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ARTICLE

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Diversified crop rotation and management system influence durum yield and quality

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Abstract

Diversified crop rotation, sequence of crops within a rotation, and management system may affect durum (*Triticum turgidum* L.) yield and quality. This study investigated the impact of stacked vs. alternate-year rotation and conventional vs. ecological management system on dryland durum growth, yield, quality, and N relations from 2008 to 2011 in the northern Great Plains. Stacked rotations were durum–durum–canola (*Brassica napus* L.)–pea (*Pisum sativum* L.) (DDCP) and durum–durum–flax (*Linum usitatissimum* L.)–pea (DDFP). Alternate-year rotations were durum–canola–durum–pea (DCDP) and durum–flax–durum–pea (DFDP). Continuous durum (CD) was also included for comparison. Conventional management included the combination of tillage, recommended seed rate, broadcast N fertilization, and reduced stubble height; ecological management included no-tillage, increased seed rate, banded N fertilization, and greater stubble height. Durum height was 4–7 cm taller in the ecological than the conventional management with DCDP, DDCP, and DFDP. Plant height, spike number, grain yield, aboveground biomass, N accumulation, N removal index, and N-use efficiency were 8–46% greater in the ecological than the conventional management in wet years, but were 15–26% greater in the conventional management in dry years. Plant height, spike number, aboveground biomass, and seed weight varied with crop rotations and years. The ecological management improved durum growth, yield, and N relations in wet years, but the conventional management was superior in dry year. Producers can enhance dryland durum yield and quality by using the ecological management, especially in wet years, rather than relying on crop rotations.

1 | INTRODUCTION

Durum wheat (*Triticum turgidum* L.) is the second most dominant crop after spring and winter wheat crops (*T. aestivum* L.) in dryland cropping systems in the northern Great Plains (Allen, Lenssen, Sainju, Caesar-TonThat, & Evans, 2014; Clarke et al., 1998; Lenssen et al., 2012) and

Abbreviations: CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea; DFDP, durum–flax–durum–pea; HVAC, hard vitreous amber color.

performs better than other cereal crops following summer fallow in the durum–fallow rotation in arid and semiarid regions with limited precipitation (Tanaka, Lyon, Miller, Merrill, & McConkey, 2010). While tilled durum–fallow had been the conventional dryland cropping system in this region due to limited precipitation, use of no-till systems has increased soil water conservation and precipitation-use efficiency (Tanaka et al., 2010). The improved soil water conservation of these systems has allowed adoption of continuous cropping systems that largely eliminated summer fallow and enhanced annualized crop yields and producers' net income (Zentner et al., 2002). Recent U.S. agricultural census data suggests that the area under the no-till system increased by 73% from 2012 to 2017, with 7.0 million ha under no-till management in 2017 in Montana (USDA, 2019). Reduced soil and environmental quality, increased cost of inputs, and decreased economic return in crop–fallow and monocropping systems also led to increased diversification of dryland cropping systems in this region (Gan et al., 2003). Diversified crop rotations including pulses and oilseed crops have increased crop yields compared to monocropping and crop–fallow systems due to more efficient use of water and N (Gan et al., 2003; Miller & Holmes, 2005). Other benefits of diversified crop rotations include reduced N fertilization rate and N leaching, enhanced soil fertility, improved weed and pest control (Fernandez, Zentner, McConkey, & Campbell, 1998; Miller & Holmes, 2005), and reduced soil erosion potential (Feng, Sharratt, & Young, 2011).

The sequence and type of crops in diversified crop rotations can affect durum yield and quality by influencing soil water and nutrients. Miller and Holmes (2005) observed that durum grain yield and N accumulation were 15–19% greater following flax (*Linum usitatissimum* L.) and 19–24% greater following pea (*Pisum sativum* L.) than following spring wheat in years with normal or above-average precipitation. Gan et al. (2003) reported that durum grain yield and protein concentration increased by 7 and 11%, respectively, following pulses compared to following spring wheat due to increased soil available water and N. Following oilseed crops, grain yield and protein concentration increased by 5 and 6%, respectively. They also found that grain yield and protein concentration further increased following two consecutive years of pulses and oilseed crops. Allen et al. (2014) found that durum yield was greater following canola (*Brassica juncea* L.) quality than following crambe (*Crambe abyssinica* Hochst. ex. R.E. Fries) or camelina (*Camelina sativa* L. Crantz). Similarly, N accumulation (a quality parameter) in durum grain was greater following canola than following wheat, as the long taproot of canola redistributed soil N from deeper layers to the surface (Kirkegaard, Howe, & Mede, 1999). The patterns of durum yield and N accumulation

Core Ideas

- The effect of crop rotation and management system was examined on durum yield and quality.
- Durum growth, yield, and quality varied with crop rotations and climatic conditions.
- Conventional management was superior for durum yield and quality in dry conditions.
- Ecological management enhanced durum growth, yield, and quality in wet conditions.

following crop types, however, depend on the amount and timing of precipitation. In years with below-average precipitation, durum grain yield and N accumulation were greater following spring wheat than following flax and pea (Miller & Holmes, 2005). Stacked rotations, where the same crop or crop type is grown consecutively for two or more years in rotation before planting another crop type, may reduce pest and weed infestations compared to alternate-year rotations (Garrison, Miller, Ryan, Roxburgh, & Shea, 2014; Nichols, Verhulst, Cox, & Govaerts, 2015).

