

# Long Term Sugarcane Cultivation Effect on Selected Physical and Hydraulic Properties of Soils at Three Ethiopian Sugarcane Estates

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**Abstract:** The long term use of heavy weighted agricultural vehicles for sugarcane cultivation has caused long lasting soil physical and hydraulic properties altering. However, information on the extent of change is scant. In this context, a study was conducted in 2017 to investigate the effect of long term mechanized sugarcane cultivation on status of soil physical and hydraulic properties at three pioneer Ethiopian Sugar Estates. In order to achieve this objective, Composite and core soil samples were collected from 0-30 layer of fields for laboratory analysis. Results of the study indicated that soils under cultivation had higher clay contents than uncultivated soils. The bulk density and total porosity values were out of optimum ranges for sugarcane cultivation. Soils under sugarcane had higher available water holding capacity than the uncultivated soils. Available water holding capacity of the three estates is above the threshold value ideal for sugarcane cultivation. The mean basic infiltration rate value of uncultivated land was greater than the cultivated lands. From these findings one can conclude that long term cultivation of sugarcane induces soil compaction which decreased the total pore space of a soil mainly by increasing fineness of the soils. The existing soil management based on pF<sub>2</sub> classes of the three estates is poorly related with soil physical and hydraulic parameters. The gradual water releasing behaviors manifested by clay soils of Ethiopian Sugar Estates could be considered as an asset in increasing yield per fields of the estates if accompanied by good soil water managements. Hence, to maintain sustainability of sugarcane production in the three estates; soil management practices that can protect/ ameliorate soil compaction are important. Nevertheless, to develop a concrete recommendation and to measure the long term effects of sugarcane cultivation on properties of state soils further research studies are needed.

**Keywords:** Cultivated and Uncultivated Soils, Hydraulic Property, Soil Physical Property

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## 1. Introduction

Soil physical degradation due to long term sugarcane cultivation is one of the most significant constraints to increased production of sugarcane in Ethiopia [1]. The use of heavy machinery, such as tractors for operations like cultivation, planting, fertilizer application, weed control and cane extraction during wet conditions and under low soil organic matter during sugarcane production have aggravated the situation. Moreover, sugarcane production in Ethiopia involves mechanized cultivation for increased cropping intensity, timeliness, higher work rates, and lower labour requirements in order to satisfy the local high demand for white sugar. Nevertheless, machinery overuse has been found

to be the main cause for soil compaction [2, 3].

Soil compaction is the main physical form of soil degradation [4] which can alters soil structure, limits water infiltration, increase in bulk density and penetration resistance, reduces root penetration in the soil and have adverse effects upon sugarcane growth [5]. Associated with these changes in physical properties of soil water, nutrients and airflow towards the plant roots are also restricted. These restrictions may reduce the crop growth and yield [6].

Yield decline is an issue that has plagued sugarcane production systems in several sugar cane producing countries around the world for more than half a century. Despite, Ethiopia is one of the countries with the highest sugarcane yield in the world; sugar cane yield decline is currently

becoming the major area of attention in the Ethiopian Sugar Estates. Studies in Ethiopian sugar estates also showed the declining productivity of the fields due to effects of soil compaction on soil physicochemical properties [7]. Long-term annual yield data obtained from the three estates showed a decline in cane [8]. For instance, the cane yield per ha in Wonji-Shoa sugar cane plantation has declined by about 48.63% over the last 54 years (1954-2008), by 49.03% at Metahara (1969-2008) and by 26.63% decrease at Finchaa (1997-2008) [9, 10].

Research report by Alvarez *et al.* [11] has shown that long-term monoculture and excessive tillage along with practices that deplete organic matter all contribute to yield decline. Several researchers have suggested that the most serious factor associated with soil compaction under sugarcane production is the loss of soil organic matter due to intensive tillage (e.g. [12, 13]. Moreover, Barzegar *et al.* [14] indicated that long-term sugarcane cultivation under low soil organic matter condition altered soil properties.

Currently, there is dramatic increase in irrigated areas along with increased machinery uses in most monoculture sugarcane farms in the country. If not properly managed, this has a potential to induce land degradation and consequent decline in cane yield. Thus, sustainability of sugarcane agro-industry will be in question unless the main causes for yield decline could be addressed and solved. Therefore, identifying and understanding the cause of the yield decline has paramount importance to design and recommend appropriate management strategies. Moreover, evidences on the impact of long-term mechanized cultivation for sugarcane production on soil physical properties are important inputs for planning soil and land management practices in large scale mechanized irrigated sugarcane farms in the sugar estates. Keeping in view the above facts, this study was conducted with objective of determining the effects of long term mechanized sugarcane production on soil physical and hydraulic properties at Wonji-Shoa, Metahara and Finchaa Sugar Estates taking uncultivated soils nearby the farms as references.

