



Precipitation Storage Efficiency during Fallow in Wheat-Fallow Systems

David C. Nielsen* and Merle F. Vigil

ABSTRACT

Precipitation storage efficiency (PSE) is the fraction of precipitation received in a given time period that is stored in the soil. Average fallow PSE for Great Plains wheat (*Triticum aestivum* L.)-fallow (W-F) production systems have ranged widely (10–53%). Study objectives were to compare PSE in conventionally tilled (CT) and no-till (NT) W-F systems over 10 seasons at Akron, CO, against published values and to identify meteorological conditions that may influence PSE. Soil water measurements were made four times during each fallow period, dividing the fallow season into three periods (first summer, fall–winter–spring, second summer). Precipitation was measured in the plot area and other meteorological conditions were measured at a nearby weather station. The 14-mo fallow PSE averaged 20% (range 8–34%) for CT and 35% (range 20–51%) for NT, much lower than previously reported for NT at Akron. During the second summer period, PSE was not different between the two systems. The largest PSE difference between the two systems was seen during the fall–winter–spring period (32 vs. 81%). Fallow soil water increased an average of 111 mm under CT and 188 mm under NT. The PSE during the three fallow periods was related to tillage, precipitation, air temperature, vapor pressure deficit, and wind speed, but sometimes counter-intuitively. A simple linear regression using inputs of tillage system, percentage of fallow precipitation events with amounts between 5 and 15 mm, and percentage of fallow precipitation events with amounts > 25 mm can be used to estimate PSE and fallow period water storage.

THE PREDOMINANT CROPPING SYSTEM of the central Great Plains continues to be W-F. Fallow as a practice associated with crop rotation had its origins in Mediterranean agriculture (Karlen et al., 1994) and continues to be used throughout the semiarid and arid regions of West Asia and North Africa (Ryan et al., 2008), although some implementations of fallow in these areas are “weedy fallow” in which weeds are allowed to grow for animal grazing, and thus no soil water is stored during the fallow period. Fallow in the Great Plains has been defined as a farming practice wherein no crop is grown and all plant growth is controlled by cultivation or chemicals during a season when a crop might normally be grown (Haas et al., 1974). Summer fallow has been practiced widely across the 15 western states of the United States and the farmed areas of the prairie provinces of Canada in response to widely varying precipitation from year to year. The primary reason for summer fallow is to stabilize crop production and reduce the chances of crop failure by forfeiting production in one season in anticipation that there will be at least partial compensation by increased crop production the next season.

Precipitation storage efficiency is the fraction of precipitation that falls in a given time period that is stored in the soil profile. It is calculated as:

$$\text{PSE (\%)} = 100 \times \left[\frac{\text{ending soil water} - \text{beginning soil water}}{\text{precipitation between beginning and ending soil water measurements}} \right] \quad [1]$$

Greb et al. (1967) reported a 3-yr average fallow PSE from W-F systems at three Great Plains locations (Sidney, MT; Akron, CO; North Platte, NE) of 22, 30, and 29%, respectively, with approximately 3.4 t ha⁻¹ of wheat residue present following harvest. Fallow PSE was lower when less residue was present and greater with more residue present. Another 3-yr study at North Platte, NE (Smika and Wicks, 1968) found a fallow period PSE of 32% with stubble mulch tillage and 43% with NT fallow management. The 3-yr average fallow PSE at Sidney, MT, was 33% for stubble-mulch and 38% for NT (Tanaka and Aase, 1987). Peterson et al. (1996) summarized PSE research conducted in the 1980s and 1990s from eight locations across the Great Plains from Texas to Saskatchewan. They reported PSEs ranging from 10 to 42% and that PSE appeared to be independent of the climatic zones in which the data were collected.

Farahani et al. (1998) uniquely analyzed 7 yr of PSE data from NT W-F systems at three sites in eastern Colorado by dividing the 14-mo fallow period into three periods: (i) early (wheat harvest in July until mid-September); (ii) overwinter period (from fall to early May); and (iii) later period (from spring to wheat planting in mid-September). The mean PSE values averaged across sites and years for the three periods were 12% for the early

USDA-ARS, Central Great Plains Research Station, 40335 County Road GG, Akron, CO 80720. Received 10 Sept. 2009. *Corresponding author (david.nielsen@ars.usda.gov).

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Abbreviations: PSE, precipitation storage efficiency; W-F, wheat-fallow; CT, conventionally tilled; NT, no-till; DUL, drained upper limit.

period, 61% for the overwinter period, and -4% for the later period, with an overall fallow period PSE of 19%.

Smika (1983) reported distinctly greater PSE values from NT W-F plots in Akron, CO, than reported for the NT systems over the 14-mo fallow period in the citations given above. The 3-yr average PSE was 19% where all crop residues were removed during the fallow period (but the soil was not tilled), compared with 27% where all crop residues were flat on the soil surface and 53% where half of the residue was flat and half of the residue was standing. In this study, weekly increases in soil water content were mostly related to precipitation and weekly decreases in soil water content were mostly related to wind speed (greater soil water loss with greater wind speed). Another data set from Akron reported by Smika (1990) gave 12-yr average PSE values of 41% for stubble mulch fallow and 49% for NT fallow in W-F plots.

