

ORIGINAL ARTICLE

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Canopy closure, yield, and quality under heterogeneous plant spacing in sunflower

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Abstract

Deviation from uniform target plant population density in sunflower (*Helianthus annuus* L.) production may negatively affect canopy closure, yield, and grain quality. The objective of this study was to evaluate the effects of plant density heterogeneity on yield, quality, and canopy closure in confectionery and oilseed sunflowers. Field experiments consisted of fixed differences in the number of skips/doubles per plot while maintaining equal total number of plants, and stand gaps with proportional decreasing plant counts. These were conducted in Minnesota, Texas, and Colorado, USA. Experiments revealed that yield was occasionally influenced by heterogeneity, with more uniform stand density yielding higher; however, substantial changes in uniformity of plant density often resulted in no differences in yield. Confectionery sunflowers compensated for yield losses in thinner stands mainly by producing larger seeds (observed range of 0.1%–46.2% of seeds over a 9.53 mm sieve), while oilseed sunflowers increased seed production per head (as shown by invariable test weight across treatments within environments). Plants that were unharvestable for any cause (most often due to head rot disease or lodging) were more prevalent in less uniform stands, and faster canopy closure was achieved in uniformly spaced plants. Although sunflower is very resilient to stand uniformity issues, these findings underscore the importance of uniform sunflower plant spacing for effective weed suppression and crop performance and highlight the need for further research into sunflower yield compensation mechanisms.

Abbreviations: CO19, Burlington, Colorado, 2019; CV, coefficient of variation; DAP, days after planting; EVCI, enhanced vegetation coloration index; G1, 1-m gap; G2, 2-m gap; G3, 3-m gap; G4, two 2-m gap; GCP, ground control points; LAI, leaf area index; LSD, least significant difference; MN19, Moorhead, Minnesota, 2019; MN20, Moorhead, Minnesota, 2020; SD1, 6.25% skips with 6.25% doubles; SD2, 12.5% skips with 12.5% doubles; SD3, 25% skips with 25% doubles; SD4, 37.5% skips with 37.5% doubles; TX19, Dalhart, Texas, 2019; TX20, Dalhart, Texas, 2020; UAV, unmanned aerial vehicle.

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1 | INTRODUCTION

Sunflower (*Helianthus annuus* L.) is a crop that is sown at low population density (35,000–60,000 plants ha⁻¹; NDSU Extension, 2020), relative to other crops, which could make sunflower more sensitive to departures from equal spacing. Common irregularities are skips, doubles, and gaps. Skips and doubles are often caused by unequal seed distribution through poor planter singulation. A skip occurs when no plant exists where one plant is expected, and a double occurs where two

or more plants are present where one plant is expected. Gaps are often caused by planter malfunctions, wildlife, environmental conditions (e.g., crusting and soil moisture issues), or cutworm/wireworm damage.

Yield loss in sunflowers has been attributed to spacing heterogeneity in the few studies that have explored the role of intra-row spacing on sunflower yield and seed quality. Robinson et al. (1982) examined this using repeating patterns of irregular spacing, which allowed for perfect replication of plant spacing. They showed spacing heterogeneity in sunflower can lower yields by as much as 31% with an average 10% yield reduction. Further, their uniform plant density showed the highest yield and oil percentage. They also found that lodging was greater in nonuniform population densities. Differences in seed quality were determined to be of little economic importance.

Huang and Hoes (1980) studied the effect sunflower density has on the incidence of *Sclerotinia* basal stalk rot [caused by *Sclerotinia sclerotiorum* Lib. (de Bary)]. Closer spacings resulted in a higher rate of spread and less time required for infection. Disease incidence increased from 66% for properly singulated plants to 83% for clumps of 7–10 plants.

Huang and Hoes (1980) and Robinson et al. (1982) have shown compelling information regarding the effects of plant spacing heterogeneity on yield. However, much has changed since the early 1980s, including the widespread adoption of vacuum planters and precision planting controls and monitors that very accurately control and report seed spacing (including skips/doubles) and gaps, at least when properly calibrated and monitored. A poorly calibrated modern planter is more likely to result in skips and doubles than clumps of 7–10 plants, usually due to poorly adjusted singulators. Further, the genetics of sunflower hybrids have changed considerably and may exhibit different tolerance of plant spacing than previously observed. Additionally, we have more tools to study the effects of plant spacing heterogeneity, including remote sensing capabilities that allow for simplified, repeated measures of plant canopies throughout the season.

