Sowing date and sowing method influence on camelina cultivars grain yield, oil concentration, and biodiesel production

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Abstract

Sowing date and sowing method can have a profound influence on the productivity of alternative crops like camelina in semiarid agroecosystems. The objective of this study was to determine the effects of sowing date, sowing method, and cultivar on morphology, phenology, grain yield, oil concentration, oil, and biodiesel production of camelina. A 2-year study was carried out at the University of Nevada, Reno Main Station Field Laboratory, during the spring to early summer of 2016 and 2017. Treatments were two sowing dates (SD) of 18 March 2016 (early SD) and 17 April 2016 (late SD) in Year 1 and 11 April 2017 (early SD) and 11 May 2017 (late SD) in Year 2. The change in SD in the second year was due to the excessively wet field condition preventing land preparation and sowing. There were two sowing methods (SM) imposed (broadcast and drill) and three cultivars of camelina (Blaine Creek, Columbia, and Pronghorn) arranged in a 3 × 2 × 2 factorial in a randomized complete block design experiment with four replications. Responses were considered different if $p < 0.05$. Grain yield of camelina was influenced by SD in Year 1 and SD × SM interaction in Year 2. In Year 1, grain yield was greater for early (921 kg/ha) compared to late SD (503 kg/ha, SE = 101). In Year 2, for early SD grain yield was not different between SM (average = 594 kg/ha), but for late, it was greater for drill (676 kg/ha) than broadcast (130 kg/ha, SE = 75). For broadcast SM, grain yield was greater for early (587 kg/ha) compared to late SD (130 kg/ha, SE = 75), but for drill SM, grain yield was not different between SD (average = 639 kg/ha). Oil concentration was affected by SD in both years, and in Year 1, for example, it was greater for drill (676 kg/ha) than broadcast (130 kg/ha, SE = 75). For broadcast SM, grain yield was greater for early (587 kg/ha) compared to late SD (130 kg/ha, SE = 75), but for drill SM, grain yield was not different between SD (average = 639 kg/ha). Oil concentration was affected by SD in both years, and in Year 1, for example, it was greater for early (295 g/kg) versus late SD (284 g/kg SE = 2.7). Both oil and biodiesel production followed a similar pattern to grain yield in this study. Based on the magnitude of differences observed in both years of this study, late SD and broadcast sowing are not viable options for farmers who want to venture into camelina production in Nevada.

Key words
biodiesel, camelina cultivar, grain yield, oil concentration, sowing date, sowing method
1 | INTRODUCTION

The global focus on energy security along with efforts to lower greenhouse gas emissions has propelled many governments to establish stringent policies on cleaner energy production, particularly biofuels’ production targets and utilization, coupled with sustained efforts that focused on research and development of bioenergy crops (e.g., Glithero, Ramsden, & Wilson, 2012; Radzi & Droge, 2014; Wright, 2006). One such crop that has gained a revived interest is the ancient oilseed crop camelina (Camelina sativa [L.] Crantz) as a high potential feedstock for biodiesel and jet fuel production (Vollmann & Eynck, 2015). Some competitive advantages offered by camelina are its short growth cycle, low fertilizer input requirements for optimum grain production (Putnam, Budin, Field, & Breene, 1993), low water requirements relative to canola (Gao, Caldwell, & Jaing, 2018), its unique oil composition and properties (Berti, Gesch, Eynck, Anderson, & Cermak, 2016), its ability to thrive successfully on marginal lands (McKenzie, Smallfield, Fasi, & Martin, 2011), and therefore diminish competition for traditional agricultural farmlands needed for food and feed production (Chen, Bekkerman, Afshar, &Neill, 2015). First-generation biofuel crops like corn, canola, and soybean are under scrutiny because of their direct competition for food and feed production (Mohr & Raman, 2013; Ziolkowska, 2014). Therefore, camelina, a crop not widely utilized for its food value, can minimize the negative impact on the food production chain (Yang, Caldwell, Corscadden, He, & Li, 2016) and may be deemed less controversial in the food versus fuel debate (Naik, Goud, Rout, & Dalai, 2010). These characterizations make camelina a valuable alternative crop for semiarid and arid environments where water deficits and marginal lands are a direct challenge to traditional agricultural crops’ production.

Apart from the limitation of water availability, there are multiple agronomic factors that challenge sustainable agriculture production in semiarid and arid environments. The date and method of sowing are two such factors that are known to alter crop productivity globally (Aiken, Baltensperger, Krall, & Pavlista, 2015; Fasi, Martin, Smallfield, & McKenzie, 2012; Schillinger, Wysocki, Chastain, Guy, & Karow, 2012; Sieling, Böttcher, & Kage, 2017). In semiarid environments like northern Nevada, cultivation of spring crops can be curtailed by environmental circumstances at the recommended time of sowing. Typically, late February to late March has been recommended as the ideal time for the sowing of spring crops in northern Nevada because of the favorable temperature and soil moisture. However, a major challenge during spring crop cultivation is the inclement weather patterns and the time when water is released for agricultural irrigation. For example, delay in agricultural operations (e.g., land preparation) for sowing is a common occurrence in northern Nevada due to the unpredictable heavy snowfalls, snowpacks, and rapid snowmelt that are of frequent occurrences during mid-February to late March period. Further, low soil temperatures that occur frequently during this period can stymie crop development and ultimately crop productivity (Urbaniak, Caldwell, Zheljzakov, Lada, & Luan, 2008). One approach that may mitigate this effect on timely land preparation and sowing is delayed sowing of bioenergy crops like camelina to a later date when conditions are more ideal for land preparation and sowing. The literature on how sowing date affects multiple crops is quite comprehensive, and the majority reviewed by these authors indicated that a delay in sowing by at least 30 days after optimal sowing dates resulted in lower grain yield irrespective of crop species used (e.g., Adamsen & Coffelt, 2005; Bastidas et al., 2008; Dose, Eberle, Forcella, & Gesch, 2017; Gesch, 2013; Hocking & Stapper, 2001; Pal, Mahajan, Sardana, & Chauhan, 2017). This decline in grain yield of late sowing spring crops has been attributed to the prevailing moisture conditions at the time of sowing, shorter growth duration between sowing and flowering, and heat stress that lead to a restriction in reproductive development, that is, a reduction in the number of flowers, pods, and the number and size of seeds per pod (Adamsen & Coffelt, 2005; Farré, Robertson, Walton, & Asseng, 2002).

Another integral consideration is the method of sowing, for example, whereby broadcasting can alleviate some of the pitfalls associated with drill seeding on moist land, reduce sowing duration on large cultivated areas (Ball, 1986), and also can reduce substantially the overall production cost associated with bioenergy crop production if optimum establishment were to occur. However, broadcasting has its challenges. For example, poor seed-to-soil contact limits germination and successful stand establishment resulting in suboptimal crop yield due to lower plant population density (Beatty, Eldridge, & Simpson, 1982). In conditions of northern Nevada where wind gust can reach a velocity of 25 miles/hr can cause displacement of the sown seeds for small-seeded crops like camelina and, thus, reduce stand establishment or even result in complete crop failure. Further, for broadcast sowing, the utilization of greater quantity of seed per unit area of land is a common recommendation relative to drill seeding, but this has the potential of increasing the overall production cost, thereby affecting the profitability of bioenergy crops like camelina.

