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Management and Tillage Influence Barley Forage Productivity and Water Use in Dryland Cropping Systems

Andrew W. Lenssen
Iowa State University, alenssen@iastate.edu

U. M. Sainju
United States Department of Agriculture

J. D. Jabro
United States Department of Agriculture

B. L. Allen
United States Department of Agriculture

R. G. Evans
United States Department of Agriculture

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Abstract

Annual cereal forages are resilient in water use (WU), water use efficiency (WUE), and weed control compared with grain crops in dryland systems. The combined influence of tillage and management systems on annual cereal forage productivity and WU is not well documented. We conducted a field study for the effects of tillage (no-till and tilled) and management (ecological and conventional) systems on WU and performance of forage barley (Hordeum vulgare L.) and weed biomass in two crop rotations (wheat [*Triticum aestivum* L.]–forage barley–pea [*Pisum sativum* L.] and wheat–forage barley–corn [*Zea mays* L.] –pea) from 2004 to 2010 in eastern Montana. Conventional management included recommended seeding rates, broadcast N fertilization, and short stubble height of wheat. Ecological management included 33% greater seeding rates, banded N fertilization at planting, and taller wheat stubble. Forage barley in ecological management had 28 more plants m^{-2}, 2 cm greater height, 65 more tillers m^{-2}, 606 kg ha^{-1} greater crop biomass, 3.5 kg ha^{-1} mm^{-1}greater WUE, and 47% reduction in weed biomass at harvest than in conventional management. Pre-plant and post-harvest soil water contents were similar among tillage and management systems, but barley WU was 13 mm greater in 4-yr than 3-yr rotation. Tillage had little effect on barley performance and WU. Dryland forage barley with higher seeding rate and banded N fertilization in more diversified rotation produced more yield and used water more efficiently than that with conventional seeding rate, broadcast N fertilization, and less diversified rotation in the semiarid northern Great Plains.

Disciplines

Agronomy and Crop Sciences | Plant Biology | Plant Breeding and Genetics | Plant Pathology | Weed Science

Comments

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Management and Tillage Influence Barley Forage Productivity and Water Use in Dryland Cropping Systems

A. W. Lenssen,* U. M. Sainju, J. D. Jabro, B. L. Allen, and R. G. Evans

ABSTRACT

Annual cereal forages are resilient in water use (WU), water use efficiency (WUE), and weed control compared with grain crops in dryland systems. The combined influence of tillage and management systems on annual cereal forage productivity and WU is not well documented. We conducted a field study for the effects of tillage (no-till and tilled) and management (ecological and conventional) systems on WU and performance of forage barley (Hordeum vulgare L.) and weed biomass in two crop rotations (wheat [*Triticum aestivum* L.]–forage barley–pea [*Pisum sativum* L.] and wheat–forage barley–corn [*Zea mays* L.] –pea) from 2004 to 2010 in eastern Montana. Conventional management included recommended seeding rates, broadcast N fertilization, and short stubble height of wheat. Ecological management included 33% greater seeding rates, banded N fertilization at planting, and taller wheat stubble. Forage barley in ecological management had 28 more plants m^{-2}, 2 cm greater height, 65 more tillers m^{-2}, 606 kg ha^{-1} greater crop biomass, 3.5 kg ha^{-1} mm^{-1} greater WUE, and 47% reduction in weed biomass at harvest than in conventional management. Pre-plant and post-harvest soil water contents were similar among tillage and management systems, but barley WU was 13 mm greater in 4-yr than 3-yr rotation. Tillage had little effect on barley performance and WU. Dryland forage barley with higher seeding rate and banded N fertilization in more diversified rotation produced more yield and used water more efficiently than that with conventional seeding rate, broadcast N fertilization, and less diversified rotation in the semiarid northern Great Plains.

Annual forages are well adapted to semiarid environments, including the Great Plains. A wide range of forage species, including cool-season grasses (Droushiotis, 1984), warm-season grasses (Lenssen and Cash, 2011), and grass–legume mixtures (Carr et al., 2004; Lenssen et al., 2010) can grow well in semiarid environments. Any of these annual forages can be used to effectively diversify dryland cropping systems (Entz et al., 2002).

