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Crop water and nitrogen productivity in response to long-term diversified crop rotations and management systems

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ABSTRACT

Diversified crop rotation and management strategies may affect crop water and N productivity. We studied the effect of tillage, crop rotation, and management system on pre-plant and postharvest soil water storage, annualized crop yield, water use, and water and N productivity from 2005 to 2010 in the northern Great Plains, USA. Tillage were conventional tillage and no-tillage; crop rotations were continuous spring wheat (*Triticum aestivum* L.) (CW), spring wheat-pea (*Pisum sativum* L.) (WP), spring wheat-forage barley (*Hordeum vulgare* L.)-pea (WBP), and spring wheat-forage barley-corn (*Zea mays* L.)-pea (WBCP). Managements were traditional (a combination of recommended seeding rate, broadcast N fertilization, early planting, and short stubble height) and alternate (a combination of increased seeding rate, banded N fertilization, late planting, and tall stubble height) systems. Aboveground biomass was 16–85%, preplant soil water 23–118%, postharvest soil water 38–246%, and water productivity 28–61% greater with WBCP than CW in 3 out of 6 yr. Crop water use and biomass N accumulation varied with tillage, crop rotations, and management systems in various years. Grain yield was 26–41% and grain water productivity 25–32% lower with WBP than other crop rotations. Grain N accumulation was 20–52%, grain N productivity 23–60%, and grain and biomass N removal indices 18–153% greater with WP than CW and WBCP, but biomass N productivity was 98–110% lower with CW than other crop rotations. Diversified crop rotation with longer rotation length increased crop yield, soil water storage, and water productivity, but shorter rotation with legume increased grain and biomass N productivity and N removal.

1. Introduction

Performance of dryland crops in arid and semiarid regions is affected by soil water and N availability (Miller et al., 2003; Lenssen et al., 2014; Sainju et al., 2019). In the semiarid northern Great Plains, USA, limited precipitation and a short growing season present major challenges for sustainable crop production. Crops can sometime fail due to the erratic nature of precipitation, resulting in a substantial loss of producers' farm income (Major et al., 1991; Nielsen et al., 2010). Because dryland crop production depends on soil water storage at planting and precipitation during the growing season as long as nutrients are not limited, water from precipitation should be properly captured, stored in the soil, and used efficiently by crops (Unger et al., 2006; Nielsen et al., 2010). To reduce the negative consequences of excessive N fertilization on soil and environmental quality, improved management techniques are needed to reduce N fertilization rates without compromising crop yields. As a result, both soil water and N should be efficiently used to sustain dryland crop yields and meet food demand for the growing population (Unger et al., 2006; Nielsen et al., 2010; Lenssen et al., 2014).

In the northern Great Plains, alternate year crop-fallow rotation and continuous monocropping are conventional cropping systems still practiced by many producers. Crop-fallow reduces annualized crop yield and soil organic matter compared to continuous monocropping, which reduces yield compared to crop rotation due to increased disease and pest infections (Farahani et al., 1998; Johnston et al., 2002; Sainju et al., 2009). Diversified crop rotations that include cereals, pulses, and forages can increase crop yields compared to continuous monocropping by efficiently using soil water (Lenssen et al., 2014, 2018a, 2018b; Schlegel

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Abbreviations: BNP, aboveground biomass N productivity; BNRI, aboveground biomass N removal index; BWP, aboveground biomass water productivity; CW, continuous spring wheat; GNP, grain N productivity; GNRI, grain N removal index; GWP, grain water productivity; WBP, spring wheat-forage-barley-pea; WBCP, spring wheat-forage barley-corn-pea; W-P, spring wheat-pea.

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et al., 2017, 2019). The sequence of crops in diversified crop rotations are arranged in such a way that low water requirement and N supplying crops are followed by high water and N requirement crops (Unger et al., 2006; Lenssen et al., 2014). For example, spring wheat and corn are high water and N demanding crops, while pea and forage barley are low water and N demanding crops (Miller et al., 2003; Lenssen et al., 2018b). The N fixing and N supplying ability of pea residue can reduce N fertilization rate to succeeding crops (Miller et al., 2003; Lenssen et al., 2018b). Sequencing cool and warm season crops in the rotation can also efficiently utilize soil water and control weeds (Anderson, 2005; Lenssen and Cash, 2011). Several researchers (Lenssen et al., 2018a; Schlegel et al., 2017) have reported that soil water storage, crop yield, and water-use efficiency were greater with diversified crop rotations than monocropping. Diversified cropping systems not only reduce farm inputs, but also sustain dryland crop yields and enhance producers' farm income (Singer and Cox, 1998; Katsvairo and Cox, 2000).

Tillage has a variable effect on dryland crop yield, water use, and water- and N-use efficiency. No-tillage enhances dryland crop yields by increasing soil water storage and water-use efficiency compared to conventional tillage by reducing evaporation and increasing infiltration capacity (Hatfield et al., 2001; Nielsen et al., 2005). Lenssen et al. (2014, 2015) observed that no-tillage increased dryland spring wheat yield and water-use efficiency compared to conventional tillage during dry years, but tillage had a variable effect on forage barley yield and water-use efficiency in various years. Numerous researchers (Payne et al., 2001; Machado et al., 2008; Lenssen et al., 2018a) reported no effect of tillage on pea yield, but others (Lafond et al., 2006; Ruisi et al., 2012) found increased pea yield with no-tillage compared to conventional tillage. Dryland corn yield was greater (DeFelice et al., 2006; Lenssen et al., 2018b) or lower (Vetsch and Randall, 2002) in no-tillage than conventional tillage, or not affected by tillage (Meyer-Aurich et al., 2006). Allen et al. (2016) reported that tillage had no effect on forage barley yield and N-use efficiency.

