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Dryland Pea Production and Water Use Responses to Tillage, Crop Rotation, and Weed Management Practice

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Abstract

Pea (*Pisum sativum* L.) has been used to replace fallow and to sustain dryland crop yields in arid and semiarid regions, but information to optimize its management is required. We evaluated pea growth, yield, and water use in response to tillage, crop rotation, and weed management practice from 2005 to 2010 in the northern Great Plains, United States. Tillage systems were no-tillage and conventional tillage, and crop rotations were spring wheat (*Triticum aestivum* L.)–pea (W-P), spring wheat–forage barley (*Hordeum vulgaris* L.)–pea (W-B-P), and spring wheat–forage barley–corn (*Zea mays* L.)–pea (W-B-C-P). Weed managements were traditional (conventional seeding rates, early planting, broadcast N fertilization, and reduced stubble height) and improved (variable seeding rates, delayed planting, banded N fertilization, and increased stubble height) practices. Pea plant stand, height, pod number, grain and biomass yields, and water-use efficiency (WUE) were 4 to 23% greater with the improved than the traditional weed management practice, but seed number per pod was 5% greater with the traditional practice. Plant height, pod number, biomass and grain yields, preplant and postharvest soil water contents, and WUE were 2 to 51% greater with W-B-P and W-B-C-P than W-P. Pea yield and WUE increased with extended crop rotation with nonlegumes and the improved weed management due to enhanced plant growth and seed characteristics as a result of greater soil water availability, seeding rate, and wheat stubble height. Dryland pea yield and water use can be enhanced by using extended diversified crop rotations and by increasing seeding rate and wheat stubble height.

Disciplines

Agriculture | Agronomy and Crop Sciences | Hydrology | Soil Science | Weed Science

Comments

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ABSTRACT

Pea (*Pisum sativum* L.) has been used to replace fallow and to sustain dryland crop yields in arid and semiarid regions, but information to optimize its management is required. We evaluated pea growth, yield, and water use in response to tillage, crop rotation, and weed management practice from 2005 to 2010 in the northern Great Plains, United States. Tillage systems were no-tillage and conventional tillage, and crop rotations were spring wheat (*Triticum aestivum* L.)–pea (W-P), spring wheat–forage barley (*Hordeum vulgaris* L.)–pea (W-B-P), and spring wheat–forage barley–corn (*Zea mays* L.)–pea (W-B-C-P). Weed managements were traditional (conventional seeding rates, early planting, broadcast N fertilization, and reduced stubble height) and improved (variable seeding rates, delayed planting, banded N fertilization, and increased stubble height) practices. Pea plant stand, height, pod number, grain and biomass yields, and water-use efficiency (WUE) were 4 to 23% greater with the improved than the traditional weed management practice, but seed number per pod was 5% greater with the traditional practice. Plant height, pod number, biomass and grain yields, preplant and post-harvest soil water contents, and WUE were 2 to 51% greater with W-B-P and W-B-C-P than W-P. Pea yield and WUE increased with extended crop rotation with nonlegumes and the improved weed management due to enhanced plant growth and seed characteristics as a result of greater soil water availability, seeding rate, and wheat stubble height. Dryland pea yield and water use can be enhanced by using extended diversified crop rotations and by increasing seeding rate and wheat stubble height.

Core Ideas

- Management strategies for dryland pea production and soil water use are lacking.
- Tillage, crop rotation, and weed management effect on pea production were studied.
- Pea growth and yield and water use increased with diversified crop rotation.
- Increased seeding rate and stubble height also increased pea yield and water use.
- Diversified crop rotation and improved weed management can enhance pea production.

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Sustainable intensification of crops to increase yields should include pulse crops, such as dry pea, in arid and semiarid regions (Miller et al., 2015). Pea has been increasingly grown to replace fallow in these regions because it adapts well and requires less water to grow than cereals (Lenssen et al., 2007; Miller et al., 2003a). In the semiarid region of northern Great Plains in the United States, area under pea has been steadily increasing, but that under fallow has been decreasing since 1970 (Miller et al., 2015; Tanaka et al., 2010). Pea provides both rotational and nonrotational benefits to succeeding crops by increasing their yields and by enhancing soil and environmental quality (Stevenson and van Kissel, 1996). Rotational benefits include increased N supply from pea residue because of its higher N concentration as a result of atmospheric N fixation, thereby reducing N fertilization rates, and greater soil water availability to succeeding crops due to its reduced water uptake (Miller et al., 2003b; Stevenson and van Kissel, 1996). Nonrotational benefits include reduced incidences of weed, pests, and disease infections; increased P, K, and S availability; improved soil structure and growth substance released from pea residue (Stevenson and van Kissel, 1996); reduced N leaching (Payne et al., 2000); and decreased greenhouse gas emissions (Lupwayi and Kennedy, 2007; Sainju et al., 2014a, 2014b) compared with continuous nonlegume cropping. Other benefits include reduced risk of crop failure, enhanced biodiversity, and increased farm income (Miller et al., 2015; Zentner et al., 2002).

Dry pea is as an excellent source of protein and fiber in human and livestock diets (Hood-Niefer et al., 2012). It is one of the major sources of protein for people in developing countries where availability of other protein sources, such as meat and milk, are limited and for vegetarian people who do not consume meat (Tzitzikas et al., 2006). Because it can be grown easily, does not require much water to grow, needs little P and K fertilizers, and is a good N-fixer, pea is widely popular in south Asia and Africa (Tao et al., 2017; Tzitzikas et al., 2006). Pea starch is also widely used in processing noodles (Ratnayake et al., 2002; Tan et al., 2009).

Crop yields of improved cultivars are usually projected based on the performance of cultivars over a wide range of soil and climatic conditions. The response of plants across variable environments is termed as the "genetics × environment interaction"

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Abbreviations: CT, conventional tillage; NT, no-tillage; W-B-C-P, spring wheat–forage barley–corn–pea; W-B-P, spring wheat–forage barley–pea; W-P, spring wheat–pea; WUE, water-use efficiency.

(Hatfield and Walthall, 2015). As global land resources are limited, a goal to meet the demand of 9 billion people by doubling the food production by 2050 can only be achieved by considering the genetics × environment × management interaction, which can efficiently utilize soil water and nutrients and increase the actual crop yield rather than increasing the yield potential (Hatfield and Walthall, 2015). This will also help lead to more resilient and sustainable crop production in a changing climate. Improved management techniques to enhance crop growth and yield in such conditions are lacking for grain legumes, such as pea (Lafond et al., 2011; Nleya and Rickertsen, 2011).