Awais et al. (2017) quantified leaf area index (LAI), a canopy closure statistic, and found it was highly associated with achene yield ($R^2 = 0.95$) and radiation use efficiency for yield ($R^2 = 0.88$) in sunflower grown in a semi-arid environment. Mouillon et al. (2020) compared weed suppression of two sunflower hybrids planted at two population densities, 6.1 and 8.6 seeds m^{-2} . They observed a negative relationship between sunflower plant density and weed biomass ($R^2 = 0.60$, $p = 0.03$). Although no significant differences were found for sunflower yield, the higher density treatment had enhanced weed suppression. These studies show the close relationship that canopy closure has to yield and weed competition in sunflower and could be useful as another metric to understand plant spatial dynamics.

Villalobos et al. (1994) showed how sunflower can compensate for differences in stand density. In their study, the

Core Ideas

- Substantial changes in uniformity of plant density often resulted in no differences in sunflower yield or quality.
- Yield was influenced by heterogeneity in some site-years, with more uniform stand density producing higher yields.
- Unharvestable plants due to disease, lodging, or other losses were more prevalent in less uniform plant populations.
- Faster canopy closure, which is linked to yield and decreased weed competition, occurred in uniformly spaced plots.

number of florets per head and seed mass decreased with increasing plant density. As the rate of increase in total seed number with increased plant density was counterbalanced by the rate of decrease in the number of florets per head and seed size, the yield plateaued when the two rates offset each other. Seed oil content increased with density and varied among hybrids, which was due to a combination of reduced seed mass and small changes in oil content on a per-seed basis.

The objective of this study was to evaluate the effects of plant density heterogeneity on yield, quality, and canopy closure in confectionery and oilseed sunflowers, using modern assumptions and conditions. We used controlled frequency of skips and doubles in sunflower while maintaining the same total plant population to simulate unequal seed distribution that could be encountered with an improperly calibrated vacuum planter. We also employed gap treatments to simulate planter malfunctions, wildlife, or cutworm damage. These methods help overcome the limitations of previous methodologies and provide insights that are more applicable to real-world conditions. Using these experimental conditions, we measured the effect stand heterogeneity has on canopy closure, sunflower yield, and seed quality. We accomplished this using a diverse set of environments across the sunflower growing region in the Great Plains of the United States, and a combination of traditional and high-throughput phenotyping methods, including a method to assess canopy closure in sunflower using data from unmanned aerial vehicle (UAV)-mounted cameras.

2 | MATERIALS AND METHODS

The experiments were conducted during 2019 near Moorhead, Minnesota (Moorhead, Minnesota, 2019 [MN19]; 46.9211 N, −96.6709 W); Dalhart, Texas (Dalhart, Texas, 2019 [TX19]; 36.0665 N, −102.2308 W); and Burlington,

Colorado (Burlington, Colorado, 2019 [CO19]; 39.3195 N, −102.1878 W). Locations in 2020 included Moorhead, Minnesota (Moorhead, Minnesota, 2020 [MN20]; 46.9210 N, −96.6783 W) and Dalhart, Texas (Dalhart, Texas, 2020 [TX20]; 36.0834 N, −102.2122 W). The oilseed hybrid N4H521 CL (NuSeed Americas) and confectionery hybrid RRC 2215 (Red River Commodities) were used in all environments.

The plots were 3.04 m (10 feet) wide by 9.14 m (30 feet) long, with four rows and 76 cm (30 inches) spacing between rows. Each row was seeded with 360 seeds and hand thinned while applying treatments at the V2 plant stage (Schneider & Miller, 1981). Each thinning treatment was assigned to the resulting plots in a randomized, complete block design with four replicates. The treatments included a uniformly distributed control at the target density for the environment, four skip/double treatments, and three gap treatments (with a fourth gap treatment added in 2020). The skip/double treatments have equal skips to doubles, so the plant population remains equal to the uniformly distributed control, and they were placed within the plot at random. The skip/double treatments were 6.25% skips with 6.25% doubles (SD1), 12.5% skips with 12.5% doubles (SD2), 25% skips with 25% doubles (SD3), and 37.5% skips with 37.5% doubles (SD4). The gap treatments were developed identically to the control treatment, with the addition of a 1-m (G1), 2-m (G2), or 3-m (G3) gap to one of the two middle rows at a random position within the plot and not near the edge. In 2020, an additional gap treatment was added with two, co-located 2-m gaps (G4) in the center two rows. The gap treatments are the only ones with a population that deviated from the target population averaged across each plot.