Diversification and intensification of dryland wheat-based farming systems in the United States and Canadian prairie can improve sustainability through enhanced capture and utilization of precipitation in water-limited regions (Farahani et al., 1998; Lenssen et al., 2014). Inclusion of forages in wheat-based systems can improve weed (Schoofs and Entz, 2000; Derksen et al., 2002) and arthropod control (Olfert et al., 2002). Replacing summer fallow with forage barley increased profit in a durum (*T. durum* Desf.) annual forage rotation compared to durum–summer fallow (Lenssen et al., 2010).

A.W. Lenssen, Dep. of Agronomy, Iowa State Univ., Ames, IA 50011, and formerly: USDA-ARS, Northern Plains Agricultural Research Lab., Sidney, MT.; and U.M. Sainju, J.D. Jabro, B.L. Allen, and R.G. Evans, USDA, ARS, ASRU, Sidney, MT 59270. Received 8 Aug. 2014. Accepted 19 Nov. 2014.
*Corresponding author (alenssen@iastate.edu).

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Annual forages typically use less water than grain crops in the northern Great Plains (NGP). Aase and Pikul (2000) reported that water used annually by pea–oat (*Avena sativa* L.) forage mixtures ranged from 110 to 275 mm compared with 245 to 375 mm by wheat for grain over the course of a 5-yr study. Lenssen et al. (2010) found barley forage and barley–pea forage mixtures typically had similar annual WU, averaging 215 and 221 mm, respectively, compared with 260 and 257 mm used by durum following barley and barley–pea forages. Additionally, durum had mean WU of 259 mm following foxtail millet [*Setaria italica* (L.) P. Beauv.], a warm-season grass also harvested for forage in their study. Conversely, durum in rotation with summer fallow had mean WU of 301 mm, about 40 mm greater than that by the annual forages, resulting in 767 kg ha^{-1} increased grain yield. Replacing summer fallow with annual forages can impact WU and grain yield of the subsequent crop, but still can enhance the overall system sustainability (Lyon et al., 2004; Lenssen et al., 2010).

Cultural management and the application of agroecological principles can improve competitiveness of barley with weeds in grain production systems (Altieri, 1995). In Alberta, Canada, O'Donovan et al. (2001) observed that greater barley seeding rate decreased wild oat (*A. fatua* L.) seed production by 53% in the absence of herbicide use when barley was harvested for grain. Studies in Australia reported that increased seeding rate of barley reduced rigid ryegrass (*Lolium rigidum* Gaudin)

Abbreviations: NGP, northern Great Plains; POSTH2O, post-harvest soil water 0- to 122-cm depth; PREH2O, pre-plant soil water 0- to 122-cm depth; SW, spring wheat; WU, water use; WUE, water use efficiency.

tiller density (Paynter and Hills, 2009). Wild oat had less interference with taller barley cultivars at greater seeding rates than shorter cultivars at lower seeding rates (O'Donovan et al., 2000). Banding N fertilizer improved cereal N uptake and decreased weed N uptake (Blackshaw et al., 2002) and wild oat fecundity (O'Donovan et al., 2008). Anderson (1999, 2000, 2005) documented that combining three cultural practices can reduce or preclude the need for herbicide applications in some annual grain crops, including corn (*Zea mays* L.) and proso millet (*Panicum miliaceum* L.). Beckie (2007) reviewed herbicide and other cultural management practices that can mitigate the negative impact of herbicide-resistant wild oat and green foxtail [*Setaria viridis* (L.) Beauv.]. The cultural practices included use of diversified rotations with forages, higher crop seeding rates, and taller cereal cultivars. O'Donovan et al. (2007) summarized integrated approaches to weed management for spring-seeded crops in the Canadian prairie, presenting concepts in harmony with those of Beckie (2007), and stressed the need for further studies.

