Evaluation of planting technologies and management in wheat

by

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Abstract

Genotype by seeding rate interaction can play a critical role in wheat (*Triticum aestivum* L.) yield potential. The objectives of this study were to i) quantify wheat yield response and ii) early-season plant establishment related to the planting technology under diverse seeding rates and with contrasting varieties relative to their tillering ability. Four studies were established at two locations during two growing seasons (2015-16 and 2016-17) at Ashland Bottoms (dryland and conventional till in the first year and no-till in the second year) and at Topeka (irrigated and no-tillage for both years) field research stations (KS, US). Two winter wheat varieties were planted with two different planting systems (singulated and conventional drill) at four different seeding rates (45, 90, 135, and 180 kg ha^{-1}). Early-season measurements consisted of stand counts, canopy coverage (estimated via imagery collection via small-unmanned aerial vehicle systems - sUAVS), determination of early-season gaps within the stand of plants, and spacing between plants. Early season measurements (emergence progression, stand count, and canopy coverage) and biomass did not present differences among treatments. At Ashland, across 2-yrs, single factors seeding rate and genotype significantly impacted yields. Seeding rate factor positively affected yields, ranging from 4.7 to 5.4 Mg ha^{-1} with seeding rates going from 45 to 135 kg ha^{-1}, respectively. For the genotype factor, the variety WB Cedar (high-tillering) presented an overall yield of 605 kg ha^{-1} greater than WB 4458 (low-tillering). Across locations, the seeding system did not influence yields for both years of the study. At Topeka, the seeding system significantly influenced yields in 2017, with singulation outyielding the drill system, in 161 kg ha^{-1}. Further research is needed at a farmer-scale testing more winter wheat varieties and focusing on lower seeding rates to better understand the potential benefits of the implementation of this new technology.

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Chapter 1 - Literature Review

Winter wheat genotype, seeding rate and new planting technologies.

Wheat (*Triticum spp.)* is an important cereal crop around the world. Wheat has been domesticated eight thousand years ago and has been a staple food in many civilizations (FAO, 2012). Wheat is also considered the universal cereal of the Old World (Feldman & Levy, n.d.). Nowadays, wheat is the largest grain produced and an important source of calories and protein for human nutrition (Feldman & Levy, n.d.). As for land use, more than 230 million hectares were planted worldwide in 2013-2014 season, grown in more land than any other commercial crop, with a production of 730 million tons (FAO, 2017).

The United States (US) the fifth largest producer, with more than 18 million hectares planted and a production of 55 million tons (FAO, 2017). A largest portion of all the wheat production comes from the Great Plains and the Northwest regions, including the following states: Kansas, North Dakota, Montana, Washington, Oklahoma, South Dakota and Colorado. From all wheat production, winter wheat accounts for 70% to 80% (USDA, 2017). The state of Kansas planted 3.5 million hectares of winter wheat in the 2015-2016 season, with a total production of 13 million tons (USDA, 2017).

Productivity is affected by the outcome of the complex interaction between genotype (G), environment (E), and management practices (M). Genotype x environment (GE) interaction has been broadly analyzed; the environment effect is considered as one of the most important factor influencing wheat quality characteristics (Johnson et al., 1972; Faridi and Finley, 1989), such as protein.

Genotype differences are crucial to maximize production of wheat. Thus to determine the best variety fit for an environment several trials are evaluated year at different growing regions.

These wheat varieties should not only perform well from an agronomic standpoint but should also present some distinctness, uniformity, and stability (Wang et al., 2014). Breeders evaluate agronomic traits when performing variety selection, such as grain yield, grain quality, drought tolerance, winter hardiness, disease resistance among another factors (Wang et al., 2014).

University- and private- variety testing trials evaluate performance of different varieties in different environments. These assessments are performed every year to evaluate the differences related to changes in the weather and release of new varieties, allowing the farmer to choose the best option for each particular environment. In the state of Kansas, every year a list is released with the main variety for each region (K-State 2017). More information about other states can be found in each university website related to their areas.

Major limiting factors affecting wheat production are temperature, solar radiation, and water supply (Anderson, 2010). Nitrogen (N) content in the soil is also important and correlated with the amount of protein in the grain; nonetheless, grain protein response varied across genotypes under comparable soil N status. Studies showed that applying N at blooming or close to this stage could increase the protein level of the grain (Miezan et at 1977), but it could not be an economically viable way to increase grain quality. In addition, water availability also contributes to increase in grain quality and production.

Management practices exert a large influence on attainable wheat yield. Fine-tuning management practices can assist in closing yield gaps and improve farmer yields. Some of the best management practices for improving wheat production include seeding rate, tillage, planting date, balanced nutrient fertilization, row spacing, and fungicide/insecticide protection.

Variety - Tillering

The tillering ability varies with the genotype and environment; and also highly influenced by planting density/seeding rate, studies have shown that reduced seeding rate can cause unusual tillering (Thompson et al., 1993) and variable and delayed maturation in some situations, affecting management at harvest. Tillers have the same structure as the main shoot ascending from the axils of the basal leaves; however, only some of the tillers will produce a spike at anthesis. Under favorable conditions, one to two tillers per plant are a usual number (Curtis et al., 2002), and many others will abort before anthesis (Gaagher and Biscoe, 1978). Winter wheat has greater number of tillers compared to spring wheat (Curtis et al., 2002). Tillers are an important part of the wheat plant, as the final grain yield depends directly on plants per area, tillers per plant, kernels per tiller and weight per kernel (Gulnaz et al, 2011). Tillering can also partially or totally compensate differences in plant number and issues with the crop establishment allowing for crop recovery. Consequently, tillering plays an important role in the final crop productivity.

Genotype differential ability in tillering can affect individual plant response to the use of aboveground and exploration of underground soil resources, Geleta et al (2002) have found differences in plant high at different seeding rates, with higher plants in smaller seeding rates and as increases the plant high decreases, reflecting competition for resources. Tillering potential (plastic property) refers to the capability of the plants, grasses and cereals, to produce lateral branches. Because that is driven by variety and the environment, seed companies classify the tillering potential for each variety. When in low population and an ideal environment wheat have the ability to compensate under relatively lower seeding rates to establish good stands with many tillers (Geleta et all. 2002), however in high plant densities the same wheat plant can produce just one, or no tillers at all, in this case the plant invests more biomass in height and growth.

Environment

Winter wheat planting (sowing) for depending on region within Kansas occurs by mid-September until late-October. Wheat can germinate in temperatures between 4^o and 37^o C, but with an optimum ranging from 12^o to 25^oC (Spilde, 1989). The water content required for wheat germination is around 35 to 45 percent of the seed weight (Evans et al., 1975). Wheat can be produced under diverse environments (Hanson et al., 1982). The final wheat yields are affected, among other factors by environment effects such as drought, heat, low temperatures, soil salinity and fertility (Curtis et al., 2002).

Tillage is a method that can be utilized to control the weeds, with no-till presenting more weed density than the conventional till (Dorado et al., 1999; Sims and Guethle, 1992). Weed density and use of herbicides potentially increases under no-till and with this the cost of production (Kegode et al., 1999). However, no-till systems are used in order to maintain water storage and avoid exposure to soil erosion. With appropriate management practices water loss by soil evaporation can be reduced in no-till systems, consequently, increasing water use efficiency at the system-level (WUE). When in a condition that tillage is reduced some concerns about the stands are observed, the previous crop residue can interfere with penetration by some seeding delivering systems (Carr et al., 2003), as result sometimes seeding rates are increased in those conditions of reduced or no tillering.

Under irrigation, high-yielding crop will be accompanied by a large nutrient removal, primarily for nitrogen (N) (Curtis et al., 2002). In a study evaluating achieving high-yielding wheat (CYMMIT, Mexico), 7 Mg ha^{-1}, a total of 600 kg N ha^{-1} (between soil N and fertilizer N) was required to satisfy the crop N needs (Curtis et al., 2002).

Seeding rate factor

Winter cereals have the capacity to tiller abundantly; therefore, seeding rate management is not considered as an essential and critical practice for improving yields. Nonetheless, under water-limited environments (e.g. rainfed), selecting the optimum seeding rate to maximize yields and improve the WUE becomes a critical practice (Curtis et al., 2002).

For wheat crop, yield response to seeding rate is generally a plateau without portraying any yield penalty unless the seeding rate is overly large or small. Yield environment, herein defined as the maximum attainable yield under best management practices for a site, is a very important factor to determine the optimum seeding rate for wheat, some environmental factors that may limit this maximum yield environment and wheat quality are, precipitation; temperature; day length, soil types and management practices (Geleta et al., 2002). Optimum seeding rates can vary between regions, according to climatic conditions, soil, planting time, and varieties (Gate, 1995). Studies have shown that better the environmental resources, higher will be the required optimal seeding rate (Holliday, 1960) Finding the optimum seeding rate is very important to maximize yield production. For wheat, yield response to seeding rate have shown to increase until a certain rate then plateauing with a potential yield, and decrease when seeding rate increases, this can be described by the competition between plants for water and nutrients resources (Blue et al., 1990). Seeding rate can play a critical role in wheat production reflecting in the number of plants, tillers and final number of heads at maturity (Xinglong, 2013). The same study demonstrated larger yield when seeding rate increased until a certain point, right after increasing seeding rate produced a negative yield impact. Seeding rate can play a critical role in understanding how the singulation technology is affected as the number of seeds sown increases.

Lower seeding rates were found to effectively maximize yields in wheat relative to superior seeding rate, without finding a clear yield response to seeding rate (50 vs. 100 kg ha^{-1}) (Curtis et al., 2002). In agreement to the previous finding, other studies conducted by CIMMYT for several seasons presented that lower seeding rates could be used without affecting yield under irrigation.

Uniformity in wheat

Early-season stand uniformity is critical to achieve a high yielding system; however, due to its tillering ability, wheat can compensate for reduced stands. Wheat cultivars differ in their ability to compensate for poor or non-uniform stand, usually by increasing the number of tillers per plant and modifying the number of grains per spike under different conditions (Curtis et al., 2002).

The timing of seedling emergence has been shown to influence the final grain yield (Gan et al., 1992). Failure on seedlings to emerge and early season vigor can be affected by soil type, mostly physical factors (Addae et al., 1990), such as depth of sowing. Planting technologies are always evolving to get the best response by the crops. The utilization of conventional seeding systems (e.g., air seeders) has demonstrated the need for continued improvement in wheat uniformity and plant spacing. Better planter technologies can allow better uniformity, and potential reduction in seeding rate (seed savings). Better uniformity can allow attaining superior yields at equal use of inputs, and utilizing less seeds with less cost to the producers, besides the importance of reducing pre and post- harvest losses.

Research Question and Justification

Winter wheat is one of the most relevant field crops in the central Great Plains region of the US. Evaluation of more efficient seeding systems at varying genotypes (tillering ability) and under different seeding rates is still a critical research knowledge gap.

Specific research objectives of this research was to compare a new planting technology system, for improving early-season wheat establishment, under a genotype by seeding rate interaction.

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Chapter 2 - Early-Season Wheat Uniformity

Abstract

Genotype by seeding rate interaction can play a critical role in understanding wheat (*Triticum aestivum* L.) early-season establishment. The objective of this study was to analyze how a new planting technology affects early-season crop establishment. One study were established at two locations during two growing seasons (2015-16 and 2016-17): i) at Ashland Bottoms (dryland and conventional till in the first year and no-till in the second year) and ii) at Topeka (irrigated and no-tillage for both years) field research stations (KS, US). Two winter wheat varieties (WB Cedar and WB 4458) were planted with two different planting systems (singulated and conventional drill) at four different seeding rates (45, 90, 135, and 180 kg ha^{-1}). To characterize early-season wheat establishment, measurements consisted of stand counts, canopy coverage (estimated via imagery collection via small-unmanned aerial vehicle systems - sUAVS), and determination of early-season gaps within the stand of plants and spacing between plants. Early season measurements did not present differences between treatments, neither emergence of plants and gap presented differences for the planting technologies, but portrayed an expected trend related to seeding rate, with an increase of number of plants as the seeding rate increases.

Introduction

Establishment of a crop is very important to achieve high grain yield, however because of its plasticity wheat is able to compensate especially when growing under optimal conditions. Cultivars differ in their ability to compensate for poor or non-uniform stand, usually by increasing the number of tillers per plant, research indicated that tiller production declined as the seeding rate increased (Carr et al., 2003), that also could be present when in situations with poor stand. But with some differences in the cultivars, presenting in some cases differences in grain per spike under different environmental conditions (Curtis et al., 2002).

The timing of seedling emergence has shown to influence final grain yield (Gan et al., 1992), with early emergence yielding more. Failure on seedlings, such as lack of uniformity can be affected by soil type and physical factors (Addae et al., 1990) such as planting depth. Planting technologies are always evolving to get the best response by the crops; wheat is still a crop that has room for improvement, together with other small grain crops such as canola. The utilization of conventional seeding systems (e.g., air seeders) has demonstrated the need for continued improvement in wheat uniformity and plant spacing. Better planter technologies can allow: i) better uniformity and ii) potential reduction in seeding rate (seed savings). Better uniformity can allow to close the yield gap (herein defined as maximum minus attainable yields) without increasing the fertilizer and pesticide cost, and utilizing less seeds lowering the seed cost for farmers; besides the importance of reducing pre and post- harvest losses.

Wheat uniformity can be important for final yield, the use of new technologies can help to improve early-season plant uniformity resulting in a better outcome specially when lowering seeding rate. Emergence, stand count and gap evaluation are crucial measurements to better understand how early-season crop establishment affects final yields.

Research Question and Justification

Conventional seeding systems have demonstrated the need for continued improvement in wheat uniformity within plants, and plant spacing. Better planting technologies can allow, better uniformity and potential reduction in seeding rate (seed savings). The objective of this study was to analyze the effect of a new planting technology on earl-season plant establishment under contrasting wheat varieties and at varying seeding rates.

Hypothesis

This study have as hypothesis that, singulation system improves plant uniformity and, consequently, yields in wheat.

Material and Methods

Locations

The study was conducted over two growing seasons (2015-16 and 2016-17) at two locations in the state of Kansas. The first experimental site was located at Ashland Bottoms (39^o 07’ 34” N, 96^o 38’ 08” W), east-central Kansas, in a Wymore silty clay soil loam (fine, smectitic, mesic Aquertic Argiudolls). The trial was established under conventional tillage practices in 2015-16 and under no tillage in 2016-17 following soybean (*Glycine max* L.) in both growing seasons. The second site was located at Topeka (39^o 04’ 35” N, 95^o 46’ 04” W), northeast Kansas, in a Eudora silt loam and sandy loam (coarse-silty, mixed, superactive, mesic Fluventic Hapludolls). The trial in this location was conducted under full irrigation conditions also following soybeans. For year two at both locations some issues were observed due to the previous crop residue, the residue was not well distributed and affect some areas of the field with a poor stand of plants.

Experimental Design

At both locations, the experimental design consisted of a split-split plot design with two main factors, two sub-factors, and four sub-sub factor for a total of sixteen treatments and five replications. The main plot was genotype and consisted of two levels: WB 4458, a genotype with low tillering ability; and WB-Cedar, a genotype with high tillering capacity. The sub-plot was planting system and also consisted of two levels: conventional gravity-induced drill versus seed singulation. Sub-sub-plot was seeding rate and consisted of four different levels: 45; 90; 135; 180 kg ha^{-1} (Table 2.2). In order to test the sub-factor planting system at comparable seeding depths and speeds for the two different strategies, a drill-planter combination was developed by John Deere specifically for this study. The equipment consisted of 24 rows spaced 19 cm apart in one side of the tractor performing the conventional gravitational drilling of wheat seeds; while the remaining 24 rows in the opposite side of the tractor performed seed singulation similar to a row-crop planter (each row has its own singulation plate). Due to the nature of the equipment used, only the seeding rate was randomized within genotype by planting system combination. Plots were 25 m long and 4.6 m wide, with a 19 cm row spacing.

Management Practices

All plots were planted using a John Deere planter, in which half of the rows (4.5 m) was conventional drill and the other half (4.5 m) was seed singulation, as detailed above. During the 2015-16 growing season, 56 kg of nitrogen (N) ha^{-1} was applied prior to planting as urea and ammonium nitrate (UAN, 30-0-0) to ensure that N was not limiting for fall growth, and an additional 56 kg N ha^{-1} was applied at Feekes GS 3 to avoid any seasonal-N limitation. Nitrogen fertilization followed K-State University recommendations for a yield goal of 4 Mg ha^{-1}. Planting dates are shown in Table 3. At both locations, weeds were controlled using commercial herbicide, and a complete control was achieved. Similarly, at Topeka during the 2015-16 growing season, the entire experiment was treated with a foliar fungicide around Feekes GS 9. Plots were harvested with a John Deere 3300 small plot combine for the entire length (25 meter) and 3 central meters. For yield calculation the grain moisture was adjusted to 13.5%.

Vegetative Evaluations

Speed and uniformity of plant emergence were measured in three replications within each treatment in each location using a new methodology developed for this study. This methodology consisted of selecting two middle rows and establishing two and a half linear meters in each plot (Figure 2.8A), measuring individual plant emergence at two-day intervals. A first baseline emergence measurement was taken seven days after planting, followed by an additional emergence count every two days for a total of five emergence sampling times. Newly emerged plants were marked with small wooden sticks with the corresponding emergence date, as shown in Figure 2.8B. This methodology allowed us to keep track on the progression of emerged plants each measuring time, for a more precise analysis on uniformity and plant emergence as affected by planting strategy. A final stand count measurement was performed a week after the last emergence timing to collect the final number of emerged plants. At each emergence sampling time, canopy coverage pictures were taken in the same two selected rows in order to obtain an estimation of the plant coverage for each treatment combination. For this procedure, a camera (Cannon EOS) was placed in a tripod at 1.6 m above the soil ground facing down and capturing 1.25 square meters for each imagery collected. This method was also utilized to count manually the number of plants in the image, and compare with the final measurement collected at the field. Stand count was obtained as the result of the total number of plants in the emergence evolution measurement, as described above.

Gap analysis measurements consisted of measuring distance between plants bigger than ten centimeters, were collected in Feekes GS 2, around four to five weeks after sowing, in order to evaluate the occurrence and pattern of plant-to-plant gaps in the final stand. For this analysis, nine linear meters were established in the middle of each plot. Due to labor and time constrain, this evaluation was done in only four targeted treatments (drill 90 kg ha^{-1} WB Cedar; drill 90 kg ha^{-1} WB 4458; singulated 90 kg ha^{-1} WB Cedar; singulated 90 kg ha^{-1} WB 4458) and in three replications for the first year (2015-16 season), and in all treatments for one replication for the second year (2016). In addition to manually measured plant-to-plant gaps, for the second year gaps were also determined using hand-held RTK (Trimble R10) equipment. The gap analysis methodology consisted of extending a measuring tape in the ground besides each individual row, counting the final number of plants, and determining the exact physical location of each gap relative to the beginning of the plot. For the purpose of our evaluation, only gaps greater than 10 cm were considered as a "gap" between plants within a row. Simultaneously, digital images were collected using a small-unmanned aerial vehicle systems (sUAVS) flown at approximately 60 m above the crop canopy, model 3DR IRIS+ (3DR Site Scan™) using a multi-spectral MicaSense camera (model RedEdge™), which simultaneously captures five discrete spectral bands (IR, Infra-red, Near IR, Red, Blue, and Green). Two out of the discrete bands were used to differentiate the soil from the plants (i.e. IR and Near IR). All imagery data collected in the field was evaluated in the lab with a combination of techniques to detect gaps and in order to compare with the information collected in the field, herein termed as ground truthing data.

Statistical Analyses

An analysis of variance (ANOVA) was performed to test differences for main factors and interaction using R software (R Core Team, 2017). Normality and homogeneity of variances were tested across all site-years. The treatment factors (planting system, genotype, and seeding rate) were considered as fixed factors, while the location and year were considered as random factors. Each main effect (system, genotype and plant density) and subsequent interactions were nested within blocks. Homoscedastic and heteroscedastic models were compared using Likelihood Ratio Test (LRT) and normality of the residuals was tested using Shapiro-Wilk test. Least squares means were calculated through "lsmeans" (Lenth, 2016) package and separated using Tukey's HSD test from "multicomp" (Hothorn et al., 2008) R package. Final stand count was tested using the "nlme" (Pinheiro et al., 2017) package of R (R Core Team, 2017) with the data analyzed individually across years and location.

Results and Discussion

Progression of Emergence

The emergence of plants was measured very closely, with plants counted in a two-day basis. The main goal of this measurement was to evaluate and quantify the difference in number of plants and their emergence progression between planting systems. The postulate that singulation can improve plant-to-plant uniformity and spacing, consequently presenting a better plant establishment was tested following the progression of emerged plants. For all the treatments evaluated on this study, planting system factor did present an influence on the final number of emerged plants relative to the drill conventional planter technology, but without any statistical difference. At Ashland location, 2015-16 season (Figure 2.9), at both 45 and 90 kg ha^{-1} seeding rates both wheat varieties presented similar number of plants (95 plants in the 2.4 square meter) when singulation was compared against the drill planter system. For the 135 kg ha^{-1} seeding rate, a slight difference in the number of emerged plants in favor to the singulation system relative to the conventional system (139 vs. 137 emerged plants for singulation vs. drill, respectively). At the highest seeding rate, 180 kg ha^{-1}, larger number of emerged plants was measured relative to the other seeding rates, with minor differences (statistically not significant Table 2.5) in favor to the singulation system, as presented for the previous seeding rate (183 vs. 178 emerged plants for singulation vs. drill, respectively). The progression of emergence occurred as expected, with greater number of emerged plants as the seeding rate increased. The low-tillering variety WB 4458 presented similar results for progression of emergence, at the lowest seeding rate (45 kg ha^{-1}) without presenting any statistical differences across planting systems. Similar trends were observed for the intermediate seeding rates (90 and 135 kg ha^{-1}), with minor or no differences for the final number of emerged plants across planting technologies. For the highest seeding rate, 180 kg ha^{-1}, singulation presented an initial slower emergence but attaining a similar number of emerged plants at the end of the plant progression (70 days after planting, Figure 2.9). In synthesis, the current site-year (specify the year) had similar outcomes with small or no differences across planting technologies within a seeding rate level. Increases in seeding rate were reflected in a greater number of plants emerged, with a more concentrated emergence around 15 days after planting time. At Ashland, for second season 2016-17, the progression of emergence had similar results as relative to the first growing season for the high-tillering variety WB Cedar with similar trends for the 45 and 90 kg ha^{-1}, with the only difference between these two rates related to the increase on the number of plants as seeding rate increases. For the highest seeding rates (135 and 180 kg ha^{-1}) singulation technology resulted in less of emerged plants but without presenting any statistical difference relative to conventional drill system (248 vs. 284 emerged plants for singulation vs. drill, respectively). For the low tillering variety WB 4458, only small differences yet not statistically significant were documented in the number of emerged plants for the 90 kg ha^{-1} seeding rate (Figure 2.10).

