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Original Research

Site-Specific Soil Properties of the US Climate Reference Network Soil Moisture

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Core Ideas

- This study quantifies the variability of soils at US Climate Reference Network sites.
- Soil properties were determined from the analysis of soil core samples.
- Soil properties displayed large variability with depth and location within and among sites.
- Variability of soil properties helped determine and interpret soil moisture variability.

The objective of this study was to provide direct measurements of soil properties for 70 of the 114 US Climate Reference Network (USCRN) sites across the continental United States. Soil properties determined from the analysis of soil core samples include the particle size distribution (PSD, consisting of sand, silt, and clay contents), soil texture classifications, bulk density (BD), and the soil moisture content at water potentials of 33 kPa (field capacity, FC) and 1500 kPa (wilting point, WP). Sand, silt, and clay contents of the 70 sites indicated about 10 soil texture classifications as follows: three sites with loamy sand, 15 with sandy loam, two with clay, 11 with silt loam, five with clay loam, 10 with loam, seven with sand, eight with silty clay loam, four with sandy clay, and three with silty clay. The comparison of soil properties among soil depths and pits indicated considerable variability, with the silt, clay, and sand contents varying more with soil depth than with location at individual sites. The silt content tended to decrease with soil depth, clay tended to increase, and sand tended to vary randomly with depth. Regression lines fitted to values of FC and WP between the pits indicated a slope > 0.8, R^2 > 0.88, and RMSE ranging from 2.7 to 4%. Compared with FC and WP, BD was less consistent among the pits, with slope = 0.6, R^2 = 0.4, and RMSE of about 0.2 g cm^{-3}.

Abbreviations: BD, bulk density; CEC, cation exchange capacity; FC, field capacity; PSD, particle size distribution; PTF, pedotransfer function; USCRN, US Climate Reference Network; WP, wilting point.

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The US Climate Reference Network (USCRN), deployed since 2004 to monitor near-surface air temperature and precipitation across the United States (Diamond et al., 2013), added soil moisture measurements during 2009 to 2010 (Bell et al., 2013). Such a vast expanse of long-term, high-quality surface climate data has the potential to improve applications in many areas, including remote sensing (Sahoo et al., 2008; Panciera et al., 2014; Zarco-Tejada et al., 2003), drought predictions (Torres et al., 2013), flood forecasts (Gourley et al., 2012), and hydrological, climate, and weather models (Pielke, 2001; Reen et al., 2014; Vereecken et al., 2008; Kustas et al., 2005; Crow and Wood, 2002). Examples of similar soil moisture networks in the United States include SCAN (Schaefer et al., 2007), the North Carolina Environmental and Climate Observing Network (Pan et al., 2012), and the Oklahoma Mesonet (Scott et al., 2013), but they do not include detailed aboveground climate observations and the national coverage of the USCRN. However, USCRN soil moisture is measured with HydraProbes, which determine the volumetric soil moisture based on nominal soil properties, and actual knowledge of site-specific soil properties would help to quantify the variability of soil moisture. Interactions among soil characteristics affect the retention and flow of water in the bulk soil (Jury et al., 1991). The USCRN sites are distributed widely across the United States, and sites tend to differ in terms of soil, climate, and vegetation conditions. In addition, direct determination of soil properties and soil structures of key interest to soil moisture often requires the collection and analysis of field soil samples, which is a large investment in resources for the USCRN program.

Unlike soil moisture and climate variables that can be measured continuously and automatically, the physical properties and structure of soil systems are not easily amenable to remote or automated observations. Determining site-specific soil properties often requires collecting field soil samples and analyzing them in the laboratory. Because the effort required to determine in situ soil properties imposes a tedious and expensive burden on such monitoring programs, such soil data are frequently missing from routine soil moisture measurements and must be obtained from US county soil survey maps that were estimated using aerial photographs, sparse soil samples, remote sensing, and qualitative soil classification by soil surveyors (Ferguson and Hergert, 1999). The State Soil Geographic (STATSGO) database of the USDA Soil Conservation Service (1993) and the Soil Survey Geographic (SSURGO) database provided by the USDA–NRCS (1995) are the two such widely used US soil data products. However, the large scale of national soil survey data excludes small-scale soil features that affect point measurements of soil moisture. Adoption of large-scale soil survey data to site-specific soil moisture measurements therefore must consider the variability of soil properties for different sites (Ferguson and Hergert, 1999). Errors in soil factors and unresolved variability in soil properties may ultimately lead to misinterpretation and even unrealistic and unnecessary evaluation of soil moisture measurements. For example, Fortin and Moon (1999) evaluated the errors associated with the use of soil survey data for estimating plant-available water in the northeastern region of British Columbia, Canada. They found errors for fractions of sand, silt, and clay derived from soil survey data that were 8 to 18% of measured values and as much as 51% for organic C. The use of estimated soil depths from soil survey data caused significant differences between measured and predicted plant-available water, where prediction errors were 38 mm for the Ap horizon and 95 mm for the B horizon, representing 21 and 33% of the measured values, respectively.

Evaluations of USCRN soil moisture data indicate the need for a comprehensive data management and control system to produce high-quality soil moisture data (Bell et al., 2013). Despite detailed documentation of the network's soil instrumentation methodology, data quality control strategies, and potential applications of the soil moisture data, evaluations have not included change patterns of soil properties related to soil moisture. This is in part because relevant soil properties were unfortunately determined after deploying the USCRN soil moisture network.

Zamora et al. (2011) used gravimetric measurement to evaluate the manufacturer-provided calibration for the soil moisture observing networks of the NOAA Hydrometeorology Testbed, which consists of 14 stations in California, five stations in Arizona, and one in Colorado. On average, a quadratic calibration function that related the reflectometer response to volumetric water content was successfully used to evaluate soil moisture climatology and hourly soil moisture changes related to the potential for flash flooding. The difference between the site-specific calibration using the gravimetric measurements and manufacturer-provided calibration was as high as 25% at one California station.

Existing USCRN soil moisture evaluations rely essentially on manufacturer-produced soil moisture calibration formulations that do not explicitly account for the soil heterogeneity that can occur at individual USCRN sites. The lack of site-specific soil property data limits the ability of the USCRN program to adequately assess and interpret the complex and variable soil moisture measurements. For example, despite the success of adopting the HydraProbe, the USCRN has suffered a large number of probe failures, averaging a loss of about 60 probes annually. Probe failures seem to be a function of a complex interaction between the soil-water-chemistry dynamics and the HydraProbe (Seyfried et al., 2005), and specific reasons behind probe failures have been difficult to identify and remedy. Probe failures are a major concern for the USCRN program because of the high cost of replacing failed sensors, and they also hamper the network's ability to provide continuous measurements of soil moisture. Evaluating both the physical and chemical properties of the soil offers a good opportunity to understand complex field conditions that may complement strategies to explore soil effects on soil moisture and development of the HydraProbes.

Another important reason for providing accurate descriptions of soil properties is to enhance the value and usefulness of soil moisture measurements for many applications, including drought, flood, weather, and climate predictions. Providing soil properties in conjunction with soil moisture data for the individual USCRN stations therefore has two important values: (i) improving fundamental calibrations of soil moisture by using supporting soil data for the exact locations of soil moisture measurements; and (ii) quantifying changes in soil moisture due to soil factors and realistically validating, interpreting, and enhancing the use of USCRN soil moisture data.

The primary objectives of this study were to document the complex soil characteristics of the various USCRN soil moisture measurement locations; quantify the magnitude, horizontal variability, and vertical distributions of soil physical properties; and provide a comprehensive in situ soil data set that can be used to quantify the impact of soil factors on soil moisture. In particular, field soil samples were used to determine select soil physical properties, including bulk density, texture, and the soil water content at both field capacity (FC) and the permanent wilting point (WP) (Jury et al., 1991), which represent the critical range of soil water that controls drainage and the transfer to and from plants. The approach of this study to measure the soil properties at the location where moisture sensors were deployed will improve the use of USCRN soil moisture data in many applications by relieving them of the burden of taking site-specific soil property measurements. Combining the measurements of soil moisture with soil property and climate data in a modeling framework offers the opportunity to fully assess soil moisture budgets across USCRN stations.

Methods

US Climate Reference Network Stations

The USCRN stations comprise 114 land-based sites sparsely distributed across the continental United States. On average, there are about two stations in each state, and the actual number of stations in the various states ranges from as high as seven and eight in California and Texas, respectively, to as low as one in eight other states (Iowa, Tennessee, Wisconsin, Michigan, Indiana, Ohio, Pennsylvania, and New Hampshire) (Fig. 1). Each site was carefully selected to best represent the regional climate. Native grasses are allowed to grow, and the immediate vicinity of each station is protected from trees, brush, and all land development. Sites are located in various land covers of the United States, including agricultural research stations, national parks, forests, grasslands, and wildlife reservations. Electric power to the sites is obtained from either commercial electricity, solar power, or wind power. Detailed descriptions of the site selection criteria for the USCRN program have been presented elsewhere (Bell et al., 2013; Diamond et al., 2013).

Climate Measurements

Until the soil moisture sensors were deployed during 2009 to 2011, the USCRN mission was largely confined to measurements of aboveground climate variables, with the primary focus on providing long-term, high-quality hourly measurements of air temperature and precipitation. To satisfy this requirement, redundant triplicate measurements of air temperature and precipitation observations are recorded. The triplicate air temperature measurements are recorded using three independent platinum resistance thermometers, each protected within its own fan-aspirated radiation shield (Model 076B, Met One Instruments). The triplicate precipitation measurements are made with a Geonor weighing precipitation gauge with three independent vibrating-wire weighing transducers (All-Weather Precipitation Gauge, Model T-200B). The aspirated shields are mounted at a height of 1.5 m on a 3-m tower. The Geonor and a tipping bucket precipitation gauge are typically also mounted at a height of 1.5 m and at a distance of ~15 m from the tower. The two gauges are mounted on two different masts about 2 m apart, and both gauges are positioned inside a small Double Fence Intercomparison Reference wind shield to minimize the effects of wind on the precipitation measurements. Several other climate variables are also measured with sensors mounted at 1.5 m. These include radiometric ground surface temperature (SI-111 Infrared Radiometer, Apogee Instruments), solar radiation (SP Lite Pyranometer, Kipp & Zonen), relative humidity (HMT-337, Vaisala), wetness (DRD11A rain detector), and wind speed (014A wind speed sensor, Met One Instruments).