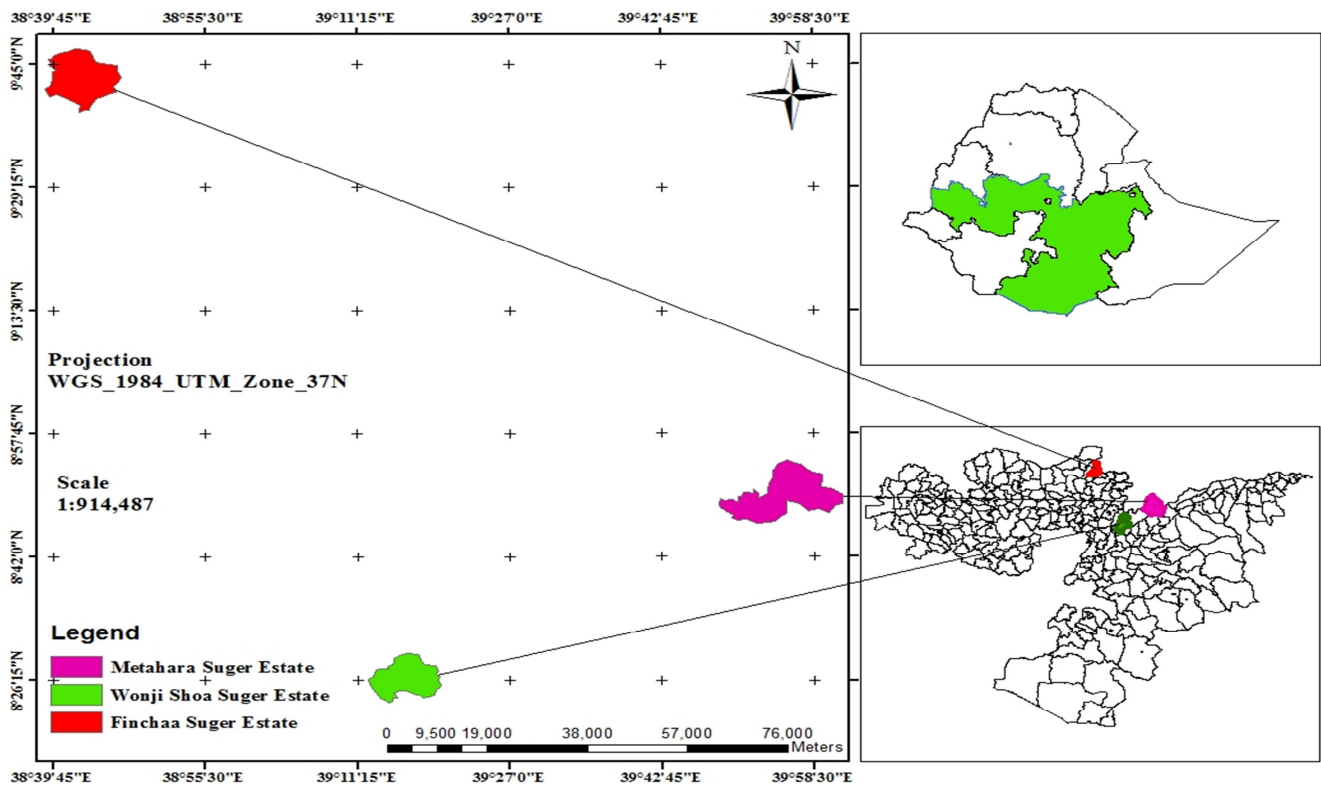


Figure 1. Location map of Finchaa, Metahara and Wonji-Shoa Sugar Estates in Ethiopia.