The development of agronomic best management practices has been one of the central themes of feedstocks production globally to assure an economic and environmentally sustainable supply of feedstock materials (e.g., Radzi & Droge, 2014). Any factor that affects the yield of these bioenergy crops will have a simultaneous negative impact on their profitability. To date, there has been a dearth of information on studies focusing on sowing date and method interaction on camelina productivity in semiarid irrigated systems of Nevada. Therefore, this study focusing on
sowing date and method sought to provide a mechanism to elucidate valuable information on cultivation practices for camelina production in semiarid irrigated agroecosystems. The objective of this study was to determine the effects of sowing date, sowing method, and cultivar on camelina morphology, phenology, grain yield, oil concentration, oil, and biodiesel production.

### 2 | MATERIALS AND METHODS

#### 2.1 | Site description and weather conditions

This 2-year field trial was conducted at the University of Nevada, Reno Main Station Field Laboratory, Reno, NV (39°30′ N, 119°44′ W, and altitude of 1,339 m) during the spring to early summer growing seasons of 2016 (Year 1) and 2017 (Year 2). At the experimental site, the soil is classified as a Truckee silt loam (a fine-loamy, mixed, superactive, mesic Fluvaquentic Haploxerolls). Before the experiment commenced during each growing season, soil samples were randomly collected to a depth of 15 cm across the experimental sites and composited prior to soil analysis being carried out at a commercial laboratory (A & L Western Agricultural Laboratories, Modesto, CA). There were variations in soil chemical characteristics, particularly nitrate-N, P, K, Ca, Mg, and Na between site-year of this experiment (Table 1). Weather data during the months of the growing seasons were recorded for accumulated monthly precipitation, evapotranspiration (ET), mean monthly air temperature, solar radiation, and accumulated monthly growing degree days (GDD) from the Western Regional Climate Center, Desert Research Institute Weather Station located approximately 1,000 m from the research plots along with their corresponding 30-year average monthly values from the U.S. Climate Data, Reno, NV (Table 2). For the two years in which this study was carried out, the summed monthly precipitation, ET, mean air temperature, monthly accumulated GDD varied for each growing season relative to the 30-year average, but mean solar radiation did not deviate widely across the two growing seasons (Table 2; Figure 1). Cumulative supplemental irrigation over the growing season from sowing to harvest was 343.1 and 470.1 in 2016 and 330.1 and 481.3 mm in 2017 for late and early sowing dates, respectively (Figure 1).

### 2.2 | Treatments and experimental design

The treatments used in this experiment were two sowing dates (SD) on March 18 (early SD) and April 17 (late SD) during the 2016 growing season and for the 2017 growing season, April 11 (early SD) and May 11 (late SD), which corresponded to a month apart. The change in SD in the second year was a result of heavy snowfall and snowmelt in February to late March, which caused flooding at the experimental site, and thus, sowing was delayed until conditions were suitable for land preparation and sowing operation. There were two sowing methods (drill and broadcast), and three camelina cultivars (“Blaine Creek,” “Pronghorn,” and “Columbia”). These treatments were arranged in a 3 × 2 × 2 factorial combination of a randomized complete block design experiment with four replications of each treatment combination.

### 2.3 | Plot establishment and management

Glyphosate [(N-(phosphonomethyl) glycine] was applied at a rate of 1.12 kg a.i. per ha to control weeds before seedbed preparation and sowing. On the scheduled SD, a seeding rate of 5 kg/ha was used in both years for both the drill- and broadcast-seeded treatments using a Plotseed XL plot seeder (Wintersteiger AG., Ried im Innkreis, Austria). For the drill-seeded treatment, seeds were placed at 1 cm depth with a 20-cm row spacing, and for the broadcast-seeded treatment, the planter was raised six inches above the ground and all tubes were separated from each disk before planting. A light ring roller was used to improve seed-to-soil contact on the broadcast-seeded plots. A total of 48 plots were used in both years of this study, and plot size for both drill and broadcast sowing was 7.62 m long by 1.83 m wide with 1.5-m alleyway between blocks. Nitrogen fertilizer using urea (46-0-0) during both years was applied at a rate of 80 kg N per ha, and based on soil test results, P was applied at an application the rate of 40 kg/ha as triple superphosphate (0-45-0). Based on soil test recommendation, no K fertilizer was applied in both years of the study. The N and P fertilizers were applied as a single application two weeks after germination for each SD using a 65-Series Adjustable Slotted Bottom fertilizer spreader (Gandy Company, Owatonna, MN, USA). Postemergence weed control was carried out manually for broadleaf weeds because there is no broadleaf herbicide labeled for use on camelina while Sethoxydin

#### Table 1 Soil chemical characteristics at the research sites prior to seeding camelina during the spring growing seasons of 2016 and 2017 at the University of Nevada, Reno Main Station Field Laboratory in Reno, NV, USA

| Year   | Organic matter (g/kg soil) | pH  | CEC Meq/100 g | NO₃-N (mg/kg soil) | P  | K  | Ca  | Mg  | Na  |
|--------|---------------------------|-----|---------------|-------------------|----|----|-----|-----|-----|
| 2016   | 61.0                      | 7.8 | 26.2          | 25.0              | 12.0 | 568 | 3,737 | 602 | 265 |
| 2017   | 55.0                      | 7.8 | 26.3          | 9.0               | 22.0 | 682 | 3,705 | 620 | 220 |
(Poast) (2-[1-(ethoximino) butyl]-5-[2-(ethylthio)-propyl]-3-hydroxy-2-cyclohexen-1-one) was used at a rate of 0.5 kg a.i. per ha against grass weeds. Supplemental irrigation was provided once every 7 days from a solid-set sprinkler irrigation system using aluminum pipe (76.2 mm diameter) and galvanized risers (19.05 × 12.7 mm diameter) at 1,372 mm above the soil surface. Each riser was fitted with a 12.7-mm plastic Xcel-Wobbler nozzle (Senninger Irrigation Inc., Clermont, FL, USA) and water pressure set at 207 kPa for a distribution radius of 9.1 m throughout the growing season. Weekly irrigation amount was administered based on grass reference ETo using the FAO Penman–Monteith method (data collected from the weather station at the experimental site) and crop coefficients developed for camelina at different growth stages (Hunsaker, French, Clarke, & El-Shikha, 2011).

Supplemental irrigation of experimental plots was terminated 2 weeks prior to seed harvesting for each sowing date.

2.4 | Data collection and calculations

Field measurements on each experimental unit were carried out at 60 days after sowing for the following parameters of light interception (LI) using a LI-191 SA Quantum sensor (LI-COR Biosciences Inc., Lincoln, NE, USA) connected to a LI-1500G datalogger (LI-COR Biosciences Inc., Lincoln, NE, USA), leaf area index (LAI) using a LAI-2200C Plant Canopy Analyzer (LI-COR Biosciences Inc., Lincoln, NE, USA), and chlorophyll index (SPAD) using a SPAD-502 Plus Chlorophyll Meter (Minolta, Spectrum Technologies Inc., Aurora, IL). The number of days after sowing to flowering (DASF) was recorded when a visually estimated 50% of the plant population in each plot reached anthesis. Also, the number of days after sowing to physiological maturity (DASM), that is, when greater than 50% of pods in each plot turned brown in color, was recorded for each experimental unit. Growing degree days (GDD) was used to describe the timing of flowering and physiological maturity of camelina and was computed by using the formula described below by McMaster and Wilhelm (1997).

\[
\text{GDD} = \sum_i \frac{T_{\text{max}} + T_{\text{min}}}{2} - T_{\text{base}},
\]

where \(T_{\text{max}}\), \(T_{\text{min}}\), and \(T_{\text{base}}\) represent daily maximum, minimum air temperature, and the base temperature respectively. A base temperature of 5°C was used for GDD computation as was suggested by Aiken et al. (2015).