Soil Moisture and Soil Temperature Measurements

Between April 2009 and August 2011, HydraProbe soil moisture sensors were deployed at the 114 USCRN stations in the continental United States (Fig. 1). The various USCRN stations support the growth of different types of grasses: sparse desert grasses and shrubs, prairie grasses, dense grasses, and pasture grasses. While most sites are level, many are sloped at the tower location. At each station, three locations 1.5 to 5 m from the base of the main meteorological tower were selected to measure soil moisture and soil temperature profiles (Bell et al., 2013). Soil moisture measurement locations were typically installed with Location 1 in the north (0°), Location 2 in the east-southeast (120°), and Location 3 in the west-southwest (240°). However, many sites did not adopt this exact

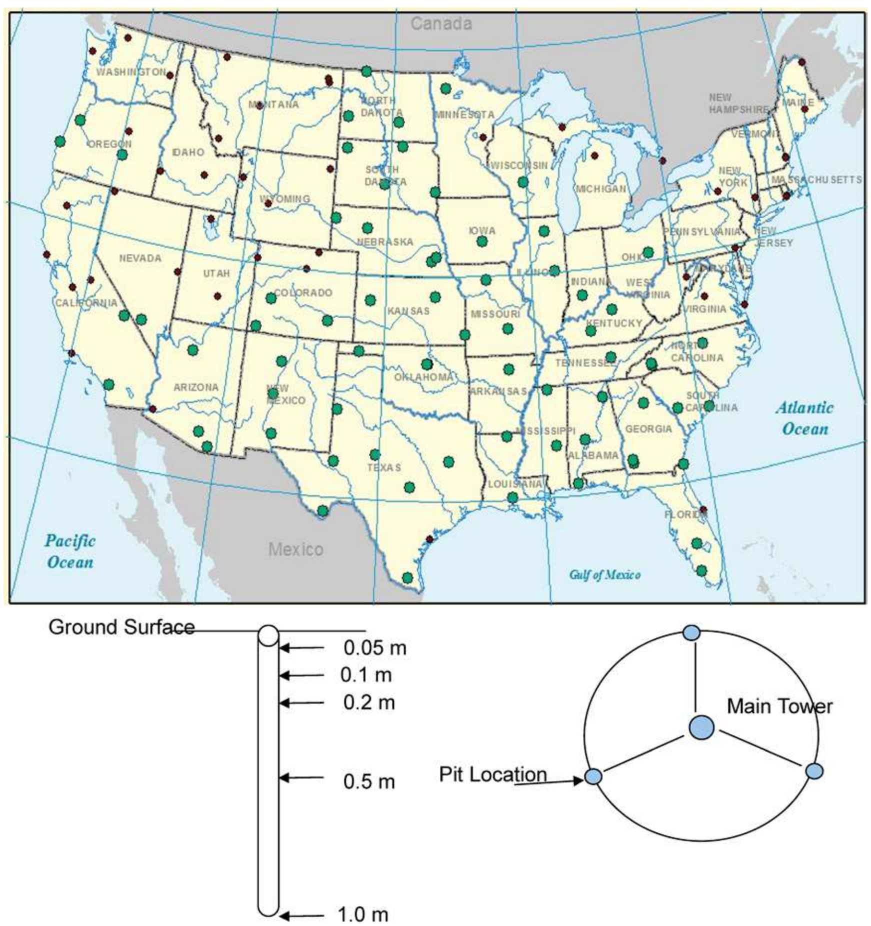

Fig. 1. The US Climate Reference Network site locations across the continental United States, with the three soil moisture measurement pit locations centered on the main tower for measurements of aboveground climate variables. The red symbols show sites without soil analysis and the green symbols show sites with soil analysis.

configuration because of the heterogeneous nature of the various sites and challenges encountered while excavating the soil to install the soil moisture probes. At each location, a pit was dug with a diameter of about 0.25 m to a depth of about 0.6 m, and from a depth of 0.6 to 1 m, a 0.1-m-diameter pit was augured. Inside each pit, HydraProbes were inserted into the pit wall horizontally at 0.05, 0.1, 0.2, and 0.5 m and vertically at 1 m. For a number of stations where bedrock at shallow depths prevented deep excavation, probes were buried at 0.05 and 0.1 m, and for a few stations where only one pit was possible, the pit was used to bury three HydraProbes at depths of 0.05 and 0.1 m, respectively. Pits were carefully backfilled to ensure that the refilled pits matched as well as possible the undisturbed soil at the station. Volumetric soil water content and soil temperature as well as the climatic measurements are recorded with Campbell Scientific dataloggers that compute hourly average values. Geostationary Operational Environmental Satellite (GOES) transmitters located at the sites are used to transmit the site data to the NOAA GOES data collection center at Wallops Island, VA.

Soil Samples

During HydraProbe installation at each USCRN station, soil core samples with a cylindrical volume of 90.43×10^{-6} m^3 (diameter 0.048 m and length 0.05 m) were collected at the soil depths where the probes were buried using a commercial manual soil core sampler (W.W. Grainger). One sample was collected at each depth to obtain a total of 15 soil samples per site with five depths; the number of samples for sites with only shallow soils was dependent on the maximum depth possible. Each sample was collected and stored inside a 0.05-m by 0.048-m-diameter cylindrical metal sleeve. Metal sleeves with soil samples were tightly sealed to prevent moisture loss. The following soil physical properties were determined from the soil samples: bulk density (BD), particle size distribution (PSD), and soil volumetric water content at matrix pressures of 33 kPa (FC) and 1500 kPa (WP). In addition to the physical properties, soil chemical properties including total C, total N, total S, cation exchange capacity (CEC), pH, and trace metals Mn, Ca, Mg, Na (cmol kg^{-1}), and K were also measured. To obtain the soil properties, the stored soil samples were shipped to and analyzed by the National Soil Survey Center in Lincoln, NE.

Determination of Soil Properties

Although soil samples were collected for the 114 USCRN soil moisture measurement sites, soil samples for about 44 sites were lost in an unfortunate fire during analysis at the National Soil Survey Center; thus, this study has provided analysis of soil properties for 70 USCRN sites. The laboratory analysis of soil properties was divided into two groups: one group determined the PSD (the sand, silt, and clay contents) at each soil depth based on composite soil samples for all three pits; the second group determined the BD and soil water contents at FC and WP based on soil core samples at each soil depth for each pit at each station. The composite sample was used for PSD to reduce the high cost of analyzing individual soil samples. These latter soil properties were therefore determined for soil depths of 0.05, 0.1, 0.2, 0.5, and 1 m at the three soil moisture measurement locations at each station site. For nine of the station sites, soil properties were determined at only 0.05 and 0.1 m because shallow soils underlain by rocks prevented moisture measurements below the 0.1-m depth. Because we did not have independent measurements of soil properties for the USCRN sites against which to evaluate the accuracy of our measurements, it was not possible for us to distinguish between natural site-induced differences and measurement errors. Instead, we evaluated the consistency and representativeness of the soil property data by evaluating the means and standard deviations of the triplicate soil properties at the various soil depths at each site.

Results and Discussion

Evaluation of the Variability of Soil Properties

The PSD of the silt, sand, and clay determined through the laboratory analysis of soil core samples collected at 70 USCRN stations are available at the ATDD-NOAA ftp site (ftp://ftp.atdd.noaa.gov/pub/wilson/Supplemental_Table_T1.xls). Values of PSD determined at five distinct soil depths were obtained based on the analysis of the composite soil core samples collected from the three locations at each site. Values of silt, sand, and clay contents exhibited great variability among individual soil depths, with silt tending to decrease, clay tending to increase, and sand varying randomly with depth. The soil texture defined by combining the silt, clay, and sand contents yielded soil texture classifications that varied more with site location than with soil depth (Fig. 2). For example, the soils at the Shabonna, IL, site were classified as silty clay loam at all depths, with silt contents ranging from 50 to 65%, 30% clay, and 5 to 20% sand. This was consistent with the soil triangle classification for silty clay loam, with silt ranging from 60 to 75%, clay 27 to 40%, and sand 0 to 20% (Jury et al., 1991).

Means and standard deviations of silt, sand, and clay contents for all depths at the 70 stations are shown in Table 1. Values of silt, clay, and sand contents clearly vary not only among site locations but also among soil depths. Means of silt, clay, and sand led to 10 soil texture classifications at 68 stations: loamy sand (three), sandy loam (15), clay (two), silt loam (11), clay loam (five), loam (10), sand (seven), silty clay loam (eight), sandy clay loam (four), and silty clay (three). Ratios of the standard deviations to the mean values of silt, clay, and sand also indicated strong variations with soil depth, with ratio values ranging from 0 to 60% for silt and from 0 to 120% for clay and sand. The wide range of silt, clay, and sand contents found within individual USCRN sites demonstrates the need to provide soil physical properties data for the soil moisture monitoring network locations.

In addition to PSD, which mostly represents soil parent materials, the analysis of soil water content at FC and WP and soil BD was also

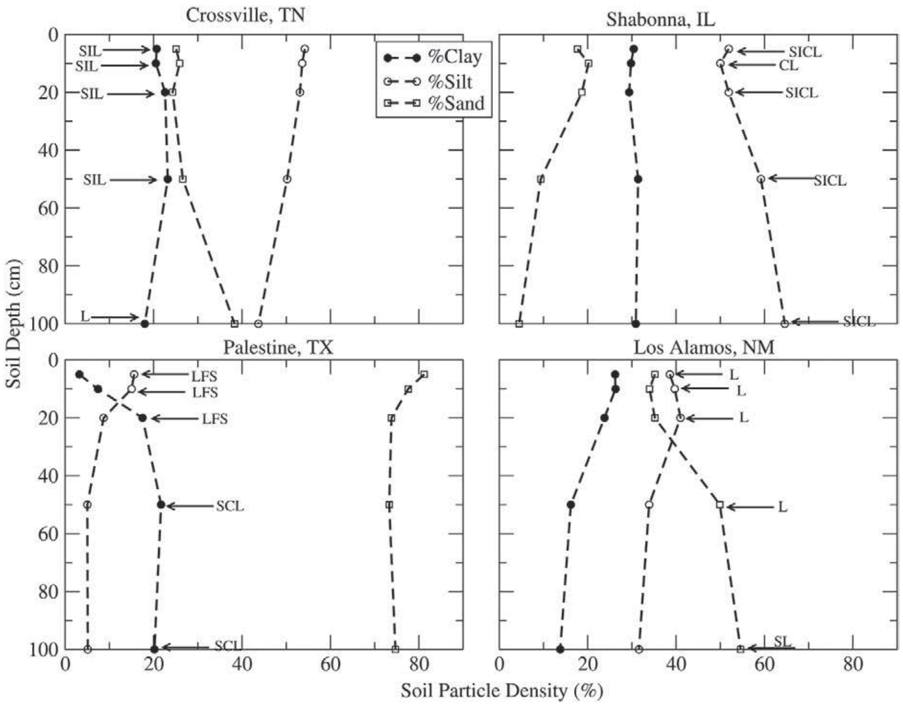

Fig. 2. Profiles of soil particle density (clay, silt, and sand) at four US Climate Reference Network stations in four different states, including Tennessee, Illinois, Texas, and New Mexico, with soil texture profiles of loam (L), silt loam (SIL), silty clay loam (SICL), sandy clay loam (SCL), loamy fine sand (LFS).

