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Abstract. *Competition for water is becoming more intense in many parts of the U.S., including west-central Nebraska. It is believed that reduced tillage, with more crop residue on the soil surface, conserves water, but the magnitude of water conservation is not clear. A study was initiated on the effect of residue on soil water content and corn yield at North Platte, Nebraska. The experiment was conducted in 2007 and 2008 on plots planted to field corn (*Zea mays *L.). In 2005 and 2006, soybean was grown on these plots. There were two treatments: residue-covered soil and bare soil. Bare-soil plots were created in April 2007. The residue plots were left untreated. In April 2008, bare-soil plots were recreated on the same plots as in 2007. The experiment consisted of eight plots (two treatments with four replications each). Each plot was 12.2 m × 12.2 m. During the growing season, soil water content was measured several times in each of the plots at six depths, down to a depth of 1.68 m, using a neutron probe. The corn crop was sprinkler-irrigated but purposely water-stressed, so that any water conservation in the residue-covered plots might translate into higher yields. In 2007, mean corn yield was 12.4 Mg ha^{-1} in the residue-covered plots, which was significantly (p = 0.0036) greater than the 10.8 Mg ha^{-1} in the bare-soil plots. Other research has shown that it takes 65 to 100 mm of irrigation water to grow this extra 1.6 Mg ha^{-1}, which may be considered water conservation due to the residue. In 2008, the residue-covered soil held approximately 60 mm more water in the top 1.83 m compared to the bare soil toward the end of the growing season. In addition, mean corn yield was 11.7 Mg ha^{-1} in the residue-covered plots, which was significantly (p = 0.0165) greater than the 10.6 Mg ha^{-1} in the bare-soil plots. It would take 30 to 65 mm of irrigation water to produce this additional 1.1 Mg ha^{-1} of grain yield. Thus, the total amount of water conservation due to the residue was 90 to 125 mm in 2008. Water conservation of such a magnitude will help irrigators to reduce pumping cost. With deficit irrigation, water saved by evaporation is used for transpiration and greater yield, which may have even greater economic benefits. In addition, with these kinds of water conservation, more water would be available for competing needs.*

Keywords. *Corn, Crop residue, Irrigation, Soil water, Water conservation.*

In much of the U.S. Great Plains, water is the primary limiting factor controlling dryland production, and loss of water through evaporation (E) is large, especially in less intensive cropping systems with considerable periods of fallow (Farahani et al. 1998a; Farahani et al. 1998b). In many parts of the U.S., including west-central Nebraska, irrigation water is a precious commodity. Groundwater levels have been falling (McGuire, 2004; McGuire and Fischer, 1999), and stream flow has been decreasing, leading to competition among water users. For example, it has been a challenge for Nebraska to supply the required amount of water to Kansas through the Republican River. Irrigated agriculture is a major consumer of water, and a reduction of irrigation throughout the Republican River basin could provide additional water that can help meet stream flow requirements in the Republican River. In addition, by saving irrigation water, irrigators will reduce pumping cost and more water will be available for competing needs, such as wildlife habitat, endangered species, and municipalities.

It is generally believed that increasing crop residue levels leads to water conservation. However, crop residue that is removed from the field after harvest is gaining value for use in livestock rations and bedding, and as a source of cellulose for ethanol production. The water conservation value of crop residue needs to be quantified so crop producers can evaluate whether to sell the residue or keep it on their fields (Klocke et al., 2009).

The effects of no-till and conventional tillage on soil and water dynamics are controversial. Strudley et al. (2008) showed that except for an increased soil water retention time for no-till, all other effects due to no-till were inconclusive. Producers have expressed concerns about production practices where high levels of crop residue are present on the soil surface. These concerns include the increased use of chemi-

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cals, and wetter soil and lower soil temperatures delaying planting and retarding plant development during early vegetative growth, and less uniform germination and emergence using planting equipment that cannot operate adequately in the residue.

However, in the semi-arid climate of the western Great Plains, vegetative growth of crops under no-till management can catch up to the growth of crops under tilled management by the reproductive growth stage (Klocke et al., 1985). In the hot and dry summers of this environment, reduced soil temperatures and increased soil water under crop residue during and after the reproductive stage benefit the crop and outweigh the drawbacks experienced earlier in the cropping season (Klocke et al., 1985).

Crop residue reduces the energy of water droplets impacting the soil surface and reduces the detachment of fine soil particles that tend to seal the surface, leading to crust formation. This sealing and crusting process can be enhanced by subsequent soil surface drying. Crust formation reduces infiltration and promotes runoff because precipitation or irrigation rates may be greater than the rates at which the soil is able to absorb water. Residue also increases surface storage of rain or irrigation water. In addition, it slows the velocity of runoff water across the soil surface, allowing more time for infiltration (Steiner, 1994). Dickey et al. (1983) used a rainfall simulator at Sidney, Nebraska, to demonstrate differences in infiltration and runoff from no-till wheat stubble and plowed soils. In the experiment, 76 mm of water was applied, resulting in 44 mm of runoff on the plowed soil and only 5 mm on the no-till soil.

Standing residue helps to conserve water by causing snow to settle, rather than blow to field boundaries, by slowing the wind velocity just above the residue (Black and Siddoway, 1977; Steiner, 1994). Subsequent melting snow is more likely to infiltrate into the soil because the stubble slows runoff, enhancing soil water storage. This water can then be used for crop production in the subsequent growing season.

When the soil surface is wet from a recent irrigation or precipitation event, evaporation from bare soil will occur at a rate controlled by atmospheric demand (fig. 1). The evaporation rate decreases as the soil surface dries over time because water that is deeper in the soil is not transported to the surface quickly enough to maintain the rate of wet-soil evaporation; the drying surface soil starts to act as a barrier to water transport (Lascano and van Bavel, 1986; fig. 1).

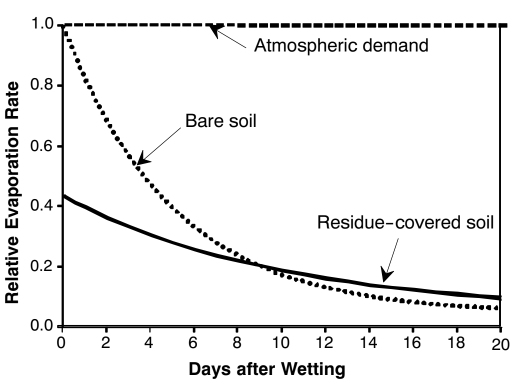


Figure 1. Evaporation rates, relative to atmospheric demand, from bare and residue-covered soil after a single wetting event (irrigation or rainfall), a conceptual diagram (adapted from Watts and Klocke, 2004).

If the soil surface is covered with residue, it is shielded from solar radiation, and air movement just above the soil surface is reduced. This reduces the evaporation rate from a residue-covered surface compared to bare soil (Willis, 1962; Unger and Parker, 1976; Smika, 1983; Villalobos and Fereres, 1990; Heilman et al., 1992; Aiken et al., 1997). Surface moisture under the residue will continue to evaporate slowly, but a number of days after the wetting event, the evaporation rate from the residue-covered surface can exceed that of the bare surface (fig. 1).