In summary, for this (specify which) site-year, lack of significance of emerged plants was observed as the implementation of the new planting technology system, with a clear trend of increasing the number of emerged plants as the seeding rate increases. As for timing of emergence, the majority of the plants emerged within the 15 days after the initial emergence time, with no difference between seeding technologies.

For the second location, Topeka 2015-16 season, the number of emerged plants did not present any statistical differences between planting systems. For the high tillering variety WB Cedar (Figure 2.11), singulation system presented greater number of plants emerged relative to the conventional technology, but without statistically differing (197 vs. 185 emerged plants for singulation vs. drill, respectively). All seeding rates, except for the highest, presented similar trend with similar number of emerged plants across planter technologies. For the 180 kg ha^{-1} seeding rate, singulation presented a superior number of emerged plants but with large variability. The low tillering variety, WB 4458, presented variability within treatments across all the seeding rates (Figure 2.11), portraying similar number of plants (139 per 2.4 square meters) for the 45 kg ha^{-1} across planting systems. For the 90 kg ha^{-1}, the conventional (drill) system had a greater number of emerged plants relative to the singulation planter technology. However, for the highest seeding rates, 135 and 180 kg ha^{-1}, the singulation system presented bigger number of plants, but yet without being statistical significant. The majority of the plants were emerged around fifteen days after planting with a final count at seventy days reflecting the one hundred percent emergence. For the second year at this location, the high tillering variety WB Cedar presented similar number of emerged plants for 45 and 90 kg ha^{-1} and both planting systems. The rate of 135 kg ha^{-1} is the one with more differences between systems, with singulation portraying smaller number of emerged plants overall even though with no significant differences. For the highest seeding rate, 180 kg ha^{-1}, both planting systems presented a similar emergence progression. The low tillering variety, WB 4458, at the lowest seeding rates 45 and 90 kg ha^{-1} presented similar results for singulation and conventional systems, with an expected increase of plants as the seeding rate increases. Seeding rates of 135 and 180 kg ha^{-1} portrayed similar trend for both systems, with the singulation presenting lower number of plants, but not significantly different. Early establishment of plants was not affected by the planting system at all four site years, some small differences were observed between systems but without depicting a consistent trend.

Stand Count

For the first year of the study at both locations, the final stand count was calculated after the emergence evolution measurement, the total number of plants was used to calculate plants per square meter. Based on seed size and target seeding rate, the targeted number of plants was compared against the final number, measured under field conditions. For Ashland at the lowest seeding rate (45 kg ha^{-1}), planting systems presented a small difference on number of plants for the singulation in the low tillering variety and overall all variables reached the target seeding rate (Figure 2.13A). For the 90 kg ha^{-1}, the final number of plants for the low tillering variety (WB 4458) was lower relative to the targeted seeding rate, and as the seeding rate increases the gap between the final stand count and the targeted number of plants (Figure 2.13). For the 2015-16 season, a severe drought period after planting (10-15 days after planting) might partially explain the low plant establishment and the large gap presented for some treatment combinations between the targeted number of plants and the final number determined in the field. For the second season, 2016-17, greater final stand count in Topeka gap and decreased between the targeted and measured plants in the field occurred. Better uniformity and early-season plant establishment was documented in this location due to the irrigation as compared to Ashland. Nonetheless, at the highest seeding rate, 180 kg ha^{-1}, and for the low tillering variety the stand count did not reach the targeted seeding rate. Year one at both locations presented a good stand count across all treatments, with Ashland location presenting an overall lower number of plants per square meter and larger gap between the targeted number of plants and the final number measured under field conditions. Whereas at the Topeka location, irrigated, most of the treatments achieved greater number of plants, with only one variety at the highest seeding rate presenting a lower number of plants than expected.

For the second year of the study the same parameter was used to calculate number of plants per square meter, however the way to calculate the targeted number of plants was performed by counting all plants in nine-linear meters for all treatments before tillering. Both locations presented similar trend, with no differences between planting systems and varieties. However, as the seeding rate increases the gap between counted- and targeted- plants increases

Gap and imagery analyses

This measurement has as an objective to better understand the new planter technology and its flaws, in seed distribution uniformity, in the early establishment when compared with the conventional sowing system. As mentioned in the methodology section, for the first year of the experiment evaluations were performed for the 90 kg ha^{-1} for both varieties and planting systems in all three repetitions. For the conventional system, six rows were selected out of 24 for this analysis; locations did not present significant differences for gap count. In the figure 2.19 number or gaps per row is placed for both varieties, left side low tillering WB 4458 and right side with the high tillering WB Cedar, numbers around the circle refer to the plot and row number, respectively. Greater number of gaps was documented for the WB Cedar variety with an average of seven gaps per row (Figure 2.20); while the low tillering WB 4458 resulted in an average of three gaps per row. When evaluating the new technology, the machine has four different delivering systems within the singulation, herein termed as: “CM”; “4rh”; “8rh” and “Bank”. Therefore, we count the gaps in twelve out of 24 rows, in order to evaluate all the different systems (Figures 2.17 and 2.18). Main point of the gap analysis was to identify any trend WB 4458, the red lines are separating the four systems named above, and the systems have a different number of rows analyzed, number of gaps for this treatment, 90 kg ha^{-1} / WB 4458 / Singulation have an average of five gaps per row.

The high tillering variety WB Cedar presented less number of gaps when compared with the WB 4458 (Figure 2.20), which could be partially explained by the tillering process and the lack of a precise ability to differentiate the main plant from the tillers. Imagery data was also collected in parallel to the ground measurements to test a process for automatic gap identification. The software and imagery are still being processed with the goal of identifying and developing a method for rapid gap identification via sUAS imagery, the main point on the gap analysis was to better understand the pattern of gap occurrence (Figure 2.21) under both planting systems. For each planting system, imagery from all replications was combined to understand if the gaps were always placed at the same geo-spatial position within the plot. From the evaluation, it can be concluded that the gaps were randomly allocated within the plots without identifying any consistent pattern that could be connected with the performance of the machinery. For the first season, imagery data was collected right before winter, resulting very hard to identify and differentiate individual plants to quantify the true gap between plants within the row line. Conventional (Drill) and singulation did not have any statistical difference in the number of gaps. When evaluating at the planting systems within the singulation (Figure 2.20), the "4rh" was the one with the lower number of gaps for WB Cedar variety and the "8rh" presented the higher number of gaps for the low tillering WB4458. The results from the first season assisted the planter company to take informed decisions in preparation of the second year for this research project.

For the second year of the study, all treatments were evaluated across locations. Methods of observations were increased as well; implementation of the RTK equipment capturing gps coordinates and flights at lower canopy height improved overall precision in capturing plant gaps. Results from the measurements collected with the RTK, are shown after a correlation against the ground truthing data showed a satisfactory relationship (R^2 = 0.71 Figure 2.16) correlation that allow us to validate the RTK data. Conventional system at Ashland presented an average of five gaps per row, with greater number of gaps for WB Cedar relative to WB 4458 (Figure 2.21C). For the second year of the study, modifications for the singulation technology established three main systems herein termed as: “4 Offset”; “8 Offset” and “CM”. Similar number of gaps for both varieties, with slightly more for the high tillering variety (Figure 2.24) and the low tillering variety with the “8 Offset” demonstrating better efficiency for these systems. The “CM” system presented more gaps when compared to the other singulation options. The imagery collected for this year is presented in Figure 2.24 where the RTK points were placed in the picture, as for the imagery analysis, the most constraining factor is related to the step of identifying each row within the picture since the plants were at the early growth stages. Next steps for this method are to automatize the “row-identification” method to improve plant versus soil segmentation and speed up the gap identification process.

Conclusions

The objective of this study was to understand how the new technology affects early wheat establishment at varying seeding rates and contrasting genotypes. Out of the four site years analyzed, none responded to the new technology. Although differences for seeding rate and genotype were observed, dynamics of emergence presented an expected trend for seeding rate, with more number of emerged plants as the seeding rate increases. Stand count presented the closest number of plants when compared with the targeted seeding rate for Topeka 2015-16. For the gap measurement, first year of results showed more number of gaps in the low tillering variety, affected due to the timing of sampling for this variable. In the second year, better timing (earlier in the season, right close to emergence) and more accurate data collection permitted to obtain a lower number of gaps for the low tillering variety WB 4458 relative to the WB Cedar across the locations and treatments evaluated in this study. Further testing on imagery analysis and computer vision will assist on improving early-gap identification in a faster and more precise approach.

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Figures

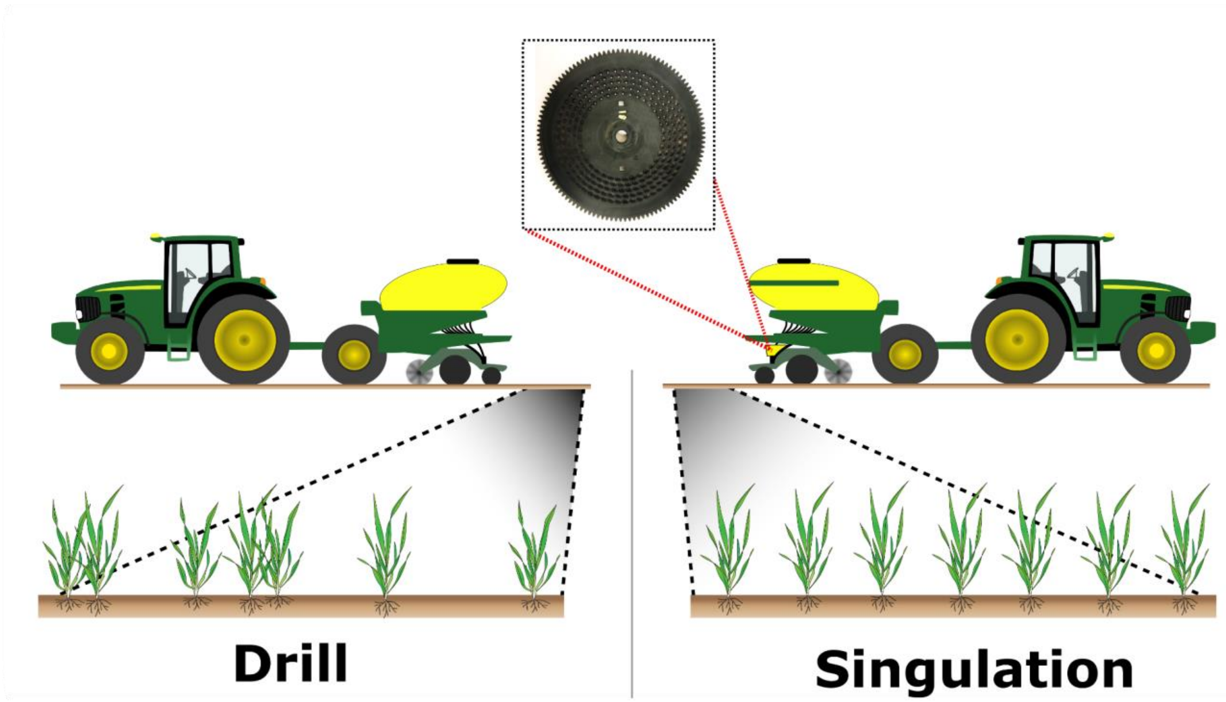


Figure 2.1 Description of systems on plant uniformity.

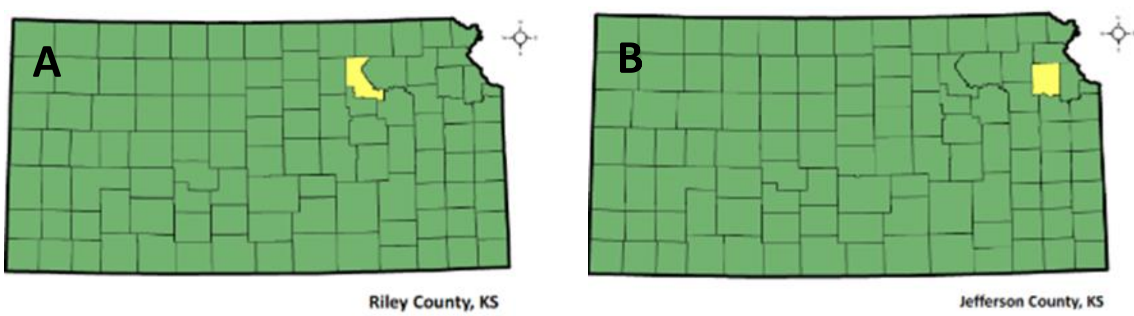


Figure 2.2 Locations (A) Ashland and (B) Topeka at Kansas.

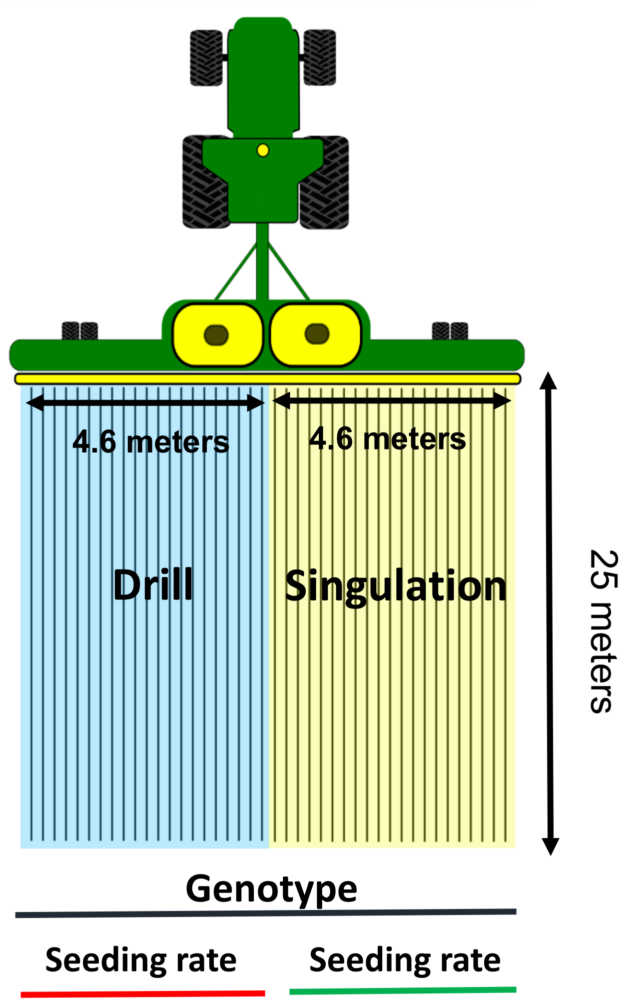


Figure 2.3 Planter set up, experimental design.

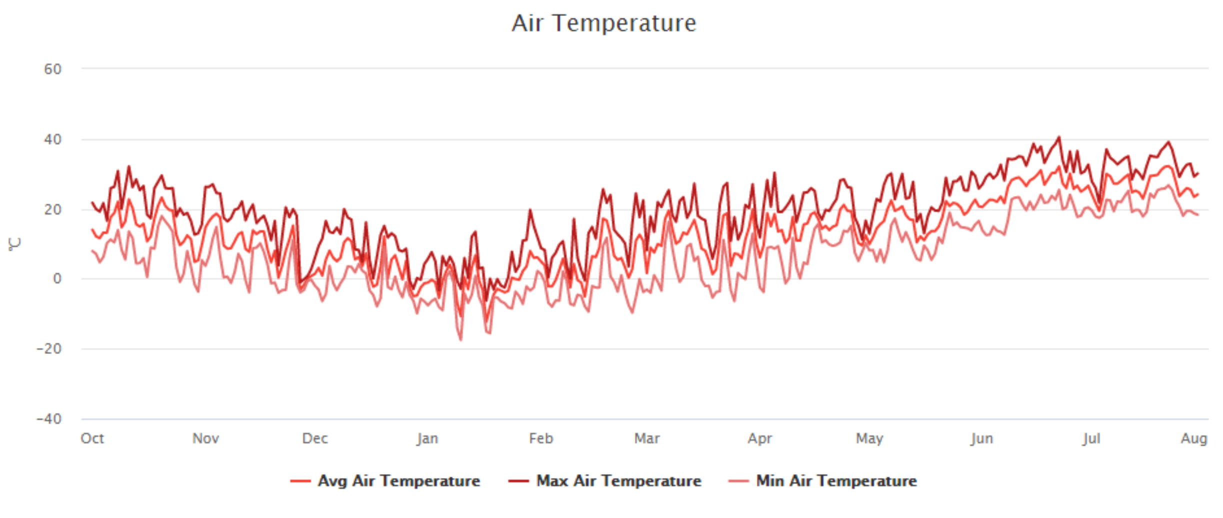


Figure 2.4 Ashland temperature Season 2015-16, Mesonet.

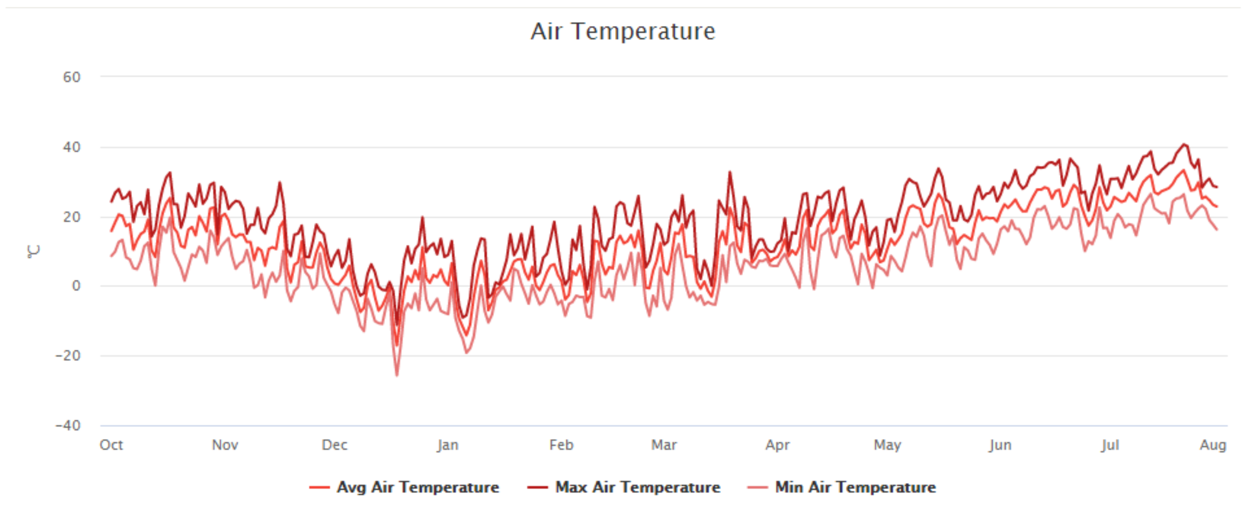


Figure 2.5 Ashland temperature Season 2016-17, Mesonet.

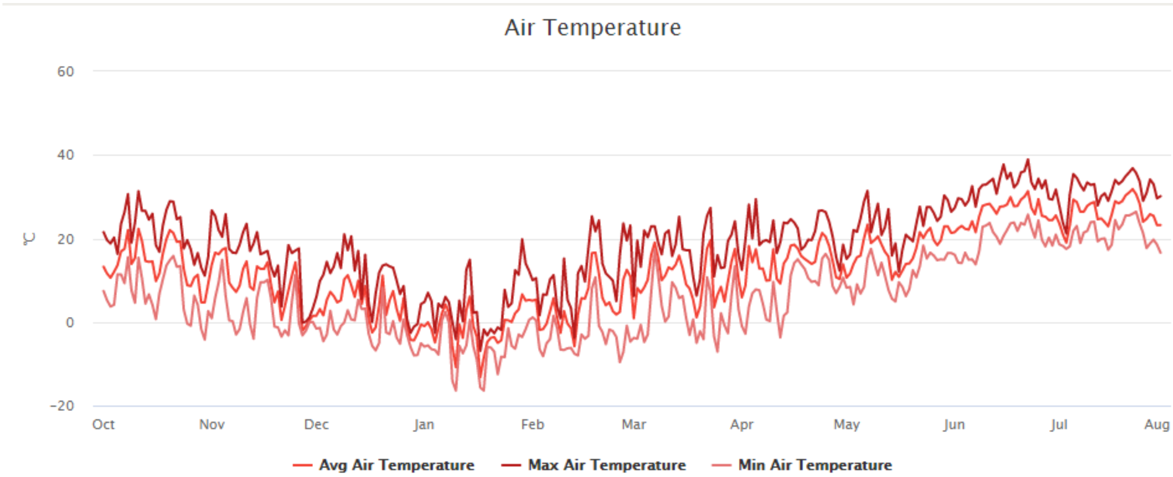


Figure 2.6 Topeka temperature season 2015-16, Mesonet.

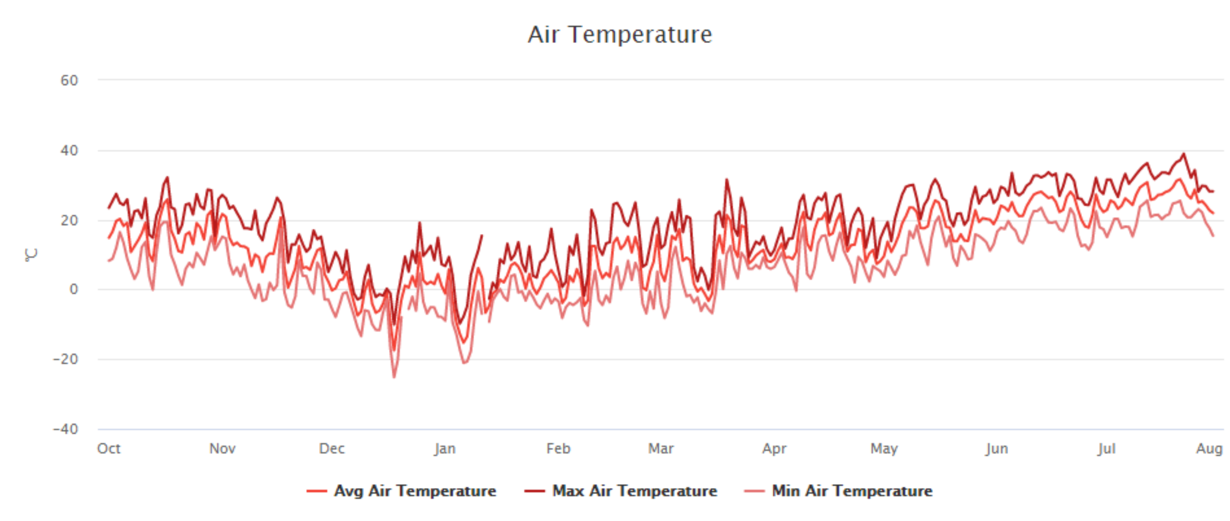


Figure 2.7 Topeka temperature season 2016-17, Mesonet.

