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Crop Diversification, Tillage, and Management System Influence Spring Wheat Yield and Water Use

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Abstract

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Disciplines

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Comments

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ABSTRACT

Depleted soil quality, decreased water availability, and increased weed competition constrain spring wheat production in the northern Great Plains. New management systems are necessary for improved crop productivity. The objective of our study was to compare productivity and soil water use of spring wheat (*Triticum aestivum* L.) in four crop rotations (continuous wheat, wheat–pea [*Pisum sativum* L.], wheat–forage barley [*Hordeum vulgaris* L.]–pea, and wheat–forage barley–corn [*Zea mays* L.]–pea) in two tillage (tilled and no-till) and management systems (conventional and ecological). Conventional management included recommended seed rates, early planting date, and broadcast N fertilization. Ecological management included variable seed rates, delayed planting, banded N fertilization, and increased stubble height. Spring wheat in diversified rotations averaged 35 mm greater preplant soil water content, 37 mm greater water use, 0.8 kg ha^{-1} mm^{-1} greater water use efficiency, and 473 kg ha^{-1} and 817 kg ha^{-1} greater grain and biomass yields than continuous wheat. Wheat in conventional management averaged 28 fewer heads m^{-2}, 4 additional seed head^{-1}, and 2 mg seed^{-1} heavier seed weight than wheat under ecological management, resulting in 644 kg ha^{-1} greater yield. Wheat under ecological management used 8 mm more water, but water use efficiency was 2.6 kg ha^{-1} mm^{-1} greater under conventional management. Postharvest soil water content was similar among rotations, tillage, and management systems, suggesting that wheat uses most available soil water. Spring wheat in diversified rotations planted early in the season is more resilient and should confer greater production stability than continuous wheat systems planted late.

Available water, depleted soil quality, and increased weed competition are primary constraints to crop production, including spring wheat in the northern Great Plains (NGP). Conventional grain production systems in the NGP have relied on summer fallow to accrue additional water to stabilize wheat yields. Utilization of alternate-year summer fallow, when combined with conventional tillage, has resulted in significant loss of soil organic matter and crop yields (Black and Tanaka, 1997; Bowman et al., 1999; Sainju et al., 2009). The development of diversified, continuous cropping systems in the NGP can improve precipitation storage and utilization compared with systems that include fallow (Farahani et al., 1998).

Dryland tillage systems have evolved substantially during the previous century in the NGP. Conventional tillage has become less intense than in the past (Widtsoe, 1913), and many producers have changed to minimum tillage, typically a single pass with a field cultivator before planting (Johnson et al., 1997). A single pass with a field cultivator leaves more residues on the soil surface to better capture precipitation and retain additional soil water during non-crop periods, and concomitantly decreases wind erosion compared with conventional tillage (Black and Bauer, 1983). No-tillage systems improve capture and storage of water for subsequent dryland wheat production better than conventional or minimum tillage. Additionally, conversion from minimum tillage to no-tillage can increase soil organic C (Sainju et al., 2006, 2009). No-tillage provides better ecosystem services than minimum tillage (Blanco-Canqui et al., 2013; Lal, 2013) and changes pests and pest management options (Derksen et al., 2002; Krupinsky et al., 2007; O'Donovan et al., 2007). Anderson (2005) documented decreased weed seed survival with no-tillage compared with conventional tillage. Anderson (1999) documented that no-tillage corn had a 48% decrease in density of associated weeds compared with minimum tillage corn.

Crop rotations can be designed to use limited water resources more efficiently. Wheat is a high water use crop in semiarid environments. Sequencing wheat with crops that use less water may improve wheat yield and water productivity compared with continuous wheat. Field pea and other pulse crops use less water than wheat and typically allow for additional available soil water for the subsequent crop due to their decreased rooting depth and earlier harvest compared with wheat (Miller et al., 2003). Annual

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Abbreviations: HI, harvest index; NGP, northern Great Plains; POSTH$_2$O, postharvest soil water content at the 0- to 120-cm depth; PREH$_2$O, preplant soil water content at the 0- to 120-cm depth; WU, soil water use; WUE, water use efficiency.

Table 1. Monthly annual mean precipitation and air temperature during the growing season (April–September) from 2005 to 2010 at the experimental site.

Month	2005	2006	2007	2008	2009	2010	68-yr avg.†
				Precipitation, mm			
Apr.	2	80	21	11	39	29	29
May	83	44	128	28	8	142	50
June	115	55	49	32	56	71	72
July	36	30	21	32	70	51	54
Aug.	19	36	8	23	38	56	37
Sept.	2	67	19	22	13	20	34
Jan.–Dec.	324	339	280	189	282	415	357
				Air temperature, °C			
Apr.	8.6	8.9	5.6	5.2	5.4	7.8	7.0
May	10.9	13.7	13.0	12.2	11.9	10.3	13.3
June	17.7	18.2	18.6	16.3	16.5	17.0	18.1
July	21.6	24.1	24.7	22.0	18.8	20.1	21.2
Aug.	19.8	21.3	20.3	21.2	18.6	20.2	20.4
Sept.	15.7	13.3	14.5	14.5	18.1	12.8	14.2

† Long-term averages from National Oceanic and Atmospheric Administration (www.nws.noaa.gov) for Sidney, MT, located 8 km south of the research site.

forage crops, including cool-season (Lenssen, 2008; Lenssen et al., 2010) and warm-season species (Lenssen et al., 2010; Lenssen and Cash, 2011), also are highly water efficient. Sequencing cool-season and warm-season crops can improve weed management (Anderson, 2005); however, few warm-season grain crops are well adapted to dryland conditions in the NGP.