Eventually, after many days without rain or irrigation, the cumulative evaporation from the bare and residue-covered soils will be the same. Bond and Willis (1969) confirmed this when they showed that, on soil without a growing crop, cumulative evaporation became almost identical for several mulch amounts when evaporation was permitted for a sufficiently long time without rewetting the surface. In the conceptual diagram in figure 1, this point has not yet been reached after 20 days. In reality, this point is seldom reached because more frequent wetting events result in more days with higher evaporation rates from bare soil than from residue-covered soil. The net effect over a season is that total evaporation is expected to be greater from bare soil.

Tolk et al. (1999) found that soil water under a mulched surface was being used for crop growth and yield rather than for evaporation of soil water. Research conducted near North Platte, Nebraska (Todd et al., 1991), and Garden City, Kansas (Klocke et al., 2009), showed that soil water evaporation from bare fine sand and silt loam soils can be as much as 30% of evapotranspiration (ET) during the irrigation season of corn and soybean. Evaporation was only 15% of total ET when wheat straw or no-till corn stover completely covered the soil surface from early June to the end of the growing season, translating into a 63 mm to 75 mm water savings for the growing season. Soil water content increases with increasing amounts of residue in dryland cropping systems, and wheat stubble can save an additional 50 mm of water during the non-growing season (Nielsen, 2006) if the soil profile can retain the water. These water savings in the growing and non-growing seasons would combine to a total of 125 mm per year. Not all of this can be expected to be effective for crop growth and yield. However, if only half of the 125 mm water savings can contribute to crop yield, yield increases may be as much as 0.67 Mg ha^{-1} for soybeans and 1.88 Mg ha^{-1} for corn in water-short areas or areas where water allocations are below full crop water requirements.

Van Donk et al. (2004) enhanced the process-based energy and water balance model (ENWATBAL; Van Bavel and Lascano, 1993; Evett and Lascano, 1993) with the capability to simulate the effect of mulch on evaporation and soil water content, and showed, in a simulation study, reduced evaporation from a mulched surface. Lamm et al. (2009) found that strip-till and no-till generally had greater water use than conventional tillage (chisel/disk plowing). This small increase in total seasonal water use (less than 10 mm) for strip-till and no-till compared to conventional tillage can probably be explained by the higher grain yields for the strip-till and no-till systems.

Research to quantify the effect of crop residue on the soil water balance has been limited and has produced a range of results. Some of the data and anecdotal evidence are based on rainfed cropping systems, and results may be different for irrigated systems. More research is needed to quantify the ef-

fect of crop residue on components of the soil water balance, especially for irrigated agriculture. Such research would especially be relevant to sprinkler irrigation; typically, center pivots wet the soil every 3 to 10 days, which increases evaporation on bare soils with each wetting event.

Therefore, a field study was conducted to determine the effect of crop residue on soil water content and corn yield under conditions of deficit irrigation. In 2007, the residue was predominantly from previous soybean crops; in 2008, it was predominantly from the 2007 corn crop.

Methods

The study was conducted at the University of Nebraska-Lincoln, West-Central Research and Extension Center in North Platte, Nebraska (41° 10′ N, 100° 45′ W, 861 m elevation above sea level). The soil type is a Cozad silt loam (Fluventic Haplustolls) with an average water content of 0.29 m^3 m^{-3} at field capacity and 0.11 m^3 m^{-3} at wilting point (Klocke et al., 1999). The climate at North Platte is semi-arid, with an average annual precipitation of 508 mm and a reference ET of 1403 mm. On average, about 80% of the annual precipitation occurs during the growing season, which extends from late April to mid-October (USDA, 1978).

The experiment was initiated in 2007 on plots planted to field corn. The plots were in no-till corn in 2004 and in no-till soybean in 2005 and 2006. There were two treatments: residue-covered soil and bare soil. In April 2007, bare-soil plots were created using a dethatcher and subsequent hand-raking and shoveling, effectively removing the residue. The residue-covered plots were left untreated. In April 2008, the same bare-soil plots were recreated by using similar methods as in 2007. The residue-covered plots were again left untreated.

The experiment consisted of eight plots (two treatments with four replications each, fig. 2). Within each replication, the treatments (bare soil and residue-covered soil) were assigned randomly to the plots. Each of the eight plots was 24.4 m × 24.4 m. The actual experimental plots were 12.2 m × 12.2 m, centered in these larger plots. The areas outside the smaller experimental plots were border (buffer) zones.

No-till management was practiced on the plots. The only residue disturbance came from the planting operation in 2007 and 2008 and from the shredding of corn stalks shortly before planting in the spring of 2008. The shredding operation left no corn stalks standing.

Residue cover and mass were measured in June and October 2007 and in July 2008. Residue cover was measured with the line-transect method (USDA, 2002) using a 15.2 m (50 ft) measuring tape. Residue hits or misses were evaluated at each of the 50 footmarks. The tape was laid out over the two diagonals of each plot. This way, 100 points per plot were evaluated. The percent residue cover equals the total number of residue hits out of 100 point evaluations.

Residue mass was measured by collecting three samples from each plot. In June 2007 and July 2008, only two samples were taken from each bare-soil plot because there was very little residue present on these bare plots. The area of each sample was 0.76 m (equal to the row spacing) × 0.51 m. Sample locations within a plot were selected randomly. Before sampling, a picture was taken of each sample area (fig. 3). Within each sample area, percent residue cover was measured using a ruler, evaluating residue hits or misses on the two diagonals, at every inch (2.54 cm) mark. This procedure was similar to the residue cover measurements using the 50 ft tape, described above. Minimum, maximum, and average residue thickness was measured inside each sampling area. The average thickness was area-weighted and was an estimate rather than a measurement.

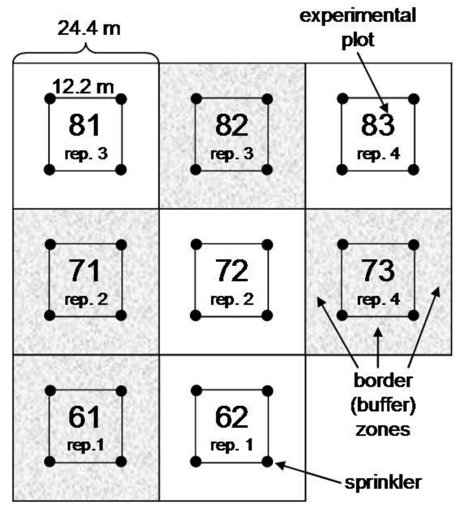


Figure 2. Physical layout of the eight experimental plots in the study (two treatments and four replications). The shaded plots are the residue-covered plots, and the others are the bare-soil plots. Plots 61 and 62 made up replication 1, plots 71 and 72 made up replication 2, plots 81 and 82 made up replication 3, and plots 73 and 83 made up replication 4. Within each replication, the treatments (bare soil and residue-covered soil) were assigned randomly to the plots. The areas outside the 12.2 m × 12.2 m experimental plots are border (buffer) zones.