Tillage has a variable effect on pea yield. Some researchers (Machado et al., 2008; Payne et al., 2000, 2001) in the Pacific Northwest of the United States have reported that tillage had no effect on pea yield. In contrast, no-tillage (NT) increased pea yield compared with conventional tillage (CT) in the Canadian Prairie (Lafond et al., 2006) and in the Mediterranean region in Europe (Ruisi et al., 2012) due to increased pod number, especially during dry periods, by increasing soil water storage. Lafond et al. (2011) found that pea yield was lower in continuous pea than spring wheat–pea and spring wheat–spring wheat–pea rotations but similar between the latter two rotations. They also observed that crop rotation had no effect on pea plant stand and water-use efficiency (WUE). Diversified crop rotations increase crop yields by efficiently using water and N compared with moncropping and effectively controlling weeds, diseases, and pests (Lenssen et al., 2007; Miller et al., 2003b; Tanaka et al., 2002). Pea grown on pea stubble resulted in 13% lower yield than grown on wheat stubble (USDA–ARS, 2002).

Improved management techniques, such as increasing seeding rates, altering planting and harvest dates, using banded N fertilization, and increasing stubble height, can enhance crop yields by suppressing weeds because weeds compete with crops, which can alter the water and nutrient availability and timing of growth for hosts and pests (Lenssen et al., 2014, 2015). Increased seeding rate increases weed and crop competition, banded fertilization limits nutrient availability to weeds, delayed planting after late application of preplant herbicide kills weed seedlings, and tall stubble increases soil water content by catching more snow and reducing light penetration into the ground, thereby reducing weed germination (Nichols et al., 2015; Strydhorst et al., 2008). Some researchers (Anderson, 2005; Entz et al., 2002; Strydhorst et al., 2008) reported that increased crop seeding rate, banded fertilization, delayed planting and harvest dates, increased retention of crop residue at the soil surface, and inclusion of forages in the crop rotation reduced weed growth compared with conventional seeding rates, normal planting and harvest dates, broadcast fertilization, reduced residue retention, and monocropping. Increased seeding rate increased pea plant stand and grain yield (Nleya and Rickertsen, 2011; Towendy-Smith and Wright, 1994), but delayed seeding date reduced the yield due to increased heat stress (Gan et al., 2002; Miller et al., 2003a). Similarly, increased wheat stubble height increased soil water storage and pea plant stand, vine length, grain yield, and WUE by trapping more snow, limiting light penetration, and reducing weed growth (Cutforth et al., 2002; Huggins and Pan, 1991).

Information on the effect of soil and crop management practices on pea growth and yield and soil water use is limited. We evaluated the effect of tillage (NT and CT), crop rotation (spring wheat–pea [W-P], spring wheat–forage barley–pea [W-B-P], and spring wheat–forage barley–corn–pea [W-B-C-P]), and weed management practice (traditional and improved) on dryland pea productivity and soil water use from 2005 to 2010 in the semiarid region of the northern Great Plains in the United States. Our objectives were (i) to examine how tillage systems, crop rotations, and weed management practices affect pea growth, seed characteristics, grain and biomass yields, and soil water use in dryland cropping systems and (ii) to determine novel management strategies that optimize soil water use and enhance pea production. We hypothesized that NT with reduced frequency of pea in rotation with nonlegumes and the improved weed management practice would enhance soil water use and pea growth and yield compared with CT with increased frequency of pea in the crop rotation and the traditional weed management practice.

MATERIALS AND METHODS

Experimental Site

The experimental site was located about 8 km northwest of Sidney, MT (47° 46′ N, 104° 16′ W, altitude 690 m). Soil at the site was a Williams loam (fine-loamy, mixed, superactive, frigid Typic Argiustolls) formed in glacial till plains and moraines. Soil at the 0- to 15-cm depth had 350 g kg^{-1} sand, 325 g kg^{-1} silt, 325 g kg^{-1} clay, 6.1 pH, and 18 g kg^{-1} organic matter. Soil pH was measured using a pH meter (Thomas, 1996), and organic matter was measured with a dry combustion C-N analyzer (Nelson and Sommers, 1996). Prior to initiation of the study, the site had been in a spring wheat–summer fallow rotation under CT for several decades. The weather station at the research site was used for collection of data on precipitation and air temperature from 2005 to 2010. Average monthly air temperature at the site ranges from −8°C in January to 23°C in July and August. Mean annual precipitation (68-yr average) is 357 mm, 70% of which occurs during the crop growing season (April–August).

Experimental Design and Treatments

The long-term dryland field study was initiated in 2004 comparing two tillage systems, three crop rotations, and two weed management practices. The experimental design was a randomized complete block in a split-plot arrangement with three replications. Tillage system was the main-plot treatment and included NT and CT. The split-plot treatment was a factorial combination of crop rotation and weed management practice. Crop rotations were W-P, W-B-P, and W-B-C-P; all phases of the crop rotation were present every year. Weed management practices were “traditional” (conventional seeding rates, broadcast N fertilization for spring wheat and forage barley, and early planting date and short stubble height for spring wheat at harvest) and “improved” (increased seeding rates, banded N fertilization, and delayed planting date and long stubble height for wheat). Table 1 provides a detailed description of the weed management practice for each crop in the rotation. Plots in NT were left undisturbed, except for applying fertilizers and planting crops in rows. Plots in CT were tilled one to two times a year to a depth of 7 to 8 cm for seedbed preparation and weed control with a field cultivator equipped with C-shanks and 45-cm-wide sweeps and coil-tooth

Table 1. Description of weed management practices used for crops in the rotation.

Crop	Weed management practice	Seeding rate	N fertilization method	Planting date	Stubble height
		million ha^{-1}			cm
Spring wheat	Traditional	2.23	Broadcast	Early Apr.	20
	Improved	2.98	Banded	Early May	30
Pea	Traditional	0.60	Banded	Early Apr.	5
	Improved	0.92	Banded	Early Apr.	5
Forage barley	Traditional	2.23	Broadcast	Early Apr.	5
	Improved	2.98	Banded	Early Apr.	5
Corn	Traditional	0.037,† 0.025‡	Broadcast	Early May	20
	Improved	0.048,† 0.025‡	Broadcast	Early May	20

† Seeding rate from 2004 to 2007.

