

Soil Water Signature of the 2005-2006 Drought Under Tallgrass Prairie at Fort Reno, Oklahoma

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This study examined changes in the seasonal pattern of soil water content under a tall grass prairie in central Oklahoma as a result of the 15-month drought of 2005-2006. The seasonal pattern of soil water content in the top 50 cm of the soil profile was minimally impacted by the drought, as this portion of the profile was recharged by sporadic precipitation events. However, no moisture reached the soil profile below 50 cm after June 2005, as all precipitation was intercepted and held by the top soil layer and rapidly consumed by evapotranspiration. The dry conditions in the lower soil profile resulted in low tallgrass prairie productivity which in turn limited livestock grazing opportunities. Heavy precipitation in March 2007 replenished the soil profile and there should be no carry-over moisture deficits from the 2005-2006 drought into the spring and early summer of 2007. © 2007 Oklahoma Academy of Science

INTRODUCTION

The water content of soil profile reflects the cumulative balance between precipitation infiltration, percolation, and evapotranspiration (ET). Under normal conditions, precipitation, evapotranspiration, and soil water follow a predictable seasonal rhythm. In the Great Plains, evapotranspiration outweighs precipitation during summer, depleting soil water. The reverse is true during winter when the soil water is usually recharged. In the presence of a meteorological drought, which is defined as a persistent precipitation deficit, the expected seasonal recharge of soil water can be disrupted, leading to an agricultural drought. An agricultural drought is a soil water deficit that stresses rangelands, pastures and dry land crops, and by extension any land cover. If the meteorological drought persists, an agricultural drought can be followed by a hydrologic drought characterized by unseasonably low groundwater or stream flow conditions. This in turn can lead to a water resources drought where water supply func-

tions of groundwater, reservoirs and lakes are impaired.

Extensive research on soil moisture and drought has been conducted in Oklahoma. Recent research includes the soil moisture and remote sensing campaigns conducted on the Little Washita River watershed, statewide soil moisture evaluation and interpretation by the Oklahoma Climatological Survey (OCS), and measurements and interpretation of soil moisture by the Department of Energy's (DOE) Southern Great Plains Cloud and Radiation Testbed in Oklahoma and Kansas. The main objective of the soil moisture and remote sensing campaigns conducted between 1992 and 2007 was to develop and evaluate new microwave and radar remote sensing technologies and algorithms for measuring surface soil moisture and wetting/drying cycles over large regions from aircraft and satellite platforms (Bryant et al., 2007; Thoma et al., 2007; Garbrecht et al., 2006; Bindlish et al., 2003; Oldak et al., 2003; Jackson et al., 1999). The focus of this remote sensing research was on soil moisture in the top 5 cm of the soil. The soil

moisture research by OCS was driven by the availability of soil moisture data at many of the 115 meteorological observation stations of the Oklahoma Mesonet, a meteorological observing network (Brock et al., 1995). The soil moisture measurements were at depths of 5, 25, 60 and 75 cm. Soil moisture from 60 Mesonet stations was spatially averaged over the State and climate divisions, and agricultural impacts of short-term droughts (less than 6 months) were discussed in terms of the 1998 and 2000 droughts (Illston and Basara, 2003). Research was also conducted on seasonal to interannual variations of soil moisture (Illston et al., 2004; Schneider et al., 2003). Illston et al. (2004) identified average seasonal soil moisture patterns over large regions of Oklahoma between 1997 and 2002. Schneider et al. (2003) presented an initial evaluation of the spatial and temporal variability of soil moisture from April 1996 through March 1999 within the DOE network. The study herein focuses specifically on identifying changes in seasonal soil moisture pattern due to the long-term drought of 2005-2006, and at depths greater than in most previous studies.

Impacts of the 2005-2006 drought in central Oklahoma on soil water response under tallgrass prairie were examined. Nine years of continuous soil water observations were available at Fort Reno in Central Oklahoma, about 30 miles west of Oklahoma City. Land cover at the observation site was tallgrass prairie, which is traditionally used for livestock grazing. A review of monthly precipitation departures from average conditions suggests that a meteorological drought at Fort Reno started in October 2005, after an unusually wet summer, and persisted through December 2006. This 15-month period (Oct 2005 through Dec 2006) was the 14th driest over the last 112-year period reaching back to 1895. The objectives of this study were to examine the soil water response to this drought; to identify departures from the normal seasonal pattern in soil water content by volume (SWCV); and to determine the amount and likelihood of precipitation required to recharge the soil profile during the fall and winter time period. The impact of persistent deficits in

soil water below 50 cm on forage production and livestock enterprises are discussed.

DATA SOURCE AND METHODS

Soil water matric potential was measured continuously starting in 1998 in a grazed tallgrass prairie field at the Grazinglands Research Laboratory, Fort Reno, Oklahoma. Soil at the site is characterized as a silt-loam in the upper 30 cm (about 20% clay content), a silty-clay loam at a depth of 55 cm (about 30% clay content), and a clay-loam or silty-clay-loam at about 125 cm (about 40% clay content). The soil water data were collected by the Atmospheric Radiation Measurement (ARM) Program, at the Southern Great Plains, Extended Facility #19 (lat. 35.557; long. -98.017), sponsored by the U.S. Department of Energy (Schneider, et al. 2003). Sixteen soil water sensors, Campbell Scientific 229-L Heat Dissipation Sensors, were installed in two profiles of eight sensors each, at depths of 5, 15, 25, 35, 65, 85, 125 and 175 cm from the ground surface. Sensors were calibrated in the laboratory prior to installation by subjecting sensors to known pressure and matric potentials (Schneider et al., 2003).

The measured soil water matric potential was quality controlled and converted to SWCV values using soil-water characteristics measured from on-site soil samples taken from the top 0.5 m of the profile (Elliott and Brown, 1998). In the remainder of the paper soil water always refers to soil water content by volume, expressed in mm/mm. Undisturbed, triplicate samples from 10 and 40 cm each were collected in the field and their water content-potential relationship measured following method D2325 of the American Society of Testing and Materials (ASTM, 1968). Volumetric water content values were validated against independent measurements of bulk density and gravimetric water content obtained post-installation (Schneider et al., 2003)

For this study, the soil profile was divided into 4 layers: the first or top layer from 0 to 50 cm (top four sensors); the second or upper layer from 50 to 100 cm (5th and 6th sensors); the third or lower layer from 100 to 150 cm (7th sensor); and the fourth or bottom

layer from 150 to 200 cm (8th sensor). Hourly SWC values at each sensor were obtained from the ARM Data Archive, a single daily value for each depth was extracted, and mean daily soil water content values were calculated for each of the four layers. Finally, high frequency daily soil water variations were filtered out using an 11-day sine-weighted filter. The resulting SWC values for each soil layer were the basis for the investigation of the seasonal pattern of the soil water content 8 years prior to, during the 2005-2006 drought, and through March 2007.

Daily precipitation data were observed at the El Reno Mesonet climate station (Brock et al., 1995) and obtained from the Oklahoma Climatological Survey. The El Reno Mesonet station is located about 3 km southwest of the tallgrass prairie field where the soil water observations were taken (Lat. 35.5484; Long. -98.0365). While precipitation on an event basis can vary between the two locations, a review of available precipitation measurements by one of the authors showed that the cumulative monthly and seasonal precipitation at the Mesonet station was sufficiently close to episodic measurements obtained at the soil water observation site to justify use of the Mesonet data.