Management practices, such as tillage system, seeding rate, method of fertilizer application, and stubble height, can affect durum and spring wheat yield and quality in the northern Great Plains (Lenssen, Sainju, Iversen, Allen, & Evans, 2014, 2018). At 120 kg N ha^{-1}, durum yielded less with no-tillage than conventional tillage during dry years, but the trend reversed during wet years in Italy (Amato et al., 2013). Mazzoncini et al. (2008) reported that no-tillage reduced durum grain yield compared to conventional tillage in Italy. Increased seeding rate increased durum grain yield due to early canopy development and enhanced water-use efficiency by reducing weed infestation, but reduced protein concentration and seed weight in the west Canadian Prairies (Isidro-Sanchez et al., 2017). Lower soil available N due to no-tillage also resulted in lower durum grain protein concentration than conventional tillage at constant N fertilization rate of 120 kg N ha^{-1} (Amato et al., 2013). Availability of N from banded N fertilization was greater to crops than weeds compared to broadcast fertilization, which resulted in decreased light penetration between rows due to earlier canopy closure (Strydhorst, King, Lopetinsky, & Harker, 2008). Greater stubble height increased soil water storage through increased snow capture during winter and decreased evaporation (Entz et al., 2002).

Studies on the effect of stacked vs. alternate-year crop rotation and management system on durum yield and quality are limited. We evaluated stacked and alternate-year crop rotations, monocropping, and two management systems (combination of tillage, seeding rate, method of

TABLE 1 Description of management systems (conventional and ecological) used for crops across rotations

Crop	Cultural practice	Tillage	Seed rate	Available N at planting[a]	N fertilization method	P fertilization rate	K fertilization rate	Durum stubble height
			kg ha^{-1}	kg N ha^{-1}		kg P ha^{-1}	kg K ha^{-1}	cm
Durum	Conventional	Tilled	1,008,000[b]	127	Broadcast	29	27	19
	Ecological	No-till	1,344,000[b]	127	Banded	29	27	33
Pea	Conventional	Tilled	600,000[b]	6[c]	Broadcast	29	27	19
	Ecological	No-till	920,000[b]	6[c]	Banded	29	27	33
Canola	Conventional	Tilled	6	94	Broadcast	29	27	19
	Ecological	No-till	9	94	Banded	29	27	33
Flax	Conventional	Tilled	34	58	Broadcast	29	27	19
	Ecological	No-till	50	58	Banded	29	27	33

[a]Available N from the sum of residual soil NO_3–N (0–60-cm depth) plus fertilizer N.

[b]Number of pure live seeds ha^{-1}.

[c]Fertilizer N from monoammonium phosphate applied at planting.

N fertilization, and stubble height) on durum yield and quality from 2005 to 2011 in the northern Great Plains. Our objectives were to: (a) examine how diversified crop rotations and management systems impact durum growth, yield, quality, and N-use efficiency; and (b) determine which crop rotation and management system enhance durum yield and quality under dryland cropping systems in the semiarid northern Great Plains.

2 | MATERIALS AND METHODS

From 2005 to 2011, a study comparing diversified dryland crop rotations and management systems on durum yield and quality was conducted in a Williams loam (fine-loamy, mixed, superactive, frigid, Typic Argiustoll) soil near Culbertson, MT. Sainju, Lenssen, Allen, Stevens, and Jabro (2016, 2017) provided detailed descriptions of soil properties, site, and climate. Crop rotations consisted of two stacked (durum–durum–canola–pea [DDCP] and durum–durum–flax–pea [DDFP]), two alternate-year (durum–canola–durum–pea [DCDP] and durum–flax–durum–pea [DFDP]) rotations, and a monocrop (continuous durum [CD]). Crop rotations had all crop phases present in three replications each year. Management systems were "conventional" (a combination of single-pass, pre-plant tillage with a field cultivator [John Deere, Model no. 2230] to a depth of 10 cm in late April, recommended seeding rate, broadcast N fertilization, and low [19 cm] stubble height) and "ecological" (a combination of no-tillage, increased seeding rate, banded N fertilization, and high [33 cm] stubble height) systems (Table 1). A low disturbance no-till drill (John Deere) planted durum (cultivar Mountrail) at a 20-cm row spacing to a depth of 2.5 cm in late April of each year. Nitrogen fertilizer was banded using the no-till drill in the ecological system and broadcast using a spreader (Grainger) in the conventional system at planting in late April. The height of durum stubble was maintained using a combine harvester at grain harvest in the conventional and ecological systems. For pea, canola, and flax, these treatments also varied by management systems (Table 1). Durum received N fertilizer at 127 kg N ha^{-1} from urea (46% N) and monoammomium phosphate (11% N, 26% P), P fertilizer at 29 kg P ha^{-1} from monoammonium phosphate, and K fertilizer at 27 kg K ha^{-1} from muriate of potash (52% K) for all treatments at planting. The N fertilization rate was adjusted for residual soil NO_3–N content to a depth of 60 cm determined for samples collected in the autumn of previous years in all crop rotations and also for pea residue N contribution of 9 kg N ha^{-1} (based on unreported data) in DCDP, DDCP, DFDP, and DDFP. As a result, the actual amount of N fertilizer applied to durum varied from 6 kg N ha^{-1} in 2008 to 105 kg N ha^{-1} in 2005 in CD. Phosphorus and K fertilizers were applied at recommended rates without adjusting for residual soil P and K levels. Pre-plant weeds in all treatments were controlled by applying glyphosate [*N*-(phosphonomethyl)glycine] at 3.36 kg a.i. ha^{-1} in 38 L ha^{-1} water in the spring. The experimental design included split-plot arrangement of the management system as the main-plot and crop rotation as the split-plot factor in a randomized complete block with three replications. The size of the split plot was 12.2 by 36.6 m.