Greb (1979) presented a table of fallow PSE values that indicated improvement in storing precipitation as fallow weed control shifted from intense tillage with plow and harrow (dust mulch, PSE = 19%) to conventional tillage (shallow disk and rod weeder, PSE = 24%) to improved conventional tillage (stubble mulch, PSE = 27%) to minimum tillage (stubble mulch with some herbicide use, PSE = 33%). At that time he projected PSE to improve to 40% during the period of 1976 to 1990, with minimum tillage changing to NT fallow management using herbicides for weed control in 1983. This projection was based on a predicted fallow period soil water storage of 183 mm in the 0- to 180-cm soil profile following precipitation of 457 mm.

McGee et al. (1997) reported much lower fallow PSE values than reported by Smika (1983, 1990) (average 26%, range 22 to 33% depending on slope position) from a two-season study (W-F NT) conducted at a location 55 km north of the location where Smika (1983, 1990) conducted his studies. Peterson and Westfall (2004) summarized several more recent studies reporting values of fallow PSE in W-F reduced or NT systems ranging from 17 to 35%. They stated that it appears that we cannot improve on the 35% storage efficiency that Greb achieved in the early 1970s with the current fallow technology. They surmised that greater PSE might be achieved with greater amounts of crop residue ($>6.7 \text{ t ha}^{-1}$), but that those amounts were not likely to be realized except in years with exceptional precipitation or in field positions that receive runoff water. Use of a stripper-header for wheat harvest may be a way of increasing standing residue fraction that may improve PSE through increased snow catch and reduced air movement at the soil surface (McMaster et al., 2000).

Because of the disparity between the NT PSE value reported for Akron, CO, by Smika (1983, 1990) compared with other reported NT PSE values in the Great Plains (e.g., McGee et al., 1997; Farahani et al., 1998; Peterson and Westfall, 2004), we decided to analyze more recent data recorded at Akron. Therefore, the objectives of this study were to compare PSE in CT and NT W-F systems over 10 seasons at Akron, CO, against previously published values of fallow PSE and to identify meteorological conditions that may influence PSE.

MATERIALS AND METHODS

This study was conducted at the USDA-ARS Central Great Plains Research Station, 6.4 km east of Akron, CO (40°09' N, 103°09' W, 1384 masl). The soil type was a Weld silt loam (fine, smectitic, mesic Aridic Argiustoll). In 1990, several rotations

were established to investigate the possibility of cropping more frequently than every other year, as done with the traditional W-F system. The current study analyzes data beginning with the 1996–1997 fallow period to provide time for soil water conditions to stabilize and truly manifest rotation and tillage effects, and includes 10 fallow periods ending with the 2005–2006 fallow period. A description of the plot area, tillage systems, and experimental design are given in Bowman and Halvorson (1997) and Anderson et al. (1999). Rotation treatments were established in a randomized complete block design with three replications. All phases of each rotation were present every year. Individual plot size was 9.1 by 30.5 m, with east-west row direction. Only the W-F CT and NT rotations were used in this analysis to determine the influence of tillage and climate on PSE.

Details of the weed control practices used for the CT and NT systems are given in Anderson et al. (1999). Briefly, the CT system employed four to eight sweep plow operations as needed for weed control during fallow. The NT system relied on contact and residual herbicides for all weed control.

Soil water measurements were made at four times during each fallow period: following wheat harvest in early July, and about 1 October, 1 May, and 1 October to divide the fallow season into three periods (first summer, fall–winter–spring, second summer) similar to the periods defined by Farahani et al. (1998). Soil water measurements in the 0- to 30-cm layer were made by time-domain reflectometry (Trase System I, Soil Moisture Equipment Corp., Santa Barbara, CA).¹ Soil water measurements at 45, 75, 105, 135, and 165 cm were made with a neutron probe (Model 503 DR Hydroprobe, CPN International, Martinez, CA). The neutron probe was calibrated against gravimetric soil water samples taken in the plot area. Two measurement sites were located near the center of each plot and data from the two sites were averaged to give one reading of soil water content at each sampling depth per plot. Gravimetric soil water was converted to volumetric water by multiplying by the soil bulk density for each depth. Total profile water was calculated as volumetric water multiplied by layer thickness (30 cm) and summed for the six layers of the profile. Precipitation storage efficiency was calculated as given in Eq. [1]. For example, a 400-mm increase in soil water content during the fallow period in response to 1200 mm of precipitation over that period would result in a calculated PSE of 33%. Daily precipitation was recorded as the average of measurements made at two diagonally opposite corners of the plot area. Runoff and deep percolation were assumed to be negligible during each fallow period. Other meteorological conditions were measured at a weather station about 350 m from the plot area.

