Characterizing Soil Physical Properties for Soil Moisture Monitoring with the North Carolina Environment and Climate Observing Network

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ABSTRACT

Soil moisture has important implications for meteorology, climatology, hydrology, and agriculture. This has led to growing interest in development of in situ soil moisture monitoring networks. Measurement interpretation is severely limited without soil property data. In North Carolina, soil moisture has been monitored since 1999 as a routine parameter in the statewide Environment and Climate Observing Network (ECONet), but with little soils information available for ECONet sites. The objective of this paper is to provide soils data for ECONet development. The authors studied soil physical properties at 27 ECONet sites and generated a database with 13 soil physical parameters, including sand, silt, and clay contents; bulk density; total porosity; saturated hydraulic conductivity; air-dried water content; and water retention at six pressures. Soil properties were highly variable among individual ECONet sites [coefficients of variation (CVs) ranging from 12% to 80%]. This wide range of properties suggests very different behavior among sites with respect to soil moisture. A principal component analysis indicated parameter groupings associated primarily with soil texture, bulk density, and air-dried water content accounted for 80% of the total variance in the dataset. These results suggested that a few specific soil properties could be measured to provide an understanding of differences in sites with respect to major soil properties. The authors also illustrate how the measured soil properties have been used to develop new soil moisture products and data screening for the North Carolina ECONet. The methods, analysis, and results presented here have applications to North Carolina and for other regions with heterogeneous soils where soil moisture monitoring is valuable.

1. Introduction

Soil moisture is an important forcing variable in terrestrial environments (Vereecken et al. 2008; Robinson et al. 2008; Seneviratne et al. 2010; Legates et al. 2011). Soil moisture significantly influences weather and climate, plant growth and productivity, hydrology, and soil ecology (i.e., carbon/nitrogen dynamics, and trace gas emissions). As such, the need for compilation of extensive and intensive soil moisture information has been recognized for several decades (e.g., Robock et al. 2000; Western and Grayson 1998).

Research efforts to develop new techniques for monitoring soil moisture also continue, often with focus on large-scale monitoring. One prominent area of research is remote sensing (Engman and Chauhan 1995; Jackson 1993; Jackson and Schmugge 2002). Remote sensing techniques offer promise; however, many provide information only for the top few centimeters of the soil (Robinson et al. 2008). Therefore, application of remotely sensed soil moisture data may be limited for

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determining conditions at typical plant rooting depths or for other ecological and hydrological applications, without significant complementary information (Houser et al. 1998; Robinson et al. 2008). Most remote sensing techniques also require extensive ground-based validation before application (Arya et al. 1983; Njoku et al. 2003; Drusch et al. 2004, Cosh et al. 2004). Thus, ground-based observation of soil moisture remains important even as remote sensing techniques improve (Georgakakos and Baumer 1996; Western et al. 2002; Robinson et al. 2008).

Efforts have also been made to develop regional-scale, ground-based soil moisture monitoring; examples include the Oklahoma Mesonet (Illston et al. 2008), the Illinois Soil Moisture Network (Hollinger and Isard 1994), and the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service Soil Climate Analysis Network (Schaefer et al. 2007). A potential limitation of such networks is that they represent soil moisture only at the point of observation, which may differ significantly from surrounding areas (Scott et al. 2010). Vachaud et al. (1985) proposed the concept of temporal stability for soil moisture, which attempts to explain patterns in soil moisture that persist in time. Vachaud et al. (1985) and other researchers (e.g., Martínez-Fernández and Ceballos 2005; Western et al. 1999) have demonstrated the role of soil and landscape properties in extending point soil moisture information to describe patterns in soil moisture across the landscape. As ground-based soil moisture networks continue to develop, it is critical that soil moisture observations be accompanied by careful inventory of soil and landscape properties in order to understand patterns in soil moisture. Furthermore, to apply or even to verify the quality of soil moisture monitoring data, collection of metadata is critical (Scott et al. 2010).

A vast potential number of soil properties are associated with soil moisture dynamics (Cosby et al. 1984; Vachaud et al. 1985; Western et al. 2002). Among the key soil parameters frequently assumed important to determining and interpreting soil moisture conditions are soil texture and particle size distribution (Loague 1992; Saxton et al. 1986; Ritsema and Dekker 1994; Western et al. 2002), bulk density (BD) and porosity (Gupta and Larson 1979; Saxton et al. 1986; Rodriguez-Iturbe et al. 1995; Wagner et al. 1999), water retention characteristics (Rawls et al. 1982; Feddes et al. 1988; Wagner et al. 1999; Western et al. 2002), hydraulic conductivity (Feddes et al. 1988; Western et al. 2002), and soil depth.

