Nitrogen source and rate effects on grain and potential biodiesel production of camelina in the semiarid environment of northern Nevada

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Abstract
The objective of this two-year study (2016–2017 spring) carried out at the University of Nevada, Reno Main Station Field Laboratory, Reno, NV, was to evaluate the effects of nitrogen source, rate, and camelina cultivar on grain yield and potential biodiesel production irrigated with reclaimed water. Treatments were two sources of urea fertilizer [conventional urea (CU) and polymer-coated urea (PCU)], four N rates (0, 40, 80, and 120 kg N ha⁻¹), and two cultivars of camelina (“Blaine Creek” and “Pronghorn”) arranged in a 4 × 2 × 2 factorial combinations with four replications each in a RCBD experiment. Plot size was 7.6 m long × 1.8 m wide, and camelina was seeded at a rate of 5 kg PLS seed ha⁻¹.

The quantity of light intercepted increased linearly from 44.9% to 65.9% as N application rate increased from 0 to 120 kg N ha⁻¹, and it was greater for CU (59.6%) compared to PCU (54.0%) fertilized plots. There was a linear increased in grain yield ranging from 534 to 1,010 kg/ha as N application rate increased from 0 to 120 kg N ha⁻¹, and it was greater for CU (59.6%) compared to PCU (54.0%) fertilized plots. There was a linear increased in grain yield ranging from 534 to 1,010 kg/ha as N application rate increased from 0 to 120 kg N ha⁻¹. In Year 2, grain yield of Blaine Creek (898 kg/ha) was greater than that of Pronghorn (464 kg/ha). Also, there was a linear increase in estimated biodiesel from 51.2 to 94.2 L/ha as N application rate increased. For both grain and biodiesel production, there was no advantage of using controlled-release PCU fertilizer and 80 to 120 kg N ha⁻¹ is sufficient for the cultivation of camelina in this environment. Based on the range of grain yield obtained in this study, camelina can be a potential alternative crop to integrate into the annual crop production cycle in water-limited environments like Nevada.

KEYWORDS
biodiesel, camelina genotype, grain yield, light interception, nitrogen rate, nitrogen source, nitrogen use efficiency and oil concentration

1 | INTRODUCTION
In water-deficit environments like the US state of Nevada, identifying and selection of crop types suitable for such environments can be an arduous task. Typically, crops that are adaptable and can be grown successfully in water-limited environments are not necessarily the most marketable; hence, economic returns on such crops can be negatively affected by market demands. Alfalfa (*Medicago sativa* L.) is the number one crop grown in Nevada both in land area...
cultivated (101,171 hectares) and value in dollars from tonnage produced (an estimated two hundred million dollars) on an annual basis (Nevada Agricultural Statistics Annual Bulletin, 2016). However, alfalfa is a high-water use crop (Lindenmayer, Hansen, Brummer, & Pritchett, 2011; Sheaffer, Tanner, & Kirkham, 1988) and hydrological instability in the western United States (Barnett et al., 2008; Lu et al., 2018) is a common and direct hindrance to continued production of alfalfa and thus Nevada’s agricultural production and sustainability. Therefore, adopting a strategy of crop diversification (McCord, Cox, Schmitt-Harsh, & Evans, 2015) can reduce producer’s vulnerability and accelerates agricultural productivity in water-limited agroecosystems like Nevada.

Camelina (Camelina sativa [L.] Crantz) is a reemerging oilseed crop of the Brassicaceae family and possesses the unique attribute of multiple uses. Among the many uses of camelina, the most frequent focus is on its use as a high potential biofuel feedstock mainly biodiesel and jet fuel (Ciubota-Rosie, Ruiz, Ramos, & Pérez, 2013; Keske, Hoag, Brandess, & Johnson, 2013; Liu, Savas, & Avedisian, 2013; Paulsen, Wichmann, Schuemann, & Richter, 2011), and other uses entail several industrial products such as adhesives, resins, hydrophilic monomers, gums, and coatings (Berti, Gesch, Eynck, Anderson, & Cermak, 2016; Li & Sun, 2015; Sainger et al., 2017), a high protein animal feed for different classes of livestock (Adhikari, Heo, & Nyachoti, 2016; Bullerwell, Collins, Lall, & Anderson, 2016; Jaskiewicz, Sagan, & Puzio, 2014; Pikul et al., 2014), food and supplements (Berti et al., 2016) are among the major focus of its cultivation globally. Along with the aforementioned uses, the inherent trait of high oil content (28%–48% on a DM basis) of camelina seed (Bacenetti, Restuccia, Schillaci, & Failla, 2017; Yang, Caldwell, Corscadden, He, & Li, 2016) relative to the 26.6%–40.2% oil content of canola (Malhi, Gan, & Raney, 2007) increases its potential as a non-conflicting biofuel crop, that is, it has been classified as a minor edible oilseed crop for human food supply compared to canola (Drenth, Olsen, Cabot, & Johnson, 2014; Koçar, 2017). Camelina positive net energy balance and overall net lower emissions of greenhouse gasses (Drenth et al., 2014; Dyer, Vergé, Desjardins, Worth, & McConkey, 2010; Fore, Lazarus, Porter, & Jordan, 2011), its low water demand (George, Thompson, Hollingsworth, & Orloff, 2018; Iskandarov, Kim, & Cahoon, 2014; Obour, Sintim, Obeng, & Jeliazkov Zheljazkov, 2015), low fertilizer requirements (Putnam, Budin, Field, & Breeene, 1993), and resistance to many agricultural insect pests and diseases (Iskandarov et al., 2014) make camelina an ideal alternative candidate crop for diversification and the potential for a permanent niche in the crop production cycle of water-scarce environments like Nevada. The principal agronomic factors limiting biodiesel production output from oilseed crops like camelina are grain produced per unit area of land and concentration of oil in the seed. From an agronomic management perspective, grain yield of non-leguminous crops is limited to a great extent by soil nitrogen (N) availability (Montemurro, Convertini, & Ferri, 2007), crop genotype (Studnicki et al., 2016), and hence biodiesel production. Soils in Nevada are typically low in organic matter (1%–2%), and therefore, low total soil N concentration (1–12 mg/kg) is a widespread occurrence (Chambers, Blank, Zamudio, & Tausch, 1999). Soil N deficit, often times, leads to suboptimal grain yield of non-leguminous crops due to a reduction in plant photosynthetic activity as a result of a reduction in leaf area, lower quantity of light intercepted, and lower leaf chlorophyll index (Tang, Yang, Chen, Ameen, & Xie, 2018). Even though camelina has been widely touted as a low fertilizer input crop, for the attainment of optimum yields, N fertilizer must be applied in accordance with the yield potential of camelina, water use, source, availability, and climatic conditions of the area cultivated. However, N overuse can lead to nitrate leaching and increase nitrous oxide emissions from soils leading to ecosystem deterioration, biodiversity, and human health problems (Del Moro, Sullivan, & Homeck, 2018), and ultimately, neutralizes the positive effects to be gained from renewable energy (Keane et al., 2018; Tongwane et al., 2016). Further, inorganic N fertilizer is a major variable input cost in crop production agriculture and overuse of N will substantially increase the overall production cost and hence reduce the cost-competitiveness of camelina as a biofuel crop. Nitrogen recovery and N use efficiency typically enhance the economic sustainability of cropping systems, and the response of crops to applied N and use efficiency are important criteria for evaluating crop N requirements for maximum yield (Fageria & Baligar, 2005; Maaz, Pan, & Hammac, 2016). Improve N use efficiency is desirable to improve crop yields, reducing the cost of production, and help with environmental quality (Grant et al., 2012; Maaz et al., 2016; Malhi, Soon, Grant, Lemke, & Lupwayi, 2010). A strategy that can be employed to improve N recovery and efficiency, improve the cost-effectiveness of N application in crop production, and reduce N losses from the soil–plant system is the application of controlled-release N fertilizers (Grant et al., 2012; Ladha, Pathak, Krupnik, Six, & Kessel, 2005; Yang et al., 2018; Zheng et al., 2016).

