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Shrink–swell behavior of soil across a Vertisol catena

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SUMMARY

An accurate estimate of the degree of soil cracking is important in partitioning rainfall into soil infiltration and runoff in watersheds with clay soils that shrink and swell. Usually in the application of surface hydrology models, cracking is considered to be predicted by assuming equidimensional shrinkage and a 1:3 ratio of change in soil profile thickness to depth of water loss. Our objective was to use in situ measurements of soil profile subsidence with loss of water in an apparently uniform Vertisol to determine: (1) whether or not the soil profile subsidence followed the 1:3 ratio of change in thickness to depth of water loss and (2) how the ratio of subsidence to water loss varies with the Coefficient of Linear Extensibility (COLE). The research was conducted on a catena of Houston Black and Heiden clays. Vertical soil shrinkage and swelling along with soil water content were measured at the summit, shoulder, backslope, and footslope positions of the catena. Change in soil water content along with spatial variability in COLE were the primary drivers of temporal and spatial variability of shrinkage and swelling on the catena. The rate that soil shrank or swelled with change in the amount of water stored in the soil was related to COLE, which was negatively correlated with carbonate content of the soil. Shrinkage of the soil profile with water lost was less than the commonly used 1:3 ratio. Our data supported using COLE to predict the degree to which the ratio is less than 1:3. Incorporating COLE values into a hydrology model to simulate soil shrinkage with water loss is a useful approach because COLE values have been measured for soils with shrink–swell potential and that data is available in USDA NRCS Soil Survey databases.

1. Introduction

The variable capacity of desiccation cracks for precipitation is a major cause of poor agreement between predicted and observed amounts of runoff in watersheds with clayey soils that shrink and swell (Harmel et al., 2006; Lindenmaier et al., 2006). In such watersheds, the opening and closing of cracks in any given area should depend on the temporal dynamics of soil water content within the soil profile and the potential of the soil profile to shrink or swell with change in water content (e.g., Baer and Anderson, 1997; Olsen and Haugen, 1998; Chertkov, 2007). Consequently, this is the general manner in which shrink–swell has been addressed in surface hydrology models that attempt to track the degree of soil cracking (e.g., Arnold et al., 2005; Lepore et al., 2009). In such models, temporal dynamics of water in the soil profile can be simulated with knowledge of water storage capacity of the soil, amounts of water added through rainfall or irrigation, rates of evapotranspiration, and subsurface fluxes of water. Water storage capacity of the soil profile is often estimated from measurement of water contents at given matric water potentials, commonly the water content at −33 kPa matric water potential which is considered to be field capacity. Shrink–swell potential of soil is either garnered from laboratory measured shrinkage characteristic curves, simplified shrinkage measures such as the Coefficient of Linear Extensibility (COLE), or from correlations with other known soil properties, such as clay content.

COLE and the water content at −33 kPa matric water potential are part of pedon measurements published by the USDA NRCS Soil Survey (Soil Survey Staff, 2003) and are attractive data for modeling because they can be used to characterize shrink–swell soils in hydrologic subunits. The value of COLE expresses the magnitude of change in a length scale of the natural soil matrix between water contents associated with −33 kPa matric water potential and the oven dry (105 °C) state, relative to the length scale of the oven dry state (Grossman et al., 1968). For water contents less than that associated with −33 kPa matric water potential, a layer of soil that exhibits equidimensional shrinkage and the profile settles vertically during shrinkage should have a thickness, relative to its thickness at −33 kPa matric water potential, that falls between values of

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1 and 1/(1+COLE). The areal density of crack volume ($m^3\ m^{-2}$) that could be generated per unit layer thickness of that same soil should fall between 0 and (1/(1+COLE))(1-(1/(1+COLE))^2). The areal density of crack volume is presumably near in magnitude to the capacity of cracks for holding water, an estimate needed to partition rainfall into infiltration and runoff.

The use of the water content at −33 kPa matric water potential and COLE instead of more elaborate indicators of water holding capacity and shrink–swell potential (Thomas et al., 2000; Kariuki and van der Meer, 2004) in modeling, simplifies representation of the mechanistic shrink–swell processes. First, the laboratory-determined water content associated with −33 kPa matric water potential would be used as the starting point for cracking as soil dries under field conditions. This assumption ignores a structural shrinkage phase and may be inappropriate for a soil where that phase covers an appreciable range of water content, i.e., if the water content at saturation were appreciably larger than at −33 kPa matric water potential. Second, the value of COLE provides no information about the rate of change in volume of soil with change in volume of water loss from field capacity to oven dryness – it just defines the endpoints. For soils that express equidimensional shrinkage and swelling and are rated as having a very high shrink–swell potential, the maximum rate of change in thickness with water lost is generally assumed to be near 1/3 m m^{-1} over the range of soil water content typically seen under field conditions (Aitchenson and Holmes, 1953; Yule and Ritchie, 1980; Kirby et al., 2003; Arnold et al., 2005). The corresponding rate of change in areal density of vertical crack volume with depth of water lost is 2/3 m m^{-1}. That is to say, it is assumed that under most field conditions, the residual shrinkage phase is not reached on drying and the change in volume of soil on drying equals the change in volume of water lost. Obviously, the rates would be 0 when COLE = 0 and the soil does not shrink on drying so estimating crack formation by assuming shrinkage based on the 2:3 ratio for all shrinking soils may leave a good deal of uncertainty in simulating the temporary storage of rainfall by soil cracks.

Jayawardane and Greacen (1987) showed that for soils with moderate shrink–swell potential rate of change in thickness with water lost were midway between 1/3 and 0, but gave no data indicating the COLE of the soil from which the data were collected. Our objective was to measure subsidence of soil profiles with loss of water in an apparently uniform Vertisol to determine: (1) whether or not the soil profile subsidence followed the 1:3 ratio of change in thickness to depth of water loss and (2) how the ratio of subsidence to water loss varies with COLE. If COLE can provide useful information about soil subsidence with water loss, it is also likely it can provide useful information for estimating the capacity for soil cracks to temporarily hold rainfall.

2. Materials and methods

2.1. Study area and location of measurement sites

The research was conducted in a 7 ha Coastal Bermudagrass (*Cynodon dactylon*) pasture at the USDA-ARS Grassland, Soil and Water Research Laboratory near Riesel, Texas (96.88°W, 31.47°N). The climate at the location is subtropical humid with a 70-year mean annual rainfall of 910 mm (Harmel et al., 2003) and annual temperature of 19.5 °C (Potter, 2006). The soil in the pasture is composed of Houston Black and Heiden clays, both fine, smectitic, thermic Udic Haplusterts (Soil Survey Staff, 2003). The two Vertisols were formed from weakly consolidated calcareous clays and marls (Allen et al., 2005) and when mapped they are mainly distinguished by depth to parent material, Heiden having the shallower depth. The elevation of the pasture's catena ranges from 145 m above sea level at the summit to 133 m at the footslope (Fig. 1). The pasture occupies about one quarter area of the Y2 subwatershed that is instrumented with rain gauges and a weir

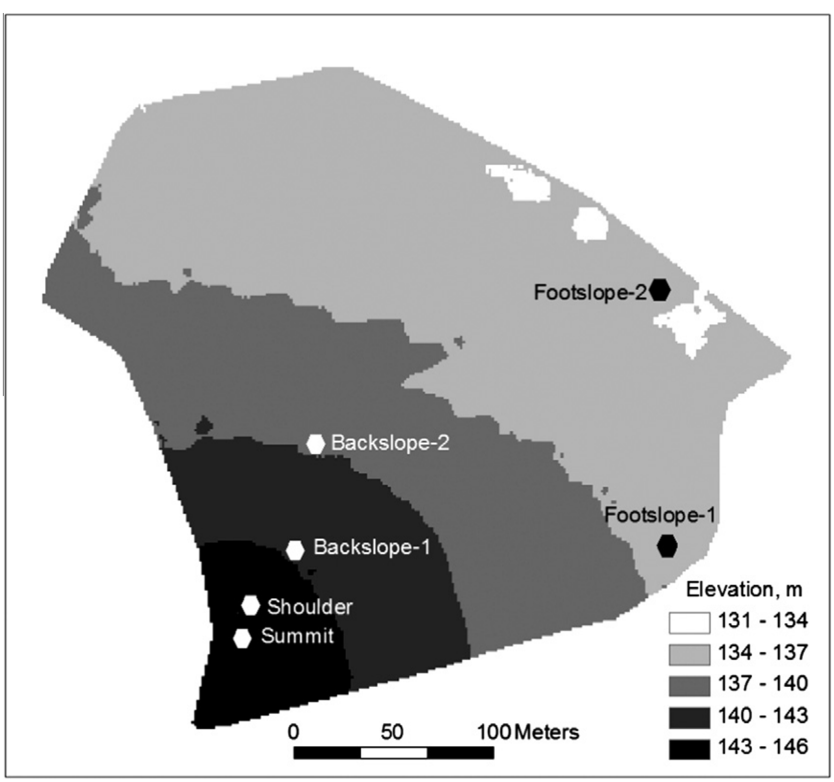

Fig. 1. Topographic map of the study area showing locations of the measurement sites at the different landscape positions.