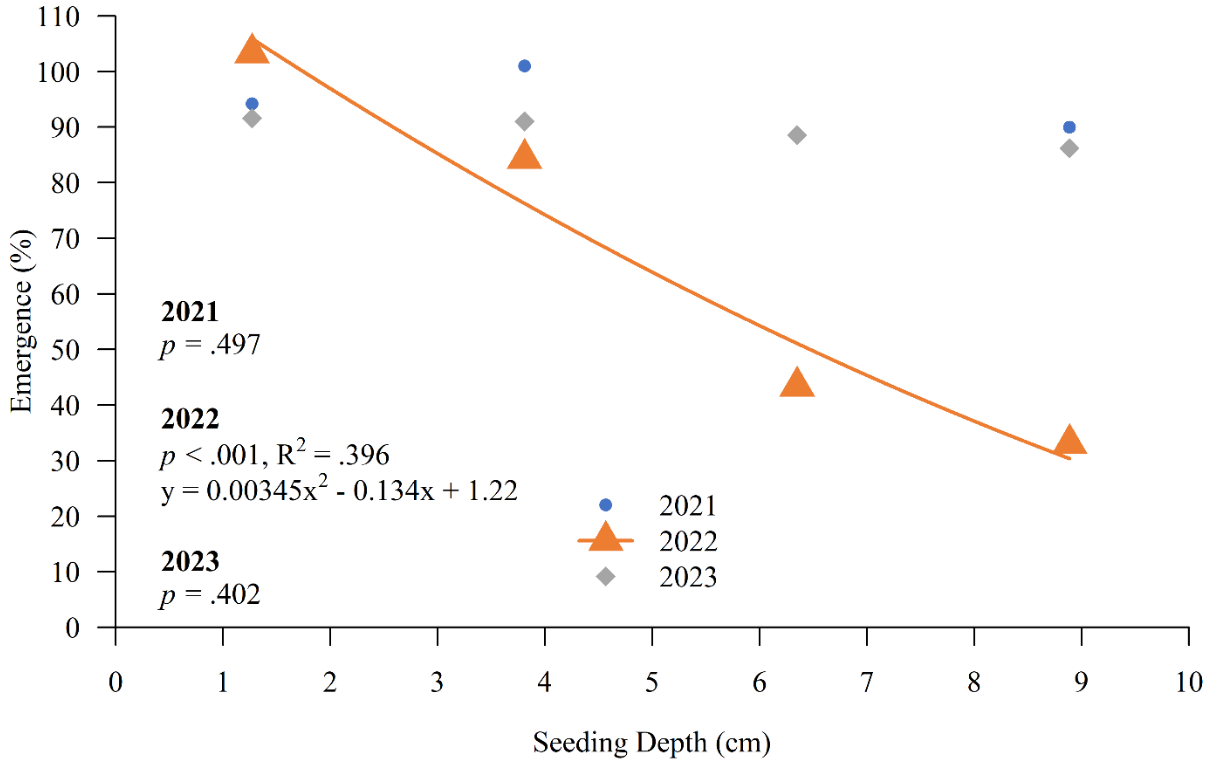

Figure 4.2. Emergence as function of seeding depth in field trials in Mason, MI in 2020–21, 2021–22, and 2022–23 (referred to as 2021, 2022, and 2023, respectively).

