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Dryland Corn Production and Water Use Affected by Tillage and Crop Management Intensity

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ABSTRACT

Management strategies to enhance dryland corn (*Zea mays* L.) production and soil water use are lacking. We evaluated the effect of tillage and crop management intensity on the growth, yield, and water use of dryland corn from 2005 to 2010 in the northern Great Plains. Tillage systems (no-tillage, NT, and conventional tillage, CT) as main-plot and crop management to corn (traditional intensity: conventional seeding rates and reduced wheat, *Triticum aestivum* L., stubble height; and improved intensity: increased seeding rate for 3 out of 6 yr and wheat stubble height) as split-plot treatments were arranged in a randomized complete block design with three replications. Corn plant stand was greater for CT than NT in 3 out of 6 yr and greater for the improved than the traditional intensity in 3 out of 3 yr. Seed number and grain yield were greater for NT than CT in 4 out of 6 yr. Biomass was greater for NT than CT in 1 out of 6 yr and greater for NT than CT in the traditional intensity. Corn plant height, seed weight, and harvest index as well as preplant and postharvest soil water, water use, and water-use efficiency were not influenced by treatments, but varied with years. Corn yield increased for NT compared with CT during years with below-average precipitation due to increased seed number and by reducing seeding rate and wheat stubble height. No-tillage with reduced seeding rate and wheat stubble height can enhance dryland corn production without affecting soil water.

Core Ideas

- Management practices for dryland corn production and water use are lacking.
- Tillage and weed management effect on corn yield and water use were conducted.
- Seed number and grain yield were greater with no-tillage than conventional tillage.
- Grain yield was also greater with reduced seeding rate and stubble height.
- No-till with reduced seeding rate and stubble height can enhance dryland corn yield.

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Lack of crop diversity is a major constraint in dryland production systems dominated by spring wheat (*Triticum aestivum* L.)–fallow in the semiarid region of the northern Great Plains, similar to those in the southern Great Plains (Patrignani et al., 2014). As dryland crop yields depend on the growing season precipitation, crops can fail due to the erratic nature of precipitation in this region (Nielsen et al., 2009, 2010). As a result, the entire region of the northern Great Plains suffers (Major et al., 1991). Diversified cropping systems not only reduces farm inputs, but also sustains dryland crop yields and enhances producers' farm income (Singer and Cox, 1998; Katsvairo and Cox, 2000a).

Availability of early maturing corn (*Zea mays* L.) cultivars has resulted in the increased production of dryland corn and enhanced crop diversity in the northern Great Plains where the growing season is relatively shorter than other regions (Major et al., 1991; Norwood and Currie, 1997). These cultivars have lower kernel number ear^{-1}, leaf area, carbohydrate production, shorter anthesis-silking interval, and earlier flowering, and are tolerant to higher plant density than conventional corn cultivars (Major et al., 1991). Corn is more attractive to producers than wheat or barley (*Horduem vulgaris* L.), due to its greater market opportunities for energy production and animal feed (Major et al., 1991; Norwood and Currie, 1997). Although the cost of production is higher for corn due to increased farm inputs, the net return can be greater for this crop (Major et al., 1991; Katsvairo and Cox, 2000a). As a result, the area under dryland corn production is increasing in the US northern Great Plains and Canadian Prairies (Major et al., 1991).

Dryland corn yield has increased at an average rate of 90 kg ha^{-1} yr^{-1} from 1939 to 2009 in the United States (Assefa et al., 2012). About half of this increase was due to genetic improvement (Duvick, 2005), and 25% due to increased air temperature (Lobell and Asner, 2003). As crop yields of improved cultivars are projected based on the performance of cultivars over a wide range of soil and climatic conditions, termed as genetics × environment interaction, crop production needs to be enhanced to feed the demand of 9 billion people by 2050 (Hatfield and Walthall, 2015). Thus, management practices should be geared to efficiently utilize soil water and nutrients and increase crop yield (Hatfield and Walthall, 2015). As a result, resilient and

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Abbreviations: CT, conventional tillage; NT, no-tillage; WUE, water-use efficiency.

sustainable crop production can be achieved in a changing climate. Management strategies to enhance dryland corn production and efficient soil water use, however, are lacking.

