

Article

Seed Yield and Water Productivity of Irrigated Winter Canola (*Brassica napus* L.) under Semiarid Climate and High Elevation

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Abstract: Canola is a cash crop produced for its highly-valued seed, and as a protein source for animal feed. While winter canola is produced mainly in the high plains, it is expanding to new environments, and is greatly incorporated into crop systems with advantages in terms of increasing crop yield and improving soil health. The objectives of this study were to evaluate eight winter canola genotypes for seed yield, and to determine their water productivity under semiarid climates and high elevations in the Four Corners region at Farmington, New Mexico. A field experiment was conducted at the New Mexico State Agricultural Science Center at Farmington for five growing seasons. Eight genotypes of winter canola (Baldur, Flash, Safran, Sitro, Virginia, Visby, Wichita, and Sumner) were arranged into the randomized complete block design. The field was fully irrigated with a center pivot irrigation system. Results showed that winter canola seed yield was dependent on genotype, varying from 2393 to 5717 kg/ha. The highest yield was achieved by Sitro, and the lowest yield by Sumner. There was inter-annual variation in canola nitrogen-use efficiency (NUE), irrigation water-use efficiency (IWUE), and crop water-use efficiency (CWUE). NUE varied from 12.9 to 50.4 kg seed/kg N, with the highest NUE achieved by Sitro, and the lowest by Sumner. IWUE varied from 0.34 to 0.80 kg/m³, and canola CWUE from 0.28 to 0.69 kg/m³. The highest water productivity was achieved by Sitro. The results of this study showed full assessment of canola production under the semiarid climate in the Four Corners region, and could improve crop productivity and profitability.

Keywords: winter canola; seed yield; irrigation; water productivity; semiarid climate; high elevation

1. Introduction

Canola (*Brassica napus* L.) is the second largest oil seed after soybean worldwide, producing high-protein meal used for animal feed during processing [1,2]. While canola was traditionally produced for birds and industry, it became more economically attractive, and the new varieties could be used for animal grazing, since the seed cake is an important source of protein in livestock feeding [3–5]. Its integration into the crop system in rotation with wheat [6] and Barley [7] significantly improved the yield of all the crops, eliminated soil-born cereal pathogens and root maggot damage, and reduced the impact of pathogen diseases on the yield of the cereals [8,9]. In 2017, United States

was the 7th largest canola oil producer (1,013,000 tons), led by Canada (18,362,000 tons), and followed by China, India, Australia, Ukraine, and Russia [10]. In North America, Canada is the largest canola producer, with 90% of the production [4] and increasing harvested yields since 1990 [11]. US canola production in 2017 was 14,143,010.097 tons, with a national average yield of 1746 kg/ha; the leading States, in order, were North Dakota, Oklahoma, Montana, Washington, Minnesota, Kansas, Idaho, and Oregon [12]. Canola yield depends on numerous factors, including genotypes [13–16], seeding density [17,18], climate [9,19–21], soil type [20], watering regime [22–25], fertilizer rate and application timing [26–32], seeding rate and depth, crop rotation, tillage practices, and planting date [33–35].

Winter canola is produced in the US mostly in North Dakota (90% of the production), Idaho, and Minnesota [36]. However, winter canola production is expanding into southern US, and has the potential for dual-purpose production for forage and seed production [37,38]. Winter canola production is adapted to the Southern Great Plains [39,40], and is expanding into the south western US [13,14,37,38]. Begna et al. [38] reported winter canola seed yield ranges of 930–4360 kg/ha for three winter canola cultivars (DKW44-10, Griffin, and Safran). Neely et al. [41] reported winter canola seed yield 387 and 2931 kg/ha for different genotypes under different planting dates across the State of Texas. While winter canola has advantages for improving global crop system production and soil health, plant lodging can negatively affect seed yield, oil quality, and harvest ability, due to inappropriate planting dates and fertilizer management [10,42–44]. In the southern United States, winter canola may suffer the early fall and late winter freezes if the optimum planting date is not respected, similar to winter wheat and maize in the Four Corners region [45]. Trostle et al. [46] reported winter canola killed by winter freeze injury at Etter, Texas. Seedling survival is affected by low temperatures, and spring frosts and canola seed yield is affected [3,47].

While extensive research activities had been conducted in the northern US, mostly in the Northern Great Plains, very limited data and information exist on winter canola establishment across the southwestern US, and at high elevations. The objectives of this study were to evaluate grain yield of some winter canola genotypes, and to determine their water productivity under semiarid climates and high elevations at Farmington, New Mexico.

2. Materials and Methods

2.1. Station Area

A long-term experiment was conducted at the New Mexico State University (NMSU) Agricultural Science Center at Farmington (Latitude 36.69' North, Longitude 108.31' West, elevation 1720 m) for the period of 2008–2013. Minimum temperature (T_{min}), maximum temperature (T_{max}), mean relative humidity (RH_{mean}), wind speed (U_2), and solar radiation (R_s) were collected on a daily basis from an automated weather station installed at the site by the New Mexico Climate Center. Annual average weather conditions during the winter canola growing period (1st September to 31st July) are presented in Figures 1 and 2.