There is a paucity of information pertaining to camelina cultivars response to N application rate in Nevada as N application rate varies for optimum yield of the crop in different regions of its cultivation (Jiang, Caldwell, Falk, Lada, & MacDonald, 2013; Malhi et al., 2014; Sintim, Zheljazkov, Obour, Garcia, & Foulke, 2015). Further, the influence of controlled-release N fertilizer on camelina...
grain production in Nevada’s semiarid climate is not known. The source and quantity of N fertilizer applied are often times dictated by genotype of the crop, existing soil nutrient supply capabilities, water supply, type of water used, and the intended use of the crop. Therefore, an understanding of camelina cultivars response to nitrogen source and rate will provide the best options for sustainable grain production of camelina in vulnerable agroecosystems like semiarid Nevada. The objective of our study was to evaluate the effects of nitrogen source, nitrogen application rate, and cultivars on grain yield and potential biodiesel production of camelina irrigated with reclaimed water.

2 | MATERIALS AND METHODS

2.1 | Site description and weather conditions

A two-year field experiment was carried out 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 (March–July) growing seasons of 2016 (Year 1) and 2017 (Year 2). The predominant soil at the experimental site is classified as a Truckee silt loam (a fine-loamy, mixed, superactive, mesic Fluvaquentic Haploxerolls). Prior to the initiation of the study at each site-year, the soil was sampled randomly to a depth of 15 cm across the experimental area of each site and composited before soil test analysis was carried out at a commercial laboratory (A & L Western Agricultural Laboratories, Modesto, CA). There were some variations in soil chemical characteristics between the two site years (Table 1). Also, the water used for supplemental irrigation was analyzed at the same commercial laboratory and the concentration of nitrate-N was considered minimal 1.5 mg/L (an estimated 3.8 kg nitrate-N during the growing period based on total irrigation applied). Weather data were collected from the Western Regional Climate Center, Desert Research Institute Weather Station located at the experimental site approximately 1,000 m away from research plots. Cumulative mean monthly precipitation and mean monthly temperature varied for each year compared to the 30-year average but solar radiation values did not deviate widely over the two years of the study (Table 2). Monthly accumulated evapotranspiration (ET) did not deviate widely over the two years of the study, and total supplemental irrigation of 470.1 and 481.3 mm was provided during the 2016 and 2017 growing seasons, respectively (Figure 1).

2.2 | Treatments and experimental design

Treatments were two N sources [conventional urea (CU) and polymer-coated urea (PCU)], four N application rates (0, 40, 80 and 120 kg N ha⁻¹), and two camelina cultivars (“Blaine Creek” and “Pronghorn”). Treatments were arranged in a 4 × 2 × 2 factorial of a randomized complete block design experiment with four replications of each treatment combination.

2.3 | Plot establishment and management

Prior to seedbed preparation and seeding, glyphosate [N-(phosphonomethyl) glycine] was applied at a rate of 1.12 kg a.i. per ha to reduce weed population during camelina growing season. Blaine Creek and Pronghorn camelina cultivars were drilled seeded on March 18, 2016, and April 11, 2017 (late seeding in the second year was due to heavy snowfall and snow melt in early-late March which caused flooding at the experimental site) at a seeding rate of 5 kg PLS per ha at a depth of 1-cm using a Plotseed XL plot seeder (Wintersteiger AG., Ried im Innkreis, Austria). In each year, the experiment was comprised of 64 plots, and the size of each plot was 7.62 m long × 1.83 m wide separated by 1.5 m alleyways between plots and blocks. In both years, N application rates using two N sources, CU (46-0-0) and PCU (45-0-0), were applied to their designated plots three weeks after germination as a single application using a 65-Series Adjustable Slotted Bottom fertilizer spreader (Gandy Company, Owatonna, MN, USA). Phosphorus was applied at seeding in both years, at a rate of 40 kg P per ha using triple superphosphate (0-45-0), and no K fertilizer was applied based on soil test recommendation. Post-emergence weed control for broadleaf weeds was carried out manually because there is no broadleaf herbicide label for use on camelina and for grass weeds, Sethoxydim (Poastr) (2-[1-ethoximinio] butyl]-5-[2-(ethylthio)-propyl]-3-hydroxy-2-cyclohexen-1-one) was used at a rate of 0.5 kg a.i. per ha. Supplemental irrigation was provided once per week 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-Wobbl 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 ET₀ 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). Crop irrigation was terminated 3 weeks prior to harvesting.

2.4 | Data collection and calculations

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 SPAD chlorophyll index (SPAD) using a SPAD 502 Plus Chlorophyll Meter (Minolta, Spectrum Technologies Inc., Aurora, IL, USA) were recorded mid-season at 60 days after planting for each experimental unit. The time interval of 60 days after sowing was chosen based on results for peak LI and LAI of a closely related species Brassica juncea (L.) in a study by Mandal and Sinha (2004). Plant height was determined by measuring the height of five randomly selected plants from the soil surface to the highest point on the plant at the time of physiological maturity (114 days after germination) in each experimental unit. To quantify yield components, three plants were randomly selected from each plot and number of branches per plant, pods per branch from three randomly selected branches on each plant, and seeds per pod from 10 pods on each plant were counted and recorded. To determine the 1,000-seed weight (TSW), an automatic seed counter Sly-C (CGoldenwall) was used to count 1,000 seeds and the weights were recorded for each experimental unit. Grain yield and biomass were quantified at physiological maturity (114 days after seed germination when >90% of the pods had changed color to brown) by harvesting an area of 5.6 m² in each experimental unit after border rows were removed using a Kincaid plot combine (Kincaid Equipment Manufacturing, Haven, KS, USA). Thereafter, the harvested seeds from each plot were cleaned separately using a Clipper Office Tester Cleaner (Clipper, Bluffton, IN, USA) 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, USA) 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.

### Table 1

| Year | Organic matter g/kg soil | pH | CEC Meq/100 g | NO₃-N | P | K | Ca | Mg | Na | SO₄²⁻⁻ | S | mg/kg soil |
|------|--------------------------|----|---------------|-------|---|---|----|----|----|-------|--|-------------|
| 2016 | 47.0                     | 7.8| 25.9          | 14    | 19| 560| 3,539| 598| 437| 95    |
| 2017 | 63.0                     | 7.9| 23.9          | 7     | 44| 670| 3,401| 538| 180| 9     |

### Table 2

| Months | Monthly precipitation (mm) | Mean air temperature (°C) | Monthly accumulated precipitation, mean air temperature, and solar radiation, at the University of Nevada, Reno Main Station Field Laboratory Reno, NV, during 2016 to 2017 growing seasons and 30-year average (1987–2017) |
|--------|---------------------------|---------------------------|--------------------------------------------------------------------------------|
|        | 2016 2017 (1987–2017)     | 2016 2017 (1987–2017)     | 2016 2017 (1987–2017)                                                                 |
| March  | 17.0 20.0 24.15           | 7.4 7.5 13.6              | 362 351                                                                            |
| April  | 30.7 23.3 18.14           | 10.6 9.2 17.3             | 483 456                                                                            |
| May    | 28.5 17.5 22.31           | 13.7 14.8 21.8            | 536 568                                                                            |
| June   | 0.00 3.56 18.02           | 20.0 19.6 25.9            | 619 605                                                                            |
| July   | 0.00 0.76 12.33           | 22.0 23.2 28.0            | 616 589                                                                            |
| Total  | 76.2 65.1 94.95           | 2,616 2,569               |                                                                                   |

### Figure 1

Total monthly accumulated evapotranspiration and supplemental irrigation at the University of Nevada, Reno Main Station Field Laboratory Reno, NV, during 2016 to 2017 growing seasons.
To determine camelina grain N concentration, 20 g of seed from each experimental unit was ground separately to pass a 1-mm screen using an Eberbach E 3,303 variable speed mini-cutting mill (Eberbach Corporation, Ann Arbor, MI). The ground samples were analyzed to determine N concentration using a Kjeltech™ 8200 Kjeldahl distillation unit (Foss North America, Inc. Eden Prairie, MN, USA). The crude protein concentration of camelina grain was determined by multiplying %N × 6.25. Nitrogen use efficiency (NUE) of grain was calculated as “recovery efficiency” of applied N (RE\textsubscript{N}) and is defined as: NUE = (Grain N uptake at F\textsubscript{N} - Grain N uptake at F\textsubscript{0})/N applied at F\textsubscript{N}. Where N uptake = N content in grain × grain yield. F\textsubscript{N} and F\textsubscript{0} refer to the amounts of each fertilizer treatment and the control, respectively (Cassman, Dobermann, & Walters, 2002).