Our work focused on characterizing soil physical properties at the point of observation for a ground-based soil moisture observation network in North Carolina. The North Carolina Environment and Climate Observing Network (ECONet), maintained by the State Climate Office of North Carolina, currently has 37 stations operating on a continuous basis across North Carolina. Soil moisture data are collected at the 20-cm depth at each of these sites. Data collection at the first sites began as early as 1999, with new sites added periodically since that time. Based on research results in the literature, we assumed a priori that characterization of soil properties could support improvement of data quality control and network soil moisture data products. However, because of the time and effort required for such data collection as new observation locations come online and because guidance for where similar efforts are underway, it may be valuable to consider the necessary breadth in soil physical property datasets collected to support soil moisture networks.

Our purpose in this report is to provide the methodology used to gather the soil physical property dataset collected for the diverse soils of the North Carolina ECONet and to examine information provided within this dataset to aid similar future efforts. We see this data collection as a fundamental component of network development here and where similar networks are being developed. The approach used in this research was based on understanding the variation of soil properties among observation sites within a land area exceeding 126 000 km^2, rather than studying specific controls on soil moisture at individual locations or local variability in soil properties. Thus, our intent was not to develop an approach to predict or model soil hydrology; rather, we aim to provide soils information that can be used as a context to understand differences in soil moisture observations among sites.

The methods, analysis, and results presented here have several applications both to North Carolina and for other regions with heterogeneous soils where soil moisture monitoring and forecasting is valuable. In particular, the analysis presented here has implications for improved data quality control, immediate use for the development of value-added soil variables such as saturation index and plant available water, and the longer-term improvement of land surface models for analysis and forecasting.

2. Methods

a. Study area

The study area was the Piedmont and coastal plain regions of North Carolina, with a climate classified as humid subtropical. At the time of data collection for this study, there were 27 North Carolina ECONet stations within these two regions (Fig. 1). The landscape at individual stations varied according to local topography, but sites were generally positioned on locally level (<5% slope)

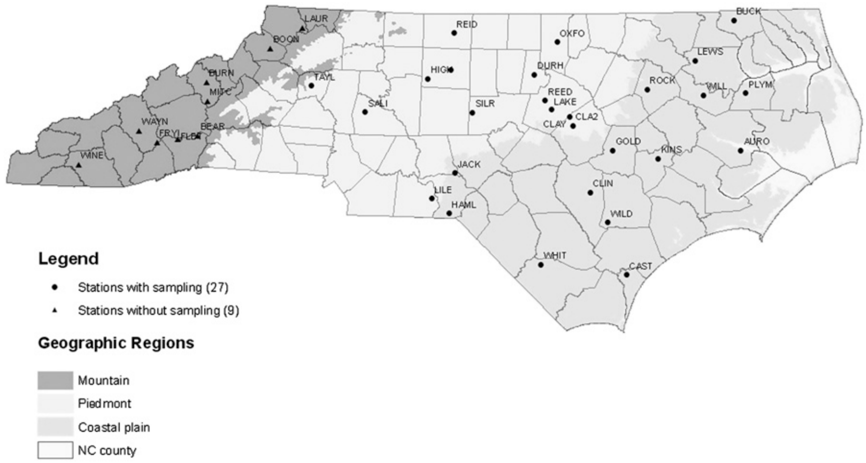

FIG. 1. North Carolina map with sampled and unsampled ECONet sites.

terrain. Land-use history at each site varied; most sites can be assumed to have been used for agriculture practices at least some time during the past hundred years. Current vegetation at each site is a mix of native and introduced grasses and weeds.

For each station, soil moisture data are collected at the 20-cm depth every 30 min, producing 48 observations per station per day. The soil moisture sensor currently installed for the North Carolina ECONet is the Theta Probe ML2X (Delta-T Devices, Cambridge, United Kingdom), which determines soil moisture indirectly based on soil dielectric properties. The volume measured by the sensor is approximately 75 cm^3 (Kaleita et al. 2005). The sensor installation depth and approximate observation volume were used to guide the soil sampling protocol for determining soil properties. We note that sensor calibration is important for collection of high-quality soil moisture data. Our focus here is on soil property measurement rather than sensor calibration, which is discussed elsewhere (e.g., Kaleita et al. 2005; Cosh et al. 2005).

b. *Soil physical properties*

1) FIELD SAMPLING

Between February 2009 and May 2010, 27 stations were sampled (Fig. 1). Three intact soil cores were collected at each site (total cores = 81), as were additional bulk soil samples. Though it was not possible to sample at the exact location where sensors were installed, it was intended that the soil being collected have characteristics similar to the soil where the moisture sensor was installed. Sampling spots were randomly selected within a 3-m-radius circle centered at the approximate location of the sensor. Three 7.6-cm-length, 6.3-cm-diameter intact soil cores, centered at 20-cm soil depth, were collected as replicates at each site. Sampling was performed using an AMS soil sampler (AMS, Inc., American Falls, Idaho). A pilot hole, prepared with an 8.9-cm-diameter hand auger, was used to access the appropriate sampling depth. Upon retrieval, cores were sealed with caps to protect their integrity and immediately weighed in the field to determine field water content. Cores were then transported to the laboratory for determination of water retention, saturated hydraulic conductivity, and bulk density (discussed below). Loose soil samples were also collected simultaneously at the 20-cm depth for soil textural analysis.