SOIL WATER CONTENT TRENDS

The seasonal pattern of SWC in the top soil layer (0-50 cm) for years 1998 through 2004 was pronounced (Figure 1). Every summer, the soil dried out as a result of evapotranspiration (ET) exceeding precipitation, and the SWC approached or reached a value of 0.25 mm/mm. During fall, precipitation began to exceed ET as the warm season grasses became dormant. Soil water was being replenished by precipitation, and by the turn of the year the SWC approached or reached a value of 0.32 mm/mm. This range of SWC corresponds almost exactly to the measured 15 and 1/3 bar SWC potentials for the soil, respectively. The 15 bar potential is nominally considered the permanent wilting point for agronomic plants, while the 1/3 bar is the nominal water-holding capacity

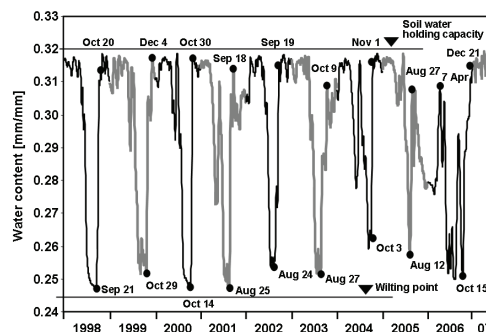


Figure 1. January 1998 – April 2007 time series of average soil water content by volume in the 0 to 50 cm soil layer at the tallgrass prairie site at Fort Reno, Oklahoma. The alternating black and grey line is used to identify individual calendar years. Dates at the bottom of the figure indicate the beginning of the fall soil-water recovery and dates at the top indicate the completion of the soil-water recovery for this soil layer.

ity for freely drained soils. In non-drought years, SWC stayed near the water-holding capacity until the end of the spring rainy season (precipitation balancing percolation to deeper layers), at which time the soil again dried out due to high ET demand, and the seasonal SWC cycle started over again. However, during the 2005-2006 drought, the SWC did not fully recover during the winter. For the first time since 1998, the SWC was only 0.28 mm/mm (2/3 bar) at the turn of the year, about halfway between wilting point and water holding capacity. Even during the spring rainy season in 2006 the SWC only briefly approached the water holding capacity.

The SWC values in the upper soil layer (50-100 cm) for years 1998 through 2004 were less variable due to the damping effect produced by the top soil layer, and typically lagged in time by about a week to a few months, consistent with the percolation time scale, but otherwise the seasonal pattern was similar to that of the top layer (Figure 2). Every summer, the SWC approached the wilting point. During fall, soil water was being replenished, and by the turn of the year or at the latest during the

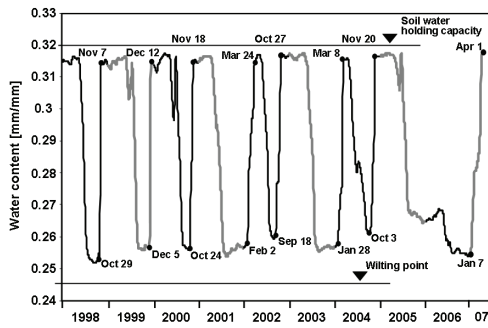


Figure 2. January 1998 – April 2007 time series of average soil water content by volume in the 50 to 100 cm soil layer at the tallgrass prairie site at Fort Reno, Oklahoma. The alternating black and grey line is used to identify individual calendar years. Dates at the bottom of the figure indicate the beginning of the fall soil-water recovery and dates at the top indicate the completion of the soil-water recovery for this soil layer.

spring high precipitation season the SWC reached the water holding capacity. During the 2005–2006 drought and for the first time since 1998, the SWC did not recover at all during winter and spring.

In the lower soil layer (100–150 cm), the seasonal pattern of the SWC was still apparent for years 1998 through 2004 and resembled that of the upper soil layer, with the exception of spring 2004, during which the SWC only recovered halfway to the water holding capacity (Figure 3), due to total precipitation in April and May of only 2.8 cm compared to the 1895–2006 average of 20.8 cm. Again, the recovery is lagged in time, typically by a month compared to the upper soil layer.

Notice that the SWC is lower during the summer of some years compared to others. The lower SWC during the summer of 1998 is likely due to the extremely dry season which drove plants to draw water from deeper soil layers. The 1998 April to September period was the driest on record since 1895, with only 21.5 cm of precipitation compared to the 1895–2006 average

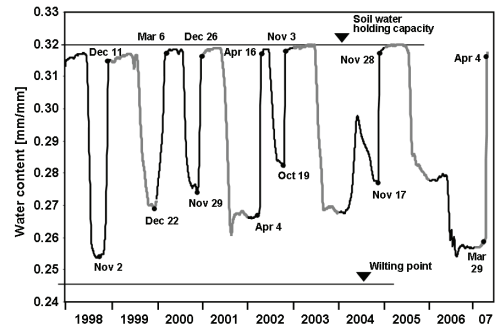


Figure 3. January 1998 – April 2007 time series of soil water content by volume in the 100 to 150 cm soil layer at the tallgrass prairie site at Fort Reno, Oklahoma. The alternating black and grey line is used to identify individual calendar years. Dates at the bottom of the figure indicate the beginning of the fall soil-water recovery and dates at the top indicate the completion of the soil-water recovery for this soil layer.

of 51.5 cm (as calculated from NOAA's divisional precipitation data). During 1999, 2000 and 2002 growing seasons the evapotranspirative demand appears to have been satisfied to a large degree by precipitation and soil water reserves from shallower soil layers. During the 2005–2006 drought, the SWC never recovered past its 2005 summer low point. No recharge occurred during winter and spring, and this lower soil layer dried out even further during the summer of 2006.

The amplitude of the seasonal pattern of SWC in the bottom soil layer (150–200 cm) is highly dampened (Figure 4), and lagged even further in time. The bulk of the plant roots do not reach that depth, and the SWC is rarely drawn down to field capacity, except during very dry growing seasons such as in summer 1999 and 2006. Most notable in the seasonal pattern of SWC is the absence of any soil water recovery whatsoever during winter 2003 and spring 2004, as well as winter 2005 and spring 2006. This lack of soil water recovery limits the water reserves the plants can draw on to bridge drought periods during the growing season.

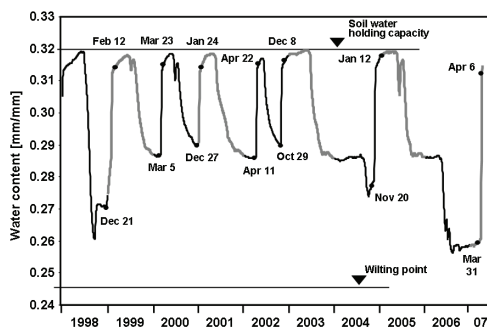


Figure 4. January 1998 – April 2007 time series of soil water content by volume in the 150 to 200 cm soil layer at the tallgrass prairie site at Fort Reno, Oklahoma. The alternating black and grey line is used to identify individual calendar years. Dates at the bottom of the figure indicate the beginning of the fall soil-water recovery and dates at the top indicate the completion of the soil-water recovery for this soil layer.

PRECIPITATION FOR RECHARGING THE SOIL PROFILE

Total amount of precipitation required to recharge this soil profile can be estimated from the seasonal pattern of SWC (Figures 1-4) and the precipitation record at the Fort Reno Mesonet climate station. Total precipitation required to recharge the top soil layer is the precipitation that fell during the fall-winter SWC recharge period. Implicitly total precipitation includes precipitation that contributes to interception and surface runoff. However, for the vegetation and the flat landscape under consideration, the precipitation amount contributing to interception and surface runoff is believed to be less than 10% of total. The beginning date of the recharge is defined as the first sign of steep increase in SWC after the summer dry period (empty profile), and the ending date is when the steep rise in SWC ends near the water holding capacity (recharged profile) (Figure 1). The recharge

