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Effects of land use on structure and hydraulic properties of Vertisols containing a sodic horizon in northern Ethiopia

I.A. Shabtai [a,b], M. Shenker [b], W.L. Edeto [c], A. Warburg [d], M. Ben-Hur [a,*]

[a] Institute of Soil, Water and Environmental Sciences, ARO, The Volcani Center, Bet-Dagan 50250, Israel
[b] Department of Soil and Water Sciences, The Robert H. Smith Faculty of Agriculture, Food and Environment, The Hebrew University of Jerusalem, Rehovot 76100, Israel
[c] Aklilu Lemma Institute of Pathobiology, Addis Ababa University, Addis Ababa, Ethiopia
[d] Department of Microbiology and Molecular Genetics, The Kuvin Centre for the Study of Infectious and Tropical Diseases, Institute for Medical Research Israel Canada, The Hebrew University of Jerusalem, Jerusalem 91120, Israel

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ABSTRACT

In recent decades significant clearing of native *Acacia seyal* and *Balanites aegyptiaca* savannah has preceded expansion of agricultural lands in the semiarid Sahel regions of northern Ethiopia. The main objective of this study was to determine the effects of changes in land uses on structure and saturated hydraulic conductivity (K_s) of a Vertisol under sodic conditions. Disturbed soil samples were taken from savannah-woodland landscape and from cultivated sorghum and sesame fields in the Humera region of Ethiopia, for determination of chemical properties, aggregate stability and K_s. Exchangeable sodium percentage (ESP) increased with soil depth, from ~2% in the 0–0.15 m layer to 8.1–10.6% in the 0.9–1.2 m layer. Swelling and dispersion was more pronounced in the subsoil (0.9–1.2 m) than in the topsoil of the three land uses, due to the higher ESP values of the former. In contrast, the topsoil was more sensitive to slaking forces than the subsoil, probably due to increased particle cohesion in the subsoil. This led to lower K_s values of the topsoils under fast than slow prewetting. The steady-state K_s values under slow prewetting and leaching with deionized water were significantly higher in the savannah-woodland soil than in the cultivated soils, down to 1.2 m depth. These differences in K_s values were associated with higher swelling values in the cultivated soils than in the savannah-woodland soil. The differences in the swelling values were manifested at the field scale, where the cracking in the cultivated soils was more intense than in the savannah soil. It was suggested that conversion of natural savannah vegetation to cultivated crops and tillage operations destabilized soil structure in the cultivated plots mainly by an increase of the swelling forces, which, in turn, reduced the K_s values.

1. Introduction

In recent decades, African grassland, woodland, and other virgin lands have increasingly been converted into cropland. For instance, an estimated 3.4 million km^2 of woody vegetation in arid and semiarid zones of Africa have become degraded through anthropogenic activities, such as agricultural expansion and deforestation (Tsegaye et al., 2010). One such area subjected to human-induced land use changes is the Humera district, located in a lowland region of Tigray, Ethiopia (Fig. 1). The economy of this district is based on sesame seed production for export, which employs 350,000–500,000 seasonal workers annually. Additionally, in 2003, the Humera region was selected by the Ethiopian authorities as an area for voluntary resettlement of farmers from overpopulated areas. As of 2007, about 16,000 households were resettled in the Humera district (DRMFSS, 2007). The influx of resettled populations and seasonal workers, combined with semi mechanized sesame production, are exerting increasing pressure on the area's diminishing natural resources. Consequently, significant clearing of the native *A. seyal*- and *B. aegyptiaca*-dominated savannah, and subsequent cultivation and grazing have taken place over the past few decades (Gebre-Michael et al., 2010) and, at present, very few areas of natural savannah remain in the region. This drastic shift in land use may seriously affect the chemical, physical, and hydraulic properties of the soil. Furthermore, it may also affect the abiotic conditions that support various soil-borne biota, e.g., the sand flies that act as vectors of the deadly kala-azar disease (Gebre-Michael et al., 2010), which poses a serious health threat in the Humera region.

* Corresponding author. Tel.: +972 39683640/25.
E-mail addresses: itamar.shabtai@mail.huji.ac.il (I.A. Shabtai), moshe.shenker@mail.huji.ac.il (M. Shenker), wssnlmm@yahoo.com (W.L. Edeto), alonw@ekmd.huji.ac.il (A. Warburg), meni@volcani.agri.gov.il (M. Ben-Hur).

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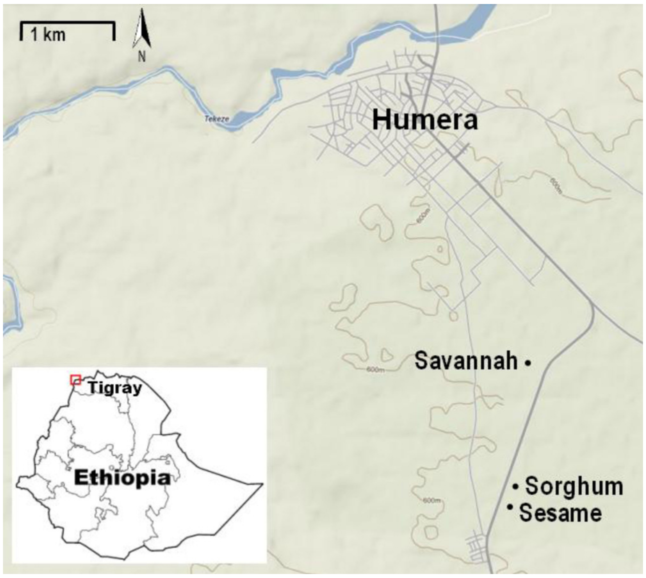

Fig. 1. Map of Ethiopia and study area.

The dominant soil in the Humera region is chromic Vertisol (Amare et al., 2009), characterized by high contents of smectitic clay minerals. Vertisols are strongly affected by moisture content: they swell when hydrated and shrink upon desiccation, causing extensive cracking during the dry season. Also, wetting of the soil may disperse clay particles. A clayey soil, such as a Vertisol, may therefore be highly sensitive to structure-altering processes under land use changes.

One property that is highly dependent on soil structure, and may, therefore, be affected, is hydraulic conductivity (K) (Bouma and Anderson, 1973; Hillel, 2004; Shainberg and Letey, 1984). Hydraulic conductivity of soil is an important parameter, which affects water and solute transport, and water availability for plants. In arid and semi-arid regions, where precipitation is scarce and unevenly distributed, the capacity of the soil to conduct and store water is crucial. For example, Kadu et al. (2003) evaluated the suitability of Vertisols in India for crop production, and found low crop yields in soils with low K values. Furthermore, reduced K values can lead to reduced infiltration and soil aeration and increased surface runoff and soil erosion (Ben-Hur, 2008; Ben-Hur and Lado, 2008; Kadu et al., 2003), with consequent alterations to the hydrological cycle, soil fertility, and soil biotic conditions.

Saturated hydraulic conductivity (K_s) is a function of pore-size distribution and tortuosity (Hillel, 2004), and also of aggregate stability (Ben-Hur et al., 2009). Clay particles in soil are associated to form aggregates and pores of various sizes by means of stabilizing agents, such as organic matter, calcium carbonate, and oxides (Bronick and Lal, 2005; Duiker et al., 2003; Gargiulo et al., 2013; Tisdall and Oades, 1982). In soil, the volume of water transmitted and the rate of transmission is greater for larger than smaller pores (Moutier et al., 1998). Lado et al. (2004) and Ben-Hur et al. (2009) found that an increase in organic matter content improved the stability of soil structure, which, in turn, augmented the soil K_s value. Deforestation and subsequent soil cultivation may reduce soil organic matter content (Collard and Zammit, 2006; Dalal and Mayer, 1986), because of reduction in organic residues added to the soil, destruction of macro-aggregates, and increased microbial oxidation of organic carbon (Whitbread et al., 1998). It was shown that, compared with native pasture or woodland soils, Vertisols used for crop production had a higher bulk density (Biro et al., 2011; McKenzie et al., 1991; Whitbread et al., 1998) and were more prone to dispersion (Cook et al., 1992; McKenzie et al., 1991; Whitbread et al., 1998). The reduction in soil organic matter content, alteration of soil porosity, soil compaction, and decline in aggregate stability could adversely affect soil K (Azooz and Arshad, 1996; Radford et al., 2000; Whitbread et al., 1998).

