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Cropping sequence and tillage system influences annual crop production and water use in semiarid Montana, USA

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Abstract

Available water is typically the biggest constraint to spring wheat production in the northern Great Plains of the USA. The most common rotation for spring wheat is with summer fallow, which is used to accrue additional soil moisture. Tillage during fallow periods controls weeds, which otherwise would use substantial amounts of water, decreasing the efficiency of fallow. Chemical fallow and zero tillage systems improve soil water conservation, allowing for increased cropping intensity. We conducted a field trial from 1998 through 2003 comparing productivity and water use of crops in nine rotations under two tillage systems, conventional and no-till. All rotations included spring wheat, two rotations included field pea, while lentil, chickpea, yellow mustard, sunflower, and safflower were present in single rotations with wheat. Growing season precipitation was below average most years, resulting in substantial drought stress to crops not following fallow. Preplant soil water, water use, and spring wheat yields were generally greater following summer fallow than wheat recropped after wheat or alternate crops. Water use and yield of wheat following summer fallow was greater than for chickpea or yellow mustard, the only other crops in the trial that followed summer fallow. Field pea performed best of all alternate crops, providing yields comparable to those of recropped spring wheat. Chickpea, lentil, yellow mustard, safflower, and sunflower did not perform well and were not adapted to this region, at least during periods of below average precipitation. Following summer fallow, and despite drought conditions, zero tillage often provided greater amounts of soil water at planting compared to conventional tillage.

Keywords: Cropping systems; Semiarid; Northern Great Plains; Water use efficiency; Crop rotation

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1. Introduction

Most of the earth's potentially arable land is already involved in some form of crop or agricultural production to sustain world populations. The prairie ecosystem of the North American Great Plains is a major contributor to world food production, however, this has not come without costs. Arable cropland of this prairie ecosystem is one of the most altered landscapes on this continent, in large part due to the predominant cropping system, summer fallow–wheat. Crop diversification, reduced fallow and reduced inputs are being promoted to improve economic and environmental sustainability (Peterson et al., 1993) but in Montana, USA, over 1.59 million ha, 36% of the dryland acreage for annual crop production, was in summer fallow in 2003 (Montana Agricultural Statistics Service, 2004). Producers are encouraged to diversify away from monocultures, primarily wheat (*Triticum aestivum*), to reduce the extent of land left in fallow, and to reduce farm inputs, especially inputs that have the greatest negative impact on the environment (Matson et al., 1997; Struick and Bonciarelli, 1997; Gregory et al., 2002).

Water is typically the most limiting factor for dryland crop production in semiarid environments (O'Leary and Connor, 1997b), and conventional summer fallow usually does increase stored soil water for the subsequent crop. Summer fallow is inefficient for precipitation storage, with about 25% of precipitation storage efficiency (as reviewed in Farahani et al., 1998). Intensification of crop production, by reduction of summer fallow frequency, provided more efficient utilization of the scarce water resource in the semiarid central Great Plains (Farahani et al., 1998). Perhaps the most important factor allowing intensification of production in semiarid regions has been improvements in water use and water use efficiency that come with the adoption of zero tillage systems (Hatfield et al.,

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2001). Research in diverse regions, including Victoria, Australia (O'Leary and Connor, 1997b; Cantero-Martinez et al., 1999), and Nebraska (Lyon et al., 1998) and Texas, USA (Baumhardt and Jones, 2002) suggest that zero tillage improved soil water storage compared to conventional tillage.

Improved soil water storage from zero tillage decreases risk associated with intensified cropping in semiarid environments. The successful inclusion of pulse and oilseed crops preceding cereals is now well documented in several dryland environments. Thomson et al. (1997) showed that white lupine (*Lupinus albus*), blue lupine (*L. angustifolius*), faba bean (*Vicia faba*), and field pea (*Pisum sativum*) produced satisfactory seed yields following wheat in Western Australia. In Saskatchewan, Canada, Miller et al. (2002a,b, 2003a,b) documented that field pea, lentil (*Lens culinaris*), and chickpea (*Cicer arietanum*) were excellent crops in sequences with spring wheat. Additionally, Miller et al. (2002b) and Gan et al. (2003) documented increased grain yield and protein of spring wheat following these pulses compared to spring wheat following spring wheat.

Oilseed crops also are adapted to semiarid environments. In a recent review, Johnston et al. (2002) summarized research from the Canadian prairie and adjacent border states of the USA, concluding that mustards (*Brassica juncea* and *Sinapis alba*), canola (*Brassica* sp.), and flax (*Linum usitatissimum*) were well adapted to cropping systems in the northern Great Plains, including Canada. They also concluded that sunflower (*Helianthus annuus*) and safflower (*Carthamus tinctorius*) were better adapted to the northern and central Great Plains of the USA, areas with warmer temperatures and longer growing seasons than the Canadian prairie.

In Montana, the predominant crop in dryland systems is spring wheat. The predominant spring wheat (SW) production systems are summer fallow–SW and summer fallow–SW–SW with minimum tillage, typically sweeps and rods. We developed a dryland cropping systems research project with considerable producer input, including several crop species and sequences. Overall, our objectives were to investigate the influence of tillage and cropping systems on crop productivity, soil quality, weed, arthropod and disease pests, and economic sustainability. Our experimental objectives were to determine: (1) yield and productivity of spring wheat and alternate crops in conventional and diversified systems and (2) water use of spring wheat and alternate crops in conventional and diversified systems.

2. Materials and methods

2.1. Experimental site

The experimental site was located on a private farm (48°48′N; 110°1′W; altitude 886 m), about 56 km WNW of Havre, Montana, USA. Long-term weather data for the specific research site are unavailable, and Havre is the nearest weather station. In 1999, a weather station was put in place at the research site for collection of precipitation and other weather data. Mean annual precipitation (1916–2003) at Havre is 305 mm, with about 233 mm occurring from April through September (Table 1). The average frost-free period is 128 days, 15 May–20 September. The 22.7 ha research area, including alleys, was located in soil mapping associations of Kevin–Elloam clay loams (Kevin soil, 60% of area, fine-loamy, mixed Aridic Argiborolls; Elloam, 28% of area, fine, montmorillonitic Typic Natriboralfs; 2–8% slopes) and Scobey–Kevin clay loams (Scobey soil, 55% of area, fine, montmorillonitic Aridic Argiborolls; Kevin soil, 30% of area; 0–4% slopes) derived predominantly from glacial till. Intensive soil sampling in April 1998 revealed average organic matter content was 1.2%, Olsen available phosphorus 10.9 ppm, exchangeable potassium 295 ppm, and pH was 7.4 for 0–15 cm depth.

Table 1
Long-term and annual monthly growing season precipitation

Month	Precipitation (LT[a]) (mm)	Year			
		2000[b]	2001[b]	2002[b]	2003[b]
April	24	12	10	3	36
May	45	24	13	36	28
June	65	49	21	112	38
July	38	10	10	27	5
August	31	3	23	43	24
September	29	29	0	25	33
Total (April–September)	233	127	77	246	164

[a] LT: long term (1916–2003) for Montana State University, Northern Agricultural Research Center, Havre, MT, located 56 km ESE of experimental site.