The assumption of negligible runoff was considered valid as the slope in the plot area was <1% and visual observations in the plot area following heavy rains did not show evidence of runoff. To assess the validity of the assumption of negligible deep percolation we compared volumetric soil water profiles throughout the fallow period against the drained upper limit (DUL) profile (Fig. 1). The DUL profile was inferred from the wettest conditions measured (end of the 1998–1999 fallow period) as suggested by Ratliff et

¹ Use of a company or product name does not imply approval or recommendation of the product by the USDA to the exclusion of others which may also be suitable.

al. (1983). The data shown in Fig. 1 clearly indicate that adequate capacity remained in the soil to store additional precipitation under CT management, but the 10-yr average NT soil water profile was very near to being at full capacity and, in some years, there may have been some small amounts of precipitation storage unaccounted for. However, since our previous measurements of soil water extraction by wheat have rarely shown any appreciable water use at 165 cm, we conclude that precipitation which moves below that depth is lost from the W-F production system in the same sense that evaporative losses are not available to the production system. Hence, a calculation of PSE ignoring small amounts of soil water storage that may have occurred below the active wheat root zone does not invalidate an analysis of PSE in the context of the W-F production system.

Residue mass at harvest was estimated from the difference between an aboveground biomass sample taken (from a 3-m² area) in late June and final grain yield (from a 42-m² area). Fraction of standing and flat residue was not quantified. Percentage residue cover was taken periodically over the fallow period by the line transect method with 200 points per plot.

Tillage treatment effects on PSE were analyzed by ANOVA. In an effort to better understand the factors controlling PSE we used best subset linear regression (STATISTIX 9, Analytical Software, Tallahassee, FL) to look for significant relationships between PSE and meteorological/management factors. We denoted tillage as a factor in the regression models (CT = 0, NT = 1). We then created the following parameters for each of the 10 data sets: total fallow period precipitation (mm); total fallow period snow (mm of water); and precipitation, snow, average solar radiation (MJ m⁻² d⁻¹), average air temperature, average vapor pressure deficit (kPa), and average wind speed (m s⁻¹) during each of the three fallow period segments.

RESULTS AND DISCUSSION

Precipitation ranged widely during the 10 fallow periods observed during the course of this study (Table 1). Precipitation during the first summer period ranged from 92 to 260 mm (average 158 mm). Precipitation during the fall–winter–spring period ranged from 41 to 213 mm (average 118 mm). Precipitation during the second summer period ranged from 183 to 377 mm (average 262 mm). Precipitation for the entire 14-mo fallow period ranged from 407 to 682 mm (average 539 mm).

Precipitation storage efficiency also ranged widely from year to year (Table 1). During the first summer period PSE ranged from 2.6 to 55.4% (average 22.7%) for CT and from 13.6 to 58.1% (average 35.0%) for NT. The PSE under NT was significantly higher ($P < 0.05$) than under CT in only three of the 10 yr, but numerically higher in 9 yr. The 10-yr average PSE was significantly higher under NT than CT ($P < 0.01$), resulting in an average soil water storage of 41 mm with CT and 60 mm with NT during this first part of the fallow period.

During the fall–winter–spring period, PSE ranged from -7.3 to 88.0% (average 31.7%) for CT and from 37.6 to 127.9% (average 80.8%) for NT. Values of PSE greater than 100% are possible because of the snow-catching potential of standing

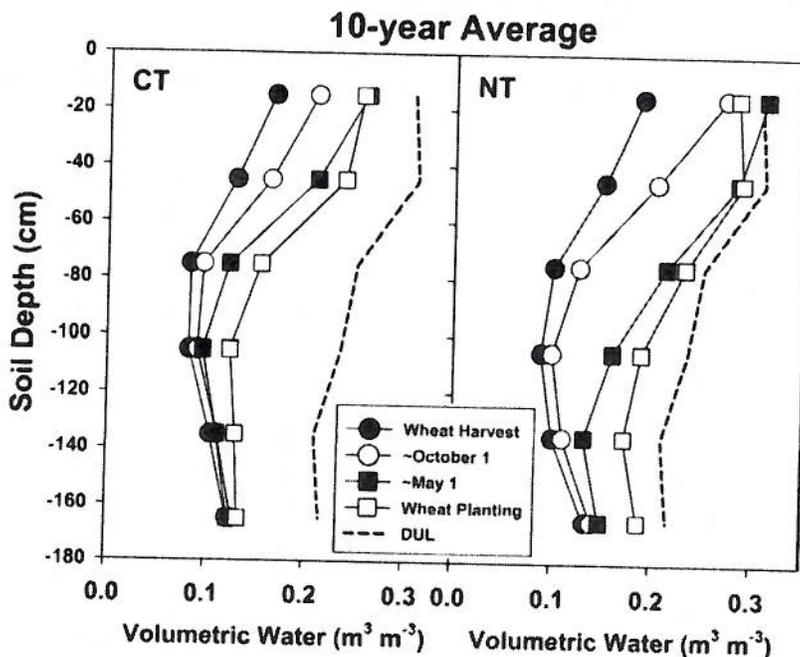


Fig. 1. Ten-year average volumetric soil water profiles at Akron, CO, under conventional till (CT) and no-till (NT) fallow management systems at wheat harvest, about 1 October, about 1 May, and at wheat planting. The drained upper limit (DUL) soil water profile is also indicated.

crop residue during snow storms with strong winds (Nielsen, 1998). The PSE under NT was significantly higher ($P < 0.10$) in seven of the 10 yr, but numerically higher in all 10 yr. The average PSE for this period was significantly higher under NT than CT ($P < 0.01$), resulting in an average soil water storage of 38 mm with CT and 94 mm with NT during this period.