Plant height was measured from the surface of the soil to the highest point on five randomly selected plants in each experimental unit at the time of harvest based on SD. Plant population count was done only in the second year of the study due to an oversight on our part from each experimental unit immediately after seed harvest. A 1-m² wireframe quad- rat was used to count plant stand in two randomly selected...
| Source of variation | df | LI  | LAI | SPAD | PH   | Branch | Pod  | Seed | TSW | PP* | DASF | DASM | GDDF | GDDM | GY   | HI  | OC  | OP  | BP  |
|---------------------|----|-----|-----|------|------|--------|------|------|-----|-----|------|------|------|------|------|-----|-----|-----|-----|
| **p Value, 2016 (Year 1)** |    |     |     |      |      |        |      |      |     |     |      |      |      |      |      |     |     |     |     |
| SD                  | 1  | <0.001 | 0.691 | <0.001 | 0.342 | 0.016 | 0.398 | 0.276 | —   | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | 0.037 | 0.002 | <0.001 | <0.001 |
| SM                  | 1  | 0.005 | 0.119 | 0.430 | 0.887 | 0.928 | 0.942 | 0.122 | 0.675 | —   | 0.455 | 0.889 | 0.568 | 0.325 | 0.853 | 0.383 | 0.354 | 0.875 | 0.875 |
| C                   | 2  | 0.022 | 0.651 | <0.001 | 0.766 | 0.010 | 0.003 | 0.834 | 0.017 | —   | 0.317 | 0.872 | 0.824 | 0.379 | 0.859 | 0.394 | 0.962 | 0.827 | 0.827 |
| SD × SM             | 1  | 0.001 | 0.353 | 0.405 | 0.411 | 0.186 | 0.826 | 0.152 | 0.780 | —   | 0.455 | 0.889 | 0.849 | 0.325 | 0.689 | 0.952 | 0.943 | 0.645 | 0.645 |
| SD × C              | 2  | 0.088 | 0.003 | 0.696 | 0.127 | 0.215 | 0.026 | 0.108 | 0.854 | —   | 0.246 | 0.692 | 0.639 | 0.379 | 0.176 | 0.474 | 0.398 | 0.201 | 0.201 |
| SM × C              | 1  | 0.043 | 0.011 | 0.978 | 0.017 | 0.518 | 0.860 | 0.218 | 0.105 | —   | 0.029 | 0.080 | 0.973 | 0.379 | 0.672 | 0.958 | 0.711 | 0.617 | 0.617 |
| SD × SM × C         | 2  | 0.053 | 0.543 | 0.944 | 0.865 | 0.939 | 0.586 | 0.250 | 0.670 | —   | 0.015 | 0.098 | 0.261 | 0.379 | 0.836 | 0.835 | 0.100 | 0.774 | 0.774 |
| **p Value, 2017 (Year 2)** |    |     |     |      |      |        |      |      |     |     |      |      |      |      |      |      |     |     |     |     |
| SD                  | 1  | 0.319 | 0.001 | <0.001 | 0.424 | 0.004 | <0.001 | 0.643 | 0.908 | 0.073 | <0.001 | <0.001 | <0.001 | <0.001 | 0.011 | 0.689 | <0.001 | 0.006 | 0.006 |
| SM                  | 1  | 0.116 | 0.831 | 0.222 | 0.007 | 0.754 | 0.005 | 0.002 | 0.358 | 0.157 | 0.218 | 0.002 | 0.678 | 0.449 | 0.004 | 0.411 | 0.695 | 0.006 | 0.006 |
| C                   | 2  | 0.251 | 0.305 | 0.168 | 0.653 | 0.129 | 0.030 | 0.894 | 0.790 | 0.184 | 0.593 | 0.566 | 0.011 | 0.393 | 0.392 | 0.452 | 0.158 | 0.327 | 0.327 |
| SD × SM             | 1  | 0.090 | 0.638 | 0.073 | 0.002 | 0.845 | 0.035 | 0.002 | 0.317 | <0.001 | 0.826 | 0.002 | 0.761 | 0.499 | 0.007 | 0.198 | 0.151 | 0.006 | 0.006 |
| SD × C              | 2  | 0.216 | 0.227 | 0.144 | 0.410 | 0.231 | 0.700 | 0.853 | 0.056 | 0.319 | 0.273 | 0.448 | 0.015 | 0.629 | 0.518 | 0.228 | 0.075 | 0.625 | 0.625 |
| SM × C              | 1  | 0.531 | 0.330 | 0.074 | 0.080 | 0.567 | 0.659 | 0.719 | 0.500 | 0.998 | 0.130 | 0.614 | 0.749 | 0.863 | 0.278 | 0.358 | 0.015 | 0.275 | 0.275 |
| SD × SM × C         | 2  | 0.007 | 0.073 | 0.360 | 0.202 | 0.618 | 0.470 | 0.020 | 0.494 | 0.603 | 0.183 | 0.395 | 0.584 | 0.155 | 0.316 | 0.703 | 0.111 | 0.374 | 0.374 |

*Plant population count was not done in the first year of the study due to an oversight on our part.*
areas at the center of each plot. To quantify grain production, an area of 5.6 m² was harvested after the removal of border rows using a Kincaid plot combine (Kincaid Equipment Manufacturing, Haven, KS). Thereafter, the harvested seeds from each plot were cleaned separately using a Clipper Office Tester Cleaner (Clipper, Bluffton, IN) and weighed to compute grain yield. Seed samples of 5 g (~3,500 seeds) from each plot were then oven-dried at 60°C using an Isotemp forced-air oven (Fisher Scientific, Hampton, NH) to determine grain moisture content. Grain yield was adjusted to 92% dry matter concentration. Harvest index (HI) of camelina was computed by dividing grain dry weight by total aboveground biomass for each experimental unit. Agronomic yield components determined at the time of harvest from three randomly selected plants in each plot for number of branches per plant, pods per branch from three randomly chosen branches on each plant, and seeds per pod from 10 pods on each plant were counted and recorded. To determine the 1000-seed weight (TSW) of each experimental unit, a seed counter Sly-C (CGoldenwall) was used to count 1,000 seeds, and thereafter, the seed mass was recorded.

The oil content of camelina grain was determined by using 0.4 g of seed from each experimental unit and analyzed using a Bruker Nuclear Magnetic Resonance (NMR) mq20 Analyzer (Bruker Corporation, Billerica, MA). Oil production was computed as grain yield × percent oil content of grain. Biodiesel production was estimated based on an assumed mechanical extraction efficiency of 80% (Kemp, 2006). The computation of biodiesel factored in a 10% post-harvest seed loss because of the inherent small seed size (e.g., Sintim, Zheljazkov, Obour, Garcia, & Foulke, 2016). Thus, 90% postharvest grain yield and oil content were used to estimate biodiesel production with the volumetric conversion factor of 1 kg/ha to 0.439 L/ha (Kemp, 2006).

2.5 | Statistical analysis

Data for this experiment were analyzed by fitting mixed models using PROC MIXED in SAS software (ver. 9.4, SAS Institute Inc, 2017). Each year’s data were analyzed separately with no comparison between the two years because of the different planting dates in the second year of the study. Sowing date, SM, cultivar (C), and their interactions were treated as fixed effects, while replication and its interaction were considered random effects. Treatment means for measured and computed parameters in this study were considered different at 0.05 level of significance, unless otherwise stated. The treatment means were separated using the PDIF option in the LSMEANS statement. Pearson’s correlation coefficients among the recorded and computed parameters were generated using the PROC CORR procedure of SAS (SAS Institute Inc, 2017).

3 | RESULTS

3.1 | Camelina canopy characteristics

The quantity of light intercepted was affected by two-way interactions of SM × C and SD × SM but not that of SD × C while three-way interaction of SD × SM × C approached significance in Year 1 of this study (Table 3). For the SM × C interaction, for broadcast-seeded camelina, LI was greater for the cultivar Columbia compared to Blaine Creek and Pronghorn, but for drill-seeded camelina, LI was not different among the three cultivars of camelina (Table 4). Further, between SM both Blaine Creek and Pronghorn intercepted greater quantity of light when drill-seeded compared to broadcast-seeded, but for cultivar Columbia, LI was not different between SM (Table 4). In relation to the SD × SM interaction, LI for early SD camelina was

| Sowing method | Cultivar       | Blaine Creek | Columbia | Pronghorn |
|---------------|---------------|--------------|----------|-----------|
| LI (%) 2016   | Broadcast     | 63.6^B1      | 80.6^A   | 70.5^B    |
|               | Drill         | 80.6^A       | 81.6^A   | 81.6^A    |
| SEM           | 3.5           | 3.5          | 3.5      |           |
| p-value^2     | 0.004         | 0.814        | 0.015    |           |
| LAI (m²/m²), 2016 | Broadcast     | 5.2^A        | 6.3^A    | 5.7^A    |
|               | Drill         | 6.6^A        | 5.4^B    | 6.6^A    |
| SEM           | 0.4           | 0.4          | 0.4      |           |
| p-value       | 0.012         | 0.105        | 0.085    |           |
| PH (cm), 2016 | Broadcast     | 83.8^B       | 87.0^AB  | 87.6^A    |
|               | Drill         | 88.1^A       | 86.5^AB  | 84.2^B    |
| SEM           | 1.5           | 1.5          | 1.5      |           |
| p-value       | 0.022         | 0.770        | 0.073    |           |
| OC (g/kg), 2017 | Broadcast     | 324.3^A      | 312.6^B  | 320.0^A   |
|               | Drill         | 310.0^B      | 318.8^AB | 324.5^A   |
| SEM           | 4.5           | 4.5          | 4.5      |           |
| p-value       | 0.012         | 0.214        | 0.360    |           |

Notes. SEM: standard error of mean.

^1Within rows, means for each parameter followed by the same uppercase letter superscripts are not different (p > 0.05) using the PDIF option in PROC MIXED. ^2Within columns, p value indicates significance (p < 0.05) between means of sowing method for each parameter using the PDIF option in PROC MIXED.
Light interception (LI), plant height (PH), plant population (PP), pods per branch, days after sowing to 50% maturity (DASM), grain yield, oil production, and biodiesel production of camelina as affected by a sowing date × sowing method during the spring season of 2016 and 2017 at the University of Nevada, Reno Main Station Field Laboratory in Reno, NV, USA

| Sowing date | Sowing method | SEM | p-value $^1$ |
|-------------|--------------|-----|-------------|
| LI (%), 2016 | Broadcast | 0.761 |
| Early | 96.4$^{A2}$ | 95.4$^{A}$ | 3.0 |<0.05 |
| Late | 47.7$^{B}$ | 67.2$^{B}$ | 3.0 |<0.001 |
| PH (cm), 2017 | Broadcast | 0.706 |
| Early | 87.2$^{A}$ | 86.1$^{A}$ | 2.2 |<0.05 |
| Late | 64.8$^{B}$ | 84.6$^{B}$ | 2.2 |<0.001 |
| PP (plants/m²), 2017 | Broadcast | 0.019 |
| Early | 103.0$^{A}$ | 70.0$^{A}$ | 10.0 |<0.05 |
| Late | 55.0$^{B}$ | 116.0$^{A}$ | 10.0 |<0.001 |
| DASM, 2017 | Broadcast | 0.002 |
| Early | 125.0$^{A}$ | 125.0$^{A}$ | 3.0 |<0.001 |
| Late | 107.0$^{B}$ | 89.0$^{B}$ | 3.0 |<0.001 |
| Oil production (kg/ha), 2017 | Broadcast | 0.884 |
| Early | 587.0$^{A}$ | 601.0$^{A}$ | 75.0 |<0.01 |
| Late | 130.0$^{B}$ | 676.0$^{A}$ | 75.0 |<0.001 |
| Biodiesel production (L/ha), 2017 | Broadcast | 0.98 |
| Early | 193.5$^{A}$ | 192.7$^{A}$ | 25.0 |<0.01 |
| Late | 40.0$^{B}$ | 212.2$^{A}$ | 25.0 |<0.001 |

Notes. SEM: standard error of mean.

$^1$Within rows, $p$ value indicates significance ($p < 0.05$) between means of sowing method for each parameter using the PDIFF option in PROC MIXED. $^2$Within columns, treatment means followed by the same uppercase letter superscript for each parameter are not different ($p < 0.05$) between sowing date using the PDIFF option in PROC MIXED.

Plant height was affected by SD and SM × C interaction in Year 1 (Table 3). Plant height was greater for early relative to late SD camelia (Table 8). In relation to the SM × C interaction, the cultivar Blaine Creek was shorter than Pronghorn but neither differed from Columbia (Table 4). For drill-seeded, cultivar Pronghorn had shorter plants than Blaine Creek and both were similar in height to Columbia (Table 4). Between SM, Blaine Creek had less height for broadcast compared to drill-seeded camelia (Table 4). While for Pronghorn, plant height tended to be greater for broadcast compared to drill SM (Table 4). In Year 2, there was an effect of SD × SM interaction on plant height (Table 3). For early SD camelia, plant height was not different between broadcast and drill SM, but at late SD, plant height was greater for drill-seeded relative to broadcast-seeded camelina (Table 5). For each SM, plant height for broadcast-seeded camelina was greater for early than late SD, but for drill-seeded camelia, plant height did not differ between SD (Table 5).

### 3.2 Camelina yield components

The number of branches/plant was affected only by C in Year 1 (Table 3), and in Year 2, there was no effect of SD, SM, C or their interactions on branches/plant (Table 3). For the main effect of C in Year 1, Columbia had a greater number of branches/plant than Blaine Creek and Pronghorn (Table 9).

not different between broadcast and drill SM, but for late SD, broadcast-seeded camelina intercepted less light than drill-seeded camelina (Table 5). Also, between SD for both broadcast and drill SM, LI was greater for early than late SD (Table 5). In Year 2, LI was affected by a three-way interaction of SD × SM × C (Table 3). For this interaction, significance in LI occurred for late SD broadcast-seeded camelina and the cultivar Pronghorn had greater LI than Columbia but neither differed from Blaine Creek (Table 6). Within each cultivar across SD and SM combinations, significance in LI only occurred for Columbia and LI was lower for late SD broadcast-seeded compared to all other SD × SM combinations (Table 6). In Year 1, LAI was affected by interactions of SD × C and SM × C (Table 3). For the SM × C interaction, LAI for drill-seeded camelina was lower for Columbia relative to Blaine Creek and Pronghorn (Table 4). Between SM, cultivar Blaine Creek had lower LAI for broadcast compared to drill seeding, while for Pronghorn, drill-seeded camelia tended to have greater LAI than broadcast-seeded camelina (Table 4). In relation to the SD × C interaction in Year 1, LAI was greater for Columbia relative to Blaine Creek at early SD and for late SD, cultivar Columbia had lower LAI than Blaine Creek and Pronghorn (Table 7). Between SD, Blaine had lower LAI for early SD than late and for Columbia, the reverse occurred of greater LAI for early compared to late SD (Table 7). In Year 2, LAI was only affected by SD (Table 3) and it was greater for early compared to late SD camelina (Table 8).