2) LABORATORY ANALYSES

Intact soil cores were used to determine saturated hydraulic conductivity values (Ks) by the constant-head method as described in Klute (1986). One end of the cylinder was covered with cheesecloth and placed in a water bath until completely saturated from the bottom. Thereafter, cores were moved to a stand for measurement, and downward flow was maintained under a constant hydraulic head of around 4.2 cm. The falling head method (Klute 1986) was applied to soil cores that did not exhibit measureable flow with the constant-head measurement during a 4-h period.

After Ks measurements, water retention measurements at pressures of 10, 33, and 66 kPa (P10, P33, and P66, respectively) were performed (Klute 1986). Intact soil cores were removed to the pressure cell and set on a prewetted ceramic plate, which permitted raising the water level to the top of the core and saturating the entire sample. The excess water was removed by siphon before water retention measurements. Gas pressure was applied in steps, and the volume of outflow after equilibrium at each pressure step was recorded. At the final pressure step, the samples were weighed, oven dried at

TABLE 1. Descriptive statistics for soil physical properties at ECONet sites in the Piedmont and coastal plain regions.

Parameter	Mean	Median	Max	Min	Std dev	Skewness	Kurtosis	CV (%)
BD (Mg m^{-3})	1.42	1.43	1.69	1.10	0.17	−0.76	−1.03	12
TP (m^{-3} m^{-3})	0.46	0.46	0.59	0.36	0.06	0.73	−1.01	13
Ks (cm h^{-1})	0.65	0.70	1.15	−0.32	0.33	1.82	0.36	47
Clay (%)	15	11	53	2	12	3.43	2.69	80
Sand (%)	63	64	90	24	17	−0.67	−0.64	27
Silt (%)	22	16	49	4	13	1.61	−0.61	59
AD (m^3 m^{-3})	0.02	0.02	0.07	0.01	0.01	4.11	5.84	50
P33 (m^3 m^{-3})	0.28	0.29	0.50	0.13	0.09	0.35	−0.23	31
P1500 (m^3 m^{-3})	0.10	0.09	0.19	0.04	0.04	1.26	−0.93	44
PAW (m^3 m^{-3})	0.18	0.19	0.33	0.07	0.06	−0.86	−0.91	32

105°C for 24 h, and reweighed. Total porosity (TP) and BD were calculated from the dry weight and sample volume of the intact sample, assuming the particle density was 2.65 g cm^{-3}.

Water retention measurements at 100-, 500-, and 1500-kPa pressure (P100, P500, and P1500, respectively) were determined with disturbed samples following procedures similar to those described by Klute (1986). The disturbed samples were air dried, ground, and passed through a 2-mm sieve prior to analysis. An additional parameter, air-dried water content (AD), was measured by allowing saturated, disturbed soil samples to dry to a constant weight under constant temperature and humidity (approximately 22°C and 30%, respectively).

Particle size distribution was determined by sedimentation using the hydrometer method (Klute 1986). Hydrometer readings were made at 0.5, 1.5, 360, and 960 min to determine the percentage of sand, silt, and clay.

3) STATISTICAL METHODS

Parameter values for the three replicate cores at each site were arithmetically averaged to obtain a single value for each parameter. Based on analyses, a soil properties dataset including 13 parameters (sand, silt, clay, BD, TP, Ks, P10, P33, P66, P100, P500, P1500, and AD) for each of 27 ECONet station was generated. Soil organic matter content is sometimes considered an important parameter for soil moisture behavior (Gupta and Larson 1979) but is not included in the present work because soils at the studied sites contained a small organic matter fraction (<2%). Parameters were analyzed using classical statistical methods to obtain the minimum, maximum, mean, median, standard deviation, and coefficient of variation (CV). A skewness–kurtosis test was performed to test normality of the dataset. Parameters that failed the normality test were log transformed to a normal distribution (Tabachnick and Findell 1996).

Eleven of the 13 parameters (excluding TP and silt content) were ultimately chosen for principal component (PC) analysis (PCA). Porosity and silt content were excluded because they were derived from BD and total content of sand and clay, respectively, and were therefore directly related to other subsets of parameters. The data were normalized to an average of zero and variance of one, and a correlation analysis was performed via a correlation matrix. The PCA [including a Kaiser–Meyer–Olkin (KMO) test measuring sampling adequacy] was then used to assess the overlap of individual parameters and collapse correlated parameters into a smaller subset of uncorrelated parameters. All statistical analyses were performed using SPSS V. 17.0 (SPSS, Inc., Chicago, Illinois).