Stand density was determined by counting plants from four 1-m row segments randomly within a plot in late May every year. Ten random plants plot^{-1} were measured to determine plant height prior to harvest. Spike number was measured from a random 1-m row segment in each plot, after which seed number spike^{-1} was determined from 10 randomly selected spikes. Harvested plants from two randomly selected 0.5 m^2 areas within each plot were oven dried at 60 °C for 7 d and weighed to determine aboveground crop biomass. A plot combine (9600 John Deere) harvested grain in August in all durum plots in each year. Grain yield was determined on an oven-dried basis (at 60 °C for 7 d) from an area of 50 m^2. Grain samples were cleaned and weighed. Seed weight was determined by weighing 100 grains. Test weight was determined by weighing grains filled in a 0.95 L container. The hard vitreous amber color (HVAC) of durum grain was measured using near-infrared spectroscopy (Dowell, 2000). Harvest index was calculated by dividing grain yield by aboveground biomass. A commercial combine harvested remaining durum within each plot and crop residue was returned to the soil. Sainju et al. (2016)) previously described management of pea, flax, and canola for this study.

Samples of durum grain and aboveground biomass were ground to 1 mm in a Wiley mill (Thomas Scientific) to measure N concentration using a C and N analyzer (LECO, Model no. 628). Grain and aboveground biomass N accumulation were calculated by multiplying yields by N concentrations. Nitrogen harvest index was determined by dividing grain N accumulation by aboveground biomass N accumulation. Crude protein concentration was calculated by multiplying grain N concentration by 5.7 (Pomeranz, 1987). Nitrogen-use efficiency was determined by dividing grain yield by N fertilization rate that included both fertilizer and soil residual N. Similarly, N removal index was calculated by dividing grain N accumulation by N fertilization rate that included both fertilizer and soil residual N. Because stacked and alternate-year crop rotations contained two phases of durum in each year and both phases of durum produced identical results; durum growth, yield, and N accumulation for each rotation in a year were determined by averaging data for all parameters of two durum phases within the rotation. Pre-plant soil water content at the 0- to 120-cm depth was determined using a calibrated neutron attenuation probe (Chanasyk & Naeth, 1996).

A linear mixed model ANOVA using the MIXED procedure of SAS (version 9.0) analyzed data for all parameters for a split-plot design where the main-plot treatment was the management system and the split-plot treatment was crop rotation (Littell, Milliken, Stroup, Wolfinger, & Schabenberger, 2006) after checking for normal distribution of residuals and homoscedasticity using the method as shown by Littell et al. (1991). Fixed effects were management system, crop rotation, year, and their interactions and random effects were replication and replication × management system interaction. When significant at $P = .05$, the least square means test (LSMEANS) separated treatment means and interactions (Littell et al., 2006). Because 2005 was the establishment year of crops, data for this year were not included for statistical analysis. Similarly, because of the different dates of seeding in conventional and ecological management systems in 2006 and in-season wind drift herbicidal damage of durum in 2007, data for 2006 and 2007 also were not used for statistical analysis.

3 | RESULTS AND DISCUSSION

3.1 | Air temperature and precipitation

At the experimental site, monthly average air temperature from July to August was greater in 2006 and 2007 than the 30-yr average (Table 2). From 2008 to 2011, the average air temperature from May to August was lower than the 30-yr average. Monthly total precipitation in May 2007, 2010, and 2010 and July and August 2009 and 2010 were greater than the 30-yr average. In contrast, precipitation from June to August 2007 and 2008 was below the 30-yr average. Growing season precipitation (April–September) accounted for 81% of the total annual precipitation and was lower in 2007 and 2008 than other years and the 30-yr average.

3.2 | Durum growth and aboveground biomass

Durum stand density differed for crop rotations, management systems, and years, with significant interactions for crop rotation × management system, crop rotation × year, management system × year, and crop rotation × management system × year (Table 3). The ecological management system increased stand density by 60% compared to the conventional system with DDFP in 2009 and by 45% with DDCP in 2010 (Table 4). Averaged across cultural practices and years, stand density was 21–41% greater with DCDP than other crop rotations (Table 5). Averaged across crop rotations and years, stand density was 37% greater in the ecological than the conventional system. Averaged across treatments, stand density was greater in 2009 than other years.

By design, the greater seeding rate (Table 1) increased stand density in the ecological system. Stacked rotation of durum with canola and pea was more effective in increasing stand density than alternate-year rotation with same crops or stacked and alternate-year rotations of durum with flax and pea (Table 5). Regardless of differences among rotations, management systems, years, and their interactions, stand density of all crops were considered suitable for dryland production in the semiarid northern Great Plains (Lenssen et al., 2012; Miller & Holmes, 2005).

