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.

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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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:

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

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

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

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.

	First summer†				Fall–winter–spring				Second summer			
	Parameter‡	Regression coefficient	*P*	Regression statistic	Parameter§	Regression coefficient	*P*	Regression statistic	Parameter¶	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).

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 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

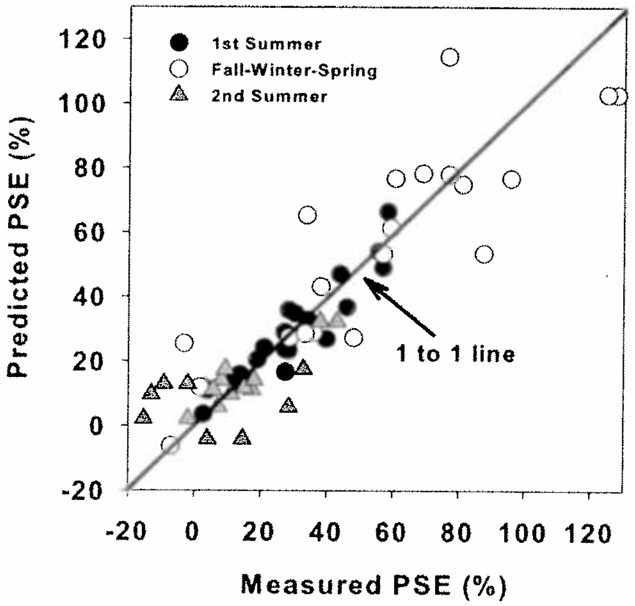

Fig. 4. Measured vs. predicted fallow precipitation storage efficiency (PSE) at Akron, CO (1996–2006), for no-till (NT) and conventional till (CT) wheat-fallow systems during three periods of the fallow season. Predicted values are generated from the linear regressions given in Table 2 based on meteorological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

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

$$\text{PSE (\%)} = -45.33 + 11.04 \times \text{tillage} + 2.161 \times (\text{PEvent5..15}) + 0.8763 \times (\text{PEvent} > 25) \quad [3]$$

where tillage is as previously defined; PEvent5..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

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-m^2 area) in late June and final grain yield (from a 42-m^2 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.

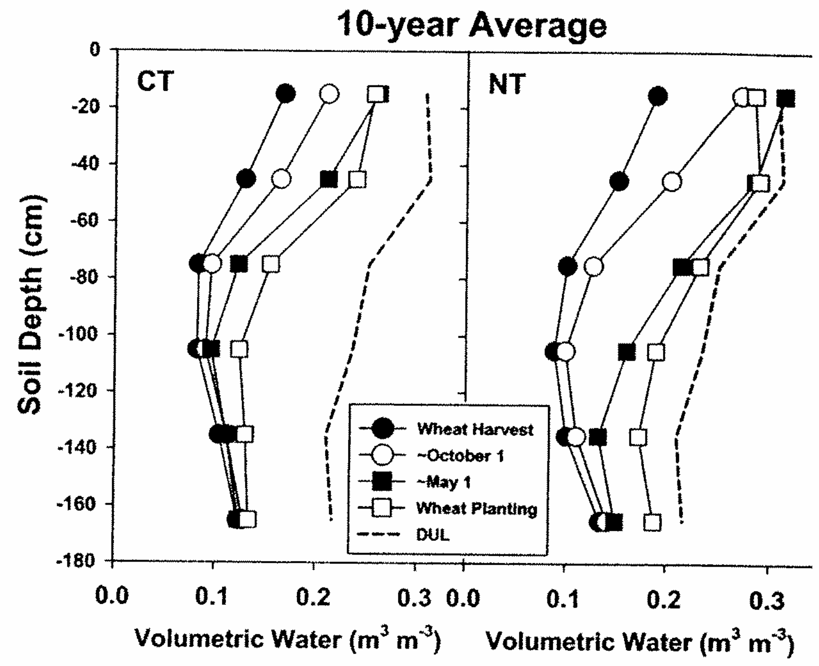

Fig. 1. Ten-year average volumetric soil water profiles at Akron, CO, under conventional till (CT) and no-till (NT) fallow management systems at wheat harvest, about 1 October, about 1 May, and at wheat planting. The drained upper limit (DUL) soil water profile is also indicated.

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 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