Other management options, such as seeding rate, stubble height, method of N fertilization and planting and harvest dates, can affect crop yield and water use (Anderson, 1999; Lenssen et al., 2014). Increased seeding rate can increase water-use efficiency by controlling weed growth and enhancing crop water uptake due to increased plant density (Tompkins et al., 1991). Tall stubble can increase soil water storage by trapping snow and reducing soil temperature, wind speed, and evaporation compared to short or no stubble (Nielsen et al., 2005; Unger et al., 2006). Some researchers (Black and Siddoway, 1977; Aase and Siddoway, 1980) in the northern Great Plains have found that a stubble height of 30–38 cm increased soil water storage at the 0–20 cm depth by 28–40 mm compared to the stubble incorporated into the soil through tillage. Banded N fertilization can limit N availability to weeds and delayed planting after late application of pre-plant herbicide can kill weed seedlings (Nichols et al., 2015; Strydhorst et al., 2008).

Because of the reduction in crop yields due to conventional cropping systems, improved management strategies are needed to enhance soil water storage, yields, water use, and water-use efficiency in the northern Great Plains. We evaluated the effect of diversified crop rotation, tillage, and management system that included a combination of seeding rate, date of planting, method of N fertilization, and stubble height on preplant and postharvest soil water storage, annualized crop yield, water use, and water and N productivity (or water- and N-use efficiency) from 2005 to 2010 in the northern Great Plains, USA. Our objectives were to: (1) examine how tillage, crop rotation, and management system affect soil water storage, crop yield, water use, and water and N productivity, and (2) determine which management strategies can enhance crop yield and water and N productivity. We hypothesized that no-tillage, diversified crop rotation, and the alternate management system would increase crop yield, water use, and water and N productivity compared to conventional tillage, continuous monocropping, and the traditional management system.

2. Materials and methods

2.1. Field site and treatments

The field site was located 8 km northwest of Sidney, Montana, USA (47° 46′N, 104° 16′W, 690 m elevation). Soil at the site was a Williams loam (fine-loamy, mixed, superactive, frigid Typic Argiustolls) with 350 g kg^{-1} sand, 325 g kg^{-1} silt, 325 g kg^{-1} clay, 6.1 pH, 12 mg kg^{-1} Olsen-P concentration, and 18 g kg^{-1} organic matter at the 0–15 cm depth. Long-term (30-yr) mean annual precipitation at the site is 340 mm, with about 80% occurring during the crop growing season from April through September. Prior to the initiation of this study, the site had been in a cereal-fallow rotation under fall and spring tillage for several decades.

The long-term dryland field study was conducted from 2004 to 2010 comparing four crop rotations in two tillage and two management systems. The experimental design was a randomized complete block in a split-plot arrangement. Tillage system was the main-plot factor and included no-tillage and conventional tillage. The conventional tillage included a single pass tillage to a depth of 8 cm with a field cultivator equipped with C-shanks attached with 45-cm wide sweeps and coil-tooth spring harrows and 60 cm bars. The split-plot factor was a factorial arrangement of management system and crop rotation. Crop rotations were continuous spring wheat (CW), spring wheat-pea (WP), spring wheat-forage barley-pea (WBP), and spring wheat-forage barley-corn-pea (WBCP), with each phase of the rotation present in every year. Management systems were traditional and alternate practices, which varied by crop (Table 1). Traditional management practice included a combination of recommended seeding rate, broadcast N fertilization for spring wheat, forage barley, and corn, early planting, and short stubble height for spring wheat. Alternate management practice included a combination of increased seeding rate, banded N fertilization for spring wheat, pea, and forage barley, late planting, and tall stubble height for spring wheat. Individual split plot size was 12.2 m by 12.2 m. There were three replicates of each treatment.

2.2. Crop management

At planting, spring wheat, forage barley, pea, and corn received recommended N fertilization rates (Table 1). Nitrogen fertilizer as urea and monoammonium phosphate was applied to all crops, except pea which received N from monoammonium phosphate. Urea was broadcast to spring wheat, forage barley, and corn in the traditional management system, and banded to spring wheat and forage barley in the alternate system. Nitrogen requirements to all crops, except pea, were adjusted for residual soil NO_3-N content in samples to a depth of 60 cm collected in the autumn of the previous year. Therefore, available N included both soil and fertilizer N. This was done to avoid excessive N application. Phosphorus fertilizer as monoammonium phosphate was banded at 13 kg P ha^{-1} and K fertilizer as muriate of potash was banded at 22 kg K ha^{-1} to all crops at planting. Fertilizers were banded at 5 cm below and to the side of the seed row.

Spring wheat (cultivar Reeder), forage barley (cultivar Haybet), and pea (cultivar Majoret) were planted with a 3.1-m wide drill at a row spacing of 20.3 cm. The drill was equipped with double-shoot Barton (http://www.flexicoil.com/barton.asp) disk openers for low disturbance single-pass seeding and fertilization. Immediately following planting, barley and pea plots were land rolled to push rocks back into the soil and protect the harvesting equipment (Saskatchewan Pulse Growers, 2000). The roller, weighing 2415 kg, consisted of a 1.1 m diameter by 3.1 m width metal cylinder attached to a carriage frame. Corn (cultivar Pioneer Hybrid 39T67-RR for 2005–2008 and 39D95-RR for 2009–2010) was planted with a John Deere 1700 Max Emerge Plus planter (Deere and Co., Moline, IL) at a spacing of 60 cm. Herbicides and pesticides were applied before crop planting, during growth, and after harvest as needed. Crops were grown under dryland conditions without irrigation.

Table 1
Management systems applied to crops in all rotations.

Crop	Management system	Seeding rate (million ha^{-1})	N fertilization method	N fertilization rate (kg N ha^{-1})	Planting date	Stubble height (cm)
Spring wheat	Traditional	2.23	Broadcast	101	Early April	20
	Alternate	2.98	Banded	101	Early May	30
Pea	Traditional	0.60	Banded	6	Early April	5
	Alternate	0.92	Banded	6	Early April	5
Forage barley	Traditional	2.23	Broadcast	67	Early April	5
	Alternate	2.98	Banded	67	Early April	5
Corn	Traditional	0.037[a], 0.025[b]	Broadcast	78	Early May	20
	Alternate	0.048[a], 0.025[b]	Broadcast	78	Early May	20

[a] Seeding rate from 2004 to 2007.
[b] Seeding rate from 2008 to 2010.

