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Topsoil removal and cultivation effects on structural and hydraulic properties

B.E. Udom*, S. Omovbude, P.O. Abam

Department of Crop and Soil Science, University of Port Harcourt, P.M.B. 5323, Port Harcourt, Nigeria

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ABSTRACT

Topsoil removal and intensive cultivation of fragile sandy loam soil may reduce water movement into and within the soil and decrease available water capacity. The purpose of this study was to determine if topsoil removal (SSR) and 10-year cultivation have adverse effects on the structural and soil water retention properties. The study was conducted on a fine sandy loam soil in humid tropical coastal plain soils in southern Nigeria. We measured particle size, soil organic matter, pore size through water desorption analysis and infiltration and related water retention properties. Results showed that topsoil removal and cultivation resulted in significant reduction in infiltration, saturated hydraulic conductivity and available water contents and increased the bulk density. Topsoil removal increased fine particle-size fractions and created a shift in pore size distribution to a greater micro porosity. Soil water storage in terms of useful available water (UAW) and easily available water (EAW) were significantly low ($p < 0.05$) in SSR, reaching 62% reduction. Top soil removal and cultivation resulted in 67% and 32% decreased OM respectively. Loss of OM leading to low water retention at 10 kPa and 1500 kPa indicates a high risk of water stress and quicker soil drying even after heavy rainfall. Loss of organic matter and silt + clay fraction were the major drivers of changes in UAW and EAW in SSR soils. The results of this study confirmed that many structural and water retention characteristics are altered by cultivation and topsoil removal, and are useful in defining the physical quality response indices of fine sandy loam soils.

1. Introduction

The soil surface state regarding to water movement away and into the soil mass may affect its evaporation, infiltration and distribution. Compaction, topsoil removal and cultivation may alter the soil surface properties, through changes in structural and water retention properties of the topsoil layer (Kargas et al., 2012). Such changes depend on the soil type and structure, amount of organic matter removed, the extent of topsoil removal, and antecedent water holding capacity of the soil (Azzoz and Arshad, 2001; Kargas et al., 2012). In fine-textured soils, topsoil removal may lead to development of surface crusts due to direct impact of raindrop on the unprotected soil surface and decreasing infiltration of water into the soil profile (Houlbrooke and Laurenson, 2013). In coarse-textured soils, high incidence of soil and nutrient losses has been reported in continuous cultivated soils (Lal, 1990). Increase in the risk of floods and droughts due to adverse influence of topsoil removal on rainfall acceptance and infiltration capacity of soil have also been reported (Shu et al., 2015). A few other effects include changes in pore size distribution induced from breaking down the exposed surfaces of micro aggregates and dispersed clays leading to increased risk of floods and drought (Lal, 1990; Woodland, 1996).

Soil organic matter (SOM) depletion following topsoil removal and cultivation is one of the critical problems in most soils of the world, because, SOM is an excellent indicator of surface soil quality and contributes to improved soil air diffusion, infiltration, water holding capacity and aggregate stability (Blanco-Canqui and Lal, 2008; Smith et al., 2013; Li et al., 2016). In high rainfall areas such as in the Niger Delta in Nigeria, topsoil removal has been found to increase soil penetration resistance (Udom and Adesodun, 2016). Faster soil warming and quicker soil drying after heavy rainfall have also been noticed in fine sandy soils due to topsoil removal, compaction and cultivation, which according to Smith et al. (2000) occur especially in the top 0–15 cm of the soil profile.

In assessing topsoil removal and cultivation effects on soil water-retention properties, information on infiltration and soil water retention characteristics (SWRC) is needed. This information permits quantification of effective pore-size distribution viz.: air-filled porosity (AFP), useful available water (UAW) and easily available water (EAW) (Cassel and Nielsen, 1886; Wall and Heiskanen, 2003) and its contribution to physical quality of the topsoil. Such quantification

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* Corresponding author.
E-mail address: ebassidy@yahoo.com (B.E. Udom).

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assessment is useful for developing long-term and process-based strategies to improve and maintain the structural and hydraulic properties of the topsoil. This quantification assessment would help farmers and land users to manage and/or improve critical soil quality functions such as bulk density, water stable aggregates, and hydraulic conductivity.

Woodland (1996) reported increased in bulk density and microporosity due to soil compaction in the Amazonian Ecuador. There are also indications that topsoil removal could impact negatively on water availability and drought stress functions, such as UAW, EAW and field capacity (Wall and Heiskanen, 2003). Cultivation of agricultural land, including tillage and use of machinery, alters the air-filled porosity and related properties of soils, similar to topsoil removal by bulldozer (Whalley et al., 2012; Udom and Ogunwole, 2015), leading to adverse impact on soil ecological services and functions, especially in high rainfall areas. However, these impacts have not been properly addressed in some tropical soils which have exposed ironstone through topsoil removal. The objective of this study was to determine the effects of topsoil removal and long-term cultivation on surface soil structure and water retention properties compared with an undisturbed forest soil. This will advance our knowledge on the impact of topsoil removal and cultivation on rainfall acceptance and infiltration capacity and topsoil structural quality in fine sandy loam soils.