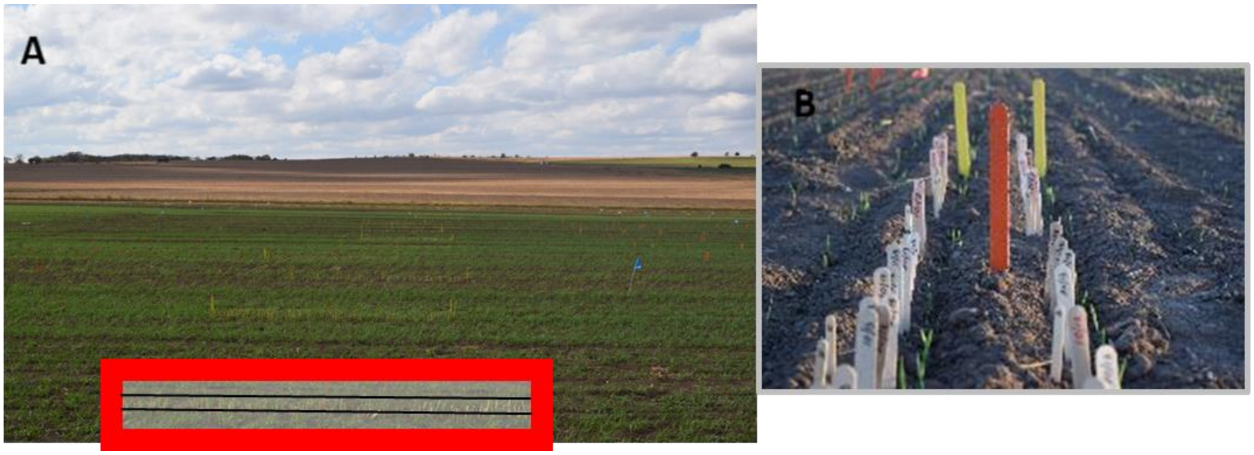


Figure 2.8(A) General view of the study area with inset indicating the two linear rows where the measurements were performed; and (B) representation of the two selected rows from one plot with the sticks keeping track of the day of emergence.

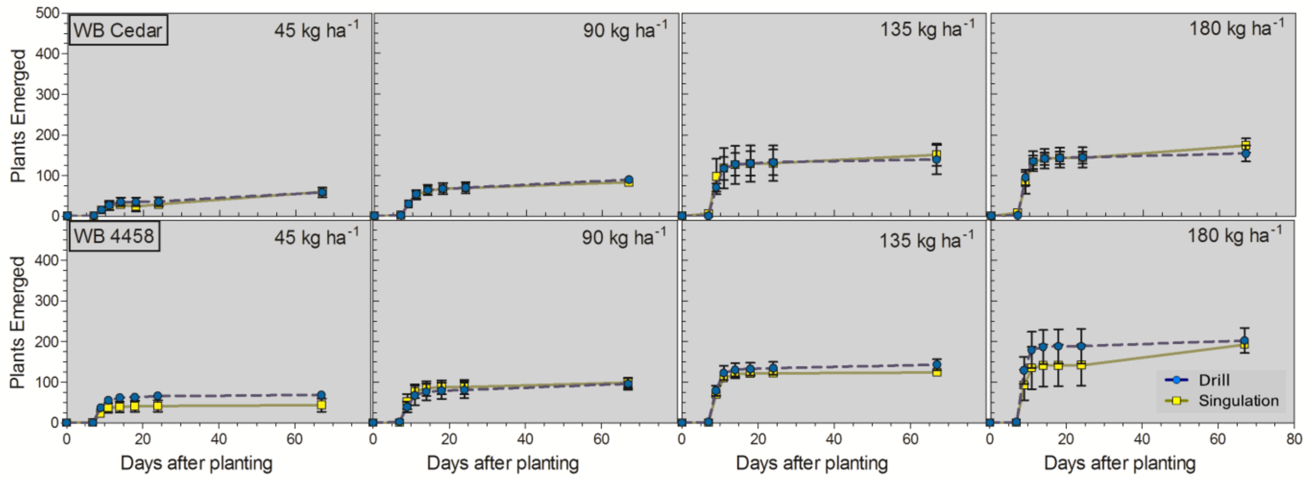


Figure 2.9 Dynamics of plant emergence, plants per 2.4 square meter, for Ashland for 80 days after sowing. Season 2015-16.

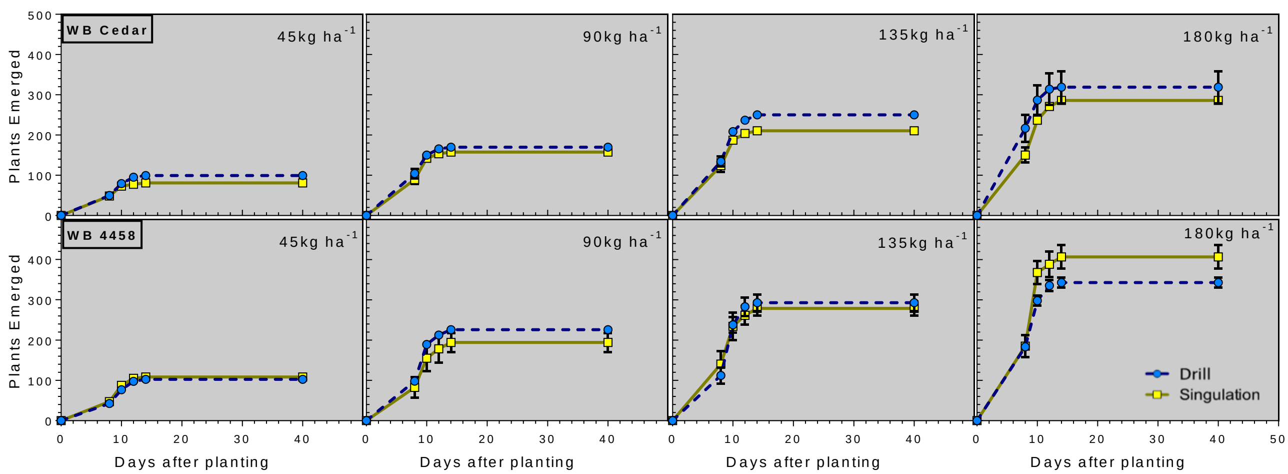


Figure 2.10 Dynamics of plant emergence, plants per 2.4 square meter, for Ashalnd for 50 days after sowing. Season 2016-17.

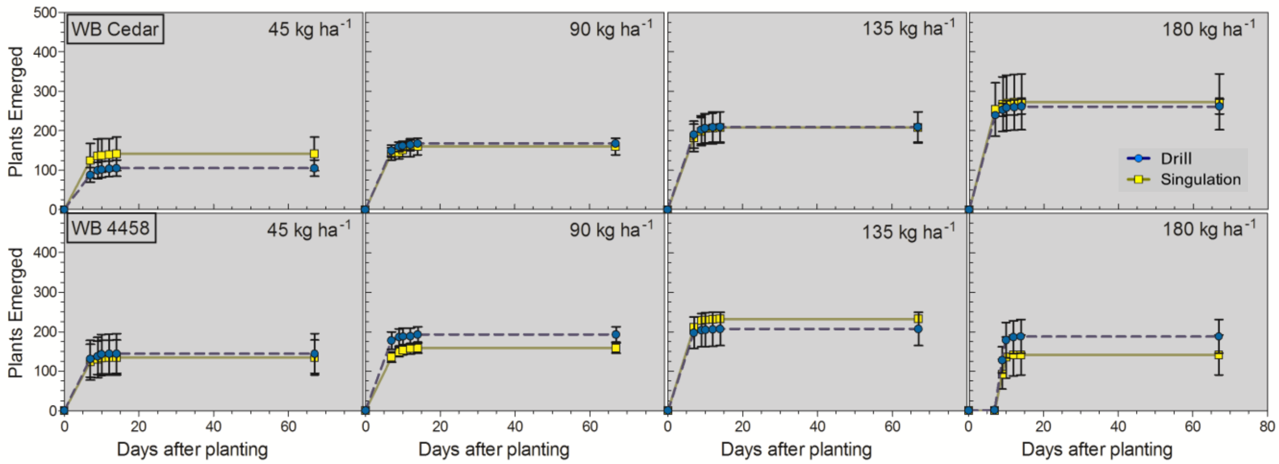


Figure 2.11 Dynamics of plant emergence, plants per 2.4 square meter for Topeka for 80 days after sowing. Season 2015-16.

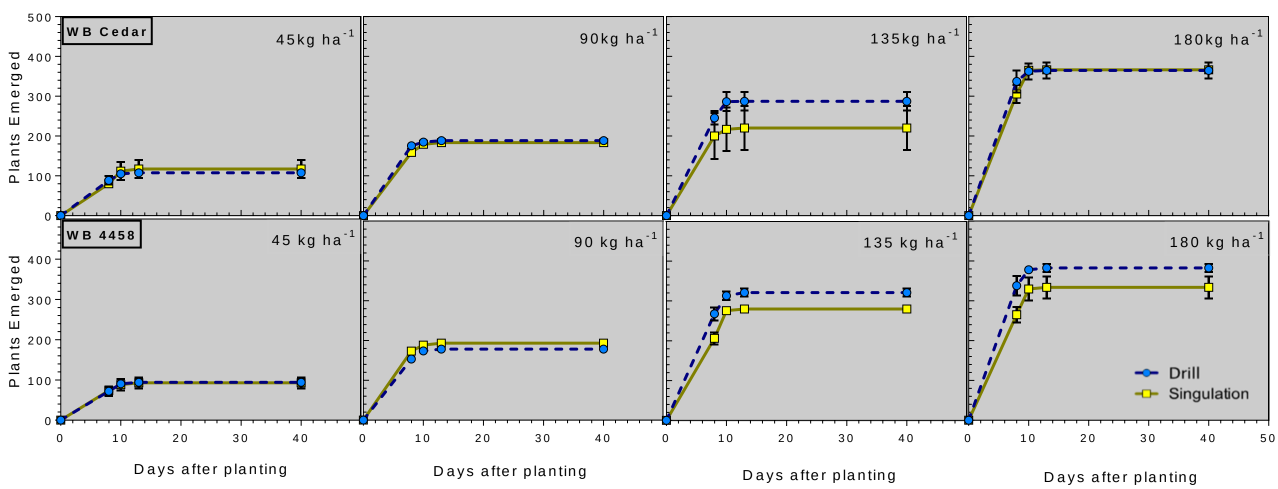


Figure 2.12 Dynamics of plant emergence, plants per 2.4 square meter, for Topeka for 50 days after sowing. Season 2016-17.

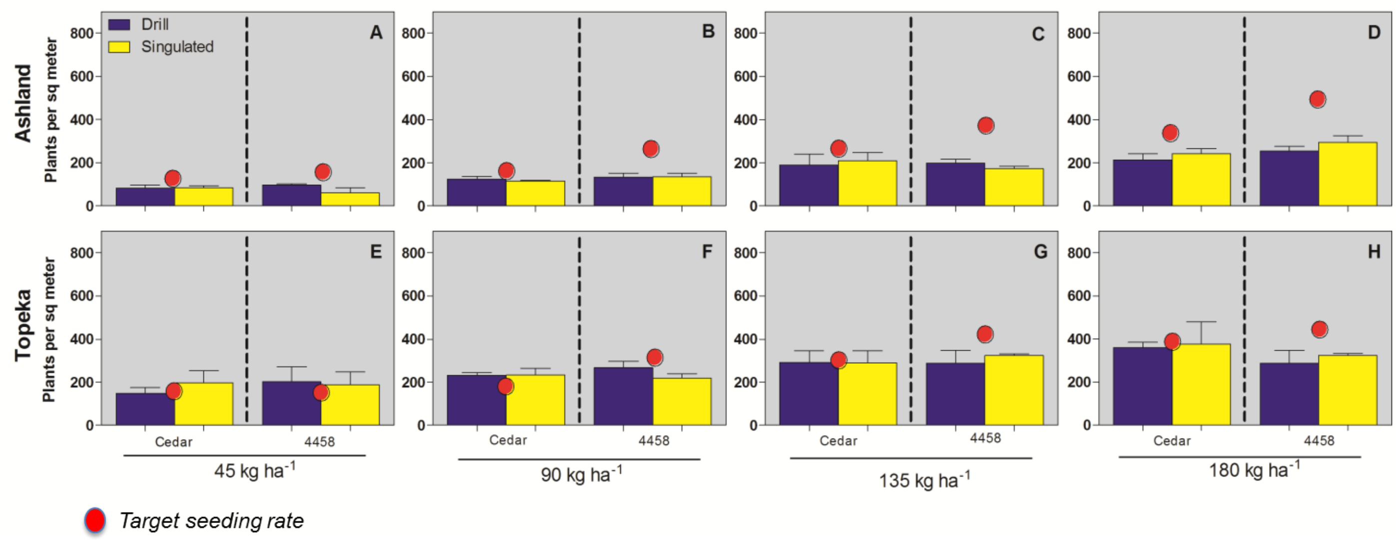
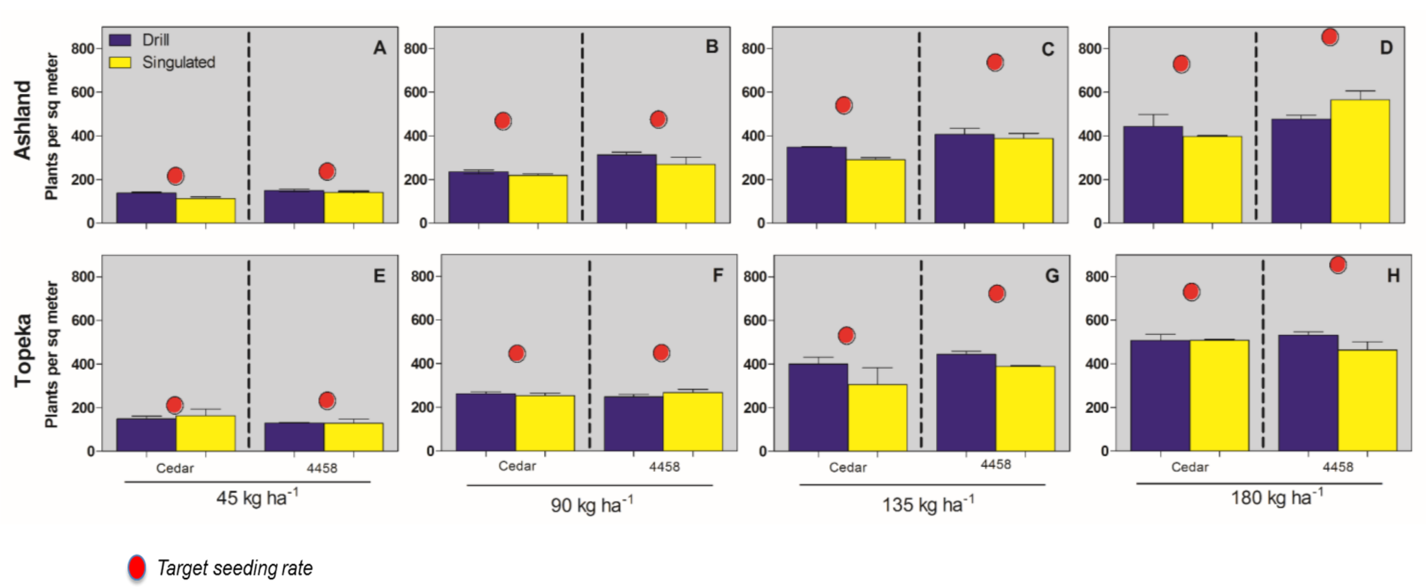


Figure 2.13 Stand count 2015-16 for Ashland and Topeka.



Target Seeding Rate. Plants per sq meter - based on 9 meters counting		
Seeding rate	**WB Cedar (HT)**	**WB 4458 (LT)**
45 kg ha^{-1}	236	261
90 kg ha^{-1}	489	494
135 kg ha^{-1}	555	733
180 kg ha^{-1}	739	913

Figure 2.14 Stand count 2016-17 for Ashland and Topeka.

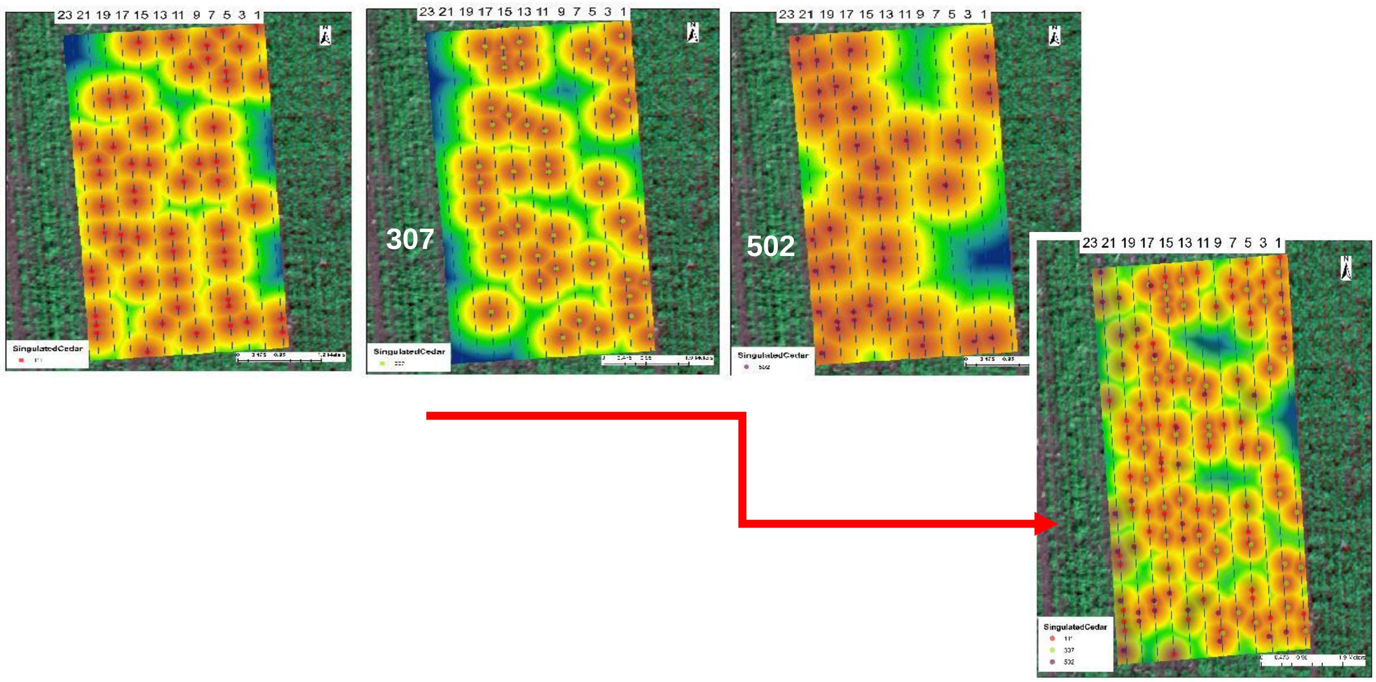


Figure 2.15 Gaps placement in the imagery, treatment: Cedar; Singulated; 80lbs. Three repetitions, then combined, Ashland 2015/2016.

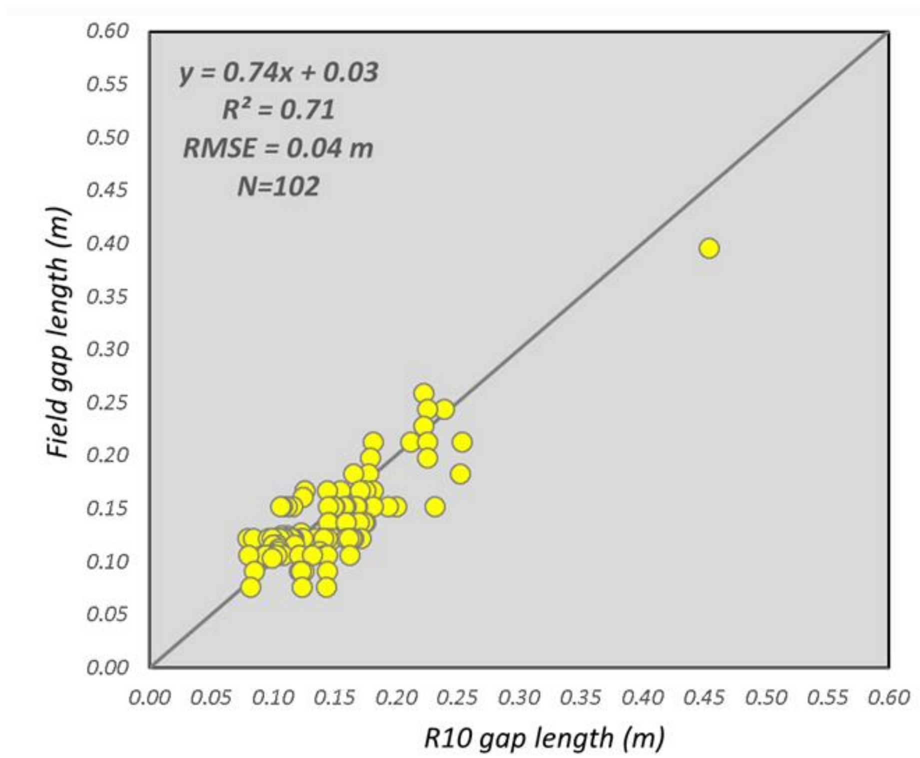


Figure 2.16 Correlation between field gaps (ground truth) vs RTK (R10) data.

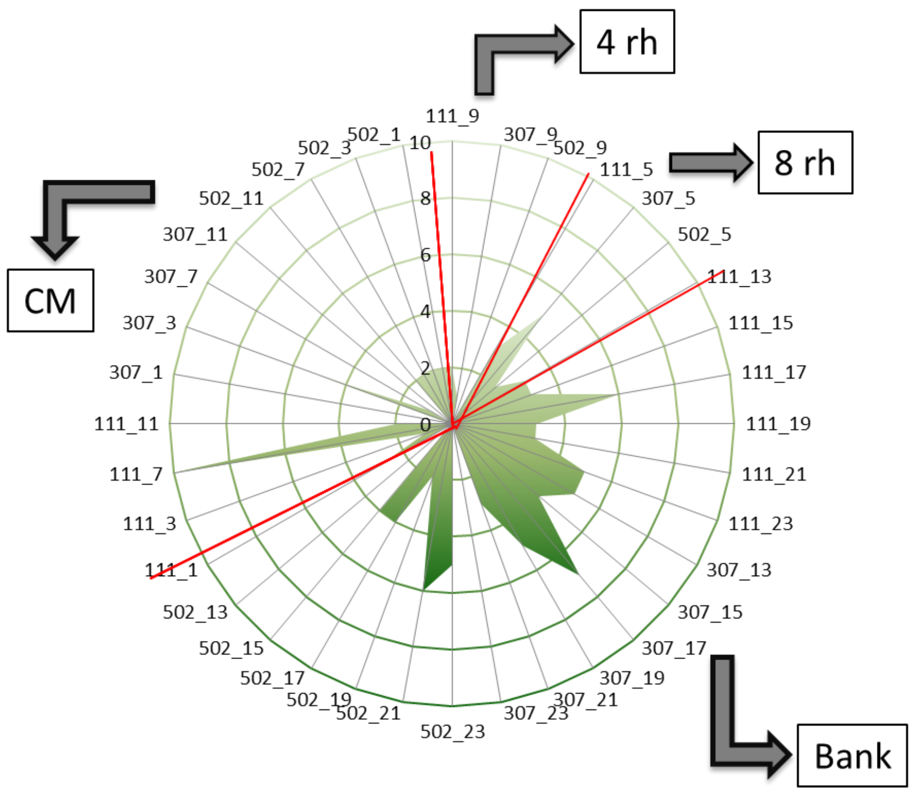


Figure 2.17 In row gap count for Ashland 2015-16, comparing different systems within singulation for WB Cedar. Numbers around the graph mean the plot and row number.

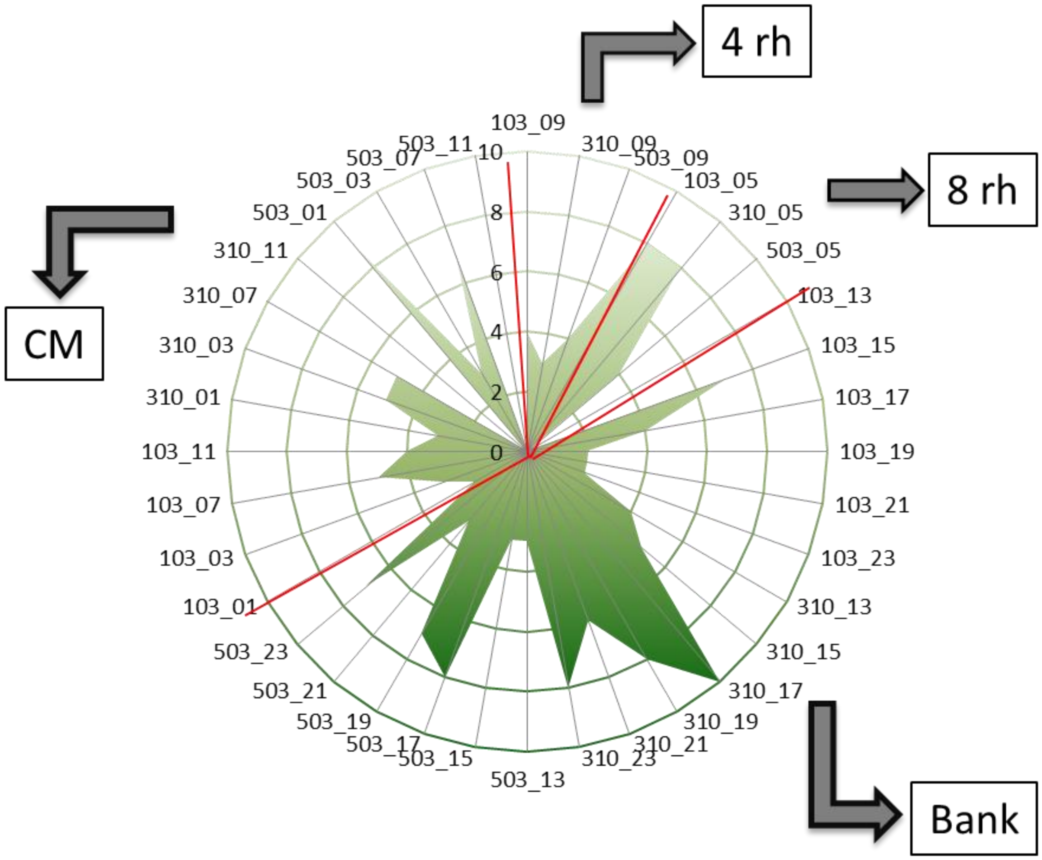


Figure 2.18 In row gap count for Ashland 2015-16 comparing different systems within singulation for WB 4458. Numbers around the graph mean the plot and row number.

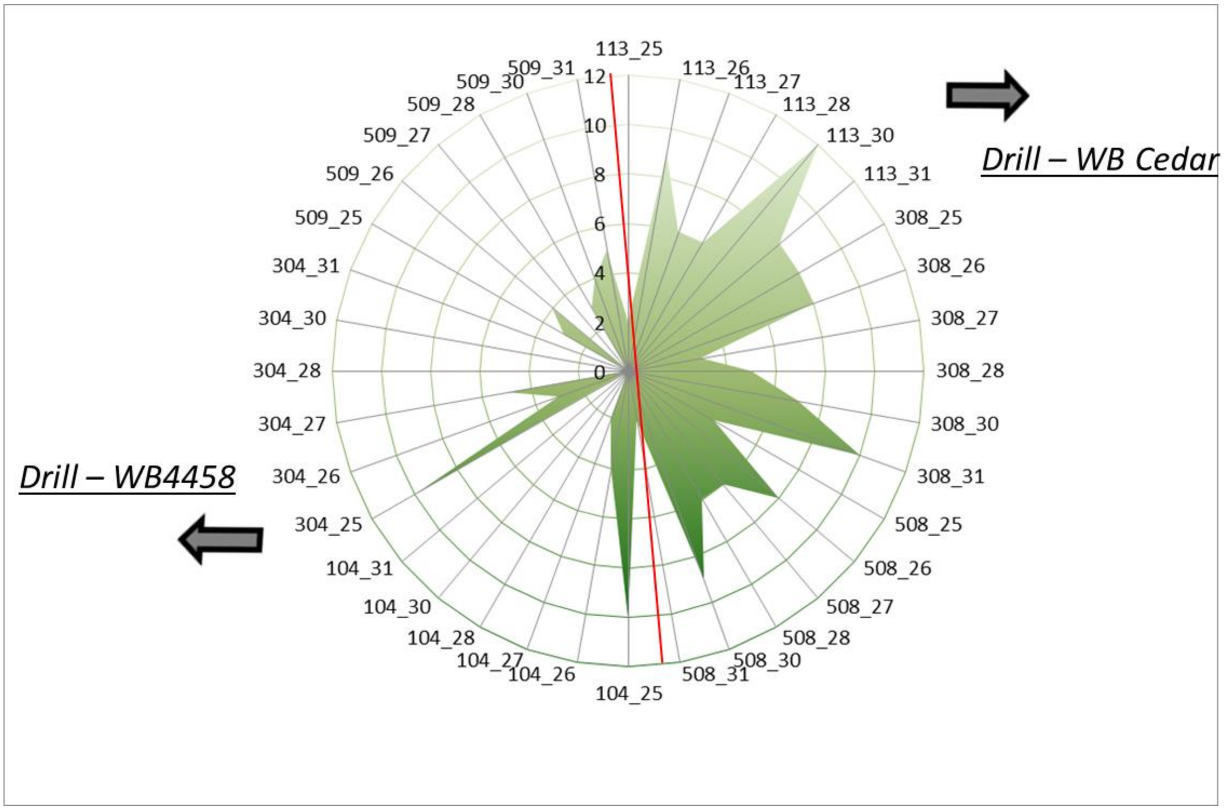


Figure 2.19 In row gap count for Ashland 2015-16, comparing drill system for both genotypes. Numbers around the graph mean the plot and row number.

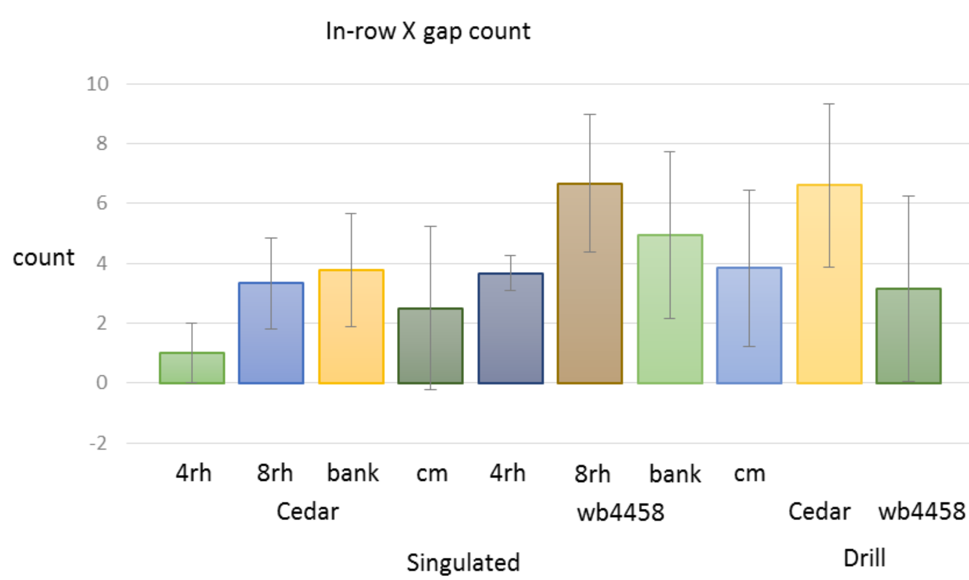


Figure 2.20 Count of gaps for each system within the singulation technology and drill, Ashland 2015-16. Numbers around the graph mean the plot and row number.

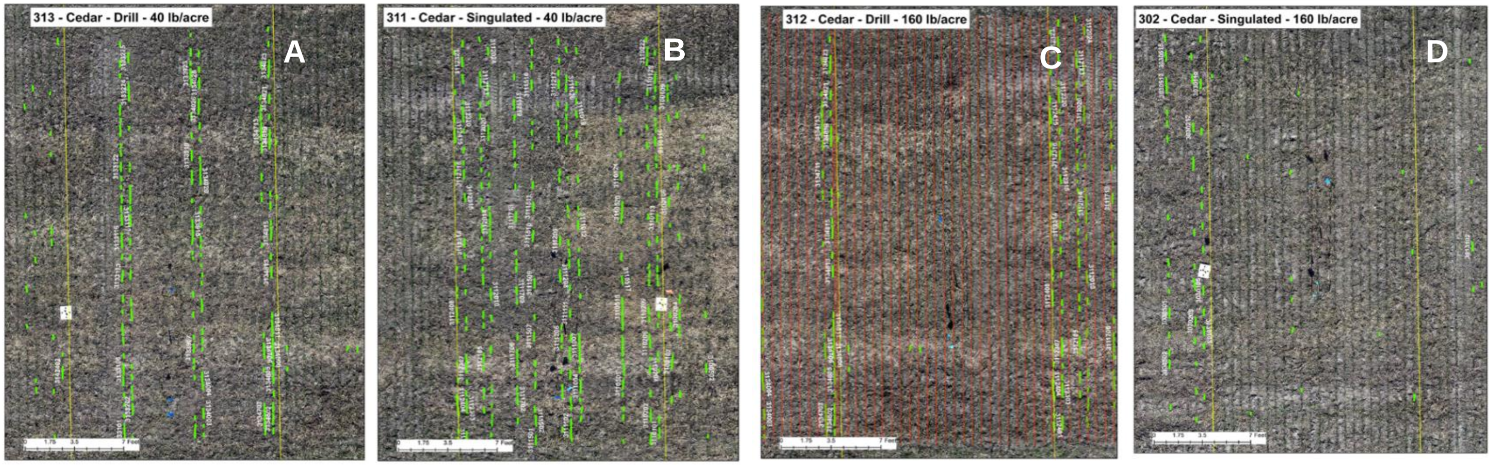


Figure 2.21 Imagery from Ashland placing the RTK gaps for four contrasting treatments: Cedar (A) Drill 45 kg ha^{-1};(B) Singulated 45 kg ha^{-1}; (C) Drill 180 kg ha^{-1} and (D) Singulated 180 kg ha^{-1} . 2017

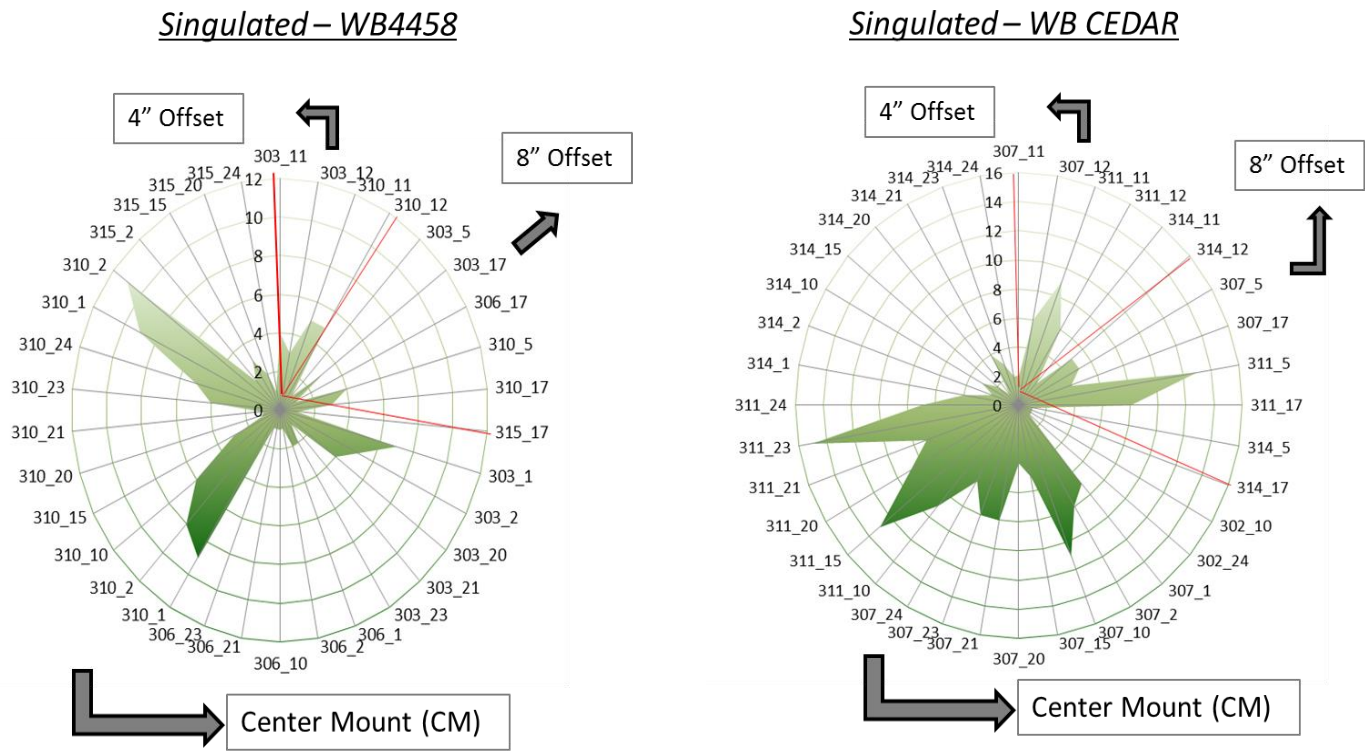


Figure 2.22 In row gap count for Ashland 2016-17 comparing different systems within singulation for WB 4458 and WB Cedar. Numbers around the graph mean the plot and row number.

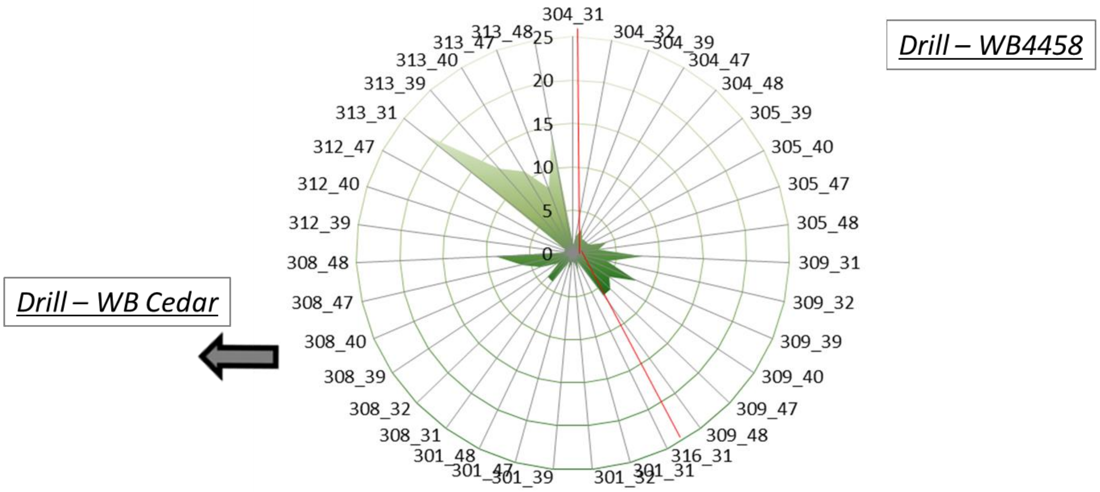


Figure 2.23 In row gap count for Ashland, comparing different systems within singulation and drill for both genotypes, 2016/2017. Numbers around the graph mean the plot and row number.

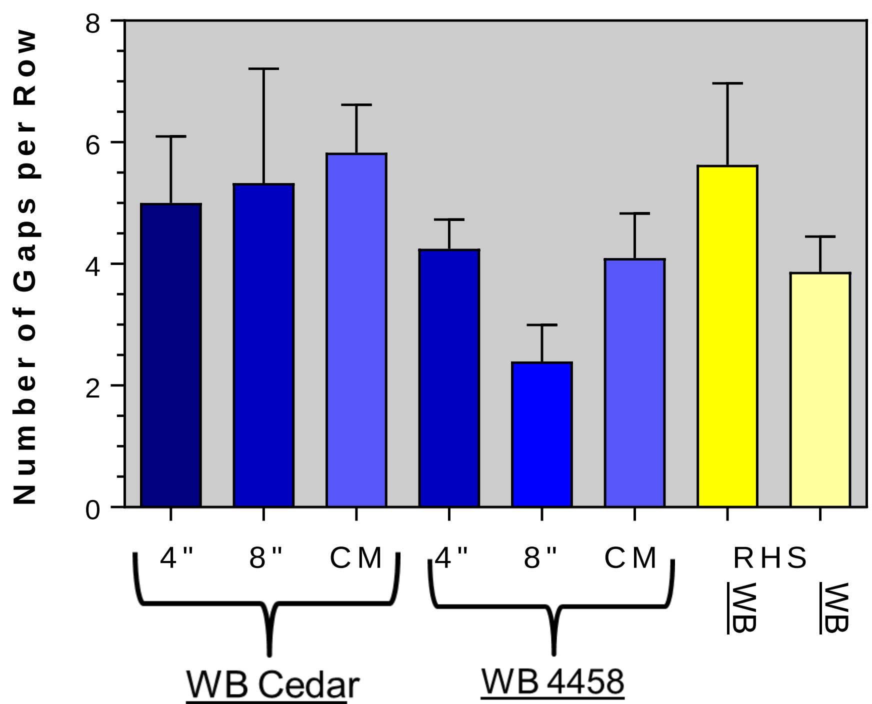


Figure 2.24 Count of gaps for each system within the singulation technology and drill, Ashland 2016/2017.

Tables

Table 2.1 Description of the factors of the experiment for location, genotype, planting system and seeding rate used.

Location	Genotype	Planting system	Seeding rate (kg ha^{-1})
Ashland (dryland, till)	WB4458 (low tillering)	Drilled	45
Topeka (irrigated, no-till)	Cedar (high tillering)	Singulated	90
			135
			180

Table 2.2 Sowing and harvesting dates for Ashland and Topeka during the 2015-16 and 2016-17 growing seasons.

	Ashland		Topeka	
Growing season	**Planting**	**Harvest**	**Planting**	**Harvest**
2015-2016	October 5	June 20	October 15	June 22
2016-2017	October 21	June 20	October 25	June 21

Table 2.3 Seed weight for both genotypes and the two years of the study.

	Seed Weight (100 seed weight)	
Genotype	**2015/2016**	**2016/2017**
WB Cedar (High tillering)	40 grams	45 grams
WB 4458 (Low tillering)	38 grams	35 grams

Table 2.4. Monthly rainfall for all site years.

	Location			
Month	**Ashland**		**Topeka**	
	2015-16	**2016-17**	**2015-16**	**2016-17**
	Precipitation (mm)			
October	0.49	2.26	0.63	0.94
November	3.68	0.25	2.99	0.19
December	2.67	0.68	1.86	0.66
January	0.40	0.80	0.60	0.93
February	0.35	0.42	0.46	0.29
March	0.36	3.44	0.84	0.79
April	7.15	4.22	5.39	3.07
May	5.71	3.12	4.59	4.51
June	1.31	2.38	2.31	4.58
July	4.85	1.08	3.58	2.09

Table 2.5 Total number of plants Ashland.

2016	
Source of variation	**P-value**
Genotype	0.3501
System	0.7579
Seeding rate	<0.001***
Genotype x System	0.2438
Genotype x Seeding rate	0.2925
System x Seeding rate	0.9254
Genotype x System x Seeding rate	0.8090

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

2017	
Source of variation	**P-value**
Genotype	<0.001***
System	0.25330
Seeding rate	<0.001***
Genotype x System	0.06816
Genotype x Seeding rate	0.07324
System x Seeding rate	0.22393
Genotype x System x Seeding rate	0.07035

Table 2.6 Plants per square feet Ashland.

2016	
Source of variation	**P-value**
Genotype	0.3603
System	0.1035
Seeding rate	0.3817
Genotype x System	0.6983
Genotype x Seeding rate	0.3366
System x Seeding rate	0.1313
Genotype x System x Seeding rate	0.6856

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

2017	
Source of variation	**P-value**
Genotype	<0.001***
System	0.28623
Seeding rate	<0.001***
Genotype x System	0.05294
Genotype x Seeding rate	0.05304
System x Seeding rate	0.21029
Genotype x System x Seeding rate	0.08632

Table 2.7 Total number of plants Topeka

2016	
Source of variation	**P-value**
Genotype	0.5612
System	0.8901
Seeding rate	<0.001***
Genotype x System	0.5871
Genotype x Seeding rate	0.9970
System x Seeding rate	0.9268
Genotype x System x Seeding rate	0.8889

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

2017	
Source of variation	**P-value**
Genotype	0.61172
System	0.07957
Seeding rate	<0.001***
Genotype x System	0.84778
Genotype x Seeding rate	0.09106
System x Seeding rate	0.10588
Genotype x System x Seeding rate	0.49073

Table 2.8 Plants per square feet Topeka

2016	
Source of variation	**P-value**
Genotype	0.5396
System	0.9084
Seeding rate	<0.001***
Genotype x System	0.5652
Genotype x Seeding rate	0.9922
System x Seeding rate	0.9095
Genotype x System x Seeding rate	0.8975

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

2017	
Source of variation	**P-value**
Genotype	0.58513
System	0.08801
Seeding rate	<0.001***
Genotype x System	0.89144
Genotype x Seeding rate	0.07512
System x Seeding rate	0.11150
Genotype x System x Seeding rate	0.57969

Chapter 3 - Genotype by Seeding Rate Interaction in Wheat Evaluation of Planting Systems – *Yield components*

Abstract

Genotype by seeding rate interaction can play a critical role wheat (*Triticum aestivum* L.) yield potential. The objective of this study was to quantify wheat yield response to the planting technology under diverse seeding rates and varieties with contrasting tillering ability. Four studies were established at two locations for two growing seasons (2015-16 and 2016-17): at Ashland Bottoms (dryland and conventional till in the first year and no-till in the second year) and at Topeka (irrigated and no-tillage for both years) field research stations (KS, US). The two winter wheat varieties (WB Cedar, high tillering and WB 4458, low tillering) were planted with two different planting systems (singulated and conventional drill) at four different seeding rates (45, 90, 135, and 180 kg ha^{-1}). Measurements consisted of stand counts, canopy coverage (estimated via imagery collection by sUAVS), determination of early-season gaps in the final stand, spacing between plants, plant growth (biomass), final yield and its components. Early season measurements and biomass did not present differences among treatments. At Ashland, across 2-yrs, single factors seeding rate and genotype significantly impacted yields. Seeding rate factor positively affected yields, ranging from 4.7 to 5.4 Mg ha^{-1} with seeding rates going from 45 to 135 kg ha^{-1}, respectively. For the genotype factor, the variety WB Cedar (high-tillering) presented an overall yield improvement of 605 kg ha^{-1} relative to WB 4458 (low-tillering). Across locations, the seeding system did not influence yields for both years of the study. At Topeka, the seeding system significantly influenced yields in 2017, with singulation outyielding the drill system, with a yield gain of 161 kg ha^{-1}. Further research is needed at a farmer-scale to better understand this new technology.

