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Effects Of Crop Residue Removal On Soil Water Content And Yield Of Deficit-Irrigated Soybean

Simon van Donk
University of Nebraska-Lincoln, simon.vandonk@unl.edu

Timothy M. Shaver
University of Nebraska

James L. Petersen
University of Nebraska - Lincoln, jpetersen2@unl.edu

Don Davison
University of Nebraska - Lincoln, ddavison1@unl.edu

Effects of Crop Residue Removal on Soil Water Content and Yield of Deficit-Irrigated Soybean

S. J. van Donk, T. M. Shaver, J. L. Petersen, D. R. Davison

Abstract. *Reduced tillage, with more crop residue remaining on the soil surface, is believed to conserve water, especially in arid and semi-arid climates. However, the magnitude of water conservation is not clear. An experiment was conducted to study the effect of crop residue removal on soil water content, soil quality, and crop yield at North Platte, Nebraska. The same field plots were planted to soybean (*Glycine max*) in 2009 and 2010. There were two treatments: residue-covered soil and bare soil. Residue (mostly corn residue in 2009 and mostly soybean residue in 2010) was removed every spring from the same plots using a flail chopper and subsequent hand-raking. The experiment consisted of eight, 12.2 m × 12.2 m, plots (two treatments with four replications each). Soybeans were sprinkler-irrigated, but purposely water-stressed, so that any water conservation in the residue-covered plots might translate into higher yields. After four years of residue removal, soil organic matter content and soil residual nitrate nitrogen were significantly smaller, and soil pH was significantly greater, in the bare-soil plots compared to the residue-covered plots. The residue-covered soil held approximately 90 mm more water in the top 1.83 m compared to the bare soil near the end of the 2009 growing season. In addition, mean soybean yield was 4.5 Mg ha^{-1} in the residue-covered plots, compared to 3.9 Mg ha^{-1} in the bare-soil plots. Using two crop production functions, it is estimated that between 74 and 91 mm of irrigation water would have been required to produce this extra 0.6 Mg ha^{-1}. In 2010, mean soybean yield was 3.8 Mg ha^{-1} in the residue-covered plots, compared to 3.3 Mg ha^{-1} in the bare-soil plots. Between 64 and 79 mm of irrigation water would have been required to produce this extra 0.5 Mg ha^{-1}. In both years, several processes may have contributed to the differences observed: (1) greater evaporation of water from the soil in the bare-soil treatment, and (2) greater transpiration by plants in the bare-soil treatment in the beginning of the growing season as a result of more vegetative growth due to higher soil temperatures in the bare-soil treatment.*

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

In western Nebraska, as in many other parts of the U.S., irrigation water is becoming scarcer. Groundwater levels in the High Plains aquifer have been falling (McGuire, 2009), and streamflows have been decreasing, leading to competition among water users. Irrigated agriculture is a major consumer of water, and a reduction in use of irrigation water could provide additional water that can help meet streamflow requirements. In addition, by conserving irrigation water, irrigators will reduce pumping costs, and more water will be available for competing needs such as wildlife habitat, endangered species, and municipalities.

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The authors are **Simon J. van Donk, ASABE Member,** Assistant Professor, Department of Biological Systems Engineering, University of Nebraska West-Central Research and Extension Center, North Platte, Nebraska; **Timothy M. Shaver,** Assistant Professor, Department of Agronomy and Horticulture, University of Nebraska, North Platte, Nebraska; **James L. Petersen,** Research Technologist, and **Don R. Davison,** Research Technician, West-Central Research and Extension Center, University of Nebraska, North Platte, Nebraska. **Corresponding author:** Simon J. van Donk, Department of Biological Systems Engineering, University of Nebraska West-Central Research and Extension Center, 402 West State Farm Road, North Platte, NE 69101; phone: 308-696-6709; fax: 308-696-6780; e-mail: svandonk2@unl.edu.

Water is the primary limiting factor controlling dryland production in much of the U.S. Great Plains, 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). One way in which water may be conserved is through crop residue management. It is generally believed that increasing crop residue levels leads to water conservation. However, crop residue 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).

Producers have expressed concerns about production practices where high levels of crop residue are present on the soil surface. These concerns include 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. By the reproductive growth stage, however, vegetative growth of crops under no-till management can catch up to the growth of crops under tilled management, at least in the semi-arid climate of the western Great Plains (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).

Another benefit of crop residue is that it reduces the energy of water droplets impacting the soil surface, thereby reducing the detachment of fine soil particles that tend to seal the surface and lead to crust formation. This sealing and crusting process can be enhanced by subsequent soil surface drying, and it 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 may increase 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). Residue, especially standing stems and stalks, also helps to conserve water by causing snow to settle, rather than blow to field boundaries (Black and Siddoway, 1977; Steiner, 1994).