Oil concentration of camelina grain from each experimental unit was determined by 0.4 g of seed and analyzed using a Bruker Nuclear Magnetic Resonance (NMR) mq20 Analyzer (Bruker Corporation, Billerica, MA, USA). Oil production was the product of yield × grain oil concentration. Potential biodiesel production was estimated based on the measured parameters, grain yield, light interception and the control, respectively (Sintim et al., 2015). Therefore, 90% of postharvest postharvest loss of camelina seed because of the small size of seed (Kemp, 2006). We adopted the approach of assuming 10% postharvest loss of camelina seed because of the small size of seed (Sintim et al., 2015). Therefore, 90% of postharvest grain yield and oil concentration was used to estimate biodiesel production using the volumetric conversion factor of 1 kg/ha to 0.439 L/ha (Kemp, 2006).

2.5 Statistical analysis

The data were analyzed by fitting mixed models using PROC MIXED in SAS software (ver. 9.4, SAS Institute, Cary, NC, USA). Nitrogen source, N application rate, cultivar, year, and their interactions were treated as fixed effects, while replication and the interaction of replication × year were considered random effects. Year was considered a fixed effect because of the variation in weather data and soil chemical characteristics of the two sites used in conducting this experiment. Responses in this study were considered different at \( p < 0.05 \) unless otherwise stated. The means’ separation using Fisher’s protected LSD was obtained using the PDIFF statement in the LSMEANS option. Orthogonal polynomial contrasts were done to examine the trends of measured parameters in response to N application rate. Pearson’s correlation coefficients among the measured parameters, grain yield, light interception (LI), leaf area index (LAI), SPAD chlorophyll index, plant height (PH), branches per plant, pods per branch, seeds per pod, thousand seed weight (TSW), harvest index (HI), N uptake, nitrogen use efficiency (NUE), oil concentration, oil production, biodiesel production, and crude protein concentration were generated using the PROC CORR procedure of SAS software (SAS Institute, 2017). Regression analyses using SAS software (SAS Institute, 2017) were conducted for those traits that correlated to quantify the relationship.

3 RESULTS

3.1 Light interception (LI), leaf area index (LAI), SPAD chlorophyll index, and plant height

There were main effects of N source and N application rate on the quantity of light intercepted but no interactions were detected (Table 3). The quantity of light intercepted was greater for camelina plots fertilized with CU compared to those fertilized with PCU (Table 4). For N rate, the response was a linear increase in the amount of light intercepted as N application rate increased (Table 5).

For LAI, there was a cultivar × N rate interaction effect (Table 3). Across the two growing seasons, there was a trend for a linear decrease in LAI of cultivar Blaine Creek as N application rate increased, however, for cultivar Pronghorn LAI increased linearly with increasing N application rate and therefore, accounted for the interaction (Table 5). Within N application rate, differences in LAI only occurred at 0 kg N ha\(^{-1}\) rate where cultivar Blaine Creek had greater LAI than cultivar Pronghorn (Table 5). There was a trend for a cultivar × N source × N rate interaction effect on LAI (Table 3; data not shown).

There were two-way interaction effects of year × cultivar and year × N rate on SPAD chlorophyll index (Table 3). For the year × cultivar interaction effect, Blaine Creek had greater SPAD Chlorophyll Index than cultivar Pronghorn during both years (Table 6). Within cultivar, no difference in SPAD Chlorophyll Index occurred between the two years of the study (Table 6). During Year 1, there was a linear increased in SPAD chlorophyll index as N rate increased but during Year 2, there was no response of SPAD chlorophyll index to N rate (Table 5). Within N rate, SPAD Chlorophyll index was greater during Year 2 than Year 1 at 0 kg N ha\(^{-1}\) but at 40 kg N ha\(^{-1}\), SPAD chlorophyll index was greater during Year 1 than Year 2 of the study (Table 5).

There was a main effect of cultivar and a two-way interaction effect of year × N rate on camelina plant height (Table 3). Plant height of cultivar Blaine Creek was greater than that of Pronghorn (Table 4). In relation to the year × N rate interaction effect, plant height response to N rate was cubic during Year 1 and plateaued at 80 kg N ha\(^{-1}\), but a linear increased in plant height as N rate increased during Year 2 (Table 5). Within N rates, plant height was greater in Year 2 than Year 1 of this study (Table 5). There
### TABLE 3 Analysis of variance (ANOVA) for light interception (LI), leaf area index (LAI), SPAD chlorophyll index (SPAD), plant height (PH), branches per plant (Branch), pods per branch (Pod), seeds per pod (Seed), thousand seed weight (TSW), grain yield (GY), harvest index (HI), N uptake, nitrogen use efficiency (NUE), grain oil concentration (OC), oil production (OP), biodiesel production (BP), and grain crude protein (CP) concentration for camelina as affected by year (Y), cultivar (C), nitrogen source (NS), nitrogen rate (NR), and their interactions. Values are probabilities for the \( F \)-statistic.

| Effect          | df | LI  | LAI | SPAD | PH  | Branch | Pod  | Seed | TSW  | GY  | HI  | N uptake | NUE | OC  | OP  | BP  | CP  |
|-----------------|----|-----|-----|------|-----|--------|------|------|------|-----|-----|-----------|-----|-----|-----|-----|-----|
| Y               | 1  | 0.949 | 0.110 | 0.761 | 0.001 | 0.367  | 0.032 | 0.002 | <0.001 | 0.506 | 0.020 | 0.381  | 0.254 | 0.005 | 0.549 | 0.623 | 0.006 |
| C               | 1  | 0.449 | 0.576 | <0.001 | 0.022 | 0.437  | 0.004 | 0.323 | <0.001 | <0.001 | 0.034 | <0.001  | 0.004 | 0.110 | 0.001 | <0.001 | 0.765 |
| Y × C           | 1  | 0.557 | 0.274 | 0.021 | 0.740 | 0.990  | 0.925 | 0.682 | 0.006 | 0.015 | 0.011 | 0.033  | 0.851 | 0.263 | 0.018 | 0.013 | 0.282 |
| NS              | 1  | 0.025 | 0.960 | 0.671 | 0.069 | 0.062  | 0.735 | 0.029 | 0.158 | 0.481 | 0.589 | 0.731  | 0.286 | 0.974 | 0.437 | 0.415 | 0.002 |
| Y × NS          | 1  | 0.538 | 0.917 | 0.311 | 0.642 | 0.702  | 0.462 | 0.417 | 0.492 | 0.183 | 0.829 | 0.145  | 0.416 | 0.918 | 0.233 | 0.221 | 0.046 |
| C × NS          | 1  | 0.906 | 0.095 | 0.764 | 0.871 | 0.493  | 0.084 | 0.818 | 0.714 | 0.145 | 0.212 | 0.129  | 0.586 | 0.914 | 0.167 | 0.158 | 0.081 |
| Y × C × NS      | 1  | 0.742 | 0.994 | 0.337 | 0.395 | 0.399  | 0.462 | 0.909 | 0.681 | 0.577 | 0.347 | 0.560  | 0.715 | 0.720 | 0.593 | 0.566 | 0.632 |
| NR              | 3  | <0.001 | 0.172 | 0.041 | 0.013 | 0.755  | 0.867 | 0.992 | 0.833 | <0.001 | 0.236 | <0.001  | 0.434 | 0.096 | <0.001 | <0.001 | 0.012 |
| Y × NR          | 3  | 0.715 | 0.432 | 0.024 | 0.038 | 0.573  | 0.387 | 0.976 | 0.802 | 0.162 | 0.609 | 0.162  | 0.233 | 0.569 | 0.166 | 0.184 | 0.008 |
| C × NR          | 3  | 0.924 | 0.013 | 0.549 | 0.635 | 0.389  | 0.093 | 0.995 | 0.883 | 0.716 | 0.568 | 0.747  | 0.680 | 0.772 | 0.753 | 0.743 | 0.499 |
| Y × C × NR      | 3  | 0.566 | 0.216 | 0.936 | 0.202 | 0.215  | 0.474 | 0.859 | 0.479 | 0.784 | 0.374 | 0.690  | 0.741 | 0.831 | 0.820 | 0.811 | 0.045 |
| NS × NR         | 3  | 0.580 | 0.694 | 0.295 | 0.352 | 0.2845 | 0.903 | 0.989 | 0.309 | 0.088 | 0.218 | 0.146  | 0.680 | 0.244 | 0.083 | 0.081 | 0.199 |
| Y × NS × NR     | 3  | 0.480 | 0.484 | 0.535 | 0.827 | 0.947  | 0.659 | 0.313 | 0.721 | 0.788 | 0.782 | 0.907  | 0.851 | 0.181 | 0.754 | 0.763 | 0.118 |
| C × NS × NR     | 3  | 0.886 | 0.082 | 0.289 | 0.426 | 0.790  | 0.867 | 0.810 | 0.642 | 0.609 | 0.490 | 0.578  | 0.372 | 0.983 | 0.672 | 0.668 | 0.824 |
| Y × C × NS × NR | 3  | 0.687 | 0.157 | 0.426 | 0.872 | 0.846  | 0.458 | 0.950 | 0.814 | 0.818 | 0.750 | 0.843  | 0.519 | 0.989 | 0.839 | 0.838 | 0.343 |
was a trend for a main effect of N source on plant height of camelina (Table 3) and camelina plots fertilized with CU tended to be taller than those fertilized with PCU (Table 4).