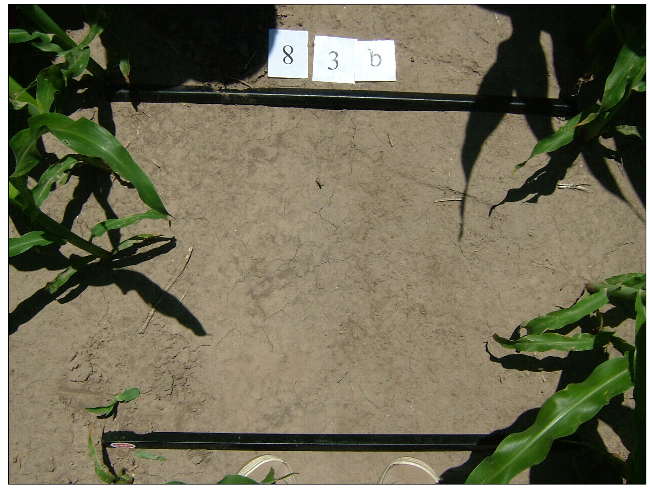
Standing soybean stems were few and short, but were nonetheless collected separately in 2007. Standing residue was defined as stems anchored in the soil with an angle greater than approximately 10° from the soil surface (Steiner et al., 1999). Only the above-ground parts of the standing stems were collected; they were broken off at the soil surface. Non-standing (surface, or flat) residue was cut on the boundaries of the sample area and collected by hand. If a piece of residue was partially buried, the entire piece was collected, unless it broke off easily at the soil surface.

All collected residue was dried in an oven for 24 h at 60°C. Standing soybean stems were counted, and their diameters and heights were measured. Non-standing residue was separated into four components. In 2007, the four components were soybean material (mostly stems), corn stalks, corn cobs, and, for the residue collected in October, newly senesced corn leaves. The corn stalks and cobs were several years old. In 2008, the four components were corn stalks, corn cobs, corn leaves and husks, and soybean material (mostly stems).

To determine the soil-free residue mass, each residue component was weighed and ground through a 1 mm sieve using a grinder (Cyclone Mill model 3010-030, UDY Corp., Fort Collins, Colo.). The resulting fine material was mixed, and three subsamples were collected, weighed, and then ashed at 500°C for 6 h. Samples were then weighed again to determine the soil-free mass of each residue component.

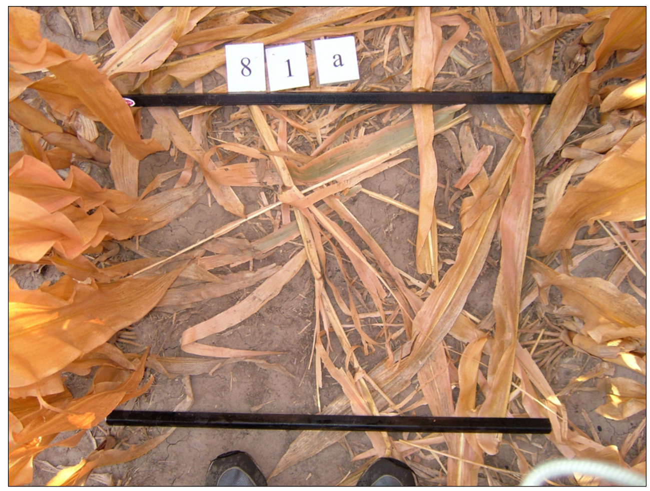
During late spring and summer, precipitation was measured using four rain gauges located adjacent to the study plots. For the rest of the year, precipitation data from a High Plains Regional Climate Center (HPRCC; www.hprcc.unl.edu) weather

(a) Residue-covered plot in June 2007



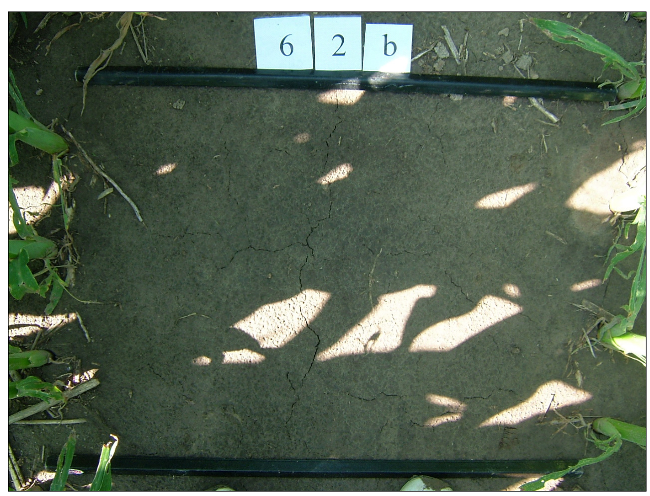
(b) Bare soil plot in June 2007

(c) Residue-covered plot in October 2007



(d) Bare-soil plot in October 2007

(e) Residue-covered plot in July 2008



(f) Bare-soil plot in July 2008

Figure 3. Sample areas in residue-covered plots and bare-soil plots. In each of the eight experimental plots, random residue samples were collected from an area of 0.51 m × 0.76 m.