The effect of tillage on corn yield has been variable. Some researchers (Katsvairo and Cox, 2000b; Vetsch et al., 2006; West et al., 1996; Pantoja et al., 2015) have documented that corn yield was lower with conventional tillage (CT) than no-tillage (NT) in Iowa, Maryland, and Illinois, but others (Meyer-Aurich et al., 2006) observed that tillage had no effect on corn grain yield in western Canada. Several researchers (Norwood, 2000; Norwood and Currie, 1997) found that NT increased dryland corn yield by 25% and net returns by 69% compared with CT in Kansas. In a meta-analysis on the effect of tillage on corn yield, DeFelice et al. (2006) found that corn yield was greater with NT than CT in the southern and western United States, similar in the central United States, and lower in the northern United States and Canada, but overall US national average yield was not different between NT and CT. They also reported that corn yield was greater with NT than CT in moderate- to well-drained soils, but slightly lower in poorly drained soils. Still others (Vetsch and Randall, 2002; Lund et al., 1993) reported that corn yield was lower with NT than CT in continuous corn, but the yield was not affected by tillage in the corn–soybean rotation. Delayed germination and emergence of seeds due to lower soil temperature and greater water content can reduce irrigated corn yield as a result of late vegetative growth, time of silking, and flowering with NT compared with CT (DeFelice et al., 2006). In contrast, increased soil water conservation and root growth can enhance dryland corn yield and water use with NT compared with CT (DeFelice et al., 2006). Because of reduced input costs, increased conservation of soil resources through reduced soil erosion, greater soil C sequestration, and similar corn yield compared with CT, NT corn production has been increasing in the United States since 1980 (DeFelice et al., 2006).

Crop yields can also be enhanced using improved crop management intensity, such as increasing seeding rates, changing row spacing, altering planting and harvest dates, and using banded N fertilization, which suppress weeds due to increased competition with crops for water and nutrients and altered timing of growth for hosts and pests (Lenssen et al., 2014a, 2014b). 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 taller stubble increases soil water content by catching more snow and reduces light penetration into the soil, thereby reducing weed germination (Strydhorst et al., 2008; Nichols et al., 2015). Some researchers (Entz et al., 2002; Anderson, 2005; 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. While irrigated corn yield is maximized at a planting density of 80,000 to 90,000 plants ha^{-1} (Coulter et al., 2011; Woli et al., 2014; Assefa et al., 2016), lower planting density (<30,000 plants ha^{-1}) is required to increase dryland corn yield due to limited availability of soil water (Major et al., 1991; Allen, 2012).

Although information on the effects of individual management practice on corn production is available, there is a lack of literature on the combination of tillage and crop management intensity on corn yield and soil water use. We evaluated the effect of tillage system (NT and CT) and crop management intensity (traditional and improved) on dryland corn growth, yield, and water use in a spring wheat–forage barley–corn–pea (*Pisum sativum* L.) rotation from 2005 to 2010 in the semiarid region of the northern Great Plains. Our objectives were to: (i) examine how different tillage systems and crop management intensity affect corn growth, seed characteristics, grain and biomass yields, and soil water use in dryland crop rotation; and (ii) determine novel management strategies that optimize soil water use and enhance corn production. We hypothesized that NT with the improved crop management intensity would enhance soil water use and corn growth and yield compared to CT with the traditional management intensity.

MATERIALS AND METHODS

Study Site

The study site was located 8 km northwest of Sidney, MT, USA (47°46′ N, 104°16′ W; altitude 690 m). Soil at the site was mapped as a Williams loam (fine-loamy, mixed, superactive, frigid Typic Argiustolls) formed in glacial till plains and moraines, with 350 g kg^{-1} sand, 325 g kg^{-1} silt, 325 g kg^{-1} clay, 6.1 pH, 18 g kg^{-1} organic matter and 12 mg kg^{-1} Olsen P. Long-term mean annual precipitation at the site is 357 mm, with 76% occurring from May to October (corn growing season). Average monthly air temperature ranges from −8°C in January to 23°C in July and August. Prior to the initiation of the study, the site had been in a spring wheat–summer fallow rotation under CT for several decades.

Treatments

The long-term dryland field study was initiated in 2004 comparing two tillage systems and two crop management intensities for corn in a spring wheat–forage barley–corn–pea rotation. The experimental design was a randomized complete block in a split-plot arrangement with three replications. Tillage system (CT and NT) was the main-plot treatment and the crop management intensity (traditional and improved) was the split-plot treatment. 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 spring harrows with 60-cm bars. In the crop rotation, each phase of the rotation was present in every year and phase followed the order: spring wheat, forage barley, corn, and pea. Traditional and improved crop management intensities for corn included conventional and increased seed rates from 2005 to 2007. For spring wheat, pea, and forage barley in the rotation, a detail description of the crop management intensity is shown in Table 1. The split plot size was 12.2 × 12.2 m and the main plot size 219.6 × 12.2 m.