2.2. Experimental Design and Crop Management

This study consisted of evaluating winter canola genotypes for seed yield under the semiarid climate and high elevation. Eight winter canola genotypes varieties (Baldur, Flash, Safran, Sitro, Sumner, Virginia, Visby, and Wichita,) were arranged in a completely randomized block design with four replications. These winter canola genotypes were continuously used as checks in a large national winter canola variety trial, coordinated by Kansas State University. The winter canola genotype was studied; the fixe effect on seed yield and other effects (management practice, soil type, etc.) were considered random, as the field was managed evenly among genotypes. The planting rate was 5.6 kg of seed per hectare. The planting date, harvesting date, applied fertilizer rate, seasonal precipitation, and seasonal applied irrigation are summarized in Table 1. The field was kept weed free by herbicide application or hand weeding, as needed. Insecticide was also applied when any

significant insect damage was noticed. The field was fully irrigated by a center pivot irrigation system to avoid drought stress.

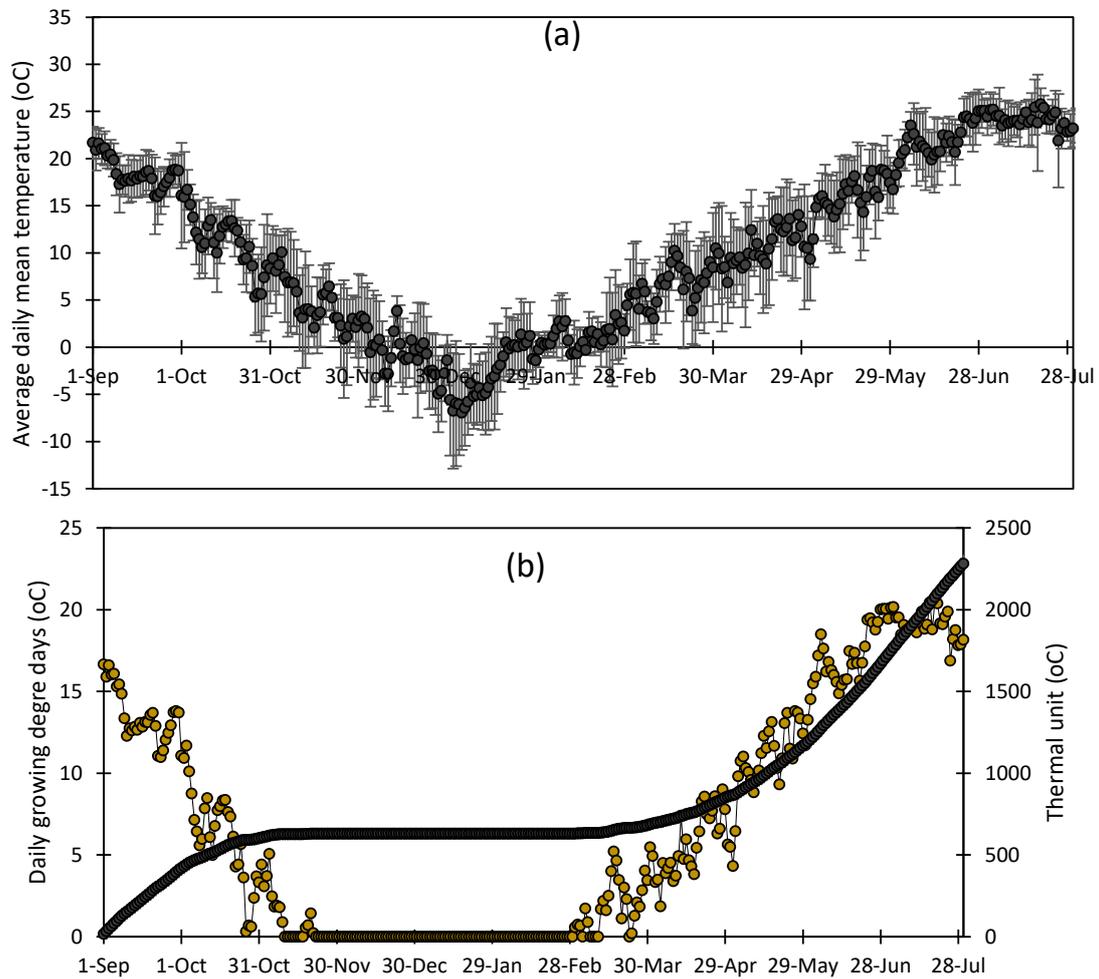


Figure 1. Trends in the (a) Daily average temperature and (b) Growing degree day and thermal unit for the period of 1st September to 31st July.

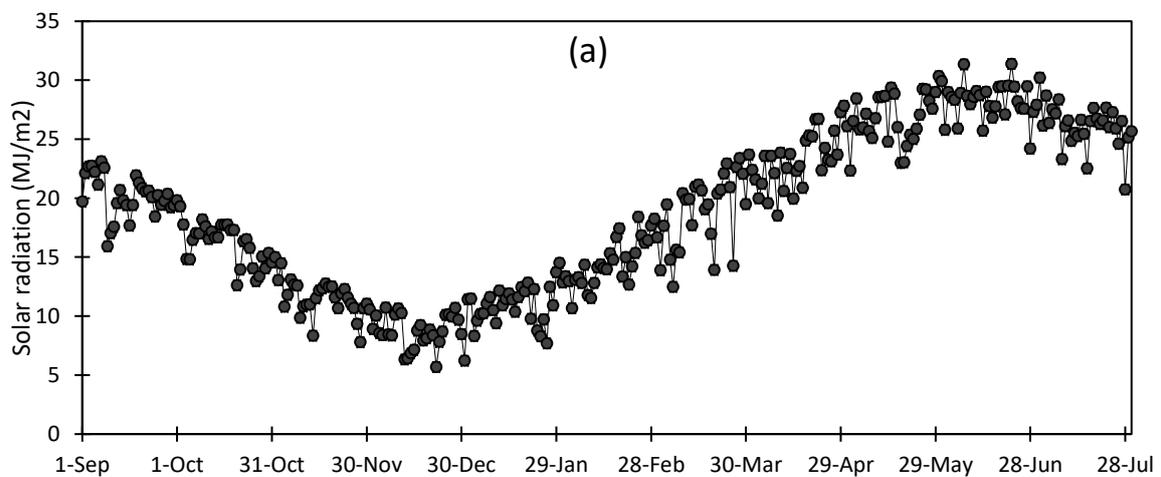


Figure 2. Cont.

