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Stacked crop rotations and cultural practices for canola and flax yield and quality

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Abstract

Canola (*Brassica napus* L.) and flax (*Linum usitatissimum* L.) are important oilseed crops, but improved management practices to enhance their yields and quality are needed. We studied the effect of stacked versus alternate-year crop rotations and traditional versus improved cultural practices on canola and flax growth, seed yield, oil concentration, and N-use efficiency from 2006 to 2011 in the northern Great Plains, USA. Stacked rotations were durum (*Triticum turgidum* L.)-durum-canola-pea (*Pisum sativum* L.) (DDCP) and durum-durum-flax-pea (DDFP). Alternate-year rotations were durum-canola-durum-pea (DCDP) and durum-flax-durum-pea (DFDP). The traditional cultural practice included a combination of conventional tillage, recommended seed rate, broadcast N fertilization, and reduced stubble height. The improved cultural practice included a combination of no-tillage, increased seed rate, banded N fertilization, and increased stubble height. Canola stand count was 36–123% greater with the improved than the traditional cultural practice in 2006, 2009, 2010, and 2011. Canola pod number and oil concentration were 3–36% greater in the improved than the traditional practice in 2007 and 2010, but trends reversed by 5–19% in 2008. Flax stand count was 28% greater with DFDP than DDFP in 2007 and 56% greater in the improved than the traditional practice in 2010. Flax pod number, seed weight, seed yield, N content, N-use efficiency, and N-removal index varied with crop rotations, cultural practices, and years. Canola growth and oil concentration increased with the improved cultural practice as well as flax growth, yield, and quality enhanced with alternate-year crop rotation and the improved cultural practice in wet years.

1 | INTRODUCTION

Canola and flax are important industrial and economic oilseed crops that can provide increased profit margin to producers (Hanson, Johnson, Hanson, & Riveland, 2008). Because of the reduction in erucic acid in fatty acid composition and glucosinates, canola is the third most important crop for vegetable oil production after soybean (*Glycine max* L.) and palm (*Elaeis guineensis Jacq.*) in the world (Assefa et al., 2018; Downey & Rimmer, 1993; Johnston et al., 2002; Vann, Reberg-Horton, & Brinton, 2016). Both canola and flax had high oil (42–44%) and protein (21–23%) concentrations (Johnston et al., 2002). Flax is also rich in omega-3 fatty acid (Johnston et al., 2002). Flax oil has high linolenic fatty acid (45—46%) and is used for paints, varnishes, soap, oil-based covering, and linoleum flooring (Heard & Comstock, 1980;

Abbreviations: DCDP, durum-canola-durum-pea; DDCP, durum-durum-canola-pea; DDFP, durum-durum-flax-pea; DFDP, durum-flax-durum-pea.

Johnston et al., 2002). Due to high protein concentration, canola and flax residues after oil extraction serve as excellent protein meals for animals (Heard & Comstock, 1980; Johnston et al., 2002). The fiber from flax biomass is an important ingredient in specialty paper and textile industries (Foulk et al., 2007).

Because of non-human food consumption but increasing industrial importance, global canola production increased from 5 Tg in 1990 to 19 Tg in 2014 (FAO, 2015). In USA, area under canola increased from 0.1 million ha in 1990 to 1 million ha in 2014 (USDA, 2015). Canola and flax are well adapted to the cool and short growing season in the semiarid northern Great Plains, USA. In this region, canola and flax were grown from 444,000 and 133,000 ha, respectively, in 1990 to 687,000 and 180,000 ha in 2017 (Assefa et al., 2018; Hanson et al., 2008; NASS, 2019). Factors, such as precipitation amount and timing, air temperature, soil crusting, seeding equipment, late spring frost, and hail damage, however, affect canola and flax production (Johnston et al., 2002).

Decreased crop yields due to increased disease and pest incidences in monocropping have led to the adoption of diversified rotations of canola and flax with other crops (Johnston et al., 2002). Rotation of canola and flax with cereals can increase crop yields and net returns (Assefa et al., 2018; Johnston et al., 2002). For each increase in the number of other crops in the rotation, canola yield increased from 0.20 to 0.36 Mg ha^{-1} (Assefa et al., 2018). Similarly, canola rotated once in three years with other crops had 22% more yield than continuous canola (Assefa et al., 2018). O'Donovan et al. (2014) reported that canola yields following legumes were 10 to 27% greater than following nonlegumes, but crop type had no effect on oil concentration. Other benefits of diversified crop rotations include reduced N fertilization rate and increased N-use efficiency (Lenssen et al., 2010), enhanced precipitation-storage and water-use efficiency (Farahani, Peterson, & Westfall, 1998; Johnston et al., 2002), enriched soil C and N fractions (Sainju, Caesar-TonThat, & Evans, 2009), and reduced erosion potential (Feng, Sharratt, & Young, 2011). The sequence and type of crops grown in crop rotation can affect soil water and nutrient availability and weed population, thereby influencing canola and flax yields and quality (Allen, Lenssen, Sainju, Caesar-TonThat, & Evans, 2014; Johnston et al., 2002). A typical alternate-year rotation includes annual crops in a cereal-broadleaf-cereal-broadleaf sequence. A typical stacked rotation contains annual crops in a cereal-cereal-broadleaf-broadleaf sequence. In the stacked rotation, herbicides with more than one year residual effect is applied in the first year of the crop, thereby effectively controlling weeds in the second year (Garrison, Miller, Ryan, Roxbourgh, & Shea, 2014). This can reduce herbicide application in the stacked rotation, thereby diminishing its adverse impact on the environment.

Core Ideas

- Management strategies are needed for canola and flax growth, yield, and quality.
- Canola and flax performance were studied with crop rotations and cultural practices.
- Improved cultural practice enhanced canola stand count and oil concentration.
- Alternate-year rotation and improved cultural practice increased flax performance.
- Improved cultural practice enhanced canola and flax performance in wet years.