### 3.2 Camelina yield components

Number of branches/plant, pods/branch, seeds/pod, and TSW were evaluated for both years in our study. There were no main effects of year, cultivar, and N rate or their interactions on branches/plant (Table 3; data not shown). However, camelina plots fertilized with CU tended to have greater branches/plant than those fertilized with PCU (Table 4).

There were main effects of year and cultivar on pods/branch (Table 3). The number of pods/branch was less in Year 1 compared with Year 2, and cultivar Blaine Creek had fewer pods per branch than Pronghorn (Table 4). There were trends for cultivar × N source and cultivar × N rate interactions effect on pods/branch (Table 3; data not shown).

In this study, only year and N source influenced seeds/pod (Table 3). In Year 1, seeds/pod was less than Year 2 and camelina plots fertilized with CU had fewer seeds/pod than those fertilized with PCU (Table 4). There was a two-way interaction effect of year × cultivar on TSW (Table 3). In both years, TSW was greater for cultivar Blaine Creek than that of Pronghorn and within each cultivar, TSW was greater in the first than the second year of the study (Table 6).

### 3.3 Grain yield, harvest index, nitrogen uptake, and nitrogen use efficiency (NUE) of camelina

Grain yield of camelina was affected by year × cultivar interaction and a main effect of N rate (Table 3). For the year × cultivar interaction effect, in Year 1, both Blaine Creek and Pronghorn had similar grain yield but in Year 2, grain yield of Blaine Creek was greater than that of Pronghorn (Table 6). Within each cultivar, grain yield of Blaine Creek and Pronghorn was not different between the two years (Table 6). There was a linear increased in grain yield of camelina as N rate increased from 0 to 120 kg N ha⁻¹ (Table 7).

There was a year × cultivar interaction effect on HI of camelina (Table 3). In Year 1, HI was not different between Blaine Creek and Pronghorn but in Year 2, HI was greater for cultivar Blaine Creek compared to Pronghorn (Table 6). Within cultivar, HI was greater in Year 2 than Year 1 for each cultivar (Table 6).

Nitrogen uptake quantified based on grain N concentration was influenced by a year × cultivar interaction and a main effect of N rate (Table 3). In relation to the year × cultivar interaction on N uptake, in Year 1, Blaine Creek and Pronghorn had similar N uptake but in Year 2, N uptake by Blaine Creek was greater than that of Pronghorn (Table 6). Within each cultivar, N uptake of Blaine Creek and Pronghorn was not different between the two years (Table 6). There was a linear increase in grain yield of camelina as N rate increased from 0 to 120 kg N ha⁻¹ (Table 7).

There was a year × cultivar interaction effect on HI of camelina (Table 3). In Year 1, HI was not different between Blaine Creek and Pronghorn but in Year 2, HI was greater for cultivar Blaine Creek compared to Pronghorn (Table 6). Within cultivar, HI was greater in Year 2 than Year 1 for each cultivar (Table 6).

Nitrogen uptake quantified based on grain N concentration was influenced by a year × cultivar interaction and a main effect of N rate (Table 3). In relation to the year × cultivar interaction on N uptake, in Year 1, Blaine Creek and Pronghorn had similar N uptake but in Year 2, N uptake by Blaine Creek was greater than that of Pronghorn. For both Blaine Creek and Pronghorn, N uptake was not different between years (Table 6). There was a positive linear increase in N uptake as N rate increased (Table 7).

**Notes.** CU: conventional urea; PCU: polymer-coated urea; SEM, standard error of mean. "Within rows, p value indicates significance (p < 0.05) between means for each parameter using the PDIFF option in PROC MIXED. \(^\text{N source.}\)

### 3.4 Camelina grain oil concentration, oil and biodiesel production, and grain crude protein concentration

Oil concentration of camelina grain was only affected by year (Table 3), and it was less in the first compared to the second year of this study (Table 4). There was a trend for a N rate effect on grain oil concentration (Table 3), and the...
response was quadratic, increasing from 0 kg N and plateaued at 40 to 80 kg N then decreased for plots fertilized at a rate of 120 kg N ha\(^{-1}\) (Table 7).

Oil and estimated biodiesel production were both affected by a year × cultivar interaction and main effect of N rate (Table 3). The year × cultivar interaction occurred because of the greater oil and biodiesel production in Year 2 for cultivar Blaine Creek than that of Pronghorn but similar oil and biodiesel production for Blaine Creek and Pronghorn in the first year (Table 6). Within each cultivar, oil and biodiesel production were not different between years (Table 6). Similar to grain yield response, there was a linear increase in oil and biodiesel production as N rate increased (Table 7).

The CP concentration of camelina grain was affected by a two-way interaction effect of year × N source and three-way interaction effect of year × cultivar × N rate (Table 3). Also, there was a trend for cultivar × N source interaction effect on CP concentration of camelina grain (Table 3; data not shown). For the year × N source interaction effect, in Year 1, grain CP concentration was greater for PCU fertilized camelina plots than CU plots but in Year 2, grain CP concentration of CU and PCU fertilized plots was not different (Table 6). For each N source, grain CP concentration was greater in Year 1 than Year 2 (Table 6). In relation to the three-way interaction, in Year 1, both Blaine Creek and Pronghorn and in Year 2, for Blaine Creek CP, concentration response to N rate was cubic, that is, fluctuating across N rate (Table 8). However, for Pronghorn in Year 2, CP concentration response to N rate tended to be cubic (Table 8). Within the 0 kg N ha\(^{-1}\) rate, CP concentration was greater for both Blaine Creek and Pronghorn in Year 1 than Year 2 of this study (Table 8). At 40 kg N ha\(^{-1}\), CP concentration of Blaine Creek was greater than Pronghorn in Year 1 but in Year 2, Pronghorn had greater grain CP concentration than Blaine Creek (Table 8). Also, grain CP concentration was greater for Blaine Creek in Year 1 than Year 2 but for Pronghorn, CP concentration did not differ between years (Table 8). At 80 kg N ha\(^{-1}\), grain CP concentration was similar between the two cultivars in Year 1 and 2 and both Blaine Creek and Pronghorn had greater grain CP concentration in Year 1 than Year 2 in this study (Table 8).