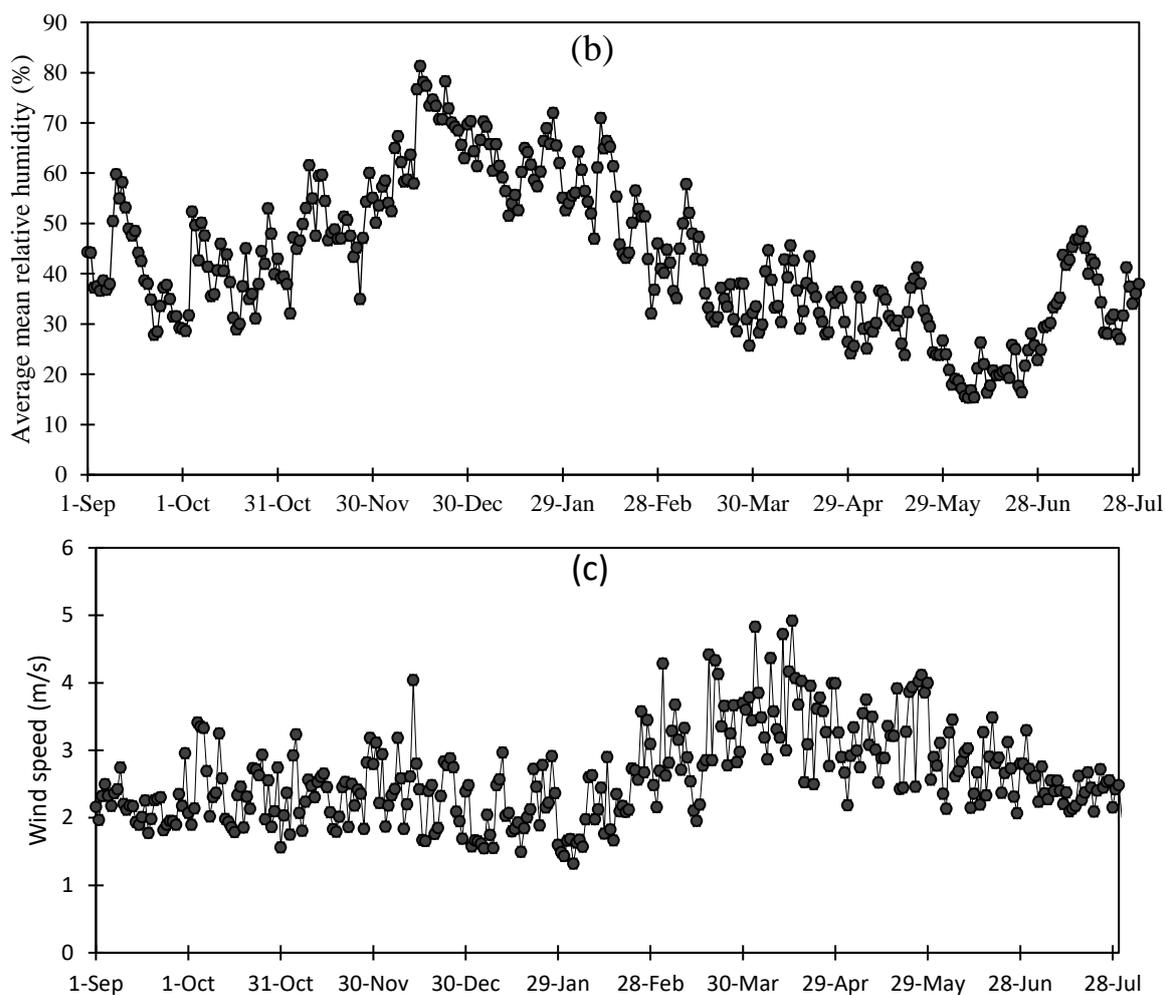


Figure 2. Trends in the average (a) Daily solar radiation; (b) Relative humidity; (c) Wind speed for the period of 1st September to 31st July.

Table 1. Canola planting and harvesting date, and the applied fertilizer rate, precipitation and irrigation applied during the 2008–2013 period.