Plant height varied by year, with significant interactions for crop rotation × management system, crop rotation ×

TABLE 2 Monthly average air temperature and total precipitation from 2006 to 2011 at the experimental site

Month	2006	2007	2008	2009	2010	2011	30-yr avg.
Air temperature, °C							
Apr.	8.9	5.6	4.9	4.8	7.2	3.6	7.5
May	13.7	13.0	11.6	11.1	9.8	10.1	13.4
June	18.2	18.6	15.4	15.8	16.6	15.8	18.2
July	24.1	24.7	21.0	17.7	19.1	20.8	21.8
Aug.	21.3	20.3	20.6	17.7	18.7	19.8	21.2
Sept.	12.0	11.8	12.7	16.7	12.0	14.5	14.7
Total precipitation, mm							
Apr.	80	21	12	53	33	35	25
May	44	128	43	24	118	172	52
June	55	49	58	27	69	71	76
July	30	21	29	100	125	42	54
Aug.	36	8	21	96	83	25	36
Sept.	67	19	62	23	23	17	32
Apr.–Sept.	311	245	225	323	451	362	275
Jan.–Dec.	339	283	336	406	522	397	343

year, and management system × year (Table 3). When averaged across years, durum was 4–7 cm taller in the ecological than the conventional system with DCDP, DDCP, and DFDP (Table 6). Durum was also 5–6 cm taller with DDFP than DCDP and DDCP in the conventional system and 5 cm taller with DFDP than DDFP in the ecological system. When averaged across management systems, durum was 7–8 cm taller with CD than other crop rotations in 2008 and 5 cm taller with DDCP than DCDP in 2011, but was 5–9 cm shorter with CD than other crop rotations in 2010 (Table 7). When averaged across crop rotations, durum was 5–7 cm taller in the ecological than the conventional system in 2010 and 2011 (Table 8). When averaged across treatments, durum was 17–29 cm taller in 2010 than other years (Table 5).

Increased soil water and N availability due to a combination of no-tillage, higher seeding rate, banded N fertilization, and taller stubble may have enhanced durum height in the ecological management system with DCDP, DDCP, and DFDP. It is likely that increased soil water conservation due to no-tillage and taller stubble, followed by enhanced soil N availability from banded N fertilization increased durum height in the ecological management system with these crop rotations. It is known that no-tillage can conserve soil water relative to conventional tillage, which results in increased dryland crop performance (Lafond, May, Stevenson, & Derksen, 2006; Ruisi et al., 2012). Similarly, tall stubble can conserve soil water by increasing snow accumulation and enhance crop yield compared to short stubble (Entz et al., 2002; Strydhorst et al., 2008). Increased water- and N-use efficiency and decreased weed competition due to higher seeding rate and banded N fertilization is well demonstrated (Isidro-Sanchez et al., 2017, Nichols et al., 2015). Alternate-year rotation of durum with flax was more effective in increasing plant height than rotation of durum with canola in the ecological management system, likely a result of increased soil water availability for durum due to lower biomass of flax than canola and shallow rooting depth of flax. Soil water content at planting was greater with DFDP than DCDP (Table 9). Aboveground biomass of canola across treatments and years averaged 4814 kg ha^{-1} compared to 2887 kg ha^{-1} for flax in this experiment, probably due to increased soil water uptake from enhanced root growth (Nielsen & Vigil, 2018). The impact of the ecological management system in increasing durum height was more pronounced in wet (2010 and 2011) than dry (2008) years probably due to greater soil water content and reduced evaporation, as pre-plant soil water content was greater in the ecological than conventional management in 2010 and 2011 ((Table 9). In contrast, stacked rotation of durum with flax increased durum height more in the conventional than the ecological management system. Monocropping enhanced durum height during the dry year in 2008, but reduced height during the wet year in 2010 compared to other crop rotations. The increased durum height with CD in 2008 was probably due to increased residual soil water availability from 2007 when durum suffered damage from herbicide application, as soil water content was greater with CD than DDCP and DDFP (Table 9). Increased water availability due to enhanced precipitation (Table 2) certainly increased durum height in 2010.

Crop rotation, year, and interactions for crop rotation × year and management system × year all significantly

TABLE 3 Analysis of variance for durum growth, seed characteristics, and yield with crop rotation (R), management system (M), and year (Yr) as sources of variance

Source	Stand density	Spike no.	Plant height	Seed no.	Seed weight	Test weight	Grain yield	Aboveground biomass	Harvest index	HVAC
	no. m^{-2}		cm	no. $spike^{-1}$	mg $seed^{-1}$	kg m^{-3}	kg ha^{-1}		kg kg^{-1}	g kg^{-1}
	P-values									
R	.004	.263	.560	.002	.825	.639	.411	.050	.082	.304
M	.033	.062	.199	.124	.363	.781	.086	.475	.945	.018
R × M	.014	.781	.009	.630	.297	.501	.158	.131	.456	.179
Yr	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
R × Yr	<.001	.019	.022	.711	.046	.295	.236	.032	.888	.668
M × Yr	.036	.015	<.001	.004	.958	.814	<.001	.012	.066	.321
R × M × Yr	.044	.202	.679	.251	.718	.708	.621	.740	.985	.691

Note. HVAC = hard vitreous amber color.

influenced aboveground biomass (Table 3). Biomass, averaged across management systems, was 1338 to 1892 kg ha^{-1} greater with DDFP than other crop rotations in 2011 (Table 7). Averaged across crop rotations, biomass was 990 kg ha^{-1} greater in the ecological than the conventional management system in 2011 (Table 8). Averaged across years and management systems, biomass was 394–534 kg ha^{-1} greater with DDFP than DCDP, DDCP, and DFDP (Table 5). Averaged across treatments, biomass was greater in 2010 than other years.