Several researchers have used various sizes of mini- or micro-lysimeters to measure evaporation on a daily basis (Lascano and van Bavel, 1986; Steiner, 1989; Todd et al., 1991; Klocke et al., 2009). However, these lysimeters have drawbacks because they do not contain crop roots, and the measurements are very localized (point measurements). Research conducted near North Platte, Nebraska (Todd et al., 1991) and Garden City, Kansas (Klocke et al., 2009) using small lysimeters 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 (*Zea mays* L.) and soybean. Evaporation was only 15% of total ET when wheat (*Triticum aestivum*) 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 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.

Process-based simulation models have also shown reduced evaporation when more residue or mulch covers the soil surface. 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. However, Lamm et al. (2009) found that strip-till and no-till, with greater amounts of residue covering the soil surface, generally had greater ET than conventional tillage (chisel/disk plowing).

Crop residue is also a valuable resource in terms of soil quality (Wilhelm et al., 2007). Research has shown that crop residue is directly related to characteristics beneficial to soil quality and crop yields, including nutrient cycling, soil organic matter (SOM), and soil organic carbon (Blanco-Canqui and Lal, 2009a). Crop residue is directly related to many soil physical and chemical properties that affect plant growth, and the removal of crop residue may adversely affect these properties. Blanco-Canqui and Lal (2009b) found that total residue removal reduced the soil nitrogen pool by 0.82 Mg ha^{-1} over a four-year period in a silt loam soil, and Fixen (2007) estimated that crop residue removal reduces nitrogen pools by 20% in the U.S. Corn Belt.

Removal of crop residue reduces soil fertility because residue is an important reservoir of essential macro- and micro-nutrient pools, and crop residue recycles SOM. Rate of residue removal, rate of residue decomposition, residue quality, rate of fertilizer applied, soil characteristics, and climate all affect the amount of nutrients depleted from the soil when residue is removed (Blanco-Canqui and Lal, 2009a).

Crop residue has also been tied to soil pH. Morachan et al. (1972), Karlen et al. (1984), and Blanco-Canqui and Lal (2009b) all reported decreases in soil pH with increased crop residue. Soil bulk density has also been affected by crop residue. Shaver et al. (2002) found that as crop residue accumulation increased, soil bulk density decreased, thereby increasing soil porosity and the potential for water infiltration.

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 effect of crop residue on components of the soil water balance, especially for irrigated agriculture. Specifically, research is needed that complements the research conducted using small lysimeters and integrates the effects (both in time and space) of crop residue with respect to water.

Therefore, a field study was conducted to determine the integrated effect of crop residue on soil water content, soil quality, and crop yield under conditions of deficit irrigation. Specific objectives were to determine the effect of removing corn residue and soybean residue on: (1) water balance components (soil water content, evaporation, transpiration), and (2) soil pH, nitrate nitrogen, organic matter, phosphorus, potassium, and bulk density.

Methods

The study was conducted at the West-Central Research and Extension Center of the University of Nebraska-Lincoln in North Platte, Nebraska (41° 10′ N, 100° 45′ W, 861 m elevation above sea level). The soil is classified as a coarse-silty, mixed, superactive, mesic Typic Haplustolls. It has 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 evapotranspiration 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. There were two treatments: residue-covered soil and bare soil. In April 2007, bare-soil plots were created using a flail chopper and subsequent hand-raking and shoveling, effectively removing the residue (table 1). The residue-covered plots were left untreated. In April 2008, 2009, and 2010, the same bare-soil plots were recreated by using similar methods as in 2007. The residue-covered plots were again left untreated. The experiment was conducted on plots planted to field corn in 2007 and 2008 (reported by van Donk et al., 2010) and soybean in 2009 and 2010 (reported in this article). All plots were in no-till corn in 2004 and in no-till soybean in 2005 and 2006 (table 1).

Table 1. Timetable for planting corn and soybean crops and removing crop residue.

Year	Month	Event[a]
2004	May	Plant corn
2005	May	Plant soybeans
2006	May	Plant soybeans
2007	April	Remove residue (mostly soybean) from four field plots
	May	Plant corn
2008	April	Remove residue (mostly corn) from four field plots
	May	Plant corn
2009	April	Remove residue (mostly corn) from four field plots
	May	Plant soybeans
2010	April	Remove residue (mostly soybean) from four field plots
	May	Plant soybeans

[a] Crop residue was always removed from the same four field plots

The experiment consisted of eight plots (two treatments with four replications each, fig. 1). 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 and from the shredding of corn stalks shortly before planting in the spring of 2008 and 2009. The shredding operation left no corn stalks standing.