Introduction

Wheat (*Triticum aestivum* L.*)* is an important cereal crop around the world, domesticated eight thousand years ago (FAO, 2012). As for land use, more than 230 million of hectares were planted worldwide in 2013-2014 season, with a production of 730 million tons (FAO, 2017). The US plays a major role as the fifth producer, with more than 18 million of hectares planted and a production of 55 million tons (FAO, 2017). A largest portion of the US wheat production comes from the Great Plains and Northwest regions, including the following states: Kansas, North Dakota, Montana, Washington, Oklahoma, South Dakota, and Colorado. Winter wheat accounts for 70% to 80% of the total US wheat production (USDA, 2017). The state of Kansas stands out as the largest winter wheat producer with, planted 3.5 million hectares to winter wheat in 2015-2016, with a total production of 13 million tons (USDA, 2017).

Final wheat productivity is affected by the outcome of the complex interaction between genotype (G), environment (E), and management practices (E). Genotype by environment (GE) interaction is broadly evaluated, with the environment playing a major role in defining wheat quality characteristics (Johnson et al., 1972; Faridi and Finley, 1989), such as yield. Nonetheless, still scarce information is available on wheat yield response to management practices.

The use of new technologies in wheat production is very important to increase the yield potential (herein defined as the maximum yield attained in each environment). Every year, many studies are performed testing commercial varieties, fungicide application, development of new and genetic modify varieties with desirable traits to increase yield in wheat. From a technology standpoint, new research on the machinery side trying to better understand plant establishment and uniformity and how this affects final yield is needed. Following this rationale, development of a planter singulating, seed by seed, with equal distance and controlled seeding rate can be very important for lowering seeding rates, maintaining yields but reducing production costs via seed savings.

Seeding rate and tillering capability (wheat varieties) play a critical role on understanding this new technology, herein termed as singulation. The genotype capability of tillering affects the new technology in two ways: First varieties different seed size helping to understand the precision of the singulation. The second factor of using contrasting genotypes is related to the tillering capability, when in a non-uniform field theoretically the high-tillering genotype will adapt and compensate better than the low-tillering variety. High-tillering wheat varieties will be more dependent on the seeding rate as each plant contributes to a single head (grains per plant) to the final yield at the unit area-scale.

Research Question and Justification

Conventional seeding systems have demonstrated the need for continued improvement in wheat uniformity and plant spacing. Better planter technologies can improve uniformity and allow for a potential reduction in seeding rate (seed savings).

The objective of this project was to quantify wheat yield response to the planting technology under diverse seeding rates and contrasting genotypes (primarily related to their tillering ability, low- vs. high-tillering).

Hypothesis

Singulation system improves plant uniformity and, consequently, yields in wheat.

Material and Methods

Locations and Soils

The study was conducted over two growing seasons (2015-16 and 2016-17) at two locations in the state of Kansas. The first site was situated at Ashland Bottoms (39º 07' 34" N, 96º 38' 08" W) in a Wymore silty clay soil loam (fine, smectitic, mesic Aquertic Argiudolls). The trial was established under conventional tillage practices in 2015-16 and under no tillage in 2016-17 following soybean (*Glycine max* L.) in both growing seasons. Soil test prior to sowing for the entire area in both locations consisted of fifteen samples with ten cores each. Ashland 2015 presented an average soil pH of 6.3, initial Mehlich-3 soil phosphorus (P) of 11.2 ppm, with some areas presenting values around 7 ppm close to the threshold recommended by Kansas State University (Leikam et al., 2003), and potassium (K) of 250 ppm. The second site was located in Topeka (39º 04' 35" N, 95º 46' 04" W), east central Kansas, in a Eudora silt loam and sandy loam (coarse-silty, mixed, superactive, mesic Fluventic Hapludolls). The trial in this location was conducted under fully irrigated conditions also following soybeans. The trial area has been under no tillage practices for the past two years. The soil at Topeka presented an initial value of soil pH of 7 (Table 1), Mehlich-3 P of 40 ppm, and an average K of 155 ppm.

Experimental Design

At both locations, the experimental design consisted of a split-split plot design with two main factors, two sub-factors, and four sub-sub-factors for a total of sixteen treatments and five replications (80 experimental units total). The main plot was genotype and consisted of two levels: WB 4458, a genotype with low tillering ability; and WB-Cedar, a genotype with high tillering capacity. The sub-plot was planting system and also consisted of two levels: conventional gravity-induced drill, versus seed singulation. Sub-sub-plot was seeding rate and consisted of four different levels: 45; 90; 135; 180 kg ha^{-1} (Table 2.2). In order to test the sub-factor planting system at comparable seeding depths and speeds for the two different strategies, a drill-planter combination was developed by John Deere specifically for this study. The equipment consisted of 24 rows spaced 19 cm apart in one side of the tractor which performed conventional gravitational drilling of wheat seeds; while the remaining 24 rows in the opposite side of the tractor performed seed singulation similar to a row-crop planter. Due to the nature of the equipment used, two factors could not be randomized in the field (i.e., genotype and planting system), while seeding rate was randomized within the genotype by planting system combination. Plots were 25 m long and 4.6 m wide, with a 19 cm row spacing.

Management Practices

All plots were planted using a John Deere planter, in which half of the rows (4.5-m) was conventional drill and the other half (4.5-m) was seed singulation, as detailed above. Planting dates are shown in Table 3. During the 2015-16 growing season, 56 kg of N ha^{-1} was applied prior to planting as urea and ammonium nitrate (UAN, 30-0-0) to ensure N was not limiting for fall growth, and an additional 56 kg of N ha^{-1} was applied in the spring at Feekes GS 3 in order to avoid any nutrient limitation for yield production. Nitrogen fertilization followed Kansas State University recommendations for a yield goal of 4 Mg ha^{-1}. At both locations, weeds were controlled using commercialized herbicide, and a complete control was achieved so these were not limiting factors.

Similarly, at Topeka during the 2015-16 growing season, the entire experiment was treated with a foliar fungicide around Feekes GS 9, due the presence of good conditions for the development of head scab. Plots were harvested with a John Deere 3300 small plot combine, for each plot we harvested the entire length (24.4 meters) and 3 central meters, since the head of our combine consisted of 1.5 meters two passes was done in each plot. For yield calculation the grain moisture was corrected to 13.5%.

Vegetative Evaluations

Aboveground biomass, leaf area index (LAI), and light interception were measured four times during the growing season, after winter dormancy. In the begging of the season three subplots, consisting of two rows and 2.5 linear meter, were selected in each plot in where, among another measurements, biomass were collected. At physiological maturity biomass was fractioned between shoot and spike to better understand distribution of nutrients and resources within the plant. Aboveground biomass was obtained from a 2.5 linear meter, samples were oven-dried for seven days at 60 ^{o}C. For the last biomass sampling, the reproductive partitioning efficiency was estimated as the total biomass ratio. Leaf area index was measured using a handheld LAI-2200C sensor as well as a traditional destructive LAI meter model LI-3100 (LI-COR Biosciences Inc., Lincon, NE). For the LAI-2200C, non-destructive measurements were taken in the field and consisted of four readings between rows in each plot (above/below canopy readings). The traditional destructive LAI measurements were performed using the same samples used for aboveground biomass collected to determine dry weight and progression of plant growth. Leaves were counted and fed individually through the sensor, which provided the leaf area, measured in square cm for each individual leaf. The LAI was then calculated using the ratio of leaf area by the corresponding soil area from which the samples were collected. Light interception was measured using a LI-COR Light Quantum Sensor (model LI 191, LI-COR Biosciences Inc., Lincon, NE) and final light interception was a result of three readings per plot. Final aboveground biomass was measured from two rows, 2.5 linear meters clipped at maturity. This sample was also used to calculate the reproductive partitioning efficiency (RPE), obtained as the ratio of head biomass to the whole plant biomass.

Statistical Analyses

Statistical analyses to test differences for main factors and interaction was performed using R software (R Development, 2009). Data was evaluated for homogeneity of variance and normality. Effects of seeding system, genotype, and plant density on biomass, yield and reproductive partitioning efficiency (RPE) were evaluated with analyses of variance (ANOVA) for a randomized complete block design with a split-split plot arrangement of treatments using the "nlme" (Pinheiro et al., 2017) package of R (R Core Team, 2017). For each site-year combination, system (main plot), genotype (split plot), and plant density (split-split plot) were fixed variables; block (n = 4) was the random variable. Each main effect (system, genotype and plant density) and subsequent interactions were nested within blocks. Homoscedastic and heteroscedastic models were compared using Likelihood Ratio Test (LRT) and normality of the residuals was tested using Shapiro-Wilk test. Least squares means were calculated through "lsmeans" (Lenth, 2016) package and separated using Tukey's HSD test from "multicomp" (Hothorn et al., 2008) R package. Fitted models for relationship between yield and seeding rate were tested for each individual year at each location, and to determine whether one model was adequate to fit all the data (GraphPad Prism 5; Motulsky and Christopoulos, 2003).

Results and Discussion

Weather conditions

The weather condition for growing wheat in Kansas was good relative to historical weather conditions for the state. Across all site-years, only in one growing season a spring freeze was observed at one location, Topeka 2015-16 season. This affected the experiment in general, but particularly the development of small spikes– presenting low RPI values - when comparing to Ashland location for the same year. In overall, a 2 Mg ha^{-1} yield advantage was documented for Ashland relative to Topeka location (Table 3.18). This result could partially be a consequence of this freeze event at Topeka that uniformly affected the experiment, and possibly reflected as a lack of statistical differences for many of the variables evaluated in this study.

Early season weather presented impacted Ashland location during the first growing season 2015-16, as there were no precipitation events within the two-week period immediately after planting. The latter situation has a relatively small influence on plant establishment, portraying the resiliency of wheat as this environmental stressor (without presenting any carryover effect on final yields). For year one, 2015-16, plant establishment at Topeka location was not influenced by soil moisture conditions due to the irrigation practices implemented early season to help the crop and produce uniform emergence and early growth.

Aboveground biomass

Aboveground biomass for Ashland portrayed a greater biomass accumulation for the singulation relative to the drill scenario (Figure 3.1), but without presenting a statistical difference between seeding systems in both years of evaluation (Table 3.4). The only statistical difference ($p<0.05$) for the first year of the study was documented in the genotype x seeding rate interaction. In overall, the first year of this study at Ashland presented challenges related to early-season weather conditions (lack of rain), variability related to the study site, and lastly connected to the evaluation of the technology (first test year with few missing and doubled rows) resulting in canopy variations across the experiment that precluded detection of significant effect of the technology or other evaluated factors on wheat yields.

The RPE did not show a statistical difference across all evaluated factors for both growing seasons, except for the genotype factor in 2016-17 growing season. In overall, RPE ranged from 50 to 65% (Table 3.7), with an overall value close to 55%, but without presenting clear trends for the factors evaluated in this study.

Aboveground biomass for Topeka portrayed a greater accumulation for singulation relative to the drill scenario, but without presenting a statistical difference for the system factor in both years of evaluation (Figure 3.2). Across years, this location did not present statistical differences among treatments. The main point for biomass production on this location was the first year of the study, with a spring freeze event affecting the total biomass production, but mostly affecting the partitioning to reproductive organs, measured as the RPE coefficient. Values for the RPE for year 1 were around 33%, close to 20% lower relative to the second year, averaging 55% (Table 3.8), demonstrating the lack of ability of the plant to allocate resources to the reproductive part result of the freeze that occurred during initial stages of the head formation process, potentially affecting the final number of grains per spike.

Grain yield

Analysis of variance was performed separately for each location. The main response for Ashland Bottoms was related to the single effect seeding rate for both years and the three-way interaction for the 2016-17 growing season (Table 3.15). The yield obtained at this location for the first year presented a large variability primarily related to the soil type (slope), weather, and tested (all factors outside of the variables tested for this study). Notwithstanding the large yield variation, this location presented the highest yield with an overall value of 5.4 Mg ha^{-1}. The latter is an indication of the plasticity of wheat to recover and compensate for lack of uniformity, even with early establishment issues and high variation.

The seeding system did not influence yields across years. Nonetheless, a descriptive comparison between seeding systems is presented in Figure 3.3, for each year and then combined across 2-yrs, clearly reflecting the lack of yield response for this factor at Ashland location. Final yields were close to 5.4 Mg ha^{-1} for 2015-16 and 4.7 Mg ha^{-1} for 2016-17 seasons (Table 3.13). Seeding rate factor significantly affected yields in both years (Table 3.15). For the first year of the study, yields improved as seeding rate increase from 45 to 135 kg ha^{-1}, reaching a plateau afterwards. An expected trend for wheat, different from other cereal crops such as corn, increase of seeding rate increases yield until a point and stabilize, this is due the capability of wheat to compensate through the tiller production. For the second year, the effect of seeding rate on yields only occurred on the low seeding rates, with a positive impact when the rate changed from 45 to 90 kg ha^{-1} (Figure 3.4), going from 4.3 Mg ha^{-1} to 4.8 Mg ha^{-1} (Table 3.13). The system by seeding rate interaction did not significantly affect yields at Ashland (Table 3.15).

For the genotype factor, in the second year (2016-17) of this location, the wheat variety West Bred Cedar ® considered to be a high-tillering variety presented greater yield 0.6 Mg ha^{-1} as compared to West Bred 4458 ® low-tillering (Table 3.17). Number of tillers were not determined in this experiment, but this could be a reason for the larger yield obtained with the high-tillering variety, that could be also explained by the RPE factor that presented a significant effect during this season (Table 3.12). Aboveground biomass for both wheat varieties presented similar values with no statistical difference, nonetheless RPI presented a significant separation with the high-tillering variety presenting a superior coefficient (66%) relative to the low-tillering one (55%). Even though aboveground biomass did not respond across wheat varieties, the capability of the plant to allocate resources more efficiently did, reflected in the RPE coefficient.

At Topeka, across years, wheat yields did not present a significant difference among treatments (Table3.18). For the second season (2016-17), seeding rate by genotype factor significantly affected yields, with an overall yield gain of 45 kg ha^{-1} from 45 to 135 kg ha^{-1} seeding rate levels (Figure 3.6). As related to the seeding system, within the same season, this factor presented a positive effect on yields (Table 3.18). Singulation system outyielded the drill treatment, presenting a yield advantage of 0.2 Mg ha^{-1} (Figure 3.5). The seeding system by seeding rate interaction did not significantly affect yields at Topeka (Table 3.18). The singulation technology influenced wheat yields in the lower seeding rates, with a trend of increasing yield gain as the seeding rate was reduced (Table3.18).

Conclusions

The objective of this study was to understand how the new technology affected grain yield at varying seeding rates and under genotypes, with contrasting tillering ability). Overall, out of the four site years analyzed only one site-year reflected superior yield gain related to the implementation of the new planting system. One site year (Topeka 2015-16) did not present significant result on yields for any of the factors analyzed, due to a weather effect - spring freeze during the early stages of the formation of the spike. In this same location, year two (2016-17) presented a significant yield benefit on implementing the singulation technology for planters. Due the size of our experimental units (112.5 m^2) the harvesting did not allow us to use a better combine technology capable to capture small differences in yields that could be observed in the other site-years. Due to the previous reason, future studies can be focused on large-scale, farmer fields, and with utilization of yield monitors to capture smaller yield differences and variability across the diverse wheat farming operations in Kansas.

For Ashland the main response for both years was related to the seeding rate, mainly in the first three rates and then reaching a plateau in the higher rate (seeding rate utilized to test the technology under supra-optimal levels). Lack of response for the new technology (singulation) was expected at the high seeding rates, reducing the potential gaps between plants, the addition of this was mainly to prove that and have the entire information to follow up in the research and work to release the new technology with all the variables possible analyzed and answer all possible questions.

Vegetative measurements presented similar results in all site-years but without any statistical difference, as mention a few times in this chapter, wheat is a plant that can adapt to the environment and with a large plasticity presenting the ability to compensate for lack of plants, covering the canopy, and still producing comparable aboveground biomass and yields relative to situations with lack of gaps and more uniform canopies, based on the observations collected during the implementation of this study for wheat crop.

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Figures

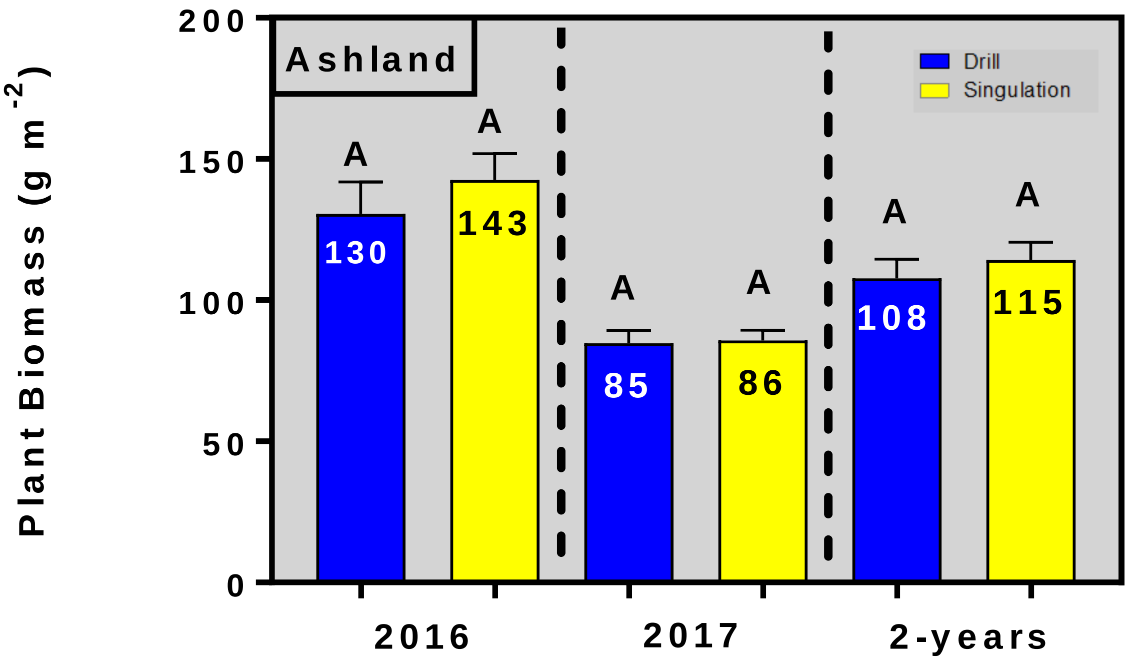

Figure 3.1 Biomass comparison of drill and singulation across all evaluated factors by year and for the 2-yrs combined analysis, Ashland location.

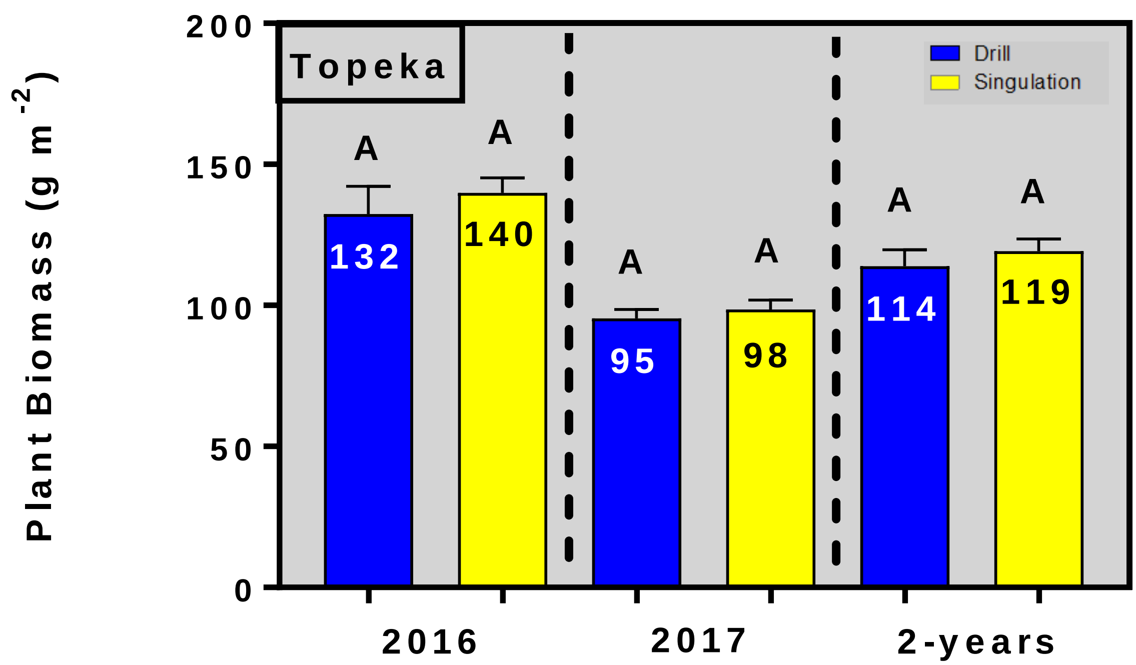

Figure 3.2 Biomass comparison of Drill and Singulation among all the factors by year and both years combined for Topeka.

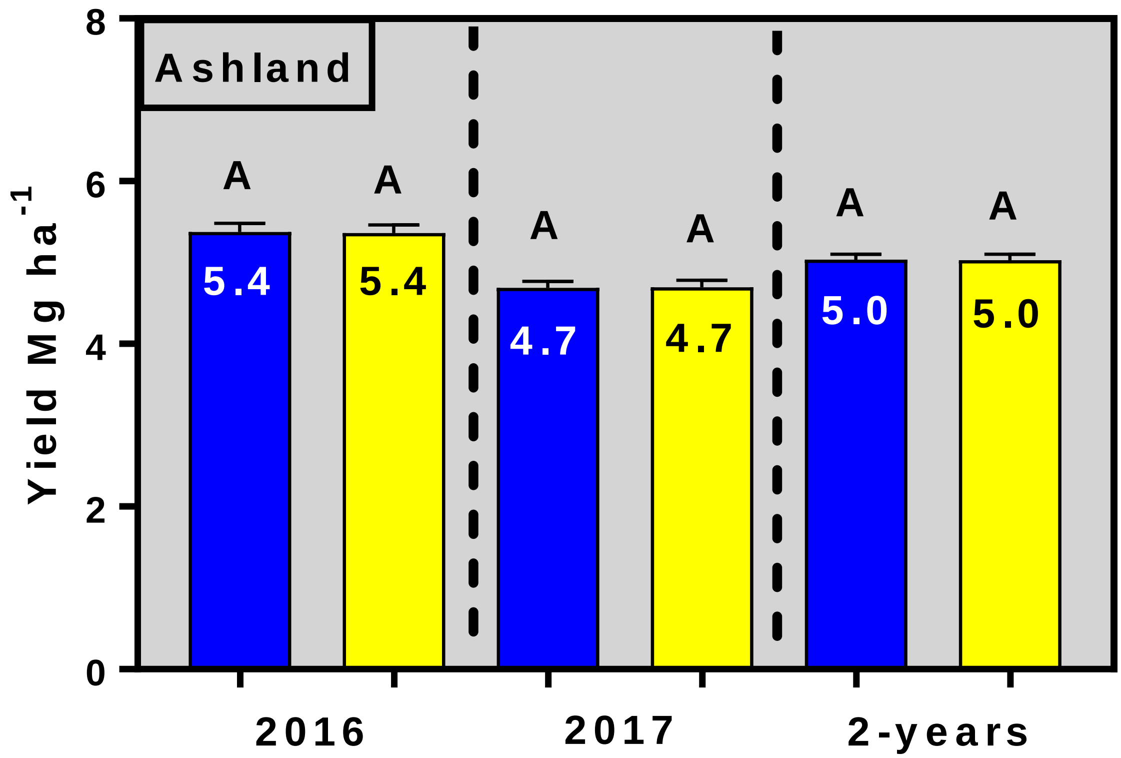

Figure 3.3 Yield comparison of Drill and Singulation among all the factors by year and both years combined for Ashland.

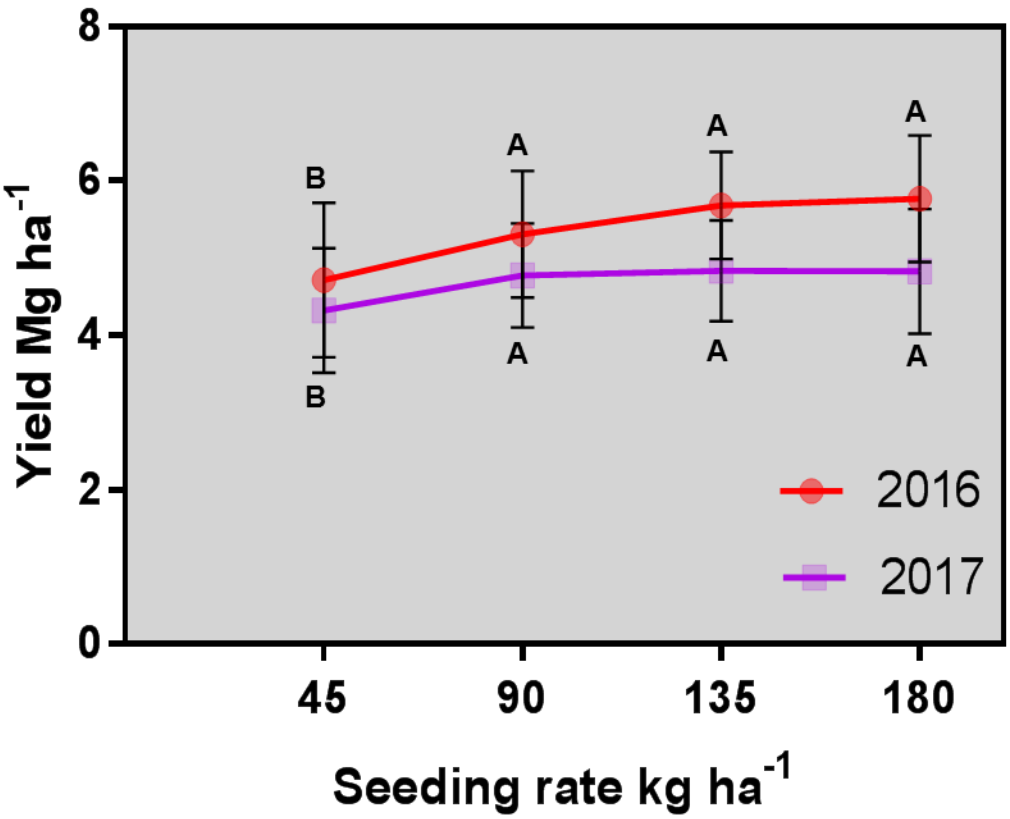

Figure 3.4 Yield response to plant density for wheat by year at Ashland bottoms location.

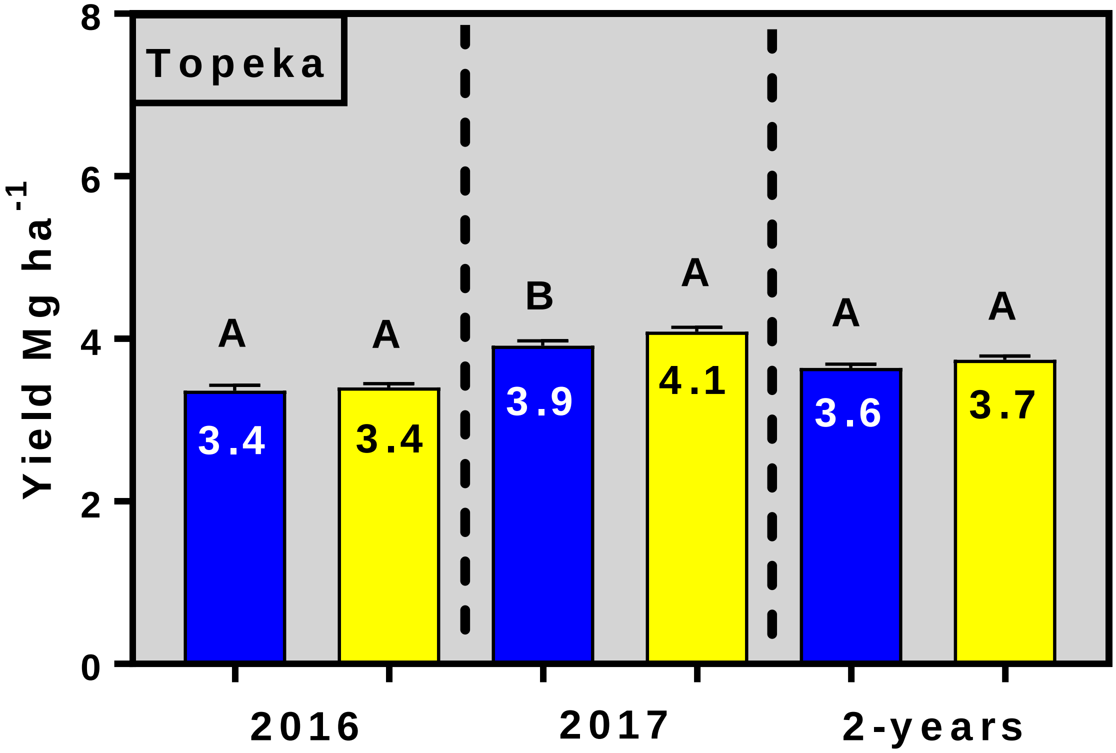

Figure 3.5 Yield comparison of Drill and Singulation among all the factors by year and both years combined for Topeka.

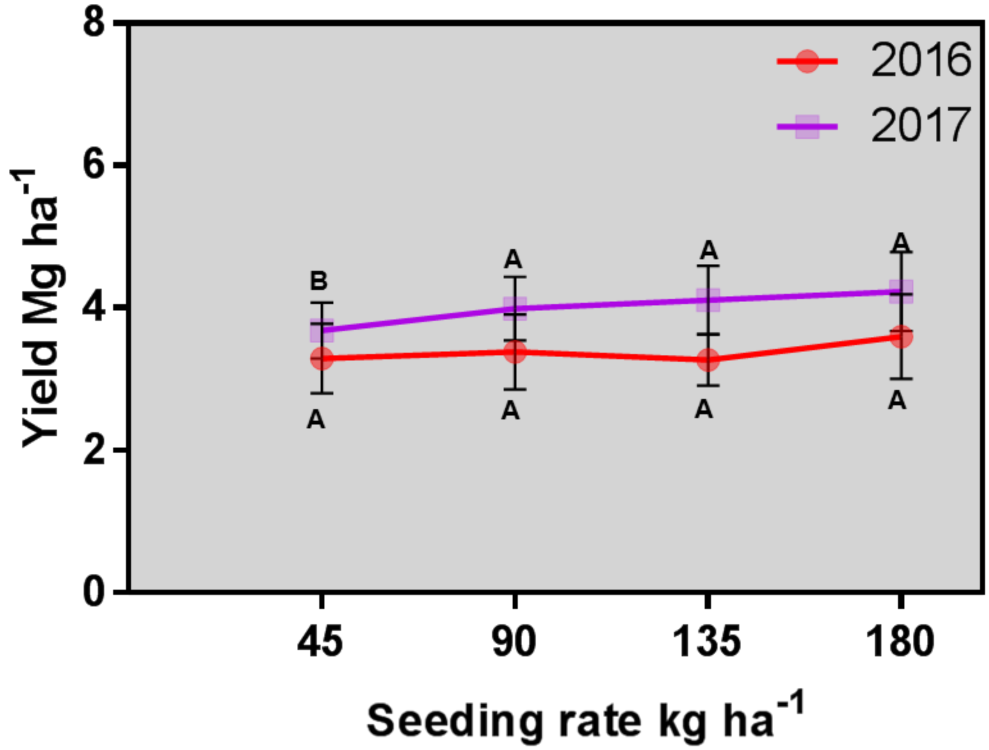

Figure 3.6 Yield response to Plant Density for wheat as an average by year at Topeka.

Tables

Table 3.1 Soil analyses values prior to planting during the 2015-16 season. Inorganic nitrogen (Nitrate – N), organic matter content (OM), soil pH, Mehlich III potassium (K) and phosphorus contents in the uppermost 0.15m of the soil profile.

	Location	
	Ashland	**Topeka**
Nitrate – N (kg N kg^{-1})	11.6	2.8
OM (g 100 g^{-1})	2.3	1.4
pH	6.3	7
K (ppm)	250.5	155.2
P (ppm)	11.2	38.8

Table 3.2 Description of the factors of the experiment for location, genotype, planting system and seeding rate used.

Location	**Genotype**	**Planting system**	**Seeding rate (kg ha^{-1})**
Ashland (dryland, till)	WB4458 (low tillering)	Drilled	45
Topeka (irrigated, no-till)	WBCedar (high tillering)	Singulated	90
			135
			180

Table 3.3 Sowing and harvesting dates for Ashland and Topeka during the 2015-16 and 2016-17 growing seasons.

	Ashland		Topeka	
Growing season	Planting	Harvest	Planting	Harvest
2015-2016	October 5	June 20	October 15	June 22
2016-2017	October 21	June 20	October 25	June 21

Table 3.4 Analysis of variance, biomass for Ashland 2016 and 2017.

2016	
Source of variation	**P-value**
Genotype	0.94664
System	0.97288
Seeding rate	0.87696
Genotype x System	0.46226
Genotype x Seeding rate	0.01212 *
System x Seeding rate	0.59365
Genotype x System x Seeding rate	0.36385

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

2017	
Source of variation	**P-value**
Genotype	0.3207
System	0.7933
Seeding rate	0.7051
Genotype x System	0.8885
Genotype x Seeding rate	0.3931
System x Seeding rate	0.2713
Genotype x System x Seeding rate	0.6873

Table 3.5 Plant biomass grams per square meter comparison by seeding rate, Ashland.

Year	System	Seeding rate (kg ha^{-1})			
		45	**90**	**135**	**180**
2016	**Singulated**	156 a	156 a	146 a	136 a
	Drill	123 a	143 a	144 a	158 a
2017	**Singulated**	79 a	88 a	84 a	91 a
	Drill	89 a	75 a	90 a	86 a

Table 3.6 Biomass and Reproductive Partitioning (Efficiency for genotype by year Ashland.

Year	Genotype	Biomass (g m^2)	RPI (%)
2016	**Cedar** (HT)	148.7 a	52% a
	WB 4458 (LT)	136.9 a	57% a
2017	**Cedar** (HT)	80.6 a	66% a
	WB 4458 (LT)	90.0 a	55% a

Table 3.7 Analysis of variance, RPI for Ashland 2016 and 2017.

2016	
Source of variation	**P-value**
Genotype	0.9362
System	0.8122
Seeding rate	0.9861
Genotype x System	0.2305
Genotype x Seeding rate	0.3816
System x Seeding rate	0.7171
Genotype x System x Seeding rate	0.5019

2017	
Source of variation	**P-value**
Genotype	0.01012*
System	0.39296
Seeding rate	0.18447
Genotype x System	0.41642
Genotype x Seeding rate	0.56726
System x Seeding rate	0.10138
Genotype x System x Seeding rate	0.51015

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 3.8 Reproductive Partitioning Efficiency by seeding rate, Ashland.

Year	System	Population (kg ha^{-1})			
		45	90	135	180
2016	Singulated	55%	55%	53%	53%
	Drill	55%	49%	65%	55%
2017	Singulated	60%	59%	62%	60%
	Drill	60%	65%	60%	58%

Table 3.9 Analysis of variance ANOVA, biomass for Topeka 2016 and 2017

2016	
Source of variation	**P-value**
Genotype	0.34030
System	0.39873
Seeding rate	0.18466
Genotype x System	0.94284
Genotype x Seeding rate	0.15935
System x Seeding rate	0.32639
Genotype x System x Seeding rate	0.48773

2017	
Source of variation	**P-value**
Genotype	0.09552
System	0.72416
Seeding rate	0.71530
Genotype x System	0.72537
Genotype x Seeding rate	0.33030
System x Seeding rate	0.10064
Genotype x System x Seeding rate	0.98440

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 3.10 Plant biomass grams per square meter comparison by seeding rate, Topeka.

Year	System	Population (kg ha^{-1})			
		45	**90**	**135**	**180**
2016	**Singulated**	132.9	129.2	138.4	159.6
	Drill	141.3	158.5	125.2	151.8
2017	**Singulated**	94.8	101.6	100.4	97.3
	Drill	91.1	90.9	98.7	101.2

Table 3.11 Analysis of variance ANOVA for Topeka 2016 and 2017.

2016	
Source of variation	**P-value**
Genotype	0.9362
System	0.8122
Seeding rate	0.9861
Genotype x System	0.2305
Genotype x Seeding rate	0.4470
System x Seeding rate	0.1797
Genotype x System x Seeding rate	0.4675

2017	
Source of variation	**P-value**
Genotype	0.8225
System	0.2887
Seeding rate	0.4892
Genotype x System	0.6142
Genotype x Seeding rate	0.9231
System x Seeding rate	0.7533
Genotype x System x Seeding rate	0.6530

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 3.12 Reproductive Partitioning efficiency by seeding rate, Ashland.

Year	System	Population (kg ha^{-1})			
		45	**90**	**135**	**180**
2016	**Singulated**	35.8%	35.8%	34.6%	35.1%
	Drill	35.2%	34.7%	36.1%	35.6%
2017	**Singulated**	65.7%	66.3%	64.6%	68.0%
	Drill	64.7%	65.8%	64.9%	65.4%

Table 3.13 Analyses of variance for yield (13% moisture) for all factors tested in the study: Planting system (drill vs. singulated), variety (4458 vs. Cedar), seeding rate (45 to 180 kg ha $^{-1}$) analyzed at two locations in Kansas (Topeka and Ashland Bottoms) for 2015 /2016 seaso n.

2016/ 2017			Location	
Planting System	**Varity**	**Seeding Rate**	**Topeka**	**Ashland**
		kg ha $^{-1}$	Mg ha $^{-1}$ (13% moisture)	
Drill	4458	45	3.5	4.5
		90	3.2	5.5
		135	3.5	5.8
		180	3.4	5.4
	Cedar	45	3.0	5.2
		90	3.5	4.9
		135	3.0	5.9
		180	3.8	5.9
Singulated	4458	45	3.5	4.8
		90	3.4	5.5
		135	3.2	5.6
		180	3.5	5.7
	Cedar	45	3.2	4.4
		90	3.4	5.3
		135	3.3	5.5
		180	3.7	6.2
Singulated			3.4	5.4
Drill			3.4	5.4
	Cedar		3.4	5.4
	4458		3.4	5.3
		45	3.3	4.7
		90	3.4	5.3
		135	3.3	5.7
		180	3.6	5.8
Average Location			3.4	5.4
Genotype (G)			ns	Ns
System (S)			ns	Ns
Seeding Rate (SR)			ns	<0.001***
S x G			ns	Ns
SR x G			ns	Ns
SR x S			ns	Ns
SR x G x S			ns	Ns

*[a]L.S.D. is the least significant difference at p<0.05. ***p<0.001; ns: not significant.*

Table 3.14 Analysis of variance for yield (13% moisture) for all factors tested in the study: Planting system (drill vs. singulated), variety (4458 vs. Cedar), seeding rate (45 to 180 kg ha^{-1})) analyzed at two locations in Kansas (Topeka and Ashland Bottoms) for <u>2016/2017 season</u>.

2016/ 2017			Location	
Planting System	**Varity**	**Seeding Rate**	**Topeka**	**Ashland**
		kg ha^{-1}	Mg ha^{-1} (13% moisture)	
Drill	4458	45	3.5	4.5
		90	3.8	4.2
		135	4.1	4.6
		180	4.4	4.8
	Cedar	45	3.7	4.3
		90	4.0	5.2
		135	3.9	5.2
		180	4.0	4.8
Singulated	4458	45	3.7	3.8
		90	4.1	4.8
		135	4.3	4.5
		180	4.6	4.5
	Cedar	45	3.9	4.3
		90	4.1	5.2
		135	4.0	5.2
		180	4.0	4.8
Singulated			4.1	4.7
Drill			3.9	4.7
	Cedar		3.9	4.9
	4458		3.9	4.5
		45	3.7	4.3
		90	4.0	4.8
		135	4.1	4.8
		180	4.2	4.8
Average Location			4.0	4.7
Genotype (G)			ns	0.011*
System (S)			0.001**	ns
Seeding Rate (SR)			<0.001***	<0.001***
S x G			<0.001***	ns
SR x G			ns	ns
SR x S			ns	ns
SR x G x S			ns	0.001***

*[a]L.S.D. is the least significant difference at p<0.05. ***p<0.001; ns: not significant.*

Table 3.15 Analysis of variance Table for Ashland 2016 and 2017.

2016		2017	
Source of variation	**P-value**	**Source of variation**	**P-value**
Genotype	0.814	Genotype	0.011*
System	0.895	System	0.964
Seeding rate	<0.001***	Seeding rate	<0.001***
Genotype x System	0.417	Genotype x System	0.280
Genotype x Seeding rate	0.131	Genotype x Seeding rate	0.836
System x Seeding rate	0.233	System x Seeding rate	0.659
Genotype x System x Seeding rate	0.308	Genotype x System x Seeding rate	0.001**

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Table 3.16 System comparison by seeding rate for both years, Ashland.

Year	System	Seeding rate (kg ha^{-1})			
		45	**90**	**135**	**180**
2016	**Singulated**	4.6	5.6	5.5	5.9
	Drill	4.8	5.2	5.8	5.6
2017	**Singulated**	4.3	4.8	4.8	4.9
	Drill	4.4	4.7	4.9	4.8

Table 3.17 Genotype comparison by year.

Year	Genotype	Yield (Mg ha^{-1})
2016	**Cedar** (HT)	5.4 a
	WB 4458 (LT)	5.3 a
2017	**Cedar** (HT)	5.0 a
	WB 4458 (LT)	4.4 b

Table 3.18 Analyze of variance ANOVA for Topeka 2016 and 2017.

2016	
Source of variation	**P-value**
Genotype	0.857
System	0.682
Seeding rate	0.983
Genotype x System	0.804
Genotype x Seeding rate	0.098
System x Seeding rate	0.951
Genotype x System x Seeding rate	0.417

2017	
Source of variation	**P-value**
Genotype	0.129
System	0.001**
Seeding rate	<0.001***
Genotype x System	0.211
Genotype x Seeding rate	<0.001***
System x Seeding rate	0.666
Genotype x System x Seeding rate	0.960

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 3.19 System comparison by seeding rate for both years, Topeka.

Year	System	Seeding rate (kg ha^{-1})			
		45	**90**	**135**	**180**
2016	**Singulated**	3.4c	3.4c	3.3c	3.6c
	Drill	3.2c	3.4c	3.3c	3.6c
2017	**Singulated**	3.8b	4.1a	4.2a	4.2a
	Drill	3.6c	3.9b	4.0a	4.2a

Chapter 4 - Conclusions

The low yield response to the new seeding technology, singulation, tested in this study as main factor with the interaction of four different seeding rates and two contrasting genotypes demonstrated that the high plasticity of wheat to compensate different levels of plant-to-plant uniformity 9migh not warrant this technology). In synthesis, the use of new technologies across all environments led to the lack of statistical difference among variables analyzed, and the need of more data (farm-scale) in order to further investigate and validate this technology before can be released by the company.

These was a low positive responses for grain yield, none out of four site-years to the singulation factor. Seeding system significantly influenced yields in Topeka 2017, with singulation outyielding the drill planting system, presenting a yield advantage of 0.2 Mg ha^{-1}. Since the singulation technology evolved during the years of the study and one study (Topeka 2016-17) presented a positive yield influence on this new planting system, a more complete set of environments with a simplified experimental design (on-farm strip design, side-by-side evaluation, only evaluation of the planting technology fixing the genotype and seeding rate factors in each farmer environment). Implementation of a more simplified approach and utilization of yield monitor technology can allow capturing smaller yield differences and permit better characterize of within-farm variability with larger plot sizes.

In addition, the new planting technology seemed to present a more likely yield response to lower seeding rates, presenting less yield advantage as the seeding rate increased from 90 to 180 kg ha^{-1} (comparable yields for drill and singulation systems from 135 to 180 kg ha^{-1} seeds per acre). In agreement to findings presented at Topeka 2016-17 location, the rest of the locations also showed a “saturation” of the yield response as the seeding rate increased over 135 kg ha^{-1} reaching a plateau.

Genotype effect on yields was observed in only one site-year, with the high-tillering variety WB Cedar outyielding the low-tillering variety WB 4458, which could be potentially explained by an increase in the number of tillers with fertile reproductive heads, with more grains per unit area, increasing final yields. Further research investigations should be performed focusing on improving the understanding of the mechanisms underpinning yield formation on wheat (tillering process).