‡ Seeding rate from 2008 to 2010.

spring harrows with 60 cm bars. The split plot size was 12.2 × 12.2 m, and the main plot size was 219.6 × 12.2 m.

Crop Management

Dry pea (cv. Majoret) and forage barley (cv. Haybet) were planted in early April and spring wheat (cv. Reeder) in early April to early May 2004 to 2010 with a 3.1-m-wide no-till drill at a row spacing of 20.3 cm. Corn (cv. Pioneer hybrids 39T67-RR from 2004 to 2008 and 39D95-RR from 2009 to 2010) was planted in early May at a spacing of 60 cm. The drill was equipped with double-shoot Barton disk openers for low-disturbance planting and single-pass seeding and fertilization (http://www.flexicoil.com/barton.asp). At planting, P fertilizer as mono-ammonium phosphate (11% N, 23% P) at 56 kg P ha^{-1} and K fertilizer as muriate of potash (52% K) at 48 kg K ha^{-1} were banded to all crops to a depth of 5 cm below and 5 cm away from the seeds. At the same time, N fertilizer as urea (46% N) and monoammonium phosphate were applied at the recommended N rates of 101, 67, and 78 kg N ha^{-1} to spring wheat, forage barley, and corn, respectively. Pea received N fertilizer at 6 kg N ha^{-1} from monoammonium phosphate. Recommended N rates included actual N rate and soil residual N, which was determined as NO_3–N content in soil samples to a depth of 60 cm collected after crop harvest in the autumn of the previous year. Actual N rate is determined by deducting soil residual N from the recommended N rate. This was done to avoid excessive application of N fertilizers. Nitrogen fertilizer was either broadcast in the traditional weed management practice or banded in the improved practice, except for corn, where N fertilizer was broadcast in both practices (Table 1). Immediately after planting, pea and barley plots were land rolled to push rocks back into soil and protect equipment used for herbicide and pesticide applications and crop harvest (Saskatchewan Pulse Growers, 2000). The roller weighed 2415 kg and consisted of a 1.1-m-diameter by 3.1-m-width metal cylinder attached to a carriage frame.

Forage barley, spring wheat, and corn seeds were treated with labeled fungicides. Damage from arthropods or foliar diseases was not observed, precluding the need for insecticide or foliar fungicide applications. Plots in NT received a preplant application of glyphosate (*N*-[phosphonomethyl] glycine) at 3.36 kg active ingredient ha^{-1} to control early-emerging weeds. Weed management in pea used fall-applied sonalan (ethalfluralin) at 0.12 kg active ingredient ha^{-1} and postemergence applications of formulated, tank-mixed bentazon (3-Isopropyl-1*H*-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxide) and sethoxydim (2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one) at 1.68 kg active ingredient ha^{-1} prior to crop flowering. Herbicide applications for spring wheat and corn were done with labeled compounds and rates that were previously described (Lenssen et al., 2014, 2015); forage barley did not receive in-crop herbicide. At postharvest, residual weeds were treated with tank-mixed glyphosate (3.36 kg active ingredient ha^{-1}) and dicamba (3, 6-dichloro-2-methoxybenzoic acid) at 0.28 kg active ingredient ha^{-1}.

Data Collection

Plant stand of pea 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 plants per plot. Pea yield component samples were obtained from a 1-m row segment at crop maturity. All pods were hand picked, placed in a paper bag, and shelled by hand. Seeds were dried in the oven at 55°C, weighed, and counted. Two days before harvest, aboveground crop biomass was determined by hand clipping two 0.5-m^2 quadrats per plot. Pea biomass was separated from weeds, dried in the oven at 55°C for 3 d, and weighed. Grain yield was determined by harvesting grains with a self-propelled combine from an area of 15 m^2. Grains were air dried, cleaned, and weighed. A sample of the grain was oven dried at 55°C for 3 d to determine dry matter yield, from which grain yield was calculated on an oven-dried basis. Harvest index was calculated by dividing grain yield by aboveground crop biomass. After measuring grain yield, the rest of the grain was harvested with a self-propelled combine, and crop residue was returned to the soil. Spring wheat, forage barley, and corn were harvested using a plot combine as described in Lenssen et al. (2014, 2015).

Soil water content at 23, 46, 61, 91, and 122 cm depths was determined with a calibrated neutron attenuation probe before planting and after harvest (Chanasyk and Naeth, 1996). Total water content at 0 to 122 cm was calculated by adding contents from individual depths. Pea water use was calculated by deducting postharvest soil water content at 0 to 122 cm from the sum of preplant soil water content at 0 to 122 cm and the growing season precipitation (Farahani et al., 1998). The WUE was calculated by dividing pea grain yield by water use (Farahani et al., 1998).

Statistical Analysis of Data

Data were analyzed using the MIXED procedure of SAS (Littell et al., 2006). Tillage was considered as the main-plot treatment, and the factorial combination of crop rotation and weed management practice was considered as the split plot

Table 2. Monthly average air temperature and total precipitation during the pea growing season (April–August) from 2005 to 2010 at the experimental site.

Month	68-yr avg	2005	2006	2007	2008	2009	2010
				Air temperature (°C)			
Apr.	7.0	8.6	8.9	5.6	5.2	5.4	7.8
May	13.3	10.9	13.7	13.0	12.2	11.9	10.3
June	18.1	17.7	18.2	18.6	16.3	16.5	17.0
July	21.2	21.6	24.1	24.7	22.0	18.8	20.1
Aug.	20.4	19.8	21.3	20.3	21.2	18.6	20.2
				Precipitation (mm)			
Apr.	29	2	80	21	11	39	29
May	50	83	44	128	28	8	142
June	72	115	55	49	32	56	71
July	54	36	30	21	32	70	51
Aug.	37	19	36	8	23	38	56
Apr.–Aug.	242	255	245	227	126	211	349
Jan.–Dec.	357	324	339	280	189	282	415

treatment. Fixed effects were tillage, crop rotation, weed management practice, year, and their interactions. Random effects were replication and replication × tillage interaction. The data for harvest index were transformed to square root values for variance normalization before analysis and transformed back for presentation of the result. Mean separations were done using the least square means test (Littell et al., 2006) when treatments and interactions were significant. Differences among treatments were considered significant at $P \leq 0.05$. Data from 2004 were not included in the analysis because 2004 was considered a crop establishment year.

RESULTS

Climate

Monthly total precipitation and average air temperature were variable over the course of the experiment from 2005 to 2010 (Table 2). Annual precipitation ranged from 189 mm (2008) to 415 mm (2010), with a 68-yr average of 357 mm. Growing-season (April–August) precipitation accounted for 68% of the total annual precipitation and was lower in 2008 (126 mm) and higher in 2010 (349 mm) than other years. Above-average precipitation occurred in May and June 2005 and in May 2007 and 2010. In contrast, below-average precipitation occurred in August 2007, April to August 2008, and May 2009. Monthly average air temperature varied less than precipitation. Notable exceptions included July 2006 and 2007, when air temperature was above the average, and May to July 2009, when temperature was below the average. For all years except 2006, air temperature in May was lower than the 68-yr average.

Pea Plant Stand and Height

Plant stand of pea varied for weed management practices and years, with significant interactions for tillage × year and weed management practice × year (Table 3). Averaged across crop rotations and weed management practices, plant stand was greater for NT than CT in 2005 but was not different between tillage systems in other years (Table 4). Averaged across tillage systems and crop rotations, plant stand was 12 to 39% greater for the improved than for the traditional weed management practice in all years (Table 5). Averaged across treatments, plant stand was greater in 2007 than other years (Table 6).

Pea height varied for weed management practices, crop rotations, and years, with significant interactions for tillage × year, weed management practice × year, and crop rotation × year (Table 3). Pea was taller for CT than NT in 2005 and 2010 when averaged across crops rotations and weed management practices (Table 4) and was taller for the improved than the traditional practice in 2007 and 2010 when averaged across tillage systems and crop rotations (Table 5). Averaged across tillage systems and weed management practices, compared with other crop rotations, pea was taller for W-B-P in 2005 and for W-B-C-P in 2006, 2007, and 2009 but shorter for W-B-C-P in 2008 (Table 7). Averaged across tillage systems, crop rotations, and years, pea was 2 cm taller for the improved than for the traditional weed management practice (Table 6). Averaged across tillage systems, weed management practices, and years, pea was 1 to 2 cm taller for W-B-P and W-B-C-P than for W-P. Averaged across treatments, pea was taller in 2007 than other years.

Pea Pod Number, Seed Number, and Seed Weight

Pod number of pea varied for weed management practices, crop rotations, and years, with significant crop rotation × year and tillage × crop rotation × year interactions (Table 3). Averaged across weed management practices, pod number was greater for W-B-P than for W-P with CT and NT in 2005, with NT in 2008, and with CT in 2010 but was greater for W-B-C-P than W-B-P with CT and NT in 2009 (Table 8). Pod number was greater for CT than NT with W-P and W-B-C-P in 2005 and with W-B-P in 2010 but was greater for NT than CT with W-B-P in 2008 and with W-B-C-P in 2010. Averaged across tillage systems, crop rotations, and years, pod number was 6% greater for the improved than the traditional weed management practice (Table 6). Averaged across tillage systems, weed management practices, and years, pod number was 11 to 12% greater with W-B-P and W-B-C-P than W-P. Averaged across treatments, pod number was greater in 2007 than other years.

Seed number pod^{-1} varied for weed management practices and years, with significant interactions for crop rotation × year and weed management practice × crop rotation × year (Table 3). Averaged across tillage systems, seed number was

Table 3. Analysis of variance for pea growth, yield, and water use (0–122 cm) with treatment factors of tillage, weed management practice, crop rotation, year, and their interactions.

Treatment	Plant stand	Plant height	Pod no.	Seed no.	Seed weight	Biomass yield	Grain yield	Harvest index	Preplant water	Postharvest water	Water use	WUE†
	no. m^{-2}	cm	no. m^{-2}	no. pod^{-1}	mg seed^{-1}	— kg ha^{-1} —			——— mm ———			kg ha^{-1} mm^{-1}
Tillage (T)	NS‡	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Weed management (M)	***	**	*	*	NS	**	***	NS	NS	NS	NS	**
T × M	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rotation (R)	NS	**	*	NS	NS	***	***	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
T × M x R	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year (Y)	***	***	***	***	***	***	***	***	***	***	***	***
T ×Y	**	***	NS	NS	NS	NS	***	NS	NS	NS	NS	**
M ×Y	***	**	NS	NS	*	*	**	NS	NS	NS	NS	*
T × M ×Y	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
R ×Y	NS	***	**	***	***	***	***	***	***	***	***	***
T × R ×Y	NS	NS	***	NS	NS	NS	NS	NS	NS	NS	NS	*
M × R ×Y	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 the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level

† Water-use efficiency.

‡ Not significant.

Table 4. Interaction between tillage and year on pea plant stand and height and grain yield.

Tillage†	2005	2006	2007	2008	2009	2010
			Plant stand (no. m^{-2})			
CT	52 a‡	73	78	73	77	75
NT	42 b	72	83	75	74	79
			Plant height (cm)			
CT	56 a	53	65	33	34	60 a
NT	53 b	56	65	35	35	55 b
			Grain yield (kg ha^{-1})			
CT	2411 a	1898	2474	457	2302	2843
NT	1974 b	2020	2468	557	2383	2964

† CT, conventional tillage; NT, no-tillage.

‡ Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

Table 5. Interaction between weed management practice and year for pea stand and height, biomass and grain yields, and water use efficiency (WUE).

Weed management†	2005	2006	2007	2008	2009	2010
			Plant stand (no. m^{-2})			
Traditional	44 b‡	65 b	73 b	69 b	57 b	64 b
Improved	51 a	80 a	89 a	78 a	93 a	90 a
			Plant height (cm)			
Traditional	54	54	64 b	34	35	55 b
Improved	56	55	66 a	34	34	61 a
			Biomass yield (kg ha^{-1})			
Traditional	4740 b	6280	7052	2531	5917	6775
Improved	5891 a	6378	7312	2630	5818	7332
			Grain yield (kg ha^{-1})			
Traditional	1988 b	1872	2388	489	2364	2726 b
Improved	2397 a	2046	2554	525	2321	3081 a
			WUE (kg ha^{-1} mm^{-1})			
Traditional	7.2 b	13.2 b	7.2	3.0	12.2	9.6 b
Improved	8.9 a	14.3 a	7.6	3.5	11.2	10.8 a

† See Table 1 for a detailed description of traditional and improved weed management practices.