[b] Precipitation values at the experimental site located 56 km WNW of Northern Agricultural Research Center, Havre, MT.

The field was in the Conservation Reserve Program from 1986 through 1997, with an undisturbed, mixed planting of crested wheatgrass (*Agropyron cristatum*) and alfalfa (*Medicago sativa*) to provide soil cover. This resident vegetation was sprayed twice in 1997 with formulated glyphosate to kill all established vegetation. Tillage operations were done prior to crop planting in spring 1998.

2.2. Trial design

The experiment consisted of nine annual crop rotations and a planting of alfalfa with three perennial grasses [western wheatgrass (*Pascopyron smithii*), slender wheatgrass (*Elymus trachycaulus*) and green needlegrass (*Nassella viridula*)]. Annual crop rotations included spring wheat, field pea, lentil, chickpea, yellow mustard, sunflower, and safflower (Table 2). The experimental design was a randomized complete block in a split-plot arrangement. Whole plot treatment was tillage system, conventional with sweeps and rods or zero tillage. Subplots were individual components of the 10 cropping sequences. Individual subplot size was 14.6 m × 30.4 m. The four ranges (replicates) were separated by 24.3 m wide alleys. Starting in 1998, each component of each sequence was present in four replications each year, for a total of 192 plots. However, because all 1998 crops followed 1997 summer fallow, and those crops scheduled for planting in 1999 that by design followed summer fallow, actually followed 2 years of summer fallow, we required two seasons for true initiation of the experiment.

Table 2
Cropping sequences for spring wheat in two tillage systems, Havre, MT, 1998–2003

Crop sequence	Crop sequence abbreviation
Continuous spring wheat	W
Fallow–spring wheat	FW
Lentil–spring wheat	LW
Fallow–spring wheat–spring wheat	FWW
Fallow–spring wheat–pea	FWP
Fallow–spring wheat–safflower	FWSaff
Fallow–chickpea–spring wheat	FCW
Fallow–mustard–spring wheat	FMW
Sunflower–pea–spring wheat	PWSun

2.3. Crop management practices

Rates for fertilizer nitrogen application were based on yield goal of 2350 kg ha^{-1} of 13.5% protein spring wheat, totaling 118 kg N ha^{-1}. Each year, soil samples taken in late fall (mid-October) were analyzed for nitrate to 1.2 m in five increments, 0–15, 15–30, 30–60, 60–90, and 90–120 cm depths. Nitrate content below the 60 cm depth was not used in calculating nitrogen fertilizer requirement. As per Montana State University recommendations (Jacobsen et al., 2003), annual applications of phosphorus (11–52–0) and potash (0–0–60) were done for all annual crops at 56 and 48 kg ha^{-1}, respectively. Preplant tillage and tillage of summer fallow plots was done with standard sweeps and rods. Regardless of tillage treatment, all fertilizers were banded at planting about 5 cm below and to the side of the seed row with a single-pass ConservaPak® (Conserva Pak Seeding Systems Indian Head, SK, Canada S0G 2K0) air seeder. Each pass of the air seeder fertilized and seeded a width of 3.66 m. Openers were a modified hoe type on 30 cm spacing. Seeding depth varied by year because of differences in depth to moist soil, but for spring wheat ranged from 3.8 to 5 cm. Crop cultivars, planting and harvest dates are provided (Table 3).

A tank-mixed application of 0.68 kg ha^{-1} of formulated bromoxynil and MCPA ester (0.92:1) in 37.8 l ha^{-1} water prior to canopy closure provided excellent control of broadleaf weeds in all wheat plots. In conventional tillage plots, post-harvest weed management was done by tillage with sweeps in 1998 and 1999, but this was changed to glyphosate application (3.36 kg a.e. ha^{-1}) in all subsequent years to prevent wind erosion. However, tillage with sweeps and rods was done about 2 days prior to planting in the spring and as needed for weed control in summer fallow plots each year. Weed management in alternate crops (crop year) was done as follows: sunflower, preplant sulfentrazone (2000–2003); pea, preemergence imazethapyr (2000), postemergence bentazon (2001–2003); chickpea, preemergence imazethapyr (2000), postemergence pyridate (2000–2003); lentil, preemergence imazethapyr (2000), fall and spring pendamethalin (2001–2002), preemergence sulfentrazone (2003); and safflower, preplant, fall-applied trifluralin (2000–2003). Control of grass weeds in pea, lentil, safflower and sunflower in 2003 was done with sethoxydim, the only year that volunteer wheat was present in the plots. By design, yellow mustard was not treated with a broadleaf herbicide. All herbicides were applied in 37.8 l ha^{-1} water, except pyridate on chickpea, which was applied in 56.7 l ha^{-1} water. The sprayer was equipped with a gasoline motor driven spray tank with full agitation on a 7.3 m spray boom.

Table 3
Cultivars, planting and harvest dates for spring wheat in 10 cropping sequences in two tillage systems, Havre, MT, 2000–2003

Crop	Year	Cultivar	Planting date	Harvest date
Spring wheat	2000	Amidon	21 April	31 July
	2001	Scholar	1 May	7 August
	2002	Scholar	2 May	19 August
	2003	Scholar	30 April	11 August
Field Pea	2000	Majoret	21 April	21 July
	2001	Majoret	1 May	24 July
	2002	Majoret	3 May	29 July
	2003	Majoret	30 April	25 July
Lentil	2000	Richlea	21 April	No harvest
	2001	Richlea	30 April	24 July
	2002	Richlea	2 May	2 September
	2003	Indianhead	30 April	12 August
Chickpea	2000	Dwelley	2 May	No harvest
	2001	Dwelley	1 May	14 August
	2002	Dwelley	2 May	20 August
	2003	CDC Chico	1 May	12 August
Yellow mustard	2000	AC Pennant	21 April	25 July
	2001	AC Pennant	30 April	23 July
	2002	AC Pennant	2 May	29 July
	2003	AC Pennant	29 May*	29 July
Safflower	2000	Montola 2000	20 April	31 August
	2001	Montola 2000	30 April	14 August
	2002	S-541	2 May	10 October
	2003	S-541	30 April	25 September
Sunflower	2000	Cenex 803	20 April	31 August
	2001	Cenex 803	30 April	No harvest
	2002	Cenex 803	3 May	10 October
	2003	Cenex 803	30 April	No harvest

Yellow mustard seedlings from the 30 April 2003 planting were killed by *Phyllotreta cruciferae* at emergence and the crop was replanted 29 May 2003.

2.4. Crop and soils data collection

Stand densities were determined by counting all plants in 4 m of row in each plot, except 2003, when 3 m of row were counted. Crop aboveground biomass was determined by clipping 1 m of row prior to seed harvest, oven drying, and weighing samples. An additional 1-m row was sampled from each spring wheat plot for reproductive tiller counts, except in 2000, when tiller count data were not obtained. Sampling never was done adjacent to plot boundaries to preclude sampling edge effects. Yield samples for all crops were taken with a self-propelled combine equipped with a 1.5 m header harvesting a 30.4 m run. Yield samples were dried, cleaned with combinations of sieves and wind, and weighed. Yield data are presented as 100% DM. Yields of alternate crops were determined following hand harvest of 4.9 m of row in 2001 because plant heights were too short for combine harvesting. Harvest index was calculated as seed yield/biomass. Spring wheat kernel weights were determined by machine counting three 1000 kernel samples or hand counting three 300 kernel samples from recropped wheat treatments in 2001 only.