A metal chain with marks made with colored zip ties was used to impose the within-row spacing based on the target population when applying treatments. The target plant population density at the Minnesota location was 54,400 seeds ha^{-1} (22,000 seeds acre^{-1}) for oilseed and 39,500 seeds ha^{-1} (16,000 seeds acre^{-1}) for confectionery. The target plant population for oilseed in Colorado and Texas was 43,000 seeds ha^{-1} (17,500 seeds acre^{-1}) and 37,100 seeds ha^{-1} (15,000 seeds acre^{-1}) for confectionery. The treatments with skips/doubles were first thinned to two plants at each mark. The treatments for single plants or skips were further thinned in a second pass of thinning to one or zero, respectively. Control treatments involved thinning the stand to one plant per chain mark. Gap treatments were constructed similar to the control, except that plants were removed within the boundaries of the gap, which was always located in the middle two rows of the four-row plot (Figure 1).

The treatments were verified within a month of application to remove late emerging plants. Weeds in the plots were controlled manually. The Colorado and Texas sites received supplemental irrigation, as needed. Prior to harvest, the plots

were scouted for disease and lodging issues, and the number of plants affected was counted in the center two rows. The middle two rows of each plot were harvested by hand and threshed using an Almaco LPR stationary thresher (Almaco) to measure yield and seed quality. The seed was dried and cleaned using the Carter-Day fractionating aspirator (Carter-Day International Inc.) and weighed for yield on a dry sample basis (~6.5% moisture at the time of weighing). Test weights were measured by weighing a gravity-fed pint cup for all treatments.

The oilseed hybrid oil percentage was measured on an 80-mL sample of each plot using an MQC Nuclear Magnetic Resonance analyzer (Oxford Instruments) with proprietary workflows and calibration developed from several sunflower hybrids of varying oil content, as independently verified by the Association of Analytical Chemists wet chemistry method 2003.05. Confectionery seed size quality was measured using a stack of four sieves with 9.53, 8.73, 7.94, and 7.14 mm (24/64, 22/64, 20/64, and 18/64 inch, respectively) slotted holes from top to bottom to measure the distribution of seed size in a pint cup (550 mL) sample. Each sieve fraction is determined on a mass basis. Hull length and width were measured by X-raying a sample of 25 seeds per plot using a Faxitron Pro X-ray Cabinet (Hologic Inc.). The X-ray images were converted to length and width data using ImageJ 1.5.3 with the parameters and pipeline shown in Figure S1. The thresholding values were visually set using the sliding contrast bars to preserve the shape of the achene. The eroding step removes small pixels that would cause error, and the dilating step restores the image to full scale.

A UAV was used to determine canopy cover at the Moorhead, MN, site at multiple time points throughout the 2019 and 2020 seasons. The UAV was a model Matrice 100 (DJI) with a multispectral Micasense RedEdge MX sensor (MicaSense). Flights were planned with the DJI Ground Station Pro 2.0.15 (DJI) mission planner. Images were processed using Agisoft PhotoScan Professional 1.7.5 (Agisoft LLC). The orthomosaic maps were analyzed using ArcGIS Pro 2.8.3 (ESRI).

Both study sites were mapped with 75% front overlap and 75% side overlap at 13 m above ground level. The MicaSense RedEdge MX reflectance calibration was performed pre-flight and post-flight. Each site had six ground control points (GCPs) made from 18.9-L (five gallon) bucket lids. A 30-cm spike was used to anchor each GCP for the duration of the season.

The images were radiometrically calibrated in Agisoft using the calibrate reflectance tool, which automatically uses values from the MicaSense reflectance panel. The images were stitched in Agisoft to make an orthomosaic of the entire study area. Each map was aligned using the georeference tool in ArcGIS (Supporting Information 1). The GCPs were used during affine transformation so that the repeated measures

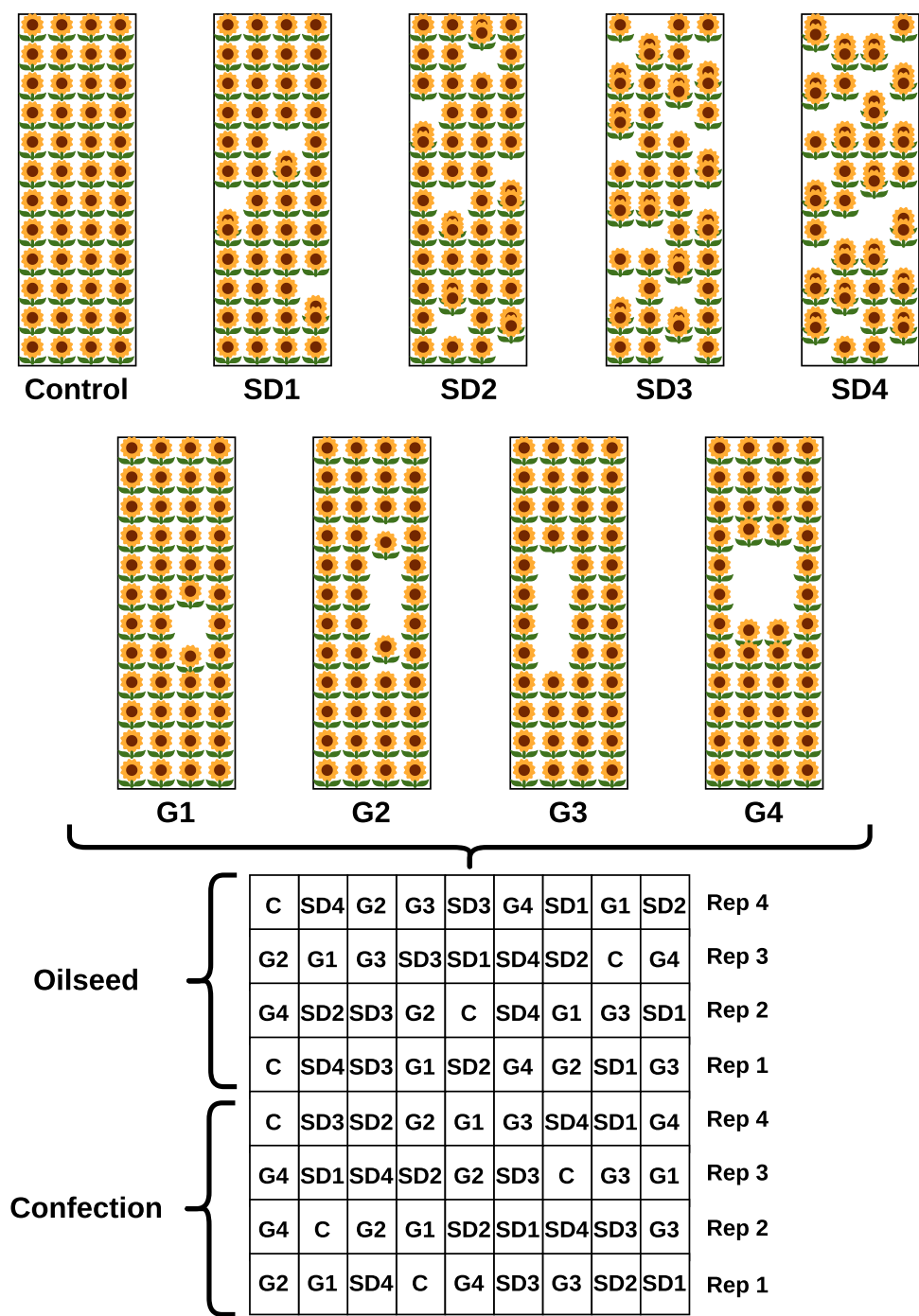


FIGURE 1 Diagram of the field experimental design. The upper portion of the diagram shows an abstraction of the sunflower spacing treatments imposed on the plots. The ratio of skips and doubles and the length of the gap treatments are shown to scale, although the total number of plants shown in the diagram is less than the actual number of plants in each treatment. The center two rows of each plot were harvested for data collection. The lower portion of the diagram shows an example of a plot randomization for one environment of the study.

could be aligned for change detection analysis in ArcGIS. Affine transformation was used to better preserve the shape of the map while aligning the maps. A polygon shapefile was created in ArcGIS to trace the perimeter of each plot. The normalized digital vegetation index was generated to increase contrast between pixels indicating plants and background

noise. In some cases, an enhanced vegetation coloration index (EVCi) generated by the formula,

$$EVCi = \frac{NIR - Blue}{Red} \times Green \tag{1}$$

increased the contrast between plant pixels and corn stover.

The ISO cluster unsupervised classification tool was used to classify the pixels using default parameters with four classes. Pixels that are classified as plants were selected. The raster to polygon tool converted selected pixels into a polygon shapefile. The pairwise clip tool was used to clip the shapefile so that plant pixels that were outside a plot were removed. The multipart to singlepart tool was used to split the plant polygons in the shapefile into individual polygons. This allows the plant canopy area to be calculated per plot and not as a field total. The area was calculated by the area geodesic option which requires a column with double value to be created in the attribute table.