## 2. Materials and Methods

### 2.1. Description of the Study Areas

#### 2.1.1. Location and Area Coverage

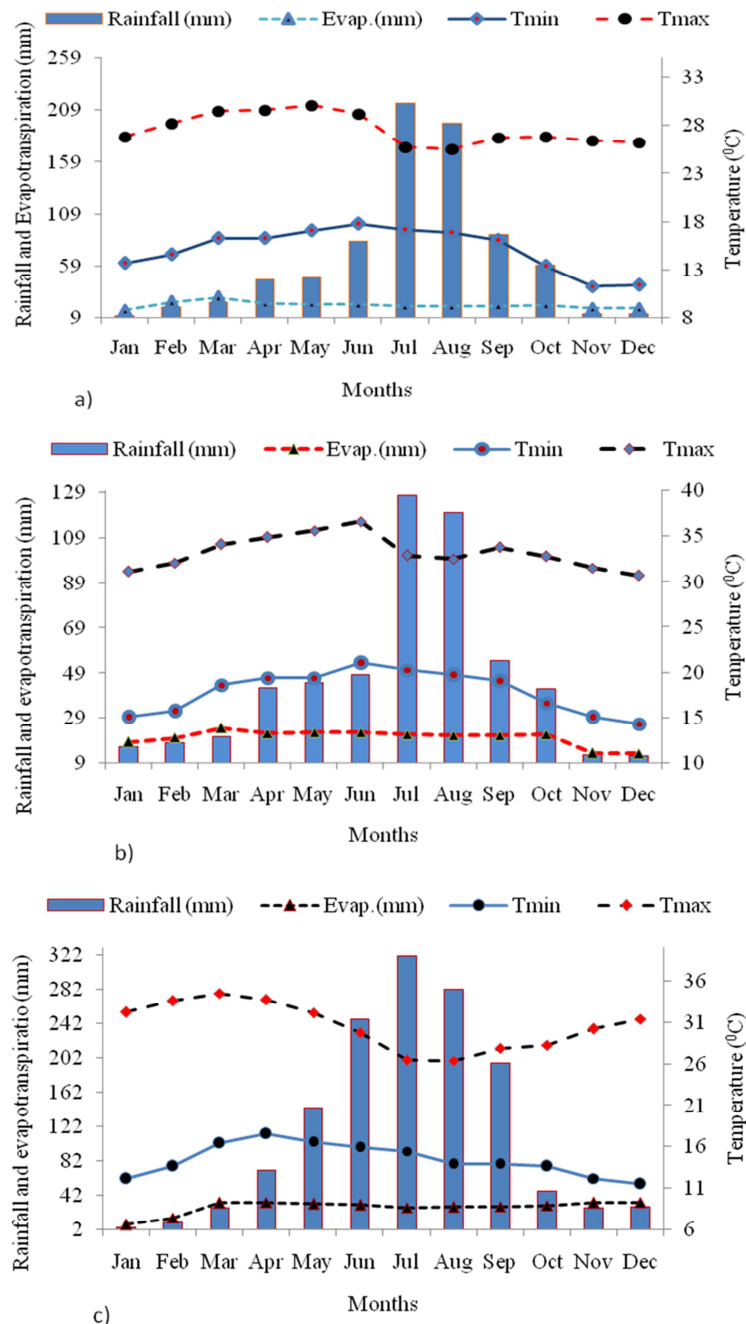
The study was conducted in 2017 at three climatically different commercial sugarcane production fields of estates. The study areas are located at a distance of 107, 200 and 374 km, respectively, from Addis Ababa within the Oromia National Regional State (ONRS). Wonji-Shoa and Metahara

Estates are located in the central part of the East African Rift Valley at 8°21'3.84" to 8°27'25.86" and 8°45'4.16" to 8°53'20.75" N latitude, 39°12'13.28" to 39°18'34.46" and 39°49'10.74" to 40°0.21'1.48" E longitude, respectively. On the other hand, Finchaa Sugar Estate is located between 9°21'18.12" to 9°25'23.01" N and 39°11'8.85" to 39°15'3.2" E (Figure 1) in the valley of southwestern highlands of Ethiopia in the Abay River Basin. The total area of land under cultivation during the study period was about 7050, 10,248 and 9,000 ha, respectively [15].

### 2.1.2. Climate

Ten years (2003-2013) climatic data (Figures 2 a and b) of the Wonji-Shoa and Metahara Estates indicated that the areas have a bimodal rainfall pattern in which small rain is received from February to April, while the main rainy season that contributes a significant proportion of the total annual rainfall is received during June to September. Nevertheless, ten years (2003-2013) climatic data from Finchaa Meteorological Station showed unimodal rainfall pattern, in

which majority of the annual rain falls between May to September (Figure 2 c). The mean annual rainfall in the study areas is 831.47, 539.39, and 1399.72 mm for Wonji-Shoa, Metahara and Finchaa Estates, respectively. Moreover, average minimum and maximum temperatures of the three estates are about 15.19 and 27.57°C for Wonji-Shoa, 17.73 and 33.24°C for Metahara and 14.40 and 30.54°C for Finchaa [16].