Samples for gravimetric soil water determinations were collected by hydraulic probe preplant and post-harvest to 1.2 m in five increments, 0–15, 15–30, 30–60, 60–90, and 90–120 cm. Water budgets were determined by calculating volumetric water from gravimetric water. Plant water use was calculated as preplant soil water + rainfall − post-harvest soil water. Water use efficiency (WUE) was calculated as grain yield/water use. Surface water runoff was not evident during the course of the study and it was assumed that neither overland flow nor leaching of water below the sampled 1.2 m soil profile occurred.

2.5. Statistical analyses

Data were analyzed with PC-SAS using general linear models with appropriate error terms for a split-plot analysis with all treatment factors considered fixed effects. Arcsine-square root transformations were done for percentage data prior to analyses. Differences among treatments are reported at the 0.05% level of significance. Following Pearson correlation analyses, selected regression analyses were computed with the PROC REG routine in PC-SAS that included examination of residuals.

3. Results

All crops in 1998 followed summer fallow in 1997, and those crops scheduled for planting in 1999 that by design followed summer fallow, actually followed two consecutive years of summer fallow. Consequently, two field seasons were required for true initiation of the crop sequences, so results from 1998 and 1999 are not presented, but are available at a project website (http://scarab.msu.montana.edu/spm/Haversite/haversite/htm) (verified 12 October 2004). Weed control in spring wheat, pea, sunflower and chickpea plots was excellent from 2000 through 2003. However, control of broadleaf weeds in zero tillage safflower and lentil was poor most years. Weed control was poor in sunflower, lentil, and pea in 1999 due to lack of sufficient rainfall for herbicide activation following October 1998 application. Weed densities in spring wheat and alternate crops will be presented in a subsequent manuscript.

3.1. Precipitation

Precipitation in 3 of the 4 years of the study was substantially below normal (Table 3). Although 2002 received normal growing season precipitation, soil moisture was poor from planting until mid-June, when a substantial snow event occurred. Cold weather damage to crops, however, was not evident. For all years of this study, 1998–2003, long-term drought in this region of the northern Great Plains impacted development and production of all crops.

3.2. Spring wheat production and soil water

The effects of year, rotation, and interactions with year, differed significantly for all crop parameters in this study, except for harvest index, so results are presented by year.

In 2000, preplant soil water content varied by crop rotation, but not by tillage system (Table 4). Wheat in the four sequences following summer fallow averaged 27 mm more preplant soil water prior to planting than did the six sequences of recropped wheat. Water use, yield and biomass of wheat varied by crop

Table 4
Soil water content, crop and biomass yields, and water use efficiencies from spring wheat in 10 crop sequences[a], Havre, MT, 2000–2003[b]

Treatment	Preplant soil water (mm)	Water use (mm)	Grain yield (Mg ha^{-1})	Biomass (Mg ha^{-1})	Harvest index (kg kg^{-1})	WUE grain (kg ha^{-1} mm^{-1})	WUE biomass (kg ha^{-1} mm^{-1})
2000							
Tillage							
Conventional	68	80	0.81	2.95	0.28 a	10.3	38.1
Zero tillage	75	87	0.82	3.37	0.25 b	9.6	40.1
Crop sequence							
W	52 c	67 c	0.50 e	2.21 e	0.23	7.6 c	33.9
FW	91 a	100 ab	1.13 b	3.84 bc	0.32	12.0 a	41.7
LW	54 c	67 c	0.54 e	2.40 e	0.24	8.5 b	37.4
F(W)W	81 ab	96 b	1.02 bc	3.39 cd	0.31	11.0 ab	37.2
FW(W)	67 bc	71 c	0.60 e	2.59 e	0.23	9.1 bc	37.8
FWP	89 a	113 a	1.33 a	4.87 a	0.28	12.3 a	45.4
FWSaff	88 a	97 a	1.02 bc	4.24 ab	0.25	10.6 ab	45.1
FMW	53 c	68 c	0.52 e	2.51 e	0.22	7.8 c	36.9
FCW	74 ab	79 c	0.84 cd	2.64 de	0.34	10.9 ab	34.0
PWSun	65 bc	72 c	0.68 de	2.93 de	0.23	9.7 a–c	41.8
2001							
Tillage							
Conventional	44 b	62	0.20	0.68 b	0.29	3.3	11.2
Zero tillage	63 a	72	0.25	0.95 a	0.25	3.2	12.6

Table 4 (*Continued*)

Treatment	Preplant soil water (mm)	Water use (mm)	Grain yield (Mg ha^{-1})	Biomass (Mg ha^{-1})	Harvest index (kg kg^{-1})	WUE grain (kg ha^{-1} mm^{-1})	WUE biomass (kg ha^{-1} mm^{-1})
Crop sequence							
W	44 cd	57 c–e	0.08 e	0.64 cd	0.18 bc	1.4 cd	11.1 c
FW	68 ab	80 ab	0.52 a	1.60 a	0.31 ab	6.8 a	21.5 a
LW	37 d	57 c–e	0.04 ef	0.23 cd	0.11 cd	0.7 cd	4.2 d
F(W)W	71 a	74 a–c	0.42 bc	1.24 b	0.37 a	6.7 a	18.6 ab
FW(W)	38 d	48 e	0.08 e	0.37 cd	0.19 bc	2.1 c	9.4 cd
FWP	62 ab	83 a	0.38 c	1.10 b	0.39 a	4.6 b	13.8 cd
FWSaff	63 ab	82 a	0.47 ab	1.67 a	0.29 ab	6.3 a	22.3 a
FMW	52 b–d	68 a–d	0.16 d	0.58 c	0.29 ab	2.3 c	9.0 cd
FCW	59 a–c	63 a–c	0.08 e	0.45 cd	0.22 bc	1.2 cd	6.4 cd
PWSun	42 cd	55 de	0.02 f	0.13 d	0.10 d	0.3 d	2.5 d
2002							
Tillage							
Conventional	83	203	1.04 b	3.40 b	0.32	5.1 b	16.7
Zero tillage	93	208	1.32 a	4.10 a	0.34	6.4 a	19.8
Crop sequence							
W	82 bc	199 b	0.94 c	3.59 b	0.27 c	4.8	18.1 a–c
FW	93 ab	206 a	1.22 a–c	4.04 a	0.31 c	5.9	19.8 a–c
LW	83 bc	218 a	1.27 ab	3.85 ab	0.34 bc	5.8	17.5 bc
F(W)W	102 a	219 a	1.43 a	4.63 a	0.31 c	6.6	21.4 ab
FW(W)	83 bc	204 b	1.18 a–c	3.47 ab	0.34 bc	5.8	17.0 c
FWP	100 a	206 b	0.97 bc	2.30 c	0.43 a	4.9	18.6 a–c
FWSaff	89 a–c	204 b	1.43 a	3.62 b	0.40 ab	7.0	17.9 a–c
FMW	81 bc	207 ab	0.99 bc	3.90 ab	0.27 c	4.8	18.7 a–c
FCW	89 a–c	208 ab	1.20 a–c	4.47 a	0.28 c	5.8	21.7 a
PWSun	78 c	198 b	1.16 a–c	3.64 b	0.31 c	5.9	18.6 a–c
2003							
Tillage							
Conventional	128 b	127	0.72	2.75	0.26	2.3	22.1
Zero tillage	148 a	137	0.77	3.11	0.25	2.3	23.2
Crop sequence							
W	117 bc	117 d	0.46 d	2.27 c–e	0.21 e	1.7 d	20.6 bc
FW	170 a	160 a	1.13 a	4.03 a	0.29 ab	2.9 a	25.8 ab
LW	108 bc	112 d	0.45 d	1.77 e	0.26 a–e	1.6 d	16.0 c
F(W)W	174 a	173 a	1.03 ab	3.43 b	0.30 a	2.4 a–c	20.5 bc
FW(W)	132 b	119 cd	0.56 cd	2.47 cd	0.23 c–e	1.9 b–d	21.4 bc
FWP	160 a	157 ab	1.05 ab	3.87 ab	0.27 a–d	2.7 a	24.6 ab
FWSaff	160 a	142 bc	0.98 b	4.22 a	0.24 c–e	2.8 a	30.0 a
FMW	103 c	104 d	0.46 d	2.07 de	0.22 de	1.8 cd	20.1 bc
FCW	125 bc	119 cd	0.66 c	2.41 cd	0.28 a–c	2.6 ab	22.6 b
PWSun	130 b	112 d	0.67 c	2.79 c	0.25 a–e	2.5 a–c	25.1 ab

[a] W, continuous wheat; FW, fallow–wheat; LW, lentil–wheat; FWW, fallow–wheat–wheat; FWP, fallow–wheat–pea; FWSaff, fallow–wheat–safflower; FMW, fallow–yellow mustard–wheat; FCW, fallow–chickpea–wheat; PWSun, pea–wheat–sunflower.

[b] Within year, means within tillage or crop sequence followed by the same letter are not significantly different at $P < 0.05$.

rotation, but not for tillage (Table 4). Growing season precipitation was 100 mm below the long-term average (Table 3), and spring wheat following summer fallow had higher yields of grain, biomass, and water use than recropped wheat. Post-harvest soil water content did not vary by either tillage or crop rotation (data not shown). Across cropping sequences, wheat following fallow used 25 mm more water than did recropped wheat, and produced 46% more grain. Harvest index of conventionally tilled wheat, 0.28 kg kg^{-1}, was greater than for zero tillage wheat, 0.25 kg kg^{-1} across rotations. The WUE_{grain} of wheat varied by rotation but not tillage system (Table 4), with a trend of wheat following fallow having better efficiency of utilization of water than recropped wheat, except for wheat following chickpea.

In 2001 precipitation was more than 150 mm below normal (Table 3), and wheat productivity was poor (Table 4). Across rotations, preplant soil water and biomass were higher for wheat in zero tillage compared to conventional tillage, but differences were not significant for water use, yield, harvest index, or WUE_{grain}. Rotation strongly influenced yield, biomass, harvest index, and WUE_{grain}, with wheat following fallow having superior performance compared to wheat following the range of crops. Across cropping sequences, wheat following fallow averaged 21 mm more available water prior to planting, and used 22 mm more water than wheat following other crops. Wheat following wheat, lentil, pea, chickpea or yellow mustard all had particularly poor yields and WUE, averaging 0.077 Mg ha^{-1} and 1.33 kg ha^{-1} mm^{-1}, respectively. Across rotations, wheat following fallow averaged four times higher grain yield and WUE$_{grain}$ than did recropped wheat.

In 2002, April and May were very dry (Table 3). Preplant soil water did not vary by tillage, but as in other years, wheat following summer fallow had more preplant soil water, except for wheat following chickpea. Across rotations, zero tillage systems had higher yield, biomass, and WUE$_{grain}$, but not harvest index, compared to wheat in conventional tillage. Substantial precipitation occurred in June, about 6 weeks after planting, and although significant, differences in yield and water use among rotations were less than in other years. Wheat following fallow averaged 13 mm more preplant soil water prior to planting, but only used 3 mm more water during the growing season. The WUE$_{grain}$ averaged 5.7 kg ha^{-1} mm^{-1}, and did not differ among rotations.

In 2003 growing season precipitation was 70 mm below the long-term average (Table 3). Tillage systems were similar for yield, biomass, harvest index, water use, and WUE of grain and biomass (Table 4). Across rotations, zero tillage had 20 mm more preplant water content than did conventional tillage systems. Rotations varied for preplant soil water content, yield, biomass, harvest index, water use, and WUE$_{grain}$ and WUE$_{biomass}$. In the dry years of 2000 and 2001, wheat following fallow had greater yield and biomass than wheat following wheat or other crops, averaging 0.51 and 1.59 Mg ha^{-1} additional grain and biomass, respectively. The WUE$_{grain}$ was low for wheat in all rotations, with wheat following summer fallow and annual crops averaging 2.7 and 2.0 kg ha^{-1} mm^{-1}, respectively.

3.3. Wheat yield components

Across rotations in 2001, wheat in zero tillage had more reproductive tillers (tillers) and kernels per unit area than did wheat produced with conventional tillage (Table 5). Kernels per tiller, kernel weight, and harvest index did not vary with tillage system, averaging 74 and 18.5, respectively. Rotations varied for tillers and kernels m^{-2}, but like tillage systems, kernels tiller^{-1} and kernel weight did not vary among rotations. Yield components of wheat following summer fallow averaged 63 more tillers, 2000 more kernels m^{-2}, and 12 more kernels tiller^{-1} than did recropped wheat.

In 2002, zero tillage wheat had more kernels m^{-2} and kernels tiller^{-1} than conventionally tilled wheat (Table 5). Rotations varied for wheat tillers and kernels m^{-2}, kernels tiller^{-1}, and kernel weight. Compared to other years, differences in yield components were relatively small for wheat following fallow compared to recropped wheat.

Across rotations, wheat produced with zero tillage had more tillers m^{-2} than wheat in conventional tillage in 2003 (Table 5). However, kernels m^{-2}, kernels tiller^{-1}, and kernel weight did not vary between tillage treatments. Tillers and kernels m^{-2} varied among rotations. Wheat following fallow averaged 264 tillers and 5725 kernels m^{-2}, more than did wheat in recropped sequences, with 181 tillers and 2880 kernels m^{-2}, respectively. Kernel weight and number per tiller did not vary among rotations, averaging 18.8 mg and 21 kernels tiller^{-1}, respectively.

