Evaluating seeding rate and cultivar impact on grain yield and end-use quality, and finding replacement methods to assess spring stands of soft red winter wheat [*Triticum aestivum* L.] in Ohio

Thesis

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Abstract

Ohio is an important source of soft red winter wheat (SRWW) [*Triticum aestivum* L.] for the milling industry, but is typically a low profitability crop for grain producers. Ohio wheat producers are concerned about a lack of consistency in both grain quality and yield, a perspective that is reflected in decreasing harvested hectares. The first objective was to reassess wheat seeding rate recommendations using four cultivars planted at seeding rates of 1.85, 2.47, 4.94, and 6.18 million seeds ha^{-1}, the second was to determine the best economic seeding rates, and the third was to examine the impact of seeding rate and cultivar on grain quality. An experiment was conducted consisting of four site-years at the Northwestern Agricultural Research Station (NWARS) and the Western Agricultural Research Station (WARS) during the 2015/2016 and 2016/2017 growing seasons. The design was a split-plot randomized complete block design with cultivar as the whole plot factor and seeding rate as the subplot factor. Wheat quality tests were performed at the USDA-ARS Soft Wheat Quality Lab (SWQL) in Wooster, OH. Significant cultivar by seeding rate interactions were observed. Agronomic optimum seeding rates ranged from 5.19 to 5.54 million seeds ha^{-1}, and economic optimum seeding rates ranged from 4.27 to 4.72 million seeds ha^{-1} depending on cultivar. Effect of seeding rate was significant for test weight and sodium carbonate solvent retention capacity. Test weight increased and damaged starch decreased as seeding rate increased. Cultivar selection impacted test weight, softness equivalency, kernel weight, glutenin strength, and starch damage. Cultivar by seeding rate interactions were significant for flour yield and protein. Generally, flour yield increased and flour protein decreased as seeding rate increased. Overall, a seeding rate of 4.94 million seeds ha^{-1} was suggested to produce the best combination of yield and grain quality.

Differences between area of land planted to wheat and area harvested indicate that poor wheat stands are being destroyed in the spring to plant more profitable crops. Current recommendations to evaluate spring stands are stem counts at Feekes growth stage (GS) 5, a practice that is not implemented by producers due to time and labor involved. Two promising replacement measurements are the normalized difference vegetation index (NDVI) and fractional green canopy cover (FGCC). An experiment was conducted consisting of four site-years at two on-farm locations in Pickaway and Crawford Counties during the 2015/2016 and 2016/2017 growing seasons. The design was a randomized complete block design with five seeding rates as the treatment. The objectives were to determine if FGCC was correlated to tiller counts, and to quantify the difference in yield prediction accuracy of tiller counts, NDVI, and FGCC (30.5 cm section of row called "1-row" and 3-row area) at Feekes GS 5 and 6, and head counts at Feekes GS 10.5. Linear regression models fit for stem counts at Feekes GS 5 and 6 vs. FGCC for 1-row at Feekes 5 and 6, respectively, were significant and were able to estimate stem density. The best estimators of yield were NDVI and 3-row FGCC measurements taken at Feekes GS 5, and can be used to estimate the proportion of yield

that will result from a spring stand. Producers may adopt the stem estimation methods when making a decision about wheat stands in the spring and consider using NDVI and FGCC for yield estimation.

Dedication

Dedicated to my parents, Linda and Rodney Goodwin, and my sisters Lillian and Jackie.

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Chapter 1: Introduction

1.1 Wheat History and Description

Wheat [*Triticum aestivum* L.] yields well over an extensive range of environmental conditions, leading many to credit it with the establishment of urban communities (FAO, 2013). Globally, wheat is grown across more land than any other agronomic crop, and total grain production is second only to corn (USDA-FAS, 2017).

There are seven classes of wheat categorized by grain protein content, endosperm structure and composition, testa (seed coat) color, and presence or absence of a vernalization requirement (Smith, 1995). Soft red winter wheat (SRWW) is the primary wheat grain produced in Ohio. “Soft” wheat is characterized by very fine flour, due to rupturing of endosperm cells during the milling process, and a protein content between 8.5-9.5% (Smith, 1995). “Red” refers to the red-tinted seed coat, and “winter” indicates the necessity for overwintering to complete vernalization (Heid, 1979). Flour produced from SRWW grain is the main component of pastries and baked goods, such as cookies and cakes (Baenziger et al., 1985).

1.2 Soft Red Winter Wheat Production in Ohio

In Ohio, 1.2 million metric tons of SRWW were harvested in 2016, making it the highest producing state in the U.S. (U.S. Wheat Associates, 2016). However, wheat hectares harvested in Ohio have been steadily declining, with 514,000 hectares harvested in 1990, 335,900 hectares in 2005, and 226,600 hectares in 2016 (NASS-USDA, 2016). Ohio producers list profitability as the most important factor in wheat production, a concern which stems from a lack of consistent grain quality and yield (OSGMP, unpublished, 2015).

The risk involved with planting winter wheat in Ohio can be quantified by calculating the difference between area planted and area harvested. Table 1.1 details the distribution of data from 1990-2017, and shows the percent loss of wheat hectares between planting and harvest (USDA-NASS, 2017). Table 1.1 also illustrates the unpredictability for percent decrease in wheat area at harvest vs. at planting among the 28 years of data. While there is no explicit reason for the year-to-year variation, it suggests weather-related issues reduce stand population, leading producers to destroy their wheat crop and plant an alternative crop (i.e., soybean) in the spring. Since few producers use the recommended method of tiller counts for stand assessment, the data raises concerns as to how destruction was deemed necessary, especially in years with abnormally large wheat hectare reduction. By re-evaluating seeding rate recommendations for current wheat varieties, testing new methods for easier, more accurate spring stand health assessments, and examining two influential yet controllable factors to provide the best flour quality, this research will increase SRWW production consistency in Ohio, and aims to prevent additional crop reduction and producer frustration.

Table 1.1. Percent reduction in wheat hectares between planting and harvesting among select years from 1990-2017 and distribution of data (data from USDA-NASS, 2017).

Harvest Year	Hectares planted	Hectares harvested	Difference (in ha)	% Change	Description
2017	186,156	169,968	16,187	8.7	Most recent
2016	234,718	226,624	8,094	3.4	50th percentile
2014	250,905	220,554	30,351	12.1	Largest
2010	291,374	283,280	8,094	2.8	25th percentile
2000	453,249	449,202	4,047	0.9	Smallest
1996	566,561	538,233	28,328	5.0	Average
1991	465,389	437,061	28,328	6.1	75th percentile
1990	526,092	513,952	12,141	2.3	Oldest

1.3 Seeding Rate

Seeding rate is a critical component in winter wheat management, as it impacts lodging and disease potential (Beuerlein et al., 1991), number of spikes per square meter (Freeze and Bacon, 1990), number of kernels/spike (Johnson et al., 1988), and kernel weight (Joseph et al., 1985). However, the effect of seeding rate on yield is unpredictable, as it is largely governed by environment and genotype (Geleta et al., 2002; Roth et al., 1984; Marshall and Ohm, 1987).

Across the Midwest, suggested optimal seeding rates are similar. Beuerlein et al. (1991) states that 237 to 334 seeds m^{-2} (2.4 to 3.3 million seeds ha^{-1}), or 100 kg ha^{-1} (Beuerlein J. and Lafever, H., 1989) is sufficient for Midwestern growers. This is now considered low in comparison to more modern recommendations. In Illinois, a higher rate of 377 to 430 seeds m^{-2} (3.8 to 4.3 million seeds/ha) is suggested (Nafziger, accessed 2017). In Kentucky, Lee et al. (2009) recommend planting between 323 and 377 seeds m^{-2} (3.2 to 3.8 million seeds ha^{-1}), to achieve a stand population of 269 plants m^{-2}; yield reductions begin below 258 plants m^{-2}.

1.3.1 Historical Seeding Rate Research

Kiesselbach (1926) experimented with seeding rates of hard red winter wheat (HRWW) in Nebraska, and determined that yield continued to increase as seeding rate increased from 50.4 to 100.8 kg ha^{-1} (originally stated as 3-6 pecks), but decreased under an additional rate of 134.4 kg ha^{-1}, averaged over 5 years of data. Martin et al. (1926) found different outcomes in Highmore, Newell, and Brookings, South Dakota when averaged over three, four, and five years, respectively. At Highmore, yield increased with rate until it peaked at 84 kg ha^{-1}, after which a sharp decrease occurred under the highest rate of 100.8 kg ha^{-1}. The highest seeding rate at Newell was 117.6 kg ha^{-1}, and it is stated that the associated yield was also the highest. In Brookings, South Dakota, yield increased until a rate of 84 kg ha^{-1}, and began to slowly decline between 84 kg ha^{-1} and the highest rate of 117.6 kg ha^{-1} (Martin et al., 1926). When summarized, optimal HRWW rates were found to be 84 kg ha^{-1} (Martin et al., 1926), 100.8 kg ha^{-1} (Kiesselbach, 1926), or 117.6 kg ha^{-1} (Martin et al., 1926) (Table 1.2). Large variation when studying what constitutes an optimal seeding rate is not bound to historical studies.

Table 1.2. Summary of optimum seeding rates (expressed in kg ha^{-1}) recommended for hard red winter wheat (HRWW) production in historical research

Harvest year(s) of trial	Optimum rate (kg ha^{-1})	Type of wheat	State	Author and year of publication
1919-1923	100.8	HRWW	Nebraska	Kiesselbach, 1926
1916, 1917, 1919	84	HRWW	Highmore, S.D.	Martin et al., 1926
1913-1916	117.6	HRWW	Newell, S.D.	Martin et al., 1926
1913-1915, 1918-1919	84	HRWW	Brookings, S.D.	Martin et al., 1926

1.3.2 Current Seeding Rate Research

As seeding rate research has progressed in the U.S., units in which treatments are reported have generally evolved from weight per area (e.g., pecks, bu ac^{-1}), to mass per area (kg ha^{-1}), to number of seeds in a given area (seeds m^{-2}). This can make comparisons impossible in some cases, but independent consideration of Tables 1-3 and 1-4 should assist in making useful conclusions.

Geleta et al. (2002) observed yield increases for seeding rates of HRWW between 16, 33, and 65 kg ha^{-1} when averaged over four site-years and twenty genotypes in Nebraska. A plateau occurred after 65 kg ha^{-1}; yields for seeding rates between 65 and 130 kg ha^{-1} were not statistically different. Blue et al. (1990) planted HRWW at 34, 67, and 101 kg ha^{-1} in southeastern Nebraska, and observed a linear increase in yield each year when averaged over locations. Johnson et al. (1988) found no significant differences in SRWW grain yield between 288 seeds m^{-2} (standard) and 576 seeds m^{-2}, in a high yielding environment in Georgia. At an Arkansas site, Freeze and Bacon (1990) similarly found that SRWW yields between a moderate and high seeding rate (280 and 560 seeds m^{-2}) were equal, and that these yields were higher than the low treatment of 140 seeds m^{-2}. Using seeding rates of 101 kg ha^{-1} (control), 168 kg ha^{-1}, and 235 kg ha^{-1}, Frederick and Marshall (1985) reported net yield changes between the control rate and each higher rate for SRWW. Five site-years of this study had non-significant net yield changes, which suggests 101 kg ha^{-1} was the optimal seeding rate (Frederick and Marshall, 1985). Joseph et al. (1985) saw differing yield responses of SRWW due to soil type, as seeding rate increased from 186, to 372, and 558 seeds m^{-2}, causing either 186 or 372 seeds m^{-2} to achieve the greatest yield in 20 cm rows. Marshall and Ohm (1987) found no yield difference between seeding rates of 377 and 538 seeds m^{-2} in 1983, but did observe a yield increase between these two rates in 1984. When using rates of 409 (recommended), 511, 613, and 715 seeds m^{-2}, Pan et al. (1994) determined 409 seeds m^{-2} to be the agronomic and economic optimum rate, when planting took place on the earliest of three planting dates (6 Oct.1989 and 2 Oct. 1990 in Clarksville, MD). Depending on the experimental location, Roth et al. (1984) found highest yields with a rate of 235 kg ha^{-1} or 101 kg ha^{-1}, but it is stated that 168 kg ha^{-1} was the best overall seeding rate for Pennsylvania.

Determining an optimal rate is crucial for recommendations, but has been found to be 65 kg ha^{-1} (Geleta et al., 2002), 101 kg ha^{-1} (Blue et al., 1990; Frederick and Marshall, 1985; Roth et al., 1984), 168 kg ha^{-1} (Roth et al., 1984), and 235 kg ha^{-1} (Roth et al., 1984) (Table 1.3). When reported in seeds per unit area, seeding rates of 186 seeds m^{-2} (Joseph et al., 1985), 280 seeds m^{-2} (Freeze and Bacon, 1990), 288 seeds m^{-2}

(Johnson et al., 1988), 372 seeds m^{-2} (Joseph et al., 1985), 377 seeds m^{-2} (Marshall and Ohm, 1987), or 409 seeds m^{-2} (Pan et al., 2013) were all considered the agronomic optimum, where grain yield was greatest (Table 1.4). Uncontrollable factors within and among growing seasons cause difficulty in providing seeding rate recommendations.

Table 1.3. Summary of optimum seeding rates (expressed in kg ha^{-1}) recommended for soft red winter wheat (SRWW) and hard red winter wheat (HRWW) production.

Harvest year(s) of trial	Optimum seeding rate (kg ha^{-1})	Type of wheat	State	Reference
1981-1982	168 or 235	SRWW	Pennsylvania	Roth et al., 1984
1981-1982	101	SRWW	Pennsylvania	Frederick and Marshall, 1985
1986-1988	101	HRWW	Nebraska	Blue et al., 1990
1997-1998	65	HRWW	Nebraska	Geleta et al, 2002

Table 1.4. Summary of optimum seeding rates (expressed in seeds m^{-2}) recommended for soft red winter wheat (SRWW) production.

Harvest year(s) of trial	Optimum seeding rate (seeds m^{-2})	Type of wheat	State	Reference
1982-1983	186 or 372	SRWW	Virginia	Joseph et al., 1985
1983-1984	377 (83') or 538 (84')	SRWW	Indiana	Marshall and Ohm, 1987
1985-1986	288	SRWW	Georgia	Johnson et al., 1988
1986-1987	280	SRWW	Arkansas	Freeze and Bacon, 1990
1990-1991	409	SRWW	Maryland	Pan et al., 1994

1.3.3 Short-Term Trends in Yield Response to Seeding Rate

Uncontrollable factors within and among growing seasons cause difficulty in providing seeding rate recommendations. Seemingly straightforward conclusions from previous research are made more complicated when inspected further. In the first site-year, Johnson, et al. (1988) obtained higher yields with 576 seeds m^{-2} than with 288 seeds m^{-2}, as opposed to equivalent yields when averaged over multiple years, due to extensive winter kill that the low rate could not make up for. For one location in 1986, Freeze and Bacon (1990) found highest yields with 140 seeds m^{-2} for four of the six genotypes tested. With yield data for seeding rates from individual site-years, Geleta et al. (2002) saw yield decline after 33 kg ha^{-1} for Lincoln, NE in 1998, but the highest yield for 130 kg ha^{-1} for the other three site-year combinations; the optimum rate was determined to lie between 65 and 130 kg ha^{-1}. Though five site-years resulted in an optimum rate of 101 kg ha^{-1}, Frederick and Marshall (1985) also reported optimum rates of 168 kg ha^{-1} and 235 kg ha^{-1} for one and two site-years respectively, due to reduced fall tillering either from moisture stress or a later planting date. Although Pan et al. (1994) indicated 409 seeds m^{-2} to be optimal overall, they did not have a significant seeding rate effect at Beltsville, MD. Additionally, at the latest seeding date (13 Nov. 1989; 15 Nov. 1990), the economically optimum rate became 511 seeds m^{-2}. Blue et al. (1990) highlighted that yield response to seeding rate in 1988 was linear when no phosphorus (P) was added, but varied between P rates of 17 and 34 kg ha^{-1}. Under 34 kg ha^{-1} of P, yield increased from 34 to 67 kg ha^{-1} of seed and decreased from 67 to 101 kg ha^{-1} of seed. The exact opposite trend was observed when the P rate was 17 kg ha^{-1} (Blue et al., 1990).

Year-to-year variability is clearly present when the effect of seeding rate is being examined as an influential factor of yield. This can occur for several reasons, including winter conditions (Johnson et al., 1988; Geleta et al., 2002), lodging potential because of increased seeding rate (Freeze and Bacon, 1990), moisture stress (Frederick and Marshall, 1985), and planting date (Frederick and Marshall, 1985; Pan, et al., 2013). While a general trend is necessary when proposing a seeding rate range, it is not complex enough to describe how yield will respond in one specific year, in one specific environment. This is supported by Geleta et al. (2002), who highlight the need for more thorough research on seeding rate, and state that it is a "predictable environmental factor that affects some agronomic and end-use quality traits of wheat".

Our SRWW seeding rate study has locations over four diverse latitudes throughout Ohio, to best account for the impact environment has on seeding rate and yield. This research relates yield to fall seeding rate in addition to spring stand health and density, something that is uncontrollable, yet arguably more critical from a management standpoint.

1.4 Wheat Stand Assessment and Yield Prediction

During winter, a wheat crop is subjected to varying levels of injury and stress that are dependent upon the degree of snow cover, freezing temperatures, soil heaving, etc. (Fowler and Gusta, 1979). Stress during tiller formation, like that remnant of a harsh winter, can slow or prevent additional tiller production (Klepper et al., 1982). Yield potential may be directly limited in a manner that may or may not be apparent by purely visual observations.

1.4.1 Tiller Counts and Current Recommendations

Current wheat stand evaluation recommendations require tiller counts to assess potential yield, or health, of a wheat stand in spring. The most commonly used growth scale in Ohio is the Feekes scale (Large, 1954). In Illinois, it is recommended to have 430-538 tillers m^{-2} by Feekes growth stage (GS) 6 to achieve a high yield, while the minimum to keep a stand in production is based on a difficult measurement of plants per area (161 to 215 plants m^{-2}) in the spring (Nafziger, accessed 2017). In Kentucky, tiller counts are to be made at Feekes GS 3, and 753-1,076 tillers m^{-2} is considered sufficient (Lee et al., 2009).

Other tiller density research focuses on the ability of tiller counts to determine nitrogen (N) requirements, an estimate based on yield potential. For SRWW under no-till production in North Carolina, Weisz, et al. (2001) observed a threshold of 550 tillers m^{-2}, below which a N application should take place at Zadoks GS 25 (Zadoks et al., 1974). Scharf and Alley (1993) consider anything under 1,000 tillers m^{-2} to be low. Donald (1968) favors a greater stand density, and states that a maximum yield can be obtained through a population that achieves one main stem per plant with no tillers, something that Joseph et al. (1985) found to occur with a tiller density of 1,116 tillers m^{-2} and a row width of 10 cm. Although these recommendations are for N timing and rate decisions, they also delineate between a poor and acceptable tiller density.

Tiller counts are rarely performed by producers, as they are tedious, time consuming, and labor intensive (Flowers et al., 2001). It is recommended that N is applied at Feekes growth stages (GS) 4-5 (“green-up”) and no later than Feekes GS 6 (stem elongation) (Wise et al., 2011), making this an important decision-making period of the growing season. At this time, a producer may choose to prevent additional inputs from being applied, destroy the wheat crop and substitute another crop, or develop a sufficient input program to counteract reduced yield potential and quality. If tiller counts are not performed, such decisions are not being made objectively, suggesting that faster, easier, and more accurate estimation methods are needed. Normalized difference vegetation index (NDVI) and fractional green canopy cover (FGCC) are two promising alternatives to early spring tiller counts.

1.4.2 NDVI Research

A replacement method for tiller counts must be capable of estimating tiller density and yield potential post-dormancy, early in the spring. Wanjura and Hatfield (1987) concluded that NDVI was the best vegetative index (VI) for early season leaf area index (LAI) and ground cover measurements for cotton [*Gossypium hirsutum* L.], soybean [*Glycine max* L.], grain sorghum [*Sorghum bicolor* L.], and sunflower [*Helianthus annus* L.]. Normalized difference vegetation index is one of many multispectral reflectance indices used to indirectly measure crop canopy variables, and is calculated using near-infrared (NIR) and red (R) wavelengths (NIR-R/NIR+R) (Phillips et al., 2004). One stipulation to NDVI is that LAI must be < 3, as it cannot distinguish differences in biomass above 3, and any result is not reliable past this point (Serrano et al., 2000; Aparicio et al., 2000).

While many studies have utilized satellite imagery, very few have examined optical handheld sensors to take readings. Satellite measurements can be distorted by atmospheric conditions, satellite position and angle (Holben, 1986; Soufflet et al., 1991), crop canopy architecture, and solar incidence (Pinter, 1993). A handheld sensor eliminates influence from the atmosphere, satellite geometry, and incoming radiation, because of the device's close proximity to the canopy and the presence of its own light source (Verhulst and Govaerts, 2010). Handheld sensors have proven useful in estimating early spring tiller density, primarily for calculating N rates. Flowers et al. (2003) showed that NDVI was "strongly and consistently correlated with [Zadoks] GS 25 tiller density", provided weeds were non-existent. Phillips et al. (2004) confirmed the reliability of NDVI to estimate tiller density at Zadoks GS 25 (Zadoks et al., 1954), in 18 of 22 locations, but suggested that calibration is needed for each major soil type at each location. Consistent with Ohio recommendations, Lukina et al. (2000) performed readings at Feekes 4 and 5, and reported significant correlation coefficients between 0.80 and 0.98 for NDVI and percent canopy cover. Percent canopy cover was determined by converting digital pictures to "binary pseudo-color images", and estimating the percent of pixels that corresponded to vegetation, a method developed by Lukina et al. (1999).

Previous research has also shown that recording NDVI values through remote sensing exhibits potential in yield prediction. Raun et al. (2001) were able to describe 83% of variation in actual yield, by using a GDD modified calculation to produce estimated yields; Estimated Yield= [(Feekes 4 NDVI + Feekes 5 NDVI)/(GDD at Feekes 5- GDD at Feekes 4)]. Similarly, Aparicio et al. (2000) found a significant coefficient of determination (r^2) =0.51 for the relationship between NDVI and yield, for durum wheat under non-irrigated conditions, when measured between heading and physiological maturity. Counterintuitively, post-anthesis measurements result in the most accurate yield estimations, but are more relevant to breeding programs (Marti et al., 2007). Around the time of grain-fill, LAI values decrease to below 3, which explains the accuracy of this late measurement period (Aparicio et al., 2000). Normalized difference vegetation index may be better suited as an alternative yield predictor to head counts, but this crop growth stage occurs too late to be used for early spring stand assessments. This does not mean NDVI will not be useful for early spring measurements, simply that it must be carefully studied prior to recommending it to producers as a reliable technique.

1.4.3 Fractional Green Canopy Cover

Fractional green canopy cover is a method of quantifying surface area covered by living plant tissue, and is measured by classifying pixels in an image and calculating the percentage of green pixels within that image. Although canopy cover (CC) is two-dimensional, strong relationships have been observed between CC and three-dimensional factors such as LAI, biomass, and yield. Nielsen et al. (2012) reported an r^2= 0.957 when regressing wheat LAI against percent CC, but specified an overestimation of predicted CC values when LAI was less than 2 m^2 m^{-2}. Lati et al. (2011) found a strong linear relationship (r^2= 0.98) between LAI and biomass of purple nutsedge [*Cyperus rotundus* L.]. Casadesús et al. (2007) also reported a strong correlation between FGCC (called “green area”) and biomass, in addition to grain yield in durum wheat. Since FGCC is strongly related to biomass, using it to estimate tiller density is plausible; limited evidence for grain yield correlation suggests the need for further research.

1.4.4 Canopeo and other FGCC mobile device applications

Canopeo (Oklahoma State University, Stillwater, OK) is a newly developed mobile device application designed to make real-time FGCC measurements quickly, easily, and accurately (Patrignani and Ochsner, 2015). Thresholds based on blue:green and red:green ratios, and the excess green index, are used to automatically classify pixels as green or not green (Patrignani and Ochsner, 2015). The excess green index categorizes darker pixels that cannot be identified by using B/G and R/G ratios alone, and is a crucial variable that similar programs lack, such as “Easy Leaf Area” developed by Easlon and Bloom (2014). Additionally, Canopeo can remove groups or individual pixels that match the color criteria but are not part of the canopy; sensitivity of the option is user controlled (Patrignani and Ochsner, 2015).

When tested for accuracy against SamplePoint (Booth et al., 2006), a leading manual pixel classification program, Canopeo classified 100% and 90% of pixels correctly for wheat images under conventional tillage and no-till, respectively. Furthermore, Canopeo is 75-2,500 times faster than SamplePoint and 20-130 times faster than SigmaScan Pro (Systat software, Chicago, IL), an automatic pixel classification program (Patrignani and Ochsner, 2015).

Multiple FGCC programs exist, but they either require a computer to analyze digital images (e.g., “SigmaScan Pro”, “SamplePoint”, and “EasyPCC”, developed by

Guo et al., 2017), are geared toward a specific crop ("VitiCanopy", developed by De Bei, et al. (2016), or lose accuracy for images with complex backgrounds or leaf overlap ("Easy Leaf Area"). Speed, accuracy, accessibility, ease of use, and no cost, makes Canopeo a practical tool for producers, yet additional experimentation is needed to prove consistency and test other potential uses.

1.5 Grain and Flour Quality

The chain of production from wheat grain to flour to baking is long and complex. Although quality can be defined differently at each step of process, quality of the final product hinges on the performance of grain producers. Once grain is harvested, additional tests must be performed to ensure efficient processing that will result in a consistently high-quality flour. The end-use is an important consideration; of the wheat not exported in 2014, 94% was used for human consumption (USDA-ERS, 2016; USDA-NASS, 2017). Test weight, softness equivalency, kernel weight, flour protein, and solvent retention capacities (SRC), all combine to impact milling properties, flour yield, and baking quality. By studying how influential management decisions such as population and cultivar alter quality factors, producers can increase the probability of producing both high yielding and high-quality grain.

1.5.1 Test Weight

Test weight is the weight of grain within a given volume, and is comprised of kernel density and packing efficiency, the latter of which is defined as the percent volume of a container occupied by grain (Finney et al., 1987). The standard for test weight in the

U.S. grading system is 772.32 kg m^{-3} for all wheat other than hard red spring and white club wheat (USDA-GIPSA, 2013). Test weight and kernel density have been found to significantly correlate to flour protein content, a value that is crucial to the type of product being baked (Schuler et al., 1995). Lower kernel protein contents, typical of soft wheat, cause formation of interior air pockets resulting in a lower kernel density and therefore lower test weight (Finney et al., 1987).

While kernel density is impacted by growing environment, packing efficiency is cultivar dependent (Ghaderi et al. 1971). Yamazaki and Briggle (1969) reported differences in packing efficiency as high as 3.77%, caused by kernel deformations among seven soft wheat varieties with identical kernel densities. Kernel deformations (e.g., indentations, "humped kernels") alter grain arrangement and limit the potential to fill empty container space (Yamazaki and Briggle, 1969; Finney et al., 1987). Shuler et al. (1994) similarly concluded that flawed (i.e., shriveled) kernels influenced test weight, but argued environment was the causal agent leading to shrunken kernels; removal of these kernels increased test weight of 24 cultivars by an average of 36 kg m^{-3}. In the absence of shriveled kernels, Gaines et al. (1997) reported no difference in test weight with kernel size, but did observe significantly greater break flour and softness equivalent values for the smallest kernels only.

The growing environment greatly impacts test weight, but controllable factors can be used to make proactive management decisions. Roth et al. (1984) reported a quadratic increase in test weight with seeding rate, and a decrease with N rates above 0 kg ha^{-1} in most cases. Souza et al. (2012) found a highly significant ($p < 0.001$) environment x cultivar interaction for test weight. Therefore, choosing a cultivar well-suited to a typical growing environment, selecting a responsible N rate, and using an agronomically optimum rate are all management decisions likely to result in higher test weights.

1.5.2 Percent Flour Yield

The amount of flour obtained from grain via the milling process (called straight grade flour yield, or flour yield), is impacted by kernel hardness, endosperm separation, cultivar yield potential, and growing environment (Marshall et al., 1986; Souza et al., 2002; Souza et al., 2012). Ease of endosperm separation from bran increases the quantity of break flour from the initial stage of milling (Souza, et al., 2012). Interestingly, test weight and kernel size were not strong indicators of flour yield even when shriveled kernels were removed (Shuey, 1960; Schuler et al., 1995). Differences in test weight of up to 41 kg m^{-3} have been observed without significant impacts on flour yield (Shuey, 1960). Souza et al. (2012) measured quality parameters of 187 soft wheat cultivars, and found only a slight positive correlation between test weight and flour yield, stating that test weight may be useful for grain elevators, but ultimately has no value for predicting flour yield in breeding programs. Flour yield is another quality that is cultivar specific, making it a critical value in wheat breeding (Yamazaki and Andrews, 1982). Flour yield typically ranges between 72% and 79%, but can vary depending on milling equipment and miller experience (Finney et al., 1987; Souza et al., 2012).

1.5.3 Softness Equivalency

Softness equivalency (SE) without adjustment to 15% moisture is calculated using the equation SE= [(grain weight - bran) – middling stock]/(grain weight - bran), where bran is material remaining above a 471 μm screen, and middling stock (also called "mids") remain above a 180 μm screen (USDA-ARS, 2017). Essentially, it is the percent of non-bran material that is break flour. Break flour is comprised of particles less than 180 μm after one cycle of milling and sieving. A high softness equivalency also indicates low starch damage, as ideal fracturing of endosperm results in intact granules, as opposed to splitting through granules that occurs with hard kernels (Pomeranz and Williams, 1990). When the end products are cookies or cakes, any degree of damaged starch is unfavorable, as an increase in flour volume during baking is restricted (Miller and Hoseney, 1997). SE is a good predictor of break flour yield in larger milling processes (Gaines et al., 1997).

1.5.4 Solvent Retention Capacity

The solvent retention capacity (SRC) tests, AACC method 56-11 (AACC, 2010) use up to four solvents to analyze specific components of flour that predict baking properties, by measuring the weight of remaining solvent absorbed by flour after mixing, centrifuging, draining, and drying samples (Guttieri and Souza, 2003). Greater sodium carbonate retention indicates high starch damage from milling, higher lactic acid values equate to stronger glutenin, sucrose measures the amount of gliadin and pentosan, and water determines overall flour absorption capacity (Souza et al., 2012). Only sodium carbonate and lactic acid SRC's were carried out in our research.

Ideal values depend on which product is going to be made. Cookie producers need flour with low water absorption, weak glutenin strength, and little starch damage; cracker baking also requires low water absorption, but high glutenin strength (Kweon et al., 2011). High levels of pentosan and damaged starch significantly increase the water holding capacity of flour (Slade and Levine, 1994), which leads to decreased production efficiency, unnecessarily high energy usage, and a fragile baked good (Souza et al., 2012). A soft flour of the highest standard would have a lactic acid SRC at or above 87%, and a sodium carbonate value at or below 64% (Kweon et al., *in press*).

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Chapter 2: Influence of soft red winter wheat seeding rate and cultivar on grain yield and end-use quality

2.1 Abstract

Seeding rate and cultivar selection are two pivotal decisions that determine grain yield and end-use quality of wheat [*Triticum aestivum* L.]. Little research has been done that examines the effects of both factors on soft red winter wheat (SRWW) in Ohio. Wheat producers need updated seeding rate recommendations to take full advantage of current commercial cultivars in a typical Ohio environment, and the milling industry requires a source of high quality grain. During the 2015/2016 and 2016/2017 growing seasons, four SRWW cultivars were evaluated at four seeding rates. Agronomic optimum seeding rates were between 5.19 and 5.54 million seeds ha^{-1}, and rates producing the greatest partial return were between 4.27 and 4.72 million seeds ha^{-1}. Effect of seeding rate was significant for test weight and sodium carbonate solvent retention capacity. Test weight increased and damaged starch decreased as seeding rate increased. Cultivar selection impacted test weight, softness equivalency, kernel weight, glutenin strength, and starch damage. Cultivar by seeding rate interactions were significant for flour yield and protein. Generally, flour yield increased and flour protein decreased as seeding rate increased. Overall, 4.94 million seeds ha^{-1} is the best seeding rate when compromising between yield, economic return, and grain quality, and should be recommended for producers.

2.2 Introduction

Wheat [*Triticum aestivum* L.] grain yield response to seeding rate has led to inconsistency in recommending optimal agronomic soft red winter wheat (SRWW) seeding rates. Under ideal environmental conditions, lower seeding rates of 1.4 million seeds ha^{-1} (approximately 33 kg ha^{-1}) have produced the greatest yield (Freeze and Bacon, 1990; Geleta et al., 2002). Optimum rates when averaged over years, genotype, and/or environments typically fall between 2.8 million and 3.77 million seeds ha^{-1}, the latter of which is suggested for conditions similar to Ohio (Freeze and Bacon, 1990; Johnson et al., 1988; Joseph et al., 1985; Marshall and Ohm, 1987). Poor growing conditions either due to weather or time of planting, have indicated seeding rates between 5.11 and 5.76 million seeds ha^{-1} are necessary for high grain yield (Pan et al., 1994; Johnson et al., 1988).

The recommended seeding rate for Ohio producers falls between 3.0 and 4.0 million seeds ha^{-1} when planting within two weeks of the Hessian fly-free date (Lindsey et al., 2017). However, the current recommendation has not been validated for at least 26 years (Beuerlein et al.,1991), and up-to-date rates for other Illinois suggest minimum rates of 3.8 to 4.3 million seeds ha^{-1} (Nafziger, 2017) and 3.2 to 3.8 million seeds ha^{-1} in Kentucky (Lee et al., 2009). New wheat cultivars have been produced throughout the past 26 years, and yield is greatly influenced by both genotype and environment (Geleta et al., 2002); therefore, it is necessary to examine yield response to seeding rate using recent cultivars in diverse environments.

Grain quality consists of factors that are governed by complex influences, namely genotype and growing environment. For example, the components of test weight are affected by both; kernel density by growing environment and packing efficiency by genotype (Ghaderi et al., 1971). Different seeding rates can be thought of as separate, controllable environments (Geleta et al., 2002), and cultivar selection is a pivotal decision to a producer's bottom line. Such choices have a greater impact than simply a producer's grain yield. A consistent supply of high quality grain is needed to facilitate the production of an ideal baking flour, and ultimately consumable baked goods. Few studies exist that focus on the impact of SRWW seeding rate on grain quality, as most focus solely on genotype. Roth et al. (1984) found that test weight increased quadratically as seeding rate increased.

Studying management practices that result in high quality grain will benefit grain producers and flour mills alike. It is hypothesized that yield will plateau at seeding rates above 2.47 million seeds ha^{-1}, confirming the current recommendations and leading to optimal economic returns. It is also hypothesized that seeding rate will impact grain starch and protein content, making it a practical management decision to influence flour yield, softness equivalency, and solvent retention capacity values, among other factors. The objectives of this study are to re-evaluate SRWW seeding rate recommendations that improve yield, economic return, and end-use quality.

2.3 Materials and Methods

2.3.1 Description of Experiment

This experiment was conducted during the 2015/2016 and 2016/2017 growing seasons, and included four seeding rates and four wheat cultivars. The experiment was conducted at the Ohio Agricultural Research and Development Center (OARDC) Western Agricultural Research Station (WARS) (39° 51' 47.6922" N, 83° 40' 20.3484" W) in Clark County, and the OARDC Northwestern Agricultural Research Station (NWARS) (41° 13' 9.12" N, 83° 45' 48.24" W) in Wood County.

A split-plot randomized complete block design was used, with four replications of treatments. The whole plot factor was cultivar and the subplot factor was seeding rate. Four cultivars differing in yield potential were selected. Cultivars consisted of 'Malabar', 'Croplan W210110R', 'Wellman W304', and 'Steyer Haubert' (hereafter referred to as Malabar, Croplan, Wellman, and Steyer) and were selected for their range of yield potential and quality traits based on results of the 2015 Ohio Wheat Performance Test (Hankinson et al., 2015). Seeding rate treatments included 1.85 million seeds ha^{-1}, 2.47 million seeds ha^{-1}, 4.94 million seeds ha^{-1}, and 6.18 million seeds ha^{-1}.

All plots were 1.7 m wide (seven rows, 19 cm apart), but plot length varied among site-years. Plot lengths for 2015/2016 were 9 and 8.84 m at NWARS and WARS, respectively. Plots in 2016/2017 were 5.64 m at NWARS and 5.94 m at WARS. All plots were planted with a custom-made planter equipped with a Great Plains 20 series row unit, a Singulator-Plus™ precision seed meter, and high-rate wheat seed discs, and harvested with a Wintersteiger combine equipped with a high capacity grain gauge (Wintersteiger, Salt Lake City, UT). Grain yield was standardized to 135 g kg^{-1} moisture content.

Table 2.1. Soil physical and chemical properties including soil texture classification, organic matter (OM) content, plant available phosphorous (P), exchangeable potassium (K), magnesium (Mg), and calcium (Ca), and cation exchange capacity (CEC), for the Northwestern Agricultural Research Station (NWARS) and the Western Agricultural Research Station (WARS) prior to trial establishment in 2015 and 2016.

Year	Site	Soil Type	Soil pH	OM	P	K	Mg	Ca	CEC
				g kg^{-1}	-----------mg kg^{-1}-----------				$cmol_c$ kg^{-1}
2015/ 2016	WARS	Kokomo clay loam	5.9	27	159	205	289	1603	14.5
2015/ 2016	NWARS	Hoytville clay	6.4	34	41	215	375	2969	20.9
2016/ 2017	WARS	Strawn-Crosby silt loam	6.5	22	126	122	351	1422	11.5
2016/ 2017	NWARS	Hoytville clay	6.4	40	56	237	427	3034	21.7

2.3.2 Experiment Agronomic Management Practices

At all site-years, soybean was the previous crop. Prior to trial establishment, soil samples were collected, and soil chemical and physical properties measured (Table 2.1). At the NWARS location during both growing season, the soil series was Hoytville (fine, illitic, mesic mollic epiaqualf). Fertilization, tillage, and fungicide programs were identical in both years. Field preparation consisted of discing followed by use of a field cultivator to prepare a level seedbed. Planting took place on 1 Oct. 2015 and 10 Oct. 2016. The plot areas received 33.6 kg N ha^{-1}, 87.4 kg P_2O_5 ha^{-1}, and 87.4 kg K_2O ha^{-1} in the fall, and 101 kg N ha^{-1} was applied as urea-ammonium nitrate (28-0-0) as a spring topdress application. A fungicide premix of Prothioconazole (2-[2-(1-Chlorocyclopropyl)-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), (Prosaro® 421 SC, Bayer CropScience LP, Research Triangle Park, NC) was applied both years at the lowest labeled product rate of 475 ml ha^{-1} with 1.25 ml L^{-1} of a non-ionic surfactant (NIS). Prosaro® was applied once at Feekes GS 10.5.1, on 31 May 2016 and 23 May 2017. During the 2015/2016 growing season, herbicide was not applied. During the 2016-2017 growing season, clopyralid (3,6-dichloro-2-pyridinecarboxylic acid, monoethanolamine salt) was applied as 292.5 ml ha^{-1} of Stinger® (Dow AgroSciences, Indianapolis, IN) for weed control. Grain was harvested on 5 July 2016 and 5 July 2017.

Prior to planting, the plot area at WARS was prepared with only a vertical tillage implement in both growing seasons. The soil series was Kokomo (fine, mixed, superactive, mesic typic argiaquoll) for 2015/2016, and a Strawn (fine-loamy, mixed, active, mesic typic hapludalf) Crosby (fine, mixed, active, mesic aeric epiaqualf) complex. Planting took place on 9 Oct. 2015 and 13 Oct. 2016. In the spring both years, 112 kg ha^{-1} of N was applied (28-0-0). The herbicide program consisted of octanoic acid ester of bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) (Moxy® 2E, Winfield Solutions, LLC, St. Paul, MN) at 1.17 L ha^{-1} of product, a premix of thifensulfuron-methyl (Methyl 3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2yl) amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylate) and tribenuron-methyl (Methyl 2-[[[[N-(4-methoxy-6methyl-1,3,5-triazin-2-yl)methylamino]carbonyl]amino]sulfonyl]benzoate) (Harmony® Extra SG, Dupont™, Wilmington, DE) at 63 g ha^{-1} of product, and 2.5 ml L^{-1} of NIS. On 31 May 2016, an application of 585 ml ha^{-1} of Prosaro® fungicide was made at Feekes GS 10.5.1. In the

2016/2017 growing season, propiconazole (Tilt®, Syngenta Crop Protection, LLC, Greensboro, NC) was applied once at Feekes GS 9 instead of Prosaro®, at a product rate of 292 ml ha^{-1}. Harmony® Extra SG and NIS were also applied in the 2016-2017 season, with the only difference being at a rate of 52.5 g ha^{-1} of Harmony® Extra SG. Harvest took place on 29 June 2016 and 29 June 2017.

2.3.3 Growing Conditions

Monthly average temperature (Table 2.2) and cumulative precipitation (Table 2.3) from October through July for the four site-years were compared to the 35-year average (1982-2016). All weather data were obtained from the associated OARDC weather station.

2.3.4 Fall Stand Count Procedure

After planting, an initial stand count was conducted for each plot, and estimated at Feekes growth stage (GS) 1 (Large, 1954) to verify seeding rate treatments (Table 2.4). Plants in a 30.5 cm linear section of row were counted at three random points within each plot and averaged.

2.3.5 Grain Quality

Grain was cleaned for 30 seconds using a fabricated air-aspirator at a fan speed of 53 revolutions per minute. Test weight was determined using a modified method (AACC International Approved Method 55-10, 2010). Single Kernel Characterization System

(SKCS) tests were performed using a SKCS 4100 (Perten Instruments, Hägersten, Sweden) (AACC Approved Method 55-31.01, 2010). The instrument tested 300 kernels for each sample and produced data for kernel hardness, diameter, and weight.

Milling did not take place unless ambient temperature was between 19-21°C, and humidity was between 58-62%. The mill unit itself was allowed to warm to a temperature of 33 ± 1°C. The milled product was then placed into a sifting unit (Great Western Manufacturing Company, Leavenworth, KS) for 90 seconds, and separated into bran, middling stock (also called "mids"), and break flour. Bran remains above the 471 μm screen, mids remain above the 180 μm screen, and break flour falls through the 180 μm screen to the bottom of the sifter (USDA-ARS, 2017).

Bran and mids were weighed, bran was discarded, and mids were poured into the Quadrumat® Jr. (C.W. Brabender® Instruments, Incorporated) reduction roll unit and sifted (Great Western Manufacturing Company) using a 213 μm mesh screen. The result was a separation of material into shorts and reduction flour. Shorts remain above the 213 μm screen and were discarded, while the reduction flour fell through, and was added to the break flour. Flour was then blended by placing jars on a vertical homemade motorized spinning wheel for 10 min. Softness equivalence (SE, in percent) was calculated using the formula: SE= (Grain Sample Weight – Bran − Mids)/(Grain Sample Weight−Bran)∗100. Adjusted flour yield (AFY) was calculated using the formula: AFY= (0.17∗(SE−52)) + (Flour Yield), and flour yield (FY) was calculated using the formula: FY= ((Grain Sample Weight−Bran)/Grain Sample Weight) ∗100.

Flour moisture and protein content were measured using a SpectraStar™ NIR analyzer (Unity Scientific, LLC, Brookfield, CT). Flour protein was adjusted to 140 g kg^{-1} water content and recorded. Flour moisture was recorded, but only used to carry out the sugar snap cookie baking test and adjust for the solvent retention capacity values. Solvent Retention Capacity (SRC) tests were carried out using the AACC Approved Method 56-11.02 (2010). Only lactic acid (LA) and sodium carbonate tests were performed.

2.3.6 Economic Analysis

Gross return was calculated by multiplying the yield for each plot by the average 2016 U.S. wheat price of \$0.156 kg^{-1} (USDA-NASS, 2017) or the May 2017 Ohio forward contract price, less basis \$0.154 kg^{-1} (Ward, 2017) depending on growing season. Partial return was calculated as the difference in gross return and cost of wheat seed. Seed cost estimates were provided by local dealers. Relative partial return was calculated as the partial return per plot divided by the respective site-year mean partial return. Relative partial return had a significant cultivar by seeding rate interaction (Table 2.5). Economic optimum is defined as the seeding rate that provides the greatest partial return.

2.3.7 Statistical Analysis

Data were analyzed by conducting an analysis of variance (ANOVA) using the MIXED procedure in SAS at $\alpha = 0.05$ (SAS Institute, Cary, NC; version 9.4). Normality and homogeneity of variance assumptions of ANOVA were not violated, as determined by examining histograms of residuals, and plots of residuals vs. predicted values. Mean separation was performed using protected differences of least squares means with α = 0.05. Data were analyzed with seeding rate and cultivar as fixed effects, and site-year and replications considered as random effects. Site-years were considered environments and used to account for variation due to year and location.

The REG procedure in SAS (SAS Institute, Cary, NC; version 9.4) was used to perform regression analysis, where model significance was determined using an α = 0.05. Accounting for location and year differences required the use of relative values, where each observation was divided by the respective site-year mean. Optimum values were calculated by solving the polynomial regression model's derivative when set equal to zero to find the maximum. Agronomic optimum was defined as the seeding rate that achieves the greatest grain yield.

2.4 Results and Discussion

2.4.1 Growing Conditions

Growing conditions at both locations and during both growing seasons were warmer than normal (Table 2.2). Over the four site-years, there were ten instances of temperatures cooler than the 35-year average, only one of which had a difference greater than 1.0 ºC. However, there were 16 total months where temperatures were more than 2.5 ºC above the 35-year average. December 2015 and February 2017 were highly abnormal, as temperatures at both locations ranged from 5.4-6.7 ºC above the 35-year average.

After March 2016 at WARS, precipitation consistently fell below the 35-year average for six consecutive months thereafter (Table 2.3). Conditions at NWARS in 2016 were also drier than normal, as precipitation fell below the 35-year average for 6 consecutive months after April. Wet conditions existed at both locations in May, June, and July 2017 with 0.3 to 8.5 cm of rainfall above the average. Both stations have near average precipitation for the first four months of 2017, with the exception of NWARS in January, which had 7.0 cm of rainfall above the 35-year average.

Poor fall weather conditions at NWARS caused the removal of two plots from the 2015/2016 growing season, and three plots from the 2016/2017 season. Although total precipitation for October 2015 was 7.0 cm, (Table 2.3), the site had received only 0.86 cm of precipitation in the first 25 days (data not shown). The lack of moisture caused poor stand establishment in many plots, and was unacceptable in two of them. Flooding in the fall of 2016/2017 required deletion of the first three consecutive plots in the first replication.

2.4.2 Fall Stand Establishment

Established fall wheat population reflected the imposed treatment of seeding rate (Table 2.4). The estimated fall populations were consistently below the target seeding rate, illustrating a common issue in stand establishment of wheat. The intended effect of seeding rate was successfully applied, as shown by the significant differences between the fall populations for each seeding rate.

Table 2.2. Change in average monthly temperature between a 30-yr average and each month within the 2015/2016 and 2016/2017 growing seasons for the Northwestern Agricultural Research Station (NWARS) and the Western Agricultural Research Station (WARS). Temperatures from 1982-2016 shown for 35-yr average. (Data from the respective WARS and NWARS weather stations)

		Average Temperature (ºC)									
Site	Year	Jan	Feb	March	April	May	June	July	Oct	Nov	Dec
WARS	30 yr avg	-2.5	-0.9	4.4	10.6	16.3	21.3	23.2	12.2	5.5	-0.2
	2015								+0.3	+2.9	+6.1
	2016	-0.2	+1.6	+3.7	-0.1	-0.4	+1.3	+0.5	+3.2	+0.8	-1.2
	2017	+3.5	+5.4	+0.1	+3.3	-0.2	+0.0	-0.5			
NWARS	30 yr avg	-4.3	-2.7	2.6	9.4	15.5	20.8	22.7	11.4	4.9	-1.3
	2015								+1.3	+3.1	+6.7
	2016	+1.7	+2.6	+4.3	-0.9	+0.3	+1.5	+1.3	+3.3	+2.5	-0.6
	2017	+4.5	+6.5	+0.7	+3.4	-0.4	+0.9	-0.1			

Table 2.3. Change in cumulative monthly precipitation between a 30-yr average and each month within the 2015/2016 and 2016/2017 growing seasons. for the Northwestern Agricultural Research Station (NWARS) and the Western Agricultural Research Station (WARS). Precipitation from 1982-2016 shown for 35-yr average. (Data from the respective WARS and NWARS weather stations)

		Average Cumulative Precipitation (cm)									
Site	Year	Jan	Feb	March	April	May	June	July	Oct	Nov	Dec
WARS	30 yr avg	7.4	6.2	8.9	10.1	11.7	10.6	10.4	5.9	8.5	7.5
	2015								+1.1	-2.8	+6.2
	2016	-4.8	+1.9	+0.0	-3.4	-4.4	-6.5	-0.1	-1.4	-6.2	+0.6
	2017	+0.0	-2.1	+2.0	-1.5	+2.3	+0.3	+8.5			
NWARS	30 yr avg	4.6	4.1	6.4	8.3	8.8	9.0	9.6	6.0	7.0	6.2
	2015								+1.0	+4.0	+1.8
	2016	-2.0	-0.8	+3.6	+0.2	-3.3	-1.5	-5.6	-0.7	-2.8	-2.5
	2017	+7.0	-1.1	-1.4	-1.2	+4.5	+4.0	+5.4			

Table 2.4. Target seeding rate and established population at the Northwest Agricultural Research Station (NWARS) and the Western Agricultural Research Station (WARS) for 2015/2016 and 2016/2017 growing seasons.

	NWARS 2015	WARS 2015	NWARS 2016	WARS 2016
Seeding Rate	Fall Population			
Million seeds ha^{-1}	-------------million plants ha^{-1}-----------			
1.85	1.40 a†	0.68 a	1.18 a	1.13 a
2.47	1.71 b	1.46 b	1.86 b	1.79 b
4.94	3.64 c	3.56 c	3.73 c	4.66 c
6.18	4.70 d	4.67 d	4.55 d	5.46 d

†Values followed by the same letter in a column are not significantly different from each other ($\alpha = 0.05$)

2.4.2 Seeding Rate by Cultivar Interaction for Yield Response

There was a significant seeding rate by cultivar interaction (Table 2.5). The yield response rate between 1.85 and 4.94 million seeds ha^{-1} was highest for Steyer, causing its yield curve to converge with Wellman and Croplan, even though grain yield was below these cultivars at the lowest two rates (Figure 2.1). Initially, Croplan and Wellman produced slightly different yields, but had similar slopes between the lowest two seeding rates. As seeding rate approached 4.94 million seeds ha^{-1}, Croplan's response rate increased slightly while Wellman's decreased. As a result, Croplan, Wellman, and Steyer were similar in grain productivity between 4.94 and 6.18 million seeds ha^{-1}, meaning their agronomically optimal seeding rates were also similar. Optimal grain production was calculated to occur at 5.19, 5.54, and 5.49 million seeds ha^{-1} for Croplan, Steyer, and Wellman, respectively.

Malabar exhibited the lowest grain yield, and the slowest but most consistent yield response to an increase in seeding rate. Although Malabar differed greatly in productivity and response to seeding rate, the optimal rate was near that of the current cultivars. The agronomic optimum seeding rate for Malabar was calculated to be 5.46 million seeds ha^{-1}. Malabar provides a reference for contrasting yield potential and yield stability among cultivars in Figure 2.1, and serves as a control to support the resulting optimum seeding rates.

2.4.3 Seeding Rate by Cultivar Interaction for Economic Partial Return

Croplan's best fitting regression model was not significant (Table 2.7), and was dropped from further consideration and Figure 2.2. When compared to agronomic optimum seeding rates, economic optimal rates were lower. Steyer had the greatest rate of partial economic return when seeding rate was increased from 1.85 to 4.72 (optimum) million seeds ha^{-1}. Wellman resulted in the lowest optimum economic seeding rate of 4.27 million seeds ha^{-1}, and the greatest partial return under the two lowest seeding rates. Wellman was the most expensive seed used in the study. Malabar provided the lowest partial return, and required a rate of 4.58 million seeds ha^{-1} to reach an optimal return.

Table 2.5. Analysis of variance for fixed effects of cultivar (C), seeding rate (SR), and cultivar by seeding rate interaction (C x SR) of data combined from all four site-years (α = 0.05).

Source	RY†	RPR	TW	Flour Yield	SE	KW	Flour Protein	LA-SRC	SC-SRC
C	0.019	0.087	0.002	<0.0001	0.0001	<0.0001	0.008	0.0004	0.005
SR	<0.0001	<0.0001	0.006	0.129	0.581	0.390	0.002	0.107	0.033
C x SR	0.0007	0.0004	0.440	0.038	0.415	0.897	0.041	0.886	0.430

†RY=relative yield calculated as plot grain yield divided by site-year mean grain yield, RPR= relative partial return calculated as the plot partial return divided by site-year mean partial return, TW=test weight, SE= softness equivalency, KW= kernel weight, LA-SRC= lactic acid solvent retention capacity, SC-SRC= sodium carbonate solvent retention capacity

2.4.4 Effect of Cultivar on Wheat Quality Factors

Cultivar was a significant effect for wheat quality factors of test weight (TW), softness equivalence (SE), kernel weight (KW), lactic acid solvent retention capacity (LA-SRC), and sodium carbonate SRC (SC-SRC) (Table 2.5). The benchmark TW of wheat at a standard moisture content of 135 g kg^{-1} is 772.32 kg m^{-3} (USDA-GIPSA, 2013). Croplan resulted in a high TW of 781.52 kg m^{-3}, and was significantly higher than the remaining three cultivars (Table 2.9). Malabar, Steyer, and Wellman produced similar respective TW values of 757.02, 759.60, and 761.47 kg m^{-3}.

Results of kernel weight differ from TW. Croplan had the highest KW of 37.24 mg, which was similar to Wellman (Table 2.9). Wellman and Steyer resulted in similar kernel weights as well, and all cultivar KW’s were greater than Malabar. A discrepancy between high KW and lower TW like that observed with Wellman and Steyer, indicate packing efficiency is the major contributing factor in their TW values. It is likely that TW did not differ among the three varieties due to physical kernel properties governed by either genotype or a negative environment (Yamazaki and Briggle, 1969; Schuler et al., 1994).

Steyer and Wellman produced equal SE values of 66.36 g $100g^{-1}$, and were high enough to be considered favorable (Table 2.9) (Baik, personal communication). The second lowest SE was Croplan with 62.70 g $100g^{-1}$, and Malabar's was statistically the lowest at 59.57 g $100g^{-1}$. Both Croplan and Malabar would result in flour with higher levels of starch damage after milling (Miller and Hoseney, 1997; Pomeranz and Williams, 1990).

An ideal LA-SRC is at or above 87 g $100g^{-1}$, and above 110 g $100g^{-1}$ is flour considered to contain strong glutenin (Kweon et al., *in press*; USDA-ARS, 2017). Therefore, all cultivars in the study produced acceptable LA-SRC values (Table 2.9). Although a leader in TW and KW, Croplan resulted in the lowest LA-SRC with a value of 88.94 g $100g^{-1}$. Steyer and Wellman yielded similar intermediate values, and Malabar produced the highest LA-SRC of 105.24 g $100g^{-1}$.

Sodium carbonate SRC's should be 64 g $100g^{-1}$ or lower, as a larger number is indicative of damaged starch (Kweon et al., *in press*). None of the four cultivars in the study met this SC-SRC criterion (Table 2.9). Malabar had the greatest SC-SRC of 69.48 g $100g^{-1}$, while the other three cultivars produced equivalent values. The greatest difference was 2.59 g $100g^{-1}$ between Malabar and Wellman.

2.4.5 Effect of Seeding Rate on Test Weight and Sodium Carbonate

An increase of seeding rate from 2.47 to 4.94 million seeds ha^{-1} produced a significant increase in TW of 3.33 kg m^{-3}. While TW increases occurred between 1.85

and 2.47 million seeds ha^{-1}, and between 4.94 and 6.18 million seeds ha^{-1}, they were not significantly different (Table 2.8).

The lowest seeding rate resulted in the greatest amount of damaged starch, indicated by an SC-SRC value of 68.11 g 100g^{-1} (Table 2.8). This was 0.44 g 100g^{-1} greater than that of 4.94 million seeds ha^{-1}. However, no seeding rates produced acceptable SC-SRC values.

2.5.6 Seeding Rate by Cultivar Interaction on Flour Yield and Flour Protein

Flour yield (FY) and flour protein (FP) were the only quality parameters with significant seeding rate by cultivar interactions (Table 2.5). The FY of Steyer improved between 2.47 and 4.94 million seeds ha^{-1}, and then plateaued (Table 2.10). Flour yield of Wellman was similar among all seeding rates except between the lowest and highest rates. Flour yield did not change among different seeding rates for Croplan and Malabar (Table 2.11). For each seeding rate, Steyer and Wellman resulted in the highest flour yield, and were not different from one another. The greatest difference observed between seeding rates across all cultivars was 0.66 g 100 g^{-1} (Table 2.10). Differences as great as 2.18, 2.23, 2.44, and 2.56 g 100 g^{-1} were observed between cultivars for rates of 1.85, 2.47, 4.94. and 6.18 million seeds ha^{-1}, respectively (Table 2.11).

The greatest FP was produced under the lowest seeding rate for all four cultivars (Table 2.10). Flour protein between seeding rates greater than 1.85 million seeds ha^{-1} did not differ for Malabar and Wellman. Flour protein for Steyer decreased significantly between 2.47 and 4.94 million seeds ha^{-1}, both of which were similar to FP under the highest seeding rate. The only difference in FP for Croplan was between 1.85 and 4.94 million seeds ha^{-1}. Although the greatest value for Croplan occurred at the lowest seeding rate, it did not differ from that of 2.47 and 6.18 million seeds ha^{-1}. For each seeding rate, Malabar had the highest flour protein content (2.11). Flour protein content was more consistent among cultivars at rates above 2.47 million seeds ha^{-1}. The greatest difference observed between seeding rates across all cultivars was 0.66 g 100 g^{-1}.

2.5 Conclusions

2.5.1 Seeding Rate and Cultivar Effect on Yield

The optimal agronomic seeding rate ranged from 5.19-5.54 million seeds ha^{-1}, and is 1.19 million seeds ha^{-1} above the currently recommended maximum rate for SRWW (Figure 2.1). Rates this high are only suggested in the case of late planting in Ohio, 3-4 weeks after the Hessian fly-free date, which ranges from 22 September in the northern-most counties to 5 October in the southern-most counties (Lindsey et al., 2017). All site-years were planted within two weeks of their respective fly free date, except for NWARS which was planted two weeks and three days after the fly-free date in 2016. The high optimum seeding rates under early planted stands support an increase in seeding rates.

When selecting a seeding rate, seed cost and impact on return must be considered, which means an agronomic rate does not always equate to a viable net profit. Everything else remaining equal, the additional cost of seed in this experiment increased returns until seeding rates reached between 4.27-4.72 million seeds ha^{-1}, depending on the individual cultivar's price (Figure 2.2). Although lower than the agronomic optimum, the most economic rates suggest an increase in recommended seeding rates as well.

Examination of Figure 2.1 leads to the conclusion that current commercial cultivars will produce similar yields at higher seeding rates. Conversely, under lower seeding rates cultivar selection becomes increasingly important. Even Malabar reacted similarly to increases in seeding rate, but the inherently low yield potential was the limiting factor. As various cultivars are used throughout multiple environments in Ohio, a higher minimum rate would improve overall wheat productivity in the state.

2.5.2 Seeding Rate and Cultivar Effect on Grain Quality

A sharp increase in test weight of 3.33 kg m^{-3} was observed between 2.47 and 4.94 million seeds ha^{-1}, followed by a plateau under the highest seeding rate (Table 2.8). When averaged over site-years and cultivars, all flour had high levels of starch damage. However, a higher seeding rate of 4.94 million seeds ha^{-1} decreased SC-SRC values significantly when compared to the lowest rate. Seeding rates near 4.49 million seeds ha^{-1} should produce higher test weights and lower starch damage than lower seeding rates.

Selecting a cultivar based upon one quality characteristic should be avoided. For example, Croplan produced the only significantly high TW, and was 24.5 kg m^{-3} greater than Malabar (Table 2.9). However, it also had the lowest glutenin strength indicated by a LA-SRC of 88.94 g $100g^{-1}$, in addition to an intermediate SE. Wellman and Steyer had lower TW, but acceptable SE, KW, and LA-SRC. Those advising producers should take multiple quality factors into consideration when aiding in cultivar selection, as opposed to focusing on grain yield and test weight alone.

2.5.3 Seeding Rate by Cultivar Interaction on Flour Yield and Flour Protein

While both factors have an impact on flour yield and protein, cultivar has a much greater influence on both than seeding rate (Table 2.11). Similar to the findings of Geleta et al. (2002), flour protein was highest at the lowest seeding rate, but did not consistently decrease with seeding rate. Additionally, flour yield increased as seeding rates increased for Steyer and Wellman only, and did not change significantly for Croplan and Malabar (Table 2.10). Based upon these findings, it would not be wise to alter seeding rate to improve flour yield and protein content. Cultivar selection is a producer's best option to achieve ideal flour yield and protein.

2.5.4 Recommendations

Seeding rate recommendations for Ohio wheat producers should be increased by no more than 25% from the lowest current rate, falling between 4.27 and 4.72 million seeds ha^{-1}. This will provide the best economic return, which was a main concern for wheat producers. If grain yield is a producer's largest concern, then seeding rates should be even higher, and fall between 5.19 and 5.94 million seeds ha^{-1}.

To achieve the best combination of grain yield, economic return, and grain quality, a seeding rate of 4.94 million seeds ha^{-1} should be used. This rate is more pertinent to flour mills who need higher quality grain. From a milling standpoint, cultivar selection should be based on a broad range of quality factors, including test weight, kernel weight, flour yield, and softness equivalency, all of which can be obtained from the Ohio Wheat Performance Test (Hankinson et al., 2017). Cultivar selection should not be based solely on yield or test weight, as the processed flour quality will likely be lower than from a cultivar with many ideal traits.