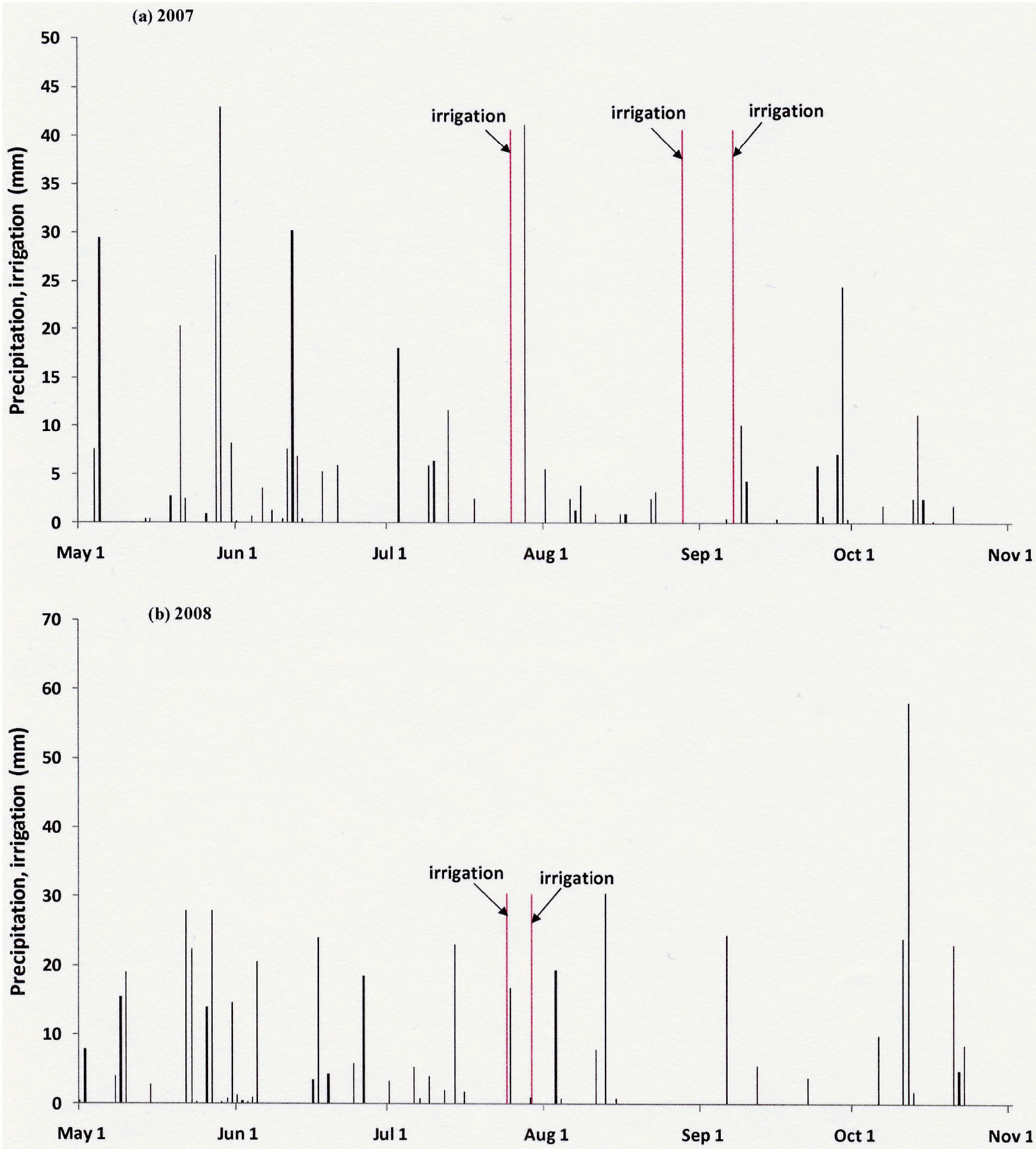


Figure 4. Daily precipitation and irrigation events at the experimental site in (a) 2007 and (b) 2008. The crop was irrigated three times in 2007 and two times in 2008.

station, located less than 2 km west of the study site, were used. Measurement of precipitation in the form of snow at this HPRCC station did not seem very reliable. Therefore, for water equivalent data from snow, data from the WCREC dryland farm, which is located 4 km south of the study plots, were used. Using these three data sources, a precipitation record was constructed for the entire two years of 2007 and 2008. Precipitation for the growing season portion of these two years is shown in figure 4.

In both 2007 and 2008, winter and spring had above average precipitation at North Platte (fig. 4, table 1). The corn crop was only irrigated three times with a total of 122 mm of water in 2007 (fig. 4a) and only two times with a total of 61 mm in 2008 (fig. 4b). The irrigation scheduling was conducted to slightly stress the corn on the residue-covered plots. By doing so, more stress and lower corn yield would be expected on the bare-soil plots.

Table 1. Monthly, seasonal, and annual precipitation (mm) at the experimental site in 2007 and 2008.

	Precipitation (mm)	
Month	2007	2008
January	11	0
February	25	4
March	59	18
April	110	100
May	144	158
June	63	80
July	86	58
August	22	59
September	54	34
October	20	130
November	0	10
December	15	4
Total	608	654
May-Sept.	368	389

During the growing season, soil water content was measured seven times in 2007 and 17 times in 2008 in each of the plots at six depths (0.15, 0.46, 0.76, 1.07, 1.37, and 1.68 m) using a neutron probe (CPN Hydroprobe). There were two neutron probe access tubes per plot: one in the corn row and one between the rows. The two tubes were located less than 1 m from each other. Data from both the in-row and the between-row tube locations were used for the results presented in the next section.

Corn was hand-harvested along 6.1 m long rows in the center of each plot. Guess rows (outside rows of the four-row planter) were not used in the yield calculation. The two-tailed, paired t-test was used to determine whether differences in yield between residue-covered plots and bare-soil plots were statistically significant.

Results and Discussion

In June 2007, the bare-soil plots were almost totally without residue (fig. 3, table 2). For the residue-covered plots, the average residue cover was 63%. It would have been higher if the planting equipment had not moved residue away from the corn rows. In October, the bare-soil plots were no longer bare because many newly senesced corn leaves covered the soil surface (fig. 3d), explaining the average residue cover of 81% (table 2). These leaves provided much cover at relatively low residue amounts in terms of mass: only 1322 kg ha^{-1} on average. In the residue-covered plots, average residue cover was also greater in October than it was in June, but residue mass was slightly less. Apparently, the mass increase due to newly senesced leaves was more than offset by mass lost to residue decomposition (decay).

In July 2008, residue mass and cover on the bare-soil plots was again minimal after residue removal in April 2008 (table 2, fig. 3f). The residue-covered plots had a mean residue cover of 91% and a mean residue mass of 6704 kg ha^{-1}, which was much more than in 2007. This was due to the fact that in 2008 the majority of the residue was corn stalks from the 2007 corn crop. In 2007, most of the residue was soybean material from the 2006 corn crop.

In 2007, the corn plants used water from all six depths, down to 1.68 m (fig. 5). In July, soil water content decreased rapidly because the corn crop was transpiring at full canopy cover, rainfall was modest, and no irrigation water was applied (fig. 5a). In late July, irrigation was followed by a large rain, which greatly increased soil water content at shallower depths (figs. 5a and 5b). In August, soil water content again decreased rapidly because of high crop water use, little precipitation, and no irrigation until late in August. As mentioned before, the crop was purposely water-stressed so that any water conservation in the residue-covered plots might translate into higher yields. In September and October, irrigation and precipitation filled up the soil profile at the shallower depths. This water stayed in the soil because of much-reduced crop water needs.

In 2007, differences in soil water content between the residue-covered and the bare-soil plots were small (fig. 5). From June through August, the bare-soil plots were somewhat drier than the residue-covered plots at most depths. In September and October, the bare-soil plots were wetter at some depths (figs. 5b and 5c), which may be explained by the field observation that the corn in the bare-soil plots dried out more and matured earlier than the corn in the residue-covered plots, apparently induced by water stress. Thus, toward the end of the growing season, the corn in the bare-soil plots stopped using water earlier than the corn in the residue-covered plots. The corn in the residue-covered plots used more water in late August and September and yielded more than the corn in the bare-soil plots.

At the beginning of the 2008 growing season, soil water content was very similar in the bare-soil and the residue-covered plots (figs. 6 and 7). In rainfed (dryland) agriculture in semi-arid climates, soil water content is often greater with residue than without residue at planting time. We do not see that here because (1) we irrigated in 2007, leaving the soil

Table 2. Residue cover, mass (free of soil), and thickness for bare-soil and residue-covered plots. Residue cover data are the result of evaluating 100 points for the presence or absence of residue (2 times 50 points on a 50 ft measuring tape). Mass and thickness data are the means of three (residue-covered plots) or two (bare plots) samples per plot. See figure 2 for the physical layout of the plots.