When planted on soils derived from glacial till, forage barley seeds are usually land rolled to protect harvest equipment from rocks. While land rolling is done to push rocks back into the soil surface, it also improves soil–seed contact, and was shown to promote emergence of six small-seeded broadleaf weeds, including horseweed [*Conyza canadensis* (L.) Cronq.], kochia [*Bassia scoparia* (L.) A.J. Scott], prickly lettuce (*Lactuca serriola* L.), redroot pigweed (*Amaranthus retroflexus* L.), Russian thistle (*Salsola tragus* L.), and tumble mustard (*Sisymbrium altisimmum* L.) (Lenssen, 2009). Kochia and horseweed are highly competitive weeds with numerous populations expressing resistance to commonly used herbicides (Heap, 2014). When forage barley was planted early in northeastern Montana, resident weeds did not produce seeds in the absence of pre-plant tillage or broad spectrum herbicide application (Lenssen, 2008). Resident weeds present in that study included wild oat, green foxtail, kochia, Russian thistle, tumble mustard, redroot pigweed, and flixweed [*Descurainia sophia* (L.) Webb ex Prantl]. Despite several studies examining a number of cultural practices for decreasing weed competition and seed production in barley for grain and forage production, few results are available on the effects of combinations of cultural practices on weed control in annual forages.

Crop yield and water productivity values are not available for annual cereal forages managed with multiple cultural practices in tilled and no-till systems. Our objective was to determine the impacts of tillage practices, management systems, and crop rotation on yield, yield components, WU, and weed biomass in forage barley in dryland cropping systems in the NGP. We hypothesized that forage barley in a no-tilled intensely managed, diversified crop rotation with ecological management will grow better, produce higher yield, use water more efficiently, and control weeds than that in a tilled, less diversified rotation with conventional management.

MATERIALS AND METHODS

The field site was located about 8 km northwest of Sidney, MT (47°46′ N, 104°16′ W; altitude 690 m). Soil at the location was mapped as a Williams loam (fine-loamy, mixed, superactive, frigid Typic Argiustoll). These soils were formed in glacial till plains and moraines. Soil at the 0- to 15-cm depth had pH 6.1 (2:1, water/soil) and concentrations of Olsen available P 12 mg kg^{-1} and organic matter 18 g kg^{-1}. Long-term mean annual precipitation at the site is 357 mm, with about 77% occurring from April to September (Table 1). Before initiation of this study, the site had been in a cereal grain–summer fallow rotation under fall and spring tillage for at least three decades. Weather data for the specific research site were not available before 1999, and Sidney is the nearest weather station. A weather station at the research site was used for collection of precipitation, air temperature, and other meteorological data from 2004 to 2011.

The long-term dryland study was initiated in 2004 comparing four crop rotations in two tillage and two management systems, and previous reports have presented results for spring wheat (Qi et al., 2013; Lenssen et al., 2014). The experimental design was a randomized complete block in a split-plot arrangement. Tillage system was the whole-plot factor and included no-tillage and conventional pre-plant tillage. Split-plots were a factorial arrangement of management system and crop rotation. Crop rotations were continuous spring wheat (SW), SW–pea, SW–forage barley–pea, and SW–forage barley–corn–pea, with all phases present every year. Management systems were conventional and ecological practices, which varied by crop (Table 2). Conventional practices included standard seeding rates, N fertilization placement for cereals, standard row spacing for corn, and short stubble height at harvest. Ecological practices were used to enhance crop competitiveness with weeds, and included denser seeding rates, banding N at planting, row spacing, and taller stubble following crop harvest. Individual subplot size was 12.2 by 12.2 m. There were three replicates of each subplot treatment combination for a total of 120 plots.

Fertilization practices were typical for the region. Specific N fertilizer recommendations for forage barley production were not available, so the N requirement of 67 kg ha^{-1} for barley forage was based on a yield goal of 2400 kg ha^{-1} of barley grain from Montana State University (Jacobsen et al., 2003). Fertilizer N rate was determined by subtracting previous year's fall soil residual NO_3–N content in the 0- to 60-cm depth

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

Month	2005	2006	2007	2008	2009	2010	68-yr avg.†
	Air temperature, °C						
April	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
August	19.8	21.3	20.3	21.2	18.6	20.2	20.4
September	15.7	13.3	14.5	14.5	18.1	12.8	14.2
	Precipitation, mm						
April	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
August	19	36	8	23	38	56	37
September	2	67	19	22	13	20	34
January–December	324	339	280	189	282	415	357