In mid- to late July, forage barley biomass yield was determined by hand clipping aboveground biomass from two 0.5 m^2 quadrats per plot and oven drying at 65 °C for 3 d. Pea and spring wheat aboveground biomass were similarly determined in late July to mid-August two days before grain harvest. Pea and spring wheat grains were harvested using a self-propelled combine equipped with a 1.5-m header from an area of 15 m^2. Grain yields were determined on an oven-dried basis after drying a sample at 65 °C for 7 d. In September, corn was harvested by hand from two 4-m rows (4.8 m^2 area) and oven dried at 65 °C for 7 d to determine aboveground biomass. Corn grain was separated from stalks and cobs, cleaned, and weighed to determined grain yield. Stubble height for spring wheat in traditional and alternate management systems was maintained by using a combine at harvest. Annualized aboveground biomass and grain yield for a crop rotation was determined by averaging aboveground biomass and grain yields of crops within the rotation in a year (total aboveground biomass or grain yield / number of crops in a rotation).

2.3. Water and nitrogen productivity

Pre-plant and postharvest soil water storage to a depth of 120 cm were determined using a calibrated neutron attenuation probe (Chanasyk and Naeth, 1996). Crop water use (Hatfield et al., 2001; Lenssen et al., 2014, 2015) was calculated as:

$$\text{Water use} = \text{Pre-plant soil water} + \text{Growing season precipitation} - \text{Postharvest soil water} \quad (1)$$

Precipitation was measured from a weather station located about 50 m from the study site. The growing season precipitation (April to September) for each crop was calculated by adding daily total precipitation from planting to harvest, assuming that water lost through surface runoff and deep percolation were negligible, as slope of the land at the experimental site was $< 2\%$ and precipitation is lower than evapotranspiration (Farahani et al., 1998).

Water productivity for aboveground biomass and grain (Machado et al., 2008; Lenssen et al., 2014, 2015) was calculated as:

$$\text{Aboveground biomass water productivity (BWP)} = \text{Aboveground biomass} / \text{water use} \quad (2)$$

$$\text{Gain water productivity (GWP)} = \text{Grain yield} / \text{water use} \quad (3)$$

Nitrogen concentration in aboveground biomass and grain of crops was determined using a C and N analyzer (LECO, St. Joseph, MI) after grinding an oven-dried sample to 1 mm. Nitrogen accumulation in aboveground biomass and grain was calculated by multiplying aboveground biomass and grain yield by their N concentration. Aboveground biomass and grain N productivity (Singer and Cox, 1998; Allen et al., 2016) were calculated as:

$$\text{Aboveground biomass N productivity (BNP)} = \text{Aboveground biomass} / \text{Available N (soil N + fertilizer N)} \quad (4)$$

$$\text{Grain N productivity (GNP)} = \text{Grain yield} / \text{Available N (soil N + fertilizer N)} \quad (5)$$

Nitrogen recovery index (Singer and Cox, 1998; Allen et al., 2016) in aboveground biomass and grain was calculated as:

$$\text{Aboveground biomass N recovery index (BNRI)} = \text{Aboveground biomass N accumulation} / \text{Available N (soil N + fertilizer N)} \quad (6)$$

$$\text{Grain N recovery index (GNRI)} = \text{Grain N accumulation} / \text{Available N (soil N + fertilizer N)} \quad (7)$$

Pre-plant and postharvest soil water storage, water use, BWP, GWP, BNP, GNP, BNRI, and GNRI for a rotation system were calculated by averaging these parameters for all crops within a rotation in a year. For example, pre-plant soil water storage for WBCP was calculated by dividing total preplant soil water storage under spring wheat, forage barley, corn, and pea by 4, because the number of crops in the rotation was 4.

2.4. Statistical analysis

Data were analyzed using the MIXED procedure of SAS (Statistical Analysis Systems, Version 9, Cary, NC) with appropriate error terms for a split plot analysis (Littell et al., 2006) after testing for normal distribution. Main plot treatment was tillage and split-plot treatment was a factorial combination of crop rotation and management system. Fixed effects were tillage, crop rotation, management system, year, and their interactions and random effects were replication and replication × tillage interaction. Means were separated by using the least square means test (Littell et al., 2006) when significantly different at $P \leq 0.05$. Data for 2004 were not included for analysis as it was considered a treatment establishment year.

3. Results

3.1. Air temperature and precipitation

Monthly air temperature for April and June was lower in 2008 and 2009 than other years and the 30-yr average (Fig. 1). Air temperature for July was greater in 2006 and 2007 than other years and the 30-yr average. In September, air temperature was greater in 2009 than other years.

Monthly total precipitation for April, June, and September was greater in 2005 than other years and the 30-yr average (Fig. 1). In May, precipitation was greater in 2005, 2007, and 2009 than other years and the 30-yr average. The July and August precipitation were lower from 2005 to 2008 than other years. Growing season (April-September) precipitation accounted for 78% of the annual (January-December) precipitation and was lower in 2008 and higher in 2006 and 2010 than other years and the 30-yr average.

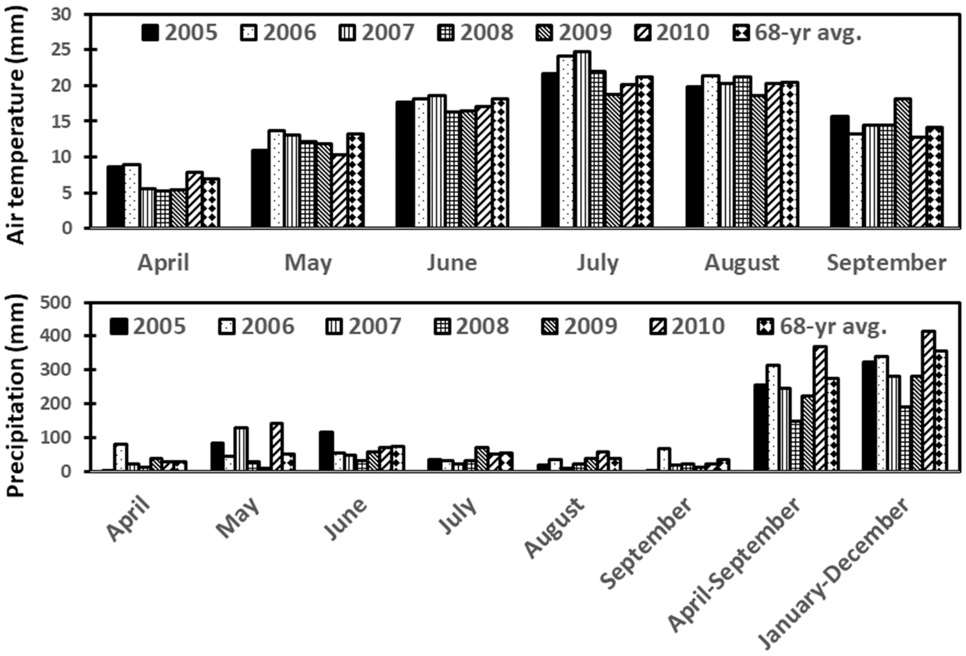

Fig. 1. Monthly mean air temperature and total precipitation from April to September at the study site. The growing season (April-September) and total annual (January-December) precipitation are also shown.