3. Results and discussion

a. Characteristics of soil properties

It is necessary to recognize that there is natural variation among sampling locations at each station site, which may limit representativeness of individual samples for describing the soil properties at the actual sensor location (Scott et al. 2010). For example, in the present dataset the CV for Ks among the three replicates collected at a given site typically exceeded 50%. The rest of the parameters, however, were relatively consistent (CVs < 5%; data not shown) among the three replicates at each site. Limited local variation in soils data obtained from small soil cores collected within a spatially confined area has also been reported by others using similar approaches (Basara and Crawford 2000) or on similar soils (Cassel 1983). Because variation among individual parameters was small for most parameters, we focus the remaining discussion on comparison of mean properties from site to site rather than local variation at a given site. The full dataset for parameters measured at each site is provided in Pan (2010).

Descriptive statistics of soil physical properties among the 27 ECONet stations are shown in Table 1. Based on the skewness and kurtosis, most of the variables (excluding AD and clay) can be described as having a normal distribution. Clay and AD required transformation, since both of their skewness and kurtosis values were >2 (Field 2005). The texture distribution (i.e., combination of sand, silt, and clay) of sampling sites is shown within a texture triangle in Fig. 2. The soil texture at ECONet sites was distributed within seven classifications, with most points falling within the four classifications: loam, sandy clay loam, sandy loam, and loamy sand. Texture points clustered in the area with sand percentage greater than 40% and clay percentage less than 40%. The relatively higher CV (80%) for clay content (Table 1) could be explained by noting that one station had observed clay content of 55% while all other stations had clay content < 40% (Fig. 2). The reason for a CV of 50% in AD may be related to the variability in clay content since air-dried water content may be highly dependent on the content and mineralogy of the clay fraction (Sumner and Kamprath 2000). Field capacity and wilting point, corresponding approximately to P33 and P1500, are two commonly used reference points for soil moisture observations. There were wide ranges for both of these parameters among the 27 stations; P33 ranged from 0.13 to 0.50 $m^3\ m^{-3}$ and P1500 ranged from 0.04 to 0.19 $m^3\ m^{-3}$. Plant available water (PAW) capacity, estimated here as the difference between P33 and P1500 (Ritchie et al. 1999), was also characterized by a wide range of values from 0.07 to 0.33 $m^3\ m^{-3}$ (Table 1).

Results from simple statistical analysis clearly indicate that most soil physical properties varied substantially among the 27 studied ECONet stations. More importantly, the physical heterogeneity would be reflected in distinct hydraulic behavior. For example, the maximum possible soil moisture (i.e., TP) at sites within the network ranged from 0.36 to 0.59 $m^3\ m^{-3}$. While the CV of TP was relatively small (13%), the difference between the upper and lower end of this TP range would result in a very different interpretation for the same soil moisture observed at different sites. Relative differences at the dry end of the soil moisture range (e.g., P1500) were also substantial. The wide range in observed soil characteristics within the network illustrates the importance of collecting soil physical properties data for soil moisture monitoring in an expansive network such as North Carolina ECONet. Numerically equivalent soil moisture observations collected from two different sites can have very different meanings in terms of relative soil wetness. The difference in relative wetness has important implications for surface energy balance (i.e., evapotranspiration) and rainfall partitioning (i.e., runoff and infiltration), assessed from the soil moisture observations. Thus, this soil information is useful for quality control in terms of establishing reasonable bounds on soil moisture data

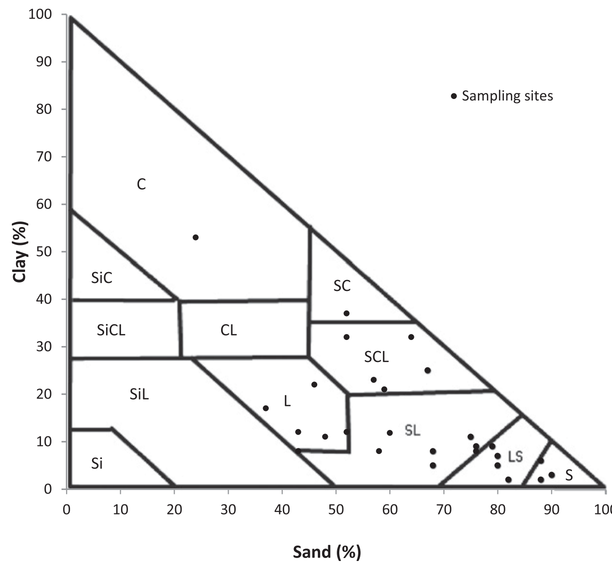

FIG. 2. Textural triangle with distribution of sampled ECONet site values. Texture classes are as defined by the USDA classification system.

observations and also enhances the potential for interpretation of soil moisture data (discussed further below).

b. *Correlations and parameter reduction for soil properties*

Beyond simply examining soil property values and distributions, as in the previous section, analysis of the correlation among parameters indicates which properties vary in a similar manner across sites. Parameter reduction can further inform interpretation about which subset of soil physical properties determines distinct soils differences between sites. With this in mind, we considered correlation and parameter reduction for soil properties in the present dataset to provide baseline information for interpretation of differences among ECONet sites. Alternately, the relationship between soil hydraulic characteristics and soil physical properties is often utilized in development of pedotransfer functions with an objective of quantifying water retention characteristics or hydraulic conductivity from more easily measured soil physical properties (Wösten et al. 2001). While this approach may have application for soil moisture modeling, here our objective was instead to broadly understand the correlation and variance of measured soil physical properties that may affect interpretation of soil moisture observations. In other words, our approach was not aimed at prediction; rather, it was aimed at identifying differences in soil properties potentially affecting soil moisture dynamics across ECONet sites.