Soil and crop management practices, such as tillage, seeding rate, fertilization, and stubble height, can affect canola and flax yields and quality (Assefa et al., 2018; Johnston et al., 2002). Holman, Maxwell, Stamm, and Martin (2011) reported that conventional tillage increased canola yield by 8% compared to no-tillage. In contrast, Johnston et al. (2002), in a review of literature, found that no-tillage increased canola yield by 1–14% compared to conventional tillage due to increased soil water storage. A meta-analysis conducted by Assefa et al. (2018) showed that tillage had no influence on canola yield. Tall stubble can reduce frost damage and increase canola survival compared to short stubble (Volkmar & Irvine, 2005).

In the northern Great Plains where growing season is short and precipitation is limited, higher seeding rate is often used to express potential plasticity of canola and flax yields and to control weeds (Albrecht & Dybing, 1973; Angadi, Cutforth, McConkey, & Gan, 2003). Angadi et al. (2003) observed that canola seed yield and biomass declined with reduced seeding rate in years with below-average precipitation, but maintained yield in years with normal or above-average precipitation. They found that seeding rate had no effect on canola seed number per pod and seed weight. Several researchers (Chen et al., 2005; Hanson et al., 2008) reported that increased seeding rate increased canola seed yield, but decreased oil concentration. Chen et al. (2005) found that seeding rate of 1.5 to 3.0 kg ha^{-1} produced optimum canola yield in central Montana, USA. Albrechtsen and Dybing (1973) reported that increased seeding rate increased flax stand count, but reduced plant height and pod number per plant. They also found that seeding rate did not influence flax seed yield, oil concentration, seed weight, seed number per pod, pod number per square meter, and test weight.

Although the effect of crop rotation and management practices (tillage, seeding rate, and N fertilization) on canola yield and quality are available (Assefa et al., 2018; Maaz, Pan, & Hammae, 2016), more studies on the effect of stacked and alternate-year crop rotations and combination of cultural practices on canola and flax growth, seed yield, oil concentration, and N-use efficiency are needed. As herbicide application has negative consequences on animal and human health, improved management practices are needed to reduce herbicide application while sustaining canola and flax yields and quality and decreasing the cost of crop production. Producers in the northern Great Plains often use the traditional cultural practice that includes a bundle of individual practices, such as conventional tillage and seeding rate, broadcast fertilization, and reduced stubble height, rather than using only one practice for canola and flax production. These practices can reduce soil organic matter, inefficiently use soil water and N, and increase chemical inputs (Farahani et al., 1998; Johnston et al., 2002; Lenssen et al., 2010; Sainju et al., 2009). Studies are needed to evaluate the effect of a combination of improved cultural practices that provide multiple benefits of reducing chemical inputs, enhancing soil health, and increasing canola and flax growth, yield, and quality. This study compared stacked vs. alternate-year rotation and traditional vs. improved cultural practice on canola and flax growth, yield, and quality from 2006 to 2011 in the northern Great Plains. The objectives were to: (1) quantify the effect of diversified crop rotations and cultural practices on canola and flax growth, seed yield, oil concentration, and N-use efficiency under dryland cropping systems in the semiarid region and (2) determine which crop rotation and cultural practice can enhance canola and flax yield and quality. We hypothesized that stacked rotation and the improved cultural practice would increase canola and flax growth, seed yield, oil concentration, and N-use efficiency compared to alternate-year rotation and the traditional cultural practice.

2 | MATERIALS AND METHODS

2.1 | Experimental detail

An experiment on diversified crop rotations and cultural practices on canola and flax yields and quality was conducted from 2005 to 2011 in a Williams loam soil (fine-loamy, mixed, superactive, frigid, Typic Argiustoll) in Froid, MT (48° 16′ N, 104° 30′ W; altitude 660 m). Sainju, Lenssen, Allen, Stevens, and Jabro (2016) showed detailed descriptions on soil properties, site, climate, treatments, and crop management for the experiment. In brief, treatments included two stacked (durum-durum-canola-pea [DDCP] and durum-durum-flax-pea [DDFP]) and two alternate-year (durum-canola-durum-pea [DCDP] and durum-flax-durum-pea [DFDP]) crop rotations as well as two cultural practices (traditional and improved). In all rotations, each crop phase of the rotation was present in every year. Because canola and flax had superior yield and quality in diversified crop rotations than monocropping (Assefa et al., 2018; O'Donovan et al., 2014), monocropping of these crops were not included in the study, except for the monocropping of durum. The traditional cultural practice included a combination of conventional tillage, recommended seeding rate, broadcast N fertilization, and reduced durum stubble height; and the improved cultural practice included a combination of no-tillage, increased seeding rate, banded N fertilization, and increased durum stubble height. In traditional and improved cultural practices, seeding rates for canola were 6 and 9 kg ha^{-1}, methods of N fertilization were broadcast and banded applications, and stubble heights were 19 cm each, respectively. For flax, methods of N fertilization were similar to canola in both cultural practices, but seeding rates were 34 and 50 kg ha^{-1} and stubble heights 13 cm each in traditional and improved cultural practices, respectively. In addition, durum stubble heights in all rotations were 19 and 33 cm in traditional and improved cultural practices, respectively. For durum and pea, these treatments varied by cultural practices, as shown by Sainju et al. (2016). Treatments were arranged in a randomized block design with three replications, with cultural practice as the main-plot and crop rotation as the split-plot factor. The size of the main plot was 192 m by 12 m and split plot 36 m by 12 m.

2.2 | Management and analysis of crops

Canola was planted in mid to late April and flax in late April to early May in each year using a low disturbance no-till drill. Canola and flax received N fertilizer at 91 and 67 kg N ha^{-1}, respectively, from urea (46% N) and monoammonium phosphate (11% N, 23% P). These N rates were adjusted by deducting soil residual NO_3-N content to a depth of 60 cm, which was determined in the fall of the previous year. Therefore, recommended N rates included both soil residual NO_3-N and fertilizer N. Canola and flax also received P fertilizer at 13 kg P ha^{-1} from monoammonium phosphate and K fertilizer at 22 kg K ha^{-1} from muriate of potash (52% K) at planting, but no irrigation. Phosphorus and K fertilizers were banded to a depth of 5 cm below and 5 cm to the side of the seed in all treatments. Nitrogen fertilizer was broadcast and incorporated to a depth of 8 cm using conventional tillage in the traditional cultural practice and banded similar to P and K fertilizers in the improved practice. Preplant weeds in all plots were controlled by applying glyphosate (*N*-[phosphonomethyl] glycine) at 3.36 kg a.i. ha^{-1}. In-season weeds were controlled by applying a tank-mixed of formulated bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) and MCPA ester (2-methy-4-chlorophenoxyacetic acid) (0.92:1) at 0.68 kg a.i. ha^{-1} and fenoxaprop-P-ethyl ((+)-ethyl 2-[4-[(6-chloro-2 benzoxazolyl)oxy]phenoxy]propanoate) at 0.09 kg a.i. ha^{-1} in 38 L water. Postharvest weeds were controlled with tank-mixed glyphosate (3.36 kg a.i. ha^{-1}) and dicamba