3.2. Annualized aboveground biomass and grain yield

Crop rotation, year, and crop rotation × year interaction were significant for annualized aboveground biomass (Table 2). Averaged across tillage and management systems, aboveground biomass was 21–33% greater with WBP and WBCP than CW and WP in 2005, 85% greater with WBCP than CW in 2008, and 20–29% greater with WBCP than WP and WBP in 2009 (Table 3). In 2010, aboveground biomass was 14–18% greater with WP and WBCP than CW and WBP. Tillage and management system did not influence aboveground biomass.

Annualized grain yield was significantly influenced by crop rotation, management system, and year, but tillage and treatment interactions were not significant (Table 2). Averaged across tillage, management systems, and years, grain yield was 26–41% greater with CW, WP, and WBCP than WBP (Table 4). Averaged across tillage, crop rotations, and years, grain yield was 14% greater with the traditional than the alternate management system. Averaged across treatments, grain yield was greater in 2005 and 2010 than other years.

3.3. Pre-plant and postharvest soil water storage

Pre-plant soil water storage varied with crop rotations, management systems, and years, with a significant crop rotation × year interaction (Table 2). Averaged across tillage and management systems, pre-plant soil water was 28% - greater with CW than WBP in 2006 (Table 3). From 2007–2009, pre-plant soil water was 23–118% greater with WBCP than CW. In 2010, pre-plant soil water was 24–49% greater with CW than WP and WBP (Table 3). Averaged across tillage, crop rotations, and years, pre-plant soil water was 14% greater in the alternate than the traditional management system (Table 4). Tillage had no influence on pre-plant soil water.

Postharvest soil water storage varied with crop rotations and years, with a significant crop rotation × year interaction, but tillage and management system were not significant (Table 2). Postharvest soil

Table 2
Analysis of variance for annualized aboveground biomass and grain yields, pre-plant and postharvest soil water storage, crop water use, grain water productivity (GWP), and aboveground biomass water productivity (BWP) with tillage (T), crop rotation (C), management system (M) and year (Y) as sources of variance.

Source	Above-ground biomass (kg ha^{-1})	Grain yield (kg ha^{-1})	Pre-plant soil water storage (mm)	Postharvest soil water storage (mm)	Crop water use (mm)	GWP (kg ha^{-1} mm^{-1})	BWP (kg ha^{-1} mm^{-1})
	P values						
T	0.361	0.578	0.338	0.438	0.865	0.570	0.269
C	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
T × C	0.567	0.869	0.670	0.614	0.999	0.859	0.602
M	0.076	**0.006**	**< 0.001**	0.614	0.694	**0.009**	0.128
T × M	0.803	0.617	0.750	0.530	0.868	0.716	0.900
C × M	0.693	0.686	0.274	0.867	0.893	0.720	0.518
T × C × M	0.524	0.903	0.559	0.704	0.889	0.921	0.570
Y	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
T × Y	0.476	0.934	0.771	0.723	0.989	0.953	0.536
C × Y	**< 0.001**	0.448	**< 0.001**	**< 0.001**	**< 0.001**	**0.006**	**< 0.001**
T × C × Y	0.800	0.999	1.000	0.924	0.999	0.999	0.774
M × Y	0.068	0.534	0.225	0.320	**0.012**	0.578	0.137
T × M × Y	0.947	0.999	0.891	0.943	0.828	0.999	0.891
C × M × Y	0.994	1.000	0.997	0.926	0.999	1.000	0.991
T × C × M × Y	0.998	1.000	0.996	0.982	0.988	1.000	0.994

Table 3
Interaction between crop rotation and year for annualized aboveground biomass and grain yields, pre-plant and postharvest soil water storage, crop water use, and aboveground biomass and grain water productivities.

Crop rotation[a]	2005	2006	2007	2008	2009	2010
	Aboveground biomass (kg ha^{-1})					
CW	5395b[b]	7289	7461	1599b	6045ab	6540b
WP	5569b	6740	7226	2465ab	5401b	7454a
WBP	6716a	6600	7315	2693ab	5048c	6428b
WBCP	7174a	6533	7422	2961a	6488a	7557a
	Preplant soil water storage (mm)					
CW	122	131a	160b	44c	55b	101a
WP	127	126ab	169ab	80b	67ab	52c
WBP	135	102b	181ab	85b	69ab	77b
WBCP	141	111ab	197a	96a	85a	85ab
	Postharvest soil water storage (mm)					
CW	32b	3c	40	3	28	39ab
WP	34b	16bc	33	8	26	30b
WBP	63a	35b	34	16	28	52ab
WBCP	82a	79a	32	22	35	54a
	Crop water use (mm)					
CW	321	264a	299b	147	222	343a
WP	321	243a	328ab	171	227	326ab
WBP	299	181b	325ab	158	200	289c
WBCP	294	173b	348a	173	220	308bc
	Grain water productivity (GWP) (kg ha^{-1} mm^{-1})					
CW	8.11	6.89b	7.84	2.48	11.60a	7.40
WP	7.98	8.25b	7.50	4.05	10.54a	8.65
WBP	6.27	8.38b	4.56	3.63	6.95b	5.76
WBCP	7.56	12.09a	4.80	3.35	9.42ab	7.83
	Aboveground biomass water productivity (BWP) (kg ha^{-1} mm^{-1})					
CW	17.2b	27.8b	25.6	11.1b	27.7ab	19.2b
WP	17.5b	24.7b	22.4	15.2ab	24.3b	23.0ab
WBP	22.9a	39.8a	22.8	17.9a	26.2ab	22.3ab
WBCP	24.5a	41.4a	21.6	17.9a	29.6a	24.6a
	Aboveground biomass N accumulation (kg N ha^{-1})					
CW	55c	101	74	26	121	132b
WP	58bc	100	93	40	123	171a
WBP	85ab	99	100	48	105	138b
WBCP	89a	92	90	49	120	146ab

[a] Crop rotations are CW, continuous spring wheat; WP, spring wheat-pea; WBP, spring wheat-forage barley-pea; and WBCP, spring wheat-forage barley-corm-pea.