The soil physical parameters we measured were generally correlated (Table 2), with a few exceptions. Bulk

TABLE 2. Correlation matrix (Pearson correlation coefficient r) of measured soil physical parameters for 27 North Carolina ECONet stations.

Parameter	BD	Ks	Clay	Sand	AD	P10	P33	P66	P100	P500	P1500
BD	1.00										
Ks	−0.25[a]	1.00									
Clay	0.30[b]	−0.29[a]	1.00								
Sand	−0.19[b]	0.30[a]	−0.72[c]	1.00							
AD	0.08[b]	0.11[b]	0.21[a]	−0.20[b]	1.00						
P10	−0.38[d]	−0.31[a]	0.36[d]	−0.50[c]	0.02[b]	1.00					
P33	0.24[b]	−0.42[d]	0.78[c]	−0.70[c]	0.12[b]	0.50[c]	1.00				
P66	0.22[b]	−0.41[d]	0.71[c]	−0.73[c]	0.10[b]	0.46[c]	0.96[c]	1.00			
P100	0.46[c]	−0.36[d]	0.78[c]	−0.68[c]	0.27[b]	0.24[b]	0.79[c]	0.78[c]	1.00		
P500	0.28[a]	−0.34[d]	0.82[c]	−0.70[c]	−0.02[b]	0.34[d]	0.73[c]	0.70[c]	0.82[c]	1.00	
P1500	0.27[a]	−0.36[d]	0.87[c]	−0.69[c]	0.11[b]	0.42[d]	0.83[c]	0.81[c]	0.85[c]	0.89[c]	1.00

[a] Significant at p (1 tailed) = 0.1.
[b] Nonsignificant.
[c] Significant at p (1 tailed) = 0.01.
[d] Significant at p (1 tailed) = 0.05.

density was only weakly or not correlated with most other parameters. The literature on the relationships between BD and other soil physical properties is not very conclusive. For example, Manrique and Jones (1991) noted that the nature of the relationship between bulk density and clay content was different among soil types, and Williams (1970) found that the relationship between bulk density and soil texture was dependent on land use and management. Considering that ECONet sites are located in different land parcels with variable soil type and historical land use, these prior observations are compatible with our observation of the weak relation between BD and most other measured soil physical properties in the dataset.

Water retention parameters were positively correlated to clay content, with the strength of the correlation increasing at the highest pressures (e.g., P1500). This is as expected since the amount of water held at 1500 kPa and greater pressure is primarily a function of soil texture, especially clay content (Stewart and Howell 2003). The correlation for AD and clay content was not significant but, at very dry conditions, mineralogy, not just clay content, may also be important. The narrower range observed for AD also likely weakened the correlation.

Individual water retention parameters were highly correlated in most cases, which is not surprising given that all represent a portion of the same pore-size distribution for a given soil. It may be noteworthy that P10 tended to be less strongly correlated with other water retention parameters or, in the case of P100, uncorrelated. The water content at this low pressure (10 kPa) may be more indicative of structurally dependent macroporosity than other measured pressures. The AD may also be viewed as a water retention parameter, but it was not correlated with the other water retention parameters. As indicated above, AD may be more closely related to mineral type (and possibly specific surface area or slight variations in organic matter content) than other water retention parameters.

There were two main exceptions to the positive correlation observed for most parameters. One was sand, which was negatively correlated with the other parameters, except Ks. The strong negative correlation ($P = 0.01$) between sand and clay content observed in our study is well recognized (Coffin and Lauenroth 1992; Kaiser et al. 1992; Rostagno 1989). The negative correlations between sand content and water retention parameters are consistent with the positive correlations between clay content and water retention parameters. Like sand, Ks was also negatively correlated with clay content and water retention parameters. Another exception was the negative correlation between BD and P10 ($P = 0.05$), which may be explained by the negative physical relationship between BD and soil porosity (i.e., void space) for retaining water at low pressures. Large soil pores tend to retain water at low pressure (P10), and large pores become uncommon in soils as the bulk density increases.

The dataset yielded a KMO statistic value of 0.778, indicating that the degree of variance among the tested parameters was greater than the accepted minimum of 0.7 to conduct a PCA (Pallant 2001). A significance value of <0.0001 for Bartlett's test of sphericity also reinforced that the parameters were suitable for a PCA (Pallant 2001). In PCA, latent roots and vectors of the correlation matrix were extracted to clarify relationships among the parameters. The characteristics of the first three PCs are listed in Table 3. The first PC accounted for 56% of the

TABLE 3. Eigenvalues and variance proportions of the first three components from the PCA. The three PCs were reduced from soil physical properties dataset collected from 27 ECONet stations. The dataset contains 11 soil physical properties for each station: BD, saturated hydraulic conductivity, clay content, sand content, AD, and water contents at −10, −33, −66, −100, −500, and −1500 kPa.

Component	Eigenvalue	Proportion of variance (%)	Cumulative proportion of variance (%)
1	6	56	56
2	1	13	70
3	1	10	80

TABLE 4. Nonrotated factor pattern matrix for the first three PCs. Weight values were multiplied by 100 and rounded to the nearest integer.

	Component		
	1	2	3
Parameter	Weights		
BD	33	84	−23
Ks	−47	7	56
Clay	89	8	12
Sand	−82	12	−15
AD	17	22	85
P10	49	−78	6
P33	92	−9	−1
P66	90	−9	−3
P100	90	26	8
P500	88	5	−10
P1500	93	1	0

variance, whereas the second and the third PCs account for only an additional 13% and 10%, respectively. This confirmed the results of the above correlation analysis that all the variables were generally strongly correlated as the first three PCs explained 80% of the total variance.

In Table 4, the first three PCs are reported with the relative weights of each standardized parameter. The parameters clay, sand, P33, P66, P100, P500, and P1500 appear to be closely related, loading on the first PC. Their similar loading suggests that, as described above, soil texture is closely related to soil water retention characteristics across the whole dataset. Bulk density and P10 were strong contributors to the second PC, but in opposed positions. Air-dried water content dominated the third PC; Ks also provided a much greater contribution to the third PC than did the other parameters.

Loading plots (Fig. 3) project the parameters from the correlation matrix onto the reduced factor space representing the main part (80%) of total data variance; thus, it is possible to visualize interrelations through the clustering of parameter points. If a variable is close to another, the variables are related to each other. Conversely, if a variable is distant from another, the relationship is weak or negative. The projections onto the axes indicate the relative contributions for the corresponding components (Norušis 1993). The loading plots delineate separate groups of highly intercorrelated or similar variables, allowing visual observations of all the variables and investigation of the physical meaning of components. Figure 3 shows that clay, P33, P66, P100, P500, and P1500 are very close to each other. This cluster of points represents the water retaining function of the soil. Parameter sand was distant from this cluster and negatively correlated ($P < 0.05$) with all the parameters composing it. The strong negative correlation could be explained by the fact that sand is unfavorable for water storage.

The general relationship between textural fraction clay and water retention is further demonstrated through the fit of a simple power model in Fig. 4. We note that previous studies of water retention parameter relationships to clay content have often incorporated multiple linear regression (e.g., Gupta and Larson 1979); however, we chose a simple power model to demonstrate the relationship to clay content alone. Strong positive relationships with clay content were observed for both P33 and P1500, with R^2 of 0.66 and 0.81, respectively. Another common parameter of interest for soil moisture observation is PAW (Table 1), which can be represented as the vertical distance between the two curves in Fig. 4. The general trend for PAW is apparent because it increased with clay content for these sites; however, the fitted power model relationship was relatively weak ($R^2 = 0.18$; not shown).

Bulk density, AD, P10, and Ks were clearly separated from the cluster of points in the loading plots of Fig. 3. Bulk density was the primary factor of the second PC, while AD was the primary factor of the third PC. As for physical meanings, BD (via its relationship to TP) and AD may be representative of the maximum and minimum limits of water content in the soil, respectively. While a water content substantially below that observed at P1500 (e.g., corresponding to AD) may not be likely in the subsurface soil, the AD parameter may be of greater importance when considering near surface soil moisture content for soil exposed directly to atmospheric drying. When it is not feasible to measure all soil parameters, the analysis of BD and AD along with soil texture could be an option. These parameters could reveal the inherent locational differences in soil physical properties at soil moisture monitoring sites, thus aiding data interpretation without the added costs of water retention measurements.

Overall, the correlation of parameters and the clustering revealed by PCA suggests that sites could be