There were main effects of SD and C on SPAD index in Year 1 (Table 3). The SPAD index was greater for late SD compared to early SD camelina in Year 1 (Table 8). In relation to the C effect, SPAD index of the three cultivars was in the order Blaine Creek greater than Columbia greater than Pronghorn (Table 9). In Year 2, SD affected SPAD index and approached significance for SM × C and SD × SM (Table 3). Early SD camelina had greater SPAD index than late SD (Table 8).

Plant height was affected by SD and SM × C interaction in Year 1 (Table 3). Plant height was greater for early relative to late SD camelia (Table 8). In relation to the C effect, broadcast-seeded camelina the cultivar Blaine Creek was shorter than Pronghorn but neither differed from Columbia (Table 4). For drill-seeded, cultivar Pronghorn had shorter plants than Blaine Creek and both were similar in height to Columbia (Table 4). Between SM, Blaine Creek had less height for broadcast compared to drill-seeded camelia (Table 4). While for Pronghorn, plant height tended to be greater for broadcast compared to drill SM (Table 4). In Year 2, there was an effect of SD × SM interaction on plant height (Table 3). For early SD camelia, plant height was not different between broadcast and drill SM, but at late SD, plant height was greater for drill-seeded relative to broadcast-seeded camelina (Table 5). For each SM, plant height for broadcast-seeded camelina was greater for early than late SD, but for drill-seeded camelia, plant height did not differ between SD (Table 5).
The number of pods/branch was affected by an interaction of SD × C in Year 1 (Table 3). For early SD, Columbia had the greatest number of pods/branch followed by Pronghorn and the least recorded was for Blaine Creek (Table 7). However, for late SD pods/branch was not different among the three cultivars (Table 7). Between SD, pods/branch for the cultivar Columbia was greater for early compared to late SD (Table 7). In Year 2, the number of pods/branch was influenced by the main effect of C and the two-way interaction of SD × SM (Table 3). The cultivar Pronghorn had a greater number of pods/branch than Blaine Creek and Columbia (Table 9). For the SD × SM interaction, late SD drill-seeded camelina had a greater number of pods/branch than late SD broadcast (Table 5). Also, between SD for broadcast-seeded camelina, the number of pods/branch was greater for early than late SD (Table 5).

In Year 1, the number of seeds/pod was not influenced by either SD, SM, C, or their interactions (Table 3; data not shown). However, in Year 2 there was a SD × SM × C interaction on seeds/pod (Table 3). Within SD and SM combinations across cultivars, no differences in seeds/pod were detected (Table 6). However, for both Blaine Creek and Columbia between SD and SM combinations, the number of seeds/pod was less for late SD broadcast-seeded relative to the other three SD and SM combinations (Table 6). In relation to the cultivar Pronghorn, late SD broadcast-seeded had less number of seeds/pod than early SD broadcast and drill but was similar to late SD drill (Table 6).

One thousand seed weight (TSW) was influenced by a main effect of C in Year 1 (Table 3). The cultivar Pronghorn had lower TSW than Blaine Creek and Columbia (Table 9). In Year 2, SD × C interaction on TSW approached significance (Table 3 & 7) with no other main effects of SD, SM, C, or their interactions.

Plant population density was only measured in Year 2 of the study, and there was a SD × SM interaction on plant population density (Table 3). For early SD, plant population was greater for broadcast than drill SM, but the reverse occurred for late SD (Table 5). For broadcast SM, plant population was greater for early than late SD, but for drill SM, plant population was greater for late than early SD (Table 5).

### 3.3 Camelina phenology

The number of days after sowing to 50% flowering (DASF) was affected by a SD × SM × C interaction in Year 1 (Table 3). For early SD broadcast-seeded, the cultivar Columbia reached 50% flowering earlier than Blaine Creek and Pronghorn (Table 6). In addition, for late SD broadcast-seeded, the cultivar Pronghorn had the least number of DASF (Table 6). Between SD and SM combinations, for the cultivar Columbia, early SD broadcast-seeded reached 50% flowering earlier than early SD drill, but the reverse occurred for the cultivar Pronghorn (Table 6). Further, both late SD broadcast-seeded camelina and late

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**TABLE 6** Light interception (LI), seeds/pod, and days after sowing to 50% flowering (DASF) of camelina as affected by a sowing date × sowing method × cultivar interaction during the spring season of 2016 and 2017 at the University of Nevada, Reno Main Station Field Laboratory in Reno, NV, USA

| Factors                                  | Cultivar2 | SEM |
|------------------------------------------|-----------|-----|
| **LI (%), 2017**                         |           |     |
| Early, Broadcast1                        | 68.8Aa    | 6.2 |
| Early, Drill                            | 76.3Aa    |     |
| Late, Broadcast                         | 62.2Ab    | 6.2 |
| Late, Drill                             | 72.3Aa    |     |
| **Seeds/pod, 2017**                     |           |     |
| Early, Broadcast                        | 11.0Aa    | 2.0 |
| Early Drill                             | 8.0Aa     |     |
| Late, Broadcast                         | 2.0Ab     |     |
| Late Drill                              | 10.0Aa    |     |
| **DASF, 2016**                          |           |     |
| Early, Broadcast                        | 74.0Aa    | 1.0 |
| Early Drill                             | 73.0Aa    |     |
| Late, Broadcast                         | 65.0Ab    |     |
| Late Drill                              | 64.0Ab    |     |

*Notes. SEM: standard error of mean.
1Within rows, means followed by the same uppercase letter superscripts are not different (p > 0.05) for each parameter using the PDIF option in PROC MIXED.
2Within columns, means followed by the same lowercase letter superscripts are not different (p > 0.05) for each parameter using the PDIF option in PROC MIXED.*
SD drill-seeded camelina, all three cultivars reached 50% flowering earlier than early SD broadcast-seeded camelina and early SD drill-seeded camelina (Table 6). In Year 2, the number of DASF was not affected by SD, SM, C, or their interactions even though SD tended to be significant (Table 3, data not shown).

The number of days after sowing to 50% maturity (DASM) was affected by SD (Table 3) and interactions involving SM × C and SD × SM × C approached significance in Year 1 of this study (Table 3; data not shown). For the SD effect on DASM, late SD camelina reached maturity in less number of days than early SD camelina (Table 8). In Year 2, there was an interaction effect of SD × SM on DASM (Table 3). For late SD, DASM was less for drill-seeded camelina compared to broadcast-seeded camelina (Table 5). For each SM between SD, DASM was less for late compared to early SD (Table 5).

### 3.4 Camelina grain yield and harvest index

Grain yield of camelina was influenced by a main effect of SD in Year 1 and an interaction effect of SD × SM in Year 2 (Table 3). In Year 1, grain yield was greater for early than late SD (Table 8). For the SD × SM interaction in Year 2, early SD grain yield was not different between SM (broadcast vs. drill), but for late SD, grain yield was greater for drill-seeded camelina than broadcast-seeded camelina (Table 5). For each SM between SD, grain yield was only different for broadcast SM and it was greater at early than late SD (Table 5). Harvest index (HI) was affected by SD in Year 1 (Table 3), but in

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**Table 7** Leaf area index (LAI), pods/branch, one thousand seed weight (TSW), and growing degree days to 50% flowering (GDDF) as influence by a sowing date × cultivar interaction during the spring season of 2016 and 2017 at the University of Nevada, Reno Main Station Field Laboratory in Reno, NV, USA

| Sowing date | Cultivar       | Blaine Creek | Columbia | Pronghorn |
|-------------|----------------|--------------|----------|-----------|
| Early       | LAI (m²/m²), 2016 | 5.4B¹        | 6.5A     | 5.8AB     |
| Late        |                | 6.5A         | 5.1B     | 6.5A      |
| SEM         |                | 0.4          | 0.4      | 0.4       |
| p-Value²    |                | 0.045        | 0.009    | 0.710     |

Pods/branch, 2016

| Sowing date | Early | Late | SEM  | p-Value² |
|-------------|-------|------|------|----------|
| LAI         | 24.0C | 39.0A| 30.0B| 0.006    |
| pods/branch | 23.0A | 27.0A| 29.0A| 0.832    |
| SPAD        | 31.7B | 40.2A| 0.80 | 0.832    |
| SPAD        | 30.5A | 24.4B| 0.90 | 0.832    |
| Plant height | 89.6A | 82.8B| 1.10 | 0.832    |
| DASM, 2016  | 62.0A | 61.0A| 1.0  | 0.832    |
| GDDM, 2016  | 496.0A| 311.0B| 342.0B| 0.832    |
| GDDF, 2017  | 709.0A| 705.0A| 706.0A| 0.832    |
| SEM         | 31.0  | 31.0 | 31.0 | <0.001   |
| p-Value     | <0.001| <0.001| <0.001| <0.001   |

Notes. SEM: standard error of mean.

1Within rows, means followed by the same uppercase letter superscripts are not different (p > 0.05) for each parameter using the PDIFF option in PROC MIXED.

2Within columns, p value indicates significance (p < 0.05) between means of sowing date for each parameter using the PDIFF option in PROC MIXED.

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**Table 8** Sowing date effects on parameters of camelina during the spring season of 2016 and 2017 at the University of Nevada, Reno Main Station Field Laboratory in Reno, NV, USA

| Parameters          | Sowing date | SEM  |
|---------------------|-------------|------|
| LAI (m²/m²), 2017   | 2.7A¹       | 1.5B  |
| SPAD, 2016          | 31.7B       | 40.2A |
| SPAD, 2017          | 30.5A       | 24.4B |
| Plant height (cm), 2016 | 89.6A     | 82.8B |
| DASM, 2016          | 62.0A       | 61.0A |
| DASM, 2016          | 125.0A      | 105.0B|
| GDDM, 2016          | 624.0B      | 727.0A|
| GDDM, 2016          | 1,365.0A    | 1,363.0B|
| GDDM, 2017          | 1,384.0A    | 1,192.0B|
| Grain yield (kg/ha), 2016 | 921.0A    | 503.0B|
| HI, 2016            | 0.11A       | 0.09B |
| OC (g/kg), 2016     | 295.0A      | 284.3B|
| OC (g/kg), 2017     | 325.1A      | 311.6B|
| Oil (kg/ha), 2016   | 271.8A      | 144.7B|
| Biodiesel (L/ha), 2016 | 79.0A  | 42.1B |

Notes. SEM: standard error of mean.

¹Within rows, means followed by the same uppercase letter superscripts are not different (p > 0.05) for each parameter using the PDIFF option in PROC MIXED.
Year 2, neither SD, SM, C, nor their interactions affected HI (Table 3; data not shown). In Year 1, HI was greater for early than late SD camelina (Table 8).

### 3.5 Camelina oil concentration, oil, and biodiesel production

Camelina grain oil concentration was affected by SD in Year 1 (Table 3) and a main effect of SD and two-way interaction of SM × C on oil concentration in Year 2 (Table 3). In Year 1 and Year 2, grain oil concentration was greater for early than late SD camelina (Table 8). In relation to the SM × C interaction in Year 2, for broadcast-seeded camelina the cultivar Columbia had lower oil concentration than Blaine Creek and Pronghorn (Table 4). However, for drill-seeded camelina the cultivar Pronghorn had greater grain oil concentration than Blaine Creek but neither were different than Columbia (Table 4). In relation to each cultivar between SM, Blaine Creek had less oil concentration for drill SM compared to broadcast SM (Table 4).

Both oil and biodiesel production followed a similar pattern to grain yield and were influenced by SD in Year 1 (Table 3) and SD × SM interaction in Year 2 (Table 3). In Year 1, both oil and biodiesel production were greater for early than late SD camelina (Table 8). In Year 2, for early SD camelina neither oil nor biodiesel production was affected by SM, but for late SD, both were greater for drill-seeded camelina than broadcast-seeded camelina (Table 5). While broadcast-seeded camelina had greater oil and biodiesel production at early than late SD, drill-seeded camelina showed no SD effect on the two parameters (Table 5).

### 4 DISCUSSION

In the preceding section, we have presented data from a factorial experiment studying the effects of SD, SM, and cultivar of camelina on multiple response parameters over 2 years. However, our discussion of the results focuses on the principal response variables of grain yield, oil concentration, oil, and estimated biodiesel production. All other appurtenant response parameters, namely canopy morphological characteristics, yield components, and phenology, were mainly used to explain the observed differences in the principal response variables in this study.

Agronomic management practices such as SD and SM along with the cultivars used in crop production are primary considerations of farmers that are known to alter crop productivity because of the length of calendar time, temperature occurrences during sensitive phenological events, and the accumulation of heat units from sowing to physiological maturity (e.g., Ahmad et al., 2017; Pavlista, Isbell, Baltensperger, & Hergert, 2011). Of the three factors studied, SD in the first year and an interaction of SD × SM in the second year were the factors that influenced camelina grain yield in this study (Table 3). Pertaining to the SD effect in the first year, there was a 45.4% decrease in grain yield for the late SD relative to that of early SD camelina (Table 8). In the second year, grain yield of broadcast-seeded camelina decreased by 77.9% for late compared to early SD (Table 5). Further, averaged across SD, there was a 43.9% increase in grain yield for drill-seeded relative to broadcast-seeded camelina (Table 5). To postulate an explanation for the observed responses of camelina grain yield, we examined the correlation coefficients among grain yield, canopy morphological characteristics, yield components, and phenology (Table 10).

Among the aforementioned parameters that provided a partial account for the disparity in grain yield between early and late SD, PH was consistent in both years and positively correlated with LI in Year 1 \((r = 0.63)\) and 2 \((r = 0.47)\) even though there was no significant relationship between grain yield and LI in Year 2 (Table 10) of this study. In addition to SD, the differences in grain yield between SM (Table 5) can also be partially explained by the taller plants and greater LI for drill-seeded camelina versus broadcast-seeded camelina in Year 2 (Table 5). The productivity of crop plants is proportionally linked to the quantity of light harvested as it dictates carbon uptake and use by plants (Cannell, Milne, Sheppard, & Unsworth, 1987; Duursma et al., 2012). The greater LI for early SD and drill-seeded camelina in our study, probably favored greater photosynthetic activity and thus, leading to the

| Parameters | Cultivar | Blaine Creek | Columbia | Pronghorn | SEM |
|-----------|---------|-------------|----------|-----------|-----|
| SPAD, 2016    | 40.2A1  | 35.2B       | 32.4C    |           | 1.0 |
| Branches/plant, 2016 | 40.0B  | 70.0A       | 48.0B    |           | 6.8 |
| Pods/branch, 2017   | 19.0B   | 20.0B       | 26.0A    |           | 2.0 |
| TSW (g), 2016   | 2.0A    | 1.8A        | 1.7B     |           | 0.07|

Notes. SEM: standard error of mean; TSW: thousand seed weight.

\(^1\)Within rows, means followed by the same uppercase letter superscripts are not different \((p > 0.05)\) for each parameter using the PDIFF option in PROC MIXED.