[b] Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.

water, averaged across tillage and management systems, was 82–156% greater with WBP and WBCP than CW and WP in 2005 (Table 3). Postharvest soil water was also 333–344% greater with WBCP than CW, WP and WBP in 2006 and 80% greater with WBCP than WP in 2010.

3.4. Crop water use

Crop water use varied with crop rotations and years, with significant interactions for crop rotation × year and management system × year (Table 2). Averaged across tillage and management systems, water use was 40–53% greater with CW and WP than WBP and WBCP in 2006 (Table 3). In 2007, water use was 23% greater with WBCP than CW. In 2010, water use was 24–49% greater with CW than WBP and WBCP. Averaged across tillage and crop rotations, water use was 17% greater with the alternate than the traditional management system in 2009 (Table 5). Tillage did not affect crop water use.

3.5. Water productivity

Crop rotation, year, and crop rotation × year interaction were significant for BWP, but treatment and management system were not significant (Table 2). Averaged across tillage and management systems, BWP was 31–68% greater with WBP and WBCP than CW and WP in 2005 and 2006 and 61% greater with WBP and WBCP than CW in 2008 (Table 3). In 2009, BWP was 22% greater with WBCP than WP. In 2010, BWP was 28% greater with WBCP than CW.

The GWP was influenced by crop rotation, management system, and year, with a significant crop rotation × year interaction (Table 2). Averaged across tillage and management systems, GWP was 44–75% greater with WBCP than CW, WP, and WBP in 2006. In 2009, GWP was 52–67% greater with CW and WP than WBP (Table 3). Averaged across

Table 5
Interaction between management system, crop rotation, tillage, and year for crop water use and aboveground biomass N accumulation.

Management system[a]	Tillage[b]	2005	2006	2007	2008	2009	2010
		Crop water use (mm)					
Traditional		318	213	331	163	198b[c]	319
Alternate		300	217	324	161	231a	314
		Aboveground biomass N accumulation (kg N ha^{-1})					
	CT	67b	94	95a	38	119	156a
	NT	76a	102	83b	44	115	137b

[a] See Table 1 for the description of management systems.

[b] Tillage are CT, conventional tillage; and NT, no-tillage.

[c] Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.

Table 4
Effect of crop rotation, management system, and year on annualized aboveground biomass and grain yields, pre-plant and postharvest soil water storage, crop water use, grain water productivity (GWP), and aboveground biomass water productivity (BWP).

Treatment	Above-ground biomass (kg ha^{-1})	Grain yield (kg ha^{-1})	Pre-plant soil water storage (mm)	Postharvest soil water storage (mm)	Crop water use (mm)	GWP (kg ha^{-1} mm^{-1})	BWP (kg ha^{-1} mm^{-1})
Crop rotation[a]							
CW	5721b[b]	2014a	102b	24c	266ab	7.39a	21.4b
WP	5824b	2151a	108b	24c	270a	7.51a	21.7b
WBP	5800b	1528b	108b	38b	244c	5.92b	25.3a
WBCP	6352a	1932a	119a	51a	252bc	7.83a	26.6a
Management system[c]							
Traditional	6051	2049a	103b	33	257	7.72a	24.2
Alternate	5797	1767b	117a	35	259	6.61b	23.3
Year							
2005	6526c	2396a	131b	53a	309b	7.48b	20.5d
2006	6790b	1744b	118c	33c	215c	8.90a	34.2a
2007	7356a	2037b	177a	35bc	327a	6.18b	23.1c
2008	2429e	610c	76de	12d	162d	3.37c	15.5e
2009	5745d	2032ab	69e	29c	217c	9.63a	27.0b
2010	6990ab	2419a	86d	44ab	316ab	7.41b	22.3cd

[a] Crop rotations are CW, continuous spring wheat; WP, spring wheat-pea; WBP, spring wheat-forage barley-pea; and WBCP, spring wheat-forage barley-corm-pea.

[b] Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.

[c] See Table 1 for the description of management systems.

tillage, crop rotations, and years, GWP was 14% greater with the traditional than the alternate management system (Table 4). Tillage had no effect on GWP.

3.6. Aboveground biomass and grain nitrogen accumulation

Aboveground biomass N accumulation varied with crop rotations and years, with significant interactions for tillage × year and crop rotation × year (Table 6). Averaged across crop rotations and management systems, aboveground biomass N was 13% greater with no-tillage than conventional tillage in 2005, but was 12–13% greater with conventional tillage than no-tillage in 2007 and 2010 (Table 5). Averaged across tillage and management systems, aboveground biomass N was 53–62% greater with WBCP than CW and WP in 2005 (Table 3). In 2010, aboveground biomass N was 24–30% greater with WP than CW and WBP. Management system had no effect on aboveground biomass N.

Grain N accumulation varied with crop rotations and years, but tillage, management system, and their interaction were not significant (Table 6). Averaged across tillage, management systems, and years, grain N was 20–52% greater with WP than CW, WBP, and WBCP (Table 7). Averaged across treatments, grain N was greater in 2007 and 2009 than 2006, 2008, and 2010.