During the second summer period, PSE ranged from -2.0% to 37.7% (average 10.6%) for CT and from -15.2 to 42.7% (average 12.0%) for NT. Average soil water storage during this period was about 33 mm for both CT and NT. The PSE under NT was significantly higher than under CT in only 1 yr (2003–2004), but was numerically higher in 6 of 10 yr. The PSE under NT was significantly lower than under CT in 2 yr and numerically lower in 4 of 10 yr. It may be that this lower PSE sometimes observed under NT was due in part to conditions where the soil profile was mostly filled to capacity such that the soil surface stayed wetter longer following precipitation events resulting in higher evaporative losses of water (Peterson and Westfall, 2004). Bond and Willis (1969) demonstrated in a laboratory study with a fine sandy loam that soil water evaporation rate after about 7 d of drying would be higher from a soil covered with 4480 kg ha⁻¹ of residue than from a bare soil, and remain substantially higher than from bare soil if drying continued for another 2 wk. Additionally, as stated in the Materials and Methods, we cannot rule out the possibility that in some years there may have been filling of the entire 0- to 180-cm soil profile to field capacity before the end of the fallow period such that some deep percolation and storage of precipitation occurred below the lowest soil water measurement depth in the NT plots. The soil water profiles shown in Fig. 1 indicate that, on average, the situation did not occur under CT management. But the average ending water content at wheat planting is close to the DUL under NT and likely there were some years when there may have been some precipitation storage unaccounted for. As stated earlier, whether precipitation

Table 1. Fallow period precipitation, soil water storage, and precipitation storage efficiency (PSE) for conventional till (CT) and no-till (NT) wheat fallow systems at Akron, CO.†

	Precipitation	Change in soil water		PSE		Precipitation	Change in soil water		PSE	
		CT	NT	CT	NT		CT	NT	CT	NT
	mm					mm				
		First summer					Fall-winter-spring			
1996–1997	213	6	29	2.8	13.6ns	41	–1	33	–2.4	80.5*
1997–1998	116	3	24	2.6	20.7*	131	47	90	35.9	68.7ns
1998–1999	165	50	72	30.3	43.6ns	140	40	84	28.6	60.0‡
1999–2000	260	144	151	55.4	58.1ns	101	49	97	48.5	96.0ns
2000–2001	159	43	45	27.0	28.3ns	154	87	197	56.5	127.9‡
2001–2002	174	22	69	12.6	39.7*	50	17	38	34.0	76.0ns
2002–2003	129	5	36	3.9	28.7*	213	71	163	33.3	76.5**
2003–2004	56	15	15	26.8	26.8ns	83	73	104	88.0	125.3**
2004–2005	92	18	31	19.6	33.7ns	157	3	93	1.9	59.2**
2005–2006	220	101	125	45.9	56.8ns	109	–8	41	–7.3	37.6*
Average	158	41	60	22.7	35.0**	118	38	94	31.7	80.8**
		Second summer					Entire fallow			
1996–1997	264	39	40	14.8	15.2ns	517	43	102	8.3	19.7*
1997–1998	212	18	38	8.5	17.9ns	460	68	153	14.8	33.3ns
1998–1999	377	142	161	37.7	42.7ns	682	232	318	34.0	46.6*
1999–2000	222	–4	–20	–1.8	–9.0ns	584	188	228	32.2	39.0*
2000–2001	310	34	–40	11.0	–12.9‡	623	165	202	26.5	32.4ns
2001–2002	183	13	52	7.1	28.4ns	407	52	159	12.8	39.1*
2002–2003	244	–5	–37	–2.0	–15.2‡	586	71	163	12.1	27.8**
2003–2004	277	26	91	9.4	32.9**	416	114	210	27.4	50.5**
2004–2005	309	53	18	17.2	5.8ns	558	75	142	13.3	25.4ns
2005–2006	225	9	33	4.0	14.7ns	554	102	199	18.4	35.9‡
Average	262	33	34	10.6	12.0	539	111	188	20.0	35.0**

* Differences between PSE due to tillage treatment within a fallow period are significant at $P = 0.05$.

** Differences between PSE due to tillage treatment within a fallow period are significant at $P = 0.01$.

† First summer runs from wheat harvest (about 10 July) to about 30 September; Fall-winter-spring runs from about 1 October to about 30 April; Second summer runs from about 1 May to wheat planting (about 20 September).

‡ Differences between PSE due to tillage treatment within a fallow period are significant at $P = 0.10$.

§ ns, differences between PSE due to tillage treatment within a fallow period are not significant.

is lost from the active wheat root zone through surface evaporation or through movement below the root zone, the conclusions are the same regarding no difference in PSE between NT and

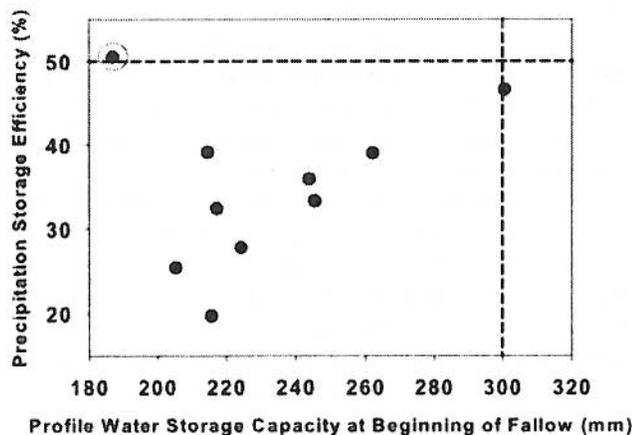


Fig. 2. Precipitation storage efficiency under no-till conditions during the 14-mo fallow period between wheat crops in wheat-fallow systems at Akron, CO as related to profile water storage capacity at the beginning of the fallow period. The circled point is from the very dry 2003–2004 fallow period. The dashed vertical line at 300 mm indicates the maximum storage capacity for a Weld silt loam (0- to 180-cm profile).

CT systems and the consequences in relation to water stored for wheat crop growth, development, and yield.

Precipitation storage efficiency for the entire fallow period ranged from 8.3 to 34.0% (average 20.0%) for CT and from 19.7 to 50.5% (average 35.0%) for NT. The PSE under NT was significantly higher than under CT in seven of 10 yr, but was numerically higher in all 10 yr. Average soil water storage during the entire fallow period was 111 mm with CT and 188 mm with NT.

The 10-yr average PSE value of 20% for the entire fallow period with CT is much lower than the shorter term average values reported for stubble mulch systems in North Platte, NE (32%), by Smika and Wicks (1968) and in Sidney, MT (38%), by Tanaka and Aase (1987). But the data in Table 1 also indicate that there were 2 yr when the PSE for the entire fallow period was greater than 30%. Similarly, the 10-yr average PSE of 35% for NT is much lower than the 3-yr average NT PSE of 53% reported by Smika (1983) but much higher than the 7-yr average of 19 to 22% reported by Farahani et al. (1998) and McGee et al. (1997) for W-F NT systems in eastern Colorado.

One reason that it may not be possible to regularly obtain PSE > 50% may be due to the root zone storage capacity of the soil. Soil profile water storage capacity was calculated as the DUL profile water minus the profile water measured at the beginning of the fallow period. As shown in Fig. 2, PSE under NT

conditions generally increased as profile water storage capacity at the beginning of the fallow period increased; that is, the drier the soil was at the beginning of the fallow period, the greater the PSE. The exception noted by the circled point in Fig. 2 was during the very dry 2003–2004 fallow period with only 416 mm of precipitation, of which 67% (277 mm) fell during the second summer period (Table 1). Using the lower limits of volumetric water content generally assumed valid for winter wheat grown on the Weld silt loam at this location (Nielsen and Vigil, 2005) produces a maximum storage capacity of 300 mm. Figure 2 indicates a PSE of just under 50% at this maximum storage capacity.

Fallow periods with storage capacity at the beginning of the fallow period <300 mm occur when soil water was poorly extracted by the preceding wheat crop, or when precipitation occurs at the end of the wheat growing period when wheat is maturing and demand for water decreases rapidly. In some of those cases there will be fallow periods with high precipitation which will exceed the storage capacity of the soil. As mentioned previously, that will likely lead to longer periods of time with a wet soil surface that will increase evaporative losses, percolation of water below the 165 cm measurement depth used in this study, and perhaps to water loss by runoff under some circumstances. Had we measured soil water content deeper than 165 cm we may have observed PSE > 50% over the entire 14-mo fallow, but as stated earlier, that water stored at deeper soil depths would typically be unavailable for use by the next wheat crop, and should be considered a loss when calculating PSE important to the W-F production system.

As stated earlier, one of our objectives was to better understand the meteorological, tillage, and residue factors influencing PSE using best subset linear regression. The best regression model was found to be:

$$\text{PSE (\%)} = -14.21 + 14.97 \times \text{tillage} + 1.1928 \times \text{snow3} + 32.0 \times \text{VPD2} + 11.98 \times \text{WS1} - 1.245 \times \text{Rad1} \quad [2]$$

where tillage = 0 for CT and 1 for NT; snow3 = total snow (mm of water) during the second summer period; VPD2 = average vapor pressure deficit (kPa) during the fall–winter–spring period; WS1 = average wind speed (m s^{-1}) during the first summer period; and Rad1 = average solar radiation ($\text{MJ m}^{-2} \text{d}^{-1}$) during the first summer period.