Early-season plant determinations portrayed a lack of response to planting technology, although plant growth differences for seeding rate and genotype factors were observed. The emergence progression presented an expected trend for seeding rate, with greater number of emerged plants as the seeding rate increases. There was only one location, Topeka 2015-16, for which the final number of plants was close to the proposed target seeding rate; the rest of the site-years showed similar plant gap between the final number of plants and the targeted seeding rate. Number of gaps did not present differences for the planting systems, the main response was to the seeding rate in the second year. Nonetheless, more information is needed to find new approaches for more effectively and precisely estimate the number of gaps. Following this rationale, utilization of imagery data seemed to be a promising technique for rapid gap quantification but more sophisticated software “training” and knowledge in computer science (computer vision techniques) should be implemented for capturing all gaps in a faster and more accurate way.

Appendix – Statistic Analyses

YIELD

ASHLAND 2016

Source of variation	Chisq	Df	P-value
Genotype	0.054	1	0.814
System	0.017	1	0.895
Population	37.932	3	<0.001***
Genotype x System	0.658	1	0.417
Genotype x Population	5.630	3	0.131
System x Population	4.273	3	0.233
Genotype x System x Population	3.598	3	0.308

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 sys = Drill:

Gen	Pop	Lsmean	SE	Df	Lower CL	Upper Cl
4458	40	67.09300	4.598749	32.62	57.73262	76.45338
Cedar	40	76.58400	4.598749	32.62	67.22362	85.94438
4458	80	81.55600	4.598749	32.62	72.19562	90.91638
Cedar	80	72.82214	4.753227	36.49	63.18660	82.45768
4458	120	86.81600	4.598749	32.62	77.45562	96.17638
Cedar	120	86.81600	4.598749	32.62	77.64462	96.36538
4458	160	80.10600	4.598749	32.62	70.74562	89.46638
Cedar	160	87.09600	4.598749	32.62	77.73562	96.45638

sys = Singulated:

Gen	Pop	Lsmean	SE	Df	Lower CL	Upper Cl
4458	40	71.18100	4.598749	32.62	61.82062	80.54138
Cedar	40	65.83200	4.598749	32.62	56.47162	75.19238
4458	80	81.66800	4.598749	32.62	72.30762	91.02838
Cedar	80	78.78300	4.598749	32.62	69.42262	88.14338
4458	120	83.43097	4.433145	27.48	74.34232	92.51963
Cedar	120	79.48567	5.032926	39.55	69.31012	89.66123
4458	160	84.47600	4.598749	32.62	75.11562	93.83638
Cedar	160	91.72300	4.598749	32.62	82.36262	101.08338

Degrees-of-freedom method: satterthwaite
Confidence level used: 0.95

overall sys
$lsmeans

sys	Lsmean	SE	df	Lower. CL	Upper. CL
Drill	79.88477	2.700087	5.34	73.07570	86.69383
Singulated	79.57246	2.703195	5.37	72.76361	86.38131

Results are averaged over the levels of: gen, pop
Degrees-of-freedom method: satterthwaite
Confidence level used: 0.95

$contrast

Contrast	Estimate	SE	Df	t. ratio	p.value
Drill - Singulated	0.3123119	2.007039	58.94	0.156	0.8769

Results are averaged over the levels of: gen, pop

3-way interaction

Simultaneous Tests for General Linear Hypothese

$`gen = 4458`	**Estimate**	**Std. Error**	**T value**	**Pr(>|t|)**
Drill,40 - Singulated,40 == 0	-4.088	5.633	-0.726	0.9959
Drill,40 - Drill,80 == 0	-14.463	5.633	-2.568	0.1889
Drill,40 - Singulated,80 == 0	-14.575	5.633	-2.588	0.1818
Drill,40 - Drill,120 == 0	-19.723	5.633	-3.502	0.0188 *
Drill,40 - Singulated,120 == 0	-16.338	5.498	-2.971	0.0763
Drill,40 - Drill,160 == 0	-13.013	5.633	-2.310	0.3056
Drill,40 - Singulated,160 == 0	-17.383	5.633	-3.086	0.0581
Singulated,40 - Drill,80 == 0	-10.375	5.633	-1.842	0.5950
Singulated,40 - Singulated,80 == 0	-10.487	5.633	-1.862	0.5818
Singulated,40 - Drill,120 == 0	-15.635	5.633	-2.776	0.1209
Singulated,40 - Singulated,120 == 0	-12.250	5.498	-2.228	0.3509
Singulated,40 - Drill,160 == 0	-8.925	5.633	-1.585	0.7574
Singulated,40 - Singulated,160 == 0	-13.295	5.633	-2.360	0.2801
Drill,80 - Singulated,80 == 0	-0.112	5.633	-0.020	1.0000
Drill,80 - Drill,120 == 0	-5.260	5.633	-0.934	0.9814
Drill,80 - Singulated,120 == 0	-1.875	5.498	-0.341	1.0000
Drill,80 - Drill,160 == 0	1.450	5.633	0.257	1.0000
Drill,80 - Singulated,160 == 0	-2.920	5.633	-0.518	0.9995
Singulated,80 - Drill,120 == 0	-5.148	5.633	-0.914	0.9835
Singulated,80 - Singulated,120 == 0	-1.763	5.498	-0.321	1.0000
Singulated,80 - Drill,160 == 0	1.562	5.633	0.277	1.0000
Singulated,80 - Singulated,160 == 0	-2.808	5.633	-0.499	0.9996
Drill,120 - Singulated,120 == 0	3.385	5.498	0.616	0.9985
Drill,120 - Drill,160 == 0	6.710	5.633	1.191	0.9313
Drill,120 - Singulated,160 == 0	2.340	5.633	0.415	0.9999
Singulated,120 - Drill,160 == 0	3.325	5.498	0.605	0.9987
Singulated,120 - Singulated,160 == 0	-1.045	5.498	-0.190	1.0000
Drill,160 - Singulated,160 == 0	-4.370	5.633	-0.776	0.9938

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Adjusted p values reported -- single-step method)

Simultaneous Tests for General Linear Hypotheses

$`gen = Cedar`	Estimate	Std. Error	t value	Pr(>|t|)
Drill,40 - Singulated,40 == 0	10.7520	5.6327	1.909	0.5502
Drill,40 - Drill,80 == 0	3.7619	5.7595	0.653	0.9979
Drill,40 - Singulated,80 == 0	-2.1990	5.6327	-0.390	0.9999
Drill,40 - Drill,120 == 0	-10.4210	5.6327	-1.850	0.5891
Drill,40 - Singulated,120 == 0	-2.9017	5.9924	-0.484	0.9997
Drill,40 - Drill,160 == 0	-10.5120	5.6327	-1.866	0.5784
Drill,40 - Singulated,160 == 0	-15.1390	5.6327	-2.688	0.1465
Singulated,40 - Drill,80 == 0	-6.9901	5.7595	-1.214	0.9245
Singulated,40 - Singulated,80 == 0	-12.9510	5.6327	-2.299	0.3111
Singulated,40 - Drill,120 == 0	-21.1730	5.6327	-3.759	<0.01 **
Singulated,40 - Singulated,120 == 0	-13.6537	5.9924	-2.278	0.3225
Singulated,40 - Drill,160 == 0	-21.2640	5.6327	-3.775	<0.01 **
Singulated,40 - Singulated,160 == 0	-25.8910	5.6327	-4.597	<0.01 ***
Drill,80 - Singulated,80 == 0	-5.9609	5.7595	-1.035	0.9670
Drill,80 - Drill,120 == 0	-14.1829	5.7595	-2.463	0.2315
Drill,80 - Singulated,120 == 0	-6.6635	6.1150	-1.090	0.9565
Drill,80 - Drill,160 == 0	-14.2739	5.7595	-2.478	0.2247
Drill,80 - Singulated,160 == 0	-18.9009	5.7595	-3.282	0.0344 *
Singulated,80 - Drill,120 == 0	-8.2220	5.6327	-1.460	0.8249
Singulated,80 - Singulated,120 == 0	-0.7027	5.9924	-0.117	1.0000
Singulated,80 - Drill,160 == 0	-8.3130	5.6327	-1.476	0.8166
Singulated,80 - Singulated,160 == 0	-12.9400	5.6327	-2.297	0.3118
Drill,120 - Singulated,120 == 0	7.5193	5.9924	1.255	0.9112
Drill,120 - Drill,160 == 0	-0.0910	5.6327	-0.016	1.0000
Drill,120 - Singulated,160 == 0	-4.7180	5.6327	-0.838	0.9901
Singulated,120 - Drill,160 == 0	-7.6103	5.9924	-1.270	0.9060
Singulated,120 - Singulated,160 == 0	-12.2373	5.9924	-2.042	0.4630
Drill,160 - Singulated,160 == 0	-4.6270	5.6327	-0.821	0.9912

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Adjusted p values reported -- single-step method)

ASHLAND 2017

Analysis of Deviance Table (Type II Wald chisquare tests)

Source of variation	Chisq	Df	P-value
Genotype	6.417	1	0.011*
System	0.001	1	0.964
Population	18.039	3	<0.001***
Genotype x System	1.165	1	0.280
Genotype x Population	0.853	3	0.836
System x Population	1.600	3	0.659
Genotype x System x Population	15.842	3	0.001**

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

<u>sys = Drill:</u>

Gen	**Pop**	**Lsmean**	**SE**	**Df**	**Lower CL**	**Upper Cl**
4458	40	66.33000	4.643003	11.49	56.16359	76.49641
Cedar	40	65.09291	4.678112	11.84	54.88447	75.30136
4458	80	62.44000	4.643003	11.49	52.27359	72.60641
Cedar	80	77.49000	4.643003	11.49	67.32359	87.65641
4458	120	67.90500	4.643003	11.49	57.73859	78.07141
Cedar	120	76.74000	4.643003	11.49	66.57359	86.90641
4458	160	71.32000	4.643003	11.49	61.15359	81.48641
Cedar	160	70.79000	4.643003	11.49	60.62359	80.95641

sys = Singulated:

Gen	**Pop**	**Lsmean**	**SE**	**Df**	**Lower CL**	**Upper Cl**
4458	40	56.11000	4.643003	11.49	45.94359	66.27641
Cedar	40	70.60000	4.643003	11.49	60.43359	80.76641
4458	80	71.34000	4.643003	11.49	61.17359	81.50641
Cedar	80	72.84000	4.643003	11.49	62.67359	83.00641
4458	120	67.51000	4.643003	11.49	57.34359	77.67641
Cedar	120	75.36000	4.643003	11.49	65.19359	85.52641
4458	160	67.09000	4.643003	11.49	56.92359	77.25641
Cedar	160	77.87000	4.643003	11.49	67.70359	88.03641

Degrees-of-freedom method: satterthwaite
Confidence level used: 0.95

overall sys

$lsmeans

sys	Lsmean	SE	df	Lower. CL	Upper. CL
Drill	69.76349	3.596752	4.34	60.07715	79.44983
Singulated	69.84000	3.596041	4.34	60.15284	79.52716

Results are averaged over the levels of: gen, pop
Degrees-of-freedom method: satterthwaite
Confidence level used: 0.95

$contrast

Contrast	Estimate	SE	Df	t. ratio	p.value
Drill - Singulated	-0.07651076	1.432928	56.1	-0.053	0.9576

Results are averaged over the levels of: gen, pop

3-way interaction

Simultaneous Tests for General Linear Hypotheses

$`gen = 4458`	**Estimate**	**Std. Error**	**T value**	**Pr(>|t|)**
Drill,40 - Singulated,40 == 0	10.220	4.048	2.525	0.20667
Drill,40 - Drill,80 == 0	3.890	4.048	0.961	0.97801
Drill,40 - Singulated,80 == 0	-5.010	4.048	1.238	0.91693
Drill,40 - Drill,120 == 0	-1.575	4.048	-0.389	0.99993
Drill,40 - Singulated,120 == 0	-1.180	4.048	0.292	0.99999
Drill,40 - Drill,160 == 0	-4.990	4.048	-1.233	0.91846
Drill,40 - Singulated,160 == 0	-0.760	4.048	-0.188	1.00000
Singulated,40 - Drill,80 == 0	-6.330	4.048	-1.564	0.76925
Singulated,40 - Singulated,80 == 0	-15.230	4.048	-3.762	0.00897 **
Singulated,40 - Drill,120 == 0	-11.795	4.048	-2.914	0.08918
Singulated,40 - Singulated,120 == 0	-11.400	4.048	-2.816	0.11160
Singulated,40 - Drill,160 == 0	-15.210	4.048	-3.758	0.00915 **
Singulated,40 - Singulated,160 == 0	-10.980	4.048	-2.713	0.14039
Drill,80 - Singulated,80 == 0	-8.900	4.048	-2.199	0.36837
Drill,80 - Drill,120 == 0	-5.465	4.048	-1.350	0.87520
Drill,80 - Singulated,120 == 0	-5.070	4.048	-1.253	0.91206
Drill,80 - Drill,160 == 0	-8.880	4.048	-2.194	0.37077
Drill,80 - Singulated,160 == 0	-4.650	4.048	-1.149	0.94268
Singulated,80 - Drill,120 == 0	3.435	4.048	0.849	0.98928
Singulated,80 - Singulated,120 == 0	3.830	4.048	0.946	0.97986
Singulated,80 - Drill,160 == 0	0.020	4.048	0.005	1.00000
Singulated,80 - Singulated,160 == 0	4.250	4.048	1.050	0.96418
Drill,120 - Singulated,120 == 0	0.395	4.048	0.098	1.00000
Drill,120 - Drill,160 == 0	-3.415	4.048	-0.844	0.98963
Drill,120 - Singulated,160 == 0	0.815	4.048	0.201	1.00000
Singulated,120 - Drill,160 == 0	-3.810	4.048	-0.941	0.98046
Singulated,120 - Singulated,160 == 0	0.420	4.048	0.104	1.00000
Drill,160 - Singulated,160 == 0	4.230	4.048	1.045	0.96510

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Adjusted p values reported -- single-step method)

Simultaneous Tests for General Linear Hypotheses

*$`gen* = Cedar`	**Estimate**	**Std. Error**	**T value**	**Pr(>|t|)**
Drill,40 - Singulated,40 == 0	-5.507	4.088	-1.347	0.8763
Drill,40 - Drill,80 == 0	-12.397	4.088	-3.032	0.0668
Drill,40 - Singulated,80 == 0	-7.747	4.088	-1.895	0.5600
Drill,40 - Drill,120 == 0	-11.647	4.088	-2.849	0.1032
Drill,40 - Singulated,120 == 0	-10.267	4.088	-2.511	0.2119
Drill,40 - Drill,160 == 0	-5.697	4.088	-0.047	0.8562
Drill,40 - Singulated,160 == 0	-12.777	4.088	-3.125	0.0528
Singulated,40 - Drill,80 == 0	-6.890	4.048	-1.702	0.6858
Singulated,40 - Singulated,80 == 0	-2.240	4.048	-0.553	0.9993
Singulated,40 - Drill,120 == 0	-6.140	4.048	-1.517	0.7953
Singulated,40 - Singulated,120 == 0	-4.760	4.048	-1.176	0.9355
Singulated,40 - Drill,160 == 0	-0.190	4.048	-3.758	1.0000
Singulated,40 - Singulated,160 == 0	-7.270	4.048	-1.796	0.6253
Drill,80 - Singulated,80 == 0	4.650	4.048	1.149	0.9427
Drill,80 - Drill,120 == 0	0.750	4.048	0.185	1.0000
Drill,80 - Singulated,120 == 0	2.130	4.048	0.526	0.9995
Drill,80 - Drill,160 == 0	6.700	4.048	1.655	0.7151
Drill,80 - Singulated,160 == 0	-0.380	4.048	-0.094	1.0000
Singulated,80 - Drill,120 == 0	-3.900	4.048	-0.963	0.9777
Singulated,80 - Singulated,120 == 0	-2.520	4.048	-0.623	0.9984
Singulated,80 - Drill,160 == 0	2.050	4.048	0.506	0.9996
Singulated,80 - Singulated,160 == 0	-5.030	4.048	-1.243	0.9153
Drill,120 - Singulated,120 == 0	1.380	4.048	0.341	1.00000
Drill,120 - Drill,160 == 0	5.950	4.048	1.470	0.8199
Drill,120 - Singulated,160 == 0	-1.130	4.048	-0.279	1.00000
Singulated,120 - Drill,160 == 0	4.570	4.048	1.129	0.9476
Singulated,120 - Singulated,160 == 0	-2.510	4.048	-0.620	0.9985
Drill,160 - Singulated,160 == 0	-7.080	4.048	-1.749	0.6559

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Adjusted p values reported -- single-step method)

TOPEKA 2016

Analysis of Deviance Table (Type II Wald chisquare tests)

Source of variation	Chisq	Df	P-value
Genotype	0.024	1	0.857
System	0.167	1	0.682
Population	6.290	3	0.983
Genotype x System	0.061	1	0.804
Genotype x Population	6.276	3	0.098
System x Population	0.346	3	0.951
Genotype x System x Population	2.838	3	0.417

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

sys = Drill:

Gen	**Pop**	**Lsmean**	**SE**	**Df**	**Lower CL**	**Upper Cl**
4458	40	51.457	3.189052	59.65	45.07718	57.83682
Cedar	40	44.240	3.189052	59.65	37.86018	50.61982
4458	80	48.314	3.189052	59.65	41.93418	54.69382
Cedar	80	52.523	3.189052	59.65	46.14318	58.90282
4458	120	51.475	3.189052	59.65	45.09518	57.85482
Cedar	120	45.301	3.189052	59.65	38.92118	51.68082
4458	160	50.204	3.189052	59.65	43.82418	56.58382
Cedar	160	56.905	3.189052	59.65	50.52518	63.28482

sys = Singulated:

Gen	Pop	Lsmean	SE	Df	Lower CL	Upper Cl
4458	40	51.697	3.189052	59.65	45.31718	58.07682
Cedar	40	48.287	3.189052	59.65	41.90718	54.66682
4458	80	50.534	3.189052	59.65	44.15418	56.91382
Cedar	80	50.282	3.189052	59.65	43.90218	56.66182
4458	120	48.124	3.189052	59.65	41.74418	54.50382
Cedar	120	49.650	3.189052	59.65	43.27018	56.02982
4458	160	52.091	3.189052	59.65	45.71118	58.47082
Cedar	160	54.785	3.189052	59.65	48.40518	61.16482

Degrees-of-freedom method: satterthwaite
Confidence level used: 0.95

overall sys

$lsmeans

sys	Lsmean	SE	df	Lower. CL	Upper. CL
Drill	50.05238	1.375353	8.35	46.90381	53.20094
Singulated	50.68125	1.375353	8.35	47.53268	53.82982

Results are averaged over the levels of: gen, pop
Degrees-of-freedom method: satterthwaite
Confidence level used: 0.95

$contrast

Contrast	Estimate	SE	Df	t. ratio	p.value
Drill - Singulated	-0.628875	1.537944	60	-0.409	0.6841

Results are averaged over the levels of: gen, pop

3-way interaction Simultaneous Tests for General Linear Hypotheses

$`gen = 4458`	**Estimate**	**Std. Error**	**T value**	**Pr(>|t|)**
Drill,40 - Singulated,40 == 0	-0.240	4.350	-0.055	1.000
Drill,40 - Drill,80 == 0	3.143	4.350	0.723	0.996
Drill,40 - Singulated,80 == 0	0.923	4.350	0.212	1.000
Drill,40 - Drill,120 == 0	-0.018	4.350	-0.004	1.000
Drill,40 - Singulated,120 == 0	3.333	4.350	0.766	0.994
Drill,40 - Drill,160 == 0	1.253	4.350	0.288	1.000
Drill,40 - Singulated,160 == 0	-0.634	4.350	-0.146	1.000
Singulated,40 - Drill,80 == 0	3.383	4.350	0.778	0.994
Singulated,40 - Singulated,80 == 0	1.163	4.350	0.267	1.000
Singulated,40 - Drill,120 == 0	0.222	4.350	0.051	1.000
Singulated,40 - Singulated,120 == 0	3.573	4.350	0.821	0.991
Singulated,40 - Drill,160 == 0	1.493	4.350	0.343	1.000
Singulated,40 - Singulated,160 == 0	-0.394	4.350	-0.091	1.000
Drill,80 - Singulated,80 == 0	-2.220	4.350	-0.510	1.000
Drill,80 - Drill,120 == 0	-3.161	4.350	-0.727	0.996
Drill,80 - Singulated,120 == 0	0.190	4.350	0.044	1.000
Drill,80 - Drill,160 == 0	-1.890	4.350	-0.434	1.000
Drill,80 - Singulated,160 == 0	-3.777	4.350	-0.868	0.988
Singulated,80 - Drill,120 == 0	-0.941	4.350	-0.216	1.000
Singulated,80 - Singulated,120 == 0	2.410	4.350	0.554	0.999
Singulated,80 - Drill,160 == 0	0.330	4.350	0.076	1.000
Singulated,80 - Singulated,160 == 0	-1.557	4.350	-0.358	1.000
Drill,120 - Singulated,120 == 0	3.351	4.350	0.770	0.994
Drill,120 - Drill,160 == 0	1.271	4.350	0.292	1.000
Drill,120 - Singulated,160 == 0	-0.616	4.350	-0.142	1.000
Singulated,120 - Drill,160 == 0	-2.080	4.350	-0.478	1.000
Singulated,120 - Singulated,160 == 0	-3.967	4.350	-0.912	0.984
Drill,160 - Singulated,160 == 0	-1.887	4.350	-0.434	1.000

(Adjusted p values reported -- single-step method)

Simultaneous Tests for General Linear Hypotheses

$`gen = Cedar`	**Estimate**	**Std. Error**	**T value**	**Pr(>|t|)**
Drill,40 - Singulated,40 == 0	-4.047	4.350	-0.930	0.9818
Drill,40 - Drill,80 == 0	-8.283	4.350	-1.904	0.5537
Drill,40 - Singulated,80 == 0	-6.042	4.350	-1.389	0.8588
Drill,40 - Drill,120 == 0	-1.061	4.350	-0.244	1.0000
Drill,40 - Singulated,120 == 0	-5.410	4.350	-1.244	0.9152
Drill,40 - Drill,160 == 0	-12.665	4.350	-2.912	0.0885
Drill,40 - Singulated,160 == 0	-10.545	4.350	-2.424	0.2487
Singulated,40 - Drill,80 == 0	-4.236	4.350	-0.974	0.9764
Singulated,40 - Singulated,80 == 0	-1.995	4.350	-0.459	0.9998
Singulated,40 - Drill,120 == 0	2.986	4.350	0.686	0.9971
Singulated,40 - Singulated,120 == 0	-1.363	4.350	-0.313	1.0000
Singulated,40 - Drill,160 == 0	-8.618	4.350	-1.981	0.5027
Singulated,40 - Singulated,160 == 0	-6.498	4.350	-1.494	0.8077
Drill,80 - Singulated,80 == 0	2.241	4.350	0.515	0.9995
Drill,80 - Drill,120 == 0	7.222	4.350	1.660	0.7120
Drill,80 - Singulated,120 == 0	2.873	4.350	0.660	0.9977
Drill,80 - Drill,160 == 0	-4.382	4.350	-1.007	0.9716
Drill,80 - Singulated,160 == 0	-2.262	4.350	-0.520	0.9995
Singulated,80 - Drill,120 == 0	4.981	4.350	1.145	0.9438
Singulated,80 - Singulated,120 == 0	0.632	4.350	0.145	1.0000
Singulated,80 - Drill,160 == 0	-6.623	4.350	-1.523	0.7922
Singulated,80 - Singulated,160 == 0	-4.503	4.350	-1.035	0.9670
Drill,120 - Singulated,120 == 0	-4.349	4.350	-1.000	0.9727
Drill,120 - Drill,160 == 0	-11.604	4.350	-2.668	0.1525
Drill,120 - Singulated,160 == 0	-9.484	4.350	-2.180	0.3784
Singulated,120 - Drill,160 == 0	-7.255	4.350	-1.668	0.7073
Singulated,120 - Singulated,160 == 0	-5.135	4.350	-1.180	0.9344
Drill,160 - Singulated,160 == 0	2.120	4.350	0.487	0.487