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

from the total N requirement. Nitrogen fertilizer as urea was broadcast using a calibrated, air-delivery pull-type granular applicator (Valmar Airflo Inc., Elie, MB) before pre-plant tillage in the conventional management and banded 5 cm below the surface and to the side of the seed row at planting in the ecological management. The only means of incorporation for broadcast N fertilizer in no-till plots was via natural rainfall following application. Phosphorus as monoammonium phosphate (11–52–0) and K as muriate of potash (0–0–60) were banded at planting in both management systems to wheat, barley, and pea and corn at 56 kg P_2O_5 ha^{-1} and 45 kg K_2O ha^{-1}, respectively.

Pre-plant conventional tillage was done with a single pass of a field cultivator equipped with C-shanks attached with 45-cm wide sweeps and coil-tooth spring harrows with 60-cm length bars. Tillage to a depth of 7 to 8 cm was controlled by stabilizer wheels on the field cultivator frame. For both management systems, SW cultivar Reeder, forage barley cultivar Haybet, and green field pea cultivar Majoret were planted with a 3.1-m wide drill with row spacing of 20.3 cm. The drill was equipped with double-shoot Barton (www.flexicoil.com/barton.asp) disk openers for low disturbance, single-pass seeding and fertilization. Barley seeding rate was 2.23 and 2.98 million pure live seed (PLS) ha^{-1} in conventional and ecological management systems, respectively (Table 2). Immediately following planting, barley and pea plots were land rolled. The roller consisted of a 1.1 m in diameter by 3.1 m width metal cylinder attached to a carriage frame. Total weight of the roller was 2415 kg. Hybrid corn cultivar 39T67-RR (Pioneer Hybrids International, Inc., Johnston, IA) was planted in mid-May in a skip-row (plant two rows, skip one row) configuration on 56-cm row spacing for 2004 to 2007. From 2008 to 2010, corn planting was done on 56- and 112-cm row spacing for conventional and ecological management systems, respectively. Ecologically managed SW was planted in early May, about 3 wk after planting in the conventionally managed system to allow emergence of the first flush of wild oat. Economic damage from arthropods or foliar diseases was not observed in this study, precluding the need for insecticide or foliar fungicide applications crops.

Each year no-till plots received a pre-plant application of glyphosate [N-(phosphonomethyl)glycine] [3.36 kg a.i. ha^{-1} in 37.8 L ha^{-1}] to control early emerging weeds. Barley did not receive an in-crop herbicide in any year. Weed management for SW, pea, and corn was done each year with appropriate, labeled herbicides for broadleaf and grass weeds. When post-harvest weed populations warranted, a post-harvest tank-mixed application of glyphosate and dicamba (3,6-dichloro-o-anisic acid) [3.36 kg and 0.56 kg a.i. ha^{-1}, respectively, in 37.8 L ha^{-1} water] was applied following harvest of barley forage.

Stand density of barley was determined at the one- to two-leaf stage by counting plants in four 1-m length rows in each plot. Aboveground crop and weed biomass was determined by hand clipping two 0.5 m^2 quadrats per plot when barley was at Zadoks stages 71 to 73 (Zadoks et al., 1974). Weeds were separated from crops and samples were transported to a laboratory, dried in a forced air oven at 55°C, and weighed.

Total biomass was calculated as the sum of crop and weed aboveground biomass. Plant height was determined on 10 stems in each plot. Stem density, including main stems and reproductive tillers, was determined from 1-m of row. Individual stem weight (g $stem^{-1}$) was calculated as:

$$\text{Stem weight} = \text{Total CB}/\text{Stems} \qquad [1]$$

where CB is crop aboveground biomass (g m^{-2}) and Stems is the sum of main stem and reproductive tiller density (no. m^{-2}). Forage was removed from plots using a self-propelled swather equipped with a 3.7-m header followed by baling with a JD375 round baler. Biomass yield data are presented as 100% dry matter.