Year	Planting Date	Harvesting Date	Soil Type	Previous Crop	N-P2O5-K2O-	Precipitation	Irrigation	Water Supply
					ZnSO4			
					(kg/ha)	(mm)	(mm)	(mm)
2008	5-Sep							
2009	3-Sep	29-Jul	Doak sandy loam	Potatoes-Fallow	168-58-67-0	122	711	833
2010	7-Sep	29-Jul	Doak sandy loam	Corn-Fallow	129-58-67-0	130	660	790
2011	8-Sep	21-Jul	Doak sandy loam	Oats-Fallow	185-0-0-0	142	704	846
2012	6-Sep	16-Jul	Doak sandy loam	Potatoes-Fallow	112-58-67-16	115	737	852
2013		18-Jul	Doak sandy loam	Potatoes-Fallow	230-117-135-40	89	615	703

2.3. Thermal Unit (TU)

The Thermal Unit (TU) is the accumulation of the growing degree days (GDD), i.e., cumulative temperature that contributes to plant growth during the growing season, and is expressed as follows:

$$TU = \sum_{i=1}^n \frac{T_{\max} + T_{\min}}{2} - T_{\text{base}} \quad (1)$$

where T_{\max} = maximum air temperature, T_{\min} = minimum air temperature, T_{base} = base temperature threshold for winter canola (5 °C), and n = number of days. The base temperature for calculating growing degree days is the minimum threshold temperature at which plant growth starts. Thermal time requirements for canola were recorded in GDD using 5 °C as the base temperature [48]. The maximum and minimum temperature thresholds of 30 °C and 5 °C respectively were used. All temperature values exceeding the threshold were reduced to 30 °C, and values below 5 °C were taken as 0 °C, because no growth occurs above or below the threshold (base) temperature values. If the average daily temperature was below the base temperature, the TU value was assumed to be zero.

2.4. Crop Water Use Efficiency

Seasonal irrigation water use efficiency (IWUE) and crop water use efficiency related to total water supply (CWUE) were estimated by the following equations:

$$IWUE = \frac{\text{Yield}}{\text{Seasonal irrigation amount}} \quad (2)$$

$$CWUE = \frac{\text{Yield}}{\text{Seasonal water supply}} \quad (3)$$

where IWUE and CWUE are in kg/m³, yield is in kg/ha, the seasonal irrigation amount in mm.

2.5. Statistical Analysis

The effects of canola varieties and the seasons, as well as their potential interaction on canola yield, were analyzed using an analysis of variance (ANOVA) in PROC MIXED in SAS (2001) (SAS Institute, Cary, NC, USA). Separation of means was determined with the LSMEANS statement at the 5% significance level, to identify any potential significant differences between eight winter canola genotypes' seed yields.

3. Results and Discussion

3.1. Climatic Conditions during the Winter Canola Growth Period

Weather conditions at the experimental site during the winter canola growing season was reported for the period of 1st September to 31st July (Figure 1). There was only a slight difference in wind speed, air temperature, relative humidity, and solar radiation among growing seasons. Seasonal average wind speed varied from 2.44 to 2.80 m/s; the strongest wind occurred during the 2008–2009 season. Average season T_{\max} varied from 17.18 to 19.13 °C, the T_{\min} varied from 1.98 to 3.33 °C, and T_{mean} varied from 9.3 to 10.7 °C. The highest solar radiation occurred during the 2012–2013 season, with an average seasonal daily R_s value of 19.12 MJ/m². Average daily mean temperature decreased from 21.6 on (1st September) to -7.0 °C on 4 January, and increased thereafter to 25.4 °C. Air temperature remained below freezing point from 8 January to 15 February (Figure 1a). Thermal time requirements for canola were recorded in GDD using 5 °C as the base temperature [48], and decreased from 16.61 °C to 0 °C from 1st–September 10 November, remaining basically null until March 5, and increasing thereafter to 19.8 °C (Figure 1b). Winter canola was in the dormancy period without physiological activity and growth from early November to early March. The cumulative GDD

(thermal unit) increased from September to early November, remaining constant during the winter canola dormancy period and increasing thereafter when the average air temperature was above the winter canola base temperature (5 °C). Average seasonal total thermal units accumulated were 2283 °C (Figure 1b). Daily average solar radiation showed the same trends as those of the daily air temperature, ranging from 5.7 to 31.4 MJ/m², and averaging 18.68 MJ/m² (Figure 2a). Average daily relative humidity varied from 15.4% to 81.3%, increasing from September to mid-December and decreasing toward the end of the growing season (Figure 2b). Seasonal average relative humidity was 42.9%, revealing the dryness of the local semiarid climate with very non-significant precipitation during the season, and considerable irrigation requirements during all the five growing seasons (Table 1). Seasonal wind speed averaged 2.6 m/s, and was the strongest in March and April, with daily variability during the rest of the season (Figure 2c).