An important problem in the NGP is the development of herbicide-resistant weed populations (Heap, 2014). Integrated management systems are necessary for weed control (O'Donovan et al., 2007). Crop canopies can be manipulated by ecological management strategies to improve their competitiveness with weeds, reducing weed growth and seed production (Anderson, 2005). Anderson (1999, 2003) documented that a combination of three cultural tactics (greater seeding rate, narrower rows, and delayed planting) provided greater reduction of weed biomass than using only one or two tactics. Delayed planting of competitive cereals such as wheat and barley can be an effective tactic to decrease the impact of wild oat (*Avena fatua* L.) (Beckie et al., 2012). Inclusion of forages can improve weed management within a cropping system (Entz et al., 2002). Barley harvested as forage was documented to be highly competitive with weeds (Lenssen, 2008). In the absence of both preplant burndown and in-crop herbicide applications, early planted barley harvested as forage did not produce any weed seeds (Lenssen, 2008). Weeds present in that study included green foxtail [*Setaria viridis* (L.) Beauv.], kochia [*Bassia scoparius* [L.] A.J. Scott], redroot pigweed (*Amaranthus retroflexus* L.), and horseweed [*Conyza canadensis* [L.] Cronq., weeds that occur commonly in the NGP with populations resistant to multiple herbicide modes of action (Heap, 2014). Cropping system diversification can decrease the incidence of diseases (Krupinsky et al., 2007; Lenssen et al., 2013).

The objective of this study was to determine the combined influences of tillage, management system, and crop rotation on spring wheat, pea, forage barley, and corn yields, water use, soil C and N pools, N cycling, and weed community. We hypothesized that diversified crop rotation with ecological management under a no-till system would enhance spring wheat yield and water use compared with continuous wheat with conventional management under a conventional till system.

MATERIALS AND METHODS

The experimental site was located about 8 km northwest of Sidney, MT (47°46′ N lat; 104°16′ W long; altitude 690 m). Soil at the location was mapped as a Williams loam (fine-loamy, mixed, superactive, frigid Typic Argiustolls). These soils formed in glacial till plains and moraines. Soil at the 0- to 15-cm depth had a pH of 6.1, Olsen-P of 12 mg kg^{-1}, and organic matter of 18 g kg^{-1}. Long-term (68-yr) mean annual precipitation at the site was 357 mm, with about 77% occurring from April through September (Table 1). Weather data for the specific research site were not available before 1999, and Sidney was the nearest weather station, about 8 km distant. A weather station at the research site was used for collection of precipitation, air temperature, and other environmental data from 2004 through 2010.

The long-term dryland study was conducted from 2004 to 2011 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 treatment, and included no-tillage and conventional preplant tillage. Split-plot treatments were a complete factorial combination of management system and crop rotation components. Management systems were conventional and ecological practices, which varied by crop (Table 2). Crop rotations were continuous spring wheat, spring wheat–pea, spring wheat–forage barley–pea, and spring wheat–forage barley–corn–pea, with all components present every year. Before the initiation of this study, the site had been in a traditional cereal grain–summer fallow rotation under fall and spring tillage for at least three decades. Today, wheat following wheat is the most common system in the region. Given the reduction in wheat–fallow land area at the initiation of our experiment,

Table 2. Description of conventional and ecological management practices used for crops in rotation.

Crop	Management practice	Seeding rate	N fertilization	Planting date	Stubble height
		million seeds ha^{-1}			cm
Spring wheat	conventional	2.23	broadcast	early April	20
	ecological	2.98	banded	early May	30
Pea	conventional	0.60	banded†	early April	5
	ecological	0.92	banded	early April	5
Forage barley	conventional	2.23	broadcast	early April	5
	ecological	2.98	banded	early April	5
Corn	conventional	0.04	broadcast	early May	20
	ecological	0.05	banded	early May	30

† Pea and barley received 6 kg ha^{-1} of N from monoammonium phosphate banded at planting.

there was little reason to include this rotation in the experiment. Individual split plot size was 12.2 by 12.2 m. There were three replicates of each split-plot treatment for a total of 120 plots.

Fertilization practices were typical for the region. The N requirement of 118 kg N ha^{-1} for spring wheat was based on a yield goal of 2350 kg ha^{-1} using recommendations from Montana State University (Jacobsen et al., 2003). Fertilizer N rate was determined by subtracting previous year's late fall residual NO_3–N content in the 0- to 60-cm depth from the total N requirement. Nitrogen fertilizer as urea was applied using a calibrated, air-delivery pull-type granular applicator (Valmar Airflo Inc., Elie, MB, Canada) before preplant tillage. Phosphorus fertilizer as mono-ammonium phosphate (11–52–0) was applied at 56 kg P_2O_5 ha^{-1} and K fertilizer as muriate of potash (0–0–60) at 45 kg K_2O ha^{-1} annually to all wheat, barley, corn, and pea plots at planting. Total available N for barley and corn was 73.3 and 84.5 kg ha^{-1}, respectively. Nitrogen fertilizer was broadcast or banded to a depth of 5 cm in the conventional management and banded in the ecological management (Table 2) and P and K fertilizers were banded in all plots.