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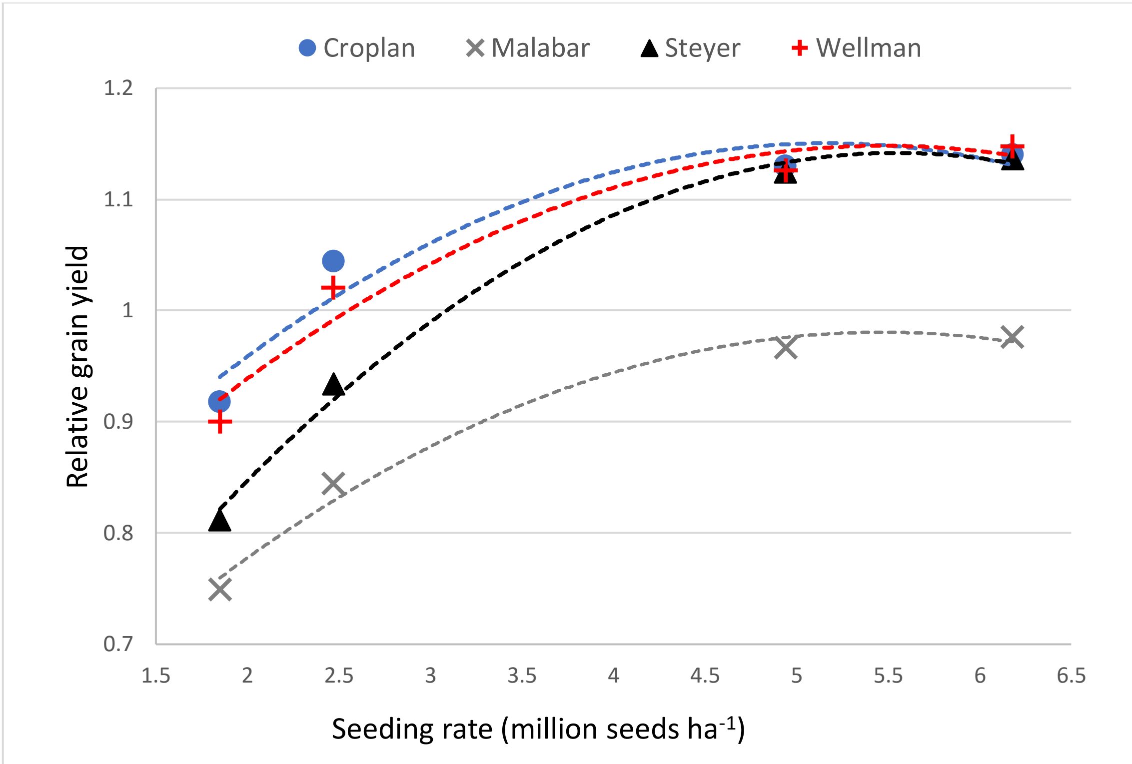

Figure 2.1. Polynomial regression lines of four cultivars fit to relative grain yield vs. seeding rates of 1.85, 2.47, 4.94, and 6.18 million seeds ha^{-1}, averaged over four site-years. Relative grain yield calculated as total grain yield divided by site-year mean.

Table 2.6. Regression models fit to relative grain yield vs. seeding rate, the r^2 value and p-value of each model, and the calculated maxima (agronomic optimum) for each cultivar.

Cultivar	Equation	r^2	Model P-value	Agronomic Optimum (million seeds ha^{-1})
Croplan	$Y = -0.01875x^2 + 0.1946x + 0.6446$	0.4012	<0.0001	5.19
Malabar	$Y = -0.0169x^2 + 0.1844x + 0.4762$	0.4552	<0.0001	5.46
Steyer	$Y = -0.0235x^2 + 0.2602x + 0.4205$	0.8417	<0.0001	5.54
Wellman	$Y = -0.0173x^2 + 0.1899x + 0.6284$	0.7012	<0.0001	5.49

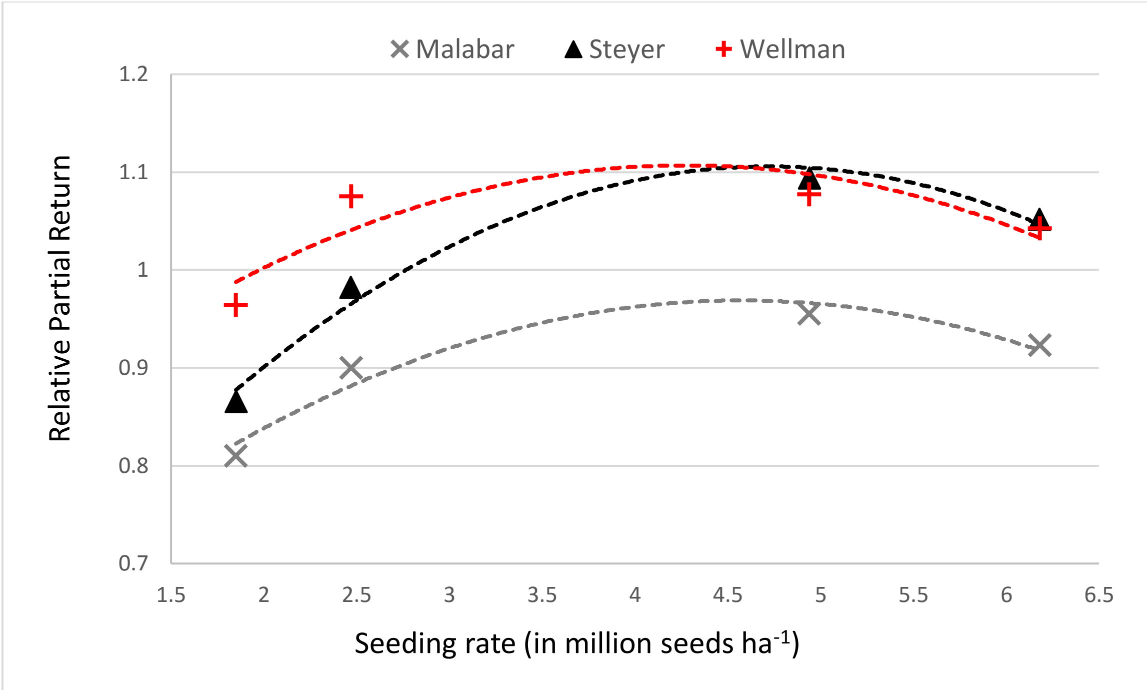

Figure 2.2. Polynomial regression lines of three cultivars fit to relative partial return vs. seeding rates of 1.85, 2.47, 4.94, and 6.18 million seeds ha^{-1}, averaged over four site-years. Relative partial return calculated as the partial return for each plot divided by the mean site partial return. Partial return calculated as the difference in gross return and costs of wheat seed. Gross return based on grain yield and the 2016 U.S. average wheat price of \$0.156 kg^{-1} (USDA-NASS, 2017), or the May 2017 Ohio forward contract price, less basis \$0.154 kg^{-1} (Ward, 2017) depending on season. Seed cost estimates from local dealers.

Table 2.7. Regression models fit to relative partial return vs. seeding rate, the r^2 value and p-value of each model, and the calculated maxima (agronomic optimum) for each cultivar ($\alpha = 0.05$)

Cultivar	Equation	r^2	Model P-value	Economic Optimum (million seeds ha^{-1})
Croplan	NS	0.0889	0.064	-
Malabar	$Y = -0.0197x^2 + 0.1800x + 0.5568$	0.1626	0.006	4.58
Steyer	$Y = -0.0277x^2 + 0.2617x + 0.4881$	0.6409	<0.0001	4.72
Wellman	$Y = -0.0203x^2 + 0.1735x + 0.7362$	0.2479	0.0002	4.27

NS= not significant at $\alpha = 0.05$

Table 2.8. Mean test weight and sodium carbonate solvent retention capacity (SC-SCR) of four cultivars for each seeding rate averaged over four site-years

Seeding Rate	Test weight	SC-SRC
Million seeds ha^{-1}	-------kg m^{-2}------	-------g 100g^{-1}-----
1.85	761.63a†	68.11b
2.47	763.64a	67.91ab
4.94	766.96b	67.67a
6.18	767.38b	67.58a

†Values followed by the same letter in a column are not significantly different from each other (α = 0.05)

Table 2.9. Mean test weight, softness equivalence (SE), kernel weight (KW), lactic acid solvent retention capacity (LA-SRC), and sodium carbonate solvent retention capacity (SC-SCR) of four seeding rates for each cultivar averaged over four site-years

Cultivar	Test weight	SE	KW	LA-SRC	SC-SRC
	--kg m^{-2}--	g 100g^{-1}	mg	g 100g^{-1}	g 100g^{-1}
Croplan	781.52b†	62.70b	37.24c	88.94a	67.80a
Malabar	757.02a	59.57a	32.28a	105.24c	69.48b
Steyer	759.6a	66.36c	35.73b	99.17b	67.10a
Wellman	761.47a	66.36c	36.05bc	97.58b	66.89a

†Values followed by the same letter in a column are not significantly different from each other (α = 0.05)

Table 2.10. Mean flour yield and flour protein for individual cultivars at seeding rates of 1.85, 2.47, 4.94, and 6.18 million seeds ha^{-1} averaged across four site years.

Seeding Rate	Cultivar			
Million seeds ha^{-1}	Croplan	Malabar	Steyer	Wellman
	Flour Yield			
	---------- g 100g^{-1} ----------			
1.85	69.63a†	69.09a	71.08a	71.27a
2.47	69.97a	69.18a	71.24a	71.41ab
4.94	69.99a	69.19a	71.63b	71.49ab
6.18	69.98a	69.15a	71.74b	71.71b
	Flour Protein			
	---------- g 100g^{-1} ----------			
1.85	7.56b	8.23b	7.94c	7.66b
2.47	7.39ab	7.97a	7.62b	7.43a
4.94	7.31a	7.93a	7.36a	7.39a
6.18	7.46ab	7.84a	7.50ab	7.34a

†Values followed by the same letter in a column are not significantly different from each other (α = 0.05)

Table 2.11. Mean flour yield and flour protein of seeding rates for each cultivar averaged across four site years.

Cultivar	Seeding Rate (million seeds ha^{-1})			
	1.85	2.47	4.94	6.18
	Flour Yield			
	---------- g 100g^{-1} ----------			
Croplan	69.63a†	69.97b	69.99b	69.98b
Malabar	69.09a	69.18a	69.19a	69.15a
Steyer	71.08b	71.24c	71.63c	71.74c
Wellman	71.27b	71.41c	71.49c	71.71c
	Flour Protein			
	---------- g 100g^{-1} ----------			
Croplan	7.56a	7.39ab	7.31a	7.46a
Malabar	8.23b	7.97c	7.93b	7.84b
Steyer	7.94ab	7.62b	7.36a	7.50a
Wellman	7.66a	7.43a	7.39a	7.34a

†Values followed by the same letter in a column are not significantly different from each other (α = 0.05)

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Chapter 3: Replacement methods for spring stand assessment of soft red winter wheat [*Triticum aestivum* L.] in Ohio

3.1 Abstract

Winter wheat [*Triticum aestivum* L.] is exposed to factors such as soil heaving, and freezing temperatures without snow cover, that can reduce stem formation between fall planting and Feekes growth stage (GS) 4 in spring. Recommendations for wheat producers are to count stems to estimate yield potential of the crop at Feekes GS 5. Due to the time and labor involved in counting stems, producers do not use this recommendation, creating a need for easier and accurate methods to estimate yield potential. The normalized difference vegetation index (NDVI) and fractional green canopy cover (FGCC) are two promising technologies that may make estimating wheat yield easier early in the spring. The objectives were to determine if FGCC is correlated to tiller counts, and to quantify the difference in yield prediction accuracy of tiller counts, NDVI, and FGCC (30.5 cm section of row called "1-row" and 3-row area), at Feekes GS 5 and 6, and head counts at Feekes GS 10.5. Linear regression models fit for stem counts at Feekes GS 5 and 6 vs. FGCC for 1-row at Feekes 5 and 6 respectively were significant, and were able to estimate stem density. The best estimators of yield were NDVI and 3-row FGCC measurements taken at Feekes GS 5, and can be used to estimate the proportion of yield that will result from a spring stand. Producers may adopt the stem

estimation methods when making a decision about wheat stands in the spring, and consider using NDVI and FGCC for yield estimation.

3.2 Introduction

Winter wheat [*Triticum aestivum* L.] is particularly vulnerable between planting in fall and Feekes (Large et al., 1954) growth stage (GS) 4 in the spring. Freezing temperatures, soil heaving, lack of snow cover, and delayed planting are a few factors that can reduce wheat tiller density in the spring (Fowler and Gusta, 1979; Lindsey et al., 2017). Tiller density is a standard parameter for estimating yield potential and can be used as a basis for spring nitrogen recommendations (Weisz et al., 2001). However, tiller counts are tedious, time consuming, and rarely performed by producers (Flowers et al., 2001). Normalized difference vegetation index (NDVI) and fractional green canopy cover (FGCC) are two methods that may provide an alternative method to tiller counts.

Wheat producers need a method to assess spring stand quality that is both easy and accurate. A visually poor wheat stand in the spring may be tilled under, to avoid adding inputs to a stand that does not appear profitable. Producers are not using stem counts to make this decision, meaning there is no basis for determining a “good” stand from a “bad” one.

Normalized difference vegetation index is one of many multispectral reflectance indices used to indirectly measure crop canopy variables and is calculated using near-infrared (NIR) and red (R) wavelengths (NIR-R/NIR+R) (Phillips et al., 2004). Normalized difference vegetation index has been shown to be a good estimator of tiller density at Feekes GS 3 over various diverse environments (Flowers et al., 2003; Phillips et al., 2004). However, NDVI may not be reliable when leaf area index (LAI) is greater than 3, which may impact recommendations based on NDVI at Feekes GS 5 or later (Serrano et al., 2000; Wise et al., 2011). Therefore, testing of NDVI at Feekes GS 5 and 6 is necessary to ensure it is a reliable measure of spring stand quality at crucial points of decision making for Ohio wheat producers.

Fractional green canopy cover measures the canopy surface area by using automatic pixel classification. Canopeo (Oklahoma State University, Stillwater, OK) is a free mobile device application that is capable of classifying pixels in images to estimate green biomass (Patrignani and Ochsner, 2015). Canopeo has shown to correctly classify 100% of pixels in an image of wheat under conventional tillage and 90% for no-till (Patrignani and Ochsner, 2015). A strong correlation has been shown to exist between FGCC and biomass, in addition to grain yield in durum wheat (Casadesús et al., 2007). The use of FGCC to estimate tiller density and yield potential of a wheat stand is reasonable, but requires further study confirm if its use can facilitate the use of recommendations to make spring stand management decisions. Validating newer, easier methods of yield estimation in spring stands will provide producers with accurate, scientifically based results to make informed decisions about their wheat crop.

It is hypothesized that FGCC of a 3-row area will be the best option for estimating tiller density, as it accounts for a greater area. It is also hypothesized that NDVI and 3-row FGCC at Feekes GS 5 will be the best replacement methods for stem counts. The objectives of this study were to determine if FGCC is correlated to tiller counts, and to quantify the difference in yield prediction accuracy of tiller counts, NDVI, and FGCC (30.5 cm section of row, hereafter called “1-row”, and 3-row area), at Feekes GS 5 and 6, and head counts at Feekes GS 10.5.