‡ Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

greater for W-P than W-B-P and W-B-C-P with the traditional management practice in 2005 but was greater for W-B-P than other crop rotations with the improved practice in 2005 and 2008 (Table 9). Seed number was greater for W-B-C-P than W-P with traditional and improved practices in 2009 and 2010. Seed number was greater for the traditional than the improved practice with W-P in 2005 and with W-P and W-B-C-P in 2009, but the trend reversed with W-B-P and W-B-C-P in 2005. Averaged across tillage systems, crop rotations, and years, seed number was 5% greater with the traditional than the improved practice (Table 6). Averaged across treatments, seed number was greater in 2005 and 2006 than other years.

Pea seed weight varied among years, with significant interactions for weed management practice × year, crop rotation × year, and weed management practice × crop rotation × year (Table 3). Averaged across tillage systems, seed was heavier for W-P than W-B-P and W-B-C-P with the improved management practice in 2005, but the trend reversed with traditional and improved practices in 2008 (Table 9). Seed was heavier for the improved than the traditional practice with W-P in 2005, but the trend reversed with W-B-C-P in 2008. Averaged across treatments, seed was heavier in 2009 than other years (Table 6).

Pea Biomass and Grain Yields and Harvest Index

Aboveground biomass and grain yields of pea varied for weed management practices, crop rotations, and years, with significant interactions for tillage × year, weed management practice × year, and crop rotation × year, except for the tillage × year interaction for biomass yield (Table 3). Averaged across tillage systems and crop rotations, pea biomass was greater for the improved than the traditional management practice in 2005 (Table 5). Averaged

Table 6. Pea growth, yield, and water use as affected by weed management practice, crop rotation, and year.

Treatment	Plant stand	Plant height	Pod no.	Seed no.	Seed weight	Biomass yield	Grain yield	Harvest index	Preplant water	Postharvest water	Water use	WUE†
	no. m^{-2}	cm	no. m^{-2}	no. pod^{-1}	mg $seed^{-1}$	–kg ha^{-1}–				–mm–		kg ha^{-1} mm^{-1}
Weed management practice‡												
Traditional	62 b§	49 b	310 b	3.8 a	203	5549 b	1971 b	0.35	100	47	236	8.7 b
Improved	80 a	51 a	330 a	3.6 b	206	5893 a	2154 a	0.35	98	43	237	9.4 a
Crop rotation¶												
W-P	69	49 b	295 b	3.6	203	5175 c	1831 c	0.34	83 b	30 c	237	7.4 c
W-B-P	71	50 a	333 a	3.6	203	5812 b	2045 b	0.35	102 a	45 b	241	9.3 b
W-B-C-P	72	51 a	331 a	3.8	208	6177 a	2311 a	0.36	111 a	61 a	233	10.5 a
Year												
2005	47 d	55 c	290 d	4.5 a	211 c	5316 d	2193 c	0.43 a	117 b	66 b	278 b	8.0 d
2006	72 c	54 c	313 cd	4.4 a	185 d	6329 b	1959 d	0.31 c	111 b	82 a	159 d	13.7 a
2007	81 a	65 a	412 a	3.8 b	177 e	7182 a	2471 b	0.35 b	164 a	27 d	341 a	7.4 d
2008	74 bc	34 d	194 e	2.2 d	163 f	2580 e	507 e	0.19 d	77 c	15 e	153 d	3.2 e
2009	75 bc	34 d	333 c	3.2 c	259 a	5868 c	2343 b	0.40 a	69 c	45 c	203 c	11.7 b
2010	77 ab	58 b	376 b	4.0 b	232 b	7054 a	2904 a	0.42 a	54 d	37 cd	286 b	10.2 c

† Water-use efficiency

‡ See Table 1 for a detailed description of weed management practices.

§ Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

¶ W-B-P, spring wheat–forage barley–pea; W-B-C-P, spring wheat–forage barley–corn–pea; W-P, spring wheat–pea.

across tillage systems and weed management practices, biomass was greater for W-B-P than W-P and W-B-C-P in 2005 but was greater for W-B-C-P than W-P in 2006, 2009, and 2010 (Table 7). Averaged across tillage systems, crop rotations, and years, biomass was 6% greater for the improved than the traditional practice (Table 6). Averaged across tillage systems, weed management practices, and years, biomass was 6 to 16% greater for W-B-C-P and W-B-P than W-P. Averaged across treatments, biomass was greater in 2007 and 2010 than other years.

Averaged across crop rotations and weed management practices, pea grain yield was greater for CT than NT in 2005 (Table 4). Averaged across tillage systems and crop rotations, grain yield was greater for the improved than the traditional weed management practice in 2005 and 2010 (Table 5). Averaged across tillage systems and weed management practices, grain yield was greater for W-B-C-P than W-P in 2005, 2006, 2009, and 2010 (Table 7). Average grain yield across tillage systems, crop rotations, and years was 8% greater for the improved than the traditional practice (Table 6). Grain yield, averaged across tillage systems, weed management practices, and years, was 12 to 21% greater for W-B-C-P and W-B-P than W-P. Grain yield, averaged across treatments, was greater in 2010 than other years.

Harvest index varied for years, with a significant crop rotation × year interaction (Table 3). Averaged across tillage systems and weed management practices, harvest index was greater for W-P and W-B-C-P than W-B-P in 2005 but was greater for W-B-P in 2008 and for W-B-C-P in 2009 than other crop rotations (Table 7). Averaged across treatments, harvest index was greater in 2005, 2009, and 2010 than other years (Table 6).

Soil Water Content and Pea Water Use

Preplant soil water content varied for crop rotations and years, with a significant interaction for crop rotation × year (Table 3). Averaged across tillage systems and weed management practices, preplant soil water content was greater for W-B-P than W-P and W-B-C-P in 2005, but the trend reversed in 2006 (Table 7). In 2007, 2008, and 2009, preplant soil water content was greater for W-B-C-P than W-P. Averaged across tillage systems, weed management practices, and years, preplant soil water content was 19 to 25% greater for W-B-P and W-B-C-P than W-P (Table 6). Averaged across treatments, preplant soil water content was greater in 2007 than other years.