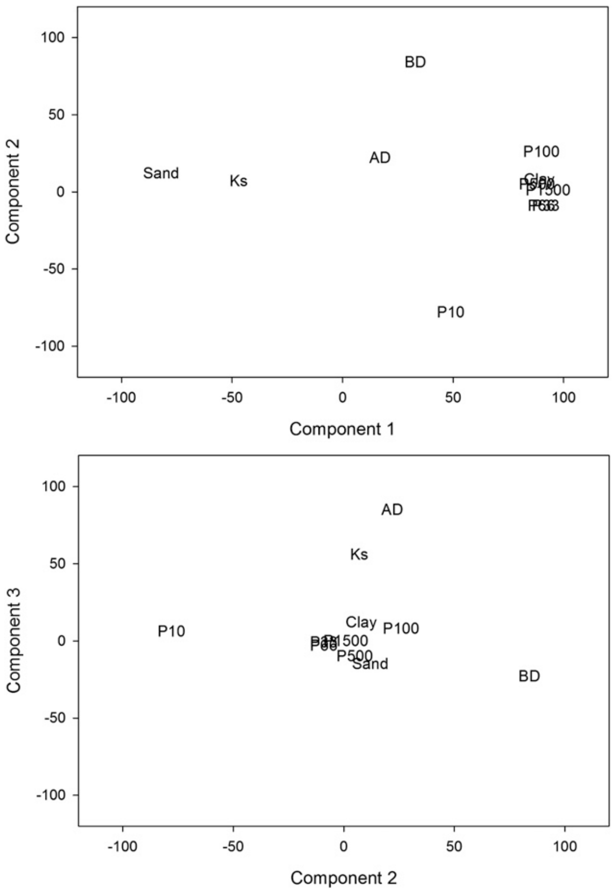

FIG. 3. Two-dimensional loading plots of the weights of the first three PCs in reduced factor space. Parameter labels indicate coordinates within the plots. Parameters are defined in the text.

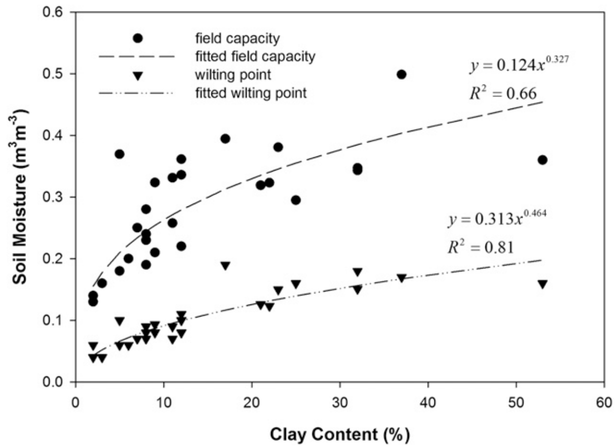

FIG. 4. Field capacity and wilting point relationships to clay content. The equations for the fitted lines are given next to the lines. The vertical distance between the lines represents PAW.

separated into groups according to a few specific soils properties, with texture being among these. This has important implications for interpretation of soil moisture observations, as it suggests that textural information, potentially available from sources such as Soil Survey, provides a primary context for initial separation of sites according to soils characteristics within this network. This result needs to be considered further in additional work and would also depend greatly on the purposes for which soils information is being used.

c. *Application of soil physical property data for interpretation of soil moisture observations*

The soil physical property dataset described above is currently being utilized to develop additional soil moisture products and quality control measures for North Carolina ECONet data. As a basic example for how these data might be used for quality control, we consider the measured total porosity of the soils. By definition, TP represents the upper limit of moisture storage in the soil (i.e., the volume of nonsolid space) and therefore provides an upper boundary for plausible soil moisture observations in nonexpansive soils. We used TP measured from each of the 27 North Carolina ECONet sites in the Piedmont and coastal plain regions as a screening parameter for daily mean soil moisture observations collected since site establishment. Record length varied by site, but there was an average record length of 8 yr from the 27 sites, encompassing 198 site years and >72 000 daily soil moisture observations. Based on a simple screening of the data, we identified seven sites in the historical record that had 5% or more of daily soil moisture observations exceeding the measured TP. Further examination of these seven sites indicated significant improvement in the data record after a network sensor upgrade (i.e., replacement of earlier sensors with the currently used theta probe) was completed in 2003, with only two sites showing 5% or more exceedance of TP since that time. Recovery of historical data records that failed this screening may not be possible and testing the accuracy of sensors (i.e., calibration) likely requires more extensive field campaigns (e.g., Kaleita et al. 2005), but the measured soil physical property dataset provides an otherwise absent standard by which historical soil moisture data could be judged.

The soil physical property dataset is also being used to offer additional soil moisture products. Beyond soil volumetric water content, the North Carolina ECONet database now also provides a saturation index and plant available soil water as public products. The saturation index, a measure of soil water content relative to the soil pore volume (Hillel 2004), is computed as the observed water content divided by the measured TP for each site and varies between zero and one. The plant available water is an indicator of soil water stored at a range of tensions available to the plant (Hillel 2004). For North Carolina ECONet, plant available water is computed as the observed soil water content minus the soil water retained at 1500-kPa pressure (i.e., P1500). An upper threshold value is set at P33 minus P1500 and a lower threshold value is set at zero. Example data (soil moisture, saturation index, and plant available water) collected concurrently at three ECONet sites are shown in Fig. 5. We can see by simple comparison that, while soil moisture is consistently lower at one site (Clinton), plant available water there is often as high as or higher than the other compared sites. The saturation index for the same site indicates that, despite lower soil moisture content, relative wetness is generally as high as or higher than those observed at the other sites. These measures, saturation index and plant available water, provide examples of soil moisture cast within the context of soil properties at a given site and have interpretations beyond soil moisture content reported as a raw number. Capability to make such interpretations requires knowledge of soils information. Soils information allows soil moisture observations to be converted to useful information as well as data more directly suited for use in climate and hydrology models.