The summarize within tool from the analysis toolbox summed the area of plant polygons within each plot polygon. The spatial join tool from the analyst toolbox was used to merge these attribute tables by the location. A new column was created in the attributes table of the joined tables. This column was used to calculate the plant canopy.

$$\text{Percent canopy} = \frac{\text{Area of plant}}{\text{Area of plot}} \times 100. \quad (2)$$

This process was repeated for each collection date.

All data except percent canopy were analyzed using the GLM procedure in the SAS 9.4 software (SAS Institute). Models included effects for replication and treatment and were analyzed separately for confectionery and oilseed type in each environment. Tukey-adjusted least significant differences (LSDs) were calculated at the 95% confidence level for mean comparisons.

For percent canopy, repeated measures were taken at several dates after planting (DAP) to measure the temporal dynamics of canopy closure. An arcsine square root transformation of percent canopy was used to normalize the distribution of percentage cover data. A linear model using the MIXED procedure (SAS Institute) was used to analyze the resulting data. The fixed effects were treatment, time, and their interaction, with time treated as a repeated measure with an unstructured covariance matrix. Replication was a random effect in the model. Similarly, the analysis was also run by time points, with treatment as a fixed effect and replication as a random effect. The Tukey-adjusted LSDs were calculated at the 95% confidence level for mean comparisons. Analyses were conducted separately for confectionery and oilseed types in each year.

3 | RESULTS

Due to some plots exhibiting inconsistent emergence, it was not possible to place full treatments at every site-year. When plots were lost, the control and more extreme heterogeneity treatments were kept. The CO19 site-year consisted of the control, G3, G2, SD3, and SD4 treatments for confectionery.

The TX19 site-year did not have the G1 or SD1 treatments for both confectionery and oilseed. The TX20 also did not have the G1 treatment for confectionery and oilseed. All other sites had the complete set of treatments.

No significant differences were found among treatments for any measured phenotype within the CO19, TX19, and TX20 confectionery trials, or the CO19 and TX20 oilseed trials (Tables S1–S4).

Percent canopy closure (in units of crop cover m^2 land area $\text{m}^{-2} \times 100$) was measured in the MN19 and MN20 site-years using UAV-mounted sensors. The control always had the highest measured percent canopy closure at each DAP for both oilseed and confectionery. This was expected because the control was properly singulated, and the plants do not have to compensate for a gap or skip (Figure 2). Treatments with more severe gaps and skips had significantly slower canopy closure than the control. The MN19 oilseed G2, SD3, SD4, and G3 treatments were 1.4, 1.4, 1.9, and 3.2 units, respectively, less canopy closure than the control at 64 DAP. The MN19 confectionery G3 and SD4 treatments were 2.7 and 3.2 units, respectively, less than the control at 64 DAP. The MN20 oilseed G3 and G4 treatments were 4.4 and 4.7 units, respectively, under the control at 62 DAP. The MN20 confectionery SD4 and G4 treatments were 2.6 and 3.0 units, respectively, under the control at 62 DAP. Treatments with a greater percent of their plot having small gaps such as the SD4 treatment or a larger gap such as the G4 treatment, in general, had less and slower canopy closure than the control.

Plants that could not be harvested due to lodging or disease were counted and included in a category of unharvestable plants. For the MN19 site-year, all the gap oilseed treatments had fewer unharvestable plants than the SD4 treatment (Table 1).

The treatment effects for yield at individual site-years were not significant in most cases for oilseed and were never significant for confectionery (Tables S1–S6). Oilseed yields exhibited significant treatment differences in the TX19 and MN20 site-years (Table 2). At the TX19 site, the yield for the SD2 treatment was greater than the control or G3 treatments. The yield for the G4 treatment was less than the SD1, SD2, G2, and control treatments at the MN20 site.

The confectionery test weight for the SD1 treatment was less than the G4 treatment at the MN20 site (Table 3). No significant differences were found for confectionery hull length or width measured using ImageJ. Differences were found for the similar measure of confectionery seed size (i.e., using sieves). For the 9.53-mm sieve size, the G4 treatment was greater than the G2 treatment at the MN20 site-year but similar to the other treatments (Table 3). With respect to seed oil percentage in the oilseed hybrid, the G2 and SD3 treatments had greater seed oil percent than the control, SD2, SD4, and G3 treatments at the TX19 site-year (Table 4).