Soil water content at 23-, 46-, 61-, 91-, and 122-cm depths was determined using a calibrated neutron probe before planting and after harvest (Chanasyk and Naeth, 1966). Crop WU(in millimeters) was calculated as:

$$WU = PREH_2O + PRECIP - POSTH_2O \qquad [2]$$

where $PREH_2O$ is the pre-plant soil water content (mm, 0- to 1.22-m depth), PRECIP is the total seasonal precipitation between pre-plant and post-harvest soil sampling, and $POSTH_2O$ is the post-harvest soil water content (mm, 0- to 1.22-m depth) (Farahani et al., 1998). Water-use efficiency (kg ha^{-1} mm^{-1}) was calculated as:

$$WUE_{forage} = FB/WU \qquad [3]$$

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

Crop	Management practices	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	0.037‡ 0.025§	broadcast	early May	20
	ecological	0.048‡ 0.025§	broadcast	early May	30

† Spring wheat, pea and barley received 6 kg ha^{-1} of N from monoammonium phosphate banded at planting.
‡ Seeding rate for 2005 to 2007.
§ Seeding rate for 2008 to 2010.

where FB is the forage aboveground biomass yield (kg ha^{-1}) of barley and weeds and WU (mm) is water use (Eq. [2]) (Farahani et al., 1998).

Data were analyzed with PC-SAS (SAS Institute, 2008) using the MIXED procedure with appropriate error terms for a split-plot analysis with tillage, management, crop rotation, and year factors considered as fixed effects and replication as a random effect (Littell et al., 1996). Tillage was considered as the main plot and the factorial combination of crop rotation and management as the split-plot for data analysis. Mean separations were done using protected LSD by least square means test (Littell et al., 1996); differences among treatments were reported as significant at $P \le 0.05$. Assumptions of normality were tested using PROC UNIVARIATE (SAS Institute, 2008), and when necessary, data were transformed before analyses. Specifically, weed biomass data were normalized using a Log_{10} transformation before analysis of variance, however, non-transformed mean values are presented in the manuscript for the convenience of readers. Linear regression analysis was done to determine the relationship between total aboveground biomass and WU. Comparison of slopes from regression functions was done at the 95% confidence limit). Data from 2004 were not included in the analysis because all crops followed summer fallow that year. Surface water runoff was not evident in 2004 to 2010 and it was assumed that neither overland flow nor drainage of water below 1.22 m occurred in those years. However, runoff did occur on three rainfall events in 2011, so data for barley productivity and soil water for that year were not included in the analysis.

RESULTS AND DISCUSSION

Weather

Monthly total precipitation and air temperatures were variable over the course of the experiment, typical for the semiarid NGP (Table 1). Annual precipitation ranged from 189 mm (2008) to 415 mm (2010). Although monthly total

Table 3. Forage barley early season stand density, height, yield components, barley, weed, and total biomass, pre-plant soil water content (0- to 1.22-m depth), post-harvest soil water content (0- to 1.22-m depth), water use (WU), and water use efficiency (WUE) for total forage (WUE_{forage}) from 2005 to 2010, Sidney, MT.

Treatment	Stand	Height	Stem density	Stem weight	Barley biomass	Weed biomass	Total biomass	Pre-plant water	Post-harvest water	WU	WUE_{forage}
	no. m^{-2}	cm	no. m^{-2}	g tiller^{-1}		kg ha^{-1}		mm, 0–1.22-m depth		mm	kg ha^{-1} mm^{-1}
Tillage system											
Tilled	191	64	580	0.9	4641	353	4994	87	40	197	24.0
No-till	185	63	580	0.9	4805	253	5058	88	45	192	26.1
Management system											
Conventional	174b†	63 b	547b	0.9	4420b	385a	4805b	88	39	198	23.3b
Ecological	202a	65 a	612a	0.9	5026a	221b	5247a	87	46	191	26.8a
Rotation											
Wheat–Barley–Pea	187	64	577	0.9	4770	211	4981	85	47	188b	25.9
Wheat–Barley–Corn–Pea	190	64	583	0.8	4676	395	5071	90	38	201a	24.2
Year											
2005	166c	84a	700a	0.8c	5260b	716a	5976b	101c	88a	239b	22.6cd
2006	152d	72c	353d	1.5a	5107b	448a	5555b	118b	26d	166c	31.7a
2007	187b	75b	665ab	1.0b	6894a	93b	6987a	137a	42c	278a	25.5bc
2008	232a	41f	492c	0.4e	2145d	74b	2219d	52e	16d	105e	20.9d
2009	196b	47e	628b	0.6d	3818c	22c	3841c	54de	15d	141d	27.8b
2010	197b	66d	641ab	0.8c	5114b	464a	5578b	64d	68b	238b	21.7cd
Tillage (T)	ns‡	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Management (M)	***	*	**	ns	**	**	*	ns	ns	ns	*
T × M	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Rotation (R)	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
T × R	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
M × R	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
Year (Y)	***	***	***	***	***	***	***	***	***	***	***
T × Y	*	**	ns	ns	**	**	**	ns	ns	ns	ns
M × Y	**	ns	ns	ns	*	ns	ns	ns	ns	ns	*
T × M × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
R × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
T × R × Y	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
T × M × R × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

* Significant at $P \le 0.05$.

** Significant at $P \le 0.01$.

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

† Means followed by different lowercase letter within a column and treatment are significantly different at $P \le 0.05$ by the protected LSD.

‡ ns, not significant.

precipitation during the growing season (April–September) was close to the normal, above-average precipitation occurred in May of 2005, 2007, and 2010. Below-average precipitation occurred in June and July 2007, and April to July 2008. Daily average air temperatures varied less than precipitation. Notable exceptions, however, included July 2006 and 2007 when air temperature was above the normal and May to July 2009 when temperature was below the normal (Table 1). For most years, May mean temperature was lower than the long-term normal.

Barley Forage

Barley stand density varied for management and year, with significant interactions for tillage × year, and management × year (Table 3). Averaged across crop rotations and management systems, stands were denser in the till than no-till treatment in 2005 and 2006 (Table 4). However, in the other years, stand densities were similar between tillage systems. By design, ecological management included a greater seeding rate to achieve greater average stand density across tillage and crop rotations which occurred in all years, except 2006 (Table 5). Averaged across treatments, stand density was greater in 2008, a year with lower precipitation, than other years. Barley appeared to germinate and emerge well in relatively dry conditions.

Plant height at harvest varied for management and year, with significant tillage × year interaction (Table 3). Averaged across crop rotations and management systems, barley forage was taller in tilled than no-till practice in 2007, but the trend reversed in 2008 (Table 4). Increased soil water content favored plant height in the no-till treatment during dry years. Averaged across years, crop rotations, and tillage practices, barley was taller in the ecological than conventional management (Table 3). Reduced competition from weeds during late planting of spring wheat may have increased barley plant height in the ecological management. Taller crop canopies are more competitive with weeds than shorter canopies (Anderson, 1999, 2005).

Table 4. Interaction of tillage system with year for forage barley early season stand density, height, barley biomass, weed biomass, and total forage biomass, Sidney, MT.

Tillage system	2005	2006	2007	2008	2009	2010
			Stand density, no. m^{-2}			
Tilled	180a†	163a	190	230	193	193
No-till	151b	142b	184	233	199	201
			Height, cm			
Tilled	85	71	77a	40b	48	67
No-till	83	73	73b	42a	47	65
			Barley biomass, kg ha^{-1}			
Tilled	4814b	4608 b	7476a	2000	3889	5061
No-till	5706a	5606 a	6312b	2291	3748	5167
			Weed biomass, kg ha^{-1}			
Tilled	927a	488	32	92	6b	571
No-till	505b	408	155	55	39a	356
			Total forage biomass, kg ha^{-1}			
Tilled	5740	5096b	7507a	2092	3895	5632
No-till	6211	6014a	6467b	2346	3786	5523

† Means followed by different lowercase letter within a column in a year are significantly different at $P \leq 0.05$ by protected LSD.