Postharvest soil water content varied for crop rotations and years, with significant interactions for crop rotation × year and weed management practice × crop rotation × year (Table 3). Averaged across tillage systems, postharvest soil water content was greater for W-B-C-P than W-P with the traditional and improved practices in 2005 and 2006, with the traditional practice in 2009, and with the improved practice in 2010 (Table 9). Postharvest soil water content was greater for W-B-P than W-P with the traditional practice in 2007 and 2010 and with the improved practice in 2008 but was greater with W-P than W-B-P with the improved practice in 2007 and greater for W-B-C-P than W-B-P with the improved practice in 2009. Postharvest soil water content was greater for the traditional than the improved practice with W-B-C-P in 2005 and with W-B-P in 2007 and 2010, but the trend reversed with W-B-P in 2005 and with W-P in 2009. Averaged across tillage systems, weed management practices, and years, postharvest soil water content was 26 to 51% greater for W-B-C-P and W-B-P than W-P (Table 6). Averaged across treatments, postharvest soil water content was greater in 2006 than other years.

Soil water use by pea varied among years, with a significant interaction for crop rotation × year (Table 3). Averaged across tillage systems and weed management practices, water use was greater for W-B-P in 2005 and for W-P in 2006 than other crop rotations (Table 7). Water use was greater for W-B-P and W-B-C-P than W-P in 2007 and 2008. Averaged across treatments, water use was greater in 2007 than other years (Table 6).

Pea WUE varied for weed management practices, crop rotations, and years, with significant interactions for tillage × year, weed management practice × year, crop rotation × year, and tillage × crop rotation × year (Table 3). Averaged across weed

Table 7. Interaction between crop rotation and year for pea growth, yield, and water use (0–122 cm depth)

Crop rotation†	2005	2006	2007	2008	2009	2010
			Plant height (cm)			
W-P	51 c‡	53 b	64 b	35 a	32 b	57
W-B-P	59 a	54 b	64 b	37 a	33 b	58
W-B-C-P	55 b	57 a	68 a	30 b	38 a	59
			Biomass yield (kg ha^{-1})			
W-P	3829 c	5887 b	6855	2204	5322 b	6955 b
W-B-P	6754 a	6222 ab	6932	3006	5248 b	6711 b
W-B-C-P	5365 b	6879 a	7758	2531	7034 a	7495 a
			Grain yield (kg ha^{-1})			
W-P	1737 b	1798 b	2388	290	2013 b	2763 b
W-B-P	2476 a	1940 ab	2416	758	1910 b	2770 b
W-B-C-P	2366 a	2139 a	2609	472	3104 a	3178 a
			Harvest index			
W-P	0.49 a	0.31	0.35	0.13 c	0.38 b	0.41
W-B-P	0.37 b	0.31	0.35	0.25 a	0.37 b	0.42
W-B-C-P	0.44 a	0.31	0.34	0.19 b	0.44 a	0.43
			Preplant soil water (mm)			
W-P	91 c	131 a	122 b	45 b	54 b	58
W-B-P	150 a	63 b	183 a	100 a	61 b	58
W-B-C-P	112 b	139 a	186 a	88 a	94 a	48
			Water use (mm)			
W-P	272 b	230 a	296 b	128 b	199	295
W-B-P	307 a	118 b	360 a	172 a	203	285
W-B-C-P	254 b	130 b	366 a	160 a	208	277

† W-B-P, spring wheat-forage barley-pea; W-B-C-P, spring wheat-forage barley-corn-pea; and W-P, spring wheat-pea

‡ Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test

Table 8. Interaction among tillage, crop rotation, and year on pea pod number and water use efficiency (WUE).

Crop rotation†	Pod number		WUE	
	CT‡	NT‡	CT	NT
	no. m^2		kg ha^{-1} mm^{-1}	
		2005		
W-P	258 b§ A¶	195 c B	7.3 b	5.9 b
W-B-P	364 a	373 a	8.7 ab	7.7 a
W-B-C-P	314 ab A	236 b B	10.2 a A	8.4 a B
		2006		
W-P	295	284	7.4 c	8.2 c
W-B-P	300	345	14.6 b B	18.9 a A
W-B-C-P	317	337	16.7 a	16.4 b
		2007		
W-P	400	425	8.8	7.7
W-B-P	420	404	7.1	6.6
W-B-C-P	432	391	7.1	7.3
		2008		
W-P	159	158 b	2.0 b	2.5
W-B-P	195 B	258 a A	4.8 a	4.2
W-B-C-P	198	199 ab	2.5 a	3.5
		2009		
W-P	317 b	349 a	10.7 b	9.5 b
W-B-P	277 c	313 b	9.6 b	9.8 b
W-B-C-P	395 a	348 a	14.2 a B	16.2 a A
		2010		
W-P	357 b	348 b	8.8 b	10.0 ab
W-B-P	452 a A	294 b B	9.8 ab	9.7 b
W-B-C-P	334 b B	472 a A	11.3 a	11.7 a

† W-B-P, spring wheat–forage barley–pea; W-B-C-P, spring wheat–forage barley–corn–pea; W-P, spring wheat–pea.

‡ CT, conventional tillage; NT, no-tillage.

§ Numbers followed by different lowercase letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

¶ Numbers followed by different uppercase letters within a row in a set are significantly different at $P \leq 0.05$ by the least square means test.

management practices, WUE was greater for W-B-C-P than W-P with CT and NT in 2005 and 2009 and with CT in 2006, 2008, and 2010 (Table 8). Water-use efficiency was greater for W-B-P than W-P with NT in 2005, with CT and NT in 2006, and with CT in 2008 but was greater for W-B-C-P than W-B-P with NT in 2010. Water-use efficiency was greater for CT than NT with W-B-C-P in 2005, but the trend reversed with W-B-P in 2006 and with W-B-C-P in 2009. Averaged across tillage systems and crop rotations, WUE was greater with the improved than the traditional weed management practice in 2005, 2006, and 2010 (Table 5). Averaged across tillage systems, crop rotations, and years, WUE was 7% greater for the improved than the traditional practice (Table 6). Averaged across tillage systems, weed management practices, and years, WUE was 10 to 30% greater with W-B-C-P and W-B-P than W-P. Averaged across treatments, WUE was greater in 2006 than other years.

DISCUSSION

Increased seeding rate and wheat stubble height probably increased pea plant stand with the improved compared with the traditional weed management practice in all years (Tables 5 and 6). It is possible that increased seeding rate reduced weed growth through increased competition with pea in the improved weed management practice, thereby promoting plant stand. Nleya and Rickertsen (2011) and Towendy-Smith and Wright (1994) reported that pea plant stand increased with increased seeding rate as a result of reduced weed growth. Other possible reasons are increased soil water conservation through enhanced snow catchment and decreased light penetration as a result of increased wheat stubble height, which reduced weed growth in the improved practice. Increased crop plant stand with greater stubble height as a result of enhanced soil water content has been reported (Aase and Siddoway, 1980; Huggins and Pan, 1991). The reasons for increased plant stand with CT compared with NT in 1 out of 6 yr (Table 4) were not clear. Although above-average precipitation in May 2005 (Table 2) may have favored water percolation in the soil, thereby enhancing seed germination and plant stand with CT, similar precipitation amounts occurred in May 2007 and 2010. Overall, tillage had no impact on plant stand (Table 3). Similarly, crop rotation did not influence pea plant stand, a fact that was corroborated by other studies (Lafond et al., 2011; Nleya and Rickertsen, 2011). Greater plant stand in 2007 than other years was probably due to favorable air temperature and above-average precipitation in May (Table 2), which enhanced pea germination and emergence.

Enhanced soil water distribution at the plow layer during above-average precipitation in May also appeared to increase pea plant height with CT in 2005 and 2010 (Table 4). Similarly, efficient water use by pea due to increased seeding rate and wheat stubble height likely increased plant height with the improved weed management practice in 2007 and 2010 (Table 5) when the precipitation during the critical pea growth stage in May was

Table 9. Interaction among weed management practice, crop rotation, and year on pea pod number and seed weight and postharvest soil water (0–122 cm depth)

Crop rotation†	Seed number		Seed weight		Postharvest soil water	
	Traditional‡	Improved‡	Traditional	Improved	Traditional	Improved
	no. pod^{-1}		mg seed^{-1}		mm	
			2005			
W-P	5.1 a§ A¶	4.3 b B	211 B	247 a A	39 c	51 b
W-B-P	4.3 b B	5.0 a A	195	209 b	61 b B	78 a A
W-B-C-P	3.8 c B	4.5 b A	204	203 b	94 a	73 a
			2006			
W-P	4.4	4.3	189	189	38 c	25 c
W-B-P	4.3	4.4	180	183	78 b	73 b
W-B-C-P	4.5	4.4	188	182	131 a	146 a
			2007			
W-P	4.0	3.8	173	178	28 b	33 a
W-B-P	3.8	3.6	175	180	45 a A	10 b B
W-B-C-P	4.1	3.7	181	176	23 b	24 ab
			2008			
W-P	2.0	1.8 b	129 c	132 b	15	2 b
W-B-P	2.2	2.5 a	165 b	186 a	13	24 a
W-B-C-P	2.3	2.0 b	200 a A	166 a B	20	17 ab
			2009			
W-P	3.3 b A	2.8 b B	268	256	23 c B	44 ab A
W-B-P	3.0 b	2.8 b	258	248	44 b	29 b
W-B-C-P	4.0 a A	3.5 a B	263	263	72 a	58 a
			2010			
W-P	3.9 b	3.8 b	229	239	35 b	26 b
W-B-P	4.1 a	3.8 b	226	232	51 a A	30 ab B
W-B-C-P	4.4 a	4.0 a	230	239	38 ab	42 a

† W-B-P, spring wheat–forage barley–pea; W-B-C-P, spring wheat–forage barley–corn–pea; W-P, spring wheat–pea.

‡ See Table 1 for a detailed description of weed management practices.

§ Numbers followed by different lowercase letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

¶ Numbers followed by different upper letters within a row in a set are significantly different at $P \leq 0.05$ by the least square means test.

higher than in other years. Huggins and Pan (1991) reported that tall stubble height of wheat resulted in longer internodes and greater vine length of pea due to limited sunlight penetration in the Pacific Northwest. In contrast, Nleya and Rickertsen (2011) found that seeding rate had no effect on pea plant height in the northern Great Plains. Although plant height varied with crop rotations in various years (Table 7), overall plant height increased with decreased frequency of pea in the rotation due to increased length of the rotation with nonlegumes, which appeared to follow a trend similar to preplant soil water content (Table 6). It is likely that increased soil water content at planting as affected by crop rotation influenced plant height. Lafond et al. (2011) also reported increased plant height with reduced frequency of pea in the crop rotation with nonlegumes. Similar to plant stand, the increased precipitation and favorable air temperature in May probably increased plant height in 2007 compared with other years. Shorter plant height of pea closer to the ground results in substantial difficulty when harvesting grains with a combine harvester (Nleya and Rickertsen, 2011).

Increased seeding rate also likely increased pea pod number in the improved compared with the traditional weed management practice (Table 6). This is in contrast to results reported by Nleya and Rickertsen (2011) and Towendy-Smith and Wright (1994), who observed that increased seeding rate decreased pea pod number. Increased seeding rate, however, reduced the overall number of seeds pod^{-1} in the improved practice, a finding similar to results reported by Nleya and Rickertsen (2011) and Towendy-Smith and Wright (1994). Although pod number varied with tillage systems and crop rotations in various years (Table 7), the overall greater pod number with W-B-P and W-B-C-P than W-P (Table 6) suggests that the reduced frequency of pea in rotation with nonlegumes favors the number of pea pods. Like pod number, seed number and weight varied with crop rotations and weed management practices in various years (Table 8). Tillage had no effect on pod number or on seed number and weight; these observations are similar to those reported by Ruisi et al. (2012). Greater pod number in 2007 than other years followed trends similar to those for plant stand and height but in contrast to those for seed number and weight (Table 6).

Although increased grain yield with CT compared with NT in 2005 was similar to that observed for plant stand and height (Table 4), tillage, overall, had no impact on pea grain and biomass yields. This is similar to results reported in the Pacific Northwest (Machado et al., 2008; Payne et al., 2000, 2001). In contrast, NT increased pea grain and biomass yields compared with CT due to increased soil water conservation in the Canadian Prairies (Lafond et al., 2006) and in the Mediterranean region in Europe (Ruisi et al., 2012). Because pea requires less soil water than wheat and barley, increased soil water conservation with NT does not have much impact on pea yield in the northern Great Plains (Lenssen et al., 2007; Miller et al., 2003a, 2003b).