Crop Management

At planting in May 2004–2010, P fertilizer as monoammonium phosphate (11% N, 23% P) at 24 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 seeds. At the

Table 1. Description of crop management intensities used for crops in the rotation.

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

† Seeding rate from 2005 to 2007.

‡ Seeding rate from 2008 to 2010.

same time, N fertilizer as urea (46% N) and monoammonium phosphate were applied at 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. Nitrogen fertilization rate for each nonlegume crop was adjusted by deducting soil NO_3–N content in samples to a depth of 60 cm collected after crop harvest in the autumn of the previous year from recommended N rates. This was done to avoid excessive application of N fertilizers. Nitrogen fertilizer was either broadcast in the traditional crop management intensity or banded in the improved intensity to spring wheat and forage barley, but was banded to pea and broadcast to corn in both intensities (Table 1). 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. The drill was equipped with double-shoot Barton disk openers for low disturbance planting and single-pass seeding and fertilization. Corn (cv. Pioneer hybrids 39T67-RR from 2004–2008 and 39D95-RR from 2009–2010) was planted using a John Deere 1700 MaxEmergePlus planter (Deere and Company, Moline, IL) in early May at a spacing of 60 cm. Corn seeding rates differed between two crop management intensities from 2005 to 2007, but were at lower rates that were similar between intensities from 2008 to 2010 (Table 1). Immediately following planting, pea and barley plots were land rolled to push rocks back into soil and protect equipment used for pesticide applications and crop harvest (Saskatchewan Pulse Growers, 2018). The roller weighed 2415 kg and consisted of a 1.1 m diameter × 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 a.i. ha^{-1} to control early emerging weeds. As corn was resistant to glyphosate, the herbicide was also used at the same rate as above to control weeds at corn leaf 6 to leaf 7 growth stages (Abendroth et al., 2011). Herbicide applications for spring wheat, forage barley, and pea were done with labeled compounds and rates that were previously described (Lenssen et al., 2014a, 2014b). Postharvest residual weeds in spring wheat, forage barley, and pea were treated with tank-mixed glyphosate (3.36 kg a.i. ha^{-1}) and dicamba (3, 6-dichloro-2-methoxybenzoic acid) at 0.28 kg a.i. ha^{-1}.

Stand count of corn was determined at the one-to-two leaf stage by counting plants in four 3-m rows in each plot. Shortly before harvest in October 2004–2010, plant height was determined on 10 plants per plot using a meter stick (Allen, 2012). Corn biomass and yield component samples including ear number, seed number, and seed weight were obtained from 10 plants at maturity (Doberman, 2005). All ears were hand-picked, placed in a paper bag, and shelled by hand. Seeds were dried in the oven at 55°C for 3 d, weighed, and counted. Corn biomass samples were dried in a forced air oven at 55°C for 3 d and weighed. Grain yield was determined by hand harvesting ears from an area of 10.2 × 3.6 m (Bartel et al., 2017). Grains were shelled from ears, 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 remainder of the grain was harvested with a self-propelled combine and crop residue was returned to the soil. Spring wheat and pea were harvested using a plot combine as described in Lenssen et al. (2014b) and forage barley was harvested by swathing and bailing (Lenssen et al., 2014a).

Soil water content at 23-, 46-, 61-, 91-, and 122-cm depths was determined by 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. Corn 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, assuming water lost through runoff and deep percolation are negligible (Farahani et al., 1998). Water-use efficiency (WUE) was calculated by dividing corn grain yield by water use (Farahani et al., 1998).

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 crop management intensity as the split-plot treatment. Fixed effects were tillage, crop management intensity, year, and their interactions. Random effects were replication and the replication × tillage interaction. Data for harvest index were transformed to square root values for variance normalization before analysis and back-transformed 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 and interactions were considered significant at $P \leq 0.05$. Data from 2004 were not included in the analysis as it was considered a crop establishment

Table 2. Monthly mean air temperature and total precipitation during the corn growing season (May–October) from 2005 to 2010 at the experimental site.