3.7. Nitrogen productivity and removal index

Crop rotation and year were significant for BNP, GNP, BNRI, and GNRI, but tillage, management system, and their interaction were not significant (Table 6). Averaged across tillage, management systems, and years, BNP was 98–111% greater with WP, WBP, and WBCP than CW (Table 7). The GNP was 23–115% greater and GNRI 41–139% greater with WP than CW, WBP, and WBCP. The BNRI was 18–154% greater with WP than CW and WBCP. Averaged across treatments, BNP was greater in 2007 than 2005, 2008, and 2009. The GNP was greater in 2010 than 2006 and 2008. The BNRI was greater in 2006, 2009, and 2010 than other years. The GNRI was greater in 2009 than 2006, 2008, and 2010.

4. Discussion

4.1. Crop yield

The greater annualized aboveground biomass with WP, WBP, and WBCP than CW in 2005 and 2010 (Table 3) when the growing season precipitation was near or above the 30-yr average (Fig. 1) was probably due to soil water and N benefits of crop rotation compared to monocropping. In WP, WBP, and WBCP, lower water demanding crops, such as pea and forage barley, were followed by higher water demanding crops, such as spring wheat and corn, thereby increasing the amount of soil water available to succeeding crops and enhancing the overall yield of the rotation system. Pea matures 3–7 wk earlier than spring wheat and corn, thereby increasing water available to succeeding crops (Lenssen et al., 2018a). Furthermore, pea, being a legume, fixes N from the atmosphere, supplies N from its residue, and reduces N fertilization rates to succeeding crops. Forage barley is also harvested 4–8 wk earlier than spring wheat and corn, which enhances more water availability and yield of succeeding crops (Lenssen et al., 2015). A longer duration of fallow between crops can capture precipitation and increase soil water storage as long as soil profile is not saturated and evaporation is lower than the precipitation capture (Farahani et al., 1998; Unger et al., 2006; Nielsen et al., 2010). Another benefit of the rotation system is the reduced infestations of weeds, diseases, and pests, which help to enhance yields compared to monocropping where increased pest infestations reduces yield. Numerous researchers (Farahani et al., 1998; Johnston et al., 2002; Lenssen et al., 2014, 2018a, 2018b; Schlegel et al., 2017, 2019) have demonstrated increased crop yield with diversified crop rotations compared to continuous monocropping.

Absence of grain in forage barley reduced annualized grain yield with WBP compared to other crop rotations (Table 4). Grain yield, however, was not different among CW, WP, and WBCP, suggesting that crop rotation can sustain grain yield compared to monocropping. Early planting, together with recommended seeding rate, broadcast N fertilization, and short stubble height increased grain yield with the traditional management system. Cool-season crops, such as spring wheat, forage barley, and pea, are usually planted early in the semiarid northern Great Plains to take advantage of soil water from snowmelt and grain fill prior to greater drawdown of soil water, enhancing yields. However, crops can be planted late to control delayed emerging weeds by pre-plant herbicide application or tillage if soil water is not a limiting factor for crop production (Anderson, 1999; Lenssen et al., 2014). Near or above-average growing season precipitation increased grain yield in 2005 and 2010 compared to other years. Below normal precipitation reduced aboveground biomass and grain yield in 2008 compared to other years.

The non-significant effect of tillage on annualized aboveground biomass and grain yield was probably due to varying effect of tillage on various crops. From the same experiment, Lenssen et al. (2014, 2015) found that spring wheat yield was greater with no-tillage than conventional tillage during dry years, but tillage had varying effect on forage

Table 6
Analysis of variance for annualized aboveground biomass and grain N accumulations, aboveground biomass N productivity (BNP), grain N productivity (GNP), aboveground biomass N recovery index (BNRI) and grain N recovery index (GNRI) with tillage (T), crop rotation (C), management system (M) and year (Y) as sources of variance.

Source	Above-ground biomass N accumulation (kg N ha^{-1})	Grain N accumulation (kg N ha^{-1})	BNP[a] (kg ha^{-1} [kg N ha^{-1}]$^{-1}$)	GNP[a] (kg ha^{-1} [kg N ha^{-1}]$^{-1}$)	BNRI[a] (kg N ha^{-1} [kg N ha^{-1}]$^{-1}$)	GNRI[a] (kg N ha^{-1} [kg N ha^{-1}]$^{-1}$)
	P values					
T	0.562	0.980	0.789	0.862	0.757	0.908
C	**< 0.049**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
T × C	0.603	0.748	0.904	0.944	0.848	0.962
M	0.554	0.064	0.983	0.515	0.688	0.843
T × M	0.880	0.818	0.778	0.921	0.899	0.960
C × M	0.861	0.823	0.935	0.914	0.961	0.974
T × C × M	0.633	0.913	0.742	0.988	0.909	0.987
Y	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
T × Y	**0.045**	0.901	0.992	0.991	0.790	0.994
C × Y	**< 0.001**	0.215	0.779	0.812	0.559	0.605
T × C × Y	0.995	0.999	1.000	1.000	1.000	1.000
M × Y	0.154	0.772	0.939	0.82	0.927	0.995
T × M × Y	0.971	1.000	0.998	1.000	0.999	1.000
C × M × Y	0.998	1.000	1.000	1.000	1.000	1.000
T × C × M × Y	1.000	1.000	1.000	0.999	1.000	1.000

Table 7

Effect of crop rotation and year on annualized aboveground biomass and grain N accumulations, aboveground biomass N productivity (BNP), grain N productivity (GNP), aboveground biomass N recovery index (BNRI), and grain N recovery index (GNRI).

Treatment	Above-ground biomass N accumulation (kg N ha^{-1})	Grain N accumulation (kg N ha^{-1})	BNP (kg ha^{-1} [kg N ha^{-1}]$^{-1}$)	GNP (kg ha^{-1} [kg N ha^{-1}]$^{-1}$)	BNRI (kg N ha^{-1} [kg N ha^{-1}]$^{-1}$)	GNRI (kg N ha^{-1} [kg N ha^{-1}]$^{-1}$)
Crop rotation[a]						
CW	85b[b]	56b	57b	20c	0.84c	0.56c
WP	97a	67a	120a	43a	2.13a	1.34a
WBP	96a	44c	113a	32b	1.91ab	0.95b
WBCP	98a	46c	113a	35b	1.80b	0.92b
Year						
2005	71d	64ab	102b	38ab	1.24c	1.13ab
2006	98c	55b	114abc	31b	1.69a	1.07b
2007	89c	765a	126a	37ab	1.77b	1.30ab
2008	41e	19c	43d	9c	0.76d	0.33c
2009	117b	72a	99c	37ab	2.24a	1.40a
2010	147a	44b	120ab	43a	2.32a	0.44c

[a] Crop rotations are CW, continuous spring wheat; WP, spring wheat-pea; WBP, spring wheat-forage barley-pea; and WBCP, spring wheat-forage barley-corm-pea.

[b] Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.

barley yield in various years. Tillage had no effect on pea yield (Lenssen et al., 2018a), but corn yield was greater in no-tillage than conventional tillage (Lenssen et al., 2018b).

4.2. Soil water storage and water productivity

Reduced crop yield in the previous year likely increased pre-plant soil water storage with CW in 2006 and 2010 (Table 3). However, greater pre-plant soil water storage with increased length of diversified crop rotation from 2007 to 2009 suggests that balanced water use by lower and higher water demanding crops may have better optimized soil water storage with crop rotations. Some researchers (Miller et al., 2003; Lenssen et al., 2018a; Schlegel et al., 2017) have observed greater pre-plant soil water storage with diversified crop rotations than continuous monocropping. Reduction in water use by weeds due to efficient weed control from pre-plant herbicide application during late planting and two to three weeks longer time in the spring to capture precipitation, followed by increased soil water conservation due to tall stubble probably increased pre-plant soil water storage with the alternate management system. Taller stubble can decrease evaporation loss and increase preplant soil water storage compared to shorter stubble (Black and Siddoway, 1977; Aase and Siddoway, 1980). Over six years, soil water storage at planting under spring wheat was 31 mm greater in the alternate than the traditional management system (Lenssen et al., 2014). Pre-plant soil water storage plays an important role in the performance of dryland crops (Nielsen et al., 2005; Unger et al., 2006; Schlegel et al., 2017).

Efficient water use by previous crop likely reduced postharvest soil water storage with WBCP in 2005, 2006, and 2010 (Table 3) when the growing season precipitation was near or above the normal (Fig. 1). As discussed above, high water demanding crops were grown alternately with low water demanding crops in WBCP. This may have resulted in reduced water use by crops, resulting in increased postharvest soil water storage with WBCP during wet years.

Increased preplant soil water storage and growing season precipitation, followed by reduced postharvest soil water storage resulted in greater crop water use with CW in 2006 and 2010 (Table 3) when the growing season precipitation was above the 30-yr average (Fig. 1). In contrast, increased preplant soil water storage increased crop water use with WBCP in 2007 when the growing season precipitation was below the average. This suggests that diversified crop rotation can enhance water use compared to monocropping during dry years, but monocropping can do so during wet years. It would not be surprising to observe high water use with CW due to the presence of high water demanding crop, such as spring wheat, in every year. Greater water uptake due to increased seeding rate, banded N fertilization, late planting, and tall stubble increased crop water use in the alternate management system in 2009 when the growing season precipitation was below the normal.

Increased aboveground biomass but non-different or lower crop water use increased BWP with WBP and WBCP in 2005, 2008, 2009, and 2010 (Table 3). In contrast, non-different aboveground biomass, but lower water use increased BWP with WBP and WBCP in 2006. This suggests that diversified crop rotations used water more efficiently and increased water productivity compared to continuous monocropping either by increasing crop yields or decreasing water use. Increased water-use efficiency with diversified crop rotations compared to continuous monocroping has been reported by several researchers (Lenssen et al., 2018a; Schlegel et al., 2017).

Lower crop water use but non-different grain yield also increased GWP with WBCP in 2006 (Table 3). In contrast, greater grain yield, but non-different water use likely increased GWP with CW and WP in 2009. Absence of grain reduced GWP with WBP in both years. Increased grain yield, but non-different water use also increased GWP in the traditional than the alternate-year management system (Table 4). This suggests that early planting, broadcast N fertilization, recommended seeding rate, and short stubble increased grain water productivity in the traditional practice due to increased crop yield.

As with annualized crop yield, the variable effect of tillage on preplant and postharvest soil water storage, water use, and water productivity under individual crops probably resulted in the non-significant effect of tillage on these parameters for the rotation system. Our results are dissimilar to those reported by some researchers (Hatfield et al., 2001; Nielsen et al., 2005; Unger et al., 2006), who reported that soil water storage, water use, and water-use efficiency were greater with no-tillage than conventional tillage under dryland cropping systems. Differences in soil and climatic conditions among regions and tillage depth may have resulted in variable effect of tillage on these parameters. Our tillage depth was 8 cm compared to 15–20 cm depth in other regions, which may have affected evapotranspiration due to differences in soil disturbance and crop residue accumulation. Furthermore, our region receives 50–100 mm less precipitation than the central and southern Great Plains where the above researchers conducted their experiments.

Although pea and forage barley were land rolled after planting, land rolling was not done for spring wheat and corn in all rotations. Land rolling decreased pea yield (Olson et al., 2004; Lenssen, 2009), but did not influence pea water use (Lenssen, 2009), and spring wheat yield and water use (Lenssen and Sainju, 2019). These studies suggest that land rolling had minimum impact on crop yield and water use.

Growing season precipitation near or above the average (Fig. 1) increased preplant and postharvest soil water, crop water use, BWP, and

GWP in 2005, 2006, and 2007. In contrast, below-average precipitation decreased these parameters in 2008. This suggest that precipitation has a large influence on soil water storage and crop water productivity in dryland cropping systems.

4.3. *Nitrogen accumulation and productivity*

As tillage did not affect annualized aboveground biomass, differences in N concentration for individual crops probably resulted in variations in aboveground biomass N accumulation between tillage treatments in various years. The greater aboveground biomass N accumulation in no-tillage than conventional tillage in 2005 (Table 5) was due to increased N concentration in aboveground biomass of forage barley and pea in that year (Table 8). In contrast, the greater biomass N accumulation in conventional tillage than no-tillage in 2007 and 2010 was due to increased aboveground biomass N concentration in forage barley and spring wheat in 2007 and in forage barley, corn, and pea in 2010. Increased biomass N accumulation with WBCP in 2005 was due to increased aboveground biomass (Table 3). Similarly, increased biomass N accumulation with WP in 2010 was due to increased aboveground biomass (Table 3) and greater N concentration in pea and spring wheat aboveground biomass with WP in that year (Table 8). Increased grain N accumulation with WP compared to other crop rotations (Table 7) was due to greater grain yield (Table 4) and pea N concentration (Table 9). Similarly, increased grain N accumulation in 2007 and 2009 (Table 7) was due to greater pea N concentration in 2009 and spring wheat N concentration in 2007 (Table 9).