Miller and Holmes (2005) reported that durum biomass was greater following flax than following spring wheat in years with normal or above-average precipitation due to increased available soil water and residual N. The lower aboveground biomass of flax than canola may have increased available soil water and N for succeeding durum following flax compared to following canola probably due to reduced water uptake, thereby increasing biomass with DDFP compared to DCDP, DDCP, and DFDP. The ecological management system increased durum aboveground biomass in 2011 when the growing season precipitation was 87 mm above the average (Table 2), likely due to increased soil water availability.

3.3 | Durum seed characteristics and grain yield

Spike number varied by year, with significant interactions for crop rotation × year and management system × year (Table 3). Averaged across management systems, spike number was 24% greater with DCDP than DDCP in 2010 and 12–76% greater with DDFP than other crop rotations in 2011 (Table 7). Averaged across crop rotations, spike number was 23–27% greater with the ecological than the conventional system from 2009 to 2011 (Table 8). Averaged across treatments, spike number was greater in 2010 than other years (Table 5).

The greater spike number with DCDP in 2010 suggests that canola favored durum spike number in the alternate-year rotation in the wet year. In contrast, the greater spike number with DDFP in 2011 indicates that flax enhanced spike number in the stacked rotation in another wet year. Growing season (April–September) precipitation was 428 mm in 2010 and 345 mm in 2011, which were 39–226 mm greater than the precipitation received in 2008, 2009, and the 30-yr average (Table 2). Increased soil water availability due to enhanced precipitation and N availability due to N mineralization (Sainju, Lenssen, Allen, Stevens, & Jabro, 2017) may have increased spike number with DCDP and DDFP in 2010 and 2011.

Seed number $spike^{-1}$ differed by crop rotation and year, with a significant management system × year interaction

TABLE 4 Interaction between crop rotation, management system, and year on durum stand density

Management system[a]	Crop rotation CD	DCDP	DDCP	DFDP	DDFP
	Stand density, no. m^{-2}				
2008					
Conventional	88	89	95	89	91
Ecological	104	125	107	128	129
2009					
Conventional	92	96	96	98	80b[b]
Ecological	122	129	126	125	128a
2010					
Conventional	80	88	88b	84	88
Ecological	92	116	128a	120	121
2011					
Conventional	79	88	85	67	86
Ecological	113	129	123	125	73

Note. Crop rotations are CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea, and DFDP, durum–flax–durum–pea.
[a]Conventional management system is a combination of tillage, recommended seeding rate, broadcast N fertilization, and reduced stubble height; and ecological management system is a combination of no-tillage, increased seeding rate, banded N fertilization, and increased stubble height.
[b]Numbers followed by different lowercase letters within a column in a set are significantly different at $P = .05$ by the least square means test.

TABLE 5 Durum growth, seed characteristics, and yield as affected by crop rotation, management system, and year

Treatment	Stand density	Spike no.	Plant height	Seed no.	Seed weight	Test weight	HVAC	Grain yield	Above-ground biomass	Harvest index
	no. m^{-2}		cm	no. spike^{-1}	mg seed^{-1}	kg m^{-3}	g kg^{-1}	kg ha^{-1}		
Crop rotation										
CD	80c[a]	307	62	31a	38	763	848	2072	3607ab	0.40
DCDP	100b	315	61	28b	38	764	816	2032	3430b	0.40
DDCP	127a	310	62	28b	37	765	832	2059	3290b	0.41
DFDP	102b	309	62	29ab	38	767	822	2128	3335b	0.42
DDFP	105b	335	63	29ab	38	764	819	2219	3824a	0.38
Management system[b]										
Conventional	89b	288	60	30	37	765	817b	1972	3389	0.40
Ecological	122a	342	63	28	38	764	838a	2231	3605	0.40
Year										
2008	110b	305b	54c	25b	28b	732c	794c	1597c	2503c	0.39b
2009	128a	308b	51c	27b	47a	785a	769d	2392a	3045b	0.45a
2010	116b	396a	80a	32a	36a	756 b	830 b	2498a	5142a	0.35b
2011	88c	252c	63b	31a	40a	785a	918a	1921b	3300b	0.43a

Note. HVAC = Hard vitreous amber color. Crop rotations are CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea; DFDP, durum–flax–durum–pea.
[a]Numbers followed by different letters within a column in a set are significantly different at $P = .05$ by the least square means test.
[b]Conventional management system is a combination of tillage, recommended seeding rate, broadcast N fertilization, and reduced stubble height; and ecological management system is a combination of no-tillage, increased seeding rate, banded N fertilization, and increased stubble height.