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Adjusted p values reported -- single-step method)

TOPEKA 2017

Analysis of Deviance Table (Type II Wald chisquare tests)

Source of variation	Chisq	Df	P-value
Genotype	2.294	1	0.129
System	10.194	1	0.001**
Population	58.943	3	<0.001***
Genotype x System	1.561	1	0.211
Genotype x Population	28.572	3	<0.001***
System x Population	1.568	3	0.666
Genotype x System x Population	0.297	3	0.960

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

sys = Drill:

Gen	**Pop**	**Lsmean**	**SE**	**Df**	**Lower CL**	**Upper Cl**
4458	40	51.403	3.082674	6.95	44.10256	58.70344
Cedar	40	54.811	3.082674	6.95	47.51056	62.11144
4458	80	56.634	3.082674	6.95	49.33356	63.93444
Cedar	80	59.024	3.082674	6.95	51.72356	66.32444
4458	120	61.141	3.082674	6.95	53.84056	68.44144
Cedar	120	58.581	3.082674	6.95	51.28056	65.88144
4458	160	65.157	3.082674	6.95	57.85656	72.45744
Cedar	160	59.462	3.082674	6.95	52.16156	66.76244

sys = Singulated:

Gen	**Pop**	**Lsmean**	**SE**	**Df**	**Lower CL**	**Upper Cl**
4458	40	55.365	3.082674	6.95	48.06456	62.66544
Cedar	40	57.948	3.082674	6.95	50.64756	65.24844
4458	80	60.431	3.082674	6.95	53.13056	67.73144
Cedar	80	61.110	3.082674	6.95	53.80956	68.41044
4458	120	64.437	3.082674	6.95	57.13656	71.73744
Cedar	120	59.920	3.082674	6.95	67.22044	67.22044
4458	160	67.703	3.082674	6.95	60.40256	75.00344
Cedar	160	58.845	3.082674	6.95	51.54456	66.14544

Degrees-of-freedom method: satterthwaite
Confidence level used: 0.95

overall sys

$lsmeans

sys	Lsmean	SE	df	Lower. CL	Upper. CL
Drill	58.27663	2.707557	4.16	50.87495	65.67830
Singulated	60.71988	2.707557	4.16	53.31820	68.12155

Results are averaged over the levels of: gen, pop
Degrees-of-freedom method: satterthwaite
Confidence level used: 0.95

$contrast

Contrast	Estimate	SE	Df	t. ratio	p.value
Drill - Singulated	-2.44325	0.7652048	56	-3.193	0.0023

Results are averaged over the levels of: gen, pop

3-way interaction Simultaneous Tests for General Linear Hypotheses

$`gen = 4458`	**Estimate**	**Std. Error**	**T value**	**Pr(>|t|)**
Drill,40 - Singulated,40 == 0	-3.962	2.164	-1.831	0.60253
Drill,40 - Drill,80 == 0	-5.231	2.164	-2.417	0.25327
Drill,40 - Singulated,80 == 0	-9.028	2.164	-4.171	0.00248 **
Drill,40 - Drill,120 == 0	-9.738	2.164	-4.499	< 0.001 ***
Drill,40 - Singulated,120 == 0	-13.034	2.164	-6.022	< 0.001 ***
Drill,40 - Drill,160 == 0	-13.754	2.164	-6.355	< 0.001 ***
Drill,40 - Singulated,160 == 0	-16.300	2.164	-7.531	< 0.001 ***
Singulated,40 - Drill,80 == 0	-1.269	2.164	-0.586	0.99892
Singulated,40 - Singulated,80 == 0	-5.066	2.164	-2.341	0.29040
Singulated,40 - Drill,120 == 0	-5.776	2.164	-2.669	0.15369
Singulated,40 - Singulated,120 == 0	-9.072	2.164	-4.192	0.00243 **
Singulated,40 - Drill,160 == 0	-9.792	2.164	-4.524	< 0.001 ***
Singulated,40 - Singulated,160 == 0	-12.338	2.164	-5.701	< 0.001 ***
Drill,80 - Singulated,80 == 0	-3.797	2.164	-1.754	0.65229
Drill,80 - Drill,120 == 0	-4.507	2.164	-2.082	0.43843
Drill,80 - Singulated,120 == 0	-7.803	2.164	-3.605	0.01436 *
Drill,80 - Drill,160 == 0	-8.523	2.164	-3.938	0.00542 **
Drill,80 - Singulated,160 == 0	-11.069	2.164	-5.114	< 0.001 ***
Singulated,80 - Drill,120 == 0	-0.710	2.164	-0.328	0.99998
Singulated,80 - Singulated,120 == 0	-4.006	2.164	-1.851	0.58923
Singulated,80 - Drill,160 == 0	-4.726	2.164	-2.184	0.37726
Singulated,80 - Singulated,160 == 0	-7.272	2.164	-3.360	0.02849 *
Drill,120 - Singulated,120 == 0	-3.296	2.164	-1.523	0.79194
Drill,120 - Drill,160 == 0	-4.016	2.164	-1.856	0.58628
Drill,120 - Singulated,160 == 0	-6.562	2.164	-2.180	0.06659
Singulated,120 - Drill,160 == 0	-0.720	2.164	-0.333	0.99998
Singulated,120 - Singulated,160 == 0	-3.266	2.164	-1.509	0.79934
Drill,160 - Singulated,160 == 0	-2.546	2.164	-1.176	0.93534

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1(Adjusted p values reported -- single-step method)

Simultaneous Tests for General Linear Hypotheses

$`gen = Cedar`	**Estimate**	**Std. Error**	**T value**	**Pr(>|t|)**
Drill,40 - Singulated,40 == 0	-3.137	2.164	-1.449	0.8300
Drill,40 - Drill,80 == 0	-4.213	2.164	-1.947	0.5258
Drill,40 - Singulated,80 == 0	-6.299	2.164	-2.910	0.0901
Drill,40 - Drill,120 == 0	-3.770	2.164	-1.742	0.6604
Drill,40 - Singulated,120 == 0	-5.109	2.164	-2.361	0.2809
Drill,40 - Drill,160 == 0	-4.651	2.164	-2.149	0.3977
Drill,40 - Singulated,160 == 0	-4.034	2.164	-1.864	0.5807
Singulated,40 - Drill,80 == 0	-1.076	2.164	-0.497	0.9996
Singulated,40 - Singulated,80 == 0	-3.162	2.164	-1.461	0.8244
Singulated,40 - Drill,120 == 0	-0.633	2.164	-0.292	1.0000
Singulated,40 - Singulated,120 == 0	-1.972	2.164	-0.911	0.9838
Singulated,40 - Drill,160 == 0	-1.514	2.164	-0.700	0.9967
Singulated,40 - Singulated,160 == 0	-0.897	2.164	-0.414	0.9999
Drill,80 - Singulated,80 == 0	-2.086	2.164	-0.964	0.9777
Drill,80 - Drill,120 == 0	0.443	2.164	0.205	1.0000
Drill,80 - Singulated,120 == 0	-0.896	2.164	-0.414	0.9999
Drill,80 - Drill,160 == 0	-0.438	2.164	-0.202	1.0000
Drill,80 - Singulated,160 == 0	0.179	2.164	0.083	1.0000
Singulated,80 - Drill,120 == 0	2.529	2.164	1.168	0.9375
Singulated,80 - Singulated,120 == 0	1.190	2.164	0.550	0.9993
Singulated,80 - Drill,160 == 0	1.648	2.164	0.761	0.9944
Singulated,80 - Singulated,160 == 0	2.265	2.164	1.047	0.9648
Drill,120 - Singulated,120 == 0	-1.339	2.164	-0.619	0.9985
Drill,120 - Drill,160 == 0	-0.881	2.164	-0.407	0.9999
Drill,120 - Singulated,160 == 0	-0.264	2.164	-0.122	1.0000

Singulated,120 - Drill,160 == 0	0.458	2.164	0.212	1.0000
Singulated,120 - Singulated,160 == 0	1.075	2.164	0.497	0.9996
Drill,160 - Singulated,160 == 0	0.617	2.164	0.285	1.0000

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Adjusted p values reported -- single-step method)

Biomass

Ashland 2016

	gen	pop	sys	N	biomass	sd	se	ci
1	4458	40	Drill	2	141.4500	7.707464	5.4500000	69.248816
2	4458	40	Singulated	3	156.6667	46.331127	26.7492887	115.092900
3	4458	80	Drill	3	168.6000	1.044031	0.6027714	2.593516
4	4458	80	Singulated	3	183.9667	20.903668	12.0687383	51.927590
5	4458	120	Drill	2	126.6500	15.485639	10.9500000	139.132942
6	4458	120	Singulated	3	127.6333	26.723835	15.4290131	66.385685
7	4458	160	Drill	3	159.7333	6.678573	3.8558757	16.590494
8	4458	160	Singulated	3	120.2667	35.089362	20.2588527	87.166808
9	Cedar	40	Drill	2	166.1000	21.354625	15.1000000	191.863692
10	Cedar	40	Singulated	3	155.7000	41.602043	24.0189509	103.345204
11	Cedar	80	Drill	3	117.7667	23.932057	13.8171793	59.450524
12	Cedar	80	Singulated	3	129.1333	19.393126	11.1966265	48.175195
13	Cedar	120	Drill	3	156.2667	19.310705	11.1490408	47.970451
14	Cedar	120	Singulated	2	172.7500	46.598337	32.9500000	418.669446
15	Cedar	160	Drill	2	155.3500	58.053467	41.0500000	521.589704
16	Cedar	160	Singulated	3	152.2000	18.278676	10.5531986	45.406749

Topeka 2016

	gen	pop	sys	N	biomass	sd	se	ci
1	4458	40	Drill	3	156.7333	14.7527399	8.517498	36.647837
2	4458	40	Singulated	3	131.9000	2.8687977	1.656301	7.126488
3	4458	80	Drill	3	145.7667	22.9011645	13.221993	56.889646
4	4458	80	Singulated	3	136.3333	33.0699763	19.092960	82.150375
5	4458	120	Drill	2	148.1000	0.0000000	0.000000	0.000000
6	4458	120	Singulated	3	148.1667	14.0877015	8.133538	34.995791
7	4458	160	Drill	3	137.2333	26.8039798	15.475285	66.584777
8	4458	160	Singulated	3	155.4000	52.7742361	30.469219	131.098470
9	Cedar	40	Drill	3	125.8667	39.3107280	22.696059	97.653262
10	Cedar	40	Singulated	3	133.8333	25.5715337	14.763732	63.523211
11	Cedar	80	Drill	2	177.5000	23.7587878	16.800000	213.464240

12	Cedar	80	Singulated	3	121.9667	18.9592546	10.946131	47.097399
13	Cedar	120	Drill	3	109.9000	0.5196152	0.300000	1.290796
14	Cedar	120	Singulated	3	128.6000	3.0116441	1.738774	7.481339
15	Cedar	160	Drill	3	166.4333	18.7910440	10.849014	46.679541
16	Cedar	160	Singulated	3	163.7000	19.7517088	11.403654	49.065965

Ashland 2017

	gen	pop	sys	N	biomass	sd	se	ci
1	4458	40	Drill	3	88.60000	13.07708	7.550055	32.48527
2	4458	40	Singulated	3	77.73333	35.79865	20.668360	88.92878
3	4458	80	Drill	3	75.26667	24.49680	14.143236	60.85343
4	4458	80	Singulated	3	96.83333	23.63416	13.645186	58.71050
5	4458	120	Drill	3	92.13333	34.10283	19.689281	84.71614
6	4458	120	Singulated	3	90.23333	11.51709	6.649394	28.61003
7	4458	160	Drill	3	99.60000	25.46822	14.704081	63.26655
8	4458	160	Singulated	3	99.36667	11.42862	6.598316	28.39026
9	Cedar	40	Drill	3	88.86667	27.38655	15.811634	68.03197
10	Cedar	40	Singulated	3	80.03333	10.50968	6.067765	26.10749
11	Cedar	80	Drill	3	75.13333	24.70877	14.265615	61.37999
12	Cedar	80	Singulated	3	79.96667	18.47223	10.664948	45.88757
13	Cedar	120	Drill	3	87.26667	13.46749	7.775460	33.45510
14	Cedar	120	Singulated	3	77.30000	11.62024	6.708949	28.86628
15	Cedar	160	Drill	3	71.86667	13.09096	7.558071	32.51976
16	Cedar	160	Singulated	3	84.53333	17.17275	9.914692	42.65948

Topeka 2017

	gen	pop	sys	N	biomass	sd	se	ci
1	4458	40	Drill	3	90.63333	9.148953	5.282150	22.72726
2	4458	40	Singulated	3	97.83333	7.883104	4.551312	19.58272
3	4458	80	Drill	3	83.20000	13.848827	7.995624	34.40239
4	4458	80	Singulated	3	101.96667	19.703384	11.375754	48.94592
5	4458	120	Drill	3	102.50000	21.695852	12.526106	53.89548
6	4458	120	Singulated	3	109.90000	27.266646	15.742406	67.73410
7	4458	160	Drill	3	105.90000	20.072618	11.588932	49.86315
8	4458	160	Singulated	3	106.00000	18.133946	10.469639	45.04722
9	Cedar	40	Drill	3	91.63333	10.515861	6.071335	26.12285
10	Cedar	40	Singulated	3	91.83333	6.132971	3.540872	15.23514
11	Cedar	80	Drill	3	98.66667	12.168128	7.025272	30.22731
12	Cedar	80	Singulated	3	101.30000	24.049324	13.884884	59.74183
13	Cedar	120	Drill	3	94.93333	16.508281	9.531060	41.00884
14	Cedar	120	Singulated	3	90.93333	15.205372	8.778826	37.77224
15	Cedar	160	Drill	3	96.53333	19.169072	11.067269	47.61862
	Cedar	160	Singulated	3	88.56667	8.991292	5.191125	22.33561

RPI – Reproductive Partitioning Efficiency

Ashland 2016

gen	pop	sys	N	HI	sd	se	ci
1	4458	40	Drill	2	47.53837	3.8250847	2.7047433	34.367022
2	4458	40	Singulated	3	49.37447	18.5922036	10.7342138	46.185594
3	4458	80	Drill	3	56.73390	4.3670475	2.5213161	10.848347
4	4458	80	Singulated	3	56.50163	18.8796091	10.9001474	46.899549
5	4458	120	Drill	2	54.97138	18.2855778	12.9298560	164.289398
6	4458	120	Singulated	3	49.49892	11.8672672	6.8515699	29.479926
7	4458	160	Drill	3	45.61210	8.6206431	4.9771306	21.414865
8	4458	160	Singulated	3	58.15744	19.1895436	11.0790882	47.669469
9	Cedar	40	Drill	2	62.42388	23.5926983	16.6825570	211.971985
10	Cedar	40	Singulated	3	60.91194	14.8020083	8.5459435	36.770227
11	Cedar	80	Drill	3	42.28641	18.1045087	10.4526430	44.974093
12	Cedar	80	Singulated	3	53.62948	11.1678780	6.4477774	27.742547
13	Cedar	120	Drill	3	72.14285	1.4528454	0.8388007	3.609068
14	Cedar	120	Singulated	2	58.87595	13.6366451	9.6425642	122.520395
15	Cedar	160	Drill	2	70.16098	0.6562165	0.4640152	5.895872
16	Cedar	160	Singulated	3	47.11144	10.0717078	5.8149032	25.019509

Topeka 2016

gen	pop	sys	N	HI	sd	se	ci
1	4458	40	Drill	3	34.20210	0.5870009	0.3389051	1.4581911
2	4458	40	Singulated	3	36.57851	0.3800617	0.2194287	0.9441255
3	4458	80	Drill	3	34.95687	0.3641328	0.2102322	0.9045561
4	4458	80	Singulated	3	35.49879	1.4436611	0.8334981	3.5862530
5	4458	120	Drill	2	35.45016	0.5684138	0.4019293	5.1069955
6	4458	120	Singulated	3	34.29583	1.3481601	0.7783606	3.3490154
7	4458	160	Drill	3	36.16233	1.1769426	0.6795081	2.9236875
8	4458	160	Singulated	3	35.82320	0.7865503	0.4541150	1.9538991
9	Cedar	40	Drill	3	36.14547	2.8107094	1.6227638	6.9821891
10	Cedar	40	Singulated	3	35.02593	2.1989218	1.2695481	5.4624247
11	Cedar	80	Drill	2	34.28350	1.1704235	0.8276144	10.5158377
12	Cedar	80	Singulated	3	36.15856	1.9513762	1.1266276	4.8474873
13	Cedar	120	Drill	3	36.60962	0.9607747	0.5547035	2.3866967
14	Cedar	120	Singulated	3	34.88035	1.4025566	0.8097664	3.4841438
15	Cedar	160	Drill	3	35.02206	0.6662365	0.3846518	1.6550233
16	Cedar	160	Singulated	3	34.49326	0.9629420	0.5559548	2.3920804

Ashland 2017

	gen	pop	sys	N	HI	sd	se	ci
1	4458	40	Drill	3	50.56610	2.363780	1.3647292	5.871956
2	4458	40	Singulated	3	52.26830	5.014689	2.8952320	12.457178
3	4458	80	Drill	3	61.27077	5.048462	2.9147307	12.541074
4	4458	80	Singulated	3	54.21075	1.753966	1.0126529	4.357094
5	4458	120	Drill	3	55.93112	8.032204	4.6373949	19.953100
6	4458	120	Singulated	3	56.80874	5.673259	3.2754575	14.093156
7	4458	160	Drill	3	52.66097	5.745755	3.3173132	14.273246
8	4458	160	Singulated	3	54.13948	5.501694	3.1764044	13.666965
9	Cedar	40	Drill	3	69.07132	2.163282	1.2489717	5.373892
10	Cedar	40	Singulated	3	66.81234	4.234759	2.4449395	10.519726
11	Cedar	80	Drill	3	93.91685	41.109746	23.7347230	102.122271
12	Cedar	80	Singulated	3	64.27776	3.518906	2.0316413	8.741447
13	Cedar	120	Drill	3	63.62169	2.539094	1.4659467	6.307459
14	Cedar	120	Singulated	3	67.42519	5.090339	2.9389087	12.645103
15	Cedar	160	Drill	3	64.24071	2.263259	1.3066933	5.622248
16	Cedar	160	Singulated	3	66.11828	1.688814	0.9750369	4.195245

Topeka 2017

	gen	pop	sys	N	HI	sd	se	ci
1	4458	40	Drill	3	64.57225	5.834939	3.3688037	14.494793
2	4458	40	Singulated	3	64.90482	4.519170	2.6091439	11.226240
3	4458	80	Drill	3	64.65575	3.811033	2.2003007	9.467130
4	4458	80	Singulated	3	67.94205	4.503237	2.5999453	11.186662
5	4458	120	Drill	3	64.19847	3.404664	1.9656836	8.457654
6	4458	120	Singulated	3	63.96028	3.849059	2.2222552	9.561592
7	4458	160	Drill	3	64.87915	1.597123	0.9220992	3.967473
8	4458	160	Singulated	3	68.50198	4.671675	2.6971929	11.605084
9	Cedar	40	Drill	3	64.84762	2.145730	1.2388375	5.330288
10	Cedar	40	Singulated	3	66.05186	2.667771	1.5402383	6.627111
11	Cedar	80	Drill	3	67.05693	3.670901	2.1193955	9.119023
12	Cedar	80	Singulated	3	64.63254	2.748019	1.5865693	6.826457
13	Cedar	120	Drill	3	65.56708	3.259450	1.8818446	8.096924
14	Cedar	120	Singulated	3	65.19700	3.625860	2.0933911	9.007135
15	Cedar	160	Drill	3	65.86725	3.233175	1.8666743	8.031651
16	Cedar	160	Singulated	3	67.46403	3.775785	2.1799502	9.379569

Stand Count

Total number of plants, Topeka

2016	
Source of variation	**P-value**
Genotype	0.5612
System	0.8901
Seeding rate	<0.001***
Genotype x System	0.5871
Genotype x Seeding rate	0.9970
System x Seeding rate	0.9268
Genotype x System x Seeding rate	0.8889

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

2017	
Source of variation	**P-value**
Genotype	0.61172
System	0.07957
Seeding rate	<0.001***
Genotype x System	0.84778
Genotype x Seeding rate	0.09106
System x Seeding rate	0.10588
Genotype x System x Seeding rate	0.49073

Plants per square feet, Topeka

2016	
Source of variation	**P-value**
Genotype	0.5396
System	0.9084
Seeding rate	<0.001***
Genotype x System	0.5652
Genotype x Seeding rate	0.9922
System x Seeding rate	0.9095
Genotype x System x Seeding rate	0.8975

2017	
Source of variation	**P-value**
Genotype	0.58513
System	0.08801
Seeding rate	<0.001***
Genotype x System	0.89144
Genotype x Seeding rate	0.07512
System x Seeding rate	0.11150
Genotype x System x Seeding rate	0.57969

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Total number of plants, Ashland

2016	
Source of variation	**P-value**
Genotype	0.3501
System	0.7579
Seeding rate	<0.001***
Genotype x System	0.2438
Genotype x Seeding rate	0.2925
System x Seeding rate	0.9254
Genotype x System x Seeding rate	0.8090

2017	
Source of variation	**P-value**
Genotype	<0.001***
System	0.25330
Seeding rate	<0.001***
Genotype x System	0.06816
Genotype x Seeding rate	0.07324
System x Seeding rate	0.22393
Genotype x System x Seeding rate	0.07035

Total number of plants, Ashland

2016	
Source of variation	**P-value**
Genotype	0.3603
System	0.1035
Seeding rate	0.3817
Genotype x System	0.6983
Genotype x Seeding rate	0.3366
System x Seeding rate	0.1313
Genotype x System x Seeding rate	0.6856

2017	
Source of variation	**P-value**
Genotype	<0.001***
System	0.28623
Seeding rate	<0.001***
Genotype x System	0.05294
Genotype x Seeding rate	0.05304
System x Seeding rate	0.21029
Genotype x System x Seeding rate	0.08632