Table 5
Yield components of spring wheat in 10 crop sequences[a] and two tillage systems, Havre, MT, 2001–2003[b]

Spring wheat	Tillers (#/m^2)	Kernels (#/m^2)	Kernels (#/tiller)	Kernel (mg)
2001				
Tillage				
Conventional	65 b	1074 b	16	19
Zero tillage	83 a	1404 a	17	18
Crop sequence				
W	60 cd	463 e	8 ef	18
FW	112 ab	2920 a	27 a	18
LW	39 bc	180 e	6 f	20
F(W)W	108 ab	2299 bc	22 a–c	18
FW(W)	52 d	467 e	13 d–f	18
FWP	91 b	2035 c	23 ab	18
FWSaff	137 a	2558 b	19 a–d	19
FMW	88 bc	913 d	14 c–f	18
FCW	38 de	443 e	15 b–e	19
PWSun	16 e	112 e	7 f	19
2002				
Tillage				
Conventional	235	4251 b	18 b	25
Zero tillage	236	5115 a	22 a	26
Crop sequence				
W	230 a–c	4187 c	18 bc	23 b
FW	229 a–c	4784 a–c	21 b	25 b
LW	240 ab	5225 ab	22 b	24 b
F(W)W	217 bc	5668 a	28 a	25 b
FW(W)	234 a–c	4675 bc	20 bc	25 b
FWP	193 c	3026 d	16 c	32 a
FWSaff	271 a	5517 ab	21 b	26 b
FMW	269 a	4204 c	16 c	24 b
FCW	251 ab	4865 a–c	20 bc	25 b
PWSun	222 bc	4683 bc	21 b	24 b
2003				
Tillage				
Conventional	191 b	3891	23	19
Zero tillage	237 a	4141	19	19
Crop sequence				
W	195 b–d	2527 cd	14	18
FW	275 a	6160 a	28	18
LW	165 d	2230 d	14	21
F(W)W	240 a–c	5524 a	28	19
FW(W)	155 d	3105 bc	22	18
FWP	280 a	5650 a	21	18
FWSaff	262 ab	5565 a	22	18
FMW	166 d	2614 cd	24	18
FCW	189 cd	3362 b	20	20
PWSun	216 a–d	3422 b	17	19

[a] W, continuous wheat; FW, fallow–wheat; LW, lentil–wheat; FWW, fallow–wheat–wheat; FWP, fallow–wheat–pea; FWSaff, fallow–wheat–safflower; FMW, fallow–yellow mustard–wheat; FCW, fallow–chickpea–wheat; PWSun, pea–wheat–sunflower.

[b] Within year, means within tillage or crop sequence followed by the same letter are not significantly different at $P < 0.05$.

3.4. Alternate crops

3.4.1. Field pea

Effects of rotation, and interactions of tillage or rotation with year, were not significant, so results are combined across

Table 6
Soil water content, crop and biomass yields, and water use efficiencies for six alternate crops, Havre, MT, 2000–2004[a]

Treatment	Preplant soil water (mm)	Water use (mm)	Grain yield (Mg ha^{-1})	Biomass (Mg ha^{-1})	Harvest index (kg kg^{-1})	WUE grain (kg ha^{-1} mm^{-1})	WUE biomass (kg ha^{-1} mm^{-1})
Pea							
Tillage							
Conventional	81	82	0.66	2.08	0.23	6.7	30.1
Zero tillage	85	78	0.74	2.29	0.27	9.9	41.9
Year							
2000	55 c	61 c	0.48 b	3.10 ab	0.15 b	10.7 a	65.8 a
2001	42 d	33 d	0.07 c	0.53 c	0.09 b	1.8 b	21.0 b
2002	87 b	104 b	1.15 a	3.34 a	0.35 a	11.3 a	33.3 b
2003	149 a	122 a	1.11 a	2.83 b	0.40 a	9.4 a	23.9 b
Lentil							
Tillage							
Conventional	69	95 b	0.28	1.19	0.09	1.43	12.4
Zero tillage	70	109 a	0.13	1.24	0.11	0.90	13.1
Year							
2000	44 c	63 c	0.00	1.53 ab	–	–	24.7 a
2001	38 c	32 d	0.01	0.24 c	0.07	0.50	8.6 b
2002	80 b	211 a	0.72	2.41 a	0.23	3.45	11.4 b
2003	116 a	102 b	0.01	0.70 bc	0.01	0.13	6.3 b
Chickpea							
Tillage							
Conventional	93 b	117	0.25 b	1.84	0.12	1.5	18.9
Zero tillage	114 a	125	0.41 a	1.80	0.19	2.4	15.1
Year							
2000	79 c	82 c	0.00	2.24 a	–	–	28.3 a
2001	76 c	65 c	0.01 c	0.73 b	0.005 c	0.08 c	11.9 c
2002	95 b	203 a	0.73 a	2.12 a	0.36 a	3.7 a	10.5 c
2003	164 a	133 b	0.25 b	2.19 a	0.11 b	2.1 b	17.2 b
Yellow mustard							
Tillage							
Conventional	82 b	103	0.26	0.99	0.19	4.3	15.3
Zero tillage	103 a	104	0.27	1.62	0.13	3.1	20.8
Year							
2000	75 b	91 b	0.41 a	–	–	4.7	–
2001	55 b	55 c	0.23 b	1.28	0.19	6.4	33.8
2002	82 b	121 ab	0.31 ab	1.63	0.21	2.5	13.8
2003	159 a	149 a	0.09 c	1.01	0.07	0.6	6.6
Safflower							
Tillage							
Conventional	64 b	134	0.10	1.35	0.07	0.65	19.5
Zero tillage	82 a	142	0.05	1.51	0.05	0.41	21.3
Year							
2000	56 bc	67 c	0.03 b	2.84 a	0.01	0.5	43.2 a
2001	47 c	55 c	0.04 b	0.35 c	0.15	0.8	7.0 b
2002	73 b	277 a	0.20 a	–	–	0.7	–
2003	116 a	152 b	0.03 b	1.61 b	0.02	0.2	11.0 b
Sunflower							
Tillage							
Conventional	67	115	0.05	1.30	0.01	0.95	19.4 b
Zero tillage	76	118	0.18	1.42	0.01	1.34	25.7 a
Year							
2000	43 c	60 c	0.06	2.46 a	0.02	1.21	46.3 a
2001	51 bc	66 bc	0.00	0.56 c	–	–	5.7 b
2002	78 b	244 a	0.35	–	–	1.22	–
2003	113 a	95 b	0.00	1.42 b	0.01	–	15.5 b

[a] Within year, means within crop and tillage or year followed by the same letter are not significantly different at $P < 0.05$.

rotations for field pea. Tillage system did not influence preplant soil water, water use, seed yield, harvest index, or water use efficiencies of seed or biomass production of field pea (Table 6). However, years differed for all parameters measured. Field pea water use varied four-fold among years, ranging from 33 to 122 mm. Yield ranged from 0.07 to 1.15 Mg ha^{-1}, averaging 0.70 Mg ha^{-1} over the 4 years, higher than the average grain yield of recropped wheat, 0.59 Mg ha^{-1}. Harvest index of pea was higher in 2002 and 2003 than for the years with lowest water use, 2000 and 2001. Pea WUE$_{\text{grain}}$ averaged 8.3 kg ha^{-1} mm^{-1} across the 4 years, but varied widely from year to year because of the wide range in water use and yield.

3.4.2. Lentil

Across years, lentil in zero tillage used 14 mm more water than did lentil in conventional tillage (Table 6). Other parameters were not significant for the effect of tillage. Preplant soil water, water use, biomass production, and WUE$_{\text{biomass}}$ varied among years for lentil, but WUE$_{\text{grain}}$ and harvest index did not. Although not statistically significant, lentil seed yield was much higher in the wetter year of 2002 than in the three drier years. Control of kochia (*Kochia scoparia*) was poor in all lentils following application of imazethapyr, an ALS inhibitor, in 2000, and in zero tillage lentils in 2001 and 2002 following pendamethalin application, likely resulting in increased overall water use and subsequent poor lentil yields, particularly under zero tillage.

3.4.3. Chickpea

Chickpea followed summer fallow in this trial, and across years, chickpea under zero tillage had 21 mm more preplant soil water, and averaged 0.16 Mg ha^{-1} more grain than chickpea in conventional tillage (Table 6). Years varied for all parameters presented. Seed yield ranged from 0 to over 0.7 Mg ha^{-1}. Water use of chickpea averaged 121 mm, 16 mm lower than for spring wheat. Chickpea productivity was highest in 2002, a crop with normal growing season precipitation, followed by 2003, a drought year. Chickpea was present only in one rotation, following summer fallow. The preplant soil water was 164 mm in 2003, allowing for some yield potential to be expressed despite the low precipitation that season. Ascochyta blight, a foliar disease caused by *Ascochyta rabei*, caused loss of some seed pods prior to harvest in 2002. However, chickpea plots received a labeled and effective fungicide application in 2003, and disease symptoms were not observed that year or in 2000 or 2001.

3.4.4. Yellow mustard

Yellow mustard also followed summer fallow in our trial. In zero tillage, yellow mustard had 21 mm more preplant soil water than did conventional tillage (Table 6). Across years, parameters other than starting soil moisture did not vary by tillage system. However, water use and seed yield varied with respect to year. Insecticidal seed treatment was not used on yellow mustard, but replanting was required in 2003 because flea beetles (*Phyllotreta cruciferae* Goeze) killed most emerging seedlings from the initial 30 April planting date. For the other 3 years, 2000–2002, yellow mustard seed yields averaged over 0.31 Mg ha^{-1}, higher than for safflower and sunflower, the other oilseed entries in this trial. The WUE$_{\text{grain}}$ for yellow mustard averaged 4.5 kg ha^{-1} mm^{-1} over 2000–2002. Yellow mustard biomass samples were not collected in 2000, and harvest index and WUE of biomass analyses did not include data from that year.

Table 7
Linear functions predicting grain yield (kg ha^{-1}) by crop water use (mm) for spring wheat, pea, and chickpea, Havre, MT, 2000–2003

Regression function
Wheat yield = 35.9 + 5.8 × (water use, mm), $r^2 = 0.620$; $n = 79$
Pea yield = −246 + 11.8 × (water use, mm), $r^2 = 0.852$; $n = 16$
Chickpea yield = −378 + 5.2 × (water use, mm), $r^2 = 0.796$; $n = 8$

3.4.5. Safflower

Across years, safflower in zero tillage had more available water at planting (Table 6). Years varied for preplant soil water, water use, yield, biomass, and WUE of biomass. Yields of safflower were quite low. Safflower biomass samples were not collected from conventional tillage plots in 2002, and analyses of harvest index and WUE of biomass did not include data from that year. Weed management in safflower included fall-applied treflan, but broadleaf weed control was poor, particularly in zero tillage plots. Competition from kochia was intense in 2000–2002, years with dry soil in the previous fall, which probably resulted in substantial loss of the herbicide due to volatilization despite post-application tillage.

3.4.6. Sunflower

Across years, sunflower in zero tillage had more available water at planting and greater WUE of biomass production than sunflower in conventional tillage (Table 6). Years varied for preplant soil water, water use, biomass, and WUE of biomass. In 2 of 4 years, there was no measurable crop seed production.

3.5. Water use predictions of seed production

Regressions of water use predicting grain production were significant for spring wheat, field pea and chickpea (Table 7). Over 4 years, field pea had the highest grain productivity per mm water use, double that of spring wheat and chickpea. Regressions predicting yield of lentil, safflower, and mustard also were significant, but for each of these species, single year values heavily weighted the functions so they are neither presented nor discussed. Prediction of sunflower yield by water use of sunflower, which had very poor yields over 4 years, was nonsignificant.

4. Discussion

4.1. Spring wheat productivity

In general, yields and biomass of spring wheat and alternate crops were lower in our study than typically reported from Montana (Montana Agricultural Statistics Service, 2004). A region-wide drought occurred from 1998 through 2003, and crop production was severely impacted. From 2000 to 2003, precipitation averaged 154 mm from April through September, only 66% of the long-term average. Due to drought and our having initiated this experiment on a site following 10 years of crested wheatgrass and alfalfa in the Conservation Reserve Program, drainage of water did not occur below the maximum soil sampling depth of 1.2 m during this study.

In an 18-year trial, Campbell et al. (2004) compared grain yield and $\mathrm{WUE}_{\mathrm{grain}}$ of continuous spring wheat, FW, FWW, and FWWWWW and found that, although cropping frequency influenced annual productivity, yield and $\mathrm{WUE}_{\mathrm{grain}}$ of recropped spring wheat averaged 71 and 79%, respectively, of spring wheat following summer fallow, with continuous spring wheat and spring wheat following summer fallow averaging 1.83 and 2.64 Mg ha^{-1}, respectively. During the course of the trial in Saskatchewan, drought occurred only in 3 years, while another 5 years had well above average growing season precipitation. Conversely, severe drought occurred during 3 of the 4 years of our trial, and for the only year with average growing precipitation, drought was severe until mid-June, almost 6 weeks after crops were planted (Table 2). Across rotations and tillage systems, spring wheat yield averaged 0.55 and 0.97 Mg ha^{-1} for wheat following wheat compared to wheat following summer fallow. Wheat following wheat yielding only 56% of wheat following summer fallow, indicating that as conditions become drier, the overall advantages of recropping diminish.

Numerous trials have investigated diversified cropping systems in semiarid environments. In the Canadian prairie, Miller et al. (2002b) reported that spring wheat following four different pulse crops averaged 21% higher grain yield than wheat following wheat, averaging 2.39 and 2.02 Mg ha^{-1}, respectively, over eight site years. In a different study, Miller et al. (2003b) reported that spring wheat yield averaged 37% more following three pulse crops than spring wheat, primarily due to improved water use efficiency. Surprisingly, in our trial spring wheat following three pulses averaged 0.63 Mg seed ha^{-1}, only 15% greater than that of wheat following wheat. Although Miller et al. (2002b) reported 1 year of below average precipitation, both these trials were conducted during years of above average precipitation. In a Mediterranean climate, Denison et al. (2004) reported that years varied significantly for rainfed winter wheat production, primarily due to precipitation amounts and timing. Across three rotations, wheat grain production averaged 4.35 Mg ha^{-1} over 9 years. However, precipitation in several individual months of their study surpassed annual values for our site in Montana.