### DISCUSSION

Our focus in this study was to evaluate the effects of nitrogen source, rate, and cultivar on grain yield and potential biodiesel production of camelina. The ancillary data of LI, LAI, SPAD chlorophyll index, PH, and yield components were included in this study to help explain the principal response variables of grain yield and biodiesel production. For example, LI, LAI, and leaf chlorophyll concentration (SPAD Chlorophyll Index) are key agronomic traits that drive plant photosynthetic activity and ultimately crop productivity as they are important components linked to water, carbon dioxide exchange, and solar radiation interception and use (Bréda, 2003). Yield components governed crop production...
TABLE 6 Interaction effects of year x cultivar for SPAD chlorophyll index (SPAD), thousand seed weight (TSW), grain yield, harvest index, N uptake, oil production, biodiesel production, and year x N source for crude protein (CP) concentration of two camelina cultivars grown under different nitrogen sources and application rates during the spring season of 2016 and 2017 in Reno, NV, USA.

| Factors                  | Cultivar         | SEM  | P valueb |
|--------------------------|------------------|------|----------|
|                          | Blaine Creek     | Pronghorn |      |          |
| SPAD                     |                  |      |          |
| Year 1 (2016)            | 31.0b^A          | 28.7^A | 0.5     | 0.001    |
|                          |                  |      |          |
| Year 2 (2017)            | 32.0^A           | 27.4^A | 0.5     | <0.001   |
| TSW (g)                  |                  |      |          |
| Year 1 (2016)            | 1.6^A            | 1.5^A | 0.02    | 0.036    |
|                          |                  |      |          |
| Year 2 (2017)            | 1.4^B            | 1.2^B | 0.02    | <0.001   |
| Harvest index            |                  |      |          |
| Year 1 (2016)            | 0.08^B           | 0.09^A | 0.03   | 0.752    |
|                          |                  |      |          |
| Year 2 (2017)            | 0.28^A           | 0.21^A | 0.03   | 0.001    |
| N uptake (kg/ha)         |                  |      |          |
| Year 1 (2016)            | 44.8^A           | 38.9^A | 9.4    | 0.157    |
|                          |                  |      |          |
| Year 2 (2017)            | 38.6^A           | 20.2^A | 9.4    | <0.001   |
| Oil Production (kg/ha)   |                  |      |          |
| Year 1 (2016)            | 298.0^A          | 263.0^A | 70.1  | 0.257    |
|                          |                  |      |          |
| Year 2 (2017)            | 288.0^A          | 150.0^A | 70.1  | <0.001   |
| Biodiesel Production (L) |                  |      |          |
| Year 1 (2016)            | 87.0^A           | 77.0^A | 21.0  | 0.263    |
|                          |                  |      |          |
| Year 2 (2017)            | 88.0^A           | 46.0^A | 21.0  | <0.001   |
| N source                 |                  |      |          |
| Year 1 (2016)            | 294.0^A          | 304.0^A | 3.4   | 0.004    |
|                          |                  |      |          |
| Year 2 (2017)            | 269.0^B          | 271.0^B | 3.4   | 0.397    |

Notes: CU: conventional urea; PCU: polymer-coated urea; SEM, standard error of mean. *Within rows, p value indicates significance (p < 0.05) between means for each parameter using the PDIFF option in PROC MIXED. †Within columns, means followed by the same uppercase letter superscripts are not different (p > 0.05) for each parameter using the PDIFF option in PROC MIXED.. ‡N source.

The factors that influenced grain yield of camelina were year x cultivar interaction and N rate independently in this study. Grain yield of the cultivar Blaine Creek was 42.8% greater than that of Pronghorn averaged across the two years (Table 6). In relation to N rate, there was a 69.4% increase in the average grain yield for the combined 80 and 120 kg N ha⁻¹ rates compared to the average yield for 0 and 40 kg N ha⁻¹ combined in this study (Table 7). Understanding the mechanisms behind grain production for crops like camelina is vital in the development of agronomic best management practices, and in this study, grain yield of camelina was positively correlated with LI, SPAD, PH, HI, TSW, N uptake, and NUE (Tables 9 and 10). However, based on the regression model, LI, SPAD, PH, HI, and N uptake were the variables that had a significant (p < 0.05; Adjusted R² = 0.99) association with grain yield. Among the aforementioned variables, N uptake and LI had the strongest association with grain yield (Figure 2a,b). The greater N uptake by Blaine creek relative to Pronghorn (Table 6) and the increase NUE as N uptake increased (Figure 2c) thus leading to a more efficient conversion of N supply into grain production can be attributed to the observed differences in grain yield between cultivars in this study. In a study of soil N and water supply on canola NUE, Maaz et al. (2016) reported that 78%–100% of the yield difference in their study was attributed to NUE. Further, the interception of photosynthetically active radiation is closely linked to LAI (Man, Yu, & Shi, 2017), and along with leaf chlorophyll concentration are deemed the key drivers of the photosynthetic activity of plants and ultimately grain yield (Liu et al., 2017; Man et al., 2017). Therefore, the variation in grain yield between cultivars and among N rates in this study can also be attributed to the differences among the aforementioned canopy traits. In contrast to our study, grain yield between Blaine Creek and Pronghorn was not different averaged across two years in a study on agronomic responses of camelina carried out by Sintim, Zheljazkov, Obour, Garcia, and Foulke (2016). Also, positive responses of camelina grain yield to varying N application rates have been widely reported (Malhi et al., 2014; Mohammed, Chen, & Afshar, 2017; Sintim et al., 2015) and the magnitude of differences reported in these studies was dependent on the differences in increments of N applied, genotypes used, and environmental conditions where these studies were carried out. In our study, based on N source, rate, and cultivar, grain production of camelina ranged from 534 to 1,010 kg/ha and falls within the range of 127 to 3,303 kg/ha reported from studies in several countries across the globe (Czarnik, Jarecki, & Bobrecka-Jamro, 2017; Malhi et al., 2014; Sintim et al., 2015).
Based on camelina grain yield response in this study, applying N beyond 80 kg/ha did not result in a significant increase in grain yield but other studies have reported a wide variation in camelina grain yield response to N rates, ranging from 56 to 200 kg N ha⁻¹ (Jiang & Caldwell, 2016; Jiang et al., 2013; Sintim et al., 2015; Solis et al., 2013). This wide range of N required for optimum grain production is heavily dependent on genotype used, environmental conditions, and management approaches utilized in growing grain crops like camelina (e.g., Setiyono et al., 2011). Harvest index is an important trait associated with crop yields (Sinclair, 1998); it indicates directly the allocation of biomass to grain, and indirectly the partitioning between grain and biomass of camelina (Dai et al., 2016). The 28.6% greater HI for Blaine Creek relative to Pronghorn in this study may be indicative of a superior allocation of photosynthate, that is, carbon allocation (Sinclair, 1998) toward grain production for Blaine Creek compared to Pronghorn and hence the overall greater grain yield for Blaine Creek. The large disparity in HI of 94% greater in the second than first of this study is not unusual for grain crops (Singh & Stoskopf, 1971) as factors such as extreme temperatures during crop reproductive development (hot or cold), delayed sowing which shortens the vegetative stage and increases HI, and pre- and postanthesis water use can have significant influence on HI (Unkovich, Baldock, & Forbes, 2010). In Year 1 of our study, vegetative growth accounted for by overall biomass production (data not shown) was greater than Year 2 resulting in lower HI as a result of reduced partitioning of biomass to grain possibly as a result of the aforementioned factors.

The estimated biodiesel production from camelina was influenced by a year × cultivar interaction and N rate in this study. Averaged across both years, Blaine Creek produced 42.3% more biodiesel than Pronghorn (Table 6). In relation to N rate, the averaged biodiesel production of 80 and 120 kg N ha⁻¹ combined was 68% greater than that of 0 and 40 kg N ha⁻¹ combined. Biodiesel production from camelina is typically influenced by grain oil concentration and overall grain yield of the crop. There were positive correlations between oil concentration and biodiesel and among grain yield, oil concentration, and biodiesel production in this study (Tables 9 and 10). Among those variables correlated with biodiesel, the regression model indicated that grain yield, oil concentration, and N uptake were

### Table 7: Camelina grain yield, harvest index, thousand seed weight (TSW), nitrogen use efficiency (NUE), grain oil concentration, oil and estimated biodiesel production grown under different nitrogen sources and application rates during the spring season of 2016 and 2017 in Reno, NV, USA

| Parameters                      | N application rate (kg N ha⁻¹) | OPC¹ | L | Q | C | SEM |
|---------------------------------|-------------------------------|------|---|---|---|-----|
| Grain yield (kg/ha)             |                               |      |   |   |   |     |
|                                 | 0                             | 40   | 80| 120 |   |     |
|                                 | 534 Ab                        | 630 B| 962 A| 1010 A| <0.01 | 0.70 | 0.07 | 155.5 |
| Harvest index                   | 0.15                          | 0.16 | 0.17| 0.19| 0.04 | 0.88 | 0.86 | 0.03 |
| TSW (g)                         | 1.45                          | 1.43 | 1.41| 1.43| 0.59 | 0.48 | 0.80 | 0.03 |
| N uptake (kg/ha)                | 23.8 Ab                       | 29.0 B| 43.2 A| 46.5 A| <0.01 | 0.74 | 0.13 | 7.0 |
| NUE (%)                        | -                             | 22.7 | 28.2| 21.5| 0.83 | 0.20 | -   | 7.80 |
| Oil concentration (g/kg)        | 319.8                         | 325.3| 325.5| 317.7| 0.61 | 0.01 | 0.84 | 4.3  |
| Oil production (kg/ha)          | 172.1 B                       | 200.1 B| 309.8 A| 316.0 A| <0.01 | 0.62 | 0.06 | 51.9 |
| Biodiesel (L/ha)                | 51.2 B                       | 59.5 B| 91.8 A| 94.2 A| <0.01 | 0.65 | 0.06 | 15.2 |

¹Orthogonal polynomial contrast, L = linear, Q = quadratic, and C = cubic. ²Within rows, means followed by same uppercase letter superscripts are not different (p > 0.05).

### Table 8: Crude protein (CP) concentration of grain of two camelina cultivars grown under different nitrogen sources and application rates during the spring seasons of 2016 and 2017 in Reno, NV

| Factors                  | N application rate (kg N ha⁻¹) | OPC1 | L | Q | C | SEM |
|--------------------------|-------------------------------|------|---|---|---|-----|
| 2016, Blaine Creek       |                               |      |   |   |   |     |
| CP (g kg⁻¹)              |                               |      |   |   |   |     |
| 290.6Ba                   | 313.3Aa                        | 295.3Ba| 298.5Ba| 0.090 | 0.478 | 0.039 |
| 2016, Pronghorn           |                               |      |   |   |   |     |
| 295.1Aa                  | 299.6Ab                        | 293.4Aa| 303.8Ab| 0.090 | 0.478 | 0.039 |
| 2017, Blaine Creek        |                               |      |   |   |   |     |
| 267.3ABb                 | 262.3Bc                        | 269.5ABb| 276.5Ab| 0.090 | 0.478 | 0.039 |
| 2017, Pronghorn           |                               |      |   |   |   |     |
| 271.8ABb                 | 271.8ABb                       | 267.8ABb| 275.4Ab| 0.248 | 0.177 | 0.095 |
| SEM                      | 4.7                            | 4.7    | 4.7| 4.7 |   |     |

¹Orthogonal polynomial contrast, L = linear, Q = quadratic, and C = cubic. ²Within rows, means followed by same uppercase letter superscripts are not different (p > 0.05). ³Within columns, means followed by same lowercase letter superscripts are not different between years and cultivars (p > 0.05).
significant \((p < 0.001; \text{Adjusted } R^2 = 0.99)\) in accounting for the variation in biodiesel production (Figure 2d–f). Based on the strength of these relationships, grain yield as affected by N uptake (Figure 2a) was determined to be the most important factors limiting biodiesel production in this study. Therefore, any factor such as light interception, plant

**TABLE 9** Correlation coefficients among traits of two cultivars of camelina evaluated for grain and potential biodiesel production under different nitrogen sources and application rates during the spring of 2016 at Reno, Nevada USA

| Parameters\(^a\) | LI | LAI | SPAD | PH | Branch | Pod | Seed | TSW | HI | N uptake | NUE | OC | OIL | BIOD | CP |
|----------------|----|-----|------|----|--------|-----|------|-----|----|----------|-----|----|-----|------|----|
| Yield          | 0.57 | NS  | 0.58 | NS | NS     | NS  | NS   | 0.81 | 0.99 | 0.87     | 0.60 | 0.99 | 0.99 | −0.33 |
| LI             | NS  | NS  | 0.72 | NS | NS     | NS  | 0.33 | 0.55 | NS | 0.33     | 0.56 | 0.56 | 0.56 | −0.26 |
| LAI            | NS  | NS  | NS   | NS | NS     | NS  | NS   | NS   | NS | NS       | NS  | NS  | NS  | 0.46 |
| SPAD           | NS  | NS  | NS   | NS | NS     | NS  | NS   | NS   | 0.56 | 0.50     | 0.33 | 0.59 | 0.59 | −0.30 |
| PH             | 0.27 | NS  | NS   | NS | NS     | NS  | NS   | NS   | NS | 0.46     | NS  | 0.46 | 0.46 | 0.46 |
| Branch         | NS  | NS  | NS   | NS | NS     | NS  | NS   | NS   | NS | NS       | NS  | NS  | NS  | 0.39 |
| Pod            | NS  | NS  | −0.37| NS | NS     | NS  | NS   | NS   | NS | NS       | NS  | NS  | NS  | 0.80 |
| Seed           | NS  | NS  | NS   | NS | NS     | NS  | NS   | NS   | NS | NS       | NS  | NS  | NS  | 0.80 |
| TSW            | NS  | NS  | NS   | NS | NS     | NS  | NS   | NS   | NS | 0.80     | 0.66 | 0.66 | 0.80 | 0.80 |
| HI             | 0.80 | 0.66 | 0.66 | 0.80 | 0.80   | 0.80 | 0.80 | 0.80 | 0.80 | 0.80     | 0.80 | 0.80 | 0.80 | 0.80 |
| N uptake       | 0.87 | 0.58 | 0.99 | 0.99 | 0.99   | 0.99 | 0.99 | 0.99 | 0.99 | 0.99     | 0.99 | 0.99 | 0.99 | 0.99 |
| NUE            | 0.52 | 0.87 | 0.87 | NS  | NS     | NS  | NS   | NS   | NS | 0.95     | 0.95 | 0.95 | 0.95 | 0.95 |
| OC             | 0.65 | 0.65 | NS   | 0.35 | 0.35   | 0.35 | 0.35 | 0.35 | 0.35 | 0.35     | 0.35 | 0.35 | 0.35 | 0.35 |
| OIL            | 1.00 | NS  | NS   | NS  | NS     | NS  | NS   | NS   | NS | 0.95     | 0.95 | 0.95 | 0.95 | 0.95 |
| BIOD           | NS  | NS  | NS   | NS  | NS     | NS  | NS   | NS   | NS | NS       | NS  | NS  | NS  | 0.39 |

\(^a\)LI, light interception, LAI, leaf area index, SPAD, SPAD chlorophyll index, PH, plant height, Branch, number of branches/plant, Pod, number of pods/branch, Seed, number of seeds/pod, TSW, thousand seed weight, HI, harvest index, NUE, nitrogen use efficiency, OC, oil concentration of seed, OIL, oil production kg/ha, BIOD, biodiesel production L/ha, CP, crude protein concentration.