Increased BNP with WP, WBP, and WBCP compared to CW (Table 7) was due to greater annualized aboveground biomass (Table 4), but lower amount of N fertilizer applied to crops in the rotations due to N supplied by pea. Nitrogen availability to spring wheat, forage barley, corn, and pea were 101, 67, 78, and 6 kg N ha^{-1}, respectively. As a result, available N for CW, WP, WBP, and WBCP were 101, 54, 58, and 63 kg N ha^{-1}, respectively after accounting for N credit from pea residue. Similarly, increased GNP with WP compared to other rotations (Table 7) was due to increased annualized grain yield (Table 4), but lower available N. The greater BNRI and GNRI with WP than other crop rotations, except for BNRI with WBP (Table 7), were also due to increased aboveground biomass and grain N accumulations, but lower available N. These results suggest that diversified crop rotations used N more efficiently in aboveground biomass than continuous monocropping. Similarly, spring wheat-pea rotation used N more efficiently in grain and removed more N in aboveground biomass and grain than other crop rotations. Allen et al. (2016) reported that diversified crop rotation removed more N than monocropping.

Table 8

Nitrogen concentration in aboveground biomass of forage barley, corn, pea, and spring wheat as affected by tillage and crop rotation from 2005 to 2010.

Tillage[a]	Crop rotation[b]	Aboveground biomass N concentration (g N kg^{-1})					
		2005	2006	2007	2008	2009	2010
		Forage barley					
CT		17.4b[c]	15.1b	15.5a	27.0	21.0a	19.4a
NT		23.9a	17.5a	13.8b	25.4	18.5b	17.6b
		Corn					
CT		11.0	9.5	7.3	11.7	11.4	20.7a
NT		10.0	9.7	8.2	11.3	10.0	18.7b
		Pea					
CT		12.4b	15.1b	17.1	18.4	27.1	18.0a
NT		13.7a	16.4a	16.6	18.0	25.9	15.1b
		Spring wheat					
CT		9.0	14.7	10.6a	15.8	20.2	25.5
NT		9.0	14.0	9.1b	14.3	17.9	24.2
		Forage barley					
	WBP	19.8	16.8	14.3	26.5	19.7	17.4
	WBCP	21.5	15.8	15.0	25.9	19.7	19.6
		Corn					
	WBCP	10.0	9.6	7.8	11.5	10.7	19.7
		Pea					
	WP	14.9a	15.5b	17.4	19.7a	26.4ab	19.2a
	WBP	11.8b	14.6b	16.7	15.9b	25.4b	19.8a
	WBCP	13.1b	17.1a	16.4	19.1a	27.7a	10.7b
		Spring wheat					
	CW	10.1a	14.1	10.0	17.0a	20.0a	20.1c
	WP	8.2b	14.7	9.1	14.2b	19.2ab	26.8ab
	WBP	8.9ab	14.2	10.5	14.3b	17.4b	25.5b
	WBCP	8.3b	14.5	9.7	14.7b	19.6ab	27.7a

[a] Tillage are CT, conventional tillage; and NT, no-tillage.

[b] Crop rotations are CW, continuous spring wheat; WP, spring wheat-pea; WBP, spring wheat-forage barley-pea; and WBCP, spring wheat-forage barley-corn-pea.

[c] Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.

Table 9

Nitrogen concentration in grain of corn, pea, and spring wheat grain as affected by crop rotation and year.

Crop rotation[a]	Year	Grain N concentration (g N kg^{-1})		
		Corn	Pea	Spring wheat
WBCP		16.1		
WP			40.8a[b]	
WBP			40.0b	
WBCP			40.9a	
CW				29.2a
WP				27.6b
WBP				26.7c
WBCP				27.5b
	2005	16.7	34.2d	24.8c
	2006	15.7	40.3c	30.4a
	2007	16.3	39.8c	29.8ab
	2008	16.5	43.0b	30.1a
	2009	16.5	45.4a	28.9b
	2010	16.0	40.0c	22.5d

[a] Crop rotations are CW, continuous spring wheat; WP, spring wheat-pea; WBP, spring wheat-forage barley-pea; and WBCP, spring wheat-forage barley-corn-pea.

[b] Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.

The fact that tillage and management system did not affect grain N accumulation, BNP, GNP, BNRI, and GNRI suggests that these management practices had little impact on N relations. Crop rotation was the dominant treatment that influenced not only N relations, but also crop yield, water use, and water productivity.

Similar to soil water and crop water productivity, greater aboveground biomass and grain N accumulations, BNP, GNP, BNRI, and GNRI in 2006, 2007, 2009, and 2010 was due to near or above average growing season precipitation (Fig. 1) that promoted crop yield and N uptake. Below-average precipitation reduced these parameters in 2008.

5. Conclusions

Crop rotation had stronger impact on annualized aboveground biomass, grain yield, soil water storage, crop water use, and water and N productivity compared to tillage and management system in dryland cropping systems in the northern Great Plains, USA. Aboveground biomass, pre-plant and postharvest soil water storage, and BWP were greater with WBCP, but water use, grain N accumulation, GNP, and GNRI were greater with WP than other crop rotations. The effect of crop rotation on soil water storage and water use was more pronounced in years with normal or above-average precipitation. Absence of grain production with forage barley reduced annualized grain yield, pre-plant and postharvest soil water storage, water use, grain N accumulation, GNP, and GNRI with WBP. Tillage and management system had variable effect on water use and aboveground biomass N accumulation in various years. Traditional management increased grain yield and GWP, but the alternate management increased preplant soil water storage. Diversified crop rotations with increased length of the rotation increased annualized crop yield, soil water storage, and water productivity, but a two-year rotation of legume-nonlegume increased water use and N relations compared to other crop rotations in dryland cropping systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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