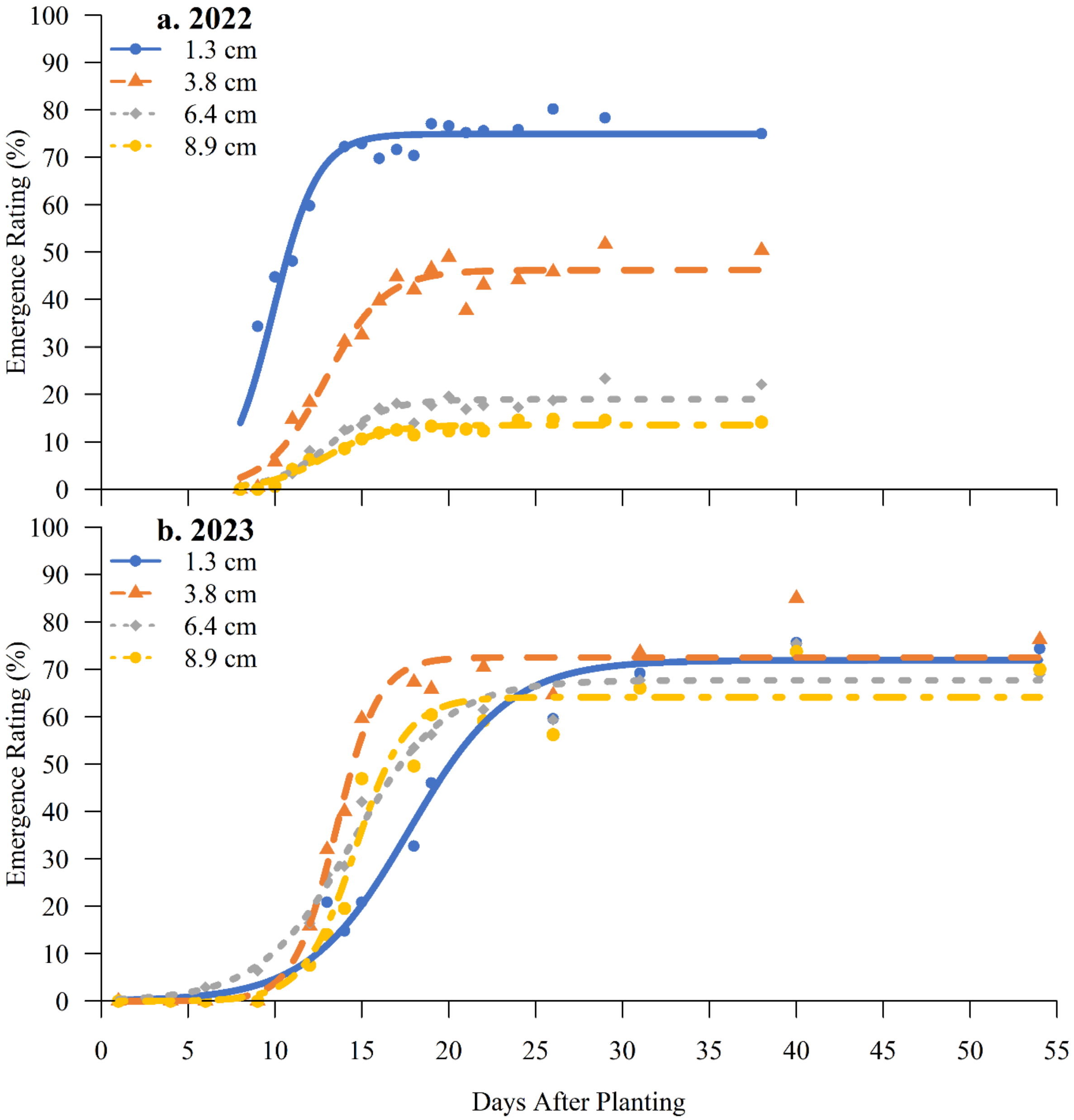

Figure 4.3. Daily emergence data and fitted logistic curves for various seeding depths in field trials in Mason, MI.

Lodging was minimal across all years and treatments with no significant trends. Since the study was conducted on the same farm across all three years, the differences between 2022 and the other years are likely weather-related. Furthermore, higher yields appear to be correlated with faster emergence and greater final emergence under shallower seeding depths. One possible explanation for the higher yields under shallower planting is that rainfall was more consistent throughout the growing season (Figure 4.4), precluding moisture-related challenges associated with shallower planting. However, rainfall throughout the season does not account for the differences in emergence. Closer examination reveals warmer fall weather for the 2022 growing season. This warmer weather likely allowed for more fall tillering, leading to higher yields, as suggested by the spring stem counts, which were higher under shallower planting (Figure 4.5). This suggests that warmer fall weather, perhaps combined with adequate rainfall throughout the growing season, allows shallower-planted wheat to take advantage of faster emergence to produce greater yields. However, under less ideal conditions, the benefits of shallower planting are balanced out by the risks of shallower planting, eliminating the impact of seeding depth on yield.