(3, 6-dichloro-2-methoxybenzoic acid) at 0.28 kg a.i. ha^{-1}. To determine stand count, plants were counted from four 1-m row segments within a plot. Plant height was determined with a meter stick from ten plants per plot prior to harvest. Pod number was measured from a 1-m row segment, after which seed number per pod was determined. Two days prior to seed harvest, plants were harvested from two 0.5 m^2 areas randomly within the plot, oven dried at 60°C for 7 d, and weighed to determine aboveground biomass yield. A plot-combine harvested canola seeds in August and flax seeds in September. Seeds were harvested from an area of 50 m^2 and seed yield was determined on an oven-dried basis (at 60°C for 7 d) after cleaning and weighing seeds and drying subsamples in the oven. Seed weight was determined by weighing 1000 seeds. Harvest index was calculated by dividing seed yield by aboveground biomass yield. A plot-combine harvested remaining seeds within the plot and crop residue returned to the soil. Sainju et al. (2016) described management of durum and pea for this study.

Nitrogen concentration in canola and flax seeds and aboveground biomass was determined using a C and N analyzer (LECO, St. Joseph, MI) after grinding samples to 1 mm. Seed and aboveground biomass N uptake were calculated by multiplying yields by N concentrations. Nitrogen harvest index, N-use efficiency, and N removal index in canola and flax (Allen et al., 2014; Lenssen et al., 2010) were calculated as follows:

$$\text{N harvest index} = \text{Seed N uptake}/\text{aboveground biomass Nuptake} \quad (1)$$

$$\text{N} - \text{use efficiency} = \text{Seed yield}/\left(\text{soil residual NO}_3\text{–N} + \text{fertilizer N}\right) \quad (2)$$

$$\text{N removal index} = \text{Seed N uptake}/\left(\text{soil residual NO}_3\text{–N} + \text{fertilizer N}\right) \quad (3)$$

While the concentration of NH_4-N is low, it usually takes a long time to measure soil N mineralization during a crop growing season. Therefore, these factors were not taken into account while calculating N-use efficiency (Allen et al., 2014; Lenssen et al., 2010). Oil concentration in canola and flax seeds was determined using a nuclear magnetic resonance (Resonance Instruments, Witney, UK).

2.3 | Statistical analysis of data

Data for canola and flax were checked for normality of variance and then analyzed separately using a MIXED procedure of SAS for a split-plot design where the main-plot treatment was cultural practice and the split-plot treatment was crop rotation (Littell, Milliken, Stroup, Wolfinger, & Schabenberger, 2006). Cultural practice, crop rotation, year, and their interactions were treated as fixed effects and replication and replication × cultural practice interaction as random effects. The least square means test separated treatment means and interactions when significant at $P = .05$ (Littell et al., 2006). Because 2005 was the establishment year of crops, data for this year were not included in the statistical analysis.

3 | RESULTS AND DISCUSSION

3.1 | Canola growth, biomass, and seed yield

Canola stand count varied with cultural practices and years, with a significant interaction for cultural practice × year (Table 1). Stand count, averaged across crop rotations, was 36–123% greater in the improved than the traditional cultural practice in 2006, 2009, 2010, and 2011 (Table 2). Averaged across crop rotations and years, stand count was 32% greater in the improved than the traditional practice (Table 3). Averaged across treatments, stand count was greater in 2009 than other years, except 2011.

Higher seeding rate may have increased canola stand count in the improved cultural practice in April-May 2006, 2010, and 2011 when air temperature and precipitation were favorable. Air temperature in April-May was 0.3 to 1.4°C greater in 2006 and total precipitation was 51 to 134 mm greater in 2006, 2010, and 2011 than the 115-yr average (Figure 1). Considering that the average weight of 1000 canola seeds is 5 g (Chen et al., 2005), overall emergence of canola was slightly lower in the improved (42%) than in the traditional practice (48%). As a result, greater stand count in the improved than the traditional practice was primarily due to higher seeding rate, although other practices (no-tillage, banded N fertilization, and taller stubble height) may have favored on stand count. No-tillage increases soil water conservation compared to conventional tillage due to undisturbed soil condition (Johnston et al., 2002; Lenssen et al., 2012). Increased seeding rate enhances stand count by reducing weed competition, banded N fertilization limits N availability to weeds, and taller stubble height increases seed germination by increasing soil water storage and limiting light penetration (Assefa et al., 2018; Entz et al., 2002; Strydhorst, King, Lopetinsky, & Harker, 2008; Volkmar & Irvine, 2005). Several researchers (Hanson et al., 2008; Vann et al., 2016) have reported that increased seeding rate increased canola stand count. The reasons for greater stand count in 2009 were not known.