3.3 Materials and Methods

3.3.1 Description of Experiment

The experiment included five seeding rates and was conducted over the 2015/2016 and 2016/2017 growing seasons, at two on-farm locations in Pickaway County (2015/2016 location: 39° 39' 7.2" N, 83° 1' 37.2" W; 2016/2017 location: 39° 39' 51.12" N, 83° 2' 29.3994" W) and Crawford County (2015/2016 location: 40° 46' 39.72" N, 82° 53' 52.7994" W; 2016/2017 location: 40° 46' 17.7594" N, 82° 54' 28.4394" W).

The experiment was a randomized complete block design with four replications of treatments. The variety used for this study was ‘Pioneer 25R40’, and seeding rate treatments were 1.85 million seeds ha^{-1}, 2.47 million seeds ha^{-1}, 3.71 million seeds ha^{-1}, 4.94 million seeds ha^{-1}, and 6.18 million seeds ha^{-1} to mimic a poor to excellent stand in the spring. All plots were 1.7 m wide (seven rows, 19 cm apart), but plot length varied among site-years. Plot length at the Crawford County location was 10.36 m for the first replication, and 8.84 m for the remaining replications in 2015/2016. At the Pickaway County location in 2015/2016, plot length was 10.06 m. During the 2016/2017 growing season, plot length was 5.94 m for both locations. All plots were planted with a custom-made planter equipped with a Great Plains 20 series row unit, a Singulator-Plus™

precision seed meter, and high-rate wheat seed discs, and harvested with a Wintersteiger combine equipped with a high capacity grain gauge (Wintersteiger, Salt Lake City, UT). Grain yield was standardized to 135 g kg^{-1} moisture content.

At all site-years, soybean was the previous crop. Prior to trial establishment, soil samples were taken and soil chemical and physical properties measured (Table 3.1). At the Crawford County location, the soil series in 2015/2016 was Luray (fine-silty, mixed, superactive, mesic typic argiaquoll) and Tiro (fine-silty, mixed, active, mesic aeric epiaqualf) in 2016/2017. Soil series for Pickaway County in 2015/2016 was Warsaw (fine-loamy over sandy or sandy skeletal, mixed, superactive, mesic typic argiudoll), and was a Miamian (fine, mixed, active, mesic oxyaquic hapludalf) Lewisburg (clayey, mixed, active, mesic, shallow aquic hapludalf) complex in 2016/2017

Table 3.1. Soil physical and chemical properties for both growing seasons at Pickaway (Pick) and Crawford (Craw) County, Ohio, including soil texture classification, organic matter (OM) content, plant available phosphorous (P), exchangeable potassium (K), magnesium (Mg), and calcium (Ca), and cation exchange capacity (CEC).

Year	Site	Soil Type	Soil pH	OM	P	K	Mg	Ca	CEC
				g kg^{-1}	---------mg kg^{-1}---------				cmol$_c$ kg^{-1}
2015/ 2016	Pick	Warsaw clay loam	6.3	27	54	154	277	1550	11.7
2015/ 2016	Craw	Luray silty clay loam	6.6	47	74	287	328	3013	19.7
2016/ 2017	Pick	Miamian-Lewsiburg silt loam	6.6	21	29	170	246	1139	9.4
2016/ 2017	Craw	Tiro silty clay	6.5	43	31	151	302	2616	17.2

3.3.2 Agronomic Management Practices

Tillage for both seasons at Crawford County was performed with a vertical tillage implement. Planting dates were 5 Oct. 2015 and 7 Oct. 2016. The fall fertilizer application for 2015/2016 included 134.5 kg K_2O ha^{-1}, 37.6 kg N ha^{-1}, and 13.45 kg S ha^{-1} as ammonium sulfate. Spring topdress application was 101 kg N ha^{-1}. In 2016/2017, the fertilizer program was the same except fall nitrogen was applied at 25.8 kg ha^{-1} and 117 kg ha^{-1} N (28-0-0) was applied in the spring. No herbicide was used in the 2015/2016 season, but insecticide at 219 ml $ha^{-1}$of Warrior II with Zeon Technology® (Lambda-cyhalothrin, Syngenta Crop Protection, LLC) and fungicide at 474 ml $ha^{-1}$of Prosaro® fungicide were applied once at Feekes GS 10.5.1 on 27 May, 2016 and 23 May, 2017. The 2016/2017 herbicide program was 52.5 g ha^{-1} of Harmony® Extra SG, 146 ml $ha^{-1}$of premixed Prothioconazole and Trifloxystrobin (E,E)-alpha-(methoxyimino)-2-[[[[1-[3-(trifluoromethyl)phenyl] ethylidene]amino]oxy]methyl]-, methylester (Stratego® YLD, Bayer CropScience LP), and 585 ml ha^{-1} of Powerlock® (modified vegetable oil, alkyl phenol ethoxylate, vegetable oil) (Winfield Solutions, LLC). Insecticide used was 183 ml ha^{-1} of Proaxis® (Gamma-cyhalothrin) (E,E)-alpha-(methoxyimino)-2-[[[[1-[3-(trifluoromethyl)phenyl] ethylidene]amino]oxy]methyl]-, methylester) (Cheminova, Inc., Research Triangle Park, NC). 474 ml ha^{-1} of Prosaro® was sprayed, along with 877 ml ha^{-1} of Plexus® adjuvant (Rosen's Inc., Liberty, MO). Grain was harvested on 12 July 2016 and 9 July 2017.

During both growing seasons in Pickaway County, soil was prepared by discing. Planting took place on 7 Oct. 2015 and 12 Oct. 2016. Fall fertilizer application for

2015/2016 was 23.5 kg N ha^{-1}, 70.6 kg P_2O_5 ha^{-1}, 93 kg K_2O ha^{-1}, and 11.1 kg S ha^{-1}. In 2016/2017, 19.6 kg N ha^{-1}, 74 kg P_2O_5 ha^{-1}, 67.3 kg K_2O ha^{-1}, and 11.2 kg S ha^{-1} were applied. Spring topdress rate for both years was 110.5 kg N ha^{-1} (28-0-0) and 2.7 L ha^{-1} of nitrapyrin (Instinct® II, Dow AgroSciences) to inhibit nitrification. 52.5 g ha^{-1} of Harmony® Extra SG herbicide was applied in March 2016. Cyfluthrin insecticide (Cyano(4-fluoro-3-phenoxyphenyl)methyl-3-(2,2-dichloroethenyl)-2,2-dimethyl-cyclopropanecarboxylate) (Tombstone™, Loveland Products, Inc., Greeley, CO) was aerial applied at 146 ml ha^{-1} of product. A mix of 986 ml ha^{-1} of metconazole fungicide (Cyano(4-fluoro-3-phenoxyphenyl)methyl-3-(2,2-dichloroethenyl)-2,2-dimethyl-cyclopropanecarboxylate) (Caramba®, BASF Corporation, Research Triangle Park, NC) and 146 ml ha^{-1} of an adjuvant (Lecithin, methylesters of fatty acids, and alcohol ethoxylate) (Franchise®, Loveland Products, Inc.) was also aerially applied. Herbicide application for the second season was 1.17 L ha^{-1} of Moxy® 2E with 1.25 ml L^{-1} NIS. The same rates of Tombstone™ and Franchise® were used in 2016/2017, but Prosaro® fungicide was applied once at Feekes GS 10.3 on 11 May, 2017 at a rate of 511 ml ha^{-1} instead of Caramba® fungicide.

3.3.3 Fall Stand, Stem and Head Count Procedure

After planting, an initial stand count was conducted for each plot, and estimated at Feekes GS 1 to verify seeding rate treatments. Plants in a 30.5 cm linear section of row were counted at three random points within each plot and averaged. The same procedure was used for stem counts at Feekes GS 5, 6, and 7 (only 2016/2017 at NWARS), and head counts at GS 10.5. Stems are defined as the main stem and tillers. For measurements at Feekes GS 5, 6, and 7, all stems were counted regardless of height or leaf number. During head counts at Feekes GS 10.5, stems less mature than Feekes GS 10 were not included in the counts.

3.3.4 Normalized Difference Vegetation Index Measurements

Normalized difference vegetation index measurements were taken at Feekes GS 5 and 6, using a Greenseeker™ handheld crop sensor (Trimble Inc., Sunnyvale, CA). The crop sensor was held parallel to the ground, at a height of 1 m from the soil surface, 53 cm from the border within the plot. At 1 m, the Greenseeker™ senses a width of 42 cm (Trimble Navigation, Ltd.). After pulling the Greenseeker™ trigger to initiate a plot reading, it was then held for the entire length of the plot. When released, an average NDVI value was recorded. A second measurement was repeated for the length of the plot walking in the opposite direction. An average NDVI value was calculated from both plot-length readings, which included the second, third, and fourth rows from the plot edge. Ambient weather (i.e., cloudiness) does not impact the accuracy of measurements (Verhulst and Govaerts, 2010).

3.3.5 Fractional Green Canopy Cover Measurements

Fractional green canopy cover (FGCC) was measured using the mobile device application called Canopeo (Oklahoma State University, Stillwater, OK). Measurements were taken at Feekes GS 5 and 6, from the same area the first stem count was performed, to compare FGCC measurements to the stem counts. Fractional green canopy cover was taken at two heights to cover a 30.5 cm section of row (1-row) and three rows of wheat (camera height and length of row covered varied based on canopy height).

3.3.6 Growing Conditions

Monthly average temperature (Table 3.2) and cumulative precipitation (Table 3.3) from October through July for four site-years were compared to the 30-year average (1985-2014) (NOAA, 2017). Data for Pickaway County were collected from a weather station in Circleville, OH (39° 36' 37.44' N, 82° 57' 19.8" W), and data for Crawford were collected in Bucyrus, OH (40° 48' 45.36'' N, 82° 58' 11.28" W).

3.3.7 Statistical Analysis

Analysis for section 3.4.2 required testing slope by site interactions ($\alpha = 0.05$) using the GLM procedure in SAS (SAS Institute, Cary, NC; version 9.4), to determine if a single linear model could be fit to the combined data set; the REG procedure could not handle the site classification variable. Once interaction significance was recorded, and for all further analysis, the REG procedure in SAS was used to perform regression analysis, where model significance was determined using an $\alpha = 0.05$. Accounting for location and year differences in section 3.4.3 required the use of relative yield, where each plot yield was divided by the respective site-year mean. Normality and homogeneity of variance assumptions of ANOVA were met, determined by examining histograms of residuals and plots of residuals vs. predicted values.

3.4 Results and Discussion

3.4.1 Growing Conditions

Monthly temperatures for both growing seasons in both locations were typically above the 30-year average, with the greatest exceptions being April (-1.3°C) and May (-1.0°C) 2016 in Crawford County (Table 3.2). The warmest temperature differences at both locations occurred in December 2015, March 2016, January 2017, and February 2017, and ranged from +3.4 to +6.5 °C above the 30-year average.

Cumulative monthly precipitation over both locations and growing seasons exhibited fluctuation and high variability compared to the 30-year average (Table 3.3). Throughout both growing seasons, Pickaway County experienced below average rainfall in 10 of 20 months, and 13 of 20 months in Crawford County. Pickaway County in 2017 was by far the wettest period, with rainfall in July, March, and April receiving 12.9 cm, 8.7 cm, and 5.9 cm above the 30-year average, respectively. Crawford in 2016 was a dry year, as May, June, July, and November had precipitation values of 3.0 cm, 4.8 cm, 9.7 cm, and 5.0 cm below the 30-year average, respectively.

3.4.2 Fall Stand Establishment

Established fall wheat population reflected the imposed treatment of seeding rate for Pickaway Count in 2015 and Crawford County in 2016 (Table 3.4). The estimated fall populations were consistently below the target seeding rate, illustrating a common issue in stand establishment of wheat. Seeding rates for Pickaway County in 2016 and

Crawford County in 2015 did not result in entirely significantly different fall populations. It is likely the correct seeding rate was imposed, but stand establishment was too variable.

Table 3.2. Change in average monthly temperature between a 30-yr average and each month within the 2015/2016 and 2016/2017 growing seasons. (Temperatures from 1985-2014 shown for 30-yr average.) (Data from NOAA, 2017)

		Average Temperature (°C)									
Site	Year	Jan	Feb	March	April	May	June	July	Oct	Nov	Dec
Pickaway	30 yr avg	-1.3	0.1	5.2	11.4	16.8	21.7	23.4	12.4	6.5	1.1
	2015								+0.7	+2.3	+6.5
	2016	-0.5	+1.2	+4.1	+0.3	-0.5	+1.1	0.0	+2.8	+1.6	-0.5
	2017	+3.6	+5.1	+0.4	+2.1	+0.3	+0.9	+0.5			
Crawford	30 yr avg	-3.6	-2.8	2.7	9.5	15.3	20.4	22.4	10.8	4.8	-1.2
	2015								+0.6	+2.4	+6.3
	2016	-0.5	+2.3	+3.9	-1.3	-1.0	+0.9	+1.1	+2.1	+1.9	-0.9
	2017	+3.4	+5.8	+0.4	+3.0	-0.7	-0.3	-0.4			

Table 3.3. Change in cumulative monthly precipitation between a 30-yr average and each month within the 2015/2016 and 2016/2017 growing seasons. (Precipitation from 1985-2014 shown for 30-yr average.) (Data from NOAA, 2017)

		Average Cumulative Precipitation (cm)									
Site	Year	Jan	Feb	March	April	May	June	July	Oct	Nov	Dec
Pickaway	30 yr avg	6.7	5.6	7.5	9.3	11.8	10.1	10.0	7.6	7.6	7.9
	2015								-2.2	-0.4	+2.4
	2016	-3.9	+3.9	+1.5	-2.2	+0.2	-2.2	-0.9	-0.7	-5.5	+1.5
	2017	+2.2	-1.9	+8.7	+5.9	-4.2	+1.2	+12.9			
Crawford	30 yr avg	6.5	5.5	6.3	8.6	10.3	11.3	11.8	6.9	7.4	7.3
	2015								0.0	-3.6	+0.5
	2016	-2.2	-0.8	+1.6	+1.0	-3.0	-4.8	-9.7	+2.1	-5.0	-2.3
	2017	+2.9	-3.0	-1.2	-1.8	+4.7	-1.3	+5.4			

Table 3.4. Target seeding rate and established population at Pickaway (Pick) and Crawford (Craw) County for the 2015/2016 and 2016/2017 growing seasons.

	Pick 2015	Craw 2015	Pick 2016	Craw 2016
Seeding Rate	Fall Population			
Million seeds ha^{-1}	-------------million plants ha^{-1}-----------			
1.85	1.40a†	1.27a	0.91a	1.34a
2.47	1.99b	1.79a	1.81a	2.41b
3.71	3.43c	3.18b	3.49b	3.96c
4.94	4.80d	3.67b	4.74c	5.04d
6.18	6.01e	5.25c	5.61c	6.41e

†Values followed by the same letter in a column are not significantly different from each other (α= 0.05)

3.4.3 Stem Estimation Measurements

One-row and three-row FGCC measurements at Feekes GS 5 and 6 had statistically similar slopes for each site-year, indicating that a single linear model could be fit to combined data sets (Table 3.5). For each model, the GS of the stem count and the FGCC measurement were the same. All models were significant at α = 0.05. The models for Feekes GS 5 and GS 6 1-row FGCC measurements, explained 3.17 and 7.8 times more variation in the data (r^2) than their 3-row counterparts, respectively. Table 3.5 includes the range of FGCC values for which each model will be accurate, to avoid extrapolation.

Table 3.5. Linear regression models of stem counts at Feekes (F) growth stage 5 and 6 vs. Feekes 5 and 6 fractional green canopy cover (FGCC) for 1-row and 3-row areas, with measurement (slope) by site-year interaction p-values, model p-values, coefficients of determination (r^2), and the range of values for which each model is accurate. Significance determined at $\alpha = 0.05$.

GS/ Measurement	Dependent Variable	Measurement x Site p-value	Model p-value	r^2	Accuracy Range (cm^2 100 cm^{-2})	Model
F5/FGCC (1-Row)	F5 Stem Counts	0.923	<0.0001	0.330	11-71	23.106x+315.78†
F5/FGCC (3-Row)	F5 Stem Counts	0.247	0.012	0.104	18-65	15.58x + 770.72
F6/FGCC (1-Row)	F6 Stem Counts	0.060	<0.0001	0.398	13-91	18.673x+355.29†
F6/FGCC (3-Row)	F6 Stem Counts	0.081	0.045	0.051	15-90	6.15x + 1079.30

†Intercepts were not significant at $\alpha = 0.05$

3.4.4 Comparison of Stem Counts, NDVI, and FGCC to Predict Yield

All regression models were significantly capable of accounting for variation in the data, except the three-row FGCC measurement at Feekes GS 6, which was dropped from further consideration (Table 3.6). Stem counts at Feekes GS 5 were the benchmark that every other yield estimation parameter was compared against. Therefore, any RMSE smaller than or equal to that of Feekes 5 stem counts (RMSE= 0.072) was considered a feasible alternative measurement.

The regression model for Feekes GS 6 NDVI readings had 5.6% more unexplained variance than stem counts at Feekes GS 5, making it the least desirable alternative choice for yield prediction. Fractional green canopy cover for 1-row at Feekes GS 5 was the second least accurate model (RMSE= 0.075), followed by the same measurement at Feekes GS 6. Head counts were also a poorer alternative to yield estimation, but only had 1.4% more unexplained variation than Feekes GS 5 stem counts. Stem counts at Feekes GS 6 proved to be better than the earlier counts, but is not an ideal choice.

The best alternative yield estimators are NDVI and three-row FGCC measurements at Feekes GS 5 (Figure 3.1 and 3.2) The three-row FGCC measurement had a highly significant regression model, in addition to 6.9% less unexplained variation than Feekes GS 5 stem counts. Feekes 5 NDVI readings were better yet, with 8.3% less variation than the benchmark.

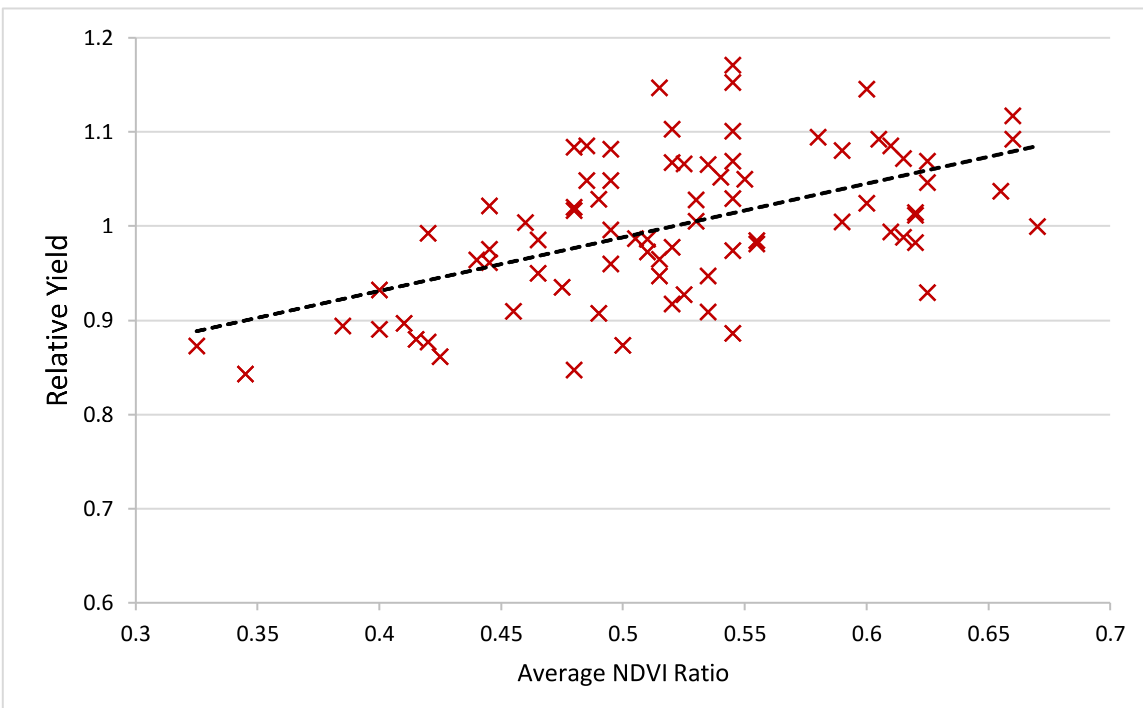

Figure 3.1. Linear regression of relative yield vs. normalized difference vegetation index (NDVI) values at Feekes growth stage 5. Relative yield was calculated by dividing plot grain yield by mean site-year grain yield.

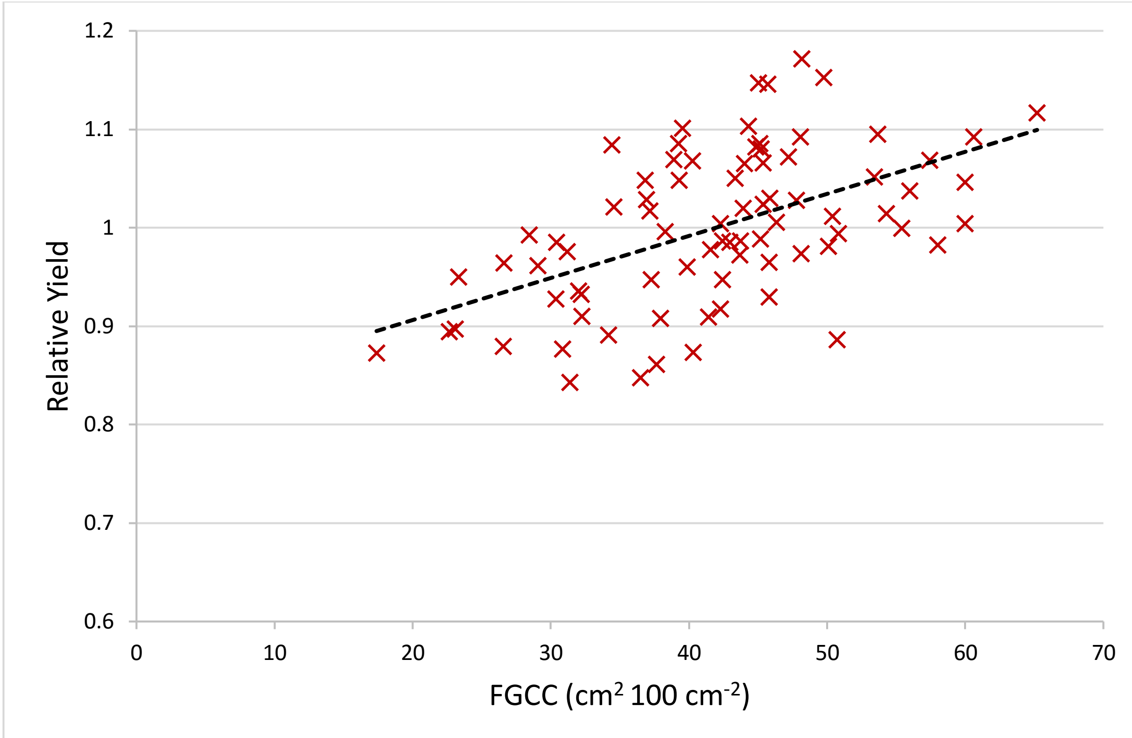

Figure 3.2. Linear regression of relative yield vs. fractional green canopy cover (FGCC) of a three-row area at Feekes growth stage 5. Relative yield was calculated by dividing plot grain yield by mean site-year grain yield.

Table 3.6. Regression equation, root mean squared error (RMSE), and model p-value for relative yield vs. stem counts, normalized difference vegetation index (NDVI), and fractional green canopy cover measurements, taken at Feekes (F) growth stage (GS) 5 and 6, and head counts. Relative yield calculated by dividing plot yield by site-year yield. NS= not significant

GS/Measurement	Model	Regression	RMSE	P-value
F5/Stem Counts	$y = 8E^{-5}x + 0.9002$	Linear	0.072	0.0001
F5/NDVI	$y = 0.5697x + 0.7033$	Linear	0.066	<0.0001
F5/FGCC (1-Row)	$y = 0.0019x + 0.9152$	Linear	0.075	0.005
F5/FGCC (3-Row)	$y = 0.0043x + 0.8208$	Linear	0.067	<0.0001
F6/ Stem Counts	$y = 0.0001x + 0.8193$	Linear	0.068	<0.0001
F6/ NDVI	$y = 0.1383x + 0.9174$	Linear	0.076	0.035
F6/FGCC (1-Row)	$y = 0.0017x + 0.8953$	Linear	0.074	0.002
F6/FGCC (3-Row)	-	Linear-NS	-	0.123
Head Counts	$y=-4E^{-7}x^2+0.0007x+0.6763$	Quadratic	0.073	0.0015

3.5 Conclusion

3.5.1 Stem Estimation

One-row FGCC, taken at Feekes GS 5 and 6 with Canopeo, are capable of accurately estimating stem counts at their respective stages (Table 3.5). These measurements may appeal to those with experience using stem counts to make decisions, who would like an easier way to estimate them as opposed to replacing stem counts entirely. Canopeo is free and accurate, making it a viable and easily adopted tool. Crop insurance adjusters, and producers using stem counts for N recommendations would benefit from the use of Canopeo as a basis for decision making.

3.5.2 Capability of NDVI and FGCC to Predict Yield

The results indicate that NDVI and three-row FGCC measurements at Feekes GS 5 are better yield estimators than stem counts at Feekes GS 5, and were capable of replacing stem counts to assess spring stand quality in this experiment (Table 3.6). Although NDVI is the more accurate of the two measurements, lower accuracy of Canopeo may be offset by the fact that it is free. Wheat producers should be cognizant of their stand as spring approaches, in order to ensure measurements are taking place at Feekes 5. If a sizeable decision must be made at Feekes GS 6, stem counts would be the recommended method at this time. However, if a producer wants a general idea of stand quality to satisfy personal curiosity, then a 1-row FGCC measurement at Feekes GS 6 would suffice.

The results for FGCC measurements indicate that FGCC is sensitive to growth stage and plant height. Fractional green canopy cover was both the second-best and second-worst estimator of yield at Feekes GS 5, when used for 1-row row and three-row measurements, respectively. The camera height required to take 1-row measurements was much closer than the required 60 cm minimum height, and may have been causing the difference in accuracy (Oklahoma State University, 2015). It is unclear as to why there was such large variation in the same measurements under Feekes GS 6, but it is believed to be related to the change in canopy architecture between GS 5 and 6.

Feekes GS 6 NDVI readings were not anticipated to be the least accurate, but there is a good reason for the result. NDVI has proven to be unreliable when the canopy has a LAI above 3 (Serrano et al., 2000). Feekes GS 6 is the beginning of stem elongation, and ideally N should have been applied prior to this stage (Wise et al., 2011). A flush of vegetative growth between Feekes 5 and 6 likely rendered NDVI incapable of providing accurate estimates at Feekes GS 6.

Wheat producers have alternatives to counting stems for yield estimation. It is suggested that producers at least adopt FGCC to estimate stem density when making decisions about spring wheat stands. The normalized difference vegetation index is a very good yield estimator, and was the best option in this experiment. When using the yield estimation equations, it is important to note that the output is the proportion of potential yield.

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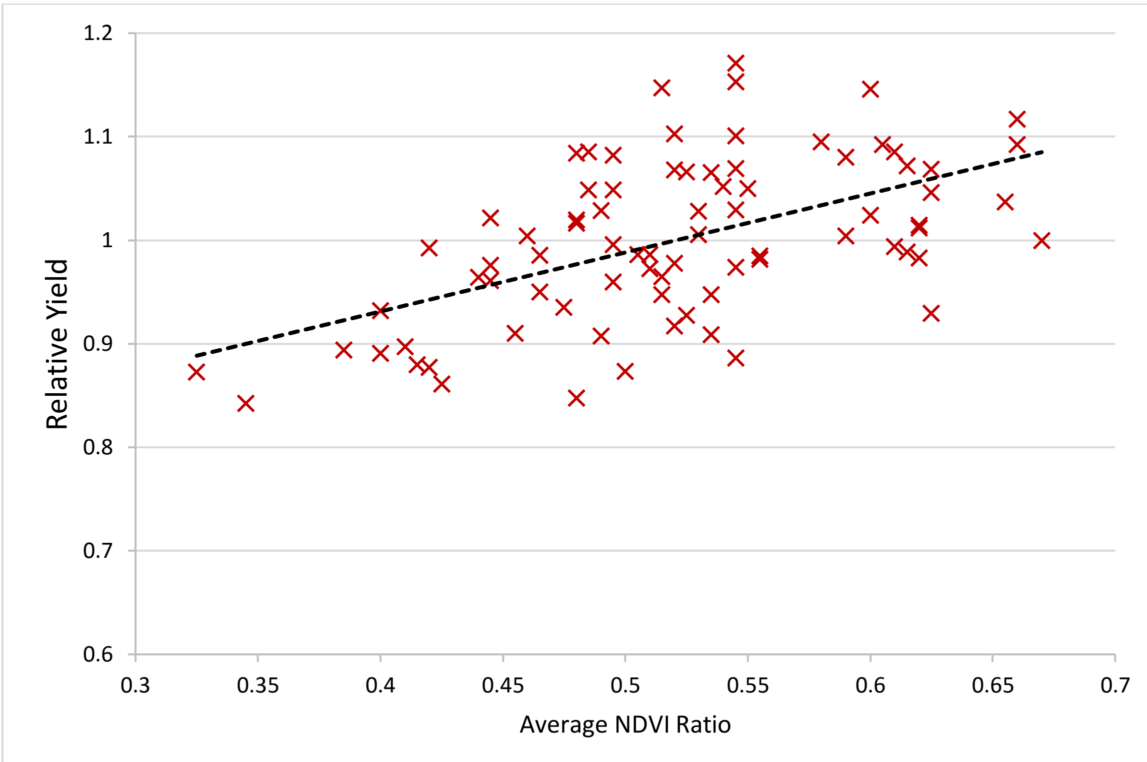
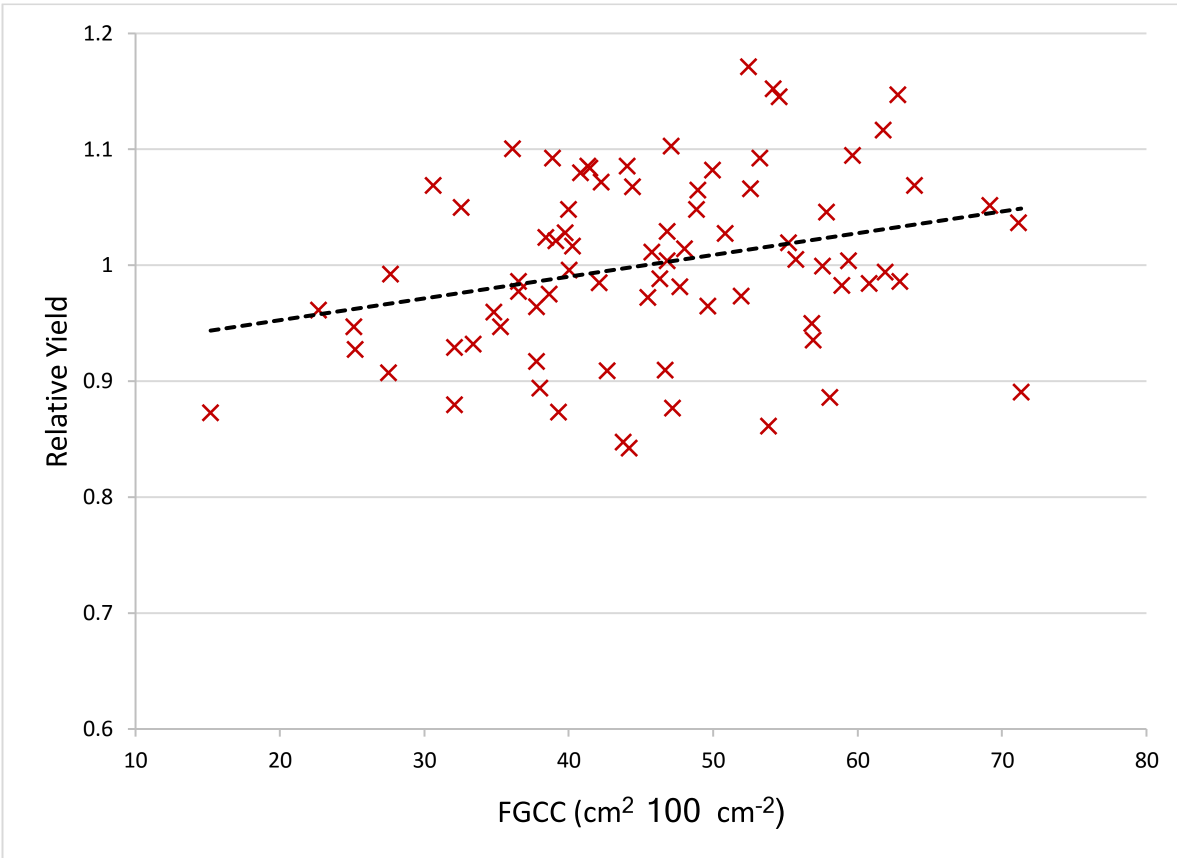
Appendix A: Linear Regression of Relative Yield vs. NDVI at Feekes Growth Stage 5



