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Effect of temperature on soil structural stability as characterized by high energy moisture characteristic method

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ABSTRACT

Temperature is a key factor that can affect soil properties and processes. Surface tension-viscous flow (STVF) theory is widely used to explain the temperature effects on soil hydraulic properties. We hypothesized that one of the reasons for deviation of measured soil water retention data from the STVF theory predictions is due to the temperature effects on soil structural stability (i.e., near-saturated pore size distribution [PSD]). Therefore, the objective of this study was to evaluate the effect of temperature on soil structural stability as characterized using the high energy moisture characteristic (HEMC) method in a wide range of arid and semi-arid soils of Iran. Aggregates of 28 soil samples were fast-wetted to mimic the natural conditions of soils during rainfall and irrigation. Four ambient temperatures (5, 10, 15 and 30 °C) were applied using an incubator during the wetting of aggregates, and after that HEMCs in the matric suction (h) range of 2 to 50 hPa were measured. Both van Genuchten (VG) and modified van Genuchten (MVG) models were fitted to the HEMC data and structural stability indices were calculated. The results generally showed that ambient temperature significantly altered soil PSD and structural stability, and as temperature increased: (i) an expansion of entrapped air initiated by the formation of microbubbles, was enhanced, (ii) water content at near full saturation $h = 2$ hPa (θ_{2hPa}) decreased, and at $h = 50$ hPa (θ_{50hPa}) it increased, leading to a reduction in the volume of drainable pores [VDP], and thus (iii) the soil structural index [SI] and slope at the inflection point of HEMC [S_i] decreased, and (iv) amount of macropores (h, 2–12 hPa) was markedly decreased, however, micropores (h, 12–50 hPa) were not notably affected or were increased at high temperature due to intensive shifting of macropores into micropores. These findings imply that soil structure was damaged due to loosening effects of high temperatures on inter-particles bonds and increased repulsive forces between clay particles. Cluster analysis showed that the effect of ambient temperature on the structural stability was greatest in carbonate-rich soils with low clay and organic carbon (OC) contents and was least in the soils rich in OC. The results of this study could be important for projecting the effect of global warming and climate change on soil structure and erosion.

1. Introduction

Soil structure is described by the arrangement of primary particles into secondary components, which are called aggregates. Structural stability is the capability of soil to hold solid and pore space architecture when exposed to external stresses (i.e., tillage, irrigation, cropping, compaction, climate, etc.). Structure is a key property of soils which can affect different processes (i.e., water retention, infiltration, runoff generation, and soil erosion) in the soil and environment and largely used to evaluate soil quality and susceptibility to runoff and erosion (Dexter, 1988; Amezketa, 1999; Barthès and Roose, 2002; Mamedov and Levy, 2013).

Temperature is a key factor in the context of climate that may affect soil functioning and physical quality. The effect of temperature on soil hydraulic conductivity, infiltration (Constantz, 1982; Levy et al., 1989), water retention (Romero et al., 2001; Bachmann et al., 2002; Jacinto et al., 2009), and runoff and erosion (Ariathurai and Arulanandan, 1978; Ronan et al., 1998; Sachs and Pariente, 2017) have been reported in numerous studies, although many complexities and ambiguities in the interpretation of data still remain. Surface tension-viscous flow theory (STVF theory) is widely used as an acceptable concept to explain the temperature effects on soil hydraulic properties. The response of soil hydraulic properties to the variation of temperature due soil surface modifications can be explained by change in surface tension and

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viscosity of water in this theory (Philip and de Vries, 1957). However, the results of Jacinto et al. (2009) showed that the soil water retention capacity decreased with temperature, greater than that predicted by the change in surface tension, especially at high temperatures and low matric suctions. Experimental data by Haridasan and Jensen (1972), She and Sleep (1998) and Bachmann et al. (2002) revealed that decrease in matric suction due to an increase in temperature was considerably greater than the rate which is predicted using the STVF theory of Philip and de Vries (1957). Grant and Bachmann (2002) proposed four mechnisms to explain greater dependency of matric suction to temperature than that predicted by Philip and de Vries (1957) theory as follows: 1) increases of entrapped-air with an increase in temperature, 2) water expansion due to an increase in temperature, 3) the effect of temperature-mediated solute concentration on surface tension of the soil water, and 4) the sensitivity of soil-water contact angle to temperature. Although these mechanisms were closely linked to the effect of temperature on soil hydraulic properties, they could not completely explain the results associated with intricate interaction of soil properties and conditions (e.g., Gao and Shao, 2015).