Canola plant height differed among years, with a significant cultural practice × year interaction (Table 1). Averaged across crop rotations, canola was 13 cm taller in the traditional than the improved practice in 2009 (Table 2). Averaged across treatments, canola was 9 to 34 cm taller in 2007, 2010, and 2011 than other years (Table 3). Lower competition

TABLE 1 Analysis of variance for canola and flax growth and yield with crop rotation (R), cultural practice (C), and year (Y) as sources of variance

Source	Stand count no. m^{-2}	Pod no. no. m^{-2}	Plant height cm	Seed no. no. pod^{-1}	Seed weight Mg $seed^{-1}$	Seed yield kg ha^{-1}	Aboveground biomass yield kg ha^{-1}	Harvest index kg kg^{-1}
***P*-values**								
Canola								
R	.862	.762	.542	.495	.539	.582	.707	.854
C	.023	.880	.176	.509	1.000	.370	.779	.420
R × C	.667	.493	.950	.067	1.000	.349	.128	.725
Y	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
R × Y	.329	.383	.193	.748	.853	.400	.705	.847
C × Y	<.001	.020	.024	.756	.797	.167	.521	.596
R × C × Y	.835	.540	.545	.478	.797	.506	.994	.973
Flax								
R	.578	.277	.597	.747	.324	.876	.127	.955
C	.650	.896	.607	.350	.867	.736	.468	.405
R × C	.345	.744	.927	.930	.683	.203	.315	.469
Y	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
R × Y	.044	.241	.609	.946	.009	.260	.094	.492
C × Y	.044	.158	.372	.548	.808	.020	.251	.306
R × C × Y	.956	.037	.724	.572	.012	.049	.474	.153

TABLE 2 Interaction between cultural practice and year on canola stand count, pod number, plant height, and seed oil concentration

Cultural practice[a]	Year 2006	2007	2008	2009	2010	2011
Canola stand count (no. m^{-2})						
Traditional	13b[b]	63	43	77b	72b	71b
Improved	29a	60	47	113a	98a	109a
Canola pod number (no. m^{-2})						
Traditional	2756	4364b	5944a	2673	4368	4342
Improved	1954	5935a	4985b	1988	4530	4820
Canola plant height (cm)						
Traditional	73	98	86	72a	99	95
Improved	72	99	85	59b	97	96
Canola seed oil concentration (g kg^{-1})						
Traditional	359	384	406a	423	403b	417
Improved	353	384	388b	424	417a	411

[a]Traditional cultural practices are conventional tillage, recommended seed rate, broadcast N fertilization, and reduced stubble height; and improved cultural practices are no-tillage, increased seed rate, banded N fertilization, and increased stubble height.

[b]Numbers not followed by a common letter within a column in a set are significantly different at $P = .05$ by the least square means test.

among plants for water and nutrients due to reduced seeding rate, increased nutrient mineralization and availability due to conventional tillage, and enhanced exposure to sunlight due to lower stubble height may have increased canola plant height in the traditional practice in 2009 (Assefa et al., 2018; Entz et al., 2002; Strydhorst et al., 2008; Volkmar & Irvine, 2005). Cultural practice had no effect on plant height in other years. Hanson et al. (2008) found that seeding rate had no effect on canola plant height. Increased air temperature in 2007 or above-average precipitation during the growing season in 2010 and 2011 (Figure 1) may have increased canola plant height in these years.

Canola pod number also differed by year, with a significant cultural practice × year interaction (Table 1). Averaged across crop rotations, pod number was 36% greater in the improved than the traditional practice in 2007, but the trend reversed by 16% in 2008 (Table 2). Averaged across treatments, pod number was greater in 2007 and 2008 than other years (Table 3). Similar to stand count, increased soil water and N availability may have increased pod number in the improved practice in 2007 when air temperature was higher and growing season precipitation was near the average (Figure 1). On the other hand, reduced competition among plants due to lower seeding rate may have enhanced pod number in the traditional practice in 2008 when the growing season precipitation was below the average. Angadi et al. (2003) found that increased seeding rate decreased canola pod number per plant. Lower stand count may have increased pod number in 2007 and 2008 through increased branching and pod retention in each node (Angadi et al., 2003; Assefa et al., 2018).

Canola seed number per pod, seed weight, seed yield, aboveground biomass yield, and harvest index varied with

TABLE 3 Canola and flax growth and yield as affected by cultural practice and year

Treatment	Stand count	Pod number	Plant height	Seed number	Seed weight	Seed yield	Aboveground biomass yield	Harvest index
	no. m^{-2}	no. m^{-2}	cm	no. pod^{-1}	Mg seed^{-1}	kg ha^{-1}	kg ha^{-1}	kg kg^{-1}
Canola								
Cultural practice[a]								
Traditional	57b[b]	4075	87	24	2.8	1342	4853	0.24
Improved	75a	4035	85	23	2.8	1436	4775	0.24
Year								
2006	21e	2355c	72c	21d	1.0e	1124c	3886bc	0.25b
2007	62c	5149a	99a	26ab	3.0c	1215c	6899a	0.16d
2008	45d	5465a	86b	28a	4.1a	1161c	4555b	0.20bc
2009	95a	2331c	65d	21d	3.8b	758d	5076b	0.13d
2010	85b	4449b	98a	24bc	2.8c	1883b	4722b	0.32a
2011	90ab	4581b	95a	22 cd	2.3d	2192a	3746c	0.38a
Flax								
Year								
2006	135a	1982c	50b	6.0c	4.9c	286c	2275c	0.16b
2007	156a	2719b	44c	5.8c	3.6d	234c	2492c	0.15b
2008	81b	2541bc	57a	8.1a	5.4b	650b	2275c	0.25a
2009	94b	3832a	54ab	8.9a	6.1a	724b	4407a	0.17b
2010	139a	4371a	59a	7.3ab	5.3b	1258a	4203a	0.29a
2011	96b	4544a	50b	6.9b	5.9a	644b	3380b	0.17b

[a]Traditional cultural practices are conventional tillage, recommended seed rate, broadcast N fertilization, and reduced stubble height; and improved cultural practices are no-tillage, increased seed rate, banded N fertilization, and increased stubble height.
[b]Numbers not followed by a common letter within a column in a set are significantly different at $P = .05$ by the least square means test.

years, but treatment had no effect on these parameters (Table 1). Seed number and seed weight were greater in 2008 than other years, except 2007 (Table 3). Seed yield was greater in 2011 and aboveground biomass in 2007 than other years. Harvest index was greater in 2010 and 2011 than other years.