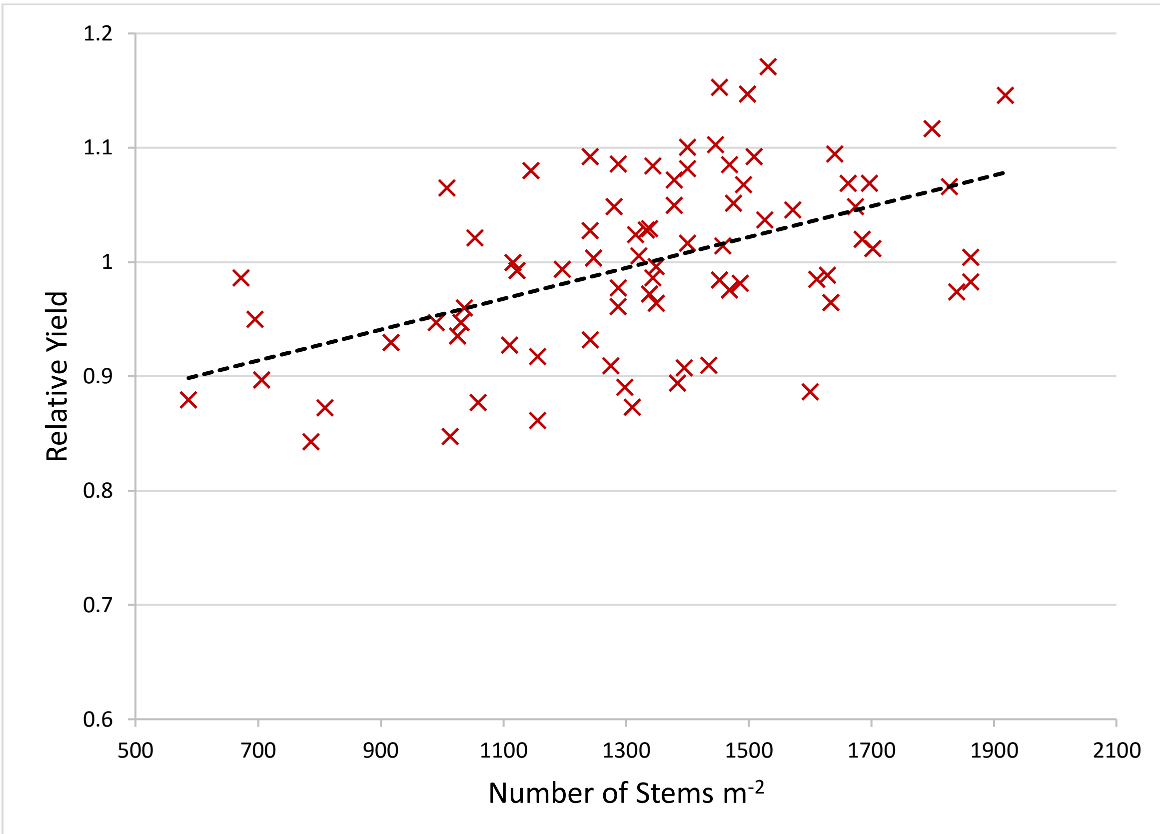
Linear regression of relative yield vs. normalized difference vegetation index (NDVI) values at Feekes growth stage 5. Relative yield was calculated by dividing plot grain yield by mean site-year grain yield.

Appendix B: Linear Regression of Relative Yield vs. 1-Row FGCC at Feekes Growth Stage 5



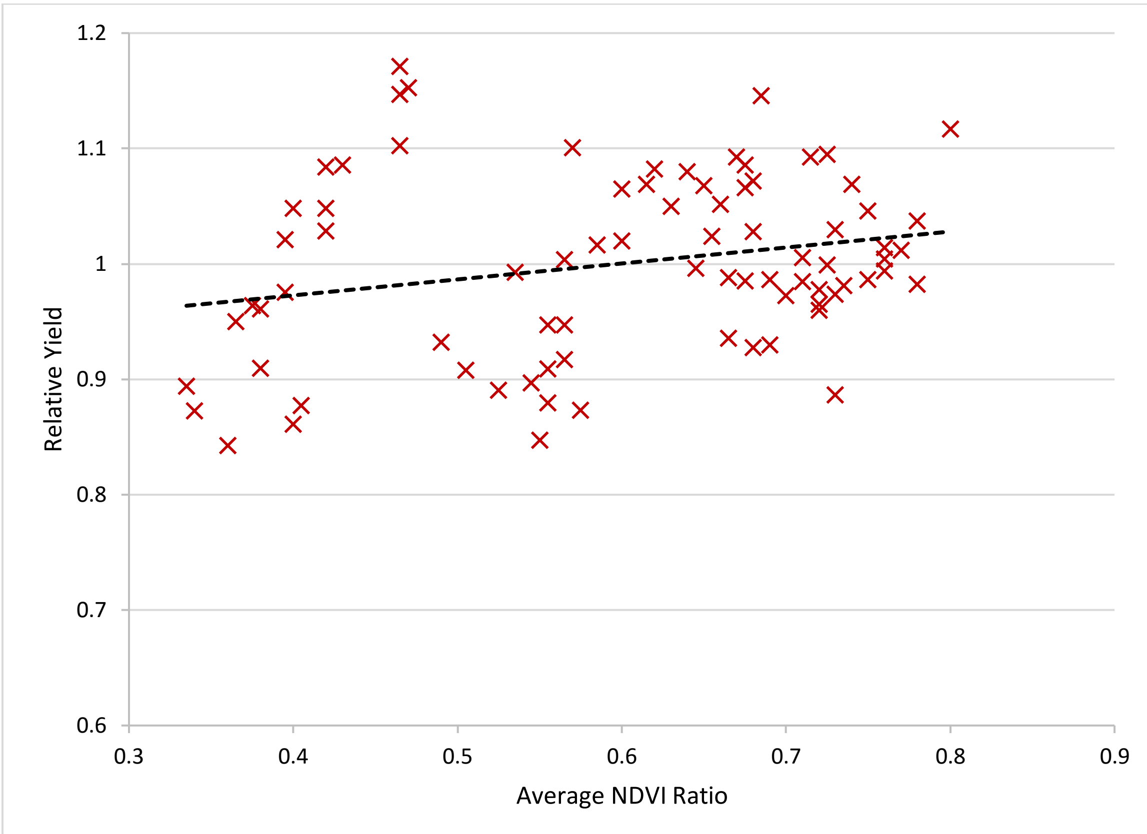
Linear regression of relative yield vs. fractional green canopy cover (FGCC) for 1-row at Feekes growth stage 5. Relative yield was calculated by dividing plot grain yield by mean site-year grain yield.

Appendix C: Linear Regression of Relative Yield vs. Stem Counts at Feekes Growth Stage



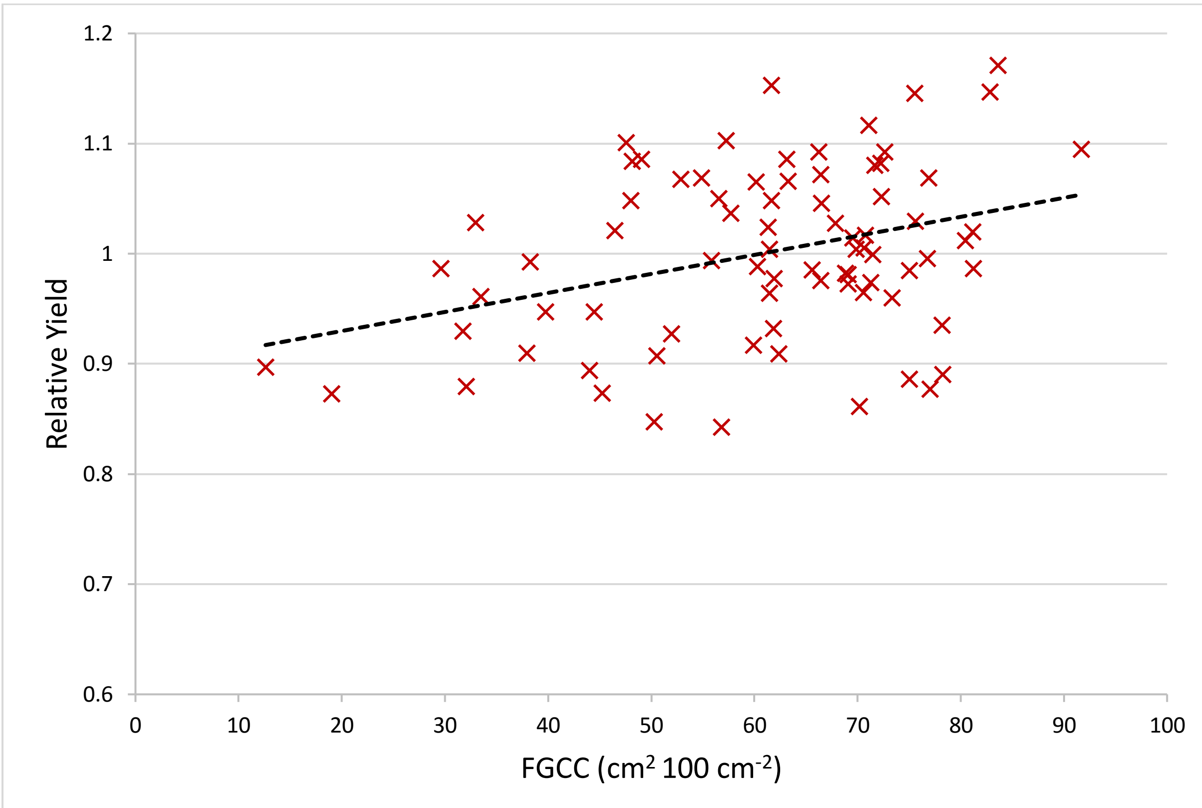
Linear regression of relative yield vs. stem counts at Feekes growth stage 6. Relative yield was calculated by dividing plot grain yield by mean site-year grain yield.

Appendix D: Linear Regression of Relative Yield vs. NDVI at Feekes Growth Stage 6



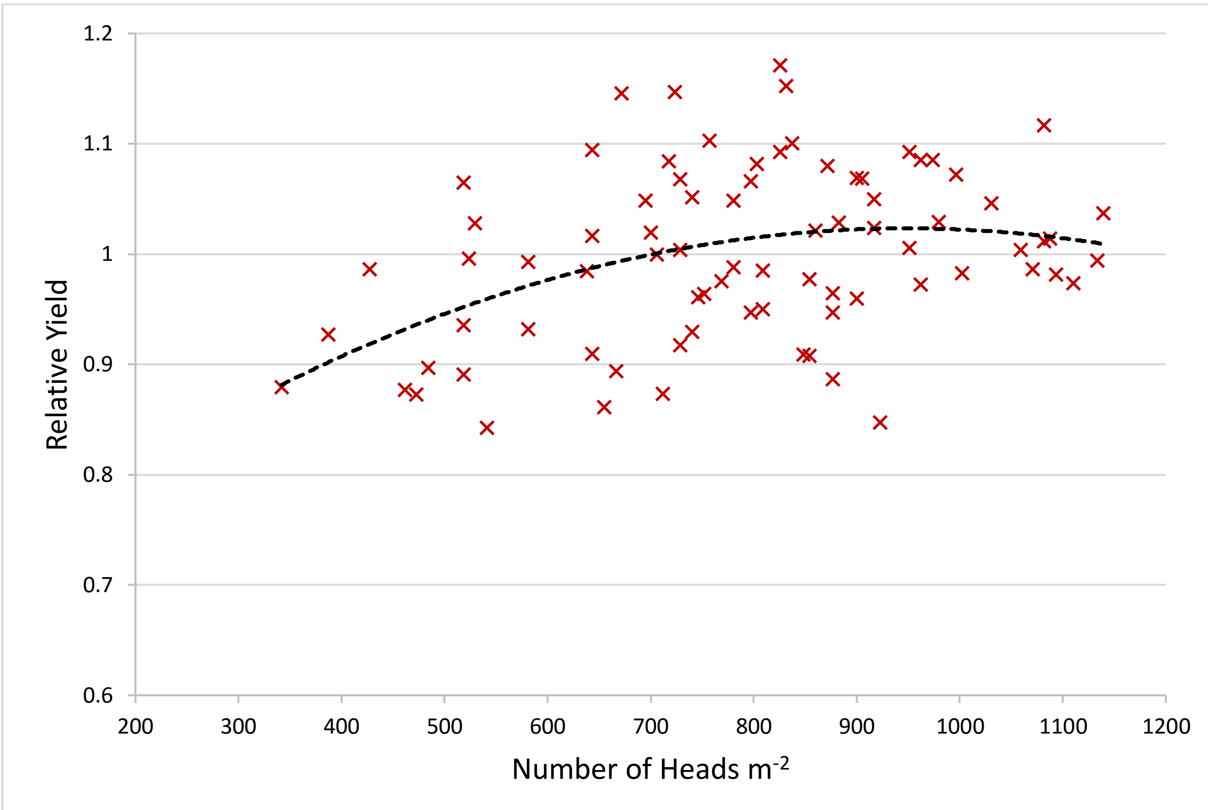
Linear regression of relative yield vs. normalized difference vegetation index (NDVI) values at Feekes growth stage 6. Relative yield was calculated by dividing plot grain yield by mean site-year grain yield.

Appendix E: Linear Regression of Relative Yield vs. 1-Row FGCC at Feekes Growth Stage 6



Linear regression of relative yield vs. fractional green canopy cover (FGCC) for 1-row at Feekes growth stage 6. Relative yield was calculated by dividing plot grain yield by mean site-year grain yield.

Appendix F: Linear Regression of Relative Yield vs. Head Counts at Feekes Growth Stage 10.5



Quadratic regression of relative yield vs. head counts at Feekes growth stage 10.5. Relative yield was calculated by dividing plot grain yield by mean site-year grain yield.