Residue cover was measured in April and July 2009 and in April and August 2010 using the line-transect method (USDA-NRCS, 2002) with a 15.2 m (50 ft) measuring tape. The presence or absence of residue was observed 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 in July 2009 and August 2010. Three samples were collected from each residue-covered plot. Only two samples were taken from each bare plot

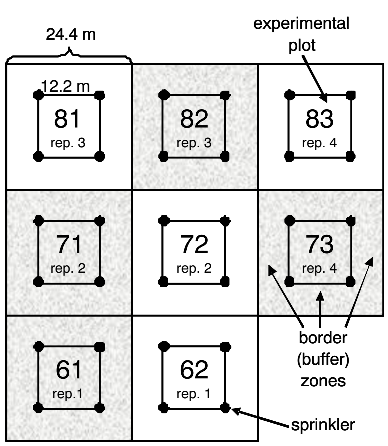

Figure 1. Layout of the eight experimental plots in the study (two treatments and four replications). The shaded plots are the residue-covered plots; the others are the bare-soil plots. Plots 61 and 62 made up replication 1, plots 71 and 72 made up replication 2, plots 81 and 82 made up replication 3, 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.

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 plots were selected randomly. Minimum, maximum, and average residue thickness was measured inside each sample area. 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 and weighed. Subsamples were ground through a 1 mm sieve using a grinder (model 3010-030 Cyclone Mill, 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 the growing season, soil water content was measured nine times in 2009 and ten times in 2010 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, Boart Longyear Company, Martinez, Cal.). There were two neutron probe access tubes per plot: one in the crop row, and one between the rows. The two tubes were located less than 1 m from each other.

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 station, located less than 2 km west of the study site, were used. 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 calendar years of 2009 and 2010. Precipitation for the growing season portion of these two years is shown in figure 2.

Both years had above-average precipitation at North Platte (figs. 2 and 3); thus, less irrigation was required than in average years. The soybean crop was irrigated the same in both treatments. It was irrigated two times with a total of 76 mm of water in 2009 (fig. 2a) and five times with a total of 127 mm in 2010 (fig. 2b). The irrigation scheduling was conducted to slightly stress the crop on the residue-covered plots. By doing so, even more stress and therefore a lower crop yield would be expected on the bare-soil plots. Two criteria were used for stressing the soybean crop: (1) applying less irrigation water than required for full replacement of ET using weather data from the HPRCC weather station, and (2) allowing soil water content to fall below 50% depletion (0.20 $m^3 m^{-3}$ for this soil) in the soil region where most of the water extraction is expected (between 0 and 1.2 m soil depth).

ET was calculated as the residual of the water balance with deep percolation and runoff assumed to be equal to zero, which seem to be reasonable assumptions. The study field is located in the North Platte River valley. It is flat with 0% to 1% slopes. The field was inspected often, and no signs of runoff were ever observed.

At the conclusion of the study, soil samples were collected from each plot to determine if removing crop residue over a period of four years (two years corn and two years soybean) had an effect on certain soil chemical and physical properties. Each plot was divided into quadrants, and soil samples from each quadrant were collected to a depth of 20 cm. Samples were analyzed by Olsen Labs (McCook, Neb.) using standard

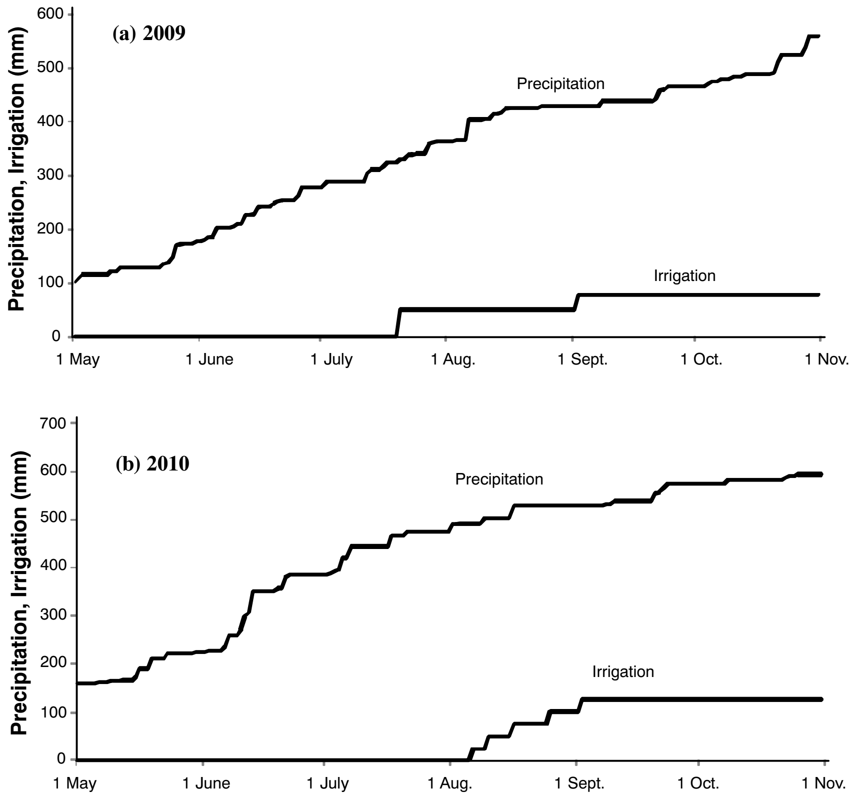

Figure 2. Daily precipitation and irrigation events at the experimental site. The crop was irrigated two times in 2009 and five times in 2010.