2. Materials and methods

2.1. Description of study site

The study was conducted in 2015 and 2016 in the humid Niger-Delta of Nigeria (04°15′N, 07°30′E). The soil is derived from unconsolidated coastal plain sands and alluvium of the Niger Deltaic and classified as *Arenic acrisol* (USDA, 2012), dominated by kaolinite and oxides of Fe and Al. The soil is moderately well-drained with a low base saturation, low pH of 4.6, and low fertility status. Organic matter content is < 1.0% below the 20 cm depth (Akamigbo and Igwe, 1990). The rainy season is from March to November; with two peaks in July and September (NIMET, 2014). Mean annual rainfall is in excess of 2000 mm, with 80% of the rainfall between the months of May and October. Mean temperature at wet season ranged from 26 °C to 33 °C, and at dry season between 26 °C and 36 °C (Okpon et al., 1998). The site was previously cleared with bulldozer for construction works, removing the topsoil in the process, leaving exposed compacted subsoil.

2.2. Experimental area

Three locations were used for soil sample collections: (1) 10-year forested area, extending about 50 ha, dominated by *Imperata cylindrica* and shrubs such as *Alcornea cordifolia* and *Ficus exasparata* as undergrowth (Site A). (2) 10-year continuous cultivated area, extending about 420 ha, cultivated to maize and cassava (Site B). (3) Compacted subsoil, extending about 20 ha, with 25 to 30 cm of top soil previously removed with a bulldozer during site clearing for construction, leaving exposed compacted subsoil (SSR) (Site C). After 10 years, the exposed subsoil is characterized with regenerated scanty vegetation consisting mainly of *Panicum maximum* and *Cynodon dactylon*. Each of the sites located on a 5% slope was divided into four replicate subareas based on physiographic/landscape positions for soil sample collections. Since the slope of the land can influence infiltration rate and amount of water retained in the soil, the study area was delineated into upslope, middle slope, downslope and the relatively flat areas for representative soil sampling.

2.3. Soil sampling and measurement of infiltration

Ten disturbed and undisturbed core soil samples were collected at 0–30 cm depth in duplicates, making a total of 120 bulk and core samples. The bulk soil samples were air-dried, sieved through 2 mm mesh and stored for laboratory analysis.

Infiltration measurement was carried out along a transect at 120 positions in the field using the double ring infiltrometer (Carter, 1993) with inner and outer rings of 30 cm and 60 cm diameters, respectively. A constant head of 5 cm was maintained for 2 h until steady state infiltration was achieved. The infiltration rate (I) was calculated according to Bower (1986) as:

$$\mathrm{I} = \frac{Q}{A\ \mathrm{x}\ t} \tag{1}$$

where Q is the volume of water infiltrating, A is area of the soil surface exposed to infiltration and t is time.

2.4. Laboratory analyses

2.4.1. Particle size distribution, bulk density and water-retention characteristics

Particle size distribution was determined with air-dried soil sample by the method of Gee and Bauder (1986). Bulk density determined with core samples by the method of Black and Hartage (1986) as:

$$\text{Bulk density} = \frac{Md\ (g)}{Vb\ (cm3)} \tag{2}$$

where M_d *is* mass of oven-dried soil and V_b is the volume of bulk soil.

Soil water-retention characteristics (SWRC) were measured on undisturbed core samples 5 cm × 6 cm (diameter × height) in the laboratory, using the pressure chamber apparatus with ceramic plates. Saturation of the soil samples was achieved by adding water slowly until water was about half way to the top of the soil core and allowed to soak for 24 h. After saturation, samples were subjected to pressures 0–10 kPa using the hanging water column method as described by Wang and Benson (2004), and 1500 kPa using the pressure plate apparatus. Excess water drained through the ceramic plate until balance was established between pressure force and water retention force in the soil samples after 2 days. The gravimetric water content (θm) in the samples was measured after oven-drying the soil at 105 °C and was converted to volumetric water content (θv) by multiplying θm by the bulk density of each core sample. The following suctions were obtained: 0, 6, 10, 100, 1000 and 1500 kPa. The water content at 10 kPa and 1500 kPa represent the field capacity (FC) and permanent wilting point (PWP), respectively as suggested by Cassel and Nielsen (1886). The useful available water (UAW) and easily accessible water (EAW) which was used to assess the tendency of water stress were calculated from the water retention relationship using the following equations:

$$\mathrm{UAW(mm)} = \frac{1}{10} \times (FC - PWP) \times BD \times Z \tag{3}$$

where BD is the dry bulk density, Z the depth of soil (cm), and $FC - PWP$ is the available water (AW) (Hillel, 2004), and

$$EAW\ (mm) = UAW\ \mathrm{x}\ \frac{2}{3} \tag{4}$$

2.4.2. Aggregate stability, saturated hydraulic conductivity, porosity and organic matter

Aggregate stability was measured by the mean weight diameter (MWD) of water stable aggregates using the wet-sieving method as described by Kemper and Rosenau (1986). In this method, 50 g of 4.75 mm dry-sieved aggregates were placed in the topmost of a nest of sieves: 2.0, 1.0, 0.5, and 0.25 mm. The aggregates were pre-soaked by capillary in distilled water for 15 min and oscillated vertically in water 20 times, using 4 cm amplitude in a mechanical agitator. The remaining stable aggregates on each sieve were oven-dried at 50 °C for 24 h and weighed. The percentage of the stable aggregates on each sieve representing water stable aggregates (WSA) was calculated as:

$$\mathrm{WSA} = \frac{MR}{MT} x \frac{100}{1} \tag{5}$$