While this model was able to reproduce PSE fairly well (Fig. 3, $R^2 = 0.89$, $P < 0.01$), some of the parameters selected seemed to make sense, while others did not. Tillage was an obvious factor that made sense. The regression equation indicated an increase of nearly 15 PSE points when NT was employed, presumably as a result of less soil stirring and less surface residue destruction. Likewise, the decrease of 1.2 PSE points for every $\text{MJ m}^{-2} \text{d}^{-1}$ increase of average solar radiation during the first summer period seems correct: greater solar radiation leading to greater evaporation and lower PSE. Also, a late spring/early summer snow storm during the second summer period could increase PSE. But greater PSE with greater vapor pressure deficit during the fall–winter–spring and with greater wind speed during the first summer seems counter-intuitive. It also seems counter-intuitive that no other precipitation parameters were identified as important influences on PSE prediction other than snow during the second summer period. Contrary to the data reported by Greb et al. (1967), residue mass did not appear as an important variable affecting

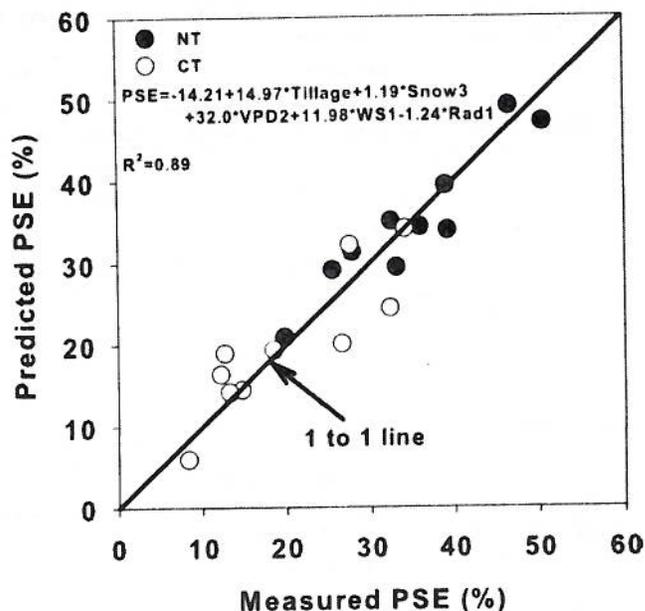


Fig. 3. Measured vs. predicted fallow precipitation storage efficiency (PSE) at Akron, CO (1996–2006) for no-till (NT) and conventional till (CT) wheat-fallow systems. Parameters in the regression prediction equation are Tillage (= 0 for CT, 1 for NT), Snow3 [total snow (mm of water) during the second summer period], VPD2 [average daily vapor pressure deficit (kPa) during the fall–winter–spring period], WS1 [average daily wind speed (m s^{-1}) during the first summer period], and Rad1 [average daily solar radiation ($\text{MJ m}^{-2} \text{d}^{-1}$) during the first summer period].

PSE. Residue mass in that study ranged from 0 to 10 T ha^{-1} , with PSE ranging from 16 to 34%. The estimated residue mass in the current study ranged from 0.9 to 11.7 (average 5.2) T ha^{-1} for CT and ranged from 2.9 to 11.5 (average 6.1) T ha^{-1} for NT.

We hypothesized that perhaps a better understanding of the important meteorological conditions controlling PSE could be gained if we looked at each of the three fallow segments separately. We used best subset regression to identify the best four-parameter regression model for each fallow period. Those results (Table 2) are again sometimes easily understood and sometimes not. For the first summer period the regression model ($R^2 = 0.86$, $P < 0.01$) indicated an increase of 12 PSE points when NT was used compared with CT. Increasing precipitation during the period increased PSE, but precipitation coming as snow decreased PSE. Increasing temperatures decreased PSE.

For the fall–winter–spring period, the regression model ($R^2 = 0.74$, $P < 0.01$) indicated an increase of 49 PSE points when NT was used compared with CT. Similar to the first summer period, increasing temperatures decreased PSE. Greater wind speeds during the period resulted in greater PSE, which seems counter-intuitive as the greater wind speeds should have caused increased evaporation, unless the greater wind speeds were not associated with periods when the soil surface was wet. If the greater wind speeds were associated with periods of snowfall and resulted in greater drifting of snow and snow capture, then the positive regression coefficient makes sense. However, it does not make sense that increased snow during this period should result in decreased PSE as indicated by the regression coefficient of -0.7532 .

The regression model for the second summer period was not significant ($R^2 = 0.36$, $P = 0.13$). The small increases in PSE indicated by the positive regression coefficients for the tillage

Table 2. Best subset regression analysis summary for best four-parameter models to predict precipitation storage efficiency (PSE,%) for three fallow periods at Akron, CO (1996–2005). The model was: PSE = intercept + A × parameter 1 + B × parameter 2 + C × Parameter 3 + D × Parameter 4.