Morrison, McVetty, and Scarth (1990) observed that lower seeding rate increased canola seed number per pod, but others (Angadi et al., 2003; Hanson et al., 2008) found that seeding rate had no effect on seed number per pod and seed weight. Johnston et al. (2002) and Assefa et al. (2018) found that diversified crop rotations increased canola seed yield compared to continuous canola due to reduction in disease occurrences. Because the number of crops were similar in both stacked and alternate rotations in our study, the sequence of crops in these rotations did not affect canola seed yield. Some researchers (Assefa et al., 2018; Hanson et al., 2008; Vann et al., 2016) reported that increased seeding rate increased canola seed yield, while others (Chen et al., 2005; Christensen & Drabble, 1984; Degenhardt & Kondara, 1981) found that seeding rate had no effect on seed yield. Seeding rate also had no effect on canola harvest index (Angadi et al., 2003). Our results showed that canola seed number per pod, seed weight, seed yield, aboveground biomass yield, and harvest index were not altered by crop rotations and cultural practices, although plant stand, pod number, and plant height varied between cultural practices in various years.

Below-average precipitation in 2008 produced greater seed number per pod and heavier seed, probably due to reduced stand count (Table 3). Increased plant height may have enhanced seed yield in 2011 and aboveground biomass in 2007 when the growing season precipitation was near or above the average (Figure 1). Brandt and McGregor (1997) found that canola seed yield increased by 5.9 kg ha^{-1} for each 1 mm increase in precipitation. Seed yield was particularly low in 2009, probably due to reduced seed number per pod as a result of lower air temperature at seed formation. Air temperature in July and August was 3.5 to 4.1°C lower in July and August in 2009 than the 115-yr average (Figure 1). Lower than normal air temperature can reduce canola seed yield (Brandt & McGregor., 1997; Johnston et al., 2002). Greater seed yield than aboveground biomass increased harvest index during the above-average growing season precipitation in 2010 and 2011. The reverse was true in 2007 and 2009 when reduced seed yield compared to aboveground biomass reduced harvest index.

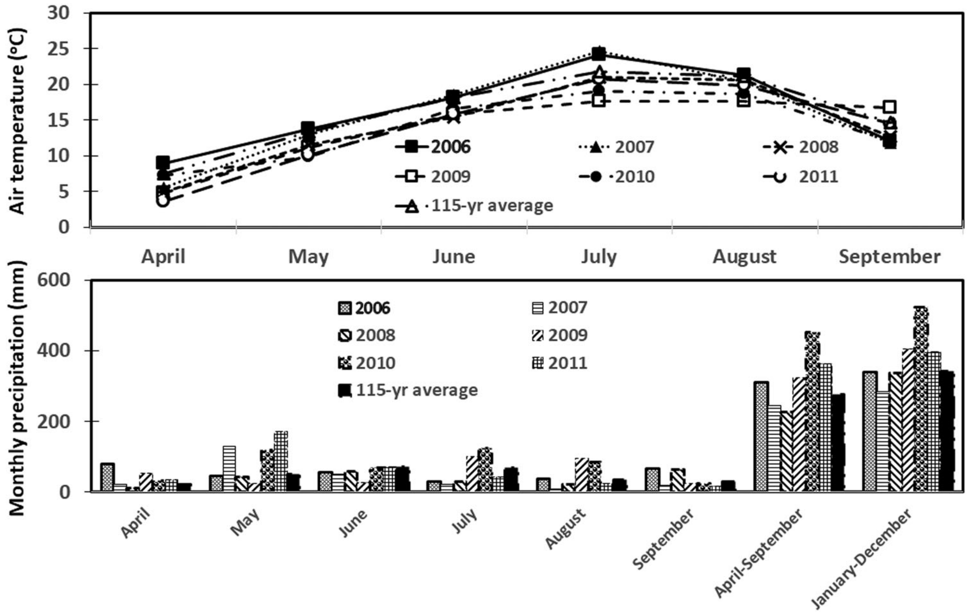

FIGURE 1 Monthly air temperature and total precipitation from April to September 2006 to 2011 at the experimental site. Growing season (April–September) precipitation and total annual (January-December) precipitation are also shown in the bottom figure

TABLE 4 Analysis of variance for canola and flax N uptake, N use-efficiency, and oil concentration with crop rotation (R), cultural practice (C), and year (Y) as sources of variance

Source	Seed N uptake	Above-ground biomass N uptake	N harvest index	N removal index	Seed oil concentration	N-use efficiency
	kg N ha^{-1}	kg N ha^{-1}	kg kg^{-1}	kg N kg^{-1} N	g kg^{-1}	kg seed kg^{-1} N
***P*-values**						
Canola						
R	.469	.975	.857	.511	.204	.574
C	.526	.935	.752	.599	.523	.379
R × C	.391	.981	.501	.525	.483	.342
Y	<.001	.001	<.001	<.001	<.001	<.001
R × Y	.619	.656	.595	.329	.405	.400
C × Y	.179	.993	.240	.239	.008	.168
R × C × Y	.481	.907	.904	.452	.785	.513
Flax						
R	.903	.115	.605	.713	.313	.884
C	.645	.495	.436	.774	.366	.734
R × C	.200	.411	.520	.196	.797	.205
Y	<.001	<.001	<.001	<.001	<.001	<.001
R × Y	.262	.092	.687	.140	.109	.354
C × Y	.035	.376	.279	.043	.315	.019
R × C × Y	.049	.389	.239	.023	.785	.049

3.2 | Canola oil concentration, nitrogen uptake, and nitrogen-use efficiency

Canola oil concentration was significant for year and cultural practice × year interaction (Table 4). Averaged across crop rotations, oil concentration was 4% greater in the traditional than the improved cultural practice in 2008, but the trend reversed by 3% in 2010 (Table 2). Averaged across treatments, oil concentration was greater in 2009 than other years (Table 5). Crop rotation had no effect on oil concentration.

TABLE 5 Canola and flax N uptake, N-use efficiency, and oil concentration from 2006 to 2011

Year	Seed N uptake	Aboveground biomass N uptake	N harvest index	N removal index	Seed oil concentration	N-use efficiency
	kg N ha^{-1}	kg N ha^{-1}	kg kg^{-1}	kg N kg^{-1} N	g kg^{-1}	kg seed kg^{-1} N
Canola						
2006	52c[a]	139bc	0.42b	0.57c	355e	12.2c
2007	59c	151a	0.39b	0.63bc	384d	13.2c
2008	57c	103c	0.57a	0.62c	397c	12.6c
2009	35d	126b	0.29c	0.33d	423a	8.2d
2010	73b	132bc	0.59a	0.77b	410b	20.4b
2011	88a	155a	0.58a	0.89a	414b	23.7a
Flax						
2006	14c	72c	0.20c	0.24c	375b	5.0c
2007	11c	53d	0.27c	0.18c	376b	4.0c
2008	30b	53d	0.57a	0.53b	392a	11.3b
2009	30b	102a	0.31bc	0.54b	400a	12.6b
2010	48a	85b	0.58a	0.85a	396a	21.8a
2011	28b	76bc	0.40b	0.49b	398a	11.2b

[a]Numbers not followed by a common letter within a column in a set are significantly different at $P = .05$ by the least square means test.