In the absence of raindrop impact and external compacting pressures, there are three main mechanisms that could degrade soil structure during wetting and leaching: (i) aggregate slaking; (ii) soil swelling; and (iii) clay dispersion (Ben-Hur et al., 2009). Aggregate slaking occurs when soil is wetted rapidly and its aggregates are not strong enough to withstand the stresses produced by differential swelling, pressure of entrapped air, rapid release of heat during wetting, and mechanical action of moving water (Emerson, 1977; Kay and Angers, 1999). These stresses are termed slaking forces, and their intensity is a function of the wetting rate of the soil; the faster the wetting the stronger the slaking forces and the greater the proportion of aggregates that undergo slaking.

Soil swelling is essentially a reversible process, in which the total volume of soil increases upon hydration; it depends mainly on the soil mineralogical, chemical, and physicochemical properties (Ben-Hur et al., 2009; Dasog et al., 1988; Greene-Kelly, 1974; Lado and Ben-Hur, 2004; Smith et al., 1985). Greater swelling is expected in soils with high contents of smectitic clay minerals, high exchangeable sodium percentage (ESP), and a low electrolyte concentration in the soil solution. Swelling of clay particles increases the content of small, water-retaining pores at the expense of larger water-conducting pores (Kutilek, 1996; Moutier et al., 1998).

Clay dispersion is an irreversible process, in which quasicrystals or domains (regions of parallel alignment of individual aluminosilicate lamellae in smectite minerals) break apart and disperse because of mutual-repulsion forces (van Olphen, 1977). Dispersion of soil clay occurs instantaneously once the electrolyte concentration of the soil solution falls below a threshold value, termed the flocculation value (Oster et al., 1980), and the dispersed clay particles may migrate and plug water-conducting pores, causing a reduction in soil K_s (Frenkel et al., 1978). Clay dispersion is influenced by soil chemistry and mineralogy, and is enhanced primarily by a low electrolyte concentration in the soil solution and high ESP of the soil (Lado et al., 2004; Laird, 2006; Malik et al., 1992; Oster et al., 1980). Thus, K_s tends to decrease as soil ESP increases and as the electrolyte concentration of the soil solution decreases (McNeal and Coleman, 1966; Quirk and Schofield, 1955).

Many studies have focused on the effects of sodicity and water quality on the structure and hydraulic properties of soils (e.g., Chaudhari, 2001; Frenkel et al., 1978; Gupta and Verma, 1984; Malik et al., 1992; Shainberg and Letey, 1984). The effects of tillage on soil structure and K have also been addressed (e.g., Bandyopadhyay et al., 2003; Hewitt and Dexter, 1980; Oicha et al., 2010; Radford et al., 2000; Whitbread et al., 1998). Other studies have mainly addressed the effects of changes in land use and of cultivation on soil chemical properties, such as organic matter and nutrients contents and cycling (Collard and Zammit, 2006; Dalal and Mayer, 1986; Solomon et al., 2002). In contrast, the effects of interactions between land use changes, on the one hand, and sodic conditions, on the other hand, on soil structure and K_s of Vertisols have not been well documented. Therefore, the aim of the present study was to examine the effects of changes in land use – from natural sparse forest (savannah-woodland) to semi mechanized crop production – on soil structure and K_s of a Vertisol, under sodic conditions in the Humera region of Ethiopia.

2. Materials and methods

2.1. Studied sites and soil sampling and analysis

The research was conducted in the Humera district of northwest Tigray, Ethiopia (Fig. 1). This region is situated in a semi-arid