Parameter‡	First summer†			Parameter§	Fall–winter–spring			Parameter¶	Second summer		
	Regression coefficient	P	Regression statistic		Regression coefficient	P	Regression statistic		Regression coefficient	P	Regression statistic
Intercept	91.18	<0.01		Intercept	-12.78	0.02		Intercept	-122.76	0.04	
A Tillage	12.36	<0.01		Tillage	49.40	<0.01		Tillage	1.44	0.82	
B Precip 1	0.1933	<0.01		WS 2	27.11	0.16		Precip 3	0.1157	0.08	
C Snow 1	-3.7626	<0.01		Snow 2	-0.7532	0.02		WS 3	25.48	0.05	
D Ta 1	-4.49	<0.01		Ta 2	-9.6362	0.02		VPD 3	3.8670	0.59	
R ²			0.86				0.74				0.36
P#			<0.01				<0.01				0.13
C _p			7.2				3.2				2.1
AICc – minAICc			0.00				1.42				7.33

† First summer runs from wheat harvest (about 10 July) to about 30 September; fall–winter–spring runs from about 1 October to about April 30; second summer runs from about 1 May to wheat planting (about 20 September).

‡ Tillage = 0 for conventional tillage, 1 for no-till; Precip 1 = total precipitation (mm) during first summer; Snow 1 = total snow (mm of water) during first summer; Ta 1 = average air temperature (C) during first summer.

§ WS 2 = average wind speed (m s⁻¹) during fall–winter–spring; Snow 2 = total snow (mm of water) during fall–winter–spring; Ta 2 = average air temperature (C) during fall–winter–spring.

¶ Precip 3 = total precipitation (mm) during second summer; WS 3 = average wind speed (M s⁻¹) during second summer; VPD 3 = average vapor pressure deficit (kPa) during second summer.

P = probability that the regression or regression coefficient was significant; C_p = Mallows' C_p statistic (should be <5 for a "good" model with an intercept and four parameters); AICc – minAICc = the difference from Akaike's Information Criterion for the model from the model with the lowest value (values < 2 indicate substantial support for the regression model).

and precipitation parameters make sense, while the positive regression coefficients for the wind speed and vapor pressure deficit parameters do not.

Even though the specific meteorological parameters used in the regressions for evaluating PSE during the three fallow periods don't always make sense as factors controlling or influencing PSE, the three regressions given in Table 2 do a fairly good job of reproducing PSE over a wide range of values (Fig. 4) as did Eq. [2] for the entire fallow period (Fig. 3). However, to use any of the four regressions operationally to estimate soil water content at the end of the

fallow period would be difficult, as most farmers do not have ready access to average daily wind speed, temperature, solar radiation, and vapor pressure deficit. On the other hand, farmers do regularly measure precipitation. Therefore, we attempted another analysis of PSE based solely on the precipitation record. We hypothesized that PSE might be related to the size and frequency of precipitation events. For each of the 10 fallow seasons we determined the percentage of total precipitation events that were in the range of 0 to 5, 5 to 10, 10 to 15, 15 to 20, 20 to 25, 5 to 15, 15 to 25, and >25 mm using the first five seasons of data collected (1996–2001). The best relationship was found by best subset regression to be

$$\text{PSE (\%)} = -45.33 + 11.04 \times \text{tillage} + 2.161 \times (\text{PEvent}_{5..15}) + 0.8763 \times (\text{PEvent}_{>25}) \quad [3]$$

where tillage is as previously defined; PEvent_{5..15} is the percentage of fallow precipitation events that are between 5 and 15 mm; and PEvent_{>25} is the percentage of fallow precipitation events that are >25 mm. This simple relationship was found to account very well for the wide variations in PSE observed over the first 5 yr of the study ($R^2 = 0.89$, Fig. 5). Estimates of PSE produced by Eq. [3] for the last 5 yr of the study were significantly correlated with the measured PSE values ($r = 0.70$, $P < 0.01$), but with a bias toward overpredicting PSE at values < 30% and underpredicting PSE at values > 30%. Although it may be difficult to determine why these two precipitation parameters are most influential in determining PSE, this empirical relationship provides a very easy method that farmers can use to estimate starting soil water content at wheat planting. For example, if the precipitation over a 14-mo fallow period fell such that 30% of the events were in the 5 to 15 mm category and 8% were in the > 25 mm category, a PSE of 26.5% would be predicted for CT and 37.6% for NT. If the total precipitation over the fallow period was 635 mm, then a farmer could estimate that 168 mm of precipitation was stored in his CT fields and 239 mm in his NT fields. The relationship worked well