	Bare-Soil Plots					Residue-Covered Plots				
				Thickness (mm)					Thickness (mm)	
Date	Plot No.	Cover (%)	Mass (kg ha^{-1})	Avg.	Max.	Plot No.	Cover (%)	Mass (kg ha^{-1})	Avg.	Max.
June 2007	62	2	127	<1	8	61	63	3306	12	33
	72	1	242	<1	15	71	60	3657	15	38
	81	1	102	<1	20	82	66	3278	12	28
	83	3	114	<1	13	73	63	4341	13	40
	Mean	2	146	<1	14	Mean	63	3646	13	35
	SD	1	56	0	4	SD	2	428	1	5
October 2007	62	82	1348	2	5	61	91	2994	10	25
	72	77	1718	2	7	71	95	3215	12	28
	81	79	1292	<1	10	82	95	3607	10	35
	83	87	928	<1	5	73	94	3854	9	32
	Mean	81	1322	1	7	Mean	94	3418	10	30
	SD	4	280	1	2	SD	2	334	1	4
July 2008	62	2	168	<1	13	61	88	5919	13	37
	72	1	279	<1	13	71	89	7682	17	60
	81	3	564	<1	30	82	90	5219	13	45
	83	2	563	<1	13	73	97	7994	18	53
	Mean	2	394	<1	17	Mean	91	6704	15	49
	SD	1	174	0	7	SD	4	1166	2	9

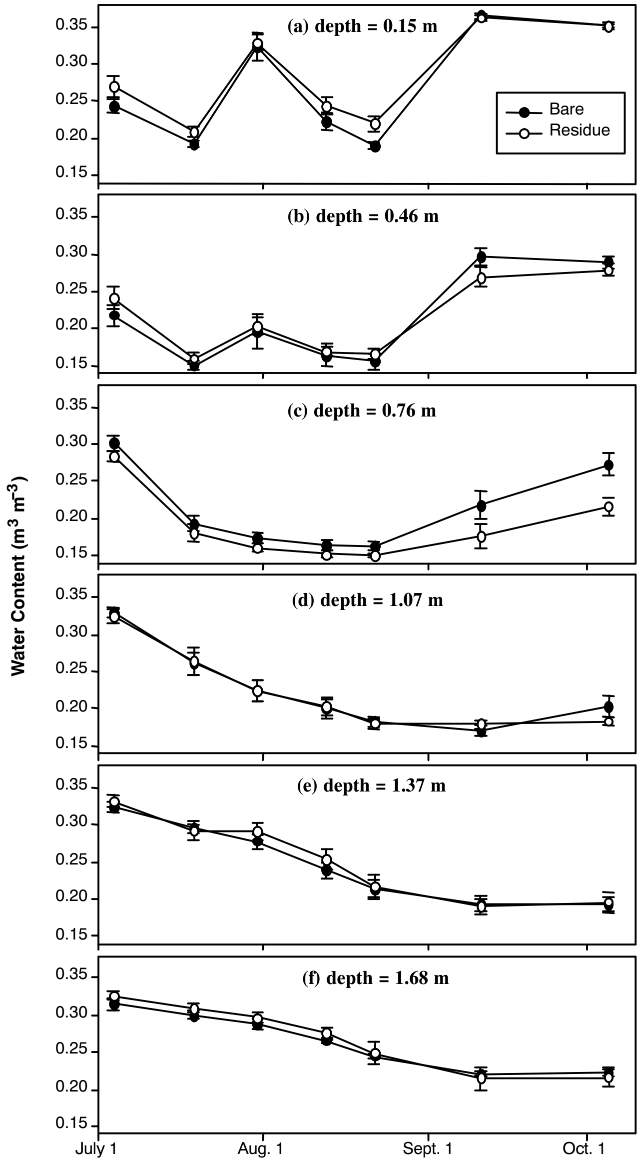


Figure 5. Mean soil water content in 2007 at six depths in bare-soil plots and in residue-covered plots. Error bars indicate plus or minus one standard error of the mean.

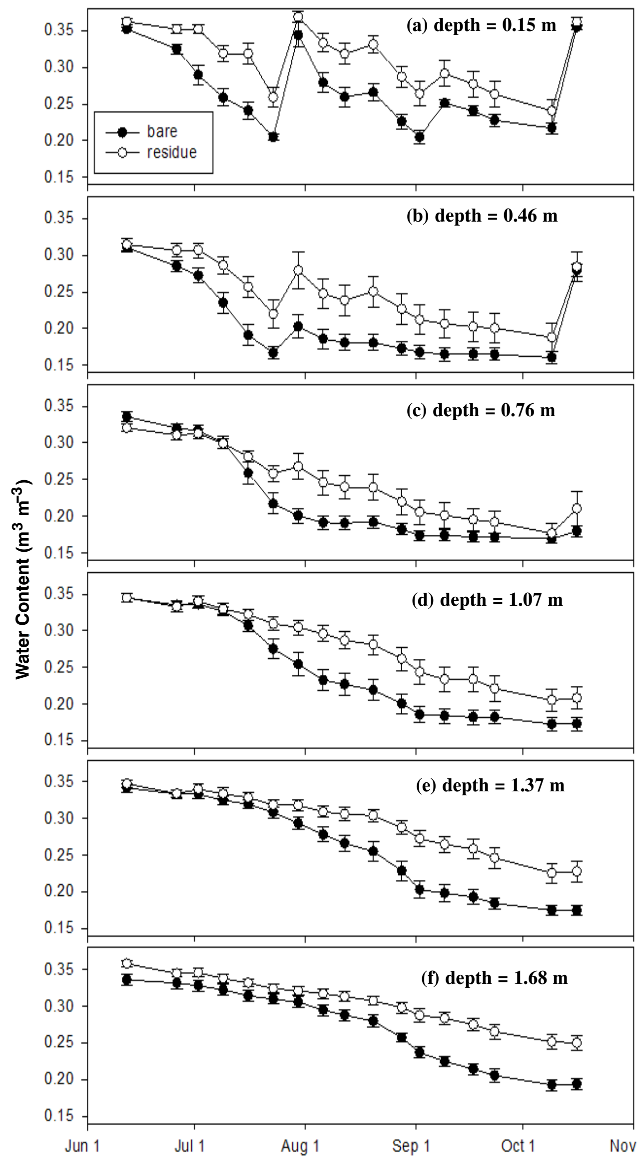


Figure 6. Mean soil water content in 2008 at six depths in bare-soil plots and in residue-covered plots. Error bars indicate plus or minus one standard error of the mean.

profile not as dry as it would have been under rainfed management, and (2) rainfall during the 2007-2008 off-season was quite abundant, filling the soil profile to above field capacity, leading to deep percolation in both the bare-soil and the residue-covered plots. There probably was a residue contribution to water conservation, e.g., through reduced evaporation, during the off-season, but this contribution was erased because more than enough precipitation occurred in late fall, winter, and especially spring to fill up the soil profile to field capacity.

The soil dried out quickly at the shallower depths in 2008 during late June and July, especially in the bare-soil plots (figs. 6a and 6b). This may be due to greater evaporation in the bare-soil plots, but most likely also because the corn plants were bigger in the bare-soil plots at this time, and therefore using more water than the plants in the residue-covered plots. This difference in plant development was

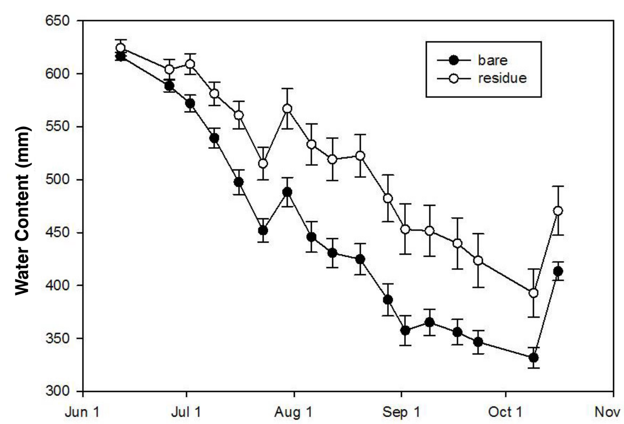


Figure 7. Total soil water content of the top 1.83 m in 2008 in bare-soil plots and in residue-covered plots. Error bars indicate plus or minus one standard error of the mean.

visually observed in all four replications and was likely caused by soil temperatures being cooler in the residue-covered soil in May and June. A difference in plant size was not observed in 2007 when the weather during the early growing season was warmer than in 2008, thus making cooler temperatures under residue less of an issue for the growth of corn plants.

Two irrigations during late July 2008 made the soil water content increase at the shallower depths (figs. 6a and 6b). By the first half of August, the bare-soil plots were much drier than the residue-covered plots in the top meter of soil (figs. 6a through 6d) but not yet at the greater depths (figs. 6e and 6f). During late August and September, the soil dried out faster in the bare-soil plots than in the residue-covered plots at the two deepest depths (figs. 6e and 6f). At the shallower depths (figs. 6b, 6c, and 6d), the bare-soil plots no longer dried out, whereas the residue-covered plots did. Apparently, in the bare-soil plots, the corn plants could no longer easily find water at the shallower depths, but they could find it at the deeper depths.

At the beginning of the soil water measurements in June, there was not much difference in soil water content in the measurement zone (top 1.83 m) between the bare-soil plots and the residue-covered plots (fig. 7). The difference developed rapidly in late June and July, reaching almost 100 mm in August. In late September and early October, the gap narrowed again, which was caused by greater crop water use in September by the corn in the residue-covered plots and heavy rains in October filling up the shallower soil layers to capacity in both treatments (fig. 6).

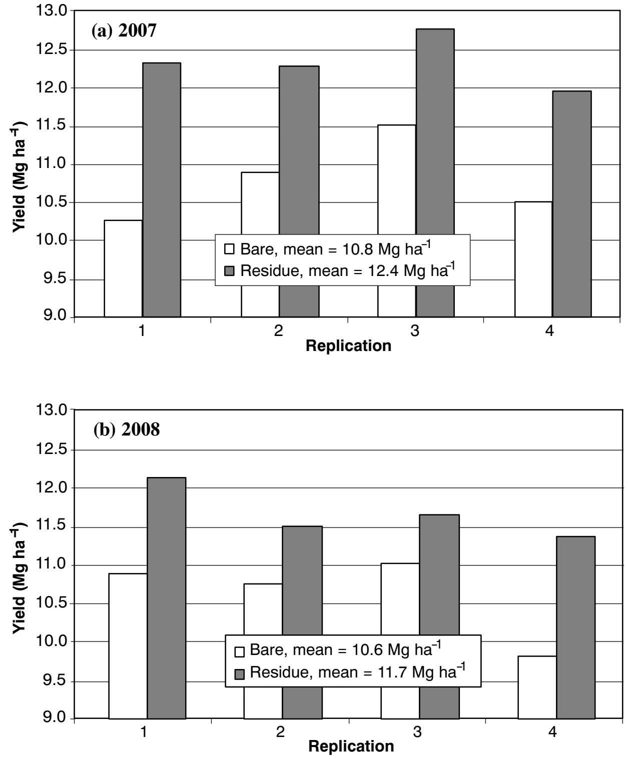


Figure 8. Corn yield in (a) 2007 and (b) 2008 for eight experimental plots: two treatments (soil residue-covered soil and bare soil) and four replications.

Table 3. Water balance and its components, including soil water content (SWC) in the top 1.83 m for the residue-covered plots and for the bare-soil plots, cumulative precipitation, cumulative irrigation, and ET calculated as the residual of the water balance with runoff and deep percolation assumed to be equal to zero. The last column shows the difference in ET between residue-covered and bare-soil plots. Dates are the dates of soil water content measurement.

Date	Residue SWC (mm)	Bare SWC (mm)	Cumul. Precip. (mm)	Cumul. Irrig. (mm)	Residue ET (mm)	Bare ET (mm)	Residue ET (mm d^{-1})	Bare ET (mm d^{-1})	Difference in ET (mm d^{-1})
4 July 2007	541	529	429	0					
19 July 2007	432	424	455	0	136	130	9.0	8.7	0.4
31 July 2007	459	452	496	41	55	55	4.5	4.5	0.0
13 Aug. 2007	395	382	511	41	79	85	6.1	6.5	-0.4
22 Aug. 2007	360	351	515	41	39	35	4.3	3.9	0.4
11 Sept. 2007	424	446	533	122	35	4	1.7	0.2	1.6
5 Oct. 2007	439	466	573	122	25	20	1.1	0.8	0.2
12 June 2008	624	616	910	122	152	187	0.6	0.7	-0.1
26 June 2008	604	588	948	122	58	66	4.2	4.7	-0.5
2 July 2008	609	572	970	122	17	39	2.8	6.4	-3.6
9 July 2008	581	539	980	122	38	43	5.4	6.1	-0.7
16 July 2008	561	498	1007	122	47	69	6.7	9.8	-3.1
23 July 2008	515	452	1007	122	46	46	6.5	6.5	0.0
30 July 2008	567	488	1025	183	27	43	3.9	6.1	-2.2
6 Aug. 2008	533	446	1045	183	54	62	7.7	8.9	-1.3
12 Aug. 2008	519	431	1053	183	22	23	3.7	3.9	-0.1
20 Aug. 2008	522	425	1084	183	28	37	3.5	4.6	-1.2
28 Aug. 2008	482	386	1084	183	40	38	5.0	4.8	0.2
2 Sept. 2008	453	358	1084	183	29	29	5.8	5.8	0.0
9 Sept. 2008	452	365	1108	183	26	17	3.6	2.4	1.3
17 Sept. 2008	440	356	1114	183	18	15	2.2	1.9	0.3
23 Sept. 2008	423	347	1118	183	20	13	3.4	2.2	1.2
9 Oct. 2008	393	332	1128	183	41	25	2.5	1.6	1.0
16 Oct. 2008	470	413	1212	183	6	2	0.9	0.3	0.6

In 2007, corn yield was significantly ($p = 0.0036$) greater in the residue-covered plots compared to the bare-soil plots (fig. 8a). The average yield of the four bare-soil plots was 10.8 Mg ha^{-1}, and the average yield of the four residue-covered plots was 12.4 Mg ha^{-1}. Soil water content between bare-soil plots and residue-covered plots was not much different throughout the 2007 growing season (fig. 5), and thus ET was not much different either (table 3). The greater yield in the residue-covered plots may be explained by E being a smaller fraction of ET, and thus T being a greater fraction of ET, in the residue-covered plots. This "transfer" of E to T due to crop residue has been documented by others (Tolk et al., 1999; Klocke et al., 2009).