period and corresponding precipitation are determined for all years that exhibited a full soil water recharge. The recharge timing and precipitation varies from year-to-year, and the averaged precipitation value is taken as the expected amount of precipitation required to recharge the top layer. The precipitation required to recharge the top two soil layers (0-100 cm) is estimated in a similar fashion, with the beginning date of the recharge being that of the top soil layer (0-50 cm; Figure 1) and the ending date being that of the upper soil layer (50-100 cm; Figure 2). Recharge for the top three soil layers (0-125 cm) is estimated with the beginning date of the recharge being that of the top soil layer (0-50 cm; Figure 1) and the ending date being that of the lower soil layer (100-150 cm; Figure 3). Similarly, for the recharge of all four layers (0-200 cm), the beginning date of the recharge is that of the top soil layer (0-50 cm; Figure 1) and the ending date that of the bottom soil layer (150-200 cm; Figure 4). The resulting expected amount of precipitation to recharge the top soil layer is 16 cm. Recharge begins at the earliest in late August and usually coincides with the beginning of the fall rainy season. The expected precipitation to recharge the top two soil layers is 29 cm; for the top three soil layers it is 32 cm; and, for the full profile it is 37 cm. The full profile can be recharged as early as November and as late as April the following year during the spring rainy season.

With regard to the 2005-2006 drought, the top layer was recharged between October and December 2006 (15 cm precipitation). The remaining three soil layers were recharged by early April 2007, mostly as a result of a very wet March that received 13 cm precipitation. Total precipitation between September 2006 and March 2007 was 38 cm, just above the previously mentioned threshold required to fill the entire soil profile. Recharge of the full soil profile by April 2007 suggested that the agricultural drought associated with the 2005-2006 meteorological drought was over, and there should be no carry-over effect from the 2005-2006 drought into the 2007 summer growing season for tallgrass prairie at Fort Reno.

ODDS OF RECHARGING THE SOIL PROFILE

The odds of recharging the soil profile were determined based on the September-March precipitation for years 1895-2006. The data showed that the average September-March precipitation during the first half of the 20th century was about 32 cm compared to nearly 40 cm over recent decades, which represents a 20% increase. Thus, de-trending the record with reference to current precipitation conditions was necessary to make the record compatible for statistical analysis of current precipitation conditions. Based on the de-trended data, the September-March precipitation exceeded 37 cm 61 times over the 112 years of available data. Hence, the threshold of 37 cm precipitation to refill the soil profile is exceeded 54% of the time. It follows that once the entire soil profile is dried out in late summer there is about a 50-50 chance for filling the soil profile by March the following spring. The odds of recharging the soil profile with September-April precipitation (one additional month) increased to 75% (84 years with $P > 37$ cm out of 112 years). Precipitation during the month of May is not considered because plant growth stage and air temperature are such that any precipitation that infiltrates is most likely to be consumed by evapotranspiration and is not available to fill the deep soil layers of the soil profile.

DISCUSSION

The four soil moisture phases, moist plateau, transitional drying, enhanced drying and recharge as described by Illston et al. (2004), are recognizable in Figure 1 through 4, though they vary somewhat from year to year. The smoother seasonal soil moisture pattern in Illston et al. (2004) is likely due to averaging effects over multiple Mesonet stations and six years of data. The drought of 1998, described in Illston and Basara (2003), is recognizable in the lower and bottom soil layers, however the effects of the short-term drought of 2000 are not apparent in the herein presented data. In the following, the effects of the 15-month drought of

2005-2006 on seasonal soil moisture pattern are described for each of the four defined soil layers.

The 2005-2006 SWC pattern in the top layer (0-50 cm) displays characteristics that are also recognized in the 1998-2004 seasonal patterns despite the 2005-2006 drought. In August 2005 and April 2006, the SWC nearly recovered to the soil water holding capacity, consistent with the seasonal pattern of earlier years, though it did not stay at the water holding capacity through the winter. In August 2006, the SWC also increased, albeit a few weeks early compared to the previous SWC pattern. This is an indication that the SWC in the top soil layer responds to large individual precipitation events, which can override the impact of the longer 2005-2006 drought on SWC in the top layer. This is in line with the conventional expectations that the variability in SWC is more pronounced in the top of the soil profile, owing to the short-timescale response to individual precipitation events and ET, whereas temporal SWC dynamics in the middle and lower profile are buffered by moisture storage and ET in the soil above (Kurc and Small, 2004; Hupet and Vanclooster, 2002; Famiglietti et al., 1998).