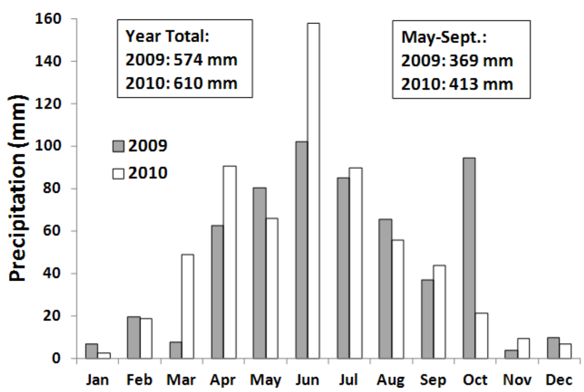

Figure 3. Monthly, seasonal, and annual precipitation at the experimental site in 2009 and 2010.

procedures for residual soil nitrate nitrogen (NO_3^-) (Mulvaney, 1996), phosphorus (P) (Bray and Kurtz, 1945), potassium (K) (Helmke and Sparks, 1996), soil pH (Thomas, 1996), and SOM content (Nelson and Sommers, 1996). Samples were also collected to a depth of 5 cm for bulk density determination. Bulk density was used as a corollary for soil compaction and was determined using the core method (Blake and Hartage, 1986).

Soybean was machine-harvested using a two-row Massey-Harris 35 combine. Guess rows (outside rows of the four-row planter) were not used in the yield calculation. The two-tailed, paired t-test was used (using the t-test function in Microsoft Excel 2007) to determine whether differences in yield between residue-covered plots and bare-soil plots were statistically significant. Analyses of variance were done for soil properties using the ANOVA procedure in SAS (SAS, 2011). The Means option was used to attain all mean values and main effect least significant differences (LSD) at $p \leq 0.1$.

Results and Discussion

Both 2009 and 2010 had precipitation well above the long-term average of 508 mm per year (figs. 2 and 3). In 2009, soybeans were only irrigated two times: 51 mm on July 21, and 25 mm on September 3. In 2010, June was especially wet, but the latter part of August and the beginning of September were very dry, necessitating four irrigations in August and one in the beginning of September (25 mm with each irrigation).

Most of the residue in 2009 was corn residue as a result of the corn crops grown in 2008 and 2007. In April 2009, residue cover was high (76%) on the bare-soil plots (table 2) because it was measured just before the annual residue removal. However, it was smaller than the residue cover on the residue-covered plots (96%) due to residue removal in April 2007 and 2008. In July 2009, residue cover was only 5% on the bare-soil plots because of residue removal in late April 2009 (table 2).

The April 2010 residue measurements were again taken shortly before annual residue removal on the bare-soil plots, accounting for the 53% cover on the bare-soil plots at this time. Residue cover was lower than in April 2009 in both treatments because of the lower residue-producing soybean crop in 2009 compared to the higher residue-producing corn crop in 2008. The same can be seen in August 2010, with a residue cover of only 67% on the residue-covered plots compared to 92% in July 2009. The mass of the residue was also considerably lower in 2010 compared to 2009 (table 2).

Table 2. Residue cover, mass, and thickness for bare-soil and residue-covered plots.

		Bare-Soil Plots				Residue-Covered Plots			
		Cover	Mass	Thickness (mm)		Cover	Mass	Thickness (mm)	
Month	Statistic[a]	(%)	(kg ha^{-1})	Average	Maximum	(%)	(kg ha^{-1})	Average	Maximum
April 2009	Mean	76	--	--	--	96	--	--	--
	SD	13	--	--	--	3	--	--	--
July 2009	Mean	5	279	<1	23	92	6028	13	44
	SD	2	110	0	2	6	448	2	8
April 2010	Mean	53	--	--	--	83	--	--	--
	SD	2	--	--	--	2	--	--	--
August 2010	Mean	1	70	<1	9	67	4039	6	17
	SD	1	111	0	3	8	348	1	3

[a] Means and standard deviations of four plots.