**TABLE 10** Correlation coefficients among traits of two cultivars of camelina evaluated for grain and potential biodiesel production under different nitrogen sources and application rates during the spring of 2017 at Reno, Nevada, USA

| Parameters\(^a\) | LI | LAI | SPAD | PH | Branch | Pod | Seed | TSW | HI | N uptake | NUE | OC | OIL | BIOD | CP |
|----------------|----|-----|------|----|--------|-----|------|-----|----|----------|-----|----|-----|------|----|
| Yield          | 0.48 | NS  | 0.31 | NS | 0.36   | NS  | NS   | 0.25 | 0.72 | 0.99     | 0.89 | NS | 0.99 | 0.99 | NS |
| LI             | NS  | NS  | 0.64 | NS | 0.64   | NS  | NS   | NS   | 0.48 | 0.39     | 0.39 | NS | 0.47 | 0.47 | NS |
| LAI            | NS  | NS  | NS   | NS | −0.30  | NS  | NS   | NS   | NS | 0.31     | NS  | NS | 0.31 | 0.31 | NS |
| SPAD           | NS  | NS  | NS   | NS | NS     | NS  | NS   | 0.55 | 0.31 | 0.31     | 0.31 | NS | 0.31 | 0.31 | NS |
| PH             | NS  | NS  | NS   | NS | NS     | NS  | NS   | 0.36 | 0.35 | 0.35     | 0.35 | NS | 0.35 | 0.35 | NS |
| Branch         | 0.32 | −0.30| NS   | NS | NS     | NS  | NS   | NS   | NS | 0.35     | 0.35 | NS | 0.35 | 0.35 | NS |
| Pod            | NS  | NS  | NS   | NS | NS     | NS  | NS   | NS   | NS | NS       | NS  | NS | 0.35 | 0.35 | NS |
| Seed           | NS  | NS  | NS   | NS | NS     | NS  | NS   | NS   | NS | NS       | NS  | NS | 0.35 | 0.35 | NS |
| TSW            | NS  | NS  | NS   | NS | 0.25   | NS  | NS   | NS   | NS | 0.88     | 0.99 | 0.99 | 0.99 | 0.99 | NS |
| HI             | 0.70 | 0.63 | NS   | 0.72 | 0.72   | NS  | 0.72 | NS   | NS | 0.90     | 0.90 | 0.90 | 0.90 | 0.90 | NS |
| N uptake       | 0.88 | NS  | 0.90 | 0.90 | 0.90   | NS  | 0.90 | 0.90 | 0.90 | 0.90     | 0.90 | 0.90 | 0.90 | 0.90 | NS |
| NUE            | NS  | NS  | 0.90 | NS  | NS     | NS  | 0.90 | NS   | NS | 0.90     | 0.90 | 0.90 | 0.90 | 0.90 | NS |
| OC             | NS  | NS  | NS   | NS  | −0.54  | NS  | NS   | NS   | NS | 0.90     | 0.90 | 0.90 | 0.90 | 0.90 | NS |
| OIL            | 1.00 | NS  | NS   | NS  | 0.90   | NS  | NS   | NS   | NS | 0.90     | 0.90 | 0.90 | 0.90 | 0.90 | NS |
| BIOD           | NS  | NS  | NS   | NS  | NS     | NS  | NS   | NS   | NS | 0.90     | 0.90 | 0.90 | 0.90 | 0.90 | NS |

\(^a\)LI, light interception, LAI, leaf area index, SPAD, SPAD chlorophyll index, PH, plant height, Branch, number of branches per plant, Pod, number of pods per branch, Seed, number of seeds per pod, TSW, thousand seed weight, HI, harvest index, NUE, nitrogen use efficiency, OC, oil concentration of seed, OIL, oil production kg/ha, BIOD, biodiesel production L/ha, CP, crude protein concentration.
height, N uptake, and NUE that alter grain yield will affect biodiesel production of camelina. The results reported by Sintim et al. (2015) concurred with the positive response in estimated biodiesel as N rate increased in this study. Sintim et al. (2015) reported a range of 81.1–164 L/ha and that maximum biodiesel production (102–168 L/ha) can be produced at a rate of 90–100 kg N ha\(^{-1}\) not too distant from the 80–120 kg N ha\(^{-1}\) rates in this study.

The year × cultivar × N rate interaction that affected grain CP concentration in this study did not follow a definitive pattern in response to N rate as it was mostly cubic, that is, increasing and decreasing among N rates for

FIGURE 2 The relationships among agronomic parameters of camelina grown under different nitrogen sources and application rates: (a) grain yield (GY) and N uptake, (b) grain yield and light interception, (c) nitrogen use efficiency and N uptake, (d) biodiesel production and grain yield, (e) biodiesel and oil concentration, and (f) biodiesel production and nitrogen uptake during the 2016 and 2017 growing seasons, Reno, NV, USA
each cultivar, and 40 kg N ha$^{-1}$ seemed to be optimal for the attainment of maximum grain CP concentration. There were correlations among CP concentration and LI, SPAD, PH, oil concentration, and N uptake (Tables 9 and 10); however, among the correlated variables, the regression model indicates that PH had the strongest association accounting for variation in CP concentration based on the coefficient of determination ($CP = 352.52 - 0.9083 \times PH; R^2 = 0.4680$; Adj $R^2 = 0.4638$). The response suggested that shorter plants may have been more efficient in translocating N to grain rather than the dilution of N for overall support in the case of taller plants. Several studies (Jiang et al., 2013; Malhi et al., 2014; Sintim et al., 2015) have reported a N rate effect on CP concentration of camelina grain, and the trend was a generally linear increase as N rates increased. The range of CP concentration (202–296 g/kg) reported in those studies compares favorably with results obtained in this study.

5 | CONCLUSIONS

This study quantified grain yield and potential biodiesel production responses from two cultivars of camelina based on two N sources and four N rates. The variations in crop yield are typically linked to genotype, environment, and management approaches applied in crop production agriculture. There are genotypic differences in cultivated varieties that alter the above and belowground morphological traits such as leaf area, leaf chlorophyll concentration, plant height, and root morphology of crop plants. These traits alter crop canopies interception of photosynthetically active radiation, water and nutrient uptake, and ultimately harvestable yield per unit land area. Our study revealed that both grain yield and biodiesel production were influenced by an interaction effect of year x cultivar and a main effect of N rate. However, the source of N applied, that is, CU and the controlled-release PCU fertilizer did not result in any statistical differences in grain yield and biodiesel production. Further, the nutrient N supplied by the irrigated reclaimed water utilized for irrigation in this study was inadequate for camelina production. Based on grain production, there was no advantage of using controlled-release PCU fertilizer for camelina production in this semiarid environment and this may be indicative of the relatively short maturation period for camelina before the full release of N from granules of PCU fertilizer. The cultivar Blaine Creek was considered superior to Pronghorn based on the greater grain yield and biodiesel observed in this study. Based on the range of N application rates used in this study in relation to the harvestable grain and biodiesel production obtained, 80 to 120 kg N ha$^{-1}$ is sufficient for the cultivation of camelina in this environment. The difference in grain yield between cultivars and among N rates can be linked to the variations in the measured agronomic traits of LI, LAI, SPAD chlorophyll index, PH, TSW, HI, N uptake, and NUE in this study. Relative to the range of grain production from camelina reported from multiple studies across the globe (127–3,303 kg/ha), and the range of grain yield obtained in this study (534–1,010 kg/ha), along with the relatively low N rate required, makes camelina a potential alternative crop to integrate into the annual crop production cycle in water-limited environments like Nevada if the market demand is adequate to improve the profitability of the crop.

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REFERENCES

Adhikari, P. A., Heo, J. M., & Nyachoti, C. M. (2016). Standardized total tract digestibility of phosphorus in camelina (Camelina sativa) meal fed to growing pigs without or phytase supplementation. Animal Feed Science & Technology, 214, 104–109. https://doi.org/10.1016/j.anifeedsci.2016.02.018

Bacenetti, J., Restuccia, A., Schillaci, G., & Failla, S. (2017). Biodiesel production from unconventional oilseed crops (Linum usitatissimum L. and Camelina sativa L.) in Mediterranean conditions: Environmental sustainability assessment. Renewable Energy, 112, 444–456. https://doi.org/10.1016/j.renene.2017.05.044

Barnett, T. P., Pierce, D. W., Hidalgo, H. G., Bonfils, C., Santer, B. D., Das, T., … Dettinger, M. D. (2008). Human-induced changes in the hydrology of the western United States. Science, 319(5866), 1080–1083.