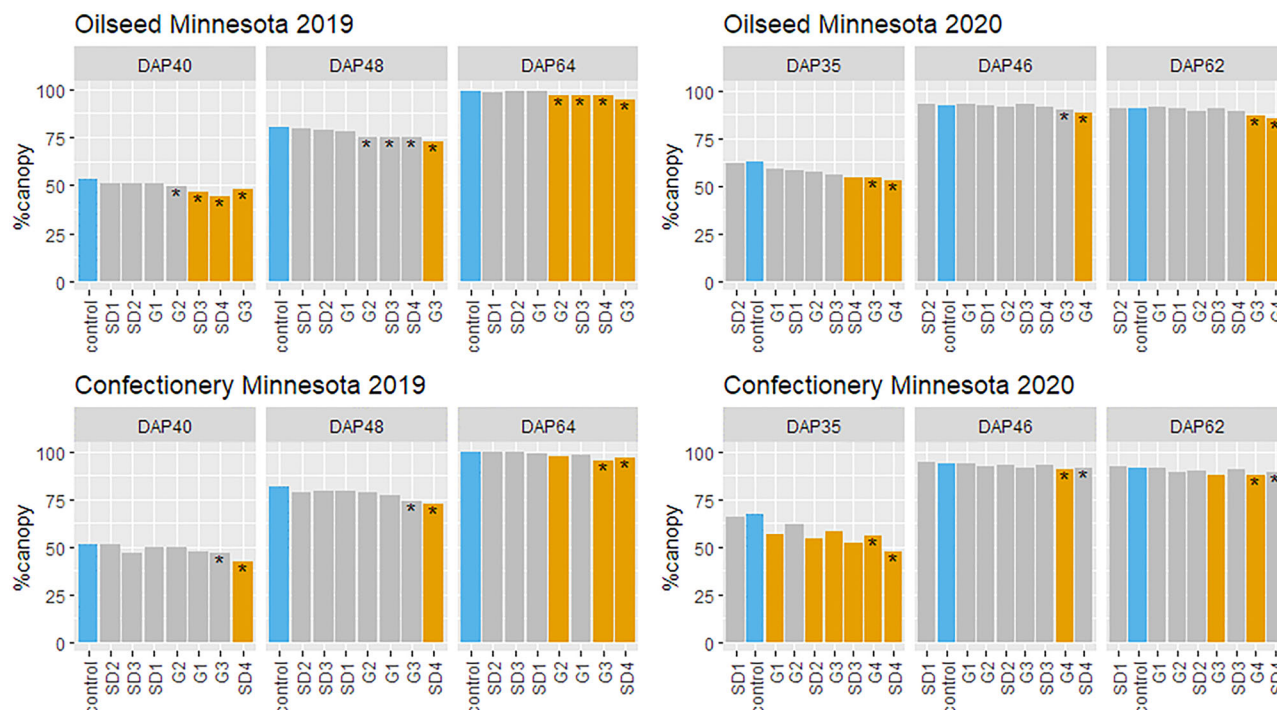


FIGURE 2 Sunflower percent canopy closure (in units of crop cover m^2 land area $\text{m}^{-2} \times 100$) by site-year and market type in response to imposed conditions of skips/doubles or gaps in plant density (Minnesota USA, 2019 and 2020). The plant spacing treatments are arranged from left to right rankwise by the final measured value. Orange bars are significantly different from the control (blue) within dates of measurement. An asterisk (*) at the top of a bar denotes treatments that are significantly different from the control in the repeated measures analysis pooled across dates of measurement, within each growing season and market type.

TABLE 1 Comparison of unharvestable plant averages in response to imposed conditions of skips/doubles or gaps in plant density (oilseed sunflower; Minnesota USA, 2019).

Treatment	MN19 (Plants ha^{-1})
Control	11,300 ab
SD1	12,200 ab
SD2	10,600 ab
SD3	11,800 ab
SD4	15,200 b
G1	8790 a
G2	7530 a
G3	7180 a
G4	—
LSD (0.05) ^a	5760
CV	22.9

Note: Means with the same letter are not significantly different; letters are organized in alphabetical order from treatment of the best performance. Dash indicates the treatment was not applied for this site-year due to sunflower seedling emergence issues in some plots.

Abbreviations: CV, coefficient of variation; G1, 1-m gap; G2, 2-m gap; G3, 3-m gap; G4, 2- to 2-m gap; LSD, least significant difference; MN19, Moorhead, Minnesota, 2019; SD1, 6.25% skips with 6.25% doubles; SD2, 12.5% skips with 12.5% doubles; SD3, 25% skips with 25% doubles; SD4, 37.5% skips with 37.5% doubles.

^aTukey's minimum significant difference ($p = 0.05$).

TABLE 2 Average yields in environments where significant differences among plant spacing treatment (skips/doubles or gaps) were observed (oilseed sunflower; Texas USA, 2019, and Minnesota USA, 2020).

Treatment	TX19 (kg ha^{-1})	MN20 (kg ha^{-1})
Control	2660 b	2950 a
G1	—	2900 ab
G2	2870 ab	2930 a
G3	2590 b	2850 ab
G4	—	2680 b
SD1	—	2960 a
SD2	3180 a	2970 a
SD3	3010 ab	2890 ab
SD4	2850 ab	2910 ab
LSD (0.05) ^a	483	241
CV	7.4	3.5

Note: Dash indicates the treatment was not applied for this site-year due to sunflower seedling emergence issues in some plots. Means with the same letter are not significantly different; letters are organized in alphabetical order from treatment of the best performance.

Abbreviations: CV, coefficient of variation; G1, 1-m gap; G2, 2-m gap; G3, 3-m gap; G4, 2- to 2-m gap; LSD, least significant difference; MN20, Moorhead, Minnesota, 2020; SD1, 6.25% skips with 6.25% doubles; SD2, 12.5% skips with 12.5% doubles; SD3, 25% skips with 25% doubles; SD4, 37.5% skips with 37.5% doubles; TX19, Dalhart, Texas, 2019.

^aTukey's minimum significant difference ($p = 0.05$).

TABLE 3 Test weight and screening size (percentage of seeds over sieve) of confectionery sunflower seed in response to plant spacing treatments (skips/doubles or gaps; Minnesota USA, 2020).

Treatment	Test weight (kg m ⁻³)	Sieve size (mm)			
		9.53 (% over sieve)	8.73 (% over sieve)	7.94 (% over sieve)	7.14 (% over sieve)
Control	277 ab	5.6 ab	36.1 a	79.5 a	96.6 a
SD1	269 b	4.5 ab	33.5 a	77.5 a	95.7 a
SD2	277 ab	6.3 ab	36.5 a	80.0 a	95.7 a
SD3	278 ab	5.0 ab	35.6 a	77.8 a	94.7 a
SD4	271 ab	4.9 ab	40.9 a	82.4 a	96.1 a
G1	275 ab	5.6 ab	36.5 a	79.8 a	95.8 a
G2	275 ab	2.8 b	29.9 a	78.3 a	95.9 a
G3	282 ab	5.4 ab	36.2 a	81.3 a	95.2 a
G4	282 a	8.0 a	40.8 a	80.6 a	95.2 a
LSD (0.05)	8	3.9	ns	ns	ns
CV	2.0	30.2	15.1	3.5	1.3

Note: Means with the same letter are not significantly different; letters are organized in alphabetical order from treatment of the best performance.

Abbreviations: CV, coefficient of variation; G1, 1-m gap; G2, 2-m gap; G3, 3-m gap; G4, 2- to 2-m gap; LSD, least significant difference; SD1, 6.25% skips with 6.25% doubles; SD2, 12.5% skips with 12.5% doubles; SD3, 25% skips with 25% doubles; SD4, 37.5% skips with 37.5% doubles; ns, not significant.

TABLE 4 Average mass of sunflower seed oil per kg of seeds in response to plant spacing treatments (skips/doubles or gaps; Texas USA, 2019).

Treatment	TX19 (g kg ⁻¹)
Control	400 b
SD1	—
SD2	396 b
SD3	416 a
SD4	400 b
G1	—
G2	416 a
G3	397 b
G4	—
LSD (0.05) ^a	14
CV	1.5

Note: Means with the same letter are not significantly different; letters are organized in alphabetical order from treatment of the best performance. Dash indicates the treatment was not applied for this site-year due to sunflower seedling emergence issues in some plots.

Abbreviations: CV, coefficient of variation; G1, 1-m gap; G2, 2-m gap; G3, 3-m gap; G4, 2- to 2-m gap; LSD, least significant difference; SD1, 6.25% skips with 6.25% doubles; SD2, 12.5% skips with 12.5% doubles; SD3, 25% skips with 25% doubles; SD4, 37.5% skips with 37.5% doubles.

^aTukey's minimum significant difference ($p = 0.05$).

4 | DISCUSSION

The G4 treatment at the MN20 site had a significantly lower percent canopy closure (Figure 2) and yield (Table 2) than the control. This result aligns with Awais et al.'s (2017) study, where canopy closure had a very close association with yield ($R^2 = 0.95$). Canopy closure was an important component in

the integrated weed management program in Mouillon et al.'s (2020) study. Their results showed that a higher sunflower density negatively correlated to weed biomass and positively correlated to yield. In our study, the treatments with more uniformly spaced plants reached canopy closure at a faster rate because they do not have to compensate for gaps or skips. A faster canopy closure will aid in early weed suppression. However, the treatments at MN19 and MN20 were weed-free (hand weeded). It is possible that there could have been more treatment differences had the treatments been subjected to weed pressure, which can occur in producers' fields.