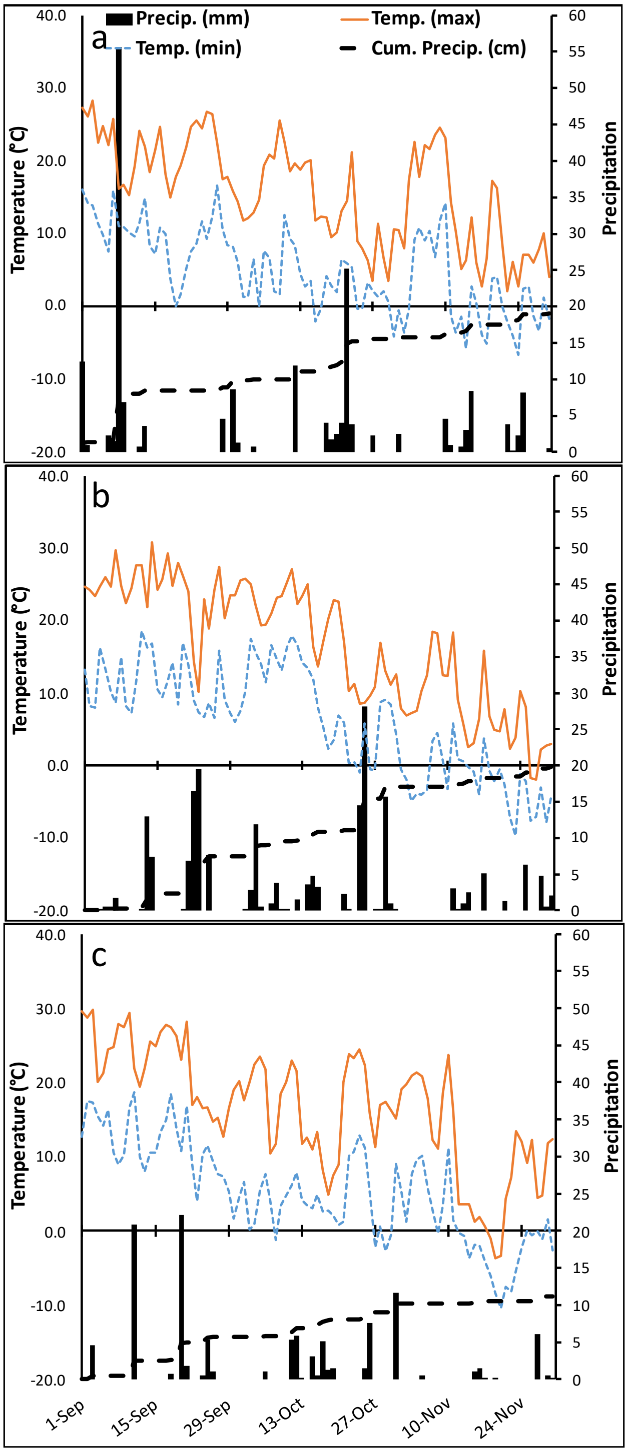

Figure 4.4. Daily emergence data for various seeding depths in field trials in Mason, MI for 2020–21 (a), 2021–22 (b), and 2022–23 (c).

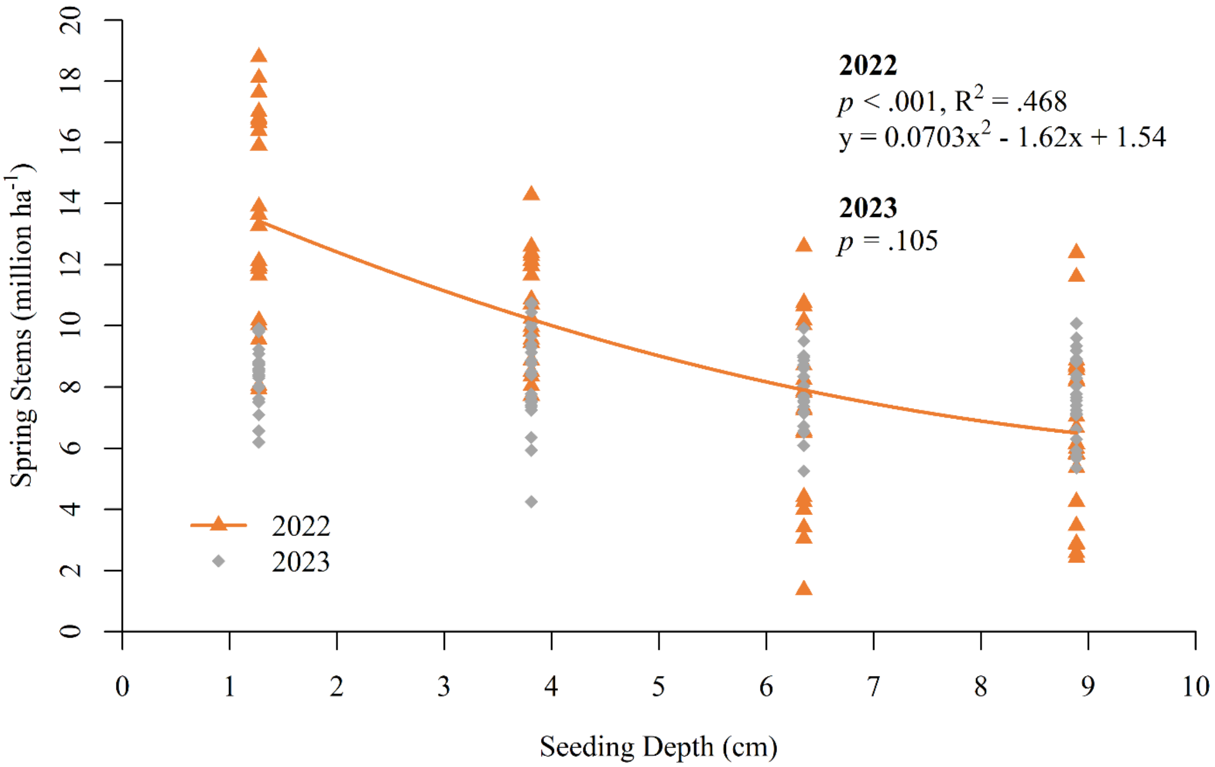

Figure 4.5. Spring stem counts as function of seeding depth, using quadratic regression, in field trials in Mason, MI in 2021–22 and 2022–23 (referred to as 2022 and 2023, respectively).

4.4 CONCLUSION

In this study, we saw that seeding depth generally had little impact on yield in winter wheat, regardless of variety genetics or seeding rate. However, in years where fall weather is warm and there is sufficient rainfall, shallower seeding depths may exhibit improved yield due to faster emergence and increased fall tillering. Based on this, we can infer that, in most years, planting methods with poor depth control might be sufficient to achieve maximum yields, and planting too shallow may result in yield loss due to winterkill or lodging. However, in years with favorable weather conditions, yields may be improved by combining more precise planting methods with shallower seeding depths.

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