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Relationships of soil shrinkage parameters and indices with intrinsic soil properties and environmental variables in calcareous soils

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ABSTRACT

This study was conducted to derive the relationships of soil shrinkage parameters and indices with soil and environmental variables in calcareous soils. Ninety nine undisturbed clods were collected from surface soils in hilly regions of Cherlgerd, western Iran. Soil shrinkage curve was measured based on *Archimedes*' principle, by covering the clods with an acrylic resin. The shrinkage curve data were modeled using Peng and Horn (2005) model. The model's fitting parameters and several shrinkage indices (i.e. relative void ratio changes, mean slopes at various shrinkage zones, coefficient of linear extensibility, and total and relative shrinkage capacities) were predicted using multiple linear regression models by including soil properties (pedotransfer functions, PTFs) and by combination of soil properties and environmental variables (soil spatial prediction functions, SSPFs) as inputs. The results showed that, on average, the structural, proportional, residual and zero shrinkage zones comprised 17.2, 66.2, 15.2 and 1.4% of total shrinkage for the studied soils. The shrinkage capacity (ShC) and relative shrinkage capacity ($\Delta e_{\text{total-rel}}$) varied, respectively, in the ranges 0.204–0.641 and 0.288–0.589 in the studied soils. While clay fraction increased the ShC and $\Delta e_{\text{total-rel}}$, organic matter had a diminishing effect on the $\Delta e_{\text{total-rel}}$. An extended structural zone was observed in fine-textured soils, presumably due to greater aggregation. Volume change in the structural shrinkage zone was greater in weakly-structured calcareous soils because carbonates would minimize resistance of aggregates against the shrinkage forces. PTFs could explain 12–48% of variability of the model's parameters, and the inclusion of topographic attributes (i.e. SSPFs) significantly increased R^2 values. Developed PTFs could explain 11–41% of variability of the shrinkage indices. The particle size fractions and relative bulk density were identified as most important soil properties for the prediction of shrinkage indices. Overall, the use of SSPFs by including topographic attributes such as dispersal area, elevation, surface curvature and plan curvature and normalized difference vegetation index (NDVI) could improve the performance of the prediction functions for soil shrinkage indices.

1. Introduction

Soils with swelling clays are usually formed in arid and semiarid regions with large seasonal variation in moisture and rainfall. Buildings and highways constructed on such soils are subjected to periodic swelling and shrinkage cycles (Basma et al., 1996). Agricultural uses and cultivation of such soils would also require proper management (USDA and NRCS, 1999). Soil shrinkage properties have been extensively used to quantify soil structure and functions. The shrinkage and swelling of a soil matrix is associated with vertical movement and cracking, which would in turn affect not only soil structure and hydraulic properties at the clod scale (Kay, 1998), but also preferential water flow at the soil horizon/profile scale (Coppola et al., 2008). Therefore, knowledge of dynamic soil shrinkage processes is essential for the prediction of water and solute transport processes, especially in swelling soils (Garnier et al., 1997).

Soil shrinkage curve (SSC) plots changes in soil volume against soil water content. The SSC can be measured by either discrete methods, e.g. Saran resin coating (Brasher et al., 1966), or quasi-continuous methods, as proposed by Braudeau and Boivin (1995), and Braudeau et al. (1999). SSC analysis of undisturbed soil samples has recently facilitated the characterization of soil structure and pore space (Peng et al., 2005; Boivin et al., 2006a, b; Schäffer et al., 2008; Boivin et al., 2009; Fontana et al., 2015). SSC modeling (Braudeau et al., 1999, 2004; Chertkov et al., 2004; Peng and Horn, 2005; Boivin et al., 2006a, b, 2009) quantifies plasma and structural pore volumes and air-filled porosity at defined water content (Boivin et al., 2006a, b, 2009). SSC, particularly when determined by the quasi-continuous method, has several advantages over other approaches to the measurement of soil physical properties. In fact, physical parameters calculated by the SSC show lower variability in comparison with other physical properties such as hydraulic conductivity and water retention functions (Boivin, 2007). Shrinkage characteristics allow calculation of hydro-structural stability,

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i.e. the ability of soil structure to resist drying stresses, based on the slopes of different domains of the SSC (Braudeau and Bruand, 1993; Braudeau and Boivin, 1995; Schäffer et al., 2008).