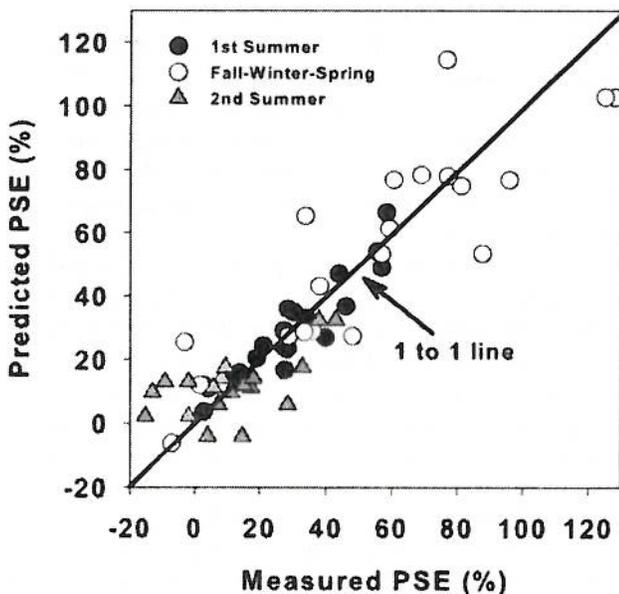


Fig. 4. Measured vs. predicted fallow precipitation storage efficiency (PSE) at Akron, CO (1996–2006), for no-till (NT) and conventional till (CT) wheat-fallow systems during three periods of the fallow season. Predicted values are generated from the linear regressions given in Table 2 based on meteorological parameters.

over a wide range of fallow period precipitation (407–682 mm, average 539 mm, Table 1). The long-term average fallow period precipitation is 560 mm for this area. The relationship given in Eq. [3] is easily incorporated into an Excel spreadsheet (available at <http://www.ars.usda.gov/Services/docs.htm?docid=19206>; verified 7 Jan. 2010) such that farmers need only enter precipitation amounts on days that precipitation occurred.

CONCLUSIONS

The results of this study demonstrated that the average PSE of 40% for NT W-F systems predicted by Greb (1979) has not been realized for northeastern Colorado and the high average PSE value (53%) previously reported by Smika (1983) for this area was perhaps anomalous. The results supported the conclusion of Peterson and Westfall (2004) that improving PSE in W-F systems beyond 35% may not be possible. The most efficient period for storing precipitation was the fall–winter–spring period, confirming the conclusions of Farahani et al. (1998). During the second summer fallow period there was no difference in PSE between NT and CT systems. Linear regression analysis revealed that NT fallow management was responsible for a 15-point increase in PSE over CT management due to increased storage efficiency by NT during the first summer and fall–winter–spring periods, but not during the second summer. Meteorological factors related to PSE were precipitation, snow, and air temperature during the first summer period; wind speed, snow, and air temperature during the fall–winter–spring period; and precipitation, wind speed, and vapor pressure deficit during the second summer period. A simple model was developed that will allow farmers to simply measure and record precipitation events to determine fallow period PSE and estimate increases in soil water content over the fallow period, but additional data sets will need to be acquired to determine the applicability of this model to other locations within the central Great Plains.

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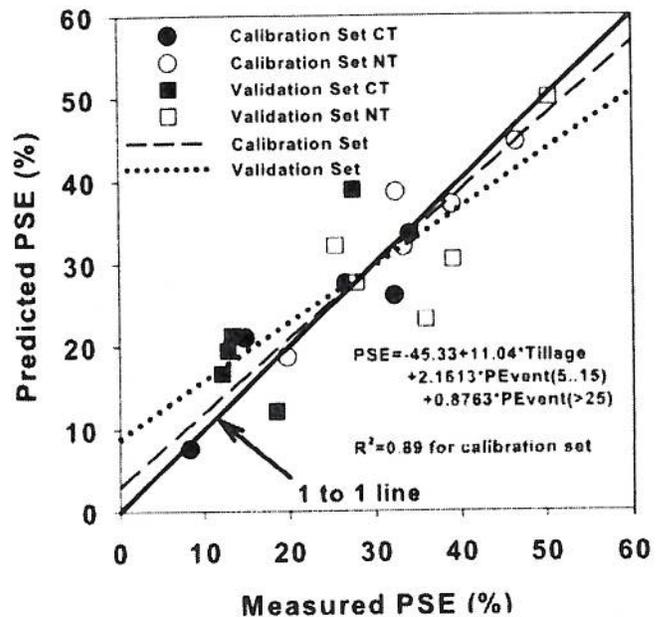


Fig. 5. Measured vs. predicted fallow precipitation storage efficiency (PSE) at Akron, CO (1996–2006), for no-till (NT) and conventional till (CT) wheat-fallow systems. Parameters in the regression prediction equation are Tillage (= 0 for CT, 1 for NT), PEvent5..15 (percentage of fallow precipitation events that are between 5 and 15 mm), and PEvent > 25 (percentage of fallow precipitation events that are greater than 25 mm). The calibration set was the first 5 yr of the study (1996–1997 to 2000–2001). The validation set was the last 5 yr of the study (2001–2002 to 2005–2006).

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