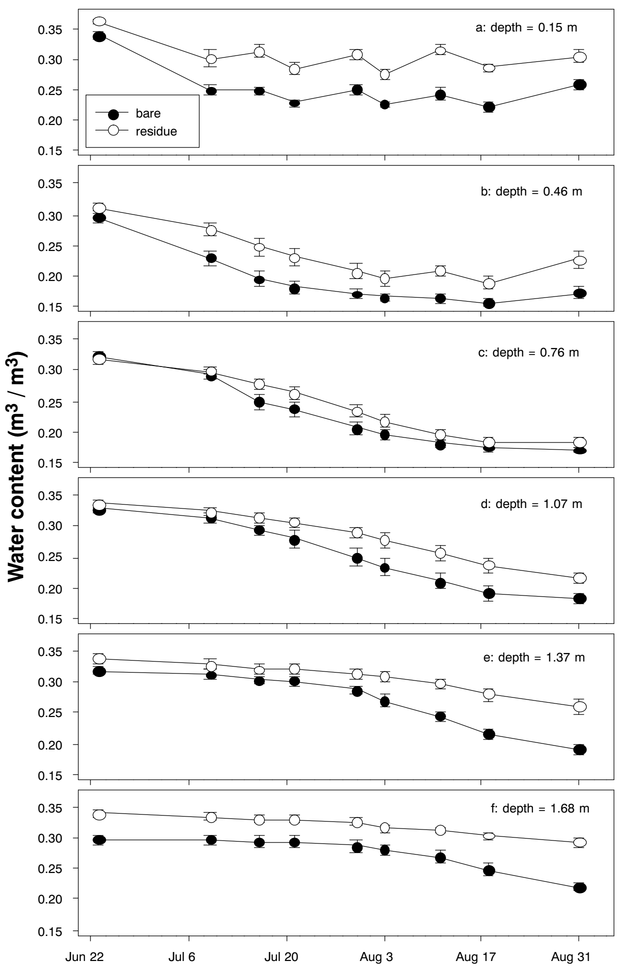

Figure 4. Mean soil water content in 2009 at six depths in bare-soil plots and in residue-covered plots. Error bars indicate plus or minus one standard error of the mean.

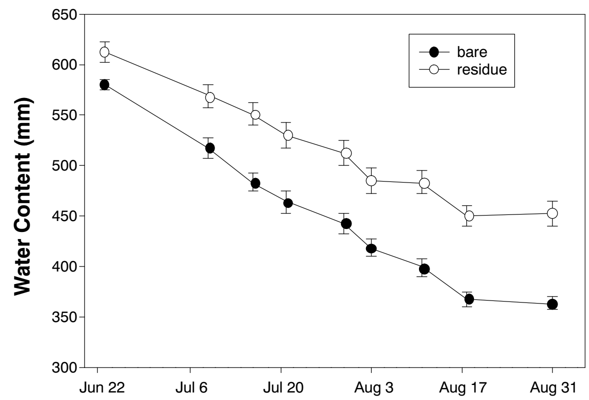

Figure 5. Total soil water content of the top 1.83 m in 2009 in bare-soil plots and in residue-covered plots. Error bars indicate plus or minus one standard error of the mean.

In 2009, the soybean plants used water from all six depths, down to 1.68 m (fig. 4). The soil dried out quickly at the shallower depths (figs. 4a and 4b) during late June and in July, especially in the bare-soil plots. Two causes were likely responsible for the faster drying of the bare soil: (1) greater evaporation in the bare-soil plots and (2) bigger soybean plants in the bare-soil plots during the first part of the growing season, which used more water than the plants in the residue-covered plots. This difference in plant development was visually observed in all four replications and was likely caused by soil temperatures being lower in the residue-covered soil in the beginning of the growing season. By August, the bare-soil plots were much drier than the residue-covered plots (table 3, figs. 4 and 5).

At the beginning of the soil water measurements in June, there was 33 mm more soil water in the residue-covered plots than in the bare-soil plots (table 3, fig. 5). This difference was likely caused by: (1) greater E from the bare-soil plots between residue removal in late April and the date of the first soil water measurement (late June), (2) greater transpiration (T) because of bigger plants in the bare-soil plots in the beginning of the growing season, and 3) carryover from 2008, especially deeper in the soil (fig. 4f). By late August, the residue-covered plots contained 89 mm more water (table 3, fig. 5).

In 2010, the soil dried out quickly at the shallower depths (figs. 6a and 6b) during July, especially in the bare-soil plots, as was observed in 2009. Later in the season, soil at deeper depths started to dry out. At the beginning of the soil water measurements in late April, there was little difference in soil water in the residue-covered plots compared to the bare-soil plots (table 3, fig. 7). The soil was filled with water close to field capacity in both treatments at this time. By the end of July, the residue-covered plots contained 50 mm more water (table 3, fig. 7), likely as a result of greater E in May, June, and July and greater T (bigger plants) in June and July. The reason for the difference only reaching 50 mm compared to almost 100 mm in 2009 may be the fact that there was more residue present on the residue-covered plots in 2009, provided by the corn crops grown in 2008 and 2007. In 2010, most of the residue came from the previous years' soybean crop, which provided less residue than the corn crop (table 2).

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 the residue-covered and bare-soil plots.

SWC Measurement Date	Residue SWC (mm)	Bare Soil SWC (mm)	Cumulative Precipitation (mm)	Cumulative Irrigation (mm)	Residue ET (mm)	Bare Soil ET (mm)	Residue ET (mm d^{-1})	Bare Soil ET (mm d^{-1})	Difference in ET (mm d^{-1})
23 June 2009	612	579	253	0	--	--	--	--	--
9 July 2009	569	516	289	0	79	99	5.0	6.2	-1.2
16 July 2009	550	483	317	0	46	62	6.6	8.8	-2.2
21 July 2009	529	464	331	0	35	33	6.9	6.6	0.3
30 July 2009	512	441	364	51	102	107	11.3	11.8	-0.5
3 August 2009	484	417	366	51	29	26	7.3	6.5	0.8
11 August 2009	482	398	406	51	42	59	5.2	7.4	-2.1
18 August 2009	450	367	428	51	54	54	7.8	7.6	0.1
31 August 2009	451	362	429	51	0	6	0.0	0.4	-0.5
27 April 2010	616	613	734	76	165	79	0.7	0.3	0.4
6 July 2010	587	550	994	76	289	323	4.1	4.6	-0.5
15 July 2010	556	512	1017	76	54	61	6.0	6.7	-0.8
23 July 2010	526	475	1048	76	62	68	7.7	8.5	-0.8
28 July 2010	488	441	1048	76	37	34	7.5	6.8	0.7
5 August 2010	446	407	1065	76	59	52	7.3	6.5	0.9
9 August 2010	430	401	1065	102	43	32	10.6	7.9	2.7
23 August 2010	437	419	1103	152	81	71	5.8	5.1	0.8
2 September 2010	391	391	1103	178	72	54	7.2	5.4	1.8
29 September 2010	399	402	1147	203	61	58	2.3	2.1	0.1

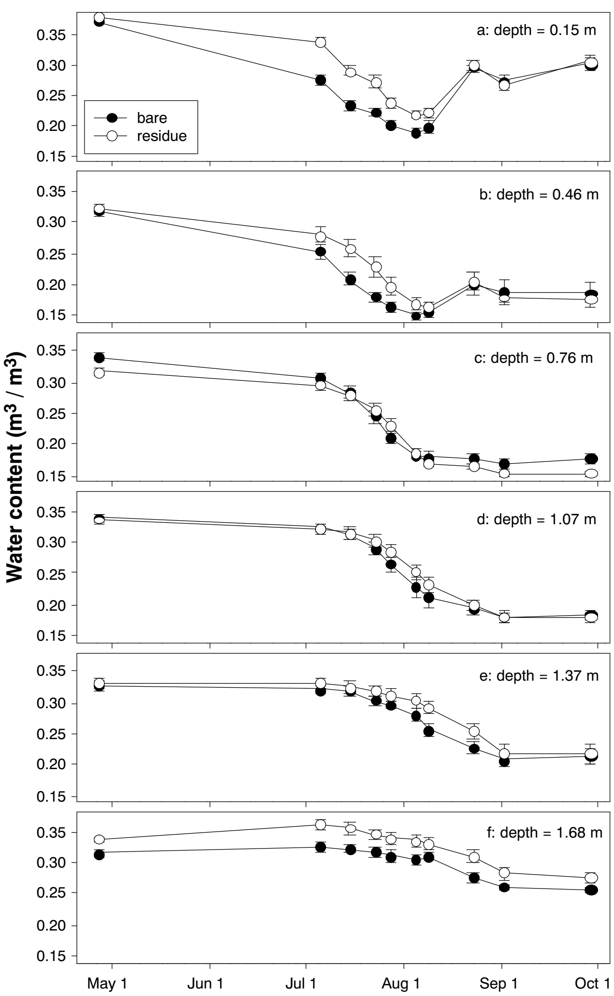

Figure 6. Mean soil water content in 2010 at six depths in bare-soil plots and in residue-covered plots. Error bars indicate plus or minus one standard error of the mean.

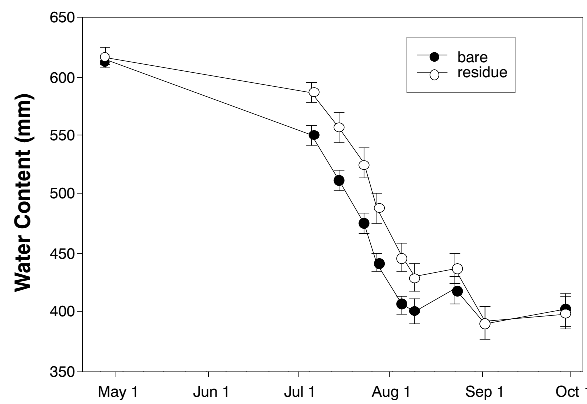

Figure 7. Total soil water content of the top 1.83 m in 2010 in bare-soil plots and in residue-covered plots. Error bars indicate plus or minus one standard error of the mean.

In September, the difference in soil water content between the two treatments was again very small (table 3, fig. 7) because of two reasons. First, the deeper soil layers were still drying out in the residue-covered plots in August, more so than in the bare-soil plots (figs. 6d and 6e). By this time, the plants in the bare-soil plots apparently used less water because they were forced to mature earlier, as induced by water stress. Second, close to the soil surface, the difference in soil water content was erased by the soil being filled to nearly field capacity resulting from irrigation, rain, and greatly diminished crop water use in September (fig. 6a).