SSC of structured soils is generally sigmoidal (e.g. Braudeau et al., 1999; Schäffer et al., 2008). Four distinct shrinkage zones, namely structural, proportional (normal), residual, and zero shrinkage, can be recognized on the SSC. These zones range between saturation and complete dryness, and specify various structural rigidities of soils upon drying (Braudeau et al., 1999; Peng and Horn, 2005, 2007). The structural zone involves the part from saturation to the macropore shrinkage limit (Braudeau et al., 2004). The proportional zone ranges from the macropore shrinkage limit to the air entry point into the soil matrix (Groenevelt and Grant, 2001). At this zone, the reduction in soil volume is proportional to the reduction in water volume (McGarry and Malafant, 1987). Zero shrinkage is defined from the shrinkage limit to the dry endpoint, where the soil volume remains approximately constant although water is completely lost from the soil (Peng and Horn, 2007). Proportional shrinkage is believed to be promoted by clay content and the nature of the clays. Structural shrinkage depends on aggregation and its factors, mainly organic matter (OM) (Boivin et al., 2004, 2009; Peng and Horn, 2007, 2013; Schäffer et al., 2008; Fontana et al., 2015).

Some approaches to SSC modeling (e.g. Braudeau et al., 1999; Chertkov, 2003) are based on the identification of different intra-aggregate and inter-aggregate pore systems (i.e. micro ≅ plasma ≅ textural ≅ clay paste and structural systems, respectively). Such approaches are built on deterministic assumptions about the behavior of these pore systems. Other approaches (e.g. Peng and Horn, 2005) attempt to perform SSC modeling with limited number of parameters. These models aim to broadly mimic the SSC, although not mainly to quantify the soil structural properties. Several mathematical models have been developed to quantify the SSC (McGarry and Malafant, 1987; Chertkov, 2003; Peng and Horn, 2005, 2007). Peng and Horn (2005) classified the soil shrinkage models into three categories: i) SSC models without the structural shrinkage zone (e.g. Chertkov, 2003), ii) SSC models without the zero shrinkage zone (McGarry and Malafant, 1987), and iii) SSC models considering all four zones (Tariq and Durnford, 1993; Braudeau et al., 1999; Groenevelt and Grant, 2001). Braudeau et al. (1999) proposed an exponential (XP) model based on conceptual assumptions about the relationships between soil structure and shrinkage. This model assumes that soil shrinkage is the summation of the shrinkage of two pore volumes, i.e. the intra-aggregate (micropore) and the inter-aggregates pore (macropore) volumes (Boivin et al., 2006a, b). Peng and Horn (2005) developed a continuous sigmoidal model based on the well-known van Genuchten (1980) model for soil water retention curve. While this model considers fewer parameters compared to previous shrinkage models, it is capable of describing the above-mentioned four shrinkage zones for a wide range of soil types. Although the model has been found to fit very well with the measured data (Peng and Horn, 2005; Peng and Horn, 2007; Rasa et al., 2009; Peng et al., 2012), Boivin et al. (2006a) showed that the XP model better fits the SSC data than Peng and Horn (2005) model. They indicated that Peng and Horn (2005) model was a poorly fitting model at the wet end of the SSCs and justified this finding by the mathematical structure of the model and overlapped effects of the model parameters.