Few cropping systems studies have been reported from environments as dry as experienced during our study. In south-central Washington, USA, at a site averaging only 152 mm average annual precipitation, Schillinger and Young (2004) reported that winter wheat following summer fallow averaged 125% higher grain yield than continuous winter wheat over 5 years, 1.19 and 0.53 Mg ha^{-1}, respectively. Annual precipitation at the North Havre site averaged 154 mm from 2000 to 2003, comparable to that reported by Schillinger and Young (2004). In Victoria, Australia, O'Connell et al. (2002) reported that yield of winter wheat after fallow and mustard (*B. juncea*) averaged 1.72 and 1.22 Mg ha^{-1}, respectively. They concluded that mustard could be a beneficial rotational crop for wheat production, except during periods of drought when wheat yields were severely decreased by replacing fallow with mustard. O'Connell et al. reported wheat yields were depressed to 0.1 Mg ha^{-1} in a year with only 153 mm precipitation, comparable to spring wheat yields in our study in 2001. Precipitation during the 6 years reported by O'Connell et al. averaged 276 mm, 68 mm less than their long-term average. Only 2 of 6 years had average rainfall, with the other years experiencing drought, and spring wheat water use and $\mathrm{WUE}_{\mathrm{grain}}$ values were similar to those reported in our study. In northeastern Colorado, USA, Nielsen and Vigil (2005) found that winter wheat yield following fallow and several legume species averaged 3.9 and 2.6 Mg ha^{-1}, respectively, which was attributed to differences in soil water content at planting. They concluded that the beneficial effects of having a legume in rotation with winter wheat were not enough to offset the yield loss due to legume water use.

The adoption of zero tillage has led to more recropped acres in the Great Plains, with a concomitant reduction in summer fallow acreage. Across 10 rotational sequences and 4 years, zero tillage wheat plots averaged 95 mm of soil water from samples taken shortly before spring planting, only 14 mm more than found under conventional tillage. Other studies have reported substantially higher amounts of water capture in zero tillage systems than tilled fallow, including O'Leary and Connor (1997a), Cantero-Martinez et al. (1999), and Nielsen et al. (2002), but these studies were conducted in higher rainfall environments. O'Leary and Connor (1997a) documented that water capture differences between zero and conventional tillage systems became smaller with decreasing rainfall, while Halvorson et al. (2002) documented that yield differences among tillage systems were minimal during years with less than 300 mm annual precipitation in North Dakota, USA. In our study, rotational and seasonal effects were generally more important for spring wheat yield, water use, harvest index, and $\mathrm{WUE}_{\mathrm{grain}}$, than tillage system, similar to results of Halvorson et al. (2002) and Latta and O'Leary (2003).

4.2. Spring wheat yield components

Terminal drought frequently occurs in the northern Great Plains of Montana, and in part is responsible for the region's reputation for producing high quality hard red spring wheat. Drought and high temperature stress were shown to decrease photosynthesis, shoot and grain mass, and kernel weight of wheat (Shah and Paulsen, 2003), thereby decreasing yield. Terminal drought typically results in smaller kernel weight (Debaeke and Aboudrare, 2004), which we observed in 2001 and 2003. However, during the course of our study, drought also occurred early in the growing season, resulting in lower tiller density for recropped wheat than for wheat following summer fallow. Other research documented that early season or preanthesis drought had significantly lower tiller and kernel densities for wheat following pea (O'Leary and Connor, 1997b) or mustard (O'Connell et al., 2002) than for wheat following fallow. In a 5-year study with annual precipitation similar to that observed during our study, Schillinger and Young (2004) reported that winter wheat following fallow averaged greater spike density, kernels spike^{-1}, and kernel weight than did continuous zero tillage spring wheat, resulting in wheat following fallow having greater yield every year.

4.3. Alternate crop productivity

4.3.1. Field pea

Pulse crops are documented to be well adapted to the northern Great Plains (Miller et al., 2002a), especially field pea (Cutforth et al., 2002; Gan et al., 2002; Johnston et al., 2002; Anderson et al., 2003; Miller et al., 2003b; McKenzie et al., 2004), with its high yield potential and excellent WUE$_{\text{grain}}$. Despite drought, seed yields of field pea in our trial were substantially greater than for other alternate crops. Pea yields, however, were substantially lower than other published trials from the northern Great Plains (Cutforth et al., 2002; Gan et al., 2002; Johnston et al., 2002; Anderson et al., 2003; Miller et al., 2003b; McKenzie et al., 2004). Nevertheless, in our trial, average WUE$_{\text{grain}}$ of field pea was superior to that of wheat in all years except 2001, a year of extreme drought (Table 3), demonstrating that even during periods of substantial drought, field pea is well adapted to the region in recrop situations.

4.3.2. Lentil

Lentil productivity was poor in our study, with average yield only about 30% that of field pea. Yields were satisfactory only in 2002, the only year with somewhat normal precipitation during our study. Other research documented that yields of lentil were similar to field pea during periods of more normal precipitation (Miller et al., 2003b), while others reported lentil yielded substantially less than field pea (Nielsen, 2001; Cutforth et al., 2002). We found WUE$_{\text{grain}}$ of lentil was lower than that of field pea, similar to the results of Nielsen (2001) and Cutforth et al. (2002), but different from the results of Miller et al. (2003b), who reported slightly superior WUE$_{\text{grain}}$ values for lentil in two of five site years. Additionally, control of kochia was particularly poor under zero tillage most years, again, due to lack of rainfall for herbicide activation, further compromising yield and WUE. Overall, our results strongly indicate that planting of lentil during moderate to severe drought is inadvisable.

4.3.3. Chickpea

Chickpea yields were lower than reported for other trials conducted in the northern (Gan et al., 2002; Miller et al., 2003b) and central Great Plains (Nielsen, 2001), and other regions (Horn et al., 1996; Dalal et al., 1997; López-Bellido et al., 2004), but were similar to those of Thomson et al. (1997), who reported both chickpea and lentil were adversely affected by climatic or biotic factors. Averaged over 4 years, chickpea yields were greater under zero than conventional tillage, similar to that of Horn et al. (1996) and Hemmett and Eskandari (2004). As seen with lentil, we found WUE$_{\text{grain}}$ of chickpea was lower than that of field pea, similar to results of Nielsen (2001) at low water use and Cutforth et al. (2002), but different from the results of Miller et al. (2003b). Unlike lentil, weed control in chickpea was excellent from 2000 to 2003. However, the crop was terminated prior to maturity on 4 July 1999 due to intense kochia competition resulting from herbicide failure due to drought. Chickpea, previously reported to have excellent yield potential and adaptation to the northern Great Plains, did poorly in our trial, and does not appear to be adapted to the drought conditions present during the years of our study.