Soybean yield was greater in the residue-covered plots compared to the bare-soil plots in 2009 (table 4). The average yield of the four residue-covered plots was 4.5 Mg ha^{-1}, and the average yield of the four bare-soil plots was 3.9 Mg ha^{-1}. During the first part of the growing season, ET was greater on the bare-soil plots (table 3) because of greater evaporation and bigger plants transpiring at higher rates. The greater yield on the residue-covered plots may be explained by two mechanisms. First, E was probably a smaller fraction of ET,

Table 4. Mean soybean yields for the two treatments (residue-covered soil and bare soil), where yields are the means of four plots (four replications), and the amounts of additional irrigation water required on the bare-soil plots to produce the extra yield produced on the residue-covered plots, estimated using two different references.

	Yield (Mg ha^{-1})				Additional Irrigation Water (mm)	
Year	Residue	Bare Soil	Difference	p	Specht et al. (1986)	Martin et al. (2007)
2009	4.5	3.9	0.6	0.0049	85	74-91
2010	3.8	3.3	0.5	0.0993	68	64-79

Table 5. Soil pH, nitrate nitrogen (NO_3^-), organic matter (OM), Bray phosphorus (P), exchangeable potassium (K) (all at 0-20 cm soil depth), and bulk density (0-5 cm soil depth) as affected by soil residue cover and bare soil after four years of residue removal.

	Soil pH	Soil NO_3^- (mg kg^{-1})	Soil OM (g kg^{-1})	Soil P (mg kg^{-1})	Soil K (mg kg^{-1})	Bulk Density (g cm^{-3})
Residue-covered soil	7.5	11.2	22.0	7.6	523.5	1.56
Bare soil	7.7	8.7	19.8	5.0	505.0	1.57
P > F	0.0663	0.0392	0.0374	0.3101	0.5788	0.7381
$LSD_{0.1}$	0.17	1.7	1.5	--	--	--

and thus T was 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). Only T contributes to plant growth and yield; E does not. Second, 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.

In 2010, soybean yield was again greater in the residue-covered plots compared to the bare-soil plots. The average yield of the four residue-covered plots was 3.8 Mg ha^{-1}, and the average yield of the four bare-soil plots was 3.3 Mg ha^{-1} (table 4). Soil water content between the bare-soil and residue-covered plots was similar at the beginning and again at the end of the 2010 growing season (fig. 7); thus, total season ET was also similar (table 3). The greater yield in the residue-covered plots may be explained by the same two mechanisms discussed earlier for 2009.

Estimates were made to translate the yield differences into the amount of water that would be required to produce this extra yield. Two different sources were used for this estimate (table 4). One of these sources was Specht et al. (1986). Based on their data, 85 mm more water would be required to produce the extra soybean yield of 0.6 Mg ha^{-1} in 2009, and 68 mm more water would be required to produce the extra soybean yield of 0.5 Mg ha^{-1} in 2010 (table 4).

The second source was data embedded in the Water Optimizer (Martin et al., 2007). An analysis with the Water Optimizer, using a medium-textured soil and an application efficiency of 0.75, indicated that an additional 74 to 91 mm of irrigation water would be required to raise the soybean yield from 3.9 to 4.5 Mg ha^{-1} (2009 yields) at North Platte, Nebraska (table 4). The 74 mm estimate was based on a fully watered yield of 5.1 Mg ha^{-1}, and the 91 mm estimate was based on a fully watered yield of 4.7 Mg ha^{-1}. The default Water Optimizer fully watered soybean yield for North Platte was below our soybean yields and was therefore not used in this analysis. For 2010, analysis using the Water Optimizer showed that an additional 64 to 79 mm of irrigation water would be required to raise the soybean yield from 3.3 to 3.8 Mg ha^{-1}.

Soil sample analysis conducted at the conclusion of the study showed that removing crop residue annually over a period of four years had significant effects on residual soil nitrate levels, soil pH, and SOM content (table 5). The most direct and obvious soil property one would expect to be affected by the removal of crop residue would be SOM, and this proved to be the case. Soil analysis showed that plots with the residue removed had significantly less SOM (19.8 g kg^{-1}) than plots with the residue left in place (22.0 g kg^{-1}) (table 5). By removing crop residue, a major source of SOM was removed, resulting in a reduction in SOM.

As a result of the reduction in SOM, one would also expect a reduction in nutrient cycling and residual soil test levels of N, P, and K. Soil analysis for N showed that residual nitrate levels were significantly lower (8.7 mg kg^{-1}) in plots where crop residue was removed than in plots where the crop residue was undisturbed (11.2 mg kg^{-1}) (table 5). These results support earlier findings from studies conducted by Blanco-Canqui and Lal (2009b) and Fixen (2007), who also discovered significant reductions in soil N with reduced crop residue. The differences observed are likely a direct result of the different amounts of SOM available for N mineralization. Analysis for soil test P and K showed no significant differences between residue-covered and bare-soil treatments. However, soil test levels were less in the bare-soil plots for P (5.0 mg kg^{-1}) and K (505.0 mg kg^{-1}) than in the residue-covered plots (P = 7.6 mg kg^{-1}, K = 523.5 mg kg^{-1}) (table 5). While these results were not statistically significant, the trends suggest that the removal of crop residue may adversely affect nutrient cycling in the soil over time.