4. Summary and conclusions

Collection of soil property data at the location of soil moisture observations for in situ monitoring networks is a fundamental part of network development. These data provide key information for interpreting site differences and soil moisture observations and for data quality control. In this study, we determined soil physical properties at 27 North Carolina ECONet soil moisture monitoring stations in the Piedmont and coastal plain regions of North Carolina. Prior to this study and despite collection of soil moisture data for the past decade, few soils metadata existed to support the North Carolina ECONet. Soils at ECONet sites fell in seven textural classes. Porosities ranged from 0.36 to 0.59 $cm^3\ cm^{-3}$, indicating a relatively wide range of upper boundaries for soil water content. Significant variability was also found for other parameters, such as water contents at pressures representative of field capacity (P33) and wilting point (P1500). As these properties individually and cumulatively influence interpretation of soil moisture dynamics, it is beneficial to understand soil properties for each monitoring site as well as the potential range of characteristics across monitored sites within the network.

High correlations were found between many of the parameters studied. A PCA reduced 11 soil physical parameters into three PCs that explained 80% of the variability within the dataset. We interpreted the first PC to represent the soil water retaining function (closely related to soil texture). The second and third PCs, which were associated primarily with bulk density (and TP) and air-dried water content, respectively, represent the upper and lower boundaries for soil moisture content under field conditions. The PCA results suggest that soil texture, bulk density, and air-dried water content may be three of the most important physical properties to characterize because they accounted for much of the variance for soil physical properties considered here. Thus, it may not be necessary to test a large number of parameters in order to develop a baseline understanding of soil physical properties at a given location within the network.

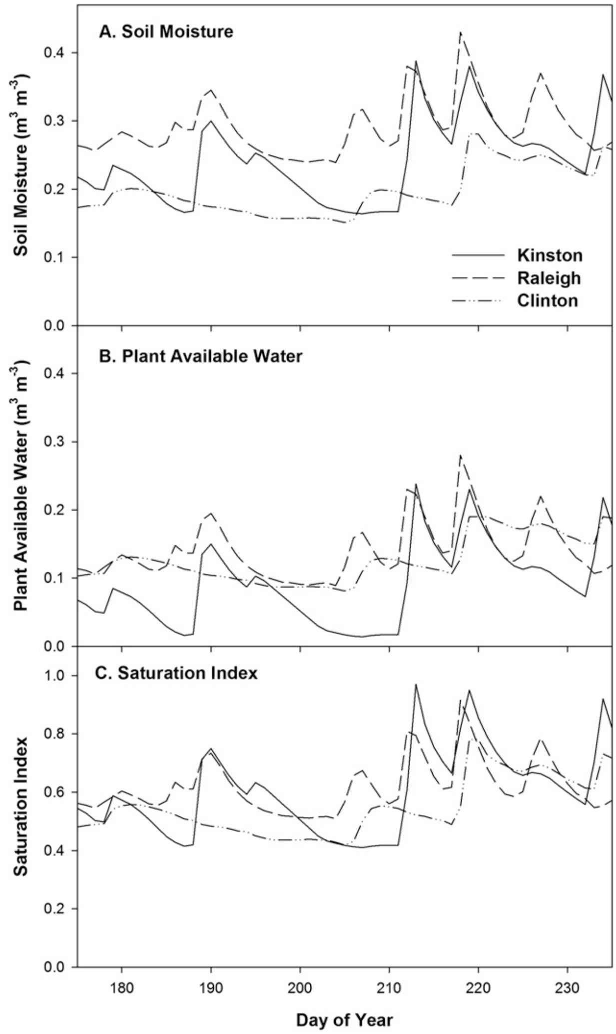

FIG. 5. Example (a) daily mean soil moisture, (b) plant available water, and (c) saturation index observations for three ECONet sites. Soil textures at the soil moisture observation depth are sandy clay loam, sandy clay loam, and sandy loam for Kinston, Raleigh, and Clinton, respectively.

Furthermore, depending on the purposes for which data will be utilized, available information on soil textures may provide a viable indicator of soils differences across sites.

We highly recommend including basic soil physical information in monitoring station metadata for similar regional networks. We expect that these data can be very helpful to evaluate soil moisture data quality on a physically realistic basis and/or for extending network products for additional applications. Information obtained in this study is currently being implemented into routine reporting procedures for the North Carolina ECONet. Specifically, soil moisture observations from the North Carolina ECONet are being modified to report more appropriate ranges of values based on the soil characteristics. In addition, more meaningful measures of soil moisture, including saturation index and plant available water, are now reported.

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