Preplant conventional tillage was done with a field cultivator equipped with C-shanks and attached to 45-cm wide sweeps and coil-tooth spring harrows with 60-cm tines. Tillage depth, 7 to 8 cm, was controlled by stabilizer wheels on the field cultivator frame. Spring wheat 'Reeder', barley 'Haybet', and green field pea 'Majoret' were planted with a 3.1-m wide drill with row spacing of 20.3 cm. Spring wheat was planted in late April in the conventional management and mid-May in the ecological management for weed control (Table 2). Forage barley and pea were planted in late April for both conventional and ecological management plots. The drill was equipped with double-shoot Barton (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. Land rollers are commonly used in the NGP to push rocks back into soil after seeding short-statured crops, including pea and annual forages, to protect combine harvesters and forage harvesting and processing equipment (Saskatchewan Pulse Growers, 2000). The roller consisted of a metal cylinder with a 1.1-m diameter by 3.1-m width, attached to a carriage frame for a total weight of 2415 kg. Hybrid corn '39T67-RR' (Pioneer Hybrids International, Inc., Johnston, IA, USA) was planted in mid-May in both conventional and ecological managements. Barley, spring wheat, and corn seeds were treated with labeled fungicide seed treatments. Damage from arthropods or foliar diseases was not observed in this study, precluding the need for insecticide or foliar fungicide applications to spring wheat or other crops. Barley was swathed at Zadoks stage 55 to 57, dried in the field, and baled (Zadoks et al., 1974).

Each year all no-till plots received a preplant application of 3.36 kg a.e. ha^{-1} glyphosate (*N*-(phosphonomethyl)glycine) in 37.8 L ha^{-1} water to control early emerging weeds. Weed management for wheat in 2005 and 2006 included fall-applied application of formulated 1.1 kg ha^{-1} trifluralin (α,α,α,trifluoro-2,6-*N*,*N*-dipropyl-p-toluidine) and 0.3 kg ha^{-1} triallate {*S*-(2,3,3-trichloroallyl) diisopropyl-thiocarbamate}. Post-emergence application of tank-mixed 0.68 kg ha^{-1} of formulated bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) and MCPA (2-ethylhexyl ester of 2-methyl-4-dichlorophenoxyacetic acid) (0.92:1) and 0.09 kg a.i. ha^{-1} fenoxaprop-P {ethyl (RS)-2-[4-(6-chloro-1,3-benzoxazol-2-yloxy)phenoxy]propionate} in 38 L ha^{-1} water was achieved each year for broadleaf and grass weed management. Weed management in other crops was done with appropriate labeled herbicides, except for barley which did not receive any in-crop herbicide applications. When weed populations warranted, a postharvest application of glyphosate (3.36 kg a.e. ha^{-1} in 37.8 L ha^{-1} water) was performed following harvest of spring wheat, regardless of treatment.

Stand density of spring wheat was determined at the one- to two-leaf stage by counting plants in four 1-m rows in each plot. Shortly before harvest, plant height was determined on 10 standing tillers per plot in the field and reproductive tiller density was determined from 1-m row. Two days before harvest, aboveground crop biomass was determined by hand clipping two 0.5 m^2 quadrats per plot. Samples were transported to a laboratory, placed into a forced air oven at 55°C until dried, and weighed. Seed number per head was determined following hand threshing of 10 randomly selected heads per plot. Individual seed weight was calculated as:

$$\text{Seed weight} = \text{Total seed weight}/\text{Number of seeds} \qquad [1]$$

Grain yield for spring wheat was determined with a self-propelled combine harvester equipped with a 1.5-m header. Grain samples were placed in a forced-air oven at 55°C, dried, cleaned with combinations of sieves and wind, and weighed. Grain yield and biomass data are presented as 100% dry matter. Plot clean-off was done with a self-propelled combine equipped with a 4-m header and chopper-spreader to evenly distribute crop residue. Plants were cut at about 20 and 30 cm above the soil surface for conventionally and ecologically managed spring wheat, respectively, except in 2008. Harvest index (HI) was calculated as:

$$\text{HI} = \text{GY}/\text{CB} \qquad [2]$$

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

Soil water content was determined by calibrated neutron attenuation before planting and after harvest (Chanasyk and Naeth, 1996) at sampling depths of 23, 46, 61, 91, and 122 cm. Spring wheat water use (WU in mm) was calculated as:

$$\text{WU} = \text{PREH}_2\text{O} - \text{POSTH}_2\text{O} + \text{PRECIP} \qquad [3]$$

where PREH_2O is the preplant soil water content (mm, 0- to 120-cm from the five sampling depths described above), POSTH_2O is the postharvest soil water content (mm, 0- to 120-cm), and PRECIP is precipitation between crop preplant and postharvest (Farahani et al., 1998). Water-use efficiency (WUE, kg ha^{-1} mm^{-1}) for spring wheat grain was calculated as:

$$\text{WUE} = \text{GY}/\text{WU} \qquad [4]$$

where GY is wheat grain yield (kg ha^{-1}) (Farahani et al., 1998). Surface water runoff was not evident and it was assumed that neither overland flow nor drainage of water below 1.2 m occurred.

Data were analyzed with PC-SAS (SAS Institute, 2012) using the MIXED procedure with tillage, management, and crop

Table 3. Spring wheat stand, height, yield components, biomass, yield, harvest index (HI), preplant soil water content ($PREH_2O$, 0–1.2 m depth), postharvest soil water content ($POSTH_2O$, 0–1.2 m depth), water use (WU), and water use efficiency for grain (WUE) from 2005 to 2010, Sidney, MT.

Treatment	Stand	Height	Heads	Seed	Seed wt	Biomass	Grain	HI	$PREH_2O$	$POSTH_2O$	WU	WUE
	no. m^{-2}	cm	no. m^{-2}	no. $head^{-1}$	mg $seed^{-1}$	kg ha^{-1}			mm			kg ha^{-1} mm^{-1}
<u>Tillage system</u>												
Tilled	213	61	384	29	28.5	6376	2332	0.37	127	21	293	7.9
No-till	215	63	395	29	28.8	6444	2406	0.38	131	24	294	8.2
<u>Management system</u>												
Conventional	183 b†	67 a	376 b	31 a	29.6 a	6953 a	2691 a	0.40 a	113 b	22	290 b	9.3 a
Ecological	246 a	58 b	404 a	27 b	27.6 b	5868 b	2047 b	0.35 b	144 a	23	298 a	6.7 b
<u>Rotation‡</u>												
Continuous wheat	214 a	60 b	362 c	28 b	27.8 b	5798 b	2014 b	0.38	102 b	24	266 b	7.4 b
Wheat–pea	204 b	63 a	380 bc	30 a	28.9 a	6473 a	2470 a	0.39	133 a	19	302 a	8.2 a
Wheat–barley–pea	215 a	63 a	420 a	30 a	28.9 a	6817 a	2540 a	0.38	136 a	23	300 a	8.5 a
Wheat–barley–corn–pea	224 a	62 a	396 b	29 ab	28.9 a	6553 a	2451 a	0.39	144 a	24	307 a	8.0 a
<u>Year</u>												
2005	134 e	75 a	467 c	30 c	32.0 b	7063 c	3318 a	0.49 a	153 b	29 ab	355 a	9.3 b
2006	192 d	56 d	564 a	31 bc	22.5 f	7714 ab	2093 d	0.27 d	128 c	1 d	266 b	8.0 c
2007	272 a	68 c	198 d	32 b	25.8 d	7869 a	2468 c	0.31 c	206 a	34 ab	351 a	7.1 d
2008	236 c	41 f	107 e	22 e	24.1 e	2588 e	1002 e	0.36 b	94 e	7 c	193 d	5.0 e
2009	251 b	50 e	476 c	26 d	37.8 a	5833 d	2703 b	0.47 a	81 f	26 b	249 c	11.2 a
2010	200 d	73 b	527 b	33 a	29.7 c	7394 bc	2630 b	0.36 b	110 d	38 a	353 a	7.5 cd
Significance							*<u>P value</u>*					
Tillage (T)	ns‡	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Management (M)	***	***	*	***	***	***	***	**	***	ns	*	***
T × M	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Rotation (R)	**	***	**	*	*	***	***	ns	***	ns	***	**
T × R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
M × R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
T × M × R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Year (Y)	***	***	***	***	***	***	***	***	***	***	***	***
T × Y	***	ns	ns	ns	**	***	*	ns	ns	ns	ns	**
M × Y	***	***	***	***	***	***	***	ns	***	ns	***	***
T × M × Y	***	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns
R × Y	*	***	ns	*	***	***	***	*	***	ns	***	***
T × R × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
M × R × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
T × M × R × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

* Significant at $P \leq 0.05$.

** Significant at $P \leq 0.01$.

*** Significant at $P \leq 0.001$.

† Means followed by different lowercase letter within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

‡ Not significant.

Table 4. Interaction of tillage system with management and year for spring wheat stand density and seed weight, Sidney, MT.

Tillage system	Stand density		Seed weight	
	Management		Management	
	Conventional	Ecological	Conventional	Ecological
	——no. plants m^{-2}——		——mg seed^{-1}——	
2005				
Tilled	142 a†	144 a	33	32
No-till	83 b	161 a	33	33
2006				
Tilled	157 b	214 a	24 a	21 b
No-till	156 b	239 a	24 a	20 b
2007				
Tilled	150 c	374 b	27 a	24 b
No-till	161 c	402 a	28 a	24 b
2008				
Tilled	248 a	209 b	25 a	24 ab
No-till	253 a	236 a	23 b	24 ab
2009				
Tilled	206 b	291 a	37	38
No-till	223 b	282 a	38	38
2010				
Tilled	218 a	200 ab	30 b	27 c
No-till	187 b	195 b	33 a	28 c

† Means followed by different lowercase letter within year and management, are significantly different at $P \le 0.05$ by the least square means test.

rotation as fixed effects, and year as a repeated measure variable (Littell et al., 1996). Tillage was considered as the main-plot factor and the factorial combination of crop rotation × management as the split-plot factor. Random variables were replication and replication × tillage interaction. The HI data were transformed to square root for variance normalization before analysis. Means separations were done using the least square means test (Littell et al., 1996), differences among treatments were reported as significant at $P = 0.05$. Regression analyses between wheat grain yield and water use were done with the PROC REG procedure in SAS. Data from 2004 were not included in the analyses because all crops followed summer fallow. Selected results for mean yield by year and management system were published previously as the dataset for calibrating the Root Zone Water Quality Model 2 with CERES-wheat for spring wheat and water use (Qi et al., 2013).

RESULTS AND DISCUSSION

Climate

Precipitation and air temperatures were variable during the experiment, typical for the semiarid NGP. Annual precipitation ranged from 189 mm (2008) to 415 mm (2010) (Table 1). Although many growing season months received near-normal precipitation, notable exceptions with above-average amounts included May 2005, May 2007, and May 2010. Growing season time periods that received substantially less than normal precipitation included August to September 2005, June to September 2007, and April to September 2008. Air temperatures varied less than precipitation; however, notable exceptions included July 2006 and 2007, which were warmer than the long-term normal and May to August 2009 when temperatures were cooler than the long-term normal (Table 1). For most years, May mean temperature was lower than the long-term normal. In 2011, the experimental site experienced runoff following snowmelt before planting. Additional runoff events occurred following intense rainfall on 10, 20, and 21 May, precluding accurate calculation of WU and WUE of wheat for that year. Consequently, we do not report wheat yield or yield components for 2011.