Barley stem density varied for management and year and stem weight for year (Table 3). Averaged across tillage practices, crop rotations, and years, stem density was greater in the ecological than conventional management. Higher seed rate and banded N fertilization also appeared to favor stem density in the ecological management. Averaged across treatments, stem density was greater in 2005 and stem weight greater in 2006 than other years. Near-normal precipitation increased stem density and weight in 2005 and 2006 but dry conditions reduced these parameters in 2008 compared with other years.

Forage barley biomass varied for management and year, with significant interactions for tillage × year and management × year (Table 3). Barley biomass, averaged across tillage and crop rotation, was higher in the ecological than the conventional management in 2005, 2006, and 2010 (Table 5). Higher seed rate and banded N fertilization increased barley biomass in the ecological management compared to conventional management during years of near or above-average precipitation. Reduced competition from weeds appeared to increase barley biomass in the ecological management when precipitation was not limited. Barley biomass was also greater in the no-till than the till treatment in 2005 and 2006, but the trend reversed in 2007 (Table 4). No-till favored barley forage biomass compared to the tilled treatment during years of adequate precipitation.

Weeds with Barley Forage

Weed and total biomass varied for management and year, with significant interactions for tillage × year (Table 3). Weed biomass was reduced by nearly 43% in the ecological than the conventional management when averaged across tillage, crop rotations, and years, documenting the improved competitiveness of a well-designed, ecologically-based management system that includes multiple cultural practices (Anderson, 2005). Barley forage in no-till had 45.5% less weed biomass than barley in tilled treatment at harvest in 2005 when averaged across crop rotations and management systems (Table 4). In 2009, weed biomass was slightly greater in no-till, but the 33 kg ha^{-1} difference observed between tillage systems is biologically and economically nonsignificant in almost any cropping system as long as weed seed production does not occur before forage harvest. Wild oat, green foxtail, and kochia accounted for 93% of the total weed individuals enumerated for 2005 to 2010. Weeds associated with barley forage never produced viable seed

Table 5. Interaction of management with year on forage barley early season stand density, biomass, and water use efficiency, Sidney, MT.

Management level	2005	2006	2007	2008	2009	2010
			Stand density, no. m^{-2}			
Conventional	153b†	151	172b	221b	168b	182b
Ecological	178a	154	202a	242a	225a	212a
			Barley biomass, kg ha^{-1}			
Conventional	4730b	4464b	6744	2078	3937	4569b
Ecological	5790a	5750a	7044	2213	3700	5659a
			Water use efficiency of total forage, kg ha^{-1} mm^{-1}			
Conventional	18.7b	27.6b	24.1	24.5	29.6	19.3
Ecological	26.6a	35.9a	27.0	21.3	25.9	24.1

† Means followed by different lowercase letter within a column in a year are significantly different at $P \leq 0.05$ by protected LSD.

despite the absence of in-crop herbicide applications (results not presented). The recent development of glyphosate-resistant kochia in the central and northern Great Plains (Beckie et al., 2013; Hall et al., 2014; Mithila et al., 2014) will likely require changes in the predominant cropping systems which include only cereal and pulse crops. Diversification with annual forages such as herbicide-free forage barley (Lenssen, 2008,2009; Lenssen et al., 2010) will decrease selection pressure for development of resistance to glyphosate and other herbicides, and improve management options where resistant weed populations are present (Mortensen et al., 2012). When averaged across treatments, weed and forage barley biomass had opposite trends among years (Table 3), suggesting strong competition between barley and weeds. Total biomass among tillage practices and years behaved similarly as barley biomass (Tables 3 and 4), suggesting the dominance of barley in controlling weeds.

Barley forage is well documented as a valuable crop for ruminant livestock production (Carr et al., 2004; Francia et al., 2006) and is well adapted for use in reduced herbicide production systems (Harker et al., 2003; Lenssen, 2008; 2009; Lenssen et al., 2010). In mechanized harvest systems, farmers harvest both crop and weed biomass as forage. Although not quantified in the current study, nutritive value of cereal forages can be suitable for beef cattle, with and without inclusion of annual legumes (Droushiotis, 1984, 1989; Carr et al., 2004; Lenssen et al., 2010). Nutritive value and palatability of common weeds often found growing with annual cereal forages can enhance overall forage value (Marten and Anderson, 1975; Nashiki et al., 2005).