Month	2005	2006	2007	2008	2009	2010	68-yr avg.
				Air temperature, °C			
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
October	7.1	3.6	8.0	4.5	7.1	7.3	7.8
				Precipitation, mm			
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
October	26	10	9	24	17	17	25
May–October	281	242	234	161	202	357	272
January–December	324	339	280	189	282	415	357

Table 3. Analysis of variance for corn growth, yield, and water use.

Parameter	Stand count	Plant height	Ear no.	Seed no.	Seed weight	Biomass yield	Grain yield	Harvest index	Pre-plant water	Post-harvest water	Water use	WUE†
	no. m^{-2}	cm	no. m^{-2}	no. ear^{-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
Crop management intensity (M)	***	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
T × M	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	NS	NS	NS	NS	NS
T × M × Y	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

* Significant at $P \leq 0.05$.

** Significant at $P \leq 0.01$.

*** Significant at $P \leq 0.001$; NS, not significant.

† Water-use efficiency.

year. Because seed rates for corn were different from 2005 to 2007, but similar from 2008 to 2010 in traditional and improved crop management intensities, crop management intensities were considered similar from 2008 to 2010 for data analysis.

RESULTS AND DISCUSSION

Climate

Monthly total precipitation and average air temperature varied 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. The growing season (May–October) precipitation accounted for 76% of the total annual precipitation and was lower in 2008 (161 mm) and higher in 2010 (357 mm) than other years. Above-average precipitation occurred in May and June 2005 and May 2007 and 2010. In contrast, below-average precipitation occurred in August 2007, May to September 2008, and May 2009. Monthly average air temperature varied less than precipitation. Notable exceptions, however, 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.

Corn Stand Count and Plant Height

Corn stand count varied with crop management intensities and years, with significant interactions for tillage × year and crop management intensity × year (Table 3). Averaged across crop management intensities, stand count was lower for NT than CT from 2007 to 2009 (Table 4). Averaged across tillage systems, stand count was greater for the improved than the traditional crop management intensity from 2005 to 2007 (Table 5). Averaged across tillage practices and years, stand count was 17% greater for the improved than the traditional intensity (Table 6). Averaged across treatments, stand count was greater in 2005 than other years. Corn plant height was not affected by treatments and their interactions, but varied among years (Table 3). Averaged across treatments, corn was 20 to 100 cm taller in 2005 than other years (Table 6).

The lower corn stand count for NT than CT from 2007 to 2009 (Table 4) was likely a result of reduced soil temperature due to increased water conservation from undisturbed condition and residue accumulation at the soil surface in years with below-average growing season (May–October) precipitation. The growing season precipitation from 2007 to 2009 was below the 68-yr average (Table 2). It could be possible that undisturbed soil condition and increased accumulation of

Table 4. Interaction between tillage and year on corn growth and yield.

Tillage system†	2005	2006	2007	2008	2009	2010
Stand count, no. m^{-2}						
CT	5.3	3.7	4.2a‡	4.0a	2.4a	4.4
NT	5.4	3.7	3.9b	3.2b	2.1b	4.4
Seed no., no. ear^{-1}						
CT	240b	369	129b	165b	296b	439
NT	309a	327	196a	274a	369a	461
Biomass yield, kg ha^{-1}						
CT	11,389	6,674	6,272	4,026	7,709b	9,984
NT	11,204	6,616	7,197	4,105	11,032a	9,843
Grain yield, kg ha^{-1}						
CT	3,060b	2,934	1,486b	736b	3,239b	4,586
NT	4,016a	2,867	2,309a	1,285a	4,769a	4,303

† Tillage systems are CT, conventional tillage; and 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 the crop management intensity and year on corn stand count.

Crop management practice†	2005	2006	2007	2008	2009	2010
Stand count, no. m^{-2}						
Traditional	4.7 b‡	3.2 b	3.5 b	3.6	2.3	4.3
Improved	6.0 a	4.2 a	4.6 a	3.6	2.3	4.3

† See Table 1 for detail description of crop management intensities.

‡ 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.

crop residue at the surface increased soil water content, which reduced soil temperature, thereby reducing seed germination and stand count for NT compared with CT. Several researchers (West et al., 1996; DeFelice et al., 2006) also found lower corn stand count for NT than CT due to lower soil temperature.