In 2008, corn yield was again significantly ($p = 0.0165$) greater in the residue-covered plots compared to the bare-soil plots (fig. 8b). The average yield of the four bare-soil plots was 10.6 Mg ha^{-1}, and the average yield of the four residue-covered plots was 11.7 Mg ha^{-1}. During the first part of the growing season, ET was greater on the bare-soil plots (table 3) because of (1) bigger plants transpiring at higher rates and (2) greater E. In September, ET was smaller on the bare-soil plots because of drier soil; it was more difficult for the crop to extract water from this drier soil. The greater yield on the residue-covered plots may be explained by (1) transfer of E to T (same as in 2007), and (2) the more vigorous early growth on the bare-soil plots was not very efficiently translated into yield (T used for this early vegetative growth was not used very efficiently). These two mechanisms may explain why yield was larger on the residue-covered plots, although total ET for the growing season was greater on the bare-soil plots.

Estimates were made to translate the yield differences into the amount of water it would take to produce this extra yield assuming that the yield differences were entirely due to the corn in the bare plots experiencing more water stress than the corn in the residue-covered plots. Four different sources of data were used for this estimate (table 4).

One of these sources was data from Garden City, Kansas, from which Klocke et al. (2008) concluded that corn yields increase 0.63 Mg ha^{-1} for each inch (25.4 mm) of irrigation water that is transferred from evaporation to transpiration (T). Based on this, the 2007 yield difference of 1.6 Mg ha^{-1} would translate into an additional 64 mm of crop-available water. Extra irrigation water that needs to be applied would be more than 64 mm because the application efficiency will be less than 100%. At a 90% efficiency, the extra irrigation water needed would be 71 mm; at a 75% efficiency, it would be 85 mm. The 2008 yield difference of 1.1 Mg ha^{-1} would translate into an additional 43 mm of crop-available water. At a 90% efficiency, the extra irrigation water needed would be 48 mm; at a 75% efficiency, it would be 58 mm.

Table 4. Amount of additional irrigation water (mm) required on the bare-soil plots to produce the extra yield produced on the residue-covered plots (1.6 Mg ha^{-1} in 2007 and 1.1 Mg ha^{-1} in 2008), estimated using four different data sources.

Data Source	Additional irrigation water (mm) 2007	2008
Klocke et al. (2008)	71-85	48-58
Melvin and Payero (2007)	79	30
Klocke et al. (2004); Schneekloth et al. (2006)	114	66
Martin et al. (2007)	66-86	43-66

Using small plots, Melvin and Payero (2007) compared three different irrigation management strategies, from fully watered to deficit irrigation, for seven locations in west-central Nebraska for four years (2003-2006). They reported the amount of irrigation water applied and corn yields. Since then, they have added two more years of data (Melvin, unpublished). Based on the findings from six years of data, our 2007 yield difference would translate into an additional 79 mm of irrigation water needed to produce the extra yield, and our 2008 yield difference would translate into an additional 30 mm of irrigation water.

Another study, similar to the one above but on much larger fields, compared four different irrigation management strategies for six locations in west-central Nebraska for six years (1996-2001) (Klocke et al., 2004; Schneekloth et al., 2006). Based on their findings, our 2007 yield difference would translate into an additional 114 mm of irrigation water needed to produce the extra yield, and our 2008 yield difference would translate into an additional 66 mm of irrigation water.

Finally, an analysis with the Water Optimizer (Martin et al., 2007), using a medium-textured soil and an application efficiency of 0.75, indicates that an additional 66 to 86 mm of irrigation water would be needed to raise corn yield from 10.8 to 12.4 Mg ha^{-1} (2007 yields) at North Platte, Nebraska. An additional 43 to 66 mm of irrigation water would be needed to raise corn yield from 10.6 to 11.7 Mg ha^{-1} (2008 yields). The greater estimates of additional irrigation water needed are based on a fully watered yield of 12.7 Mg ha^{-1} (Water Optimizer default for Lincoln County and North Platte), and the smaller estimates are based on a fully watered yield of 13.8 Mg ha^{-1}.

All of these estimates assume that the yield differences were entirely due to the corn in the bare plots experiencing more water stress. There are good reasons for this assumption. Visually, there were signs that the corn in the bare-soil plots was more water-stressed than the corn in the residue-covered plots: in September of both years, the corn plants on the bare-soil plots turned brown earlier than the corn in the residue-covered plots. The corn crop was fertilized adequately in all plots, so it is unlikely that the yield differences were caused by a lack of nutrients in the bare-soil plots. In addition, it is unlikely that differences in compaction caused the differences in yield because all plots had the same history up to the residue removal in April 2007.

Others have used various sizes of mini- or micro-lysimeters to measure evaporation on a daily basis (Klocke et al. 2009; Steiner, 1989; Lascano and van Bavel, 1986). However, the lysimeters have their drawbacks because crop roots are excluded from the lysimeters and the measurements are very localized (point measurements). Our research did not measure daily evaporation directly, but the accumulated effects of the residue with respect to water were included in the cropping season results. Thus, our approach complements the lysimeter research.

Conclusions

The effects of no-till and conventional tillage on soil and water dynamics are controversial. Producers have expressed concerns about production practices where high levels of crop residue are present on the soil surface. These concerns include the increased use of chemicals, wetter soil, lower soil

temperatures, and planting equipment that cannot operate adequately in the residue.

In 2007, the first year of our two-year study, the bare-soil plots were somewhat drier than the residue-covered plots at most depths from June through August. Mean corn yield was 12.4 Mg ha^{-1} in the residue-covered plots, which was significantly ($p = 0.0036$) greater than the 10.8 Mg ha^{-1} in the bare-soil plots. Other researchers have shown that it takes 65 to 100 mm of irrigation water to produces this extra yield of 1.6 Mg ha^{-1}. This amount may be considered water conservation due to the residue.

In 2008, the second year of our study, higher soil temperatures in the bare-soil plots in the spring and early summer caused more vigorous plant growth; consequently, ET was greater in the bare-soil plots during the first part of the growing season (bigger plants transpiring at higher rates). The increased transpiration together with increased evaporation resulted in the bare soil holding approximately 60 mm less water in the top 1.83 m compared to the residue-covered soil toward the end of the growing season. In addition, mean corn yield was 11.7 Mg ha^{-1} in the residue-covered plots, which was significantly ($p = 0.0165$) greater than the 10.6 Mg ha^{-1} in the bare-soil plots. It would take 30 to 65 mm of irrigation water to produce this extra yield of 1.1 Mg ha^{-1}. Thus, the total amount of water conservation due to the residue was 90 to 125 mm in 2008.

Water conservation of such a magnitude will help irrigators significantly reduce pumping cost. With deficit irrigation, water saved by evaporation is used for transpiration and greater yield, which may have even greater economic benefits for producers than saved pumping cost. In addition, with these kinds of water conservation, more water would be available for competing needs, including those of wildlife, endangered species, municipalities, and compacts with other states.

Additional research on water balance and crop yield is needed in the context of actual agricultural systems, for example systems where residue is removed by grazing or baling, or systems where surface residue is reduced by tillage. In this experiment, residue was artificially removed from the plots without any tillage. Water conservation may be greater in the "real world" than in our study for several reasons. A tillage pass usually results in loss of water by evaporation since, typically, it brings moist soil to the soil surface, exposing it directly to atmospheric drying forces. In addition, long-term no-till could increase infiltration and decrease runoff compared to long-term conventional tillage. We did not have this tillage contrast in our study. Finally, when comparing to a real-world scenario with fall tillage, no-till may conserve water by reducing overwinter evaporation and increasing snow trapping.