Table 1. Soil properties for soil depths of 0.05, 0.1, 0.2, 0.5, and 1 m for three soil pits averaged across 70 US Climate Reference Network sites.

Variable	Soil pit	0.05 m	0.1 m	0.2 m	0.5 m	1.0 m
Soil water content at 1500 kPa, %	1	9.2 ± 6.4	8.6 ± 6.1	9.4 ± 6.6	11.0 ± 6.5	11.0 ± 5.8
	2	9.6 ± 6.7	8.8 ± 6.2	9.9 ± 6.9	11.0 ± 6.5	11.3 ± 5.9
	3	9.6 ± 6.6	9.2 ± 6.6	9.7 ± 6.7	11.0 ± 6.3	11.4 ± 5.8
Soil water content at 33 kPa, %	1	18.8 ± 10.2	18.9 ± 10.0	20.2 ± 10.2	22.8 ± 11.6	23.0 ± 11.1
	2	19.0 ± 10.5	19.0 ± 10.5	20.7 ± 10.7	22.0 ± 11.2	22.0 ± 11.1
	3	19.0 ± 10.4	19.2 ± 10.7	20.6 ± 11.2	22.2 ± 11.4	22.5 ± 11.3
Bulk density, g cm^{-3}	1	1.33 ± 0.26	1.34 ± 0.27	1.37 ± 0.25	1.39 ± 0.24	1.37 ± 0.26
	2	1.30 ± 0.24	1.34 ± 0.24	1.36 ± 0.24	1.42 ± 0.22	1.36 ± 0.22
	3	1.34 ± 0.29	1.34 ± 0.27	1.42 ± 0.27	1.34 ± 0.24	1.41 ± 0.23
Clay, %	all	19.5 ± 12.4	19.8 ± 12.9	23.8 ± 14.4	27.6 ± 15.8	27.2 ± 14.2
Silt, %	all	38.7 ± 23.7	38.1 ± 23.6	38.34 ± 23.4	36.1 ± 21.9	38.0 ± 22.2
Sand, %	all	41.8 ± 30.9	42.1 ± 31.3	37.8 ± 31.1	36.3 ± 31.2	34.9 ± 29.6
Total C, % (w/w)	all	8.2 ± 11.6	7.8 ± 11.7	7.9 ± 12.0	9.3 ± 15.0	9.1 ± 15.5
Total N, % (w/w)	all	1.9 ± 4.6	1.6 ± 3.7	1.9 ± 3.8	2.5 ± 4.3	2.7 ± 4.4
Total S, % (w/w)	all	1.8 ± 9.9	1.3 ± 6.4	1.2 ± 4.3	1.2 ± 3.9	1.7 ± 4.4
Mn, mg kg^{-1}	all	82.0 ± 22.2	81.0 ± 22.2	81.5 ± 23.3	79.9 ± 21/6	76.5 ± 28.6
Ca, cmol kg^{-1}	all	23.6 ± 24.8	21.8 ± 19.8	25.2 ± 29.3	31.7 ± 30.7	52.6 ± 81.6
Mg, cmol kg^{-1}	all	2.9 ± 3.0	2.9 ± 2.9	3.3 ± 3.2	3.2 ± 3.1	4.4 ± 4.3
Na, cmol kg^{-1}	all	0.2 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.4 ± 0.3	2.1 ± 3.5
K, cmol kg^{-1}	all	0.7 ± 0.6	0.6 ± 0.5	0.7 ± 0.5	0.5 ± 0.4	0.6 ± 1.0
Sum of bases, cmol kg^{-1}	all	26.9 ± 26.1	25.1 ± 21.3	29.1 ± 30.4	35.5 ± 32.5	58.1 ± 83.6
Cation exchange capacity, cmol kg^{-1}	all	13.9 ± 11.6	13.4 ± 11.4	12.6 ± 14.0	10.2 ± 12.4	10.0 ± 9.2
pH	all	5.9 ± 1.0	6.0 ± 1.1	6.0 ± 1.1	6.1 ± 1.4	6.1 ± 1.5

used to evaluate the variability of soil properties among 70 USCRN stations (ftp://ftp.atdd.noaa.gov/pub/wilson/Supplemental_Table_T1.xls). The soil water content at FC and WP and the BD at depths of 0.05, 0.1, 0.2, 0.5, and 1.0 m were estimated from the mean of the three soil samples from each depth at each station. Values of FC and WP indicated a notable variability with soil depth and location among the 70 USCRN sites. For example, when the volumetric soil water contents at the WP and FC were averaged for the three locations at a station in Illinois (ftp://ftp.atdd.noaa.gov/pub/wilson/Supplemental_Table_T1.xls), the mean ± SD values were 14.6 ± 0.4, 14.4 ± 0.8, 14.3 ± 0.6, 16.4 ± 1.4, 16.3 ± 0.9% (v/v) for WP and 35.5 ± 1.5, 33.9 ± 1.5, 35.2 ± 1.7, 37.7 ± 2.0, 39.1 ± 1.2% (v/v) for FC at depths of 0.05, 0.1, 0.2, 0.5, and 1.0 m, respectively. Similarly, when WP and FC were averaged for the five depths at this site, WP = 14.3 ± 3.6 and FC = 28.7 ± 4.3% (v/v) for Pit 1; WP = 17.3 ± 2.5 and FC = 33.1 ± 1.7% (v/v) for Pit 2; and WP = 17.6 ± 2.2 and FC = 33.9 ± 1.0% (v/v) for Pit 3.

Like the WP and FC, the BD, a key indicator of soil compaction and porosity, was successfully obtained based on the analysis of soil core samples collected from the individual soil moisture measurement depths. Compared with FC and WP, BD showed more variability between individual pits than between soil depths at a given site (Fig. 3 and 4). For example, mean ± SD values of BD for the three measurement locations at the Illinois site were 1.36 ± 0.03, 1.33 ± 0.06, 1.34 ± 0.06, 1.37 ± 1.0, 1.53 ± 0.06 g cm^{-3} at depths of 0.05, 0.1, 0.2, 0.5, and 1.0 m, respectively; when BD is averaged for these five depths, mean ± SD values indicate BD = 1.5 ± 0.1 g cm^{-3} for Pit 1; BD = 1.4 ± 0.2 g cm^{-3} for Pit 2; and BD = 1.3 ± 0.2 g cm^{-3} for Pit 3. Compared with WP, FC, and BD, the soil texture at this site is classified as silty clay loam at the five depths, the PSD values of 65, 65.2, 63, 60.9, and 64% silt; 31.4, 31.3, 34.3, 37.7, and 35% clay; and 3.6, 3.5, 2.7, 1.4, and 1% sand at depths of 0.05, 0.1, 0.2, 0.5, and 1.0 m, respectively.

A further evaluation of the spatial variability in FC, WP, and BD was conducted by comparing values of FC, WP, and BD at depths of 0.05, 0.1, 0.2, 0.5, and 1.0 m among the three pits at each station. The comparison between FC and WP showed significant variability but indicated that both variables can be grouped based on their values because high values of FC corresponded to high values of WP and vice versa (Fig. 5). Values of BD, FC, and WP also showed significant variability among the three pit locations (Fig. 6). Regression lines were fitted to values of WP, FC,

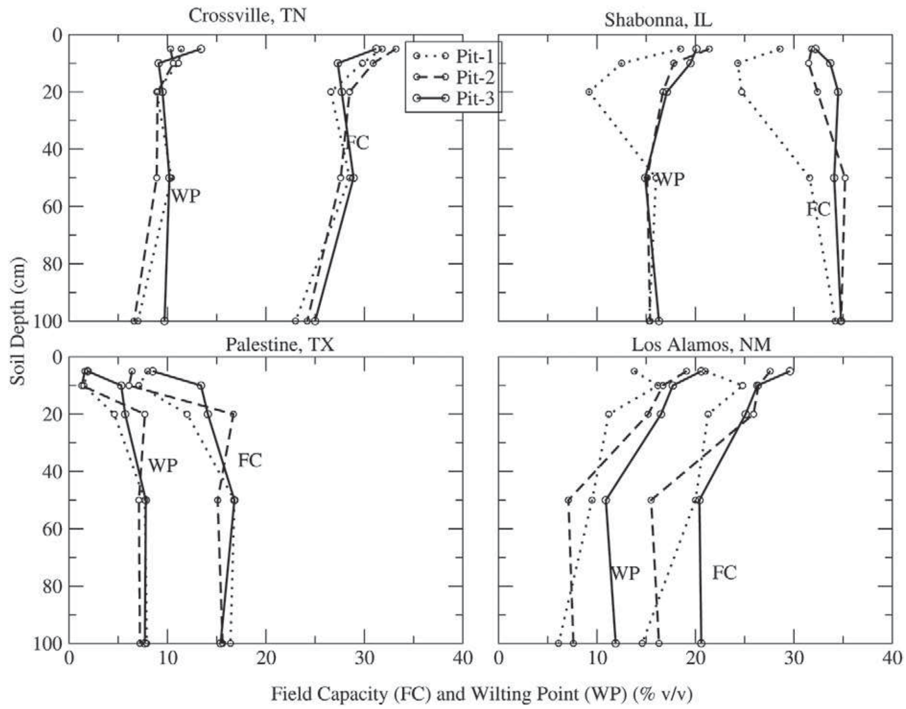

Fig. 3. Profiles of volumetric soil water contents at field capacity (FC) and wilting point (WP) at four US Climate Reference Network stations in four different states, including Tennessee, Illinois, Texas, and New Mexico

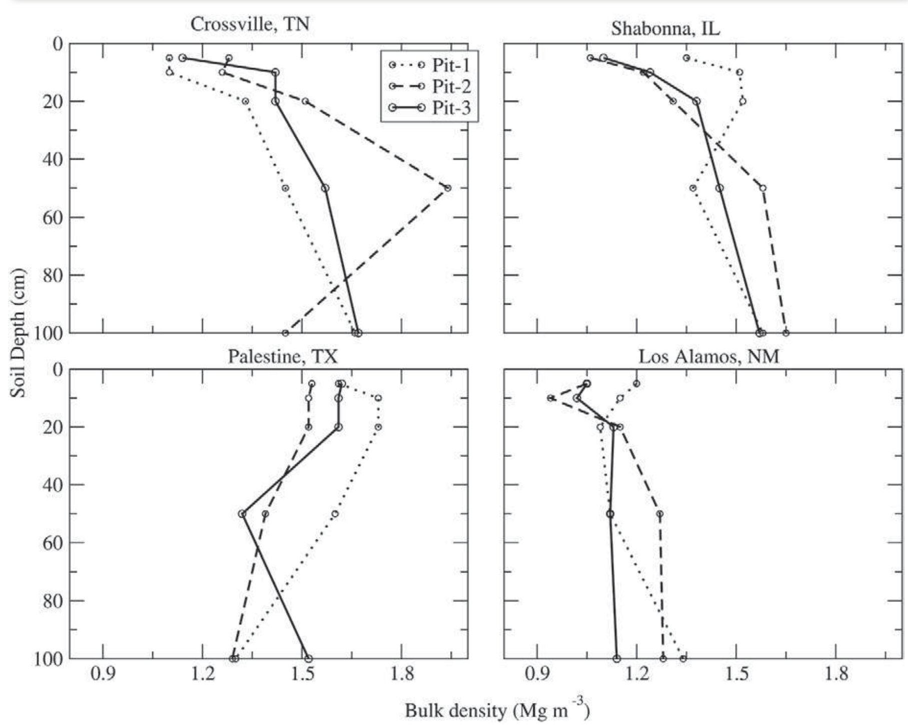

Fig. 4. Profiles of bulk density at four US Climate Reference Network stations in four different states, including Tennessee, Illinois, Texas, and New Mexico.