The greater grain and biomass yields with the improved than the traditional weed management practice in 2005 and 2010 were due to increased plant stand and height (Table 5). Growing season (April–August) precipitation was greater in 2005 and 2010 than other years and was greater than the 68-yr average (Table 2). Higher precipitation in May and June, the active growing period for pea, in these years appeared to boost pea growth and yield in the improved practice, including higher seeding rate and wheat stubble height. Enhanced soil water content and extra support to reduce lodging due to increased stubble height and efficient water use due to higher seeding rate during the periods with above-average precipitation likely increased pea grain and biomass yields in the improved practice. Greater pea yield with increased seeding rate and wheat stubble height have been reported (Huggins and Pan, 1991; Nleya and Rickertsen, 2011; Towendy-Smith and Wright, 1994).

The greater grain and biomass yields with W-B-P and W-B-C-P than W-P in most years (Table 7) suggest that reduced frequency of pea in rotation with nonlegumes favored pea yield. It appears that pea grows well and produces more yield when rotated less frequently with nonlegumes. Similar results have been reported by Lafond et al. (2011), who found that pea in continuous pea yielded less than pea in spring wheat–pea and spring wheat–spring wheat–pea rotations. It is possible that pea does not grow well when soil is enriched with N, and the increased frequency of pea in the rotation may have increased soil N content. It has been reported that pea grown on pea stubble yields less grain and biomass than pea grown on wheat stubble (USDA–ARS, 2002). It is also likely that pea grown on pea stubble is more susceptible to diseases than pea grown on non-legume residue, thereby reducing yield. Pea can be susceptible to different diseases, and a lack of crop rotation can increase disease incidence and severity, thereby compromising yield (Cousin, 1997). However, in this study, disease symptoms on pea were rare and limited to a single, isolated plant. Increased grain and biomass yields in 2007 and 2010 compared with other years were similar to increased plant stand and height and pod number, suggesting that higher precipitation during these years enhanced pea growth and yield. Pea yield is increased during years with above-average precipitation (Payne et al., 2000, 2001). Harvest index varied with crop rotations and years (Table 7), probably due to differences in the production of grain and total aboveground biomass when pea was grown in various crop rotations. Tillage and weed management practice had no effect on harvest index, similar to results reported by Nleya and Rickertsen (2011), who found that seeding rate had no effect on pea harvest index.

Increased pea grain and biomass yields with diversified crop rotations also appeared to be associated with higher preplant and postharvest soil water content because these were greater with W-B-P and W-B-C-P than W-P in most years or averaged across years (Tables 6, 7, and 9). It is possible that a lower frequency of pea in rotations with nonlegumes uses less soil water, thereby increasing preplant and postharvest soil water content in more diversified crop rotations. Water use by pea, however, varied with crop rotations and years (Table 9), but the overall water use was not different among crop rotations (Table 6). Similar results have been reported by Lafond et al. (2011). Although postharvest soil water content varied with weed management practices in various years (Table 9), preplant and postharvest water content as well as water use, averaged across years, were not affected by tillage and weed management practice (Table 6). Greater preplant and postharvest water content and water use in 2006 and 2007 than other years were proportional to pea grain and biomass yields, indicating more water use by pea in improving yields in those years.

Enhanced pea WUE with the improved compared with the traditional weed management practice in 3 out of 6 yr (Table 5) was due to increased plant stand and height as well as grain and biomass yields. It is likely that pea used water more efficiently in the improved practice in 2005, 2006, and 2010, when the growing season and total annual precipitation were higher than other years, because seeding rate and wheat stubble height increased (Table 2). Reduced competition with weeds may have resulted in enhanced WUE in this practice. Cutforth et al. (2002) observed that pea WUE was greater with increased wheat stubble height. Similarly, greater WUE with W-B-P and W-B-C-P than W-P in most years or averaged across years (Tables 6 and 8) suggests that pea used water more efficiently for its growth as the diversity of crop rotations increased. This was in contrast to results reported by Lafond et al. (2011), who found that pea WUE was not affected by crop rotation. The effect of tillage on WUE was variable among crop rotations and years (Table 7), but tillage, overall, had no effect on WUE (Table 6). Payne et al. (2001), however, reported that pea WUE was greater with CT than NT. The overall trends for pea grain and biomass yields as affected by tillage, crop rotation, and weed management practice were similar to trends for WUE (Table 6), indicating that pea yield is related to WUE. Machado et al. (2008) reported that WUE is correlated to pea yield.

Because tillage had no effect on pea production and soil water use, NT with enhanced diversified crop rotations and increased seeding rate and residue stubble height can be used to increase pea growth, yield, and soil water use. No-tillage has advantages over conventional tillage in enhancing soil and environmental quality by improving soil structure, maintaining organic matter, increasing water storage and infiltration, reducing erosion, and mitigating greenhouse gas emissions (Ruisi et al., 2012; Sainju et al., 2014a, 2014b). Another benefit is saving energy because soil is not cultivated using tillage equipment in the NT system. Additional application of herbicide, however, is needed to control weeds in the NT system. Because herbicide application and higher seeding rate increase the cost of pea production, economic analysis is needed to determine if this cost is outweighed by returns from increased pea yield and enhanced soil and environmental quality using improved management strategies compared with conventional strategies.

CONCLUSIONS

Dryland pea production and soil water use were influenced by crop rotation and weed management practice in the semiarid northern Great Plains. Reduced frequency of pea in rotation with nonlegume crops due to increased length of crop rotation increased pea plant height, pod number, grain and biomass yields, soil water storage at planting and harvest, and WUE. Similarly, increased seeding rate and wheat stubble height increased pea plant stand and height, pod number, grain and biomass yields, and WUE in the improved weed management practice. Pea growth and yield, soil water storage, and WUE responded well in years with above-average precipitation. Dryland pea production can be increased and soil water use sustained in arid and semiarid regions by using enhanced diversified crop rotations with increased seeding rate and stubble height to reduce weed growth. Additionally, because tillage had no effect on pea yield and water use, an NT system can be used for dryland pea production to enhance soil and environmental quality.

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