Increased seeding rate and wheat stubble height may have increased stand count for the improved compared with the traditional intensity from 2005 to 2007. Seeding rate for corn was greater for the improved than the traditional intensity from 2005 to 2007, but the rate decreased from 2008 to 2010 and was similar between crop management intensities in these years (Table 1). Reduced weed growth through increased competition with corn due to high seeding rate may have increased stand count with the improved crop management intensity. This was also observed by Major et al. (1991) for dryland corn production in the northern Great Plains and Canadian Prairies; however, they suggested that lower stand count is required to efficiently utilize limited soil water availability in arid and semiarid regions. Although seed rate increased by 30% in the improved compared with traditional intensity, stand count was increased by only 17%, as all planted seeds did not germinate. Increased soil water storage through enhanced snow catchment and decreased light penetration as a result of increased wheat stubble height also may have increased stand count by reducing weed growth in the improved intensity. Increased crop stand count with greater stubble height as a result of enhanced soil water content has been reported by several researchers (Aase and Siddoway, 1980; Huggins and Pan, 1991). Above-average precipitation and favorable air temperature in May and June (Table 2) may have increased stand count in 2005 than other years.

In our study, crop management intensity had little impact on corn height. West et al. (1996) reported that plant height was lower for NT than CT in irrigated crop production, but Major et al. (1991) found that plant height was not different among tillage systems in dryland corn production. Kravchenko and Thelen (2007) observed that the presence of wheat residue increased soil water content and plant height compared with no residue in no-till corn production. As with plant stand, greater plant height in 2005 than other years was probably due to above-average growing season precipitation and favorable air temperature.

Corn Ear Number, Seed Number, and Seed Weight

Corn ear number varied with years (Table 3). Averaged across treatments, ear number was greater in 2009 than other years (Table 6). Increased precipitation in July may have increased the reproductive growth and therefore ear number in 2009 than other years.

Table 6. Corn growth, yield, and water use as affected by tillage, crop management intensity, and year.

Parameter	Stand count	Plant height	Ear no.	Seed no.	Seed wt.	Biomass yield	Grain yield	Harvest index	Pre-plant water	Post-harvest water	Water use	WUE†
	no. m^{-2}	cm	no. m^{-2}	no. ear^{-1}	mg seed^{-1}	kg ha^{-1}			mm			kg ha^{-1} mm^{-1}
Tillage system‡												
CT	4.0	180	4.8	273 b§	197	7,676	2,673 b	0.34	129	75	272	10.9
NT	3.8	180	4.9	322 a	197	8,333	3,258 a	0.40	138	83	273	13.1
Crop management intensity¶												
Traditional	3.5 b	181	4.8	312	201	7,930	3,138 a	0.40	133	76	275	12.4
Improved	4.2 a	179	4.9	283	193	8,078	2,794 b	0.34	135	81	270	11.6
Year												
2005	5.3 a	213 a	5.4 b	275 c	240 a	11,296 a	3,538 b	0.31 b	177 b	129 b	305 b	11.6 b
2006	3.7 d	189 b	3.5 d	348 b	209 b	6,645 c	2,901 c	0.44 a	54 e	152 a	125 d	23.6 a
2007	4.0 c	185 b	4.5 c	163 e	219 b	6,745 c	1,897 d	0.28 b	239 a	41 d	363 a	4.9 c
2008	3.6 d	113 c	2.7 e	219 d	169 d	6,735 c	1,010 e	0.29 b	130 c	48 d	209 c	4.9 c
2009	2.3 e	189 b	7.4 a	333 b	165 d	9,370 b	4,004 a	0.44 a	96 d	31 d	286 b	14.0 b
2010	4.4 b	193 b	5.6 b	450 a	180 c	9,914 b	4,444 a	0.46 a	106 d	74 c	347 a	12.9 b

† Water-use efficiency.

‡ Tillage systems are: 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.

¶ See Table 1 for detail description of crop management intensities.

Table 7. Interaction between tillage and the crop management intensity on corn biomass yield.

Tillage system†	Crop management intensity‡	
	Traditional	Improved
	kg ha^{-1}	
CT	7215 b§B¶	8136 A
NT	8645 aA	8020 B

† Tillage systems are: CT, conventional tillage; NT, no-tillage.

‡ See Table 1 for detail description of crop management intensities.

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

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

Seed number ear^{-1} varied with tillage systems and years, with a significant interaction for tillage × year (Table 3). Averaged across crop management intensities, seed number was greater for NT than CT in 2005, 2007, 2008, and 2009 (Table 4). Averaged across crop management intensities and years, seed number was 15% greater for NT than CT (Table 6). Averaged across treatments, seed number was greater in 2010 than other years. Similar to plant height, seed weight was not affected by treatments and their interactions, but varied with years (Table 3). Averaged across treatments, seed weight was 23 to 64% greater in 2005 than other years (Table 6), despite of lower precipitation during grain fill in September (Table 2).

In contrast to plant stand, greater seed number ear^{-1} for NT than CT in 4 out of 6 yr could be a result of enhanced soil water availability due to lower evaporation from increased residue accumulation at the soil surface. This was especially true during dry years from 2007 to 2009 when the growing season precipitation was below the 68-yr average (Table 2). Although not significant, preplant and postharvest soil water content as well as corn water use and WUE were greater for NT than CT (Table 6). It is likely that increased soil water content in NT enhanced corn water uptake and increased seed number. This also holds true for greater seed number in 2010 when the growing season precipitation was greater than other years and the 68-yr average (Table 2). Seed weight, however, followed the reverse trend of seed number, as seed weight was greater in the year with near-average precipitation, such as that found in 2005. Seed weight probably decreases as the seed number in the ear increases. Precipitation during the grain-filling stage (July–August) is critical for dryland corn seed weight and yield (Nielsen et al., 2009, 2010).

Corn Biomass, Grain Yield, and Harvest Index

Corn biomass varied with years, with significant interactions for tillage × crop management intensity and tillage × year (Table 3). Averaged across crop management intensities, biomass was greater for NT than CT in 2009 (Table 4). Averaged across years, biomass was greater for NT than CT in the traditional crop management intensity (Table 7). Biomass was also greater for the improved than the traditional intensity with CT, but the trend reversed with NT. Averaged across treatments, biomass was greater in 2005 than other years (Table 6).

Increased soil water conservation also appeared to favor corn biomass for NT in 2009 when the growing season air temperature and precipitation were below the average (Table 2). It could be possible that lower air temperature enhanced corn vegetative growth, especially for NT. Similarly, increased soil water storage may have enhanced biomass for NT compared with CT with the traditional crop management intensity. Increased soil water content as a result of enhanced snow accumulation due to greater wheat stubble height also probably increased biomass with the improved than the traditional management intensity in CT. The opposite was true in NT when reduced seeding rate and wheat stubble height enhanced biomass with the traditional management intensity. Increased dryland corn biomass for NT compared with CT has been reported by some researchers (DeFelice et al., 2006; Norwood and Currie, 1997; Assefa et al., 2012). Increased dryland corn biomass due to reduced seeding rate in NT corn production was reported by Allen (2012). Greater biomass in 2005 than other years appeared to be associated with increased plant stand and height in this year (Table 6).

Corn grain yield varied with tillage systems, crop management intensities, and years, with a significant interaction for tillage × year (Table 3). Averaged across crop management intensities, grain yield was greater for NT than CT in 2005, 2007, 2008, and 2009 (Table 4). Averaged across crop management intensities and years, grain yield was 18% greater for NT than CT (Table 6). Averaged across tillage systems and years, grain yield was 11% greater for the traditional than the improved intensity. Averaged across treatments, grain yield was greater in 2009 and 2010 than other years. Harvest index was not significant for treatments and their interactions, but varied with years (Table 3). Averaged across treatments, harvest index was greater in 2006, 2009, and 2010 than other years.

The greater corn grain yield for NT than CT in 4 out of 6 yr was probably due to increased seed number ear^{-1}, as the trends were similar. Some researchers (Norwood, 2000; DeFelice et al., 2006; Norwood and Currie, 1997) have reported that NT increased dryland corn grain yield compared with CT in arid and semiarid regions due to increased soil water storage. Others (Newell and Wilhelm, 1987; Lamm et al., 2009) have found that NT increased dryland corn root growth and therefore grain yield compared with CT. Corn grain yield is related to number of ears plant^{-1}, kernel number ear^{-1}, and kernel weight (Assefa et al., 2016). Although there exists a good relationship between plant stand and grain yield for irrigated corn production (Assefa et al., 2016), this may not hold true for dryland corn production, as our results show that the trends for corn plant stand and grain yield with respect to CT and NT reversed, especially in dry years from 2007 to 2009 when the growing season precipitation was below the 68-yr average.