**Figure 2.** Ten years mean monthly rainfall, evapotranspiration (Evap), and monthly minimum (Min) and maximum (Max) temperatures of Wonji-Shoa (a), Metahara (b) and Finchaa Estates (c).

### 2.1.3. Physical Features

The study areas are characterized by diverse

physiogeographic features. At Wonji-Shoa and Metahara Estates, the slope of the field is generally very gentle and regular which makes them suitable for gravity irrigation [17].

On the other hand, Finchaa Estate is dominated by a gently undulating surface with a general slope of 1 to 8 percent northwards with high and rugged mountains, valleys and plains. Wonji-Shoa and Metahara Estates are found at altitude of 1540 and 950 meter above sea level, respectively, in the Awash River Basin. While, Finchaa Sugar Estate is found at an elevation of 1500 meters above sea level in the Abay River Basin.

#### **2.1.4. Geology, Soil Types and Soil Management Units**

Majority of soils of Wonji-Shoa, Metahara and Finchaa Estates are developed under tropical hot condition from alluvium-colluvium parent materials which include basic volcanic rocks such as (basalt, limestone), acidic volcanic rocks such as (granite, sandstone) as well as recent and ancient alluvial soils [18]. Vertisols and Fluvisols cover the major part of Wonji-Shoa [19], while Vertisols and Luvisols are dominant soils at Finchaa [20], and soils of Metahara Estate are classified as Calcaric Cambisols [21].

Moreover, the estates are grouped into a total of 13 soil management units where five, six and two of them belong to Wonji-Shoa, Metahara and Finchaa, respectively. This grouping of soil management approach for Wonji-Shoa and Metahara was adopted from Kuipers [22] though there is no documented information concerning depth of sampling, number of samples and methods of sampling for  $pF_{2.0}$  soil management classification of these estates. The first three soil groups ( $A_1$ ,  $A_2$ , and  $BA_2$ ) of Wonji-Shoa and (Class-4, Class-5, and Class-6) of Metahara are heavy textured soils; while the last two soil types ( $B_{1.4}$  and  $C_1$ ) of Wonji-Shoa and (Class-1, Class-2 and Class-3) of Metahara are light textured soils [23]. More than 95 percent of the cultivated and irrigated land soils in Finchaa are grouped in to Luvisols and Vertisols and in use for different agricultural field operations [24].

#### **2.1.5. Agricultural Production and Management**

In Wonji-Shoa plantation, the main crops cultivated are sugarcane, haricot bean and crotalaria. Moreover, fallowing is practiced using crotalaria as fallow crop for about nine months. In Metahara Estate, along with the cane plantation, the enterprise owns 140 ha of land covered with various types of fruits such as oranges, mangoes, lemons, grapefruits, etc. About 3,000 tonnes of fruits are produced annually at Metahara Estate. Sugarcane is the principal crop in Finchaa Sugar Estate but sesame and horticultural crops are also cultivated in small areas of the estate. The average land productivity is about 155, 165 and 160 tonnes of cane per hectare, respectively, for Wonji-Shoa, Metahara and Finchaa Estates. These make the Ethiopian Sugarcane plantation farms one of the highest cane producing farms in the world [25].

Planting of seedlings and transplantation of sugarcane is done manually but cultivation and chemical spraying are accomplished mechanically. Tillage operations such as uprooting, subsoiling, plowing, harrowing, labeling, and furrowing are conducted before planting cane sets. Mechanization is also used for other farm operations like

cane loading and cane haulage. Planting of sugarcane is usually practiced from mid-October to the end of June in a particular year. Sugarcane is planted at a rate of 16-18 t ha<sup>-1</sup> in the estates [26]. At Wonji-Shoa nitrogen in form of urea (46%N) is applied to all fields depending on cutting but regardless of the soil type. The rate of application is 200, 400, 500 kg ha<sup>-1</sup>, respectively, for first, second, third and above ratoons. Moreover, the most widely used fertilizer in Metahara Estate is ammonium sulfate nitrate (26% N) with the application rates of 300 kg ha<sup>-1</sup> for planting sugarcane, 500 kg ha<sup>-1</sup> for the second and third cuttings and 650 kg ha<sup>-1</sup> for the fourth and subