9-2012

Yield, Pests, and Water Use of Durum and Selected Crucifer Oilseeds in Two-Year Rotations

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Abstract

Cool-season oilseed crops are potential feedstock for biofuel production, but few studies have compared oilseed-durum (*Triticum durum* Desf.) rotations on yield, quality, water use, and pests associated with crops. We conducted an experiment under dryland conditions during 2007 to 2010 near Culbertson, MT, comparing crop productivity, water balance, and key weed and arthropod pests of 2-yr oilseed-durum rotations under zero tillage. Rotations included durum with three Brassicaceae sp., camelina [*Camelina sativa* (L.) Crantz], crambe (*Crambe abyssinica* Hochst. ex R.E. Fries), and canola-quality *Brassica juncea* L., and fallow. Over 4 yr, *B. juncea* had the highest seed and oil yields of crucifer entries. Water use was similar among oilseed crops, averaging 286 mm. Water use was similar for durum following oilseeds, averaging 282 mm, 72 mm less than for durum following fallow. Durum following fallow averaged 775 kg ha^{-1} greater grain yield than durum following oilseeds due to higher water availability and use. Camelina had greater weed biomass at harvest and lower densities of *Plutella xylostella* L. than other oilseeds. Durum in rotation with crambe had higher weed density and biomass at harvest than durum following *B. juncea* or fallow. *Brassica juncea* generally performed better than crambe or camelina, but each oilseed crop had several positive attributes. Oilseed-durum rotations can be used for biofuel feedstock and grain production, but long-term sustainability of 2-yr rotations on crop yields and pest management requires further study.

Keywords

Entomology

Disciplines

Agronomy and Crop Sciences | Entomology | Natural Resources Management and Policy

Comments

This article is from *Agronomy Journal* 04 (2012): 1295–1304, doi:10.2134/agronj2012.0057.

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ABSTRACT

Cool-season oilseed crops are potential feedstock for biofuel production, but few studies have compared oilseed-durum (*Triticum durum* Desf.) rotations on yield, quality, water use, and pests associated with crops. We conducted an experiment under dryland conditions during 2007 to 2010 near Culbertson, MT, comparing crop productivity, water balance, and key weed and arthropod pests of 2-yr oilseed-durum rotations under zero tillage. Rotations included durum with three Brassicaceae sp., camelina [*Camelina sativa* (L.) Crantz], crambe (*Crambe abyssinica* Hochst. ex R.E. Fries), and canola-quality *Brassica juncea* L., and fallow. Over 4 yr, *B. juncea* had the highest seed and oil yields of crucifer entries. Water use was similar among oilseed crops, averaging 286 mm. Water use was similar for durum following oilseeds, averaging 282 mm, 72 mm less than for durum following fallow. Durum following fallow averaged 775 kg ha^{-1} greater grain yield than durum following oilseeds due to higher water availability and use. Camelina had greater weed biomass at harvest and lower densities of *Plutella xylostella* L. than other oilseeds. Durum in rotation with crambe had higher weed density and biomass at harvest than durum following *B. juncea* or fallow. *Brassica juncea* generally performed better than crambe or camelina, but each oilseed crop had several positive attributes. Oilseed-durum rotations can be used for biofuel feedstock and grain production, but long-term sustainability of 2-yr rotations on crop yields and pest management requires further study.

The Energy Independence and Security Act of 2007 (summarized in Sissine, 2007) mandates the use of 136 billion liters of biofuel by 2022, with 79 billion liters projected to be advanced biofuels, including renewable diesel for naval ships and aviation jet fuel. The U.S. Department of Defense has established ambitious goals to purchase and use renewable fuels (Congressional Research Service, 2010; summarized in Tindal, 2011). However, current cropping systems in the United States may not be capable of producing adequate amounts of feedstock at prices competitive with petroleum-based fuels to meet desired production levels within the time stipulated in legislation and Executive Orders (Van Gerpen et al., 2008).

One region that is well suited and has a high potential for increasing agricultural production of biofuel crops is the semi-arid Northern Great Plains (NGP) in eastern Montana and western North Dakota. A common rotation in semi-arid dryland production systems in the NGP is durum–fallow. Replacing fallow with various cool-season oilseed crops in these rotations may provide a significant national contribution to biodiesel and aviation biofuel feedstocks.

Growers have traditionally perceived that the advantage of durum–fallow systems in semi-arid environments is to conserve water from incident precipitation during the fallow year that can supplement cropping season rainfall and potentially increase yields of the subsequent crop, which is typically durum. Weeds, including volunteer wheat, are controlled either by tillage or multiple herbicide applications, as needed, to conserve accrued water during the fallow period. However, tillage during fallow has resulted in large decreases in soil organic matter by as much as 50% over several decades, which is not sustainable (Follett and Schimel, 1989; Fenster, 1997). There also is a large potential for soil erosion from wind and water under tilled fallow conditions (Unger et al., 2006a). Tillage also increases evaporation losses due to soil exposure and reduced its water content (Unger et al., 2006b).

The practice of zero tillage fallow systems, often called chemical fallow, substantially improves soil water capture efficiency during fallow periods compared to conventional tillage systems and can reduce erosion losses (Nielsen and Vigil, 2010). Consequently, herbicide use during fallow periods has become the single largest use of pesticides in Montana (Johnson et al., 1997). Additionally, all chemical fallow systems currently rely primarily on glyphosate (N-phosphonomethyl glycine), a chemical with decreasing efficacy because of weeds developing resistance (Heap, 2012).

A major agronomic concern is the limited diversity of dryland crops in the region, which would be increased by the inclusion

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Published in Agron. J. 104:1295–1304 (2012)
Posted online 27 June 2012
doi:10.2134/agronj2012.0057

Abbreviations: CRP, Conservation Reserve Program; ETH-FL, ethylfluralin-tolerant weeds; HI, harvest index; NGP, Northern Great Plains; PREH$_2$O, preplant soil water content at the 0- to120-cm depth; POST, postemergence herbicide application; POSTH$_2$O, postharvest soil water content at the 0- to 120-cm depth; PRECIP, precipitation; WU, water use, WUE, water use efficiency for grain production.

of cool-season oilseed crops in these cereal-based rotations. Diversification and intensification of wheat–fallow cropping systems can provide numerous advantages in pest management (Kirkegaard et al., 2008) and has also been shown to improve precipitation-use efficiency (Farahani et al., 1998), soil quality including C and N pools (Sainju et al., 2007, 2009), and decrease erosion potential (Feng et al., 2011).

In Montana and North Dakota, about 1.82 million ha of annual cropland was in summer fallow in 2009 (NASS, 2010). In addition, several million hectares of land currently enrolled in the Conservation Reserve Program (CRP) may become available for annual dryland crop production in the near future. The diversification and intensification of wheat–fallow systems, including durum–fallow, by inclusion of cool-season oilseed crops can improve over all water utilization and long-term economic productivity of cereal-based systems, particularly in intermediate and higher rainfall areas of semi-arid prairie (Johnston et al., 2002; Krupinsky et al., 2006).

Most cool-season oilseed crops, including crambe and large-seeded false flax, camelina, are considered minor crops and have received much less research attention in numerous areas, including plant breeding and cultivar development, production agronomy, development of pest management strategies, and determination of environmental benefits. Cool-season oilseed crop production generally is rare in the drier semi-arid prairie regions due to their poor productivity under drought conditions (Álvaro-Fuentes et al., 2009) or reduced tolerance to heat stress at flowering (Angadi et al., 2000), particularly in comparison with pulses (e.g., field pea [*Pisum sativum* L.] and lentils [*Lens culinaris* Medik.]) or durum. Stand establishment can be difficult due to small seed size and limited seedling vigor compared to small grains and various pulse crops. Limited information is available on the rotational effects of various crucifer oilseed crops on the growth and yields of subsequent crops (Zubr, 1997).

Native and introduced crucifers are endemic in many areas of the semi-arid NGP, serving as suitable hosts for important arthropod pests of canola species (*B. napus* L. and *B. rapa* L.) (Brown et al., 2004; Cárcamo et al., 2012; Ritter et al., 2010). Several crucifers also are important weeds in dryland production systems, including flixweed (*Descurainia sophia* Webb ex Prantl), tansy mustard [*D. pinnata* (Walter) Britton], tall tumble mustard (*Sissymbrium altissimum* L.), and small-seeded false flax (*Camelina microcarpa* Andrz. Ex DC.) (Francis and Warwick, 2009). Weedy crucifers typically are readily controlled in cereal crops by applying herbicides but they can be exceptionally difficult to manage in crucifer crop production, except for those lines with high levels of tolerance to glyphosate or glufosinate-ammonium (2-amino-4-(hydroxymethylphosphinyl)butanoic acid.

Currently, the cultivation of oilseed feedstock to meet Renewable Fuel Standards is hampered by the lack of knowledge of production practices, including water use, potential pests, adverse influence on subsequent crops, and questions about profitability for many biofuel feedstock crops in various soil and environmental conditions. Results from long-term studies on productivity or sustainability of cereal-oilseed systems are unavailable. Consequently, we conducted an experiment to investigate crop yield and quality, pests, and water use of durum and selected cool-season oilseed crops in 2-yr rotation in the semi-arid NGP region.

MATERIALS AND METHODS

The experimental site was located at the USDA Conservation District Farm, 11 km north of Culbertson, MT (48°16’ N, 104°30’ W; altitude 660 m). The 8.2-ha field site was located in an area mapped as Williams loam (fine-loamy, mixed, superactive, frigid Typic Argiustolls, 2–8% slopes) derived from glacial till. Soil sampling in October 2001 revealed average organic matter concentration as 11 g kg^{-1}, Olsen P 8.3 mg kg^{-1}, exchangeable K 155 mg kg^{-1}, and pH 6.1 at the 0- to15-cm depth. Mean annual precipitation at the site is 340 mm, 80% of which occurs from April through September (Table 1). Previous cropping history was durum in rotation with summer fallow or annual forage crops from 2001 to 2006.

The experiment consisted of four crop rotations. Crop rotations included spring durum Mountrail in rotation with summer fallow and three crucifer oilseed crops, canola-quality *B. juncea* P45J10, crambe BelAnn (2007–2008), and Meyer (2009–2010), and camelina Celine (2007–2008) and Blaine Creek (2009–2010). The experimental design was a randomized complete block with three replications. Individual plot size was 21.3 by 61.0 m. Every phase of each crop rotation was present in each replication every year. Crucifers planted in 2007 followed durum, allowing comparison of oilseed yields from 2007 to 2010. Rotational phases preceding durum were not in place until 2007, so durum yields are provided from 2008 to 2010. Cropping history of the site included durum in rotation with foxtail millet [*Setaria italica* (L.) P. Beauv.], barley (*Hordeum vulgare* L.), Austrian winter pea [*Pisum sativum* L. ssp. *arvense* (L.) Poir.]–barley, and fallow from 2002 through 2006.

Table 1. Monthly and annual total precipitation and air temperature from 2007 to 2010 at the experimental site, 11 km north of Culbertson, MT.

	Precipitation					Temperature				
Month	2007	2008	2009	2010	105-yr avg.†	2007	2008	2009	2010	105-yr avg.†
	mm					°C				
April	10	12	53	33	24	6	5	5	7	6
May	137	43	24	118	50	14	12	11	10	13
June	75	58	27	69	77	19	16	16	17	17
July	21	29	100	125	54	24	21	18	19	21
August	22	21	96	83	36	20	21	18	19	20
September	18	62	23	23	33	15	13	17	12	14
Annual total	350	338	406	524	340					

† Long-term averages from National Oceanic and Atmospheric Administration (www.nws.noaa.gov) for Culbertson, MT, located 11 km south of the research site.

Nitrogen fertilizer rates were based on a durum yield goal of 2350 kg ha^{-1} with 135 g kg^{-1} protein, resulting in requirements of 118 kg N ha^{-1}. Fertilizer N requirements for oilseed crops was 87 kg N ha^{-1}, with residual soil NO_3–N level from the 0- to 60-cm depth (determined in mid-October) subtracted for the determination of fertilizer N rate. Annual applications of monoammonium phosphate and muriate of potash were provided to all annual crops at 56 and 45 kg ha^{-1}, respectively. Additionally, 23.5 kg S ha^{-1} as ammonium sulfate was applied annually to all crucifer plots prior to planting. Fertilizers were banded at planting about 5 cm below and to the side of each seed row, except for 2007 camelina when fertilizers were broadcast prior to planting.

Seeding dates were typical for the region. Durum was planted in mid- to late April each year at 2.22 million seeds ha^{-1}. Camelina was seeded at 6.6 kg ha^{-1} in 2007 and at 9.0 kg ha^{-1} in subsequent years. Crambe seeding rate was 38.1 kg ha^{-1}. *Brassica juncea* was planted at 9.0 kg ha^{-1} for all years. Camelina and *B. juncea* were planted in early April. Crambe, a crop with substantially less seedling frost tolerance than other crucifers, was planted in the first week of May in 2007 to 2009. Crambe required replanting in the fourth week of May due to cutworm (*Euxoa messoria*) damage (2007) and late frost (2009). Crambe was planted on 5 June 2010. Planting was done with a 3.05-m wide custom built drill equipped with double-shoot Barton (Flexi-Coil, CNH Global, Saskatoon, SK) openers for single-pass seeding and fertilization, except for camelina plots in 2007 when seeds were broadcast with an air delivery system and land rolled. Seeding depth varied by crop and year according to soil water content. Camelina was planted at 0.6 cm below the soil surface for 2008 to 2010; *B. juncea* and crambe at 1.3- and 2.5-cm depths, respectively; durum at 3.8 to 5 cm.

Stand densities of all crops were determined by counting all plants in four 1-m lengths of row in each plot at the 1- to 2-leaf stage. Weed densities were determined by species in all crops prior to in-crop herbicide application with 10 0.10-m^2 circular quadrats and prior to crop harvest with two 0.5 m^2 quadrats in each plot. They were hand-clipped, composited, and stored in a paper bag. Bagged weed samples were transported to a laboratory and placed into a forced air oven at 55°C for determination of dry matter weight.

Plots for seeding crucifers in the next year's spring received a late fall application of ethylfluralin (N-ethyl-N-(2-methyl-2-propenyl)-2,6-dinitro-4-(trifluoromethyl)benzenamine) at 9.0 kg ha^{-1} a.i. prior to soil temperature reaching 0°C in 2007, 2008, and 2009. All plots received applications of glyphosate at 3.36 kg a.i. ha^{-1} in 37.8 L ha^{-1} water prior to spring planting. A tank-mixed application of 0.68 kg ha^{-1} of formulated bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) and MCPA ester (2-methy-4-chlorophenoxyacetic acid) (0.92:1) and 0.09 kg a.i. ha^{-1} fenoxaprop-P-ethyl ((+)-ethyl 2-[4-[(6-chloro-2-benzoxazolyl)oxy]phenoxy]propanoate) in 38 L ha^{-1} water was applied prior to canopy closure to control broadleaf and grass weeds each year in durum plots. Summer fallow plots received tank-mixed applications of glyphosate and dicamba (3,6-dichloro-o-anisic acid) [at 3.36 and 0.56 kg a.i. ha^{-1}, respectively, in 37.8 L ha^{-1} water as required until 1 September, after which a single application of glyphosate (3.36 kg a.i. ha^{-1} in 37.8 L ha^{-1} water)] was applied for weed management, if necessary. Postharvest weed management was done on durum stubble with glyphosate (3.36 kg a.i. ha^{-1} in 37.8 L ha^{-1} water) and on crucifer stubble with glyphosate and dicamba (3.36 and 0.56 kg a.i. ha^{-1}, respectively, in 37.8 L ha^{-1} water).

One day prior to crop harvest, aboveground biomass from oilseed and durum plots was determined by clipping two 0.5-m^2 areas outside yield rows. Samples were oven-dried at 55°C and weighed to determine dry matter yield. Sampling was done at least 2 m away from plot boundaries to preclude sampling potential edge effects. Grain yield was determined with a self-propelled plot combine equipped with a 1.5-m wide header by cutting a 25- to 59-m length, depending on yield and year. Camelina was swathed prior to harvest in 2009–2010 to facilitate drying of weeds prior to combine operation. Grain samples were dried, cleaned with combinations of sieves and forced air, and weighed. All grain and biomass data are presented as 100% dry matter weight. Harvest index (HI) was calculated as:

$$\mathrm{HI} = \mathrm{GY}/\mathrm{CB} \qquad [1]$$

where GY is grain yield (kg ha^{-1}) and CB is aboveground crop biomass (kg ha^{-1}) (Cassman et al., 1992).

Crucifer seed oil concentration was determined by nuclear magnetic resonance. Durum kernel weights were determined by machine counting three 1000-kernel samples and weighing them. Oilseeds kernel weights were determined after hand-counting three 300- or 1000-seed samples. Soil water content was determined by calibrated neutron probe prior to planting and after harvest (Chanasyk and Naeth, 1996). Sampling depths were 23, 46, 61, 91, and 122 cm. Crop water use (WU in mm) was calculated as:

$$\mathrm{WU} = \mathrm{PREH_2O} - \mathrm{POSTH_2O} + \mathrm{PRECIP} \qquad [2]$$

where $\mathrm{PREH_2O}$ is the preplant soil water content (mm, 0 to 120 cm), $\mathrm{POSTH_2O}$ is the postharvest soil water content (mm, 0–120 cm), and PRECIP is precipitation between preplant and postharvest soil sampling (Farahani et al., 1998). Water-use efficiency (WUE, kg ha^{-1} mm^{-1}) for grain was calculated as:

$$\mathrm{WUE} = \mathrm{GY}/\mathrm{WU} \qquad [3]$$

where GY is grain yield (kg ha^{-1}) and WU (mm) is water use (Eq. [2]) (Farahani et al., 1998). Surface water runoff was not evident in 2007 to 2009 and it was assumed that neither overland flow nor drainage of water below 1.2 m occurred those years. However, runoff did occur during three rainfall events in 2010.

Statistical Analysis

Data were analyzed with SAS using the MIXED procedure (SAS Institute, 2003) for a split-plot analysis with crop rotation as main-plot factor, and year as the subplot factor. Crop rotation and year were considered as the fixed effects and replication and replication × crop rotation as the random effects. $\mathrm{Log}_{10}(x + 1)$ transformations were done for weed biomass data prior to analyses. Mean separations were done by least square means test. Differences among treatments are reported at the 5% level of significance. Regression analysis was done to determine the relationships between crop productivity and water use.

RESULTS AND DISCUSSION

Climate

Growing season monthly total precipitation and average air temperature varied among years (Table 1), typical for the continental climate of the NPG. Despite an unusually wet May, the remainder of the 2007 growing season was quite dry and substantially warmer than other years and long-term averages. The 2008 growing season also was quite dry but temperatures were near normal. The 2009 growing season was drier than long-term average through June, but the rest of the season had substantially more precipitation and cooler average temperature than the normal. The 2010 season had precipitation substantially above average for May through August, except for June, while temperatures remained lower than the normal. Hail damaged oilseed crops and durum on 20 July 2010.

Oilseed Crops

Oilseed crop stands varied by year and crop × year (Table 2). Stands were adequate for canola and crambe but establishment of camelina stands was always problematic. Stand establishment of camelina differed from crambe and *B. juncea* by having multiple emergence dates in 2007 and 2008, the years Celine was planted. At harvest in 2007 and 2008, camelina stands were similar to those of *B. juncea*, but numerous plants emerged up to 2 mo after planting, too late to produce more than marginal seed yields (A.W. Lenssen, personal observations, 2007–2010). The late emerging camelina plants likely were subjected to intense intra- and interspecific competition for water and nutrients. Additionally, we noted uneven maturity of plants as crops matured, resulting in difficulties in harvest. McVay and Khan (2011) reported that camelina stand reduction at bolting or later growth stages caused uneven maturity, resulting in harvest problems and shattering losses. In all years, minor soil crusting prevented emergence of camelina seedlings (A.W. Lenssen, personal observations, 2007–2010), however, seedlings of *B. juncea*, not known as a highly vigorous species, were able to emerge and provide adequate stands. Selection for improved seedling vigor may greatly improve stand establishment and subsequent performance of camelina.

Seed yield of oilseeds varied by crop ($P = 0.091$) and year, but the crop × year interaction was not significant (Table 2). Across years, *B. juncea* consistently had the highest yield while camelina had the lowest; crambe yield was intermediate. Years varied greatly for yield, with the highest yield across crops occurring during the wet 2009 season (127 mm precipitation during July) while severe drought strongly decreased oilseed yields in 2008 (29 mm precipitation during July) (Table 1). Despite above average precipitation in 2010, crop damage by hail caused low yields. Blackshaw et al. (2011) reported large decreases in yield in response to drought for a range of cool-season oilseeds, including canola-quality *B. juncea* and camelina. However, they also reported camelina yield exceeding 2400 kg ha^{-1} in a wetter than normal year, 2008, which was more than 400% greater than the yields in our study. Gesch and Cermak (2011) reported that fall-sown camelina yields in Minnesota ranged from 419 to 1317 kg ha^{-1}, with an overall mean of 561 kg ha^{-1}. Cool-season crucifers are not highly tolerant of heat or drought stress, and yields typically are highly variable among years (Johnston et al., 2002; Gan et al., 2007; Lenssen et al., 2007), constraining their widespread planting by dryland farmers in semiarid Montana.

Preplant available soil water content varied among years but not among oilseed crops (Table 2). Averaged across crops and years, preplant available soil water was 293 mm at the 0- to 120-cm depth. Postharvest soil water content was not consistent for crops among years, resulting in a significant crop × year interaction (Table 2). In 2007, camelina had the greatest postharvest soil water content while *B. juncea* had the least soil available water in the 0- to 120-cm profile (Table 3). Conversely, in 2010 crambe had the highest postharvest soil water content and camelina had the least. Differences among oilseed crops for postharvest available soil water were not significant in 2008 and 2009.

Water use was similar among oilseeds, averaging 286 mm over 4 yr (Table 2) and similar to the ranges reported for other cool-season oilseeds (Johnston et al., 2002; Angadi et al.,

Table 2. Seed yield, oil content, water use, preplant soil water content (PREH$_2$O, 0–1.2-m depth), postharvest soil water content (POSTH$_2$O, 0–1.2-m depth), and water use efficiency (WUE), following durum from 2007 to 2010, Culbertson, MT.

Source of variation	Seed yield	Water use	PREH$_2$O	POSTH$_2$O	WUE	Seed oil	Seed oil	Crop biomass	Harvest index
	kg ha^{-1}	mm			kg ha^{-1} mm^{-1}	g kg^{-1}	kg ha^{-1}		
Oilseed crop									
Camelina	591b†	271	304	250	2.1b	343b	215b	2752b	0.194
Crambe	841ab	299	305	261	2.8ab	277c	259b	4317a	0.173
B. juncea	958a	289	271	230	4.0a	384a	376a	4580a	0.199
Year									
2007	776b	345a	308b	199b	2.2b	304c	233b	4379b	0.181b
2008	323c	124c	201c	224b	2.6b	318c	115c	2344d	0.127b
2009	1704a	290b	289b	282a	5.8a	378a	653a	5600a	0.300a
2010	383c	386a	376a	283a	1.0c	337b	132c	3210c	0.145b
Significance					*P* value				
Crop (C)	0.091	ns‡	ns	ns	0.082	***	0.059	*	ns
Year (Y)	***	***	***	***	***	***	***	***	***
C × Y	ns	ns	ns	*	**	**	ns	ns	***

* Significant at $P \leq 0.05$.

** Significant $P \leq 0.01$.

*** Significant $P \leq 0.001$.

† Means followed by different lower case letter within a column are significantly different at $P \leq 0.05$.

‡ Not significant.

Table 3. Interaction between crop and year on postharvest soil water content ($POSTH_2O$ 0–1.2-m depth), water use efficiency (WUE), seed oil concentration, harvest index, and weed biomass for oilseed crops following durum, Culbertson, MT.

Oilseed	2007	2008	2009	2010
		$POSTH_2O$, mm		
Camelina	263a†	219	291	226b
Crambe	188ab	245	290	329a
B. juncea	146b	207	274	294ab
		WUE, kg ha^{-1} mm^{-1}		
Camelina	1.9	1.1b	4.5	0.9
Crambe	2.3	1.4b	6.4	1.0
B. juncea	2.3	6.1a	6.4	1.2
		Seed oil, g kg^{-1}		
Camelina	356a	341a	358b	317b
Crambe	220b	258b	358b	272c
B. juncea	338a	355a	419a	423a
		Harvest index		
Camelina	0.190	0.058b	0.275	0.250 a
Crambe	0.190	0.120ab	0.291	0.089b
B. juncea	0.163	0.202a	0.334	0.096b

† Means followed by different lower case letter within a parameter and column are significantly different at $P \leq 0.05$.

Table 4. Density of four weed species, ethylfluralin-tolerant weeds (ETHFL-TOL), and total weeds before postemergence herbicide application from three cool-season oilseed entries following durum from 2007 to 2010, Culbertson, MT.

Source of variation	Green foxtail	Russian thistle	Kochia	Pigweeds	ETHFL-TOL	Total
			no. m^{-2}			
Oilseed crop						
Camelina	25b†	25	1	1	9	68
Crambe	111a	10	3	2	1	136
B. juncea	17b	74	7	1	3	109
Year						
2007	74a	3b	3b	1	4ab	88b
2008	44b	<1b	<1c	1	5a	57b
2009	6c	<1b	<1c	2	<1b	11c
2010	79a	141a	10a	1	9a	261a
Significance			*P* value			
Crop (C)	*	ns‡	ns	ns	ns	ns
Year (Y)	***	**	***	ns	*	***
C × Y	**	*	ns	*	ns	ns

* Significant at $P \leq 0.05$.

** Significant $P \leq 0.01$.

*** Significant $P \leq 0.001$.

† Means followed by different lowercase letter within a column and source of variation are significantly different at $P \leq 0.05$.

‡ Not significant.

2008). Mean oilseed water use varied with years, an expected result given the variation for precipitation timing and amounts observed during this study. Given the water use values in the current study, our results indicate that these oilseed crops, despite being evolutionarily diverse, extracted soil water similarly across a wide range of environments, which is generally expected under semi-arid conditions. Water use efficiency varied for oilseeds ($P = 0.082$), year, and their interaction (Table 2). In 2008, *B. juncea* had greater WUE than camelina or crambe, but in other years WUE was similar among oilseeds (Table 3). Angadi et al. (2008) reported similar water use and WUE for *B. napus* and *B. rapa* canolas and yellow mustard under well-watered, rainfed, and drought conditions in southern Saskatchewan, Canada. However, in their study all crops had lower water use and WUE as water availability decreased.

Seed oil concentration varied by crop, year, and crop × year interaction (Table 2). Across years, *B. juncea* had the highest oil concentration while crambe had the lowest. In the seasons with significant drought stress, July to August 2007 and April to August 2008 (Table 1), *B. juncea* and camelina had similar oil concentrations, and both had higher concentrations than crambe (Table 3). In the high rainfall years of 2009 and 2010, *B. juncea* had higher seed oil concentration than either camelina or crambe. In a 2-yr multiple site trial, Blackshaw et al. (2011) found much higher oil concentrations in *B. juncea* and camelina than what we report. Oil yield varied for crop and year but the crop × year interaction was not significant (Table 2). *Brassica juncea* produced 75 and 45% more oil per ha^{-1} than camelina and crambe, respectively. Despite *B. juncea* producing higher oil yields than other crops in our study, yields were much lower than those reported in studies from Canadian prairie provinces (Johnston et al., 2002; Miller et al., 2003; Gan et al., 2007; Angadi et al., 2008). *Brassica napus* and most other crucifers are better adapted to the cooler, slightly wetter environments more typical of the Canadian prairie than the comparatively warmer and drier climate of eastern Montana. Higher precipitation in 2009 (Table 1) increased oil yield by increasing seed yield and oil concentration compared to other years (Table 2). Although precipitation was higher in 2010, hail damage reduced oil yield by reducing seed yield.

Aboveground crop biomass varied for crop and year (Table 2). Crambe and *B. juncea* had similar biomass while camelina accumulated less biomass, likely due to poor stands. Differences among years for crop biomass related well with precipitation, except in 2010 when hail damaged crops. The HI varied for year and crop × year interaction (Table 2). In 2008 *B. juncea* had the highest HI while camelina had the lowest (Table 3). In 2010, camelina had higher HI than crambe and *B. juncea*. In 2007 and 2009, HI was not different among oilseed crops. Across oilseeds, the HI was greatest in 2009, a wetter year without hail damage, while the drier years of 2007 and 2008 had lower HI.

Weed community in oilseed crops prior to in-crop herbicide application was dominated by green foxtail and Russian thistle (Table 4). Green foxtail density was greater in the later seeded crambe than in other oilseeds in 2008 and 2010, probably due to earlier emergence, stand establishment, and competitiveness of *B. juncea* and camelina (Table 5). Russian thistle density was greater in camelina in 2007, but was greater in canola than in other oilseeds in 2010 (Table 5). In 2008 and 2009, presence of this weed was minimal in all crops.

Ethylfluralin-tolerant weeds are those broadleaf species not listed as controlled on the Sonalan 10G label, and include flixweed [*Descurainia sophia* (L.) Webb ex Prantl], tall tumble mustard (*Sisymbrium altissimum* L.), littlepod false flax (*Camelina microcarpa* Andrz. ex DC.), and prickly lettuce (*Lactuca serriola* L.). Density of ethylfluralin-tolerant weeds varied among years, and consisted of only a small part of the overall weed community in the oilseeds, even after completion of the second 2-yr cycle of durum-oilseeds (Table 4).

Table 5. Interaction between crop and year on density of weeds in oilseeds before postemergence herbicide (POST) application or at harvest, Culbertson, MT.

Oilseed	2007	2008	2009	2010
	Green foxtail, no. m^{-2}, before POST application			
Camelina	56	38ab†	4	1 b
Crambe	113	81a	11	237a
B. juncea	53	14b	3	1b
	Russian thistle, no. m^{-2}, before POST application			
Camelina	6a	<1	1	92c
Crambe	1b	<1	1	373a
B. juncea	3ab	<1	<1	293b
	Green foxtail, no. m^{-2}, harvest			
Camelina	34	91a	2	33b
Crambe	90	133a	12	441a
B. juncea	36	<1b	6	53ab
	Russian thistle, no. m^{-2}, harvest			
Camelina	4	1	<1	152a
Crambe	5	2	<1	18b
B. juncea	9	<1	1	50ab
	Pigweeds, no. m^{-2}, before POST application			
Camelina	<1	3a	2ab	<1
Crambe	<1	<1b	5a	2
B. juncea	2	1ab	<1b	<1
	Total weeds, no. m^{-2}, harvest			
Camelina	59	108a	4	218ab
Crambe	142	140a	24	486a
B. juncea	69	4b	16	121b
	Weed biomass, kg ha^{-1}, harvest			
Camelina	1819	649a	257	2777a
Crambe	1364	1020a	334	624b
B. juncea	809	52b	119	1376ab

† Means followed by different lower case letter within a column and weed species are significantly different at $P \le 0.05$.

Table 6. Density of four weed species, ethylfluralin-tolerant weeds (ETHFL-TOL), total weeds, and weed biomass at harvest of three cool-season oilseed entries following durum from 2007 to 2010, Culbertson, MT.

Source of variation	Green foxtail	Russian thistle	Kochia	Pigweed	ETHFL-TOL	Total	Weed biomass
	no. m^{-2}						kg ha^{-1}
Oilseed crop							
Camelina	40	39	3	5	7a†	97ab	1375a
Crambe	169	6	2	10	1b	198a	836b
B. juncea	24	17	3	4	3ab	53b	589b
Year							
2007	53	6	7a	16a	3ab	90b	1331a
2008	75	1	2b	3b	1b	84c	574b
2009	7	<1	<1b	5b	2b	15d	237b
2010	176	75	2b	1b	8a	270a	1592a
Significance				*P* value			
Crop (C)	ns‡	ns	ns	ns	*	*	*
Year (Y)	**	***	***	**	*	***	***
C × Y	**	*	ns	ns	ns	***	**

* Significant at $P \le 0.05$.

** Significant $P \le 0.01$.

*** Significant $P \le 0.001$.

† Means followed by different lowercase letter within a column and source of variation are significantly different at $P \le 0.05$.

‡ Not significant.

Despite utilization of an effective fall-applied residual herbicide (S.R. King, personal communication, 2006), preplant-, and in-crop herbicide applications, oilseeds still had significant weed densities at harvest (Table 6). Green foxtail was the most commonly encountered weed, but redroot pigweed and kochia were important components at harvest in 2007. Later planted crambe had the highest density of green foxtail and total weeds in 2008 and 2010 (Table 5). However, crambe also had the lowest density of Russian thistle in 2010. Ethylfluralin-tolerant weeds were most dense in camelina and least dense in crambe, probably due to a longer period of emergence prior to control efforts with the preplant application of glyphosate. All weeds classified as ethylfluralin-tolerant were winter annuals or early emerging spring annuals, with most weed emergence occurring between earlier planting of *B. juncea* and camelina and the later planting of crambe. Beckie et al. (2008) compared weed suppression by yellow mustard, standard and canola quality oriental mustard (*B. juncea*), and open-pollinated and hybrid *B. napus* canola. They reported that weed density did not vary among oilseed crops at 4 wk postemergence, but at crop maturity, *B. juncea* had higher weed density and weed biomass than all other crops. Weed biomass in oilseed crops at harvest varied for crop, year, and the crop × year interaction (Table 6). Weed biomass was similar among oilseed crops in 2007 and 2009 (Table 5). In 2008, weed biomass was greater with camelina and crambe than *B. juncea*. However, in 2010 weed biomass was greatest in camelina and lowest in crambe, while *B. juncea* was similar to both. Beckie et al. (2008) reported that the least weed suppressive crop in their experiment was the canola-quality *B. juncea*, which we found to be similar to camelina and crambe in 3 of 4 yr.

Oilseeds differed for several important arthropod pests, including lygus bugs (*Lygus* spp.) and diamondback moth (*Plutella xylostella*) (Table 7). Later planted crambe had greater density of *Lygus* spp. than either camelina or *B. juncea*. Stage of crop maturity had a significant influence on *Lygus* numbers, with populations increased as crops became more mature (Table 7). Although *Lygus* were not identified to species in this study, Ritter et al. (2010) and Cárcamo et al. (2012) reported that *L. elisus* was the dominant species on *B. napus* canola in Montana and southern Alberta, respectively. It is, however, not known if *Lygus* spp. vary in their potential to damage crucifer oilseeds. Diamondback moth densities were similar on crambe and *B. juncea* but the density was much lower on camelina, indicating camelina may be nonpreferred by this pest. Diamondback moth populations on camelina remained low across crop development and maturation while populations on *B. juncea* and crambe increased over crop growth and development. Crucifer flea beetle (*Phyllotreta cruciferae*) adults can severely damage susceptible seedling crucifers (Brown et al., 2004; Cárcamo and Blackshaw, 2007), causing economic yield loss. Flea beetles were present with *B. juncea* (results not shown), but unlike the results of Milbrath et al. (1995), crambe also had similar populations. However, flea beetles were not present on camelina, confirming its nonpreference by a key pest of other Brassicaceae oilseeds. The cabbage seed pod weevil [*Ceutorhynchus obstrictus* (Marsham)]

Table 7. Number of lygus bugs and diamondback moth larvae in three oilseeds at four growth stages averaged across 4 yr, Culbertson, MT.

Source of variation	Total lygus bugs	Diamondback moth larvae
	no. 20 sweeps	
Oilseed crop		
Camelina	19.4b†	0.8b
Crambe	33.4a	6.2a
B. juncea	12.4b	8.7a
Growth stage		
Early bloom	8.2c	2.4b
Mid bloom	15.0bc	5.5a
Full bloom	23.3b	4.7ab
Late bloom	40.5a	8.1a
Significance	*P* value	
Crop (C)	**	***
Growth stage (G)	***	*
C × G	ns‡	*

* Significant at $P \leq 0.05$.

** Significant $P \leq 0.01$.

*** Significant $P \leq 0.001$.

† Means followed by different lowercase letter within a column and source of variation are significantly different at $P \leq 0.05$.

‡ Not significant.

is increasing in the NGP and may become an important pest of susceptible crucifers (Dosdall et al. 2002). Cabbage seedpod weevil adults were found in sweep samples collected from *B. juncea*, but this insect species was never collected from camelina or crambe in our experiment, confirming results of Cárcamo et al. (2012), who reported that these crucifers either were either nonpreferred or temporally escaped from pod infestation by developmental asynchrony with *C. obstrictus*.

Durum

Durum stand density varied by year and the rotation × year interaction (Table 8). Durum following camelina and crambe had higher stand density than durum following fallow in 2008, but stand densities were similar among rotations for 2009 and 2010 (Table 9). Durum grain yield varied by rotation and year, but their interaction was not significant (Table 8). Grain yield was 50% greater following summer fallow than following oilseeds. The yield advantage for cereals following summer fallow is well documented and not surprising in a semiarid climate (Widtsoe, 1913; Lenssen et al., 2007). Durum following summer fallow had more seed head^{-1} than durum following oilseeds in the dry year, 2008, however, seed head^{-1} did not vary among rotations in the two wet years (Table 9). The other measured yield components, seed weight and tiller density, varied by year but rotation or rotation × year interaction were not significant (Table 8). Crucifers contains great diversity in glucosinolates (Daxenbichler et al., 1991; Schuster and Friedt, 1998; Vaughn and Berhow, 1998), compounds that can have allelopathic effects on subsequent crops (Weston and Duke, 2003). Our study did not include durum in rotation with a crop using similar amounts of water to the oilseeds that did not contain glucosinolates, so we were not able to determine if allelopathic effects were in part responsible for the decreased yield of durum. Similar to grain yield, durum aboveground biomass varied by rotation and year (Table 8). Durum following fallow accumulated more biomass than when following oilseeds. The HI varied only by year (Table 8). Amber percentage varied for year, but rotation and rotation × year interaction were nonsignificant (results not presented). Durum attained Hard Amber Durum wheat class (USDA, 2006) in 2008 and 2010 with hard and vitreous kernel percentages of 76 and 83%, respectively. However, durum in 2009 attained only Amber Durum wheat class with mean hard, vitreous kernels of 71%.

As expected, preplant available soil water was higher for durum following fallow than following oilseeds (Table 8). However, postharvest available soil water did not vary among rotations. Durum following fallow used 72 mm more water than following oilseeds because more water was available for crop growth. This was reflected in higher grain and biomass yields for durum following fallow than following oilseeds. Mean water use for durum following oilseeds, was 283 mm, very similar to

Table 8. Durum grain and biomass yields, harvest index (HI), yield components, water use (WU), preplant soil water content (PREH$_2$O, 0–1.2-m depth), post-harvest soil water content (POSTH$_2$O, 0–1.2-m depth), and water use efficiency (WUE for grain) from 2007 to 2010, Culbertson, MT.

Durum in rotation	Grain	Biomass	HI	Seed	Seed	Tillers	Stand	PREH$_2$O	POSTH$_2$O	WU	WUE
	kg ha^{-1}			mg kernel^{-1}	no. head^{-1}	no. m^{-2}		mm			kg ha^{-1} mm^{-1}
Durum–camelina	1603b†	4786b	0.348	36.5	26.6b	309	210	309b	269	306ab	5.9b
Durum–crambe	1342b	4545b	0.316	34.5	26.8b	317	230	292b	297	261b	5.3b
Durum–*B. juncea*	1690b	4372b	0.406	35.6	26.5b	325	205	285b	269	281b	7.4a
Durum–fallow	2320a	6403a	0.388	38.2	31.1a	382	195	348a	258	355a	7.5a
Year											
2008	1250b	3533c	0.350b	22.9c	25.3b	280b	223a	244c	222b	160c	7.7a
2008	2424a	4900b	0.506a	47.5a	30.5a	298b	231a	306b	306a	292b	8.4a
2010	1543b	6647a	0.237c	38.2b	27.4b	422a	177b	376a	293a	450a	3.8c
Significance						*P* value					
Rotation (R)	**	*	ns‡	ns	*	ns	ns	*	ns	*	*
Year (Y)	***	***	***	***	***	***	***	***	***	***	***
R × Y	ns	ns	ns	ns	**	ns	*	ns	ns	ns	**

* Significant at $P \leq 0.05$.

** Significant $P \leq 0.01$.

*** Significant $P \leq 0.001$.

† Means followedby different lowercase letter within a column and parameter are significantly different at $P \leq 0.05$.

‡ Not significant.

Table 9. Interaction between crop rotation and year on durum water use efficiency, seed kernel, and plant stand following oilseeds and summer fallow, Culbertson, MT.

Durum in rotation	2008	2009	2010
		Water use efficiency, kg ha^{-1} mm^{-1}	
Durum–camelina	5.9b†	8.3	3.3
Durum–crambe	4.8b	7.7	3.6
Durum–*B. juncea*	9.8a	9.3	3.2
Durum–fallow	10.3a	8.2	3.9
		Seed kernel, no. head^{-1}	
Durum–camelina	20.9b	30.8	28.0
Durum–crambe	22.8b	30.1	27.4
Durum–*B. juncea*	23.5b	30.0	26.4
Durum–fallow	34.1a	31.4	27.7
		Stand, no. plants m^{-2}	
Durum–camelina	241ab	233	158
Durum–crambe	265a	238	187
Durum–*B. juncea*	208bc	212	196
Durum–fallow	178c	242	167

† Means followed by different lower case letter within a column are significantly different at $P \leq 0.05$.

Table 11. Interaction between crop year and rotation for density of weeds associated with durum before postemergence herbicide application or at harvest, and weed biomass at harvest, Culbertson, MT.

Durum in rotation	2008	2009	2010
		Green foxtail, no. m^{-2}, before POST application	
Durum–camelina	10	50a†	168a
Durum–crambe	8	57a	478a
Durum–*B. juncea*	10	7b	26b
Durum–fallow	10	6b	23b
		Volunteer oilseeds, no. m^{-2}, before POST application	
Durum–camelina	2a	<1a	84a
Durum–crambe	0b	0b	0b
Durum–*B. juncea*	0b	0b	1b
Durum–fallow	0b	0b	0b
		Green foxtail, no. m^{-2}, harvest	
Durum–camelina	8	329a	182a
Durum–crambe	2	336a	403a
Durum–*B. juncea*	3	80b	4b
Durum–fallow	8	100ab	10b
		Total weeds, no. m^{-2}, harvest	
Durum–camelina	8	377ab	200a
Durum–crambe	3	544a	416a
Durum–*B. juncea*	10	131b	20b
Durum–fallow	10	145b	16b
		Weed biomass, kg ha^{-2}	
Durum–camelina	1	334	157a
Durum–crambe	2	414	320a
Durum–*B. juncea*	11	103	15b
Durum–fallow	1	214	10b

† Means followed by different lower case letter within a column are significantly different at $P \leq 0.05$.

mean water use for oilseeds, indicating that productivity of both recropped durum and oilseeds was limited by available soil water. In a separate study, Lenssen et al. (2010) reported that water use and grain yield of durum following three annual forages was 80 and 77%, respectively, of that following summer fallow. The current study found that water use of durum following oilseeds was 67% of that following fallow. Annual forages require a 4 to 6 wk shorter growing season than oilseeds in our study, allowing for more soil water accumulation for the subsequent durum crop. Durum following oilseeds likely will be more compromised by limited available soil water than when following annual forages. Water use efficiency varied by rotation and year, with a significant rotation × year interaction (Table 8). Durum following fallow and *B. juncea* had higher WUE in the droughty year, 2008, but differences were not detected in the wetter years of 2009 and 2010 (Table 9). Rotation diversification can have large benefits for subsequent wheat production (Kirkegaard et al., 2008), but the benefits are minimal when their production substantially decreases available soil water.

The weed community associated with durum prior to in-crop herbicide application was dominated by green foxtail (Table 10).

Table 10. Density of weed species, volunteer oilseeds, ethylfluralin-tolerant weeds (ETHFL-TOL), and total weeds before herbicide application in durum in four rotations from 2007 to 2010, Culbertson, MT.

Durum in rotation	Green foxtail	Russian thistle	Kochia	Pigweeds	Volunteer	ETHFL-TOL	Total
				no. m^{-2}			
Oilseed crop							
Durum–camelina	61b†	6	1	4	29	1	107ab
Durum–crambe	181a	4	<1	17	0	1	205a
Durum–*B. juncea*	14b	8	<1	5	<1	1	30b
Fallow	13b	7	1	3	0	<1	26b
Year							
2008	9b	1b	<1b	2b	1	<1	14b
2009	19b	2b	<1b	1b	<1	1	26b
2010	174a	17a	1a	18a	21	1	237a
Significance				*P* value			
Rotation (R)	*	ns‡	ns	ns	**	ns	*
Year (Y)	***	***	*	***	***	ns	***
R × Y	**	ns	ns	ns	***	ns	ns

* Significant at $P \leq 0.05$.

** Significant $P \leq 0.01$.

*** Significant $P \leq 0.001$.

† Means followed by different lowercase letter within a column and source of variation are significantly different at $P \leq 0.05$.

‡ Not significant.

Table 12. Density of weed species, volunteer oilseeds, ethylfluralin-tolerant weeds (ETHFL-TOL), total weeds, and weed aboveground biomass associated with durum at harvest in four rotations from 2008 to 2010, Culbertson, MT.

Durum in rotation	Green foxtail	Russian thistle	Kochia	Pigweed	Volunteer	ETHFL-TOL	Total	Weed biomass
	no. m^{-2}							kg ha^{-2}
Oilseed crop								
Durum–camelina	173a†	2	<1	8	1	1	195a	164ab
Durum–crambe	247a	1	<1	5	1	<1	321a	245a
Durum–*B. juncea*	27b	1	<1	18	0	<1	47b	43c
Durum–fallow	39b	1	<1	6	0	<1	57b	75bc
Year								
2008	3c	<1	<1	1c	0	<1b	3b	4c
2009	211a	2	1	23a	1	<1b	299a	267a
2010	150b	2	<1	4b	1	1a	163a	126b
Significance				*P* value				
Rotation (R)	**	ns‡	ns	ns	ns	ns	*	*
Year (Y)	***	ns	ns	***	ns	**	***	***
R × Y	*	ns	ns	ns	ns	ns	*	**

* Significant at $P \leq 0.05$.

** Significant $P \leq 0.01$.

*** Significant $P \leq 0.001$.

† Means followed by different lowercase letter within a column and source of variation are significantly different at $P \leq 0.05$.

‡ Not significant.

Green foxtail populations were denser in durum following camelina and crambe than with durum following canola or fallow in 2009 and 2010 (Table 11). Volunteer camelina stands were uncommonly found in durum in 2008 and 2009, but in 2010 stands were quite dense prior to the application of the in-crop herbicide (Table 11). Despite claims that camelina will not produce volunteer seedlings in subsequently planted crops, these seedlings were present in the subsequent durum crop 2 out of 3 yr. Russian thistle and pigweeds (mixture of redroot pigweed and prostrate pigweed [*Amaranthus albus* L.]) were other important weeds associated with durum.

Green foxtail and total weed density at durum harvest varied with rotation, years, and rotation × year (Table 12). Durum following camelina and crambe had higher densities of green foxtail than durum following *B. juncea* in 2009 and 2010 (Table 11). Durum following fallow had similar density of green foxtail to durum following oilseeds in 2008 and 2009, but had lower infestation level than when following camelina and crambe in 2010. Total weed density in durum was similar among rotations in 2008, but durum following *B. juncea* and fallow had fewer weeds than when following crambe in 2009 and crambe and camelina in 2010 (Table 11). However, total weed density for durum following camelina was not significantly different from other rotations in 2009. Density of Russian thistle and kochia in durum at harvest were low and similar across rotations and years (Table 12). Densities of pigweeds and ethylfluralin-tolerant weeds varied by year but rotation and rotation × year interaction effects were not significant. Weed biomass associated with durum at harvest varied with rotation, years, and rotation × year (Table 12). Weed biomass was greater in durum following crambe and camelina than following *B. juncea* or fallow in 2010, but not in other years (Table 11). Regression analyses using weed densities or biomass to predict durum yield were not significant ($P > 0.05$ results not presented), indicating that weeds likely did not compete significantly with durum for water, nutrients, or light.

SUMMARY AND CONCLUSIONS

Oilseed crops varied for seed and oil yield, with canola-quality *B. juncea* having higher levels than camelina or crambe. Water use of oilseeds was similar among crops, but WUE of *B. juncea* was superior due to its greater yield. Overall, water use of oilseed crops and durum following oilseeds was similar, indicating that these crops used most of the available soil water in this semiarid environment. Oilseeds differed for arthropod infestations, suggesting that pest management will likely differ by oilseed species. All crucifers had substantial, diverse weed communities and biomass at harvest. However, weeds were easily managed in durum. Nevertheless, development of improved weed management systems is necessary for oilseeds in 2-yr rotations with durum. Development of oilseeds with enhanced seedling vigor, combined with integrated cultural and herbicide systems, likely would improve competitiveness with weeds, resulting in improved seed and oil yields and WUE. Durum productivity and water use was similar following diverse oilseeds, but yield and water use were higher following fallow. Two-year oilseed–durum rotations can be used for production of grain and biofuel feedstock. However, production systems optimization and testing for sustainability will require additional research on soil quality, camelina stand establishment, and weed and insect pest management.

ACKNOWLEDGMENTS

The authors express sincere gratitude to Mark Gaffri, Michael Johnson, Randall Obergfell, Joy Barsotti, Sarah Farr, Ashley Farr, Rene’ France, and Ian Kessler for excellent technical support over the course of this study.

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