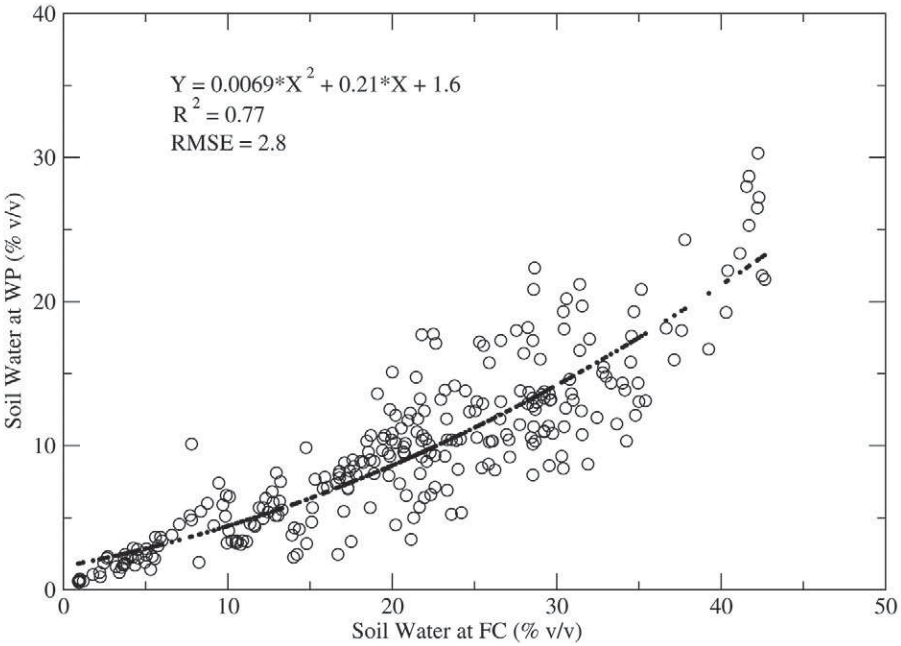

Fig. 5. Comparison of volumetric soil water content at field capacity (FC) against the wilting point (WP) for depths of 0.05, 0.1, 0.2, 0.5, and 1.0 m for Pits 1, 2, and 3.

and BD at each depth for the three pit locations to yield the slope, intercept, R^2, and RMSE. For WP and FC, the slope and R^2 were quite similar among the three pit locations, with the slope of each exceeding 0.8, R^2 exceeding 0.88, and RMSE ranging from 2.7 to 4%. For the BD, slope = 0.6 and R^2 = 0.4, which were less consistent among the three pits than WP and FC. In general, WP, FC, and BD were moderately correlated among locations. Despite the reasonable agreement among locations, the individual data points of WP, FC, and BD showed significant scatter among pits, with RMSE about 2.8% for WP, about 3.8% for FC, and 0.2 g cm^{-3} for BD. Compared with WP and FC, values of BD were the least consistent, which was expected because of the heterogeneous nature of the soils, soil moisture, and vegetation at each site. However, the overall behavior of the regression results and scatterplots suggests consistency among pits at each site. This further indicates that soil core samples provide reliable soil properties at individual soil depths and site averages, which is significant considering the challenges inherent in collecting site-specific soil property measurements.

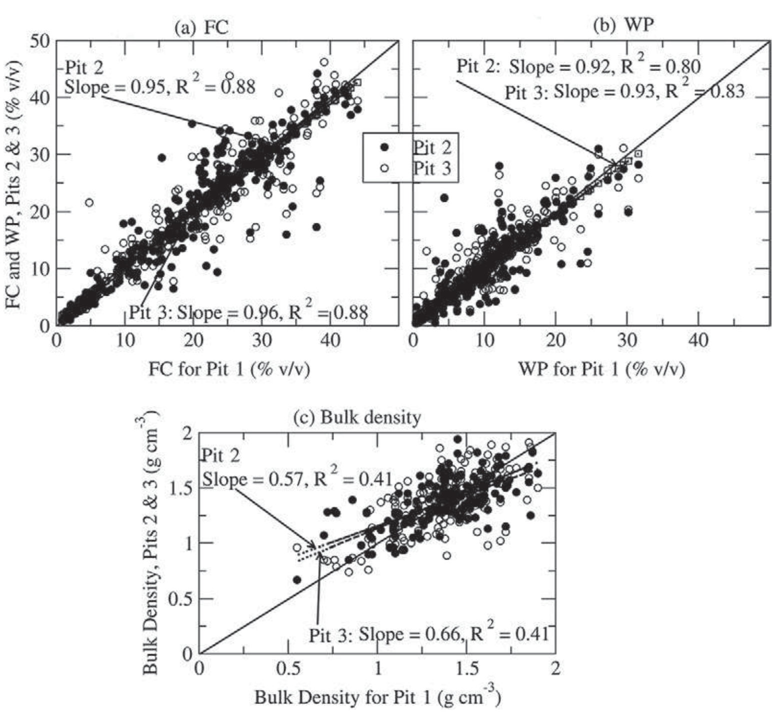

Fig. 6. Comparison of Pit 1 against Pits 2 and 3 for volumetric soil water content at (a) field capacity (FC) and (b) the wilting point (WP) and for (c) bulk density at depths of 0.05, 0.1, 0.2, 0.5, and 1.0 m.

The Effects of Soil Properties on Soil Moisture

We evaluated the effects of soil properties on soil moisture by comparing the behavior of PSD and BD with that of FC and WP at the various soil depths at each station. The aim was to investigate the effects of soil properties on soil moisture retention at sites with different soil, vegetation, and climate conditions. Values of FC and WP were positively correlated with clay content at each depth, with fitted lines with a slope of 0.61 for FC and a slope of 0.38 for WP (Fig. 7). In contrast, values of FC and WP were negatively correlated with the sand content at each soil depth, with a slope of −0.31 for FC and a slope of −0.14 for WP (Fig. 7). For both regressions, however, there was significant variability in the individual points of FC and WP. Thus, the parameters estimated by the regression indicate the general trend but do not accurately capture the distribution at each depth.

Our evaluations also showed significant variability between BD and the other soil properties, with BD uncorrelated with PSD, FC, and WP. This lack of correlation

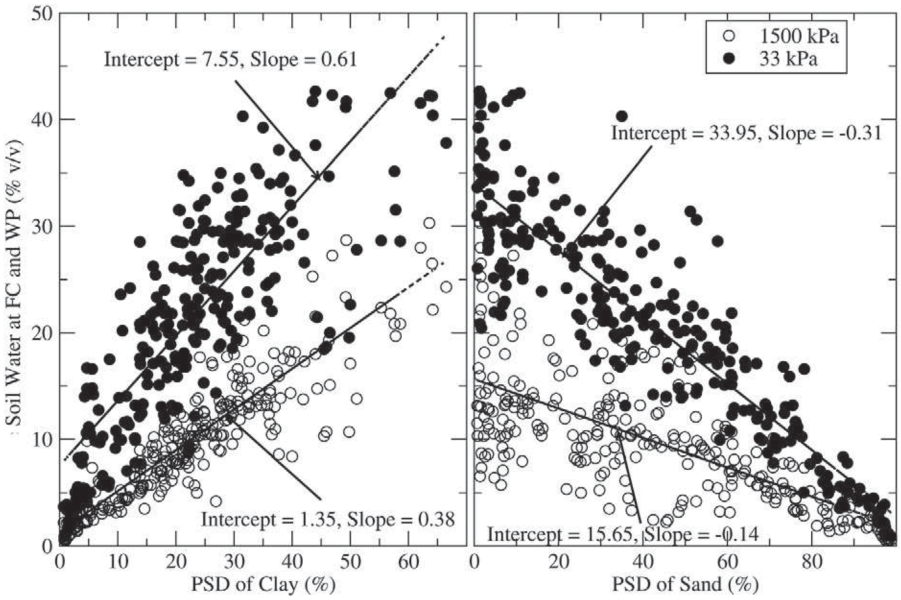

Fig. 7. Soil volumetric water content at the wilting point (WP) and field capacity (FC) as a function of clay and sand contents.

was expected because BD is the ratio of a given mass of soil to its total volume, which is a combination of solid materials and pore spaces within the soil. On the other hand, PSD, FC, and WP quantify the physical soil composition, but each factor by itself cannot represent the bulk soil volume as commonly quantified by the BD. However, some aspects of soil moisture have been investigated that depend on accurate measurement of BD to provide reliable spatial-temporal variation of water within the soil. For example, accurate measurements of BD are often needed to quantify soil hydraulic conductivities, to convert gravimetric soil water content to volumetric soil water content, and to estimate soil porosity.

Importance of Soil Properties

Variability in site-specific soil property data is a well-established research issue. This variability is largely the result of the heterogeneous nature of soils and soil moisture. Representative soil properties are difficult to determine because the heterogeneity of soils affects soil properties even at small scales. Despite important advances in the development of instruments for measuring and in numerical formulations for modeling soil moisture on a site-specific basis (Miller et al., 2007; Robinson et al., 2008), further work is still needed to evaluate site-specific soil properties for evaluating soil moisture in soil core samples.

The BD, PSD, FC, and WP were successfully quantified at the 70 USCRN stations, but at small scales, values at each station showed significant variability with depth and pit locations. Values of BD, PSD, FC, and WP varied among the five soil depths and three locations sampled at each station. While it was difficult to quantify all the factors related to the variability of the soil, soil properties determined by soil sample analysis successfully described the effects of many site-specific factors, and clearly indicated variability with depth and location. Factors that influence soil properties are complex and variable, and include soil parent materials, soil moisture, biochemical composition, vegetation conditions, climate, topography, and land use. Due to the sparse distribution of stations across the United States, USCRN site-specific soil property analysis presents difficult challenges compared with precision farming studies that often focus on a few fields (Brye et al., 2004, 2006; Corwin et al., 2003).

Notwithstanding these difficulties, many other studies have used in-field evaluations of soil physical properties to evaluate soil moisture dynamics. Several of such studies have been conducted in agricultural fields (Van Alphen and Stoorvogel, 2000; Ali et al., 2004), large-scale soil survey data evaluations (Nemes et al., 2011; Ferguson and Hergert, 1999; Fortin and Moon, 1999), land use assessments (Robinson et al., 2008; Sauer and Logsdon, 2002; Brye et al., 2006; Brejda et al., 2000), and soil moisture modeling (Tomasella et al., 2000, 2003; Cosby et al., 1984; Boschi et al., 2015; Miller et al., 2007; Zavattaro and Grignani, 2001; Hupet et al., 2004; Ahuja et al., 2010; Schaap et al., 1998, 2001). For soil moisture network sites in the United States, Pan et al. (2012) described one of the few of such studies in which they evaluated PSD, BD, saturated hydraulic conductivity, and water content at various pressure potentials across 27 soil moisture network sites statewide in North Carolina. Similar evaluations were reported across 117 Mesonet sites statewide in Oklahoma (Scott et al., 2013), across 18 transects in a 162-ha cotton (*Gossypium hirsutum* L.) field in Mississippi (Iqbal et al., 2005), and across 41 soil moisture network locations in 27-ha watershed in Germany (Qu et al., 2014).

Soil properties showed clear variability with soil depth, but values also varied with pit location at the various USCRN stations. For example, for the three USCRN sites in North Carolina, when WP was evaluated for all five soil depths, values were 13.2 ± 7.1% (v/v) for Pit 1, 14.8 ± 4.7% (v/v) for Pit 2, and 13.2 ± 7.2% (v/v) for Pit 3, while values of FC were 25.2 ± 7.6% (v/v) for Pit 1, 25.2 ± 4.7% (v/v) for Pit 2, and 23.3 ± 7.0% (v/v) for Pit 3; and for PSD, clay = 30.9 ± 12.9%, silt = 28.2 ± 4.6%, and sand = 41.0 ± 9.9%. The analysis here clearly showed that soil properties vary with location and depth, and the correct representation of such variability across sites is as important as the accurate measurement of soil properties. The variability of the soil properties is consistent with values that have been reported in the literature, mainly in precision agriculture studies, in which knowledge of site-specific soil properties has been successfully used to optimize plant water use, the application of soil nutrients, and plant growth and yields for several decades (Corwin et al., 2003; Kravchenko and Bullock, 2000; Jiang and Thelen, 2004; Sopher and McCracken, 1973; Anthony et al., 2012; Shahandeh et al., 2005; Baker et al., 2004; Brevik, 2012). The spatial variability of soil properties, soil water, soil nutrients, and the growth, development, and yields of plants within farm fields has been evaluated by analysis of soil samples collected in the fields (Mzuku et al., 2005; Liesch et al., 2011; Jung et al., 2006). Thus, measurements of soil physical and chemical properties have been used to quantify fundamental soil factors that control the spatial variability of growth, development, and plant yields in heterogeneous fields (Cassel et al., 2000; Corwin et al., 2003; Sharma et al., 2011). Such detailed evaluations of soil properties have also been performed in watersheds. For example, the variation of rock fragments and soil physical properties and their effects on infiltration and hydraulic conductivity were determined based on soil core samples collected from the top 5 cm and in situ infiltrometer measurements at 42 sites along three transects across a 147-ha watershed basin in Arkansas (Sauer and Logsdon, 2002). The impact of land leveling on soil physical and biochemical properties was successfully evaluated with soil samples collected from the top 10 cm at 50 grid points in a 4.9-ha field in Arkansas used for irrigated soybean [*Glycine max* (L.) Merr.] and rice (*Oryza sativa* L.) crops (Brye et al., 2006; Brye, 2006). The effect of hydrological conditions and landscape position on soil physical and chemical properties were evaluated with soil samples collected from a 5- to 10-m-long trench to a depth of 1.5 m on a 4100-km^2 landscape in northern California (O'Geen et al., 2008).

Several other studies have reported methods for estimating the site-specific variability of soil properties (Heuscher et al., 2005; Wendroth et al., 2006; Ahuja et al., 2010; Rogowski, 1972; Twarakavi et al., 2009; Horta et al., 2014; Van Alphen and Stoorvogel, 2000). Using soil survey databases in the United States and the Netherlands, Van Alphen and Stoorvogel (2000) reported a model for simulating soil water and nutrient processes to derive soil functional properties to predict site-specific soil characteristics for precision agriculture. Similarly, soil water characteristics, soil bulk density, and soil N content have been estimated from soil physical properties, chemical properties, and soil classifications (Zeleke and Si, 2005; Saxton and Rawls, 2006; Calhoun et al., 2001; Dessureault-Rompré et al., 2010; Heuscher et al., 2005). In addition to estimating soil characteristics, remote sensing approaches have been used to evaluate key soil properties such as soil surface roughness and moisture content (Zarco-Tejada et al., 2003; Ustin et al., 2004; Smolander and Stenberg, 2003; Li et al., 2001).

This study showed that to help evaluate soil moisture measurements it is important to consider the importance of both site location and soil depth on site-specific soil properties. For the USCRN program, where sites are sparsely scattered across the continental United States, evaluating soil properties at USCRN sites based on soil samples collected at individual sites required the investment of significant resources to implement. The vast separation of sites is an added burden to current laboratory methods used for determining soil properties. Pan et al. (2012) analyzed soil core samples collected from individual sites and successfully determined various soil physical properties, including the percentage of sand, silt, and clay and the bulk density, porosity, saturated hydraulic conductivity, and soil water content at pressure values of 10, 33, 66, 100, 500, and 1500 kPa at 27 stations of the Environment and Climate Observing Network (ECONet) in North Carolina, with soil moisture sensors buried at 20 cm. Soil core samples were collected at 20 cm but at points 3 m from the exact location of the soil moisture sensors, and the analysis did not evaluate the variability of soil properties at individual locations within the network. Among sites, the coefficient of variation of soil properties ranged from 12 to 80%. The soil texture, bulk density, and soil water content represented 80% of the total variance in the relationship among soil properties. Like our results, the clay content indicated a strong positive correlation with soil water content at 33 and 1500 kPa but the bulk density was not correlated with other soil properties. Scott et al. (2013) also found that soil moisture measurements based on the water retention curve and hydraulic conductivity parameters in a Rosetta pedotransfer function (PTF) formulation developed by Schaap et al. (2001) were greatly improved with in situ measurements of sand, silt, and clay contents, bulk density, and water content at 8 to 1500 kPa. This validation was conducted across 117 Oklahoma Mesonet soil moisture measurement sites covering an area of about 181,000 km^2 of the state. From the analysis of two replicate soil samples collected to a depth of 80 cm within a distance of 3 m from the soil moisture sensors at each Oklahoma Mesonet site, soil properties varied significantly, with bulk density ranging from 0.92 to 1.95 g cm^{-3}, sand content ranging from 2 to 88%, silt from 0 to 74%, clay from 4 to 78%, and water content at −33 kPa from 0.06 to 0.50 cm^3 cm^{-3} and at −1500 kPa from 0.01 to 0.35 cm^3 cm^{-3}. Furthermore, based on in situ soil property parameter formulations, there was a significant improvement in the Oklahoma Mesonet soil moisture data, with 32% reduction in the root mean square difference between soil moisture measurements and gravimetric measurements. Pan et al. (2012) and Scott et al. (2013) demonstrated how accurate soil property data can greatly improve the accuracy of in situ soil moisture measurements. Although they considered the soil property variability by depth and site, they did not consider the variability among locations at a given site, which our study indicates is also important. Evaluations reported by Pan et al. (2012) and Scott et al. (2013) showed that the soil variability is a site-specific issue, suggesting that results from select sites may be limited for other sites even within the same state or for sites in other states with different soils, climate, and ecological and hydrological conditions without considering the local soil conditions. Soil moisture determination based on remote sensing techniques or soil moisture probes often requires extensive ground-based validation before application. Providing site-specific soil property data with soil moisture data thus remains an important task even with the improved performance of remote sensing and soil moisture probes.

Estimated Soil Hydraulic Properties

Soil water characteristics for the hydraulic conductivity (K), FC, and WP are estimated by many soil water budget models and are critical for soil water transport studies. Because of the difficulty of measuring soil water characteristics, direct measurement is generally limited to short-term laboratory and field experiments. We evaluated PTFs that are widely used to estimate saturated hydraulic conductivity (K_s), FC, and WP in terms of soil physical properties to investigate soil water characteristics at the USCRN sites (Cosby et al., 1984; Saxton et al., 1986; Saxton and Rawls, 2006; Campbell and Shiozawa, 1992; Rawls and Brakensiek, 1985; Petersen et al., 1968; Tomasella and Hodnett, 1998; Rawls et al., 1983). Values of K_s (in cm d^{-1}) estimated by five PTFs that use sand, silt, and clay concentrations were evaluated at depths of 5, 10, 20, 50, and 100 cm (Table 2). Clearly, K was larger for high-sand-percentage soils than for high-clay or silty soils owing to differences in pore sizes, because the pore size is typically larger in sand than in clay or silt.

Results in Table 2 show that K_s varies both with PTF formulation and soil texture. The K of soil generally depends on both soil water movement and soil physical properties, and it describes the resistance of the soil to water flow. Accurate determination of K is critical for quantifying and studying water movement in and out of the soil. For a water-saturated soil profile, the hydraulic gradient of the positive water pressure in water flowing through the soil is the primary factor for determining K. For unsaturated soils, water movement is controlled both by the water content and the matric potential. Unsaturated K values are typically determined as a nonlinear function of water content or matric potential and a direct function of K, which is usually obtained from soil physical characteristics (Campbell, 1985).

In our evaluations of measured FC and WP against estimates by four PTFs using soil texture, regression correlations showed slopes of 0.76 to 1.12, R^2 of 0.72 to 0.85, and RMSDs of 6.35 to 9.06% for FC vs. PTF estimates, and slopes of 0.65 to 0.69, R^2 of 0.68 to 0.74, and RMSDs of 5.19 to 6.63% for WP vs. PTF estimates (Table 3). Soil water potential, which defines the energy state of water in the soil, depends on many factors, including water content, bulk density, soil organic matter content, texture, soil pore size

Table 2. Mean, standard deviation (SD), maximum and minimum water content at the wilting point (WP) and field capacity (FC), bulk density (BD), clay, silt, and sand contents, and saturated hydraulic conductivity estimated based on pedotransfer functions (PTFs) by Cosby et al. (1984) (K_sC1 and K_sC2), Saxton et al. (1986) (K_sS), Campbell and Shiozawa (1992) (K_sCS), and Rawls and Brakensiek (1985) (K_sRB).

Soil depth	Statistic	WP	FC	BD	Clay	Silt	Sand	K_sC1	K_sC2	K_sS	K_sCS	K_sRB
cm		%		g cm^{-3}	%			cm d^{-1}				
5	mean	9.5	19.9	1.31	18.8	34.4	46.7	66.9	70.8	76.5	58.4	207.6
	SD	6.4	10.7	0.24	11.7	21.3	28.9	60.0	62.7	100.4	68.9	287.4
	max.	28.5	46.9	1.68	49.3	84.4	97.4	246.2	255.0	493.0	271.2	1150.0
	min.	0.6	1.1	0.80	0.9	1.6	1.7	8.5	9.3	6.3	2.4	0.7
10	mean	8.9	18.6	1.33	19.0	33.5	47.5	67.9	71.5	74.2	58.1	230.0
	SD	5.4	9.9	0.23	11.8	21.7	29.2	65.3	68.0	119.3	73.0	338.2
	max.	26.7	41.6	1.73	46.9	84.8	98.3	254.1	261.4	518.1	275.3	1190.0
	min.	0.6	1.2	0.90	0.7	0.7	1.4	8.4	9.8	5.8	2.8	0.3
20	mean	9.3	20.3	1.42	22.3	34.5	43.2	61.5	63.7	67.8	49.9	156.6
	SD	4.9	9.6	0.20	12.4	21.5	29.3	67.1	69.7	125.1	72.8	293.5
	max.	17.4	35.2	1.82	45.5	75.4	98.1	252.3	259.8	511.8	284.0	1346.4
	min.	0.6	1.2	0.94	1.0	0.9	0.8	8.2	9.0	3.6	2.6	0.3
50	mean	10.7	22.1	1.42	27.2	31.4	41.4	55.8	55.8	54.1	41.4	139.1
	SD	5.5	10.2	0.19	14.2	20.7	28.5	61.7	64.1	122.4	67.9	285.5
	max.	21.8	41.8	1.84	58.6	75.5	97.9	250.6	258.3	505.6	280.8	1307.9
	min.	0.7	1.0	0.97	1.0	1.1	0.7	8.2	8.3	3.5	1.9	0.1
100	mean	11.4	23.9	1.40	27.6	33.4	39.0	51.9	52.1	50.6	37.5	126.7
	SD	5.6	10.5	0.20	15.2	21.9	28.3	59.9	61.5	114.6	62.5	250.0
	max.	23.5	41.6	1.79	57.6	72.1	97.6	247.9	256.1	496.5	266.3	1074.0
	min.	0.5	1.0	0.94	1.0	1.4	0.7	8.2	8.4	3.3	2.0	0.0

Table 3. Comparison of measured field capacity (FC) and wilting point (WP) against estimates using pedotransfer functions (PTFs) reported by Petersen et al. (1968), Tomasella and Hodnett (1998), Rawls et al. (1983), and Saxton and Rawls (2006).

PTF	Comparison	Slope	R^2	RMSD
				%
Petersen et al. (1968)	FC vs. PTF	1.12	0.72	9.06
	WP vs. PTF	0.69	0.74	6.63
Tomasella and Hodnett (1998)	FC vs. PTF	0.76	0.81	8.44
	WP vs. PTF	0.65	0.68	6.41
Rawls et al. (1983)	FC vs. PTF	0.93	0.84	6.35
	WP vs. PTF	0.71	0.76	5.51
Saxton and Rawls (2006)	FC vs. PTF	0.99	0.83	7.08
	WP vs. PTF	0.67	0.74	5.19

and distribution, and soil chemical properties (Jury et al., 1991). The complexity and variability of these factors and their impact on soil water potential makes direct measurements of FC and WP difficult to undertake in field settings (Robinson et al., 2008). Our evaluations illustrate that PTFs are a useful alternative, but expanding applications seem to require site-specific calibrations (Schaap et al., 1998, 2001).

The discrepancy among PTFs is attributed to the fact that the PTFs are empirical functions of the relationship between soil water characteristics and the soil physical properties. Soil water dynamics depend on many dependent and interdependent interactions that are too complicated to be fully captured by the empirical relationships and the small number of inputs used in PTFs; further research is therefore needed to determine how to apply PTFs successfully beyond the data sets on which they were developed (Schaap et al., 2001).

Evaluation of Soil Chemical Properties

Soil chemical properties evaluated at the 70 USCRN sites included C, N, S, trace metals (Mn, Ca, Mg, Na, and K), total bases, CEC, and pH (Table 1). Like the soil property measurements, many soil chemistry measurements were missing for many sites because soil samples were lost during the laboratory analysis. Soil chemical properties were determined at soil depths of 0.05, 0.1, 0.2, 0.5, and 1.0 m based on analysis of the composite of three soil samples collected at each depth from the three individual pits. When the mean and standard deviation of the soil chemical properties were evaluated for all depths, the chemical properties indicated clear variability in the soil at a given site and across sites. As expected, the variability in soil chemical properties was much larger across sites than with depth at a given site. However, the chemistry variability with depth was also significant. Thus, the evaluation of soil chemical properties provided in this study may be used to help identify sites with considerable soil property variability with soil depth.

The soil chemical properties demonstrated a large range of values across USCRN sites, with the means and standard deviations of C = 0.1 to 77.0% (0.0–4.0), N = 0.0 to 29.70% (4.3), S = 0.0 to 3.2% (3.4), Mn^+ = 11.8 to 100.0 cmol kg^{-1} (12.3–0.0), Ca^{2+} = 0.2 to 139.2 cmol kg^{-1} (0.1–64.6), Mg^{2+} = 0.1 to 11.7 cmol kg^{-1} (0.0–1.3), Na^+ = 0.1 to 1.8 cmol kg^{-1} (0.0–3.3), K^+ = 0.1 to 2.1 cmol kg^{-1} (0.0–1.6), total base = 0.2 to 140.9 cmol kg^{-1} (0.1–64.8), CEC = 0.6 to 56.4 cmol kg^{-1} (0.4–1.4), and pH = 3.8 to 8.3 (0.3–0.0) (ftp://ftp.atdd.noaa.gov/pub/wilson/Supplemental_Table_T1.xls). These chemical properties are known to depend on many factors acting in concert, including soil parent materials, weather, climate, water content, soil organic matter content, vegetation types, soil microorganisms, and land-use management (Bohn et al., 1985). Soil chemical properties are largely ignored in long-term measurements of soil moisture in the United States (Scott et al., 2013; Pan et al., 2012). As our results demonstrate, the analysis of soil samples collected during the installation of soil moisture sensors offers a realistic approach for determining soil chemical properties at national ground-based climate stations (Bell et al., 2013; Diamond et al., 2013).

Evaluating soil chemical properties is of particular interest for measurements recorded with the HydraProbe, as it measures the real and imaginary dielectric constants based on the reflected electromagnetic wave at a radio frequency of 50 MHz. The real dielectric constant is used to estimate the quantity of water present in the soil, while the imaginary dielectric constant is directly related to the electrical conductivity of the soil. The net concentration of all soluble ions in the bulk soil, for example Mg^{2+}, Ca^{2+}, K^+, Na^+, Cl^-, and CO_2^- that determine the electric conductivity of the soil depends on a complex combination of the soil physical and biochemical properties, climate conditions, and soil water content. High pH and the presence of ions in the soil tend to increase the electric conductivity and thus the imaginary dielectric constant of the soil. Because high pH and the presence of ions in the soil also affect soil development, soil structure, and soil physical properties that are important to soil water, they ultimately also affect the real dielectric constant. For example, soil salinity caused by a high content of salts such as NaCl accumulating in arid, irrigated, or coastal areas often causes flocculation that can reduce soil permeability or hydraulic conductivity, and this can result in poorly drained soils. In addition, Seyfried and Murdoc (2004) reported HydraProbe sensitivity to a series of KCl solution concentrations and soil types. They found that an increase in KCl solution concentration to an electrical conductivity of 0.277 S m^{-1} resulted in a noticeable decrease in the real dielectric constant, and increases beyond 0.277 S m^{-1} resulted in unrealistic values of real dielectric constants.

Conclusions

This study has provided soil core sample analysis of BD, sand, silt, and clay concentrations, and FC and WP for each soil moisture measurement depth and location across about 70 USCRN stations in the United States. These newly available soil properties will improve our ability to increase the accuracy of the USCRN soil moisture measurements. While previous studies have reported soil properties for soil moisture measurement sites elsewhere, to our knowledge these results were based on soil samples collected at points surrounding the soil moisture measurements and not at the exact location of the soil moisture measurements. The evaluation of the soil properties at the exact depth and location of soil moisture measurements in our study enhances our ability to quantify and interpret the spatial and temporal changes in water content within the soil profile. Soil properties provided at the depth and location of the USCRN soil moisture measurements may therefore serve two important research purposes: (i) improve fundamental understanding of the variability of soil properties with direct influence on the soil moisture measurements; and (ii) provide point-specific soil property data to help ensure high-quality USCRN soil moisture data.

Evaluation of the means and variances of soil properties indicated significant spatial variability, with values of the soil BD, sand, silt, and clay contents, and FC and WP showing clear variability with soil depth and location at individual sites. Values of silt, clay, and sand contents showed variations more with soil depth than with location at individual sites; silt tended to decrease with soil depth, clay tended to increase, and sand tended to vary randomly with depth. Means of silt, clay, and sand contents at each site resulted in 10 soil texture distribution classifications among the 68 sites: three sites with loamy sand, 15 with sandy loam, two with clay, 11 with silt loam, five with clay loam, 10 with loam, seven with sand, eight with silty clay loam, four with sandy clay loam, and three with silty clay. For each texture distribution classification, silt, clay, and sand concentrations showed variability in clusters with a wide range of numerical values. Consequently, the variability of soil properties with depth, location, and site was more clearly described by the silt, clay, and sand contents than by the texture distribution classification. Thus from the perspective of soil moisture measurements, when considering the impact of soil factors on soil moisture at various depths and locations, knowledge of the silt, clay, and sand contents is more useful than that of the texture distribution classification. When the soil moisture retention properties were correlated with soil properties, clay content was positively correlated with FC and WP, and sand content was negatively correlated with FC and WP. As expected, there was no correlation between BD and FC or WP.

The soil property analysis investigated the possibility that PTFs reported in the literature may be used to estimate soil hydraulic properties at USCRN sites, particularly for modeling soil water dynamics. However, further research is needed to validate this effort.

Further research will be needed to extend the evaluation of soil properties to the 44 USCRN sites that were missing from this study. An essential part of improving the evaluation of soil properties would be to also consider the evaluation of the soil hydraulic conductivity as well as the soil moisture retention curve at the 114 USCRN sites. In addition, while soil sampling evaluation has led to the successful evaluation of important soil properties in different USCRN soil environments, considerable effort is still needed to use the soil property data to maintain, process, interpret, and provide high quality soil moisture data for the different USCRN stations. Moreover, it would be useful to better understand the extent to which the soil property results for the USCRN sites, with largely grass cover, can be extended to sites with other land covers such as agricultural crops and forests.

Future efforts will extend the analysis of the soil property data presented in this study with an evaluation of the impact of site-specific soil properties on soil moisture measurements at USCRN sites representing the varying soil environments and climate regions of the continental United States. The combination of the soil properties of FC and WP with soil moisture measurements can be used to determine the plant-available water for different soil environments and soil moisture levels. Such evaluations would provide a unique opportunity to assess the quality and application of soil moisture measurements as well as evaluate the impact of both climate and soil factors on soil moisture at soil depths, landscape positions, and station sites across the United States.

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References

Ahuja, L.R., L. Ma, and T.R. Green. 2010. Effective soil properties of heterogeneous areas for modeling infiltration and redistribution. Soil Sci. Soc. Am. J. 74:1469–1482. doi:10.2136/sssaj2010.0073

Ali, I., F.D. Whisler, J. Iqbal, J.N. Jenkins, and J.M. Mckinion. 2004. Soil physical properties web database for GOSSYM and GLYCIM crop simulation models. Agron. J. 96:1706–1710. doi:10.2134/agronj2004.1706

Anthony, P., G. Malzer, S. Sparrow, and M. Zhang. 2012. Soybean yield and quality in relation to soil properties. Agron. J. 104:1443–1458. doi:10.2134/agronj2012.0095

Baker, B.J., N.R. Fausey, and K.R. Islam. 2004. Comparison of soil physical properties under two different water table management regimes. Soil Sci. Soc. Am. J. 68:1973–1981. doi:10.2136/sssaj2004.1973

Bell, J.E., M.A. Palecki, C.B. Baker, W.G. Collins, J.H. Lawrimore, R.D. Leeper, et al. 2013. U.S. Climate Reference Network soil moisture and temperature observations. J. Hydrometeorol. 14:977–988. doi:10.1175/JHM-D-12-0146.1

Bohn, H.L., B.L. McNeal, and G.A. O'Connor. 1985. Soil chemistry. 2nd ed. John Wiley & Sons, New York.

Boschi, R.S., L.H.A. Rodrigues, and M.L.R.C. Lopes-Assad. 2015. Analysis of patterns of pedotransfer function estimates: An approach based on classification trees. Soil Sci. Soc. Am. J. 79:720–729. doi:10.2136/sssaj2014.11.0452

Brejda, J.J., D.L. Karlen, J.L. Smith, and D.L. Allan. 2000. Identification of regional soil quality factors and indicators: II. Northern Mississippi Loess Hills and Palouse Prairie. Soil Sci. Soc. Am. J. 64:2125–2135. doi:10.2136/sssaj2000.6462125x

Brevik, E.C. 2012. Analysis of the representation of soil map units using a common apparent electrical conductivity sampling design for the mapping of soil properties. Soil Horiz. 53(2):32–37. doi:10.2136/sh12-01-0002

Brye, K.R. 2006. Soil biochemical properties as affected by land leveling in a clayey Aquert. Soil Sci. Soc. Am. J. 70:1129–1139. doi:10.2136/sssaj2005.0348

Brye, K.R., N.A. Slaton, M. Mozaffari, M.C. Savin, R.J. Norman, and D.M. Miller. 2004. Short-term effects of land leveling on soil chemical properties and their relationships with microbial biomass. Soil Sci. Soc. Am. J. 68:924–934. doi:10.2136/sssaj2004.9240

Brye, K.R., N.A. Slaton, and R.J. Norman. 2006. Soil physical and biological properties as affected by land leveling in a clayey aquert. Soil Sci. Soc. Am. J. 70:631–642. doi:10.2136/sssaj2005.0185

Calhoun, F.G., N.E. Smeck, B.L. Slater, J.M. Bigham, and G.F. Hall. 2001. Predicting bulk density of Ohio soil from morphology, genetic principles, and laboratory characterization data. Soil Sci. Soc. Am. J. 65:811–819. doi:10.2136/sssaj2001.653811x

Campbell, G.S. 1985. Soil physics with BASIC: Transport models for soil–plant systems. Elsevier, Amsterdam.

Campbell, G.S., and S. Shiozawa. 1992. Prediction of hydraulic properties of soils using particle size distribution and bulk density. In: M.Th. van Genuchten et al., editors, Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils, Proceedings of the International Workshop, Riverside, CA. 11–13 Oct. 1989. US Salinity Lab., Riverside, CA. p. 317–328.

Cassel, D.K., O. Wendroth, and D.R. Nielsen. 2000. Assessing spatial variability in an agricultural experiment station field: Opportunities arising from spatial dependence. Agron. J. 92:706–714. doi:10.2134/agronj2000.924706x

Corwin, D.L., S.M. Lesch, P.J. Shouse, R. Soppe, and J.E. Ayars. 2003. Identifying soil properties that influence cotton yield using soil sampling directed by apparent soil electrical conductivity. Agron. J. 95:352–364. doi:10.2134/agronj2003.0352

Cosby, B.J., G.M. Hornberger, R.B. Clapp, and T.R. Ginn. 1984. A Statistical exploration of the relationships of soil moisture characteristics to the physical properties of soils. Water Resour. Res. 20:682–690. doi:10.1029/WR020i006p00682

Crow, W.T., and E.F. Wood. 2002. The value of coarse-scale soil moisture observations for regional surface energy balance model. J. Hydrometeorol. 3:467–482. doi:10.1175/1525-7541(2002)003<0467:TVOCSS>2.0.CO;2

Dessureault-Rompré, J., B.J. Zebarth, D.L. Burton, M. Sharifi, J. Cooper, C.A. Grant, and C.F. Drury. 2010. Relationships among mineralizable soil nitrogen, soil properties, and climatic indices. Soil Sci. Soc. Am. J. 74:1218–1227. doi:10.2136/sssaj2009.0213

Diamond, H.J., T.R. Karl, M.A. Palecki, C.B. Baker, J.E. Bell, R.D. Leeper, et al. 2013. U.S. Climate Reference Network after one decade of operations. Bull. Am. Meteorol. Soc. 94:485–498. doi:10.1175/BAMS-D-12-00170.1

Ferguson, R.B., and G.W. Hergert. 1999. Sampling and spatial analysis techniques for quantifying soil map unit composition. Geophys. Monogr. 108:79–91.

Fortin, M.-C., and D.E. Moon. 1999. Errors associated with the use of soil survey data for estimating plant-available water at a regional scale. Agron. J. 91:984–990. doi:10.2134/agronj1999.916984x

Gourley, J.J., J.M. Erlingis, Y. Hong, and E.B. Wells. 2012. Evaluation of tools used for monitoring and forecasting flash floods in the United States. Weather Forecast. 27:158–173. doi:10.1175/WAF-D-10-05043.1

Heuscher, S.A., C.C. Brandt, and P.M. Jardine. 2005. Using soil physical and chemical properties to estimate bulk density. Soil Sci. Soc. Am. J. 69:51–56. doi:10.2136/sssaj2005.0051

Horta, A., M.J. Pereira, M. Goncalves, T. Ramos, and A. Soares. 2014. Spatial modelling of soil hydraulic properties integrating different supports. J. Hydrol. 511:1–9. doi:10.1016/j.jhydrol.2014.01.027

Hupet, F., J.C. van Dam, and M. Vanclooster. 2004. Impact of within-field variability in soil hydraulic properties on transpiration fluxes and crop yields: A numerical study. Vadose Zone J. 3:1367–1379.

Iqbal, J., J.A. Thomasson, J.N. Jenkins, P.R. Owens, and F.D. Whisler. 2005. Spatial variability analysis of soil physical properties of Alluvial soils. Soil Sci. Soc. Am. J. 69:1338–1350. doi:10.2136/sssaj2004.0154

Jiang, P., and K.D. Thelen. 2004. Effects of soil and topographic properties on crop yield in a north-central corn–soybean cropping system. Agron. J. 96:252–258. doi:10.2134/agronj2004.0252

Jung, W.K., N.R. Kitchen, K.A. Sudduth, and S.H. Anderson. 2006. Spatial characteristics of claypan soil properties in an agricultural field. Soil Sci. Soc. Am. J. 70:1387–1397. doi:10.2136/sssaj2005.0273

Jury, W.A., W.R. Gardner, and W.H. Gardner. 1991. Soil physics. 5th ed. John Wiley & Sons, New York.

Kravchenko, A.N., and D.G. Bullock. 2000. Correlation of corn and soybean grain yield with topography and soil properties. Agron. J. 92:75–83. doi:10.2134/agronj2000.92175x

Kustas, W.P., J.L. Hatfield, and J.H. Prueger. 2005. The Soil Moisture-Atmosphere Coupling Experiment (SMACEX): Background, hydrometeorological conditions, and preliminary findings. J. Hydrometeorol. 6:791–804. doi:10.1175/JHM456.1

Li, H., R.J. Lascano, E.M. Barnes, J. Booker, L.T. Wilson, K.F. Bronson, and E. Segarra. 2001. Multispectral reflectance of cotton related to plant growth, soil water and texture, and site elevation. J. Agron. 93:1327–1337. doi:10.2134/agronj2001.1327

Liesch, A.M., E.S. Krueger, and T.E. Ochsner. 2011. Soil structure and physical properties under rye-corn silage double-cropping systems. Soil Sci. Soc. Am. J. 75:1307–1314. doi:10.2136/sssaj2010.0292

Miller, G.R., D.D. Baldocchi, B.E. Law, and T. Meyers. 2007. An analysis of soil moisture dynamics using multi-year data from a network of micrometeorological observation sites. Adv. Water Resour. 30:1065–1081. doi:10.1016/j.advwatres.2006.10.002

Mzuku, M., R. Khosla, R. Reich, D. Inman, F. Smith, and L. MacDonald. 2005. Spatial variability of measured soil properties across site-specific management zones. Soil Sci. Soc. Am. J. 69:1572–1579. doi:10.2136/sssaj2005.0062

Nemes, A., Y.A. Pachepsky, and D.J. Timlin. 2011. Toward improving global estimates of field soil water capacity. Soil Sci. Soc. Am. J. 75:807–812. doi:10.2136/sssaj2010.0251

O'Geen, A.T., W.A. Hobson, R.A. Dahlgren, and D.B. Kelley. 2008. Evaluation of soil properties and hydric soil indicators for Vernal Pool Catenas in California. Soil Sci. Soc. Am. J. 72:727–740. doi:10.2136/sssaj2007.0123

Pan, W., R.P. Boyles, J.G. White, and J.L. Heitman. 2012. Characterizing soil physical properties for soil moisture monitoring with the North Carolina Environmental and Climate Observing Network. J. Atmos. Ocean. Technol. 29:933–943. doi:10.1175/JTECH-D-11-00104.1

Panciera, R., J.P. Walker, T.J. Jackson, D.A. Gray, M.A. Tanase, D. Ryu, et al. 2014. The soil moisture active passive experiments (SMAPEx): Towards soil moisture retrieval from the SMAP mission. IEEE Trans. Geosci. Remote Sens. 52:490–507. doi:10.1109/TGRS.2013.2241774

Petersen, G.W., R.L. Cunningham, and R.P. Tatelski. 1968. Moisture characteristics of Pennsylvania soils: I: Moisture retention as related to texture. Soil Sci. Soc. Am. J. 32:271–275. doi:10.2136/sssaj1968.03615995003200020031x

Pielke, R.A., Sr. 2001. Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. Rev. Geophys. 39:151–177. doi:10.1029/1999RG000072

Qu, W., H.R. Bogena, J.A. Huisman, G. Martinez, Y.A. Pachepsky, and H. Vereecken. 2014. Effects of soil hydraulic properties on the spatial variability of soil water content: Evidence from sensor network data and inverse modeling. Vadose Zone J. 13(12). doi:10.2136/vzj2014.07.0099

Rawls, W., and D. Brakensiek. 1985. Prediction of soil water properties for hydrologic modeling. In: Jones, E.B. and Ward, T, Editor, In proceedings for Symposium on Watershed Management in the Eighties, Denver, CO, April 30- May 1. American Society of Civil Engineering, New York, p. 293–299.

Rawls, W.J., D.L. Brakensiek, and B. Soni. 1983. Agricultural management effects on soil water processes. I: Soil water retention and Green–Ampt parameters. Trans. ASAE 25:1316–1320.

Reen, B.P., D.R. Stauffer, and K.J. Davis. 2014. Land-surface heterogeneity effects in the planetary boundary layer. Boundary-Layer Meteorol. 150:1–31. doi:10.1007/s10546-013-9860-8

Robinson, D.A., C.S. Campbell, J.W. Hopmans, B.K. Hornbuckle, S.B. Jones, R. Knight, et al. 2008. Soil moisture measurement for ecological and hydrological watershed- scale observations: A review. Vadose Zone J. 7:358–389. doi:10.2136/vzj2007.0143

Rogowski, A.S. 1972. Estimation of the soil moisture characteristic and hydraulic conductivity: Comparison of models. Soil Sci. 114:423–429. doi:10.1097/00010694-197212000-00004

Sahoo, A.K., P.R. Houser, C. Ferguson, E.F. Wood, P.A. Dirmeyer, and M. Kafatos. 2008. Evaluation of AMSR-E soil moisture results using the in-situ data over the Little River Experimental Water- shed, Georgia. Remote Sens. Environ. 112:3142–3152. doi:10.1016/j.rse.2008.03.007

Sauer, T.J., and S.D. Logsdon. 2002. Hydraulic and physical properties of stony soils in a small watershed. Soil Sci. Soc. Am. J. 66:1947–1956. doi:10.2136/sssaj2002.1947

Saxton, K.E., and W.J. Rawls. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70:1569–1578. doi:10.2136/sssaj2005.0117

Saxton, K.E., W.J. Rawls, J.S. Romberger, and R.I. Papendick. 1986. Estimating generalized soil-water characteristics from texture. Soil Sci. Soc. Am. J. 50:1031–1036. doi:10.2136/sssaj1986.03615995005000040039x

Schaap, M.G., F.J. Leij, and M.Th. van Genuchten. 1998. Neural network analysis for hierarchical prediction of soil hydraulic properties. Soil Sci. Soc. Am. J. 62:847–855. doi:10.2136/sssaj1998.03615995006200040001x

Schaap, M.G., F.J. Leij, and M.Th. van Genuchten. 2001. ROSETTA: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J. Hydrol. 251:163–176. doi:10.1016/S0022-1694(01)00466-8

Schaefer, G.L., M.H. Cosh, and T.J. Jackson. 2007. The USDA Natural Resources Conservation Service Soil Climate Analysis Network (SCAN). J. Atmos. Ocean. Technol. 24:2073–2077. doi:10.1175/2007JTECHA930.1

Scott, B.L., T.E. Ochsner, B.G. Illston, C.A. Fiebrich, J.B. Basara, and A.J. Sutherland. 2013. New soil property database improves Oklahoma Mesonet soil moisture estimates. J. Atmos. Ocean. Technol. 30:2585–2595. doi:10.1175/JTECH-D-13-00084.1

Seyfried, M.S., L.E. Grant, E. Du, and K. Humes. 2005. Dielectric loss and calibration of the Hydra Probe soil water sensor. Vadose Zone J. 4:1070–1079. doi:10.2136/vzj2004.0148

Seyfried, M.S., and M.D. Murdoc. 2004. Measurement of soil water content with a 50-MHz soil dielectric sensor. Soil Sci. Soc. Am. J. 68:394–403. doi:10.2136/sssaj2004.3940

Shahandeh, H., A.L. Wright, F.M. Hons, and R.J. Lascano. 2005. Spatial and temporal variation of soil nitrogen parameters related to soil texture and corn yield. Agron. J. 97:772–782. doi:10.2134/agronj2004.0287

Sharma, P., M.K. Shukla, and J.G. Mexal. 2011. Spatial variability of soil properties in agricultural fields of Southern New Mexico. Soil Sci. 176:288–302. doi:10.1097/SS.0b013e31821c0dab

Smolander, S., and P. Stenberg. 2003. A method to account for shoot scale clumping in coniferous canopy reflectance models. Remote Sens. Environ. 88:363–373. doi:10.1016/j.rse.2003.06.003

Sopher, C.D., and R.J. McCracken. 1973. Relationships between soil properties, management practices, and corn yields on southern Atlantic coastal plain soils. Agron. J. 65:595–599. doi:10.2134/agronj1973.00021962006500040020x

Tomasella, J., and M.G. Hodnett. 1998. Estimating soil water retention characteristics from limited data in Brazilian Amazonia. Soil Sci. 163:190–202. doi:10.1097/00010694-199803000-00003

Tomasella, J., M.G. Hodnett, and L. Rossato. 2000. Pedotransfer functions for the estimation of soil water retention in Brazilian soils. Soil Sci. Soc. Am. J. 64:327–338. doi:10.2136/sssaj2000.641327x

Tomasella, J., Y. Pachepsky, S. Crestana, and W. Rawls. 2003. Comparison of two techniques to develop pedotransfer functions for water retention. Soil Sci. Soc. Am. J. 67:1085–1092.

Torres, G.M., R.P. Lollato, and T.E. Ochsner. 2013. Comparison of drought probability assessments based on atmospheric water deficit and soil water deficit. Agron. J. 105:428–436. doi:10.2134/agronj2012.0295

Twarakavi, N.K.C., M. Sakai, and J. Šimůnek. 2009. An objective analysis of the dynamic nature of field capacity. Water Resour. Res. 45:W10410. doi:10.1029/2009WR007944

USDA–NRCS. 1995. Soil Survey Geographic (SSURGO) data base: Data use information. Natl. Cartogr. and GIS Ctr., Fort Worth, TX.

USDA Soil Conservation Service. 1993. State Soil Geographic data base (STATSGO) for the conterminous United States. Misc. Publ. 1492. US Gov. Print. Office, Washington, DC.

Ustin, S.L., D.A. Roberts, J.A. Gamon, G.P. Asner, and R.O. Green. 2004. Using imaging spectroscopy to study ecosystem processes and properties. BioScience 54:523–533. doi:10.1641/0006-3568(2004)054[0523:UISTSE]2.0.CO;2

Van Alphen, B.J., and J.J. Stoorvogel. 2000. A functional approach to soil characterization in support of precision agriculture. Soil Sci. Soc. Am. J. 64:1706–1713. doi:10.2136/sssaj2000.6451706x

Vereecken, H., J.A. Huisman, H. Bogena, J. Vanderborght, J.A. Vrugt, and J.W. Hopmans. 2008. On the value of soil moisture measurements in vadose zone hydrology: A review. Water Resour. Res. 44:W00D06. doi:10.1029/2008WR006829

Wendroth, O., S. Koszinski, and E. Pena-Yewtukhiv. 2006. Spatial association among soil hydraulic properties, soil texture, and geoelectrical resistivity. Vadose Zone J. 5:341–355. doi:10.2136/vzj2005.0026

Zamora, R.J., F.M. Ralph, E. Clark, and T. Schneider. 2011. The NOAA Hydrometeorology Testbed Soil Moisture Observing Networks: Design, instrumentation, and preliminary results. J. Atmos. Ocean. Technol. 28:1129–1140. doi:10.1175/2010JTECHA1465.1

Zarco-Tejada, P.J., C.A. Rueda, and S.L. Ustin. 2003. Water content estimation in vegetation with MODIS reflectance data and model inversion methods. Remote Sens. Environ. 85:109–124. doi:10.1016/S0034-4257(02)00197-9

Zavattaro, L., and C. Grignani. 2001. Deriving hydrological parameters for modeling water flow under field conditions. Soil Sci. Soc. Am. J. 65:655–667. doi:10.2136/sssaj2001.653655x

Zeleke, T.B., and B.C. Si. 2005. Scaling relationships between saturated hydraulic conductivity and soil physical properties. Soil Sci. Soc. Am. J. 69:1691–1702. doi:10.2136/sssaj2005.0072