4.3.4. Yellow mustard

In our trial, yellow mustard yielded similarly to that reported by O'Connell et al. (2002), 0.27 and 0.22 Mg ha^{-1}, respectively, substantially less than reports of cool-season oilseed production in other trials in the northern Great Plains (Miller et al., 1998, 2003b; as reviewed in Johnston et al., 2002). Yellow mustard WUE$_{\text{grain}}$ was similar to that reported for *B. juncea* (Miller et al., 1998), despite only yielding 14% of that reported by Miller et al. (1998). Grain WUE of *Brassica napus* in Colorado (Nielsen, 1997) was reported to range from 0.8 to 3.1 kg ha^{-1} mm^{-1}, lower than found for yellow mustard in the current study. Overall, yellow mustard productivity was low, and this crop was not well adapted to the intensity of drought experienced during our trial.

4.3.5. Safflower

Safflower productivity was low in this trial due to insufficient plant available water. Average WUE$_{\text{biomass}}$ over years was similar to that observed by Anderson et al. (2003), 20.4 and 22.4 kg ha^{-1} mm^{-1}, respectively. Safflower can produce high yields of palatable forage when soil water is adequate (Wichman et al., 2001; Yau, 2004). Conversely, WUE$_{\text{grain}}$ in our trial was substantially lower than that reported by Anderson et al. (2003), 0.53 and 6.23 kg ha^{-1} mm^{-1}, respectively, indicative of the drought conditions experienced in northcentral Montana during our trial. Miller et al. (2002b) suggested that safflower was less well adapted to the Canadian prairie of the northern Great Plains than cool-season pulse and oilseed crops. Aase and Pikul (2000) concluded that safflower was poorly adapted to the northern Great Plains because its intensive water use causes poor productivity of the subsequent crop due to very low soil water availability, unless a season of summer fallow is included for soil water recharge. Our results agree with Miller et al. (2002b), safflower is poorly adapted to the northern Great Plains, especially during periods of drought.

4.3.6. Sunflower

Sunflower performed poorly in our trial, in large due to drought. However, pronghorn (*Antelocapra americana*) feeding on reproductive buds and flowering heads decimated the crop in 2002, the only year that sunflower had not died prior to, or at, anthesis. As with safflower, sunflower can be utilized as forage, and was shown to have production of 3.8 Mg ha^{-1} with WUE$_{\text{biomass}}$ of 16.3 kg ha^{-1} mm^{-1} (Anderson et al., 2003). Biomass yields and WUE$_{\text{biomass}}$ were similar for sunflower and safflower in our trial. Despite having significantly higher seed yields than those of our trial, Miller et al. (1998) concluded that sunflower ‘Sunola’ was not well adapted to the southern regions of the Canadian prairie in Saskatchewan, in part due to its low grain yield and $\text{WUE}_{\text{grain}}$ compared to pulse and cool-season oilseeds. Nielsen et al. (1999), Norwood (2000) and Aase and Pikul (2000) also reported that soil water contents were very low following sunflower harvest, leaving the subsequent crop more prone to significant drought stress if soil water recharge was insufficient. Results from our trial show that sunflower was not adapted to the northern Great Plains during drought.

4.4. Crop yield and water use relationships

Linear regression showed spring wheat yield increased by 5.8 kg ha^{-1} mm^{-1}, lower than the yield increases of 15.8 and 8.8 kg ha^{-1} mm^{-1}, reported by O’Connell et al. (2002) and Miller et al. (2002a), respectively. Linear regression predicting seed yield of spring wheat by cumulative water use explained 62% of yield variation across the 2000–2003 growing seasons near Havre, similar to the 66% reported by Aase and Pikul (2000). These estimates explaining wheat yield variation by cumulative water use were less than those from O’Connell et al. (2002) and Miller et al. (2002a), 84 and 72%, respectively. Differences among trials could be due to the range of water use values encountered, and perhaps, due to our regressions being fitted to data from 10 rotations in two tillage systems for each of 4 years, thus including other ‘rotational effects’ into variation not explained by water use alone.

For field pea, linear regression using cumulative water use to predict seed yield showed an increase of 11.8 kg ha^{-1} mm^{-1} in our trial, similar to the mean of 10.8 kg ha^{-1} mm^{-1} calculated from trials by O’Connell et al. (2002), Miller et al. (2002a) and Borstlap and Entz (1994), and higher than the 8.0 kg ha^{-1} mm^{-1} reported by Nielsen (2001). In our trial, cumulative water use explained 85% of yield variation in our trial, similar to that of O’Connell et al. (2002), who reported that 87% of pea yield variation was explained by water use. Other trials have reported substantially poorer fits for water use predicting pea yield, including Miller et al. (2002a) and Borstlap and Entz (1994), at 37 and 55%, respectively.

We found linear regression predicted increased chickpea seed yields of 5.2 kg ha^{-1} mm^{-1}, similar to the mean of 5.6 kg ha^{-1} mm^{-1} from four trials (Grewal et al., 1984; Sivakumar and Singh, 1987; Brown et al., 1989; Miller et al., 2002a), but much lower than that reported by Nielsen (2001), 10.6 kg ha^{-1} mm^{-1}. Cumulative water use by chickpea explained nearly 80% of observed yield variation, nearly identical to that of Brown et al. (1989), 79%, and the 81% of Nielsen (2001). However, Miller et al. (2002a) reported a much poorer relationship between water use and chickpea yield, only 39%, while Grewal et al. (1984) and Sivakumar and Singh (1987) reported values of 98 and 90%, respectively.

Improved water and precipitation use efficiencies in crop production are key factors for dryland cropping systems (Farahani et al., 1998; Hatfield et al., 2001). Our results document the need for higher levels of water use and water use efficiency.

5. Conclusions

This study was conducted during a severe, region-wide drought, and production of spring wheat and alternate crops in systems with or without summer fallow was poor. Preplant soil water contents were higher following summer fallow than for any crop, and spring wheat responded to this additional water better than chickpea or yellow mustard, the only other crops in the trial that followed summer fallow. Field pea generally performed best of all alternate crops, giving seed yields at least as good as those of recropped spring wheat. Chickpea, lentil, yellow mustard, safflower, and sunflower did not perform well and were not adapted to this region during drought.

Research to intensify and diversify the cereal–fallow system has been conducted in semiarid regions throughout the world. Replacing summer fallow with pulse and oilseed crops has been successful in Asia, Australia, and North America, particularly when precipitation occurs with adequate timing and quantity. Unfortunately, semiarid zones are prone to cyclical droughts, resulting in crop failure over extensive areas, especially for continuous cropping systems in areas that average 350 mm or less precipitation per year. Summer fallow was widely adopted in Northern Plains cropping systems, in part, to stabilize wheat yields. Summer fallow likely will continue to be practiced in the drier regions of the Northern Great Plains, even in growing seasons with precipitation levels sufficient for recropping pulse and oilseed crops. Development of flexible cropping systems (Sims, 1989; Lyon et al., 2003), concurrent with improved seasonal precipitation forecasting, are highly desirable for improving dryland agriculture in semiarid regions.

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