Reduced competition among plants for soil water and nutrients due to decreased seeding rate and increased soil N mineralization due to conventional tillage along with broadcast N fertilization and shorter stubble height appeared to increase canola oil concentration in the traditional practice in 2008 when the growing season precipitation was below the 115-yr average (Figure 1). The reverse was true in the improved cultural practice, which may have increased soil water and N availability in 2010 when the growing season precipitation was above the 115-yr average. Chen et al. (2005) reported that canola oil concentration decreased by 10 to 20 g kg^{-1} as seeding rate increased. Reduction in seed yield (Table 3) likely increased oil concentration in 2009, as canola seed yield and oil content are inversely related (Chen et al., 2005).

Canola seed and aboveground biomass N uptake, N harvest index, N removal index, and N-use efficiency varied with years, but crop rotation and cultural practice had no effect on these parameters (Table 4). Seed N uptake, N removal index, and N-use efficiency were greater in 2011 than other years (Table 5). Compared to other years, aboveground biomass N uptake was greater in 2007 and 2010 and N harvest index greater in 2008, 2010 and 2011. Increased seed yield (Table 3) enhanced seed N uptake in 2011 compared to other years. Increased aboveground biomass yield (Table 3) and/or N concentration (41 g N kg^{-1} in 2011 compared to 22 to 36 g N kg^{-1} in other years) increased aboveground biomass N uptake in 2007 and 2011. Greater N uptake in seed than aboveground biomass increased N harvest index in 2008, 2010, and 2011. Increased seed yield and seed N uptake also increased N-use efficiency and N removal index in 2011 than other years. Because of the nonsignificant effect of treatments on seed yield and N concentration, canola seed and aboveground biomass N uptake, N harvest index, N removal index, and N-use efficiency also did not vary with crop rotations and cultural practices.

3.3 | Flax growth, biomass, and seed yield

Flax stand count varied with years, with significant interactions for crop rotation × year and cultural practice × year (Table 1). Averaged across cultural practices, stand count was 22% greater with DFDP than DDFP in 2007, but the trend reversed by 75% in 2008 (Table 6). Averaged across crop rotations, stand count was 56% greater in the improved than the traditional cultural practice in 2010. Averaged across treatments, stand count was greater in 2006, 2007, and 2010 than other years (Table 3).

Alternate-year rotation enhanced flax stand count in 2007 when the precipitation in May, the period for the germination of flax seeds, was 77 mm above the 115-yr average (Figure 1), probably due to increased soil water availability. In contrast, stacked rotation enhanced stand count in 2008 when the precipitation in May was 8 mm below the average. Reduction in the residual effect of herbicide applied to durum during the dry period may have increased flax stand count with stacked rotation in 2008. With May precipitation of 67 mm above the average, the improved cultural practice also increased stand count in 2010, likely a result of higher seeding rate. Albrechtsen and Dybing (1973) and Kurtenbach et al. (2019) found that higher seeding rate increased flax stand count. Near

TABLE 6 Interaction between crop rotation, cultural practice, and year on flax stand count

Treatment	Year					
	2006	2007	2008	2009	2010	2011
Flax stand count (no. m^{-2})						
Crop rotation[a]						
DFDP	139	175a[b]	59b	94	132	90
DDFP	130	137b	103a	94	147	12
Cultural practice[c]						
Traditional	140	162	73	94	109b	99
Improved	129	150	89	93	170a	93

[a]Crop rotations are DDFP, durum-durum-flax-pea; and DFDP, durum-flax-durum-pea.
[b]Numbers not followed by a common letter within a column in a set are significantly different at $P = .05$ by the least square means test.
[c]Traditional cultural practices are conventional tillage, recommended seed rate, broadcast N fertilization, and reduced stubble height; and improved cultural practices are no-tillage, increased seed rate, banded N fertilization, and increased stubble height.

TABLE 7 Interaction between crop rotation, cultural practice, and year on flax pod number and seed weight

Cultural practice[a]	Flax pod number (no. m^{-2})		Flax seed weight (mg $seed^{-1}$)	
	DFDP[b]	DDFP[b]	DFDP	DDFP
2006				
Traditional	1867	2037	4.3B[c]	5.3A
Improved	2270	1755	4.7	5.3
2007				
Traditional	3486a[d]	2902	4.0aB	5.3A
Improved	1747b	2740	3.0bB	5.3A
2008				
Traditional	2745	2338	5.3b	5.0
Improved	2148	2574	6.0aA	5.3B
2009				
Traditional	3822	7304	6.0	6.0
Improved	3356	3847	6.2	6.0
2010				
Traditional	4031b	4303	5.3	5.7
Improved	5760aA	3389B	5.3	5.0
2011				
Traditional	4940A	3241bB	6.0	6.0
Improved	4987	5008a	5.7	6.0

[a]Traditional cultural practices are conventional tillage, recommended seed rate, broadcast N fertilization, and reduced stubble height; and improved cultural practices are no-tillage, increased seed rate, banded N fertilization, and increased stubble height.
[b]Crop rotations are DDFP, durum-durum-flax-pea; and DFDP, durum-flax-durum-pea.
[c]Numbers not followed by a common uppercase letter within a row in a set are significantly different at $P = .05$ by the least square means test.
[d]Numbers not followed by a common lowercase letter within a column in a set are significantly different at $P = .05$ by the least square means test.

or above-average precipitation (Table 1) probably enhanced stand count in 2006, 2007, and 2010.