3.2. Winter Canola Seed Yield

Canola seed yield varied from 2393 to 5717 kg/ha, and there was significant dependence of seed yield on canola variety (Figure 3). Canola variety Sitro showed a highest average seed yield of 4570 kg/ha, followed by Safran, with a seed yield of 4378 kg/ha; the lowest average yield, 2932 kg/ha, was obtained by the Sumner variety (Figure 4) (Table 2). Seed yield showed significant inter-annual variability ($p = 0.001$); the highest yields were obtained during the 2011–2012 season, while the lowest yields were obtained during the 2010–2011 season. In comparison to the seed yield of Sumner (lowest yielding variety), there were 24.2, 42.4, 49.3, 55.8, 29.5, 41.8, and 20.5% higher yields for the varieties Baldur, Flash, Safran, Sitro, Virginia, Visby, and Wichita, respectively. Therefore, Sitro and Safran should be the first choice when considering Canola production under the Farmington climatic, soil, and management conditions. The results of the present study aligned with Assefa et al. [35], who reported a canola seed average yield of 3400 kg/ha for spring varieties, with a maximum yield of 6600 kg/ha, and seed average yield of 2500 kg/ha with a maximum yield of 5400 kg/ha for winter canola varieties. Pavlista et al. [20] reported a spring canola seed yield that varied among varieties (SW Patriot, Hyola 401 and Hyola 357 Magnum, SW Marksman) and regions across the US High Plains, ranging from 696 to 2326 kg/ha, with the highest yield recorded at Farmington, NM. Hergert et al. [49] reported spring canola seed yields ranging from 440 to 3289 kg/ha in western Nebraska, under full and limited irrigation settings. Assefa et al. [50] recorded a maximum yield range of 5000–7000 kg/ha. The seed yields reported in this study are higher than the average national seed yield of 2044 kg/ha for the US and 2306 kg/ha for Canada [1]. Assefa et al. [50] reported a winter canola seed yield varying from 0 to 4000 kg/ha in Manhattan, KS, while yield potential reached 7000 kg/ha. However, slightly higher yields are obtained in this study, confirming the results of Assefa et al. [50], with higher yields in the southeast USA than in the Midwest. Different performance of the same varieties used in the present study was reported across several states in the eastern, midwest and northwest US in a national canola variety trial; the highest yields were the following: 4257 kg/ha, obtained by Sitro at Fruita, Co; 4894 kg/ha by Sitro at Belleville IL; 4002 kg/ha by Safran at Carbondale, IL; 1558 kg/ha by Visby at Monmouth, IL, 2700 kg/ha by Flash at Urbana, IL [51,52]. Sitro outperformed the other varieties, and Wichita was among the lowest-yielding cultivars used at different planting dates in Manhattan, KS [50]. The high yield achieved at the Farmington site in comparison to many part of the United States [12–16] might be due to higher radiation use efficiency at the study site leading to higher levels of photosynthesis, as reported by Yang et al. [17]. Winter canola generally performed best when seeded in early September in central Iowa [53]. Winter canola yield might increase with appropriate water supply, balanced nutrition, early planting in shallow depth, high seeding rate (6 kg ha⁻¹), and diverse rotation (canola every 3 or 4 year) and the good agricultural practices [35].

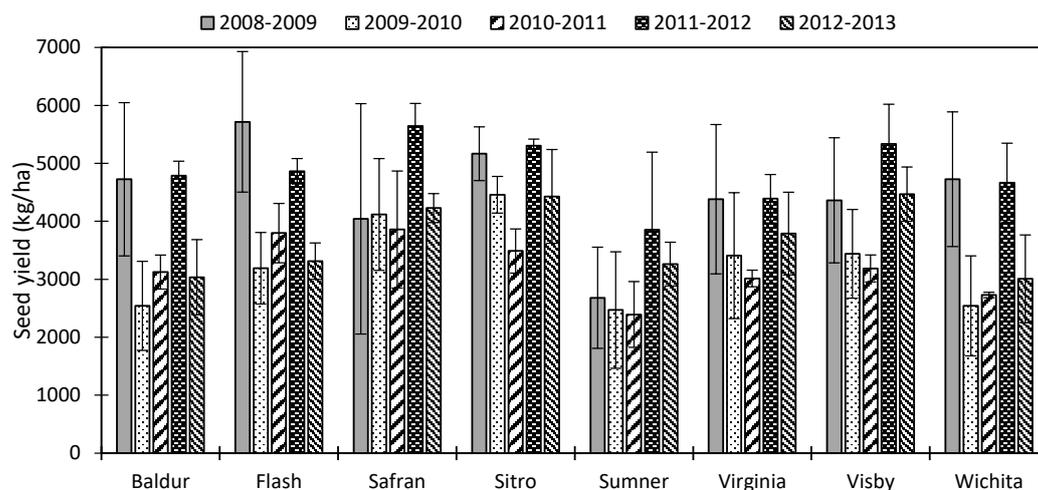


Figure 3. Average and standard deviation of winter canola seed yield for the 2008–2013 period.

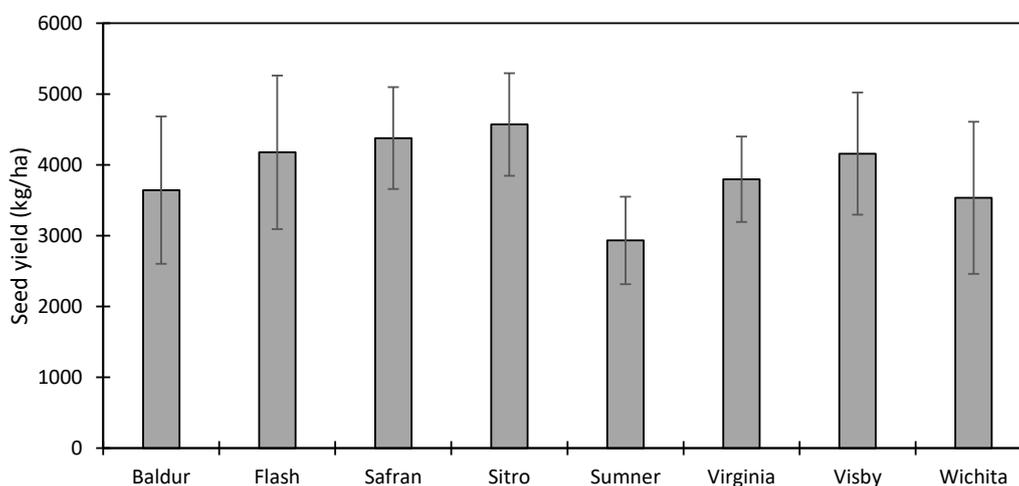


Figure 4. Average and standard deviation of winter canola seed yield for the 2008–2013 period.

Table 2. Canola seed yield, nitrogen use efficiency, irrigation and crop water use efficiencies.

Parameters	Growing Season	Varieties							
		Baldur	Flash	Safran	Sitro	Sumner	Virginia	Visby	Wichita
Seed yield (kg/ha)	2008–09	4726	5717	4043	5166	2681	4382	4363	4726
	2009–10	2541	3191	4118	4459	2469	3408	3439	2541
	2010–11	3125	3797	3859	3488	2393	3015	3188	2729
	2011–12	4787	4863	5643	5305	3854	4390	5333	4666
	2012–13	3036	3314	4228	4430	3263	3790	4469	3008
Nitrogen use efficiency (kg/kg)	2008–09	28.1	34.0	24.1	30.8	16.0	26.1	26.0	28.1
	2009–10	19.7	24.7	31.9	34.6	19.1	26.4	26.7	19.7
	2010–11	16.9	20.5	20.9	18.9	12.9	16.3	17.2	14.8
	2011–12	42.7	43.4	50.4	47.4	34.4	39.2	47.6	41.7
	2012–13	13.2	14.4	18.4	19.3	14.2	16.5	19.4	13.1
Irrigation water use efficiency (kg/m ³)	2008–09	0.66	0.80	0.57	0.73	0.38	0.62	0.61	0.66
	2009–10	0.38	0.48	0.62	0.68	0.37	0.52	0.52	0.38
	2010–11	0.44	0.54	0.55	0.50	0.34	0.43	0.45	0.39
	2011–12	0.65	0.66	0.77	0.72	0.52	0.60	0.72	0.63
	2012–13	0.49	0.54	0.69	0.72	0.53	0.62	0.73	0.49
Crop water use efficiency (kg/m ³)	2008–09	0.57	0.69	0.49	0.62	0.32	0.53	0.52	0.57
	2009–10	0.32	0.40	0.52	0.56	0.31	0.43	0.44	0.32
	2010–11	0.37	0.45	0.46	0.41	0.28	0.36	0.38	0.32
	2011–12	0.56	0.57	0.66	0.62	0.45	0.52	0.63	0.55
	2012–13	0.43	0.47	0.60	0.63	0.46	0.54	0.64	0.43

3.3. Winter Canola Nitrogen Use Efficiency

Nitrogen use efficiency (NUE) of the winter canola, defined as the ratio of seed yield to the applied nitrogen, varied with the genotypes and growing seasons (Table 2). With all genotypes combined, there was poor correlation between seed yield and the applied nitrogen rate (Figure 5). Canola genotypes had different responses to nitrogen fertilizers (Figure 5). NUE varied from 12.9 to 50.4 kg seed/kg N, and the five season average NUE was within the range of 19.3 to 30.2 kg seed/kg N (Figure 6). The highest NUE was obtained by Sitro, and the lowest by Sumner. The highest NUE across all varieties was obtained during the 2011–2012 season, and the lowest during the 2012–2013 season. Canola plot rotation, seasonal climatic conditions, nutrient management, and other agricultural practices might explain NUE variation for the same variety throughout the study period. Canola NUE decreased with higher nitrogen rates [54,55]. Koocheki et al. [56] stated that NUE varied from 4.20 to 22.03 kg seed/kg N at the research station of Ferdowsi University of Mashhad, Iran. Variation in NUE among genotypes might originate from differences in leaf area index and radiation use efficiency, and the stay green phenotype in canola, all of which affect timely nitrogen uptake efficiency during the reproductive phase of the plant [57]. Svecnjak and Rengel [58] attributed the differences in NUE among canola cultivars to differences in root to shoot ratio and harvest index. Nitrogen fertilizer application rate and timing should be considered under sandy soil conditions in the present experiment. Low fertigation rates should be applied on sandy soils to reduce deep percolation and eliminate nitrogen leaching beyond the crop root zone [59].

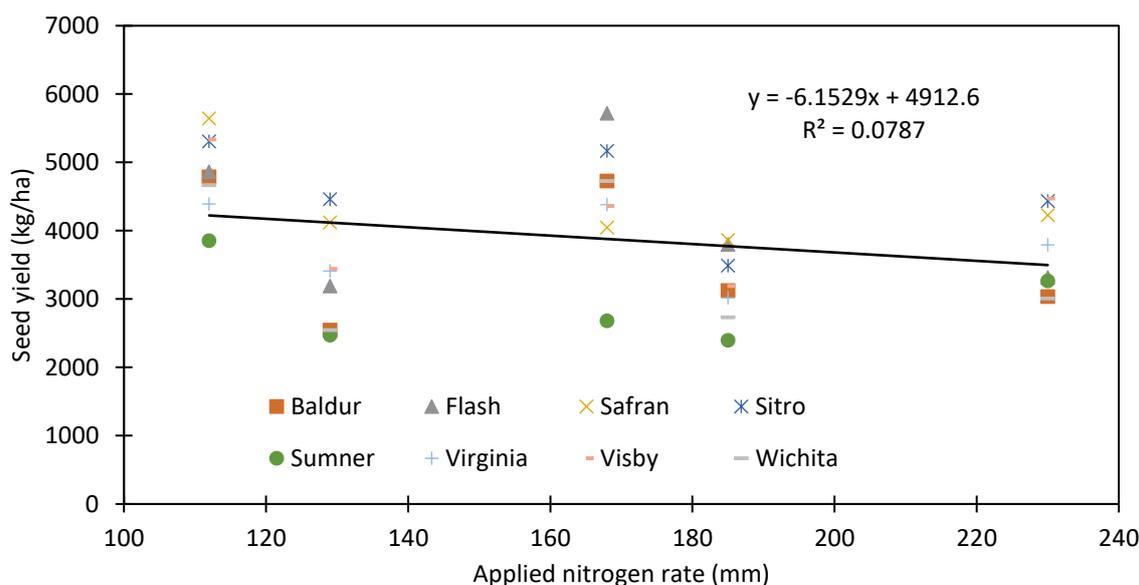


Figure 5. Relationship between winter canola seed yield and applied nitrogen amount.

3.4. Winter Canola Irrigation Water and Crop Water Use Efficiency

Winter canola IWUE varied from 0.34 to 0.80 kg/m³, and was dependent on canola genotype (Table 2). Overall, there was poor correlation between winter canola seed yield and the seasonal irrigation amount, with a regression slope of 5.7 kg seed per hectare per mm of irrigation water, representing canola IWUE of 0.57 kg/m³ water (Figure 7). On average, the highest IWUE was achieved by Sitro (0.67 kg/m³), followed by Safran (0.64 kg/m³), while the lowest IWUE was achieved by Sumner (0.43 kg/m³), whose seed yield was the lowest among the eight varieties (Figure 8a). IWUE varied with year, with no correlation between IWUE and the seasonal irrigation amounts. The results of this study are in agreement with Mousavi et al. [60], who reported that the IWUE for winter canola varied from 0.36 kg/m³ for the least efficient irrigation regime to 0.67 kg/m³ for the most efficient irrigation regime, under greenhouse conditions. Majnooni-Heris et al. [61] reported spring canola

IWUE values varying from 0.36 to 0.43 kg/m³ under different irrigation regimes at the Agriculture and Natural Resources Research Center of Yazd city, Iran. Crop IWUE decreases with increasing irrigation amounts [22,52].

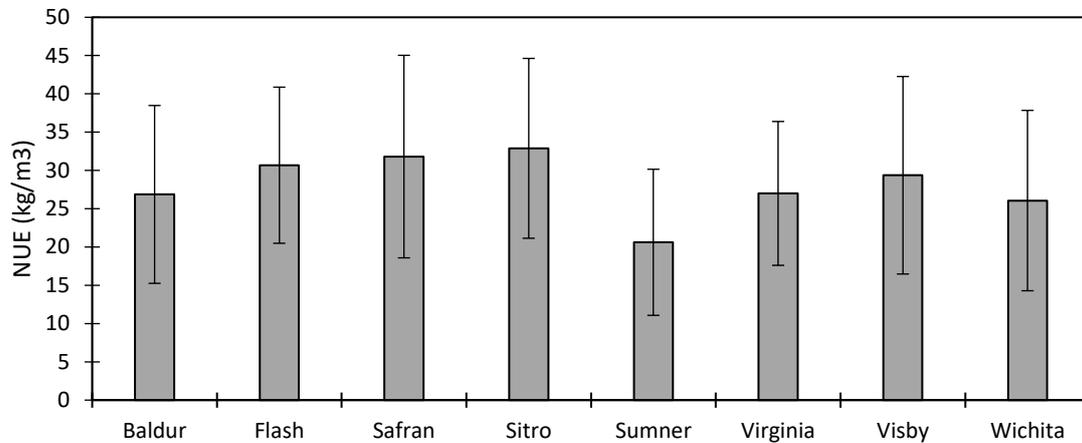


Figure 6. Average and standard deviation of winter canola seed yield.

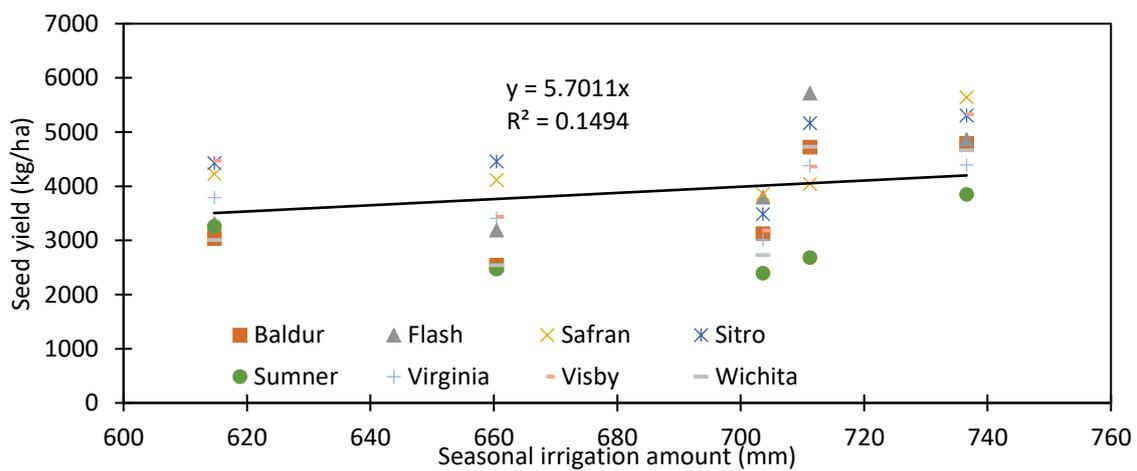


Figure 7. Relationship between winter canola seed yield and seasonal irrigation amount.

Canola CWUE showed inter-annual variability, ranging from 0.28 to 0.69 kg/m³, and averaging 0.48 kg/m³ (Table 2). Similar to the IWUE, CWUE was the highest for Sitro and the lowest for Sumner (Figure 8b). Overall, CWUE was at its maximum in the 2011–2012 season, with the greatest amount of total water supply. Canola CWUE varied from 0.27 to 0.86 kg/m³ in Iran [56] and from 0.03 to 1.8 kg/m³ in Australia [26,62]. Similar values were reported by Taylor et al. [63]. Takashima et al. [64] reported winter canola WUE varying from 0.16 to 0.67 kg/m³ in the southeastern Pampas, Argentina. Robertson and Kirkegaard [65] reported higher values of rainfed spring canola WUE, ranging from 0.4 to 1.8 kg/m³ in southern New South Wales, Australia. Canola CWUE and IWUE values could serve as guidance for water canola production under the semiarid climate of the Four Corners region.

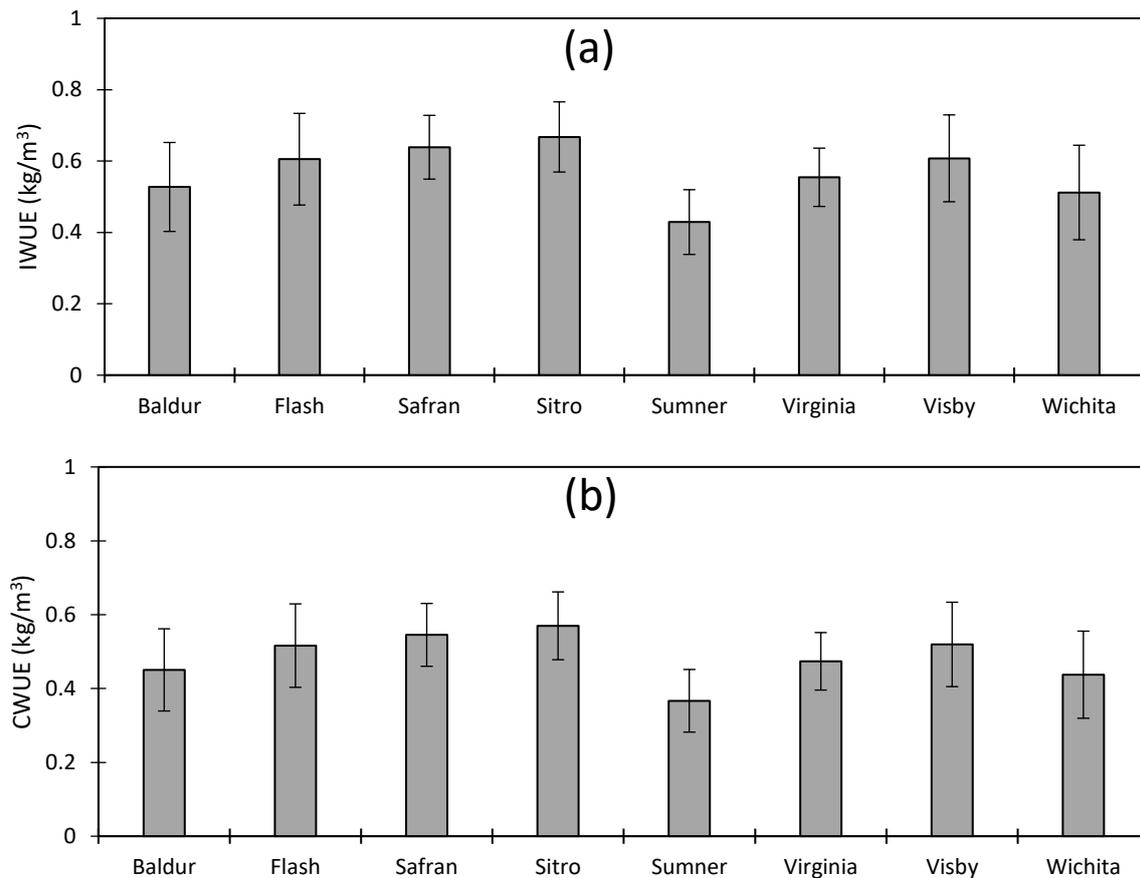


Figure 8. Trends in canola (a) IWUE and (b) CWUE as functions of canola variety (Error bars are standard deviations). IWUE, irrigation water-use efficiency; CWUE, crop water-use efficiency.

4. Conclusions

A field experiment was conducted at the New Mexico State Agricultural Science Center at Farmington, to evaluate eight winter canola genotypes for seed yield and water productivity during five growing seasons under sprinkler irrigation. Results showed feasibility of canola production in the Four Corners region, with high winter canola seed yield compared to the Southern High Plains environment. Winter canola seed yield varied from 2393 to 5717 kg/ha. The highest yield, irrigation, and crop water productivity were achieved by Sitro, and the lowest values of the respective parameters were obtained by Sumner. The high yield achieved at the study site in comparison to many part of the United States offers great promise for canola production in the Four Corners region. The results of this study showed full assessment of canola production under the semiarid climate of the Four Corners region, and could serve as guidelines for winter canola adaptability and incorporation into the crop system, and its profitability for crop producers in the region.

Author Contributions: M.O., C.O., M.W., D.S. and D.B. designed and conducted all field trials with field data collection. K.D., S.V.A., K.K., S.A. and K.L. analyzed the data, wrote and revised the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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