The lower seeding rate from 2005 to 2007 (Table 1) and wheat stubble height likely increased corn grain yield with the traditional compared with the improved crop management intensity. Corn does not yield well by increasing seeding rate in dryland cropping systems where available soil water is low and competition for water uptake is high (Assefa et al., 2016). As planting density increases, resource allocation (e.g., soil water and nutrients) decreases, and plant-to-plant competition for available resources increases, thereby limiting per plant yield potential, especially in dryland cropping systems (Assefa et al., 2016). Increased planting density in dryland corn production can result in delayed maturity due to water stress and increased shading and wind protection (Major et al., 1991). Allen (2012) found that dryland corn grain yield and precipitation storage efficiency increased by reducing seeding rate in the semiarid region of the northern Great Plains. Although reduced wheat stubble height also increased biomass with the traditional intensity in NT, the trend was opposite in CT. Corn grain yield and biomass probably behave differently with tillage and crop management intensities.

Favorable growing season air temperature and precipitation appeared to increase corn grain yield in 2009 and 2010 compared with other years. Although air temperature was lower in 2009, precipitation was greater in 2010 than other years (Table 2). Reduced heat stress and enhanced soil water availability due to above-average precipitation may have increased grain yield in these years. Dryland corn grain yield responds linearly to available soil water from precipitation and irrigation (Nielsen et al., 2010; Schlegel et al., 2018). Increased grain yield compared with biomass increased harvest index in 2006, 2009, and 2010 when air temperature and precipitation were favorable for corn growth compared with other years.

Soil Water Content at Planting and Harvest, Water Use, and Water-Use Efficiency

Soil preplant and postharvest water content as well as corn water use and WUE were not affected by treatments and their interactions, but varied with years (Table 3). Averaged across treatments, preplant water content was 62 to 185 mm greater in 2007 than other years (Table 6). Postharvest water content was 23 to 121 mm greater in 2006 than other years. Corn water use was 42 to 238 mm greater in 2007 and 2010 than other years. Corn WUE was 41 to 79% greater in 2006 than other years.

Greater postharvest soil water content in 2006, followed by increased precipitation from November to April (46 mm) and lower evapotranspiration during this period may have enhanced preplant soil water content in 2007. Lower water use by corn in 2006 than other years may have increased postharvest soil water content. In contrast, greater water use in 2007 and 2010 was probably due to increased water uptake as a result of enhanced soil water availability, as the growing season precipitation was near or above the average in these years (Table 2). Greater WUE in 2006 than other years was a result of average grain yield but lower water use by corn in this year.

Implication of Management Strategies

Our results suggest that NT with a combination of reduced seeding rate and wheat stubble height in the traditional management intensity may be used to enhance dryland corn growth and yield without affecting soil water and corn water use in the arid and semiarid regions. Although increased stubble height may trap more snow and increase soil water content, a separate study may be needed to evaluate the effect of wheat stubble height on corn growth and yield. The NT system can also enhance soil and environmental quality by improving soil structure, maintaining organic matter, increasing water storage and infiltration, reducing soil erosion, and mitigating greenhouse gas emissions compared with CT (Ruisi et al., 2012; Sainju et al., 2013, 2014). Energy is also saved by using the NT system, as soil is not cultivated using the tillage equipment in this system (Sainju et al., 2013, 2014). Additional application of herbicide, however, is often needed to control weeds in NT (Lenssen et al., 2014a, 2014b). Increased corn yield, reduced cost of seeding due to lower seeding rate and energy use, and improved soil and environmental quality may outweigh the increased cost of herbicide application in NT with the traditional management intensity.

CONCLUSIONS

Tillage system and crop management intensity influenced dryland corn production in the spring wheat–forage barley–corn–pea rotation on the semiarid region of the northern Great Plains. Corn stand count was greater for CT than NT and for the improved than the traditional crop management intensity from 2005 to 2007 when the seeding rate increased. In contrast, seed number ear^{-1} and grain yield were greater for NT than CT in most years and grain yield was greater for the traditional than the improved intensity. Biomass was greater for NT than CT and ear number greater in the traditional than improved intensity in 2009 when the growing season air temperature was below the average. Biomass was also greater for NT than CT in the traditional intensity. Preplant and postharvest soil water storage, water use, and WUE varied among years, but were not influenced by treatments. No-tillage with reduced seeding rate and wheat stubble height can enhance dryland corn yield in the spring wheat–forage barley–corn–pea rotation by increasing seed number ear^{-1} without affecting soil water content and water use compared with conventional tillage with increased seeding rate and wheat stubble height in arid and semiarid regions.

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