#### Table 9

Cultivar effects on parameters of camelina during the spring season of 2016 and 2017 at the University of Nevada, Reno Main Station Field Laboratory in Reno, NV, USA
greater partitioning of photosynthate toward grain production (Long, Zhu, Naidu, & Ort, 2006) relative to late SD and broadcast-seeded camelina. Sintim et al. (2016) evaluating agronomic responses of camelina to SD reported a similar effect to our study of taller camelina plants for early compared to late SD. From another study, Guy et al. (2014) reported a positive correlation between grain yield and PH of camelina with taller plants having greater yields which concurred with the response observed in our study.

Another key contributor to grain yield differences is plant population density as it dictates resource availability (e.g., Pereira & Hall, 2019; Testa, Reyneri, & Blandino, 2016) and can be influenced by both SD and SM. In our study, the camelina plant population density was only recorded in Year 2 due to oversight on our part, and the results of plant population between SD and SM in the second year (Table 5) were somewhat inconsistent. For the broadcast-seeded camelina, there was a pattern between plant population density and grain yield for the two SD in Year 2. The 60.8% greater plant population for early SD compared to late SD corresponds to a 3.5-fold increase in grain yield for Early SD (Table 5). However, for drill-seeded camelina the 49.5% greater plant population for late compared to early SD did not result in grain yield difference (Table 5). The inconsistencies in plant population and grain yield which also did not correlate, making plant population of limited use in offering an explanation to differences in grain yield observed in the second year of this study. Contrary to our nonexistent relationship between plant population density and grain yield, McVay and Khan (2011) studying camelina yield response to different plant population density in Montana, USA, and Kuai et al. (2015) working with rapeseed reported a direct relation between these two parameters. As it relates to the inconsistency in our results, there might have been interplant competition similar to that suggested by McGregor (1987) and McVay and Khan (2011). Our results were in agreement with those of McGregor (1987) working with rapeseed, and McVay and Khan (2011) working with camelina in that grain yields were not directly proportional to plant density.

Further, grain yield of oilseed crops is determined by the number of pods per plant, seeds per pod, and seed weight (McGregor, 1981), which can be altered by crop phenological traits due in large to environmental circumstances that occur during growth and development (McGregor, 1981). In our study, the significant effect of SD on camelina phenology can also offer a partial account for the differences in grain yield observed. For example, there were significant positive correlations between grain yield, DASF, DASM, and a negative correlation between grain yield and GDDF observed in Year 1 (Table 10). The relationships between grain yield, DASF, and DASM indicated that the longer calendar time to flowering and maturity for early SD relative to late SD (Table 6) may have lengthened the vegetative phase of early

| Parameters | LI | LAI | SPAD | PH | Branch | Pod | Seed | TSW | PP | DASF | DASM | GDDF | GDDM | HI |
|------------|----|-----|------|----|--------|-----|------|-----|----|------|------|------|------|----|
| 2016 (Year 1) | 0.58 | ns | 0.56 | ns | 0.40 | ns | ns | ns | — | 0.61 | 0.59 | ns | ns | ns |
| Yield | — | 0.61 | — | 0.61 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 |
| OC | 0.58 | ns | 0.58 | ns | 0.58 | ns | ns | ns | — | 0.58 | 0.58 | ns | ns | ns |
| OP | 0.58 | ns | 0.58 | ns | 0.58 | ns | ns | ns | — | 0.58 | 0.58 | ns | ns | ns |
| BP | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 2017 (Year 2) | 0.58 | ns | 0.56 | ns | 0.40 | ns | ns | ns | — | 0.61 | 0.59 | ns | ns | ns |
| Yield | — | 0.61 | — | 0.61 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 |
| OC | 0.58 | ns | 0.58 | ns | 0.58 | ns | ns | ns | — | 0.58 | 0.58 | ns | ns | ns |
| OP | 0.58 | ns | 0.58 | ns | 0.58 | ns | ns | ns | — | 0.58 | 0.58 | ns | ns | ns |
| BP | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
SD preanthesis and, therefore, allowing for greater dry matter accumulation and remobilization to grain filling (Sacks & Kucharik, 2011) for early compared to late SD camelina. That may also be explained by the 22.2% greater HI for early relative to late SD in our study (Table 8).

The utilization of SPAD index which is a good indicator of crop nitrogen status (Liu et al., 2017) was based on the SD factor and the timing of N application in this study. Based on the response, it is difficult to make a connection between grain yield differences in this study and SPAD index because of the negative relationship or no correlation (Table 10). It seems that the time when N was applied for the late SD in the first year and early SD in the second year favored greater plant N uptake relative to early and late SD of each year, respectively. Therefore, the difference in SPAD could be attributed to the favorable environmental conditions during late SD in the first year and early SD in the second year. However, the typical linear association between SPAD index and grain yield (Lindsey, Steinke, Rutan, & Thomison, 2016; Liu et al., 2017) did not occur in our study, which may indicate that other factors such as temperature stress were more influential in grain yield determination for late SD that may have caused flower and pod abortion. For the negative correlation between grain yield and GDDF, as the accumulation of heat units to 50% flowering increased grain yield decreased (Table 10) and this may indicate that floral initiation and development occurred at a time of high-temperature stress (Table 2), which exerts severe negative effects on overall grain yield due to pod abortion (Adamsen & Coffelt, 2005; Chen et al., 2005; Choi, Ban, Seo, Lee, & Lee, 2016) as was evident by the less pods/branch and seeds/pod for late compared to early SD in our study (Table 7 & 6). Several studies on camelina (Berti, Wilckens, Fischer, Solis, & Johnson, 2011; Gesch, 2014; Pavlista et al., 2011; Sintim et al., 2016), canola and crambe (Benga & Angadi, 2016; Chen et al., 2005; Johnson, McKay, Schneiter, Hanson, & Schatz, 1995), and on rape and turnip rape (Gross, 1964) have all reported a SD effect on grain yield with overall decrease in yield for late relative to early SD which concurred with our results. In those studies, the magnitudes of difference between early and late SD ranged from 20% to 71% and were mainly dependent on the intervals between sowing dates and the environments where those studies were conducted. The grain yield differences observed in our study fall well within this range reported in the aforementioned studies. However, contrary to our study, Aiken et al. (2015) did not detect any significant effect of SM on grain yield of spring oilseed crops, but Schillinger et al. (2012) reported an effect of SM on camelina grain yield and it was greater for broadcast-seeded camelina relative to drill-seeded camelina.

Grain yield of crop plants is generally influenced by genotype × environment interaction (Allard & Bradshaw, 1964; de Leon, Jannink, Edwards, & Kaeppler, 2016) and the management practices utilized (Hatfield & Walthall, 2015; He, Wang, Wang, & Lilley, 2017). In our study, the lack of difference in grain yield among the three camelina cultivars is not uncommon as Sintim et al. (2016), Mohammed, Chen, Lamb, and Afshar (2017), and Obour et al. (2017) reported no difference in grain yield between the camelina cultivars Blaine Creek and Pronghorn which was in agreement with our study. However, in contrast to these studies, Obour et al. (2019) reported a 19% greater grain yield for Blaine Creek compared to Pronghorn. Variations in grain yield of crop plants are typically attributed to differences in yield components and other agronomic traits, such as plant architecture in relation to plant biomass at flowering, leaf area and its relationship with intercepted solar radiation, plant density, and nitrogen use efficiency among others (Asare & Scarisbrick, 1995; Diepenbrock, 2000; Richards, 2000; Vollmann, Moritz, Kargl, Baumgartner, & Wagentridl, 2007; Zhang, Liao, Zhang, & Xu, 2012). In relation to the three cultivars used in our study, LI, SPAD, branches/plant, pods/branch, and TSW in 2016, and pods/branch in 2017 were canopy characteristics and yield components that differed. However, these differences may not have been of great biological significance as they did not translate into differences in grain yield among the three cultivars. Both Vollmann et al. (2007) and Obour et al. (2017) showed in their study that TSW was not a good predictor of camelina grain yield which concurred with the results of our study. Further, the correlations that occurred among LI, PH, Pod, and Seed with grain yield were not very strong, thus supporting the lack of grain yield difference among cultivars in this study. In agreement with our study, Sintim et al. (2016) reported no difference in plant density between Blaine Creek and Pronghorn. However, the difference in grain yield between Blaine Creek and Pronghorn reported by Obeng et al. (2019) was attributed to the greater plant density (12.5%) and TSW (7.4%) for Blaine Creek compared to Pronghorn. Crop phenology is an important regulatory mechanism that determines crop yield (Richards, 1991; Wu, Feng, Zhang, Gao, & Wang, 2017) and differs among cultivars within the same species (Rezaei, Siebert, Hüging, & Ewert, 2018; Willenborg, Luschei, Brülé-Babel, & Van Acker, 2009). In our study, with the exception of DASM in 2017, the phenological parameters were not different among the three cultivars of camelina and this similarity may support the lack of difference in grain yield possibly because of low genetic differentiation among the three cultivars. Both in contrast and similarity to our study, Sintim et al. (2016) reported that the phenological parameters of DASF, GDDF, DASM, and GDDDM were all different between the camelina cultivars Blaine Creek and Pronghorn, yet in their study, grain yield was not different between the two cultivars. This indicates that phenology alone may not be a crucial determinant of grain yield of camelina if other agronomic traits and inputs are not different. Further, Guy et al. (2014) in a study on adaptation and performance of camelina genotypes across genotypes and years showed that the cultivar × environment interaction is a major factor affecting camelina grain yield.
multiple environments in the US states of Idaho, Oregon, and Washington reported that at majority of the locations, the grain yield of Blaine Creek was not different than that of Columbia which supports the lack of yield differences between the two cultivars in our study. Overall, a range of 426–2,568 kg/ha grain yield has been reported across different regions for several cultivars of camelina (Mohammed et al., 2017; Obour et al., 2017; Sintim, Zheljazkov, Obour, Garcia, & Foulke, 2015; Urbaniak et al., 2008) and the yields among cultivars in our study were well within the reported range. Further, cultivar did not interact with the two other experimental variables of SD and SM to influence grain yield and our results were similar to those of Sintim et al. (2016) who reported no cultivar × SD interaction effect on camelina seed yield. However, in disagreement to the two studies, Berti et al. (2011) reported a cultivar × SD interaction on grain yield of camelina and this may have been due to the greater genetic differentiation among the cultivars used, the environment where the study was conducted, and the agronomic management factors involved. The three experimental variables in our study had few interaction effects with yield components, but not the phenological parameters, and thus may have been ultimately responsible for the lack of interaction among the three variables to affect grain yield.

Oil concentration of oilseed crops is a major determinant of overall oil and subsequent biodiesel production and is generally influenced by genotypic variation within species, environment, and management conditions (Gallardo, Milisich, Drago, & González, 2014). The oil concentration of camelina grain decreased by 3.6% and 4.2% from early to late SD in the first year and second year, respectively (Table 8). For broadcast-seeded camelina, the cultivar Columbia had a 2.4% and 3.7% lower oil concentration than Pronghorn and Blaine Creek, respectively, while for drill-seeded camelina, 2.4% and 3.7% lower oil concentration than Pronghorn and camelina. The reason offered for the reduction of grain oil concentration for late sowing oilseed brown mustard, and camelina. The reason offered for the reduction of grain oil concentration for late sowing oilseed crops is that high temperature during grain filling reduced oil synthesis of oilseed crops (Aksouh-Harradji, Campbell, & Mailer, 2006; Gauthier, Pellet, Monney, Herrera, & Rougier, 2017; Saldivar, Wang, Chen, & Hou, 2011; Yaniv, Schafferman, & Zur, 1995), which may have been the case in our study. The cultivar effect on oil concentration of camelina in this study was not uncommon as several studies have reported differences in oil concentration among camelina genotypes (Gesch, 2014; Guy et al., 2014; Jiang, Caldwell, & Falk, 2014; Sintim et al., 2016), but the factors imposed in our study may have had a more profound effect on cultivar response hence, the difference.

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Oil and estimated biodiesel production decreased by 87.8% for late compared to early SD camelina in the first year of the study (Table 8). In the second year, both SD and SM interacted to alter oil and estimated biodiesel production. The interaction occurred because of differences between SD for broadcast-seeded camelina and the significant effect between SM at late SD (Table 5). For late SD, oil and estimated biodiesel production of drill-seeded camelina increased by 430.5% and 431.9%, respectively, compared to broadcast-seeded camelina (Table 5). Further, for broadcast-seeded camelina, oil, and estimated biodiesel production reduced by 79.3% when seeded late compared to early (Table 5). In relation to the effects of early SD, oil, and estimated biodiesel production of camelina were similar for broadcast-seeded camelina and drill-seeded camelina (Table 5). For oil and biodiesel production, in Year 1 there were significant positive correlations with LI, PH, DASF, DASM, GDDF, GDDM, HI but a negative one with GDDF (Table 10). In Year 2, oil and biodiesel correlated with PH, Pod, Seed, and HI (Table 10). The fact that the correlation trends were similar to the grain yield relationships, and that there were significant positive correlations \( r = 0.99 \) between oil and biodiesel and grain yield in both Year 1 and Year 2 of this study evinced that a great proportion of the variation in oil and biodiesel production can be explained by grain yield. Gesch, Matthees, Alvarez, and Gardner (2018) in a study using winter camelina cultivars showed that the oil yield response in their study mirrored that of grain yield and this confirms the strong relationship between grain yield, oil, and estimated biodiesel production in our study. Further, in the first year of this study, a significant positive correlation between oil concentration, oil, and biodiesel production \( r = 0.53 \) occurred and this also would have partially accounted for the differences in oil and biodiesel production particularly as it relates to the SD effect. The negative correlation between oil concentration and GDDF \( r = −0.50 \) in the first year indicated that the same factor that affects grain yield that is, high temperature for late sowing that hastened maturity may have affected grain oil concentration as alluded to earlier in relation to oil synthesis. Similar to our study, Sintim et al.
Our study showed that delayed sowing beyond mid-March (early SD) in the first year and early April (early SD) in the second year had a negative effect on oil concentration, grain yield, oil, and biodiesel production of camelina. While the results of SM were not consistent in both years of the study, whenever there was an advantage in grain yield, oil, and biodiesel production, it favored drill relative to broadcast seeding. Therefore, drill seeding may be a more practical and sustainable approach to camelina cultivation in our environment. Among the three camelina cultivars, there were some variations in canopy characteristics (LI, LAI, and PH), yield components (branches/plant, pods/branch, seeds/pod, and TSW), and phenology (DASF, DASM, and GDDDF); however, they did not translate into differences in grain yield, oil, and biodiesel production in this study. Therefore, any of the three spring camelina cultivars can be selected for cultivation in Nevada. The diversity of crop species cultivated in semiarid agroecosystems is limited due in large to the aforementioned challenges and, therefore, based on the magnitude of differences observed in both years of this study, delayed and broadcast sowing are not viable options for farmers who want to venture into camelina production in Nevada.

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CONFLICT OF INTEREST

None declared.

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