Spring Wheat Growth and Yield

Stand density of wheat was significantly affected for numerous treatment combinations, including the rotation × year and tillage × management × year interactions (Table 3). By design, our study included greater seeding rate for spring wheat under the ecological than the conventional management to enhance crop competitiveness with weeds, which resulted in more dense stands in most years (Table 4). However, the tilled and no-tilled wheat in the earlier planted conventional management system had denser stands than the tilled and late planted ecological wheat in 2008 (Table 4), likely due to the exceptionally dry soil conditions in April and May (Table 1). Overall, tillage system did not influence stand density (Table 3). Rotations differed for stand density in 4 yr (Table 6). Stand density of wheat in the 4-yr rotation was always among the greatest when differences were significant, whereas wheat in the 2-yr rotation was always among the least dense. Spring wheat has excellent ability to compensate for lower stand densities by increasing tiller production (Otteson et al., 2008), and stands were never insufficiently dense for reasonable production in all treatments in each year of our study.

Plant height of spring wheat varied with management, rotation, and year (Table 3). Interactions were significant for management × year and rotation × year. Conventionally managed wheat was taller at maturity than wheat under ecological management in all years, except 2009 (Table 5), presumably because earlier planted wheat matured during periods of cooler air temperatures and reduced moisture stress compared with delayed planting wheat. Plant height was lower in continuous wheat than other rotations in 2008, lower in continuous wheat than wheat–forage barley–pea in 2009, and lower in continuous wheat than wheat–pea and wheat–forage barley–pea in 2010. Higher water requirement for wheat than forage barley and pea may have reduced growth and therefore plant height in continuous wheat.

The yield components, i.e., reproductive head density, seed per head, and seed weight, varied with managements, rotations, and years, having significant interaction of management × year (Table 3). Seed no. head^{-1} and seed weight also had significant rotation × year interaction and seed weight for tillage × management × year interaction. Reproductive head density, an important factor for yield (Simons and Hunt, 1983), was higher in the ecological than the conventional management in 2009 (Table 5), probably a result of greater stand density (Table 4). Seed head^{-1} was greater under the conventional than the ecological management in 4 out of 6 yr (Table 5). Excessively elevated temperature causes decreased formation of spikelets (Warrington et al., 1977; Rahman and Wilson, 1978), a possible reason how ecological management, which included a delayed planting date, resulted in fewer seed head^{-1}. Conversely, seed head^{-1} varied among crop

Table 5. Interaction between management and year on spring wheat height, heads, seed number, seed weight, biomass, grain yield, preplant soil water ($PREH_2O$, mm 0–120 cm), water use, and water use efficiency (WUE), Sidney, MT.

Management	2005	2006	2007	2008	2009	2010
			Height, cm			
Conventional	80 a†	70 a	77 a	45 a	52	76 a
Ecological	71 b	61 b	59 b	37 b	47	69 b
			Wheat heads, no. m^{-2}			
Conventional	445	556	185	126	392 b	551
Ecological	489	572	212	88	561 a	503
			Seed, no. $head^{-1}$			
Conventional	28 b	32 a	37 a	25 a	29 a	33
Ecological	32 a	29 b	27 b	19 b	23 b	33
			Seed weight, mg $seed^{-1}$			
Conventional	33 a	24 a	28 a	24	37	32 a
Ecological	31 b	21 b	24 b	24	38	28 b
			Biomass, kg ha^{-1}			
Conventional	7408 a	8590 a	9099 a	3059 a	5565 b	7997 a
Ecological	6719 b	6837 b	6639 b	2117 b	6101 a	6792 b
			Grain yield, kg ha^{-1}			
Conventional	3416	2675 a	3088 a	1223 a	2755	2989 a
Ecological	3219	1510 b	1848 b	780 b	2651	2271 b
			$PREH_2O$, mm 0–120 cm			
Conventional	134 b	129	179 b	86 b	62 b	93 b
Ecological	173 a	127	233 a	102 a	100 a	126 a
			Water use, mm			
Conventional	364 a	260	352	193	214 b	357
Ecological	346 b	265	350	192	284 a	349
			WUE, kg ha^{-1} mm^{-1}			
Conventional	9.4	10.4 a	8.9 a	6.1 a	12.9 a	8.4 a
Ecological	9.3	5.7 b	5.4 b	3.8 b	9.4 b	6.5 b

† Means followed by different lowercase letter within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

rotations in only 2 out of 6 yr (Table 6). In 2005, wheat in wheat–pea and wheat–forage barley–pea rotations had more seed $head^{-1}$ than wheat in continuous production whereas in 2010 wheat in wheat–pea had more seed $head^{-1}$ than wheat in wheat–forage barley–corn–pea (Table 6), possibly due in part to improved water status. Although the rotation × year interaction was significant for seed weight, differences were significant only in the drought year of 2008 when continuous wheat produced lighter seed than wheat in more diversified rotations (Table 6), indicating that lower water availability during drought reduced seed size in the continuous wheat system where water requirement is particularly higher than other crop rotations.

Seed weight was greater under the conventional than the ecological management across tillage systems in 2006 and 2007 (Table 4). In 2008, wheat seed was heavier under conventional tillage than no-tillage in conventional management. In 2010, wheat seed was heavier under no-tillage in the conventional management than under conventional tillage in the conventional management and under conventional tillage and no-tillage in the ecological management (Table 4). Availability of greater soil water from snowmelt early in the season appeared to increase seed weight in the conventional management regardless of tillage system in years with normal precipitation, but the trends varied with tillage during years with above-average (2010) or below-average (2008) precipitation (Table 1). The influence of drought stress at seed fill resulting in decreased seed weight in spring wheat is well known (Wardlaw, 1971). In Saskatchewan, increased seeding rate of spring wheat was shown to decrease 1000-kernel weight at harvest (Johnson, 1983).

Wheat aboveground biomass and grain yield varied with management, rotation, and year, with significant tillage × year, management × year, and rotation × year interactions (Table 3). Crop biomass was greater under the conventional than the ecological management in all years, except 2009, when the trend reversed (Table 5). Although increased soil water availability may have increased biomass in the conventional management, in 2009 higher precipitation in July produced a second set of late maturing reproductive heads in later planted wheat, thereby increasing biomass in the ecological management (Table 1). Biomass was lower in continuous wheat than other rotations in 5 out of 6 yr. However, in 2006 and 2007 biomass was not different between continuous wheat and wheat–pea or wheat–barley–pea (Table 6). Reduced preplant soil water availability (Tables 3 and 6) may have led to reduced biomass yield in continuous wheat. Wheat biomass was greater in no-tillage than conventional tillage in the drought year of 2008, indicating greater soil water conservation and increased yield under no-tillage during drought, a result similar to that reported by Lenssen et al. (2007a). When soil water was not limited during above-average precipitation in 2010, biomass was greater under conventional tillage than no-tillage.

Results for wheat grain yield were similar to those for aboveground biomass, with the conventional management having greater yield than the ecological management in 4 out of 6 yr (Table 5). In 2005 and 2009, grain yield was similar between management systems. In 3 out of 6 yr, the three diversified rotations produced greater grain yields than did the continuous wheat rotation (Table 6), suggesting that crop rotation has beneficial effect on wheat yield, a result of rotation effect in terms of greater available soil water, N, and/or weed control. In the drought year of 2008, grain production in continuous wheat was 355 kg ha^{-1}, only 29% of that for the mean of the three diversified rotations, 1217 kg ha^{-1}, indicating that crop rotation can reduce the risk of crop loss compared with monocropping even more during drought. In both 2008 and 2009, no-tillage had greater grain yield than conventional tillage (Table 7), a result of probably greater soil water conservation under no-tillage compared with conventional tillage, especially during years with below-average precipitation (Lenssen et al., 2007a). As recently as the mid-1980s, continuous cropping was not considered an appropriate practice in the NGP (Stiegler, 1987). The prediction of wheat grain yield by biomass provided the following equation:

$$\text{Grain yield (kg ha}^{-1}\text{)} = 408 + 0.307x, \qquad (r^2 = 0.532)$$

where x = crop biomass in kg ha^{-1}, which explains more than 53% of the variation in yield across the 6 yr. Other studies have found a superior relationship for biomass predicting grain yield, including

Table 6. Interaction of rotation and year on spring wheat stand, height, seed per head, seed weight, biomass, grain yield, harvest index, preplant soil water (PREH$_2$O, 0–1.2 m depth), water use, and water use efficiency for grain, Sidney, MT.

Rotation	2005	2006	2007	2008	2009	2010
Stand, no. m^{-2}						
Continuous wheat	143 a†	186	277	244 a	245 b	185 b
Wheat–pea	120 b	187	265	215 b	239 b	197 b
Wheat–barley–pea	136 ab	190	264	250 a	245 b	202 ab
Wheat–barley–corn–pea	131 ab	204	280	237 a	274 a	216 a
Height, cm						
Continuous wheat	73 b†	66	68	36 b	48 b	71 b
Wheat–pea	77 a	66	67	43 a	50 ab	74 a
Wheat–barley–pea	76 ab	65	68	44 a	52 a	74 a
Wheat–barley–corn–pea	76 ab	65	69	43 a	49 ab	72 ab
Seed, no. head^{-1}						
Continuous wheat	27 b	32	31	19	26	33 ab
Wheat–pea	31 a	30	31	25	26	35 a
Wheat–barley–pea	32 a	32	33	22	26	33 ab
Wheat–barley–corn–pea	30 ab	30	32	22	27	32 b
Seed weight, mg seed^{-1}						
Continuous wheat	32	23	26	19 b	38	30
Wheat–pea	32	22	26	26 a	38	29
Wheat–barley–pea	32	23	26	26 a	38	29
Wheat–barley–corn–pea	32	23	25	26 a	38	30
Biomass, kg ha^{-1}						
Continuous wheat	5853 c	7289 b	7461 b	1599 c	6045	6540 b
Wheat–pea	7489 ab	7593 ab	7596 b	2725 a	5480	7953 a
Wheat–barley–pea	7972 a	8049 a	7994 ab	3003 a	6157	7729 a
Wheat–barley–corn–pea	6940 b	7923 a	8426 a	3025 a	5649	7354 a
Grain yield, kg ha^{-1}						
Continuous wheat	2547 b	1798 b	2319	355 b	2519	2546
Wheat–pea	3470 a	2186 a	2422	1199 a	2733	2809
Wheat–barley–pea	3829 a	2179 a	2522	1269 a	2779	2663
Wheat–barley–corn–pea	3425 a	2208 a	2609	1184 a	2779	2502
Harvest index						
Continuous wheat	0.47 b	0.25	0.31	0.21 b	0.42	0.39
Wheat–pea	0.48 b	0.28	0.31	0.43 a	0.50	0.35
Wheat–barley–pea	0.49 b	0.26	0.31	0.42 a	0.46	0.35
Wheat–barley–corn–pea	0.54 a	0.27	0.31	0.38 a	0.49	0.34
PREH$_2$O, mm 0–120						
Continuous wheat	122 b	131	160 b	44 b	55 b	101 b
Wheat–pea	162 a	121	217 a	113 a	79 a	107 ab
Wheat–barley–pea	157 a	127	225 a	103 a	92 a	110 ab
Wheat–barley–corn–pea	172 a	134	222 a	116 a	96 a	121 a
Water use, mm						
Continuous wheat	321 b	264	299 b	147 b	222 b	343
Wheat–pea	371 a	256	360 a	210 a	256 a	357
Wheat–barley–pea	361 a	261	274 c	199 a	255 a	352
Wheat–barley–corn–pea	367 a	267	371 a	214 a	263 a	359
Water use efficiency, kg ha^{-1} mm^{-1}						
Continuous wheat	8.1 c	6.9 b	7.9	2.5 b	11.6	7.4
Wheat–pea	9.4 b	8.7 a	6.8	5.6 a	11.0	7.9
Wheat–barley–pea	10.6 a	8.6 a	6.8	6.3 a	11.2	7.6
Wheat–barley–corn–pea	9.3 b	8.2 a	7.1	5.5 a	10.9	7.0

† Means followed by different lowercase letter within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

Lenssen et al. (2010), who reported that biomass predicted 64% of variation in durum wheat grain yield in four rotations over 4 yr.

The HI of spring wheat varied with management and year, with a significant rotation × year interaction (Table 3). The conventional management had greater HI than the ecological management, suggesting that early planting in the conventional management can increase grain yield more than total aboveground biomass yield. Late planting in the ecological management may have exposed maturing spring wheat to elevated temperatures and drought stress, resulting in reduced grain yield compared with the total biomass yield and therefore HI (Badaruddin et al., 1999; Reynolds et al., 2007). The HI

Table 7. Interaction of tillage system and year on spring wheat seed weight, biomass, grain yield, and water use efficiency, Sidney, MT.

Tillage system	2005	2006	2007	2008	2009	2010
			Seed weight, mg seed^{-1}			
Tilled	33	23	25	25	38	29 b
No-till	32	22	26	24	38	31 a
			Biomass, kg ha^{-1}			
Tilled	7228	7566	7932	2202 b†	5602	7727 a
No-till	6898	7861	7806	2974 a	6063	7061 b
			Grain yield, kg ha^{-1}			
Tilled	3331	2165	2436	820 b	2580 b	2657
No-till	3304	2020	2500	1183 a	2825 a	2603
			Water use efficiency, kg ha^{-1} mm^{-1}			
Tilled	9.4	8.5 a	6.9	4.2 b	10.8	7.6
No-till	9.3	7.6 b	7.4	5.8 a	11.6	7.4

† Means followed by different lowercase letter within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

varied among rotations in 2 out of 6 yr (Table 6). In 2005, wheat in the 4-yr rotation had greater HI than all other rotations. In 2008 wheat in the three diversified rotations all had greater HI than continuous wheat (Table 6). This suggests that diversified rotations produce favorable results in increasing grain yield compared with total aboveground biomass yield.

Soil Water Content and Spring Wheat Water Use

Available soil water content at wheat planting was influenced by management, rotation, and year, with significant interactions for management × year and rotation × year (Table 3). Preplant available water was greater under the ecological than under the conventional management in all years, except 2006 (Table 5). Averaged across tillage, rotations, and years, the ecological management had 27% more available water than the conventional management (Table 3). Snowmelt in the mid-spring increased soil water at planting in the conventional management, but increased precipitation increased soil water at delayed planting in the ecological management. In 2005, 2007, 2008, and 2009, all diversified rotations had greater soil water at planting than continuous wheat (Table 6). In 2010, only wheat in the 4-yr rotation had greater soil water than continuous wheat. Averaged across tillage, management, and years, soil water at planting was 35 mm greater in diversified rotations than continuous wheat (Table 3). Reduced water use by forage barley and pea compared with wheat (results not shown) may have increased soil water in diversified rotations than continuous wheat, a case similar to that reported by various researchers in dryland cropping systems (Miller et al., 2003; Lenssen, 2008; Lenssen et al., 2010). Postharvest soil water content varied only by year, and was greater in 2010 than other years, except 2005 and 2007 (Table 3). This indicates that in continuous cropping systems, regardless of previous crop, most available water is used by crops. Greater growing season precipitation (Table 1) may have increased postharvest soil water in 2010.

Wheat water use was influenced by management, rotation, and year, with significant interactions for management × year and rotation × year (Table 3). Conventionally managed wheat used 18 mm more water in 2005 but 70 mm less in 2009 than ecologically managed wheat (Table 5). Although preplant soil water content was greater in the ecological than the conventional management (Table 5), differences in precipitation distribution during the wheat growing season (April–August) (Table 1) may have influenced water use by wheat between management systems in 2005 and 2009. An unusually high precipitation event (115 mm) occurred in June 2005, but precipitation from July to August was higher in 2009 than 2005. Early planted wheat in the conventional management probably used more soil water early in the season in 2005, but late planted wheat in the ecological management used more water late in the season in 2009. Water use was also greater in diversified rotations than continuous wheat in 3 of 6 yr, except in 2007 when water use was lower in wheat–barley–pea than other rotations (Table 6). Although higher water requirement for wheat and less preplant soil water may have reduced water use in continuous wheat in other years, the reasons for less water use by wheat in the 3-yr rotation in 2007 were not known. Averaged across tillage, management, and years, spring wheat in the three diversified rotations used 37 mm more water than continuous wheat, similar to the aforementioned 35 mm greater water content available at planting across these rotations. Our results document that cropping systems in continuous spring wheat essentially use less available soil water than spring wheat in rotations. During extended periods of drought, intensification can lead to decreased yields (Lenssen et al., 2007a, 2013) and N utilization (Lenssen et al., 2007b), but under normal conditions, intensification with crop diversification can improve system profitability (Lyon et al., 2004; Lenssen et al., 2010). The influence of the previous year's water use on subsequent preplant available water, water use, and grain yield is an important consideration in developing diversified rotation systems in water-limited regions, such as in the semiarid NGP during years with normal precipitation (Miller et al., 2002, 2003; Lenssen et al., 2010, 2012) and during periods of extended drought (Lenssen et al., 2007a, 2007b). Cutforth et al. (2013) documented that wheat utilized more water below the 80-cm depth than pulse crops, which explains in part why wheat following pea had greater preplant soil water content and WU than continuous wheat. Moreover, earlier harvest of pea than wheat provided about three to 4 wk additional time to accrue soil water for spring wheat. Water use predicted nearly 45% of variation in wheat grain yield over the 6 yr in our study (Fig. 1), similar to other reports from the NGP (Lenssen et al., 2010), but a less robust relationship than the 64% reported by Lenssen et al. (2007a) in northern Montana.

The WUE for wheat was influenced by management, rotation, and year, with significant interactions for rotation × year, management × year, and tillage × year (Table 3). The conventional management had greater WUE than the ecological management in 5 of 6 yr (Table 5). As discussed previously for grain yield, biomass, and WU, earlier planting under conventional management allowed wheat seed to fill and mature and use water more efficiently during periods of cooler temperature than late planting in ecological management. The three diversified rotations had greater WUE than continuous wheat in 3 of 6 yr (Table 6). Greater preplant soil water content and water use also resulted in higher WUE in diversified rotations than continuous wheat. The tillage system influenced WUE in 2 out of 6 yr, with

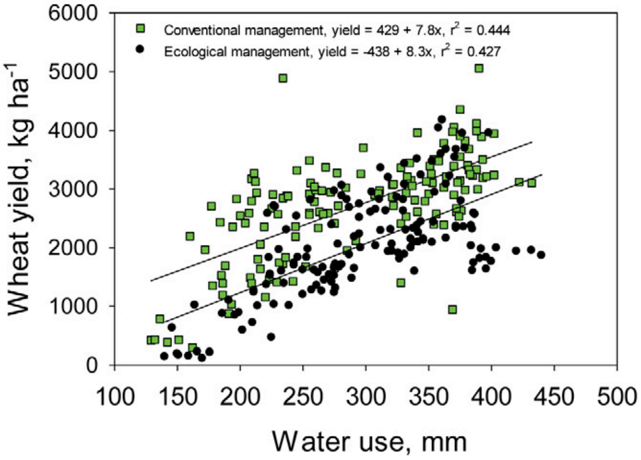

Fig. 1. Relationship between spring wheat water use and grain yield in the conventional and ecological managements, averaged across tillage and crop rotations.

conventional tillage having higher WUE in 2006 but lower in 2008 than no-tillage (Table 7). Wheat also appeared to use water more efficiently under no-tillage, which conserves more water than conventional tillage, especially during drought in 2008. During years with normal precipitation, such as in 2006 when soil water is not limited, wheat used water more efficiently in conventional tillage than no tillage. Averaged across rotation and tillage systems, conventionally and ecologically managed wheat had similar responses in grain yields to increasing water use, but conventionally managed wheat had greater grain yield and water use than ecologically managed wheat (Fig. 1).

Mean water use during 6 yr by spring wheat across treatments was 294 mm, significantly more than pea (237 mm), barley hay (196 mm), and corn (254 mm) (results not presented). Thus, wheat is a higher water use crop than pea, barley, or corn in the NGP. Having a lower water-use crop preceding wheat conferred a substantial yield advantage compared with continuous wheat.

During the past 150 yr, new technologies have allowed the expansion of wheat into areas previously considered to be unsuitable for agricultural production (Olmstead and Rhode, 2011). Development of improved varieties and management systems, and improved crop rotations has contributed to this expansion (Peterson et al., 1993; Cassman, 1999). However, strong evidence also shows yield trends for wheat production have plateaued in recent years (Grassini et al., 2013). The continued development and deployment of new cultivars with improved management practices in resilient cropping systems is essential for continued yield improvement in the future.

CONCLUSIONS

Spring wheat growth, characteristics, and yields varied with tillage, crop rotations, and management systems in the semiarid dryland cropping systems in the NGP. Spring wheat in the conventional management was taller; had decreased tiller density, but more seed head^{-1}; and greater seed weight, seed yield, and water use efficiency than wheat under ecological management. Conversely, spring wheat in the ecological management had greater plant and head densities and water use than conventional management. Similarly, grain and biomass yields, soil water content, and water use by wheat were greater in diversified crop rotations than continuous wheat. No-till increased yields and water use compared with conventional till, especially during drought, but tillage, overall, had no effect on wheat characteristics and yields. Water use predicted about 43% of the variation in yield for both conventionally and ecologically managed wheat. The inclusion of delayed planting as part of the ecological management system likely resulted in decreased wheat yield. Future research with wheat management systems should include conventional planting date with other ecological practices in comparison with conventional practices. Weed competition and profitability of ecological management will be subjects of other articles in this series. No-till diversified, crop rotations with crops planted early in the season may improve spring wheat productivity and sustainability and reduce energy inputs compared with conventional till continuous wheat planted late in the semiarid dryland cropping systems in the NGP.

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