Flax pod number differed by year, with a significant interaction for crop rotation × cultural practice × year (Table 1). Pod number was 50% greater in the traditional than the improved cultural practice with DFDP in 2007, but the trend reversed by 43 to 55% with DFDP in 2010 and with DDFP in 2011 (Table 7). Pod number was also 34 to 41% greater with DFDP than DDFP in the improved practice in 2010 and in the traditional practice in 2011. Averaged across treatments, pod number was greater from 2009 to 2011 than other years (Table 3).

Alternate-year crop rotation and the improved cultural practice increased flax pod number in 2010 and 2011 when the growing season precipitation was 87 to 176 mm above the 115-yr average (Figure 1). Increased soil water and N availability and their efficient use by flax likely increased pod number with these treatments in wet years. The reverse was true with stacked rotation and the traditional cultural practice in 2007 with near normal precipitation. Reduced residual effect of herbicides and seed rate and increased N mineralization due to tillage may have increased pod number with stacked rotation and the traditional cultural practice in 2007. Albrechtsen and Dybing (1973) observed that seeding rate had no effect on flax pod number per unit area. Greater growing season precipitation from 2009 to 2011 (Figure 1) certainly increased pod number in these years.

Flax plant height, seed number per pod, aboveground biomass yield, and harvest index varied with years, but treatments and their interactions were not significant on these parameters (Table 1). Averaged across treatments, plant height was 7 to 15 cm greater in 2008 and 2010 than other years, except 2009 (Table 3). Seed number was greater in 2008 and 2009 than other years, except 2010. Compared to other years, aboveground biomass yield were greater in 2009 and 2010 and harvest index was greater in 2008 and 2010. Flax plant height increased both in dry (2008) and wet (2010) years whose reasons were unknown. Lower stand count may have increased seed number per pod in 2008 and 2009, a case similar to that observed for canola. In contrast, increased plant height probably increased aboveground biomass in 2009 and 2010. Kurtenbach et al. (2019) did not observe the effect of seeding rate on flax plant height. Greater seed yield than aboveground biomass increased harvest index in 2008 and 2010. Differences in sequence of crops between crop rotations and variations in tillage practices, seeding rates, methods of N fertilization and stubble heights between cultural practices had no impact on flax plant height, seed number per pod, aboveground biomass yield, and harvest index.

Flax seed weight varied with years, with significant interactions for crop rotation × year and crop rotation × cultural practice × year (Table 1). With DFDP, seed weight was 25%

greater in the traditional than the improved cultural practice in 2007, but the trend reversed by 13% in 2008 (Table 7). Seed weight was 33% greater with DDFP than DFDP in the traditional practice in 2006 and 2007 and 77% greater in the improved practice in 2007, but was 12% greater with DFDP than DDFP in the improved practice in 2008. Averaged across treatments, seed weight was greater in 2009 and 2011 than other years (Table 3).

Although variations occurred with crop rotations and between cultural practices, reduced seeding rate is probably the prominent factor for producing heavier seeds in the traditional cultural practice during the near-normal growing season precipitation in 2007. In contrast, increased soil water conservation by no-tillage is likely a major factor for increasing seed weight in the improved practice during the below-normal precipitation in 2008 in alternate-year crop rotation. Albrechtsen and Dybing (1973) and Kurtenbach et al. (2019), however, did not find the effect of seeding rate on flax seed weight. Stacked rotation and the traditional practice favored seed weight during the near-normal precipitation in 2006 and 2007. Reduced stand count (Table 3) likely produced heavier seeds in 2009 and 2011.

Flax seed yield varied with years, with significant interactions for cultural practice × year and crop rotation × cultural practice × year (Table 1). Seed yield was 38% greater in the traditional than the improved cultural practice with DDFP in 2009, but the trend reversed by 64% with DFDP in 2010 (Table 8). Seed yield was 31% greater with DFDP than DDFP in the improved practice in 2010. Averaged across treatments, seed yield was greater in 2010 than other years (Table 3).

Reduced residual effect of herbicide in stacked crop rotation and increased N mineralization due to tillage and lower competition among plants due to lower seeding rate in the traditional cultural practice probably enhanced flax seed yield during slightly above-average growing season precipitation (48 mm) in 2009 (Figure 1). In contrast, increased availability and efficient use of soil water and N in alternate-year rotation and the improved practice likely increased seed yield during excessive precipitation (176 mm) in 2010. While water stress during flowering and pod development can cause flax flower abortion and reduce seed yield (Heard & Comstock, 1980), seed yield can increase by 7.6 kg ha^{-1} per 1-mm increase in precipitation after reaching a minimum water requirement of 127 mm for flax production (Johnston et al., 2002). Albrechtsen and Dybing (1973) reported that seeding rate had no effect on flax seed yield, but Kurtenbach et al. (2019) found increased flax seed yield with increased seeding rate.

3.4 | Flax oil concentration, nitrogen uptake, and nitrogen-use efficiency

Flax oil concentration, aboveground biomass N uptake, and N harvest index differed by year, but crop rotation, cultural practice, and their interaction were not significant (Table 4). Averaged across treatments, oil concentration was greater from 2008 to 2011 than other years (Table 5). Aboveground biomass N uptake was greater in 2009 than other years. Nitrogen harvest index was greater in 2008 and 2010 than other years.

The greater flax oil concentration from 2008 to 2011 was probably a result of increased pod number per square meter, seed number per pod, and seed weight in these years when air temperature in July and August, the seed formation period, was 0.6 to 4.1°C lower than the 105-yr average (Tables 3 and 5; Figure 1). Albrechtsen and Dybing (1973) showed that flax oil content was positively correlated to pod number per square meter, seed number per pod, and seed weight. Increased aboveground biomass N uptake in 2009 was due to greater aboveground biomass yield (Table 3), but similar N concentration (21–23 g N kg^{-1}) among years. Similarly, increased N harvest index in 2008 and 2010 was due to greater N removal in seed than aboveground biomass in

TABLE 8 Interaction between crop rotation, cultural practice, and year on flax seed yield and seed N uptake

Cultural practice[a]	Flax seed yield (kg ha^{-1})		Flax seed N uptake (kg N ha^{-1})	
	DFDP[b]	DDFP[b]	DFDP	DDFP
2006				
Traditional	182	398	12	15
Improved	255	309	7	19
2007				
Traditional	362	272	6	8
Improved	125	175	17	13
2008				
Traditional	711	689	22	34
Improved	482	708	31	32
2009				
Traditional	777	888a[c]	27	37a
Improved	681	552b	32	23b
2010				
Traditional	1016b	1193	63aA	43B
Improved	1666aA[d]	1157B	39b	46
2011				
Traditional	673	581	31	27
Improved	705	619	29	26

[a]Traditional cultural practices are conventional tillage, recommended seed rate, broadcast N fertilization, and reduced stubble height; and improved cultural practices are no-tillage, increased seed rate, banded N fertilization, and increased stubble height.

[b]Crop rotations are DDFP, durum-durum-flax-pea; and DFDP, durum-flax-durum-pea.

[c]Numbers not followed by a common lowercase letter within a column in a set are significantly different at P = .05 by the least square means test.

[d]Numbers not followed by a common uppercase letter within a row in a set are significantly different at P = .05 by the least square means test.

these years. Differences in sequence of crops between crop rotations and tillage practices, seeding rates, methods of N fertilization, and stubble height between cultural practices had no effect on flax oil concentration, aboveground biomass N uptake, and N harvest index.

Flax seed N uptake varied with years, with significant interactions for cultural practice × year and crop rotation × cultural practice × year (Table 4). Seed N uptake was 38% greater in the traditional than the improved cultural practice with DDFP in 2009 and with DFDP in 2010 (Table 8). Seed N uptake was 32% greater with DFDP than DDFP in the traditional practice in 2010. Averaged across treatments, seed N uptake was greater in 2010 than other years (Table 5).

Increased seed yield increased seed N uptake in the traditional compared to the improved cultural practice with DDFP in 2009, but higher N concentration (62 vs. 53 g N kg^{-1}) in flax seed increased seed N uptake in traditional practice with DFDP in 2010 and with DFDP compared to DDFP in the traditional practice in 2010. The results showed that traditional cultural practice increased seed N uptake with stacked rotation in 2009 and 2010 with near-normal or greater growing season precipitation. Increased soil N mineralization due to conventional tillage and enhanced precipitation may have increased seed N uptake in the traditional practice with DDFP and DFDP in 2009 and 2010. Similarly, higher N concentration increased seed N uptake with DFDP than DDFP in the traditional practice.

Flax N-use efficiency and N removal index also varied with years, with significant interactions for cultural practice × year and crop rotation × cultural practice × year (Table 4). Nitrogen-use efficiency was 44–72% greater in the traditional than the improved cultural practice with DFDP in 2007 and 2008 and with DDFP in 2009, but the trend reversed by 42% with DFDP in 2010 (Table 9). Nitrogen-use efficiency was 136% greater with DDFP than DFDP in the improved practice in 2008, but was 24% greater with DFDP than DDFP in the improved practice in 2010. Nitrogen removal index was 38–64% greater in the traditional than the improved practice with DDFP in 2009 and with DFDP in 2010. Nitrogen removal index was 28% greater with DFDP than DDFP in the traditional practice in 2010. Averaged across treatments, N-use efficiency and N removal index were greater in 2010 than other years (Table 5).

Increased seed yield enhanced N-use efficiency in the traditional practice with DFDP in 2007 and 2008, with DDFP in 2009, and in the improved practice with DFDP in 2010. Similarly, increased seed yield increased N-use efficiency with DDFP in the improved practice in 2008 and with DFDP in the improved practice in 2010. Increased seed N uptake enhanced N removal index in the traditional practice with DDFP in 2009 and in the improved practice with DFDP in 2010. Although N-use efficiency varied with crop rotations and cultural practices in various years, flax seed utilized N more efficiently in alternate-year rotation and the improved practice during the above-average precipitation in 2010.

TABLE 9 Interaction between crop rotation, cultural practice, and year on flax N-use efficiency and N removal index

Cultural practice[a]	Flax N-use efficiency (kg seed kg^{-1} N)		Flax N removal index (kg N kg^{-1} N)	
	DFDP[b]	DDFP[b]	DFDP	DDFP
2006				
Traditional	0.13	0.33	3.1	6.9
Improved	0.20	0.30	4.4	5.4
2007				
Traditional	0.29a[c]	0.23	6.3	4.7
Improved	0.08b	0.13	2.2	3.0
2008				
Traditional	0.50a	0.64	12.3	11.9
Improved	0.28bB[d]	0.66A	8.3	12.4
2009				
Traditional	0.69	0.63a	13.5	15.4a
Improved	0.50	0.33b	11.8	9.6b
2010				
Traditional	0.71b	0.83	28.9 aA	20.7
Improved	1.10aA	0.77B	17.6b	20.1B
2011				
Traditional	0.50	0.43	11.7	10.1
Improved	0.53	0.50	12.2	10.7

[a]Traditional cultural practices are conventional tillage, recommended seed rate, broadcast N fertilization, and reduced stubble height; and improved cultural practices are no-tillage, increased seed rate, banded N fertilization, and increased stubble height.

[b]Crop rotations are DDFP, durum-durum-flax-pea; and DFDP, durum-flax-durum-pea.

[c]Numbers not followed by a common uppercase letter within a row in a set are significantly different at $P = .05$ by the least square means test.

[d]Numbers not followed by a common lowercase letter within a column in a set are significantly different at $P = .05$ by the least square means test.

4 | CONCLUSIONS

Cultural practice had a greater impact on canola growth, yield, and quality than crop rotation, but both cultural practice and crop rotation had similar effect on flax growth, yield, and quality under dryland cropping systems in the semiarid northern Great Plains, USA. The traditional cultural practice increased canola pod number and oil concentration in dry years, but the improved practice increased stand count, pod number, and oil concentration in wet years. Alternate-year rotation and the improved cultural practice increased flax stand count in the wet year, but stacked rotation increased stand count in the dry year. Flax pod number, seed weight, seed yield, seed N uptake, N-use efficiency, and N removal index were usually greater with stacked rotation in the traditional practice in dry years, but greater with alternate-year rotation in the improved practice in wet years. While the improved cultural practice can enhance canola growth and oil concentration, both improved practice and alternate-year crop rotation can increase flax growth, yield, and quality in years with near or above-average growing season precipitation.

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