The treatments with significantly worse canopy closure than the control suggest that under certain, less optimal conditions, we may see greater yield loss with more extreme gaps and stand heterogeneity, just as we did with the larger gap treatments with our oilseed hybrid in MN20 and TX19. However, it is clear that the considerable deviation from properly singulated populations that these treatments represent would be uncommon except under extreme circumstances (i.e., very high pest pressure or extreme drought at planting). Producers with modern equipment would quickly observe planter issues that would reduce population (i.e., cause gaps due to mechanical malfunction) and also notice deviation from single seed drop. It is also noteworthy that site-year yield coefficients of variation (CVs) are very low due to the careful methods we employed in this study, which suggests that our inability to find significant differences among treatments is unlikely to be an issue of statistical power.

Skip and double treatments were more susceptible to in-season reduction in harvestable stand. In the oilseed MN19 site-year (Table 1), the SD4 treatment had significantly more unharvestable plants than the gap treatments. The gap

treatments do not have doubles and are uniform except where the gap was applied, but they are also the only treatments that had fewer plants by design. The MN19 site-year had the conditions most favorable for necrotrophic disease and lodging (i.e., more late season storm events), and as expected, the unharvestable plants in the SD4 treatment were caused by lodging or white mold (caused by *Sclerotinia sclerotiorum* (Lib.) deBary head or stalk rot infection), typically of the weaker double plants.

The findings in this study corroborate the findings of Robinson et al. (1982) and Huang and Hoes (1980), in that lodging and disease incidence occurred more frequently when stands were less uniform and/or had doubles. It is reasonable that doubles combined with high winds and/or sufficient disease pressure could result in some environments with enough unharvestable plants to cause yield loss. Thus, increased stand heterogeneity with any combination of factors that increase in-season reduction in harvestable stand could result in yield loss in locations where these stresses are severe, although we did not find that to be the case in MN19.

Seed quality traits were affected in somewhat predictable ways in confectionery sunflower. The screening size measurement for confectionery seed was taken by weighing a pint cup sample and recording the cumulative weight retained by successively smaller sieves as a percent of the pint cup sample. On the 9.53-mm sieve size, the largest gap treatment, G4, had the most confectionery seeds retained at the MN20 site. This treatment also had the highest test weight in this environment as well (Table 3). This is consistent with confectionery sunflowers compensating for plant population gaps by having an increase in seed size with lower plant populations. Confectionery sunflower producers already decrease plant populations relative to oilseed sunflowers to increase seed size and, thereby, value in that market class (NDSU Extension, 2020).

Meanwhile, seed quality traits for oilseed were less predictable in the one environment where differences were observed, TX19. No consistent trend was observed for oil content; however, it is noteworthy to mention that the instrumentation used for seed oil content is very sensitive, as exhibited by the very low coefficient of variation (1.5%). The small differences observed, if biological in nature, would impact a producer's economics very little.

This study investigated the impact of plant spacing heterogeneity on the yield, quality, and canopy characteristics of confectionery and oilseed sunflowers under a variety of simulated planter error and field conditions. Uniform plant spacing is critical in maximizing yield, minimizing risks associated with lodging and disease, and achieving faster canopy closure for effective weed suppression. Sunflowers demonstrated seemingly extreme compensatory mechanisms for yield losses resulting from lower plant populations, without negatively impacting seed quality traits. These results show that sun-

flowers can withstand a significant degree of reduction in harvestable stand before yield is reduced, and this reduction in yield appears to be predictable by canopy closure data. Further physiological research into sunflower yield compensation due to disruptions at different time points throughout the growing season (e.g., mid-season hail damage) will help us understand the limits of sunflower adaptability and, perhaps, increase sunflower adaptability for plant spacing issues through breeding efforts.

AUTHOR CONTRIBUTIONS

Neil A. Olson: Investigation; methodology; software; visualization; writing—original draft. **Calvin Trostle:** Conceptualization; funding acquisition; investigation; project administration; writing—review and editing. **Ronald Meyer:** Conceptualization; funding acquisition; investigation; project administration; writing—review and editing. **Brent S. Hulke:** Conceptualization; funding acquisition; investigation; methodology; project administration; software; supervision; visualization; writing—original draft.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data from the experiments are available at the National Agricultural Library – Ag Data Commons, <https://doi.org/10.15482/USDA.ADC/c.7320344>.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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