For the three soil layers (50-200 cm) below the top layer, the signal of the 2005-2006 drought is unequivocally clear: there was no recharge during the 2005-2006 fall, winter, or spring. In addition, the SWC during summer 2006 equaled or fell below the SWC value observed during the severe spring-summer drought in 1998. For the upper layer (50-100 cm) this was the first time since 1998 that the soil profile was not recharged, whereas it was the second time for the bottom soil layer (150-200 cm). The other time that the bottom soil layer was not recharged was in fall, winter and spring 2003-2004. In summary, the soil profile below 50 cm did not benefit from sporadic precipitation events and remained dry from early October 2005 through the end of February 2007. The full soil profile was recharged by the end of March 2007 as a result of a 38 cm total precipitation since September 2006 (March 2007 precipitation was 13 cm and the sixth wettest March in the last 113 years).

Strictly speaking the observed SWC data and calculated odds of recharging the

soil profile are only applicable to the site of observation and immediate vicinity. While the specific SWC values may be different, it can reasonably be expected that the observed seasonal pattern of the SWC is representative for general tallgrass prairie conditions in central Oklahoma, and the impact of the year-long drought led to similar soil moisture deficits with SWC approaching the wilting point. The aforementioned generalization of the drought impact on SWC is substantiated by numerous farm reports as discussed in the following.

Limited forage production and poor quality were widespread in Oklahoma during summer and fall 2006 (NASS, 2006), with regional yields 25 to 50 percent less than normal (Associated Press, 2006). The poor yields and quality are believed to be related to both the below average precipitation, and the lack of deep soil water reserves to help prairie grasses bridge the late summer dry period. The drought had a sizable impact on regional hay inventories: winter wheat forage availability was significantly reduced and hay stocks by May 1, 2006 were only 40% of 2005 levels (Stotts, 2006). By August 2006, hay prices had risen regionally by a factor of 4 or more compared to 2005, with the most dramatic gains paid for low-quality hay (Hay and Forage Grower, 2006). Prices continued to rise through October, with early November prices for grass hay running \$90-100 per ton in central Oklahoma (Oklahoma Dept. of Agriculture-USDA Market News, 2006). Poor forage conditions and high prices for hay in turn negatively impacted livestock enterprises, forcing early weaning and movement of stocker calves during the summer of 2006, cow culling, and variations in feedlot inventories (Stotts, 2006). Abundant March 2007 precipitation replenished the soil profile and broke the 2005-2006 drought. Thus, for 2007, producers can expect adequate soil water reserves for normal summer forage production, barring abnormally low late spring and summer precipitation.

CONCLUSION

The impact of the 2005-2006 Oklahoma drought on soil water content (SWC) under

tallgrass prairie at Fort Reno, Oklahoma, was investigated. The year-long drought had limited impact on the seasonal pattern of SWC in the top 50 cm of the soil profile, as this portion of the profile was recharge by sporadic precipitation events during the drought. However, no moisture reached the soil profile below 50 cm after June 2005, as all precipitation was intercepted by roots in the top soil layer and rapidly consumed by evapotranspiration. Without adequate deep soil moisture reserves, the drought led to limited forage production and poor forage quality in many regions of Oklahoma, which in turn negatively impacted livestock enterprises.

A review of the historic precipitation record indicated that about 37 cm of precipitation between September 2006 and March 2007 was needed to refill a dried out profile, and that there was about a 50-50 percent chance of receiving or exceeding this threshold precipitation amount. March 2007 received 13 cm precipitation, resulting in an accumulated September 2007 - March 2007 precipitation of 38 cm. This is greater than the threshold of 37 cm to fill the soil profile, and soil moisture measurements indeed indicated that the soil profile was entirely replenished. The abundant precipitation in March 2007 broke the drought, and in terms of soil moisture there should be no carry-over moisture deficits from the 2005-2006 drought into the spring and early summer of 2007.

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