References

Aiken, R. M., G. N. Flerchinger, H. J. Farahani, and K. E. Johnson. 1997. Energy balance simulation for surface soil and residue temperatures with incomplete cover. *Agron. J.* 89(2): 404-415.

Black, A. L., and F. H. Siddoway. 1977. Winter wheat recropping on dryland as affected by stubble height and nitrogen fertilization. *SSSA J.* 41(6): 1186-1190.

Bond, J. J., and W. O. Willis. 1969. Soil water evaporation: surface residue rate and placement effects. *SSSA Proc.* 33(3): 445-448.

Dickey, E. C., C. R. Fenster, J. M. Laflen, and R. H. Mickelson. 1983. Effects of tillage on soil erosion in a wheat-fallow rotation. *Trans. ASAE* 26(3): 814-820.

Evett, S. R., and R. J. Lascano. 1993. ENWATBAL.BAS: A mechanistic evapotranspiration model written in compiled Basic. *Agron. J.* 85(3): 763-722.

Farahani, H. J., G. A. Peterson, D. G. Westfall, L. A. Sherrod, and L. R. Ahuja. 1998a. Soil water storage in dryland cropping systems: The significance of cropping intensification. *SSSA J.* 62(4): 984-991.

Farahani, H. J., G. A. Peterson, and D. G. Westfall. 1998b. Dryland cropping intensification: A fundamental solution to efficient use of precipitation. *Advances in Agron.* 64: 197-223.

Heilman, J. L., K. J. McInnes, R. W. Gesch, and R. J. Lascano. 1992. Evaporation from ridge-tilled soil covered with herbicide-killed winter wheat. *SSSA J.* 56(4): 1278-1286.

Klocke, N. L., D. F. Heermann, and H. R. Duke. 1985. Measurement of evaporation and transpiration with lysimeters. *Trans. ASAE* 28(1): 183-189, 192.

Klocke, N. L., D. G. Watts, J. P. Schneekloth, D. R. Davison, R. W. Todd, and A. M. Parkhurst. 1999. Nitrate leaching in irrigated corn and soybean in a semi-arid climate. *Trans. ASAE* 42(6): 1621-1630.

Klocke, N. L, J. P. Schneekloth, S. R. Melvin, R. T. Clark, and J. O. Payero. 2004. Field scale limited irrigation scenarios for water policy strategies. *Applied Eng. in Agric.* 20(5): 623-631.

Klocke, N. L., R. S. Currie, and T. J. Dumler. 2008. Water savings from crop residue management. In *Proc. Central Plains Irrigation Conf.* Colby, Kansas: Central Plains Irrigation Association.

Klocke, N. L., R. S. Currie, and R. M. Aiken. 2009. Soil water evaporation and crop residues. *Trans. ASABE* 52(1): 103-110.

Lamm, F. R., R. M. Aiken, and A. A. Abou Kheira. 2009. Corn yield and water use characteristics as affected by tillage, plant density, and irrigation. *Trans. ASABE* 52(1): 133-143.

Lascano, R. J., and C. H. M. Van Bavel. 1986. Simulation and measurement of evaporation from a bare soil. *SSSA J.* 50(5): 1127-1133.

Martin D. L., R. J. Supalla, B. McMullen, and S. Nedved. 2007. Water Optimizer, a decision support tool for producers with limited water. Lincoln, Neb.: University of Nebraska-Lincoln. Available at: http://water.unl.edu/cropswater/optimizer

McGuire, V. L. 2004. Water level changes in the High Plains aquifer: Predevelopment to 2002, 1980-2002, and 2001-2002. Fact Sheet 2004-3026. Lincoln, Neb.: U.S. Geological Survey.

McGuire, V. L., and B. C. Fischer. 1999. Water level changes, 1980-1997, and saturated thickness, 1996-1997, in the High Plains aquifer. Fact Sheet 124-99. Lincoln, Neb.: U.S. Geological Survey.

Melvin, S. R., and J. O. Payero. 2007. Irrigation water conserving strategies for corn. In *Proc. Central Plains Irrigation Conf.* Colby, Kansas: Central Plains Irrigation Association.

Nielsen, D. C. 2006. Crop residue and soil water. In *Proc. Central Plains Irrigation Conf.* Colby, Kansas: Central Plains Irrigation Association.

Schneekloth, J. P., N. L. Klocke, D. R. Davison, and J. O. Payero. 2006. Furrow irrigation management with limited water. *Applied Eng. in Agric.* 22(3): 391-398.

Smika, D. E. 1983. Soil water change as related to position of wheat straw mulch on the soil surface. *SSSA J.* 47(5): 988-991.

Steiner, J. L. 1989. Tillage and surface residue effects on evaporation from soils. *SSSA J.* 53(3): 911-916.

Steiner, J. L. 1994. Crop residue effects on water conservation. In *Managing Agricultural Residues*, 41-76. P. W. Unger, ed. Boca Raton, Fla.: CRC Press.

Steiner, J. L., H. H. Schomberg, P. W. Unger, and J. Cresap. 1999. Crop residue decomposition in no-tillage small-grain fields. *SSSA J.* 63(6): 1817-1824.

Strudley, M. W., T. R. Green, and J. C. Ascough II. 2008. Review: Tillage effects on soil hydraulic properties in space and time: State of the science. *Soil and Tillage Res.* 99(1): 4-48.
Todd, R. W., N. L. Klocke, G. W. Hergert, and A. M. Parkhurst. 1991. Evaporation from soil influenced by crop shading, crop residue, and wetting regime. *Trans. ASAE* 34(2): 461-466.
Tolk, J. A., T. A. Howell, and S. R. Evett. 1999. Effect of mulch, irrigation, and soil type on water use and yield of maize. *Soil and Tillage Res.* 50: 137-147.
Unger, P. W., and J. J. Parker. 1976. Evaporation reduction from soil with wheat, sorghum, and cotton residues. *SSSA J.* 40(6): 938-942.
Villalobos, F. J., and E. Fereres. 1990. Evaporation measurements beneath corn, cotton, and sunflower canopies. *Agron. J.* 82(6): 1153-1159.
USDA. 1978. Soil survey of Lincoln County, Nebraska. Washington, D.C.: USDA Soil Conservation Service, in cooperation with University of Nebraska Conservation and Survey Division.
USDA. 2002. *National Agronomy Manual.* 3rd ed. Washington, D.C.: USDA Natural Resources Conservation Service.
Van Bavel, C. H. M., and R. J. Lascano. 1993. ENWATBAL, a numerical method to compute the water loss from a crop by transpiration and evaporation. 3rd ed. College Station, Tex.: Texas A&M University, Department of Soil and Crop Sciences, Texas Agricultural Experiment Station.
van Donk, S. J., E. W. Tollner, J. L. Steiner, and S. R. Evett. 2004. Soil temperature under a dormant bermudagrass mulch: Simulation and measurement. *Trans. ASAE* 47(1): 91-98.
Watts, D., and N. L. Klocke. 2004. Chapter 6: Crop water use. In *Irrigation Management Home Study Course.* C. Burr, ed. Publication EC98-788-S. Lincoln, Neb.: University of Nebraska Cooperative Extension.
Willis. W. O. 1962. Effect of partial surface covers on evaporation from soil. *SSSA Proc.* 26(6): 598-601.