Soil Water and Water Use

Soil water storage varied only among years (Table 3). Averaged across treatments, pre-plant soil water content was higher from 2005 to 2007 than from 2008 to 2010. The 2008 growing season had the lowest pre-plant soil water content. Post-harvest soil water content was higher in 2005 but lower in other years, particularly 2008 and 2009 when drought conditions occurred during barley growth period. The range for post-harvest soil water content among years was 73 mm.

Barley forage WU varied among crop rotations and years (Table 3). Considering that water use by weeds was negligible, mean WU by barley forage across all treatments and years was 237 mm, 57 mm less than mean spring wheat WU of 294 mm at grain harvest reported previously for this study (Lenssen et al., 2014). Other studies reported similar WU for forage barley, including Lenssen et al. (2010) who reported WU of 215 mm from a 4-yr study. Conversely, Lenssen (2008) reported forage barley WU varied by year and planting date, and ranged from 180 to near 400 mm. Averaged across tillage practices, management systems, and years, WU by barley forage was 13 mm greater in the 4-yr than the 3-yr rotation, suggesting that inclusion of corn in the rotation resulted in additional water for use by subsequent crops. Mean WU across treatments was also greater in 2007 than other years, probably a result of greater pre-plant soil water content, thereby resulting in greater barley forage and total forage biomass (Table 3). The range for WU among years was 173 mm, much greater than the range for pre-plant- and post-harvest soil water content, indicating that forage barley can increase yield with greater growing season precipitation. The Pearson correlation coefficient (r) for pre-plant soil water and total biomass yield was significant ($r = 0.593$ $P = 0.0001$, $n = 143$). Because the experimental site typically receives 77% of annual precipitation from April through September, pre-plant soil water content is a poor predictor of subsequent crop yields in continuous cropping systems. The r for WU and total biomass was significant ($r = 0.716$; $P = 0.0001$, $n = 143$).

The barley forage WUE varied with management systems and years, with a significant management × year interaction (Table 3). Barley forage had significantly higher WUE in the ecological than the conventional management in 2005 and 2006 when averaged across tillage and crop rotations (Table 5). This trend was similar to that observed for barley biomass, suggesting that barley increased forage yield by using water more efficiently in the ecological than the conventional management during years with adequate precipitation. Differences between management systems for WUE were not significant in other years. The values for WUE of barley in our study were similar to those reported previously (Lenssen, 2008; Lenssen et al., 2010), and corroborate that forage barley is a highly efficient user of valuable soil water.

Regression analysis between WU and total biomass showed that the ecological management had greater yield response with additional WU [Forage biomass (kg ha^{-1}) = 908 +22.8WU (mm); $r^2 = 0.549$] compared with the conventional management [Forage biomass = 1374 +17.2WU (mm); $r^2 = 0.541$]. Water use explained about 54% of the variation in biomass yield for both management systems. A separate study in the NGP reported that WU accounted for 45% of the yield variation of barley forage (Lenssen et al., 2010), a case similar to that observed in this study. Forage barley can produce decent yields during drought, making it an excellent crop to include in cereal or cereal–pulse rotations. Forage barley also has the potential to respond well for increased yield to greater amounts of available soil water, while leaving more water in the soil profile for the subsequent crop than other grain crops due to early harvest for hay (Lenssen et al., 2010).

CONCLUSIONS

The strategy of multicomponent, ecologically-based management of forage barley was highly successful and provided denser stands and stem numbers with greater yield and higher WUE than the conventional management. Higher seed rate, banded N fertilization, and taller SW stubble height during the previous year in the ecological management had positive responses with increased barley forage yield especially during years with adequate precipitation. Concomitantly, weed biomass at barley harvest was the same or decreased in the ecological management. Plant stand, height, and total forage biomass varied by tillage system in 2 of 6 yr, but results were not consistent between systems. The results supported only part of the hypothesis. The inclusion of forage barley in the diversified crop rotation conferred resilience to the sustainability of dryland cropping systems in the semiarid NGP. The results may be applied to other regions with similar soil and climatic conditions where small grains are grown.

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