Significant differences between crop residue treatments were also observed for soil pH. Plots with removed residue had significantly higher soil pH levels (7.7) as compared to plots with the crop residue left in place (7.5). These results support previous findings by Morachan et al. (1972), Karlen et al. (1984), and Blanco-Canqui and Lal (2009b), who all found decreases in soil pH with increased residue. The reduction in soil pH can also be tied to the differences observed in SOM, as decreased SOM can lead to increases in soil pH due to H^+ ions that are produced through the decomposition process. Reduced SOM leads to a reduction in H^+ ions, thereby raising the soil pH levels.

Bulk density is a measure of soil compaction, and one would expect that the bare-soil plots would become more compacted over time than the residue-covered plots (under no-till management). This is due to several factors, including the residue's ability to bridge on field traffic, as well as residue decomposition products that contribute to soil aggregation, which increases soil porosity and thereby decreases bulk density (Shaver et al., 2002). No significant differences were observed in bulk density between the residue-covered (1.56 g cm^{-3}) and bare-soil plots (1.57 g cm^{-3}) (table 5). Bulk density does not change very quickly, and it is likely that four years was not enough time to develop significant differences. The differences in bulk density due to crop residue observed by Shaver et al. (2002) were after 12 years of differences in residue accumulation, significantly more time than the four years of this study.

Summary and Conclusions

The residue-covered soil held approximately 90 mm more water in the top 1.83 m compared to the bare soil near the end of the 2009 growing season. In addition, the mean soybean yield was 4.5 Mg ha^{-1} in the residue-covered plots, compared to 3.9 Mg ha^{-1} in the bare-soil plots. Between 74 and 91 mm of irrigation water would have been required to produce this extra 0.6 Mg ha^{-1}. Thus, the total amount of water conservation in 2009 that may be attributed to the residue was 164 to 181 mm.

In 2010, the mean soybean yield was 3.8 Mg ha^{-1} in the residue-covered plots, compared to 3.3 Mg ha^{-1} in the bare-soil plots. Between 64 and 79 mm of irrigation water would have been required to produce this extra 0.5 Mg ha^{-1}. At the end of the growing season, there was little difference in soil water content between the bare-soil plots and the residue-covered plots. The smaller residue effect in 2010 (mostly soybean residue) may be due to the fact that less surface residue was present compared to 2009 (mostly corn residue).

In both years, several processes may have contributed to the differences observed: (1) greater evaporation of water from the soil in the bare-soil treatment, and (2) greater transpiration by plants in the bare-soil treatment in the beginning of the growing season because of bigger plants at this time, which were due to higher soil temperatures in the bare-soil treatment. Greater transpiration in the vegetative growth stage did not contribute much to soybean yield at harvest time.

Soil test results show that removing crop residue annually had a significant impact on soil quality in a relatively short period of time (four years). Soil organic matter content, soil residual nitrate levels, and soil pH were all negatively impacted by the removal of crop residue. Soil test P and K also had negative trends when crop residue was removed. While the impacts during this four-year time frame were minimal, and likely not sufficient to negatively affect crop yields, the impact on soil quality was measureable and statistically significant. Over a longer period of time, the removal of crop residue could result in even greater depletion of SOM and soil nutrient cycling, eventually negatively impacting crop yields.

More research on soil water balance, evaporation, transpiration, and crop yield is needed in the context of actual agricultural systems, such as systems in which residue is removed by grazing or baling, or systems in which surface residue is reduced by tillage. In this experiment, residue was artificially removed from the plots without any tillage. The difference in residue cover created in our experiment was quite extreme, with less than 10% cover on the bare-soil plots in both years. In the real world, such low surface residue levels are only created with considerable tillage, possibly combined with mechanical residue removal. If the difference in residue cover is less extreme than in our study, then a smaller water conservation benefit would be expected.

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 it typically 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 (we removed residue each spring, not the previous fall), no-till may conserve water by increasing snow trapping and reducing overwinter evaporation.

Water conservation of the magnitudes observed in this study will help irrigators significantly reduce pumping costs, and more water would be available for competing needs, including those of wildlife, endangered species, municipalities, and compacts with other states. When the availability of irrigation water is limited, a producer may not have the luxury to adjust pumping for irrigation. In this case, less residue will probably mean reduced yield, and the economic impact of this will likely be even greater than that of increased pumping cost. For rainfed production in semi-arid climates, yield reductions can also be expected when less residue remains on the soil surface.

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