Determination of SSC and soil shrinkage indices using discrete methods (e.g. resin method) is difficult and time-consuming. Meanwhile, indirect prediction methods such as pedotransfer functions (PTFs) and soil spatial prediction functions (SSPFs) are useful to predict sparsely available data from readily available data including soil texture and organic matter (in the case of PTFs), and environmental data, such as topographic and remotely sensed data (in the case of SSPFs), at watershed scale (Bouma, 1989; Lagacherie and McBratney, 2006). A large body of literature has applied conventional statistical techniques to develop empirical equations for the prediction of hardly-available data from soil properties in different regions and/or countries. Apparently, the prediction methods were site-specific and could not be generalized for other geographical regions with different climatic and soil attributes.

Studies on the relationships between soil constituents and SSC were generally performed at the field or local scale (except cases such as Boivin et al., 2004), and focused on a few (or even one) soil types. Mbonimpa et al. (2006a, b) combined the existing statistical models with the modified Kovacs model to predict the water retention curve and volumetric shrinkage curve using basic geotechnical properties as predictors. Despite the relatively high shrinkage and swelling capacity of calcareous soils, little information is available about their shrinkage behavior, its determinants and prediction methods at the landscape scale in arid and semiarid environments. Considering the significance of such information to effective soil management for agricultural and engineering purposes, the present study was conducted: i) to parameterize the soil shrinkage curves using Peng and Horn (2005) model and selected shrinkage indices, ii) to explore the relationships of model parameters and shrinkage indices with soil intrinsic properties, and iii) to develop PTFs and SSPFs for the prediction of model parameters and shrinkage indices using soil and environmental variables at the landscape scale, in in calcareous soils of western Iran.

2. Materials and methods

2.1. Description of the study area

This study was conducted in hilly calcareous regions on the uplands of Koohrang region of Cherlgerd watershed located in Chaharmahal-va-Bakhtiari province, western Iran (Fig. 1). The study area is located within 50° 5′ to 50° 28′ E longitudes and 32° 13′ to 32°35′ N altitudes, with an area of approximately 370 km^2. The Zagros Mountains are the largest mountain range in Iran. With a total length of 1500 km, from northwestern Iran, and roughly following Iran's western border, the Zagros range spans the whole length of the western and southwestern Iranian plateau. Koohrang region is an important basin located in central Zagros (Kelishadi et al., 2014). The mean elevation of the study area is 2360 m a.s.l. The mean annual precipitation and temperature at the site are 1440 mm and 9.4 °C, respectively. The monthly mean air temperature varies from a high of 22 °C in July to a low of −5.1 °C in January. The average precipitation ranges from a maximum of 317 mm in March to a minimum of 1.1 mm in June, July, August and September, indicating cold − wet winters and warm − dry summers category according to Köppen climate classification (www.chaharmahalmet.ir).

The soils of the study area are mainly developed on Tertiary (Cretaceous) limestone and Oligo-Miocene deposits and classified as Entisols, Inceptisols and Vertisols after Soil Survey Staff (2010), throughout the study area (Mehnatkesh et al., 2013). Major land uses include grassland, dominantly covered by *Astragalus* sp. and *Bromus* sp, dryland farming and irrigated farming mainly based on cultivation of winter wheat (*Triticum aestivum*) and alfalfa (*Medicago sativa*), respectively (Kelishadi et al., 2014). Studied soils have a variety of clay minerals including chlorite, illite, kaolinite and montmorillonite (Zolfaghari et al., 2015).

2.2. Soil sampling and physical and chemical analyses

Undisturbed soil samples (clods) with volumes in the range of 50–100 cm^3 were collected from the 0–10 cm layer in 99 locations in September 2012 (Fig. 1). Our primary goal was to study the shrinkage behavior of surface soils, which is important in soil-related studies. In addition, substantial variation in the soil properties, such as texture, calcium carbonate equivalent (CCE) and organic matter content (OM), is expected for the surface soil (Mehnatkesh et al., 2013; Kelishadi et al., 2014; Zolfaghari et al., 2015). We tried to have a good scatter of the sampling points, representative of the study region, considering soil variability, different land uses and slope positions. Disturbed soil samples