Battaglia, M. L., Lee, C., & Thomason, W. (2018). Corn yield components and yield responses to defoliation at different row widths. Agronomy Journal, 110, 210–225. https://doi.org/10.2134/agronj2017.06.0322
Berti, M., Gesch, R., Eynck, C., Anderson, J., & Cermak, S. (2016). Camelina uses, genetics, genomics, production, and management. *Industrial Crops & Products*, 94, 690–710. https://doi.org/10.1016/j.indcrop.2016.09.034

Berti, M., Wilckens, R., Fischer, S., Solis, A., & Johnson, B. (2011). Seeding date influence on camelina seed yield, yield components, and oil content in Chile. *Industrial Crops & Products*, 34, 1358–1365. https://doi.org/10.1016/j.indcrop.2010.12.008

Bréda, N. J. J. (2003). Ground-based measurements of leaf area index: A review of methods, instruments and current controversies. *Journal of Experimental Botany*, 54(392), 2403–2417. https://doi.org/10.1093/jxb/erg263

Bullerwell, C. N., Collins, S. A., Lall, S. P., & Anderson, D. M. (2016). Growth performance, proximate and histological analysis of rainbow trout fed diets containing *Camelina sativa* seeds, meal (high-oil and solvent-extracted) and oil. *Aquaculture*, 452, 342–350. https://doi.org/10.1016/j.aquaculture.2015.11.008

Cassman, K. G., Dobermann, A., & Walters, D. T. (2002). Nitrogen use efficiency, and nitrogen management. *Ambio*, 31, 132–144.

Chambers, J., Blank, R. R., Zamudio, D. C., & Tausch, R. J. (1999). *Brassica napus* riparian areas: Physical and chemical properties of meadow soils. *Journal of Range Management*, 52(1), 92–99. https://doi.org/10.2307/4003497

Ciubota-Rosie, C., Ruiz, J. R., Ramos, M. J., & Pérez, Á. (2013). Biodiesel from *Camelina sativa*: A comprehensive characterization. *Fuel*, 105, 572–577.

Czarnik, M., Jarecki, W., & Bobrecka-Chambers, J., Blank, R. R., Zamudio, D. C., & Tausch, R. J. (1999). Central Nevada riparian areas: Physical and chemical properties of meadow soils. *Journal of Range Management*, 52(1), 92–99. https://doi.org/10.2307/4003497

Dai, J., Bean, B., Brown, B., Bruening, W., Edwards, J., Flowers, M., … Wiersma, J. (2016). Harvest index and straw yield of five classes of wheat. *Biomass & Bioenergy*, 85, 223–227. https://doi.org/10.1016/j.biombioe.2015.12.023

Del Moro, S. K., Sullivan, D. M., & Horneck, D. A. (2018). Ammonia volatilization from broadcast urea and alternative dry nitrogen fertilizers. *Soil Science Society of America Journal*, 81, 1629–1639. https://doi.org/10.2136/sssaj2017.06.0181

Drenth, A. C., Olsen, D. B., Cabot, P. E., & Johnson, J. J. (2014). Compression ignition engine performance and emission evaluation of industrial oilseed biofuel feedstocks camelina, carinata, and pennycress across three fuel pathways. *Fuel*, 136, 143–155. https://doi.org/10.1016/j.fuel.2014.07.048

Dyer, J. A., Vergé, X. P. C., Desjardins, R. L., Worth, D. E., & McConkey, B. G. (2010). The impact of increased biodiesel production on the greenhouse gas emissions from field crops in Canada. *Energy for Sustainable Development*, 14, 73–82. https://doi.org/10.1016/j.esd.2010.03.001

Fageria, N. K., & Baligar, V. C. (2005). Enhancing nitrogen use efficiency in crop plants. *Advances in Agronomy*, 88, 97–185.

Fore, S. R., Lazarus, W., Porter, P., & Jordan, N. (2011). Economics of small-scale on-farm use of canola and soybean for biodiesel and straight vegetable oil biofuels. *Biomass & Bioenergy*, 35, 193–202. https://doi.org/10.1016/j.biombioe.2010.08.015

George, N., Thompson, S. E., Hollingsworth, J., & Orloff, S. (2018). Measurement and simulation of water-use by canola and camelina under cool-season conditions in California. *Agricultural Water Management*, 196, 15–23. https://doi.org/10.1016/j.agwat.2017.09.015

Grant, C. A., Wu, R., Selles, F., Harker, K. N., Clayton, G. W., Bittman, S., … Lupway, N. Z. (2012). Crop yield and nitrogen concentration with controlled release urea and split applications of nitrogen as compared to non-coated urea applied at seeding. *Field Crops Research*, 127, 170–180. https://doi.org/10.1016/j.fcr.2011.11.002

Hunsaker, D. J., French, A. N., Clarke, T. R., & El-Shikha, D. M. (2011). Water use, crop coefficients, and irrigation management criteria for camelina production in arid regions. *Irrigation Science*, 29(1), 27–43. https://doi.org/10.1007/s00227-010-0213-9

Iskandarov, U., Kim, H. J., & Cahoon, E. B. (2014). Camelina: An emerging oilseed platform for advanced biofuels and bio-based materials. In M. C. McCann, M. Buckeridge, & N. Carpita (Eds.), *Plants and Bioenergy* (pp. 131–140). New York, NY: Springer.

Jaskiewicz, T., Sagan, A., & Puzio, I. (2014). Effect of the *Camelina sativa* oil on the performance, essential fatty acid level in tissues and fat-soluble vitamins content in the livers of broiler chickens. *Livestock Science*, 165, 74–79. https://doi.org/10.1016/j.livsci.2014.04.003

Jiang, Y., & Caldwell, C. D. (2016). Effects of nitrogen fertilization on camelina seed yield, yield components, and downy mildew infection. *Canadian Journal Plant Science*, 96, 17–26.

Jiang, Y., Caldwell, C. D., Falk, K. C., Lada, R. R., & MacDonald, D. (2013). Camelina yield and quality response to combined nitrogen and sulfur. *Agronomy Journal*, 105(6), 1847–1852. https://doi.org/10.2134/agronj2013.0240

Keane, B. J., Ineson, P., Vallack, H. W., Blei, E., Bentley, M., Howarth, S., … Toet, S. (2018). Greenhouse gas emissions from the energy crop oilseed rape (*Brassica napus*): the role of photosynthetically active radiation in diurnal N2O flux variation. *GCB Bioenergy*, 10, 306–319.

Kemp, W. H. (2006). Biodiesel: Basics and Beyond, a comprehensive guide to production and use for the home and farm. Tamworth, ON, Canada: Aztext Press.

Keske, C. M. H., Hoag, D. L., Brandess, A., & Johnson, J. J. (2013). Is it economically feasible for farmers to grow their own fuel? A study of Camelina sativa produced in the western United States as an on-farm biofuel. *Biomass & Bioenergy*, 54, 89–99. https://doi.org/10.1016/j.biombioe.2013.03.015

Koçar, G. (2017). Oil crops for energy. *Encyclopedia of Sustainable Technologies*, 3, 121–130.

Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J., & Kessel, C. V. (2005). Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advances in Agronomy*, 87, 85–156.

Lawrence, R. D., Anderson, J. L., & Clapper, J. A. (2016). Evaluation of camelina meal as a feedstuff for growing dairy heifers. *Journal of Dairy Science*, 99(8), 6215–6228. https://doi.org/10.3168/jds.2016-10876

Li, Y., & Sun, X. S. (2015). Camelina oil derivatives and adhesion properties. *Industrial Crops & Products*, 73, 73–80. https://doi.org/10.1016/j.indcrop.2015.04.015

 Lindenmayer, R. B., Hansen, N. C., Brummer, J., & Pritchett, J. G. (2011). Deficit irrigation of alfalfa for water-savings in the Great Plains and Intermountain West: A review and analysis of the literature. *Agronomy Journal*, 103, 45–50. https://doi.org/10.2134/agronj2010.0224

Liu, Y. C., Savas, A. J., & Avedisian, C. T. (2013). The spherically symmetric droplet burning characteristics of Jet-A and biofuels derived from camelina and tallow. *Fuel*, 108, 824–832. https://doi.org/10.1016/j.fuel.2013.02.025
Yang, Y., Yu, L., Ni, X., Yang, Y., Liu, B., Wang, Q., … Wu, Y. (2018). Reducing nitrogen loss and increasing wheat profits with low-cost, matrix-based, slow-release urea. *Agronomy Journal, 110*(1), 380–388. https://doi.org/10.2134/agronj2017.06.0351

Zheng, W., Zhang, M., Liu, Z., Zhou, H., Lu, H., Zhang, W., … Chen, B. (2016). Combining controlled-release urea and normal urea to improve the nitrogen use efficiency and yield under wheat-maize double cropping system. *Field Crops Research, 197*, 52–62. https://doi.org/10.1016/j.fcr.2016.08.004

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