Climate parameters might considerably affect structural condition and aggregate stability of soils from semi-arid and arid regions. Romero et al. (2001) suggested that the mechanisms for the effect of temperature (in the range 22–80 °C) on water retention of Boom clay (with mixed clay mineralogy) are different for the two intra- and inter-aggregate pore spaces. The water held in the inter-aggregate pore space is controlled by the capillary forces. In this region, the effects of temperature are mainly associated with temperature dependence of surface tension and soil-water contact angle, thermal expansion of entrapped air, and dissolved air release upon heating or surface tension change caused by dilation of water. In the second region, water is held in the small pores inside the aggregates where the soil water retention characteristic would mainly depend on clay microstructure and water flow chemistry through the pores (Romero et al., 2001). van der Drift (1995) reported that the variation of temperature did not have significant effect on soil aggregate stability. However, Lavee et al. (1996) reported that seasonal dynamics of aggregate stability was controlled by soil temperature and moisture in arid and Mediterranean climate conditions. Dimoyiannis (2009) also found that rainfall and temperature are the dominant factors affecting seasonal variation of soil aggregate stability. Ambient temperature is also important in hydrology and soil erosion. In the experiment of Sachs and Pariente (2017), soil loss (e.g., erosion) increased from 5 to 18 $g\,m^{-2}$ with an increase in the temperature difference between rainfall and soil surface (i.e., with an increase in rainfall temperature from 20 to 35 °C). Authors concluded that thermophoresis due to thermal gradients in the soil solution decreased the stability of aggregates and hence increased the soil losses. Ariathurai and Arulanandan (1978) mentioned that increasing soil temperature might reduce the mutual attraction between clay particles, and as expected, the erosion rate would increase with increasing temperature while critical shear stress would decrease in a similar manner.

We hypothesized that (i) one of the reasons for deviation of measured soil water retention data from the predictions of Philip and de Vries (1957) theory is due to the temperature effects on soil structural stability (macroporosity), (ii) soil structure stability can be affected by an increase in entrapped-air and its expansion due to an increase in temperature, and (iii) changes in temperature would also affect the rate of wetting, and therefore, the temperature can indirectly affect aggregate stability as well. Increase in temperature might weaken the binding and cohesive forces between the particles and aggregates because temporal expansion coefficients would be different between the mineral particles and water, which can modify the pore (aggregate) geometry and size distribution. Moreover, entrapped air is believed to be responsible for the enhanced sensitivity to temperature of capillary pressure, and the volume of entrapped air increases with temperature, but they have not been supported by the experiment (Peck, 1960). According to the Young-Laplace equation, soil matric suction is dependent on soil-water contact angle, which would depend on temperature.

Several methods are available to measure aggregate stability but no unique method and/or procedure has been suggested yet for all soils (Le Bissonnais, 1996), since selection of the method and interpretation of the results would mostly depend on the aim of a study (Saygın et al., 2012; Pulido Moncada et al., 2015). High energy moisture characteristic (HEMC) method has been used for monitoring widely varying stability of soil structure, and adequately sensitive to distinguish small changes in aggregate and structure stability due to changes in soil properties, conditions and agricultural managements (Pierson and Mulla, 1989; Mamedov et al., 2010, 2014, 2017; Hosseini et al., 2015, 2017). In this method, the aggregate stability against precisely controlled wetting stresses is determined and its structural stability indices are related to pore size distribution (PSD). Dexter (2004) introduced the *S*-theory based on the conceptual relation between soil structure and PSD derived from the soil water characteristic curve. The slope of soil water characteristic curve at the inflection point [i.e., $S = d\theta/d(\ln h)$] was considered as an indicator of soil physical quality. Recently, Hosseini et al. (2015) adapted this theory for the HEMC method and introduced the slope of HEMC (in the h range of 0–50 hPa) at the inflection point ($S_i = d\theta/dh$) instead of S. The value of S_i represents the extent to which the aggregate porosity is concentrated into a narrow range of pore sizes. They found a positive and significant relationship between the stability indices of the original HEMC theory and the S_i, confirming the suitability of the new relative stability index (Hosseini et al., 2015).

To the best of our knowledge, no detailed quantitative investigation has been found in the literature about the effect of ambient temperature on soil structural stability. Therefore, the objective of this study was to quantitatively evaluate the effect of temperature on soil structural stability using the HEMC method in a wide range of semi-arid and arid region soils of Iran. The HEMC was also chosen to characterize the breakdown (e.g., slaking) of aggregates due to entrapped-air and hydration energy in temperature-dependent ways.

2. Materials and methods

2.1. Soil sampling and preparation

Soil samples with a vast range of physical and chemical properties were collected from the surface soils of 28 locations in Isfahan and Charamahal-va-Bakhtiari provinces, Iran, in August 2015. In each location, three soil samples from the same field were collected and mixed. The studied soils are mainly developed on carbonatic marl deposits of the Mesozoic Era, Cretaceous period (66–138 million years ago). The clay minerals of the studied soils are a mixture of smectites, kaolinite, illite, chlorite and vermiculite (Khademi and Mermut, 1998; Noruzi Fard et al., 2010). The major land uses are pasture, dryland and irrigated farming (Table 1).

Soil samples were carefully collected, air-dried and gently sieved to separate 0.5–1.0 mm intact aggregates for structural stability determination using the HEMC method. This size range of aggregates was separated because it was the predominant fraction ($>$ 50%) of macroaggregates in the soils. In the studied soils, the aggregates in the 0.5–1 mm fraction were on average 89% (in the range 100–63%) and sand particles in the 0.5–1 mm fraction are on average 11% (in the range 0–37%). Therefore, the aggregates were predominant in the 0.5–1 mm fraction in the studied soils. In fact for comparing the effect of treatments (e.g., temperature in our study) on soil structural stability indices, it is not possible and/or important to separate intact aggregates of a size range from the sand particles of the same size range for the HEMC test (Mamedov and Levy, 2013). Moreover, the stability of aggregates in a fraction (i.e., 0.5–1 mm) is compared because the sand particles are not notably affected by the treatments (e.g., temperature). This assumption is also valid in all of the studies using the HEMC