(Table 3). Seed number, averaged across crop rotations, was 13% greater with the conventional than the ecological system in 2008 (Table 8). Averaged across management systems and years, seed number was 11% greater with CD than DCDP and DDCP (Table 7). Averaged across treatments, seed number was greater in 2010 and 2011 than other years (Table 5).

Reduced seeding rate along with other management practices enhanced seed number spike^{-1} in the conventional management system during the dry year in 2008.

TABLE 6 Interaction between crop rotation and management system on durum plant height

Management system[a]	Crop rotation CD	DCDP	DDCP	DFDP	DDFP
	Plant height, cm				
Conventional	61AB[b]	59b[c]B	58bB	60bAB	64A
Ecological	63AB	63aAB	65aAB	66aA	61B

Note. Crop rotations are CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea, and DFDP, durum–flax–durum–pea.

[a]Conventional management system is a combination of tillage, recommended seeding rate, broadcast N fertilization, and reduced stubble height; and ecological management system is a combination of no-tillage, increased seeding rate, banded N fertilization, and increased stubble height.

[b]Numbers followed by different uppercase letters within a row in a set are significantly different at $P = .05$ by the least square means test.

[c]Numbers followed by different lowercase letters within a column in a set are significantly different at $P = .05$ by the least square means test.

TABLE 7 Interaction between crop rotation and year on durum plant height, spike number, aboveground biomass, and seed weight

Crop rotation	Year 2008	2009	2010	2011
Plant height, cm				
CD	60a[a]	51	74b	62ab
DCDP	52b	51	80a	60b
DDCP	53b	50	79a	65a
DFDP	53b	52	82a	64ab
DDFP	53b	50	83a	63ab
Spike number, no. m^{-2}				
CD	311	321	381ab	214b
DCDP	284	318	428a	229b
DDCP	315	307	344b	273b
DFDP	295	287	418ab	239b
DDFP	322	306	406ab	306a
Aboveground biomass, kg ha^{-1}				
CD	2944	2933	5532	3019b
DCDP	2500	3113	5422	2684b
DDCP	2435	2969	4716	3039b
DFDP	2186	3127	4789	3238b
DDFP	2448	3082	5249	4576a
Seed weight, mg $seed^{-1}$				
CD	28ab	47	38a	38c
DCDP	29a	48	34b	40bc
DDCP	26b	48	36ab	41ab
DFDP	29a	46	35b	43a
DDFP	29a	47	35b	40bc

Note. Crop rotations are CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea, and DFDP, durum–flax–durum–pea.

[a]Numbers followed by different letters within a column in a set are significantly different at $P = .05$ by the least square means test.

Growing season precipitation was 225 mm in 2008, which was 50 mm lower than the 275 mm received over the 30-yr average (Table 2). Increased distribution of carbohydrate to grain compared to vegetative growth appeared to increase seed number in the conventional system during the dry year, probably a result of stress. Seed number also increased with monocropping compared to stacked and alternate-year rotations of durum with canola and

TABLE 8 Interaction between management system and year on durum spike number, plant height, seed number, grain yield, aboveground biomass, biomass N accumulation, grain N accumulation, N removal index, and N-use efficiency

	Year			
Management system[a]	**2008**	**2009**	**2010**	**2011**
Spike number, no. m^{-2}				
Conventional	303	274b[b]	354b	222b
Ecological	308	342a	437a	282a
Plant height, cm				
Conventional	56	50	76b	60b
Ecological	53	52	83a	65a
Seed number, no. $spike^{-1}$				
Conventional	27a	28	33	30
Ecological	24b	26	31	32
Grain yield, kg ha^{-1}				
Conventional	1759	2247	2268b	1614b
Ecological	1436	2535	2726a	2229a
Aboveground biomass, kg ha^{-1}				
Conventional	2530	3012	5209	2804b
Ecological	2475	3077	5074	3794a
Aboveground biomass N accumulation, kg N ha^{-1}				
Conventional	128a	140	118b	126
Ecological	95b	143	144a	139
Grain N accumulation, kg N ha^{-1}				
Conventional	52a	63b	63b	46b
Ecological	44b	71a	78a	65a
N removal index, kg N kg^{-1} N				
Conventional	0.39	0.49	0.52	0.35b
Ecological	0.33	0.54	0.59	0.51a
N-use efficiency, kg grain kg^{1} N				
Conventional	13.8a	17.7b	17.8b	12.7b
Ecological	11.3b	19.9a	21.4a	17.5a

[a]Conventional management system is a combination of tillage, recommended seeding rate, broadcast N fertilization, and reduced stubble height; and ecological management system is a combination of no-tillage, increased seeding rate, banded N fertilization, and increased stubble height.
[b]Numbers followed by different letters within a column in a set are significantly different at $P = .05$ by the least square means test.

pea. However, as with other growth parameters, increased growing season precipitation increased seed number during wet years.

Seed weight varied by year, with a significant crop rotation × year interaction (Table 3). Averaged across management systems, durum seed was 3 mg heavier with DCDP, DFDP, and DDFP than DDCP in 2008, but was 3–4 mg heavier with CD than DCDP, DFDP, and DDFP in 2010 (Table 7). In 2011, durum seed was 3–5 mg heavier with DFDP than CD, DCDP, and DDFP. Averaged across treatments, seed weight was greater from 2009 to 2011 than 2008 (Table 5). The greater soil water availability during grain fill, however, likely produced heavier seeds during above-average precipitation from 2009 to 2011. Growing season precipitation was 98–226 mm greater from 2009 to 2011 than 2008 and the 30-yr average (Table 2). Terminal drought and high temperature stress can reduce durum kernel weight (Shah & Paulsen, 2003).

Durum grain yield varied by year, with a significant management system × year interaction (Table 3). Averaged across crop rotations, grain yield was 458–615 kg ha^{-1} greater in the ecological than the conventional management system in 2010 and 2011 (Table 8). Averaged across treatments, grain yield was 471–901 kg ha^{-1} greater in 2009 and 2010 than other years (Table 5).

The greater spike number and plant height due to increased soil water and N availability from higher seeding rate, no-tillage, banded N fertilization, and taller stubble likely led to greater durum grain yield in the ecological management system in 2010 and 2011 when the growing season precipitation was above the long-term average (Table 2). Our results are dissimilar to those reported by

TABLE 9 Pre-plant soil water content (0–120-cm depth) under durum as affected by crop rotation, management system, and year

Year	Management system[a]	Crop rotation	Pre-plant soil water content
			mm
2008	Conventional		102c[b]
	Ecological		94c
2009	Conventional		97c
	Ecological		108bc
2010	Conventional		146a
	Ecological		158a
2011	Conventional		100c
	Ecological		120b
		CD	151ab
		DCDP	148b
		DDCP	135c
		DFDP	159a
		DDFP	112d
Significance			*P*-value
Crop rotation (R)			<.001
Cultural practice (C)			.119
R × C			.194
Year (Yr)			<.001
R × Yr			.941
C × Yr			.044
R × C × Yr			.998

Note. Crop rotations are CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea; DFDP, durum–flax–durum–pea.

[a]Conventional management system is a combination of tillage, recommended seeding rate, broadcast N fertilization, and reduced stubble height; and ecological management system is a combination of no-tillage, increased seeding rate, banded N fertilization, and increased stubble height.

[b]Numbers followed by different letters within a column in a set are significantly different at $P = .05$ by the least square means test.

Amato et al. (2013) who found that durum had greater grain yield with no-tillage than conventional tillage during dry years, but the trend reversed in wet years. Mazzoncini et al. (2008), however, reported lower durum grain yield with no-tillage than conventional tillage under Mediterranean climatic conditions in Italy. The lower grain yield in 2008 was probably due to reduced soil water available due to decreased growing precipitation, as growing season precipitation was 83 mm lower in 2008 than the 30-yr average (Table 2). Reduced photosynthesis and kernel weight by reducing carbohydrate deposition during the later stages of grain filling during dry period can reduce durum grain yield (Shah & Paulsen, 2003).

Harvest index varied by year (Table 3). Averaged across treatments, harvest index was greater in 2009 and 2011 than other years (Table 5). The greater grain yield than aboveground biomass increased harvest index in 2009 and 2011 when the growing season precipitation was 4–87 mm above the 30-yr average (Table 2).

Durum test weight varied by year, but treatments and their interactions were not significant (Table 3). Test weight was greater in 2009 and 2011 than other years (Table 5). The dry growing season, 2008, had lower test weight than other years, slightly below that preferred by the milling industry (Donnelly & Ponte, Jr., 2000).

The HVAC differed for management systems and years (Table 3). The ecological management system produced seeds with greater HVAC than did the conventional system (Table 5). The HVAC was greater in 2011 and lower in 2009 than other years. The grade of durum grain is highly important in establishing its economic value (Dowell, 2000). In this study, all treatments and years surpassed the required HVAC minimum of 750 g kg^{-1} required for the highest grade, hard amber durum (Donnelly & Ponte, Jr., 2000).

3.4 | Durum nitrogen accumulation, grain protein concentration, and nitrogen-use efficiency

Durum aboveground biomass N accumulation varied by year, with a significant management system × year

TABLE 10 Analysis of variance for durum grain and aboveground biomass N accumulation, N harvest index, N removal index, grain crude protein concentration, and N-use efficiency with crop rotation (R), management system (M), and year (Yr) as sources of variance

Source	Grain N accumulation	Aboveground biomass N accumulation	N harvest index	N removal index	Crude protein concentration	N-use efficiency
	kg N ha^{-1}		kg N kg^{-1} N		g kg^{-1}	kg grain kg^{-1} N
P-values						
R	.482	.645	.727	.636	.377	.410
M	.080	.667	.121	.227	.156	.086
R × M	.205	.230	.549	.221	.390	.158
Yr	<.001	<.001	<.001	<.001	<.001	<.001
R × Yr	.101	.406	.361	.381	.861	.232
M × Yr	<.001	<.001	.225	<.001	.223	<.001
R × M × Yr	.951	.305	.594	.650	.774	.919

TABLE 11 Durum grain and aboveground biomass N accumulation, N harvest index, N removal index, grain crude protein concentration, and N-use efficiency as affected by year

Year	Grain N accumulation	Aboveground biomass N accumulation	N harvest index	N removal index	Crude protein concentration	N-use efficiency
	kg N ha^{-1}		kg N kg^{-1} N		g kg^{-1}	kg grain kg^{-1} N
2008	48b[a]	111b	0.43b	0.36c	175b	12.6c
2009	67a	142a	0.47ab	0.51a	159c	18.9a
2010	70a	131a	0.53a	0.56a	160c	19.6a
2011	56b	132a	0.43b	0.43b	165c	15.1b

[a]Numbers followed by different letters within a column are significantly different at $P = .05$ by the least square means test.

interaction (Table 10). Averaged across crop rotations, biomass N accumulation was 33 kg N ha^{-1} greater in the conventional than the ecological management system in 2008, but was 26 kg N ha^{-1} greater in the ecological than the conventional system in 2010 (Table 7). Averaged across treatments, biomass N accumulation was lower in 2008 than other years (Table 11).

Differences in aboveground biomass and N concentration between management systems affected biomass N accumulation in 2008 and 2010. Increased aboveground biomass and N concentration (50 vs. 38 g N kg^{-1}) increased biomass N accumulation in the conventional than the ecological management system in 2008 when the growing season precipitation was below the 30-yr average (Table 2). This is because aboveground biomass N is calculated as the product of aboveground biomass and N concentration. Similarly, increased N concentration (28 vs. 23 g N kg^{-1}) increased biomass N accumulation in the ecological than the conventional system in 2010 when the growing season precipitation was above the average. Increased biomass yield and N concentration also increased biomass N accumulation from 2009 to 2011 than other years.

Crude protein concentration in durum grain varied by year, but treatments and interactions were not significant (Table 10). Crude protein concentration was 11–17 g kg^{-1} greater in 2008 than other years (Table 11). Reduced grain yield (Table 11) due to below-average precipitation likely increased crude protein concentration in 2008, as grain yield and protein concentration in durum are negatively correlated (Amato et al., 2013; Gan et al., 2003; Isidro-Sanchez et al., 2017; Lenssen et al., 2012).

Grain N accumulation varied by year, with a significant interaction for management system × year (Table 10). Grain N accumulation, averaged across crop rotations, was 8 kg N ha^{-1} greater in the conventional than the ecological management system in 2008, but was 8–19 kg N ha^{-1} greater in the ecological than the conventional system from 2009 to 2011 (Table 7). Averaged across treatments, grain N accumulation was 11–22 kg N ha^{-1} greater in 2009 and 2010 than other years (Table 11).

As N concentration (29–30 g N kg^{-1}) in durum grain did not differ among treatments, increased grain yield also increased grain N accumulation in the conventional system in 2008 and in the ecological system from 2009 to 2011. Increased soil water and N availability due to no-tillage, banded N fertilization, and greater stubble height along with increased seeding rate enhanced grain N accumulation from increased yield in the ecological system during wet years from 2009 to 2011, but the conventional system had improved N accumulation in the dry year, 2008.

Nitrogen harvest index varied by year, with nonsignificant treatments and interactions (Table 10). Averaged across treatments, N harvest index was greater in 2010 than 2008 and 2011 (Table 11). More N removal in grain than aboveground biomass increased N harvest index in 2010 when the growing season precipitation was above the average, a trend similar to that observed for grain N accumulation.

Nitrogen-use efficiency and N removal index varied by year, with a significant management system × year interaction (Table 10). Averaged across crop rotations, N-use efficiency was greater in the conventional than the ecological management system in 2008, but was greater in the ecological than the conventional system from 2009 to 2011 (Table 7). Nitrogen removal index was greater in the ecological than the conventional system in 2011. Averaged across treatments, N-use efficiency and N removal index were greater in 2009 and 2010 than other years (Table 11). Increased grain yield per unit total available N likely increased N-use efficiency in the conventional system in 2008 and the ecological system from 2009 to 2011. Similarly, increased N accumulation may have increased N removal index in the ecological system in 2011. The results document that durum used N more efficiently under conventional system in the dry year while the ecological system improved N-use efficiency and N removal index in wet years. Increased N mineralization due to conventional tillage and reduced competition between plants due to lower seeding rate for N uptake may have increased durum N-use efficiency in the conventional system in the dry year. In contrast, increased N mineralization due to enhanced soil water availability and increased N availability due to banded N fertilization may have increased N-use efficiency in the ecological system in wet years.

4 | CONCLUSIONS

Crop rotation and the management system had variable effect on durum stand density. The ecological management system increased plant height compared to the conventional system in DCDP, DDCP, and DFDP. Spike number, aboveground biomass, and seed weight varied by crop rotation and year. Spike number, plant height, grain yield, aboveground biomass, grain N accumulation, N removal index, and N-use efficiency were greater in the ecological than the conventional management system in wet years, but were greater in the conventional system in the dry year. Durum HVAC was greater in the ecological than the conventional system. Test weight, harvest index, and N harvest index were greater in wet years, but grain crude protein concentration was greater in the dry year. Crop rotation had little influence on these parameters. Although durum performance varied among crop rotations and years, the ecological management system consistently improved durum growth, yield, N accumulation, and N-use efficiency compared to the conventional system in years with above-average precipitation. Improved management practices, such as no-tillage, increased seeding rates, banded N fertilization, and tall stubble height may improve dryland durum yield and N relations to a greater degree relative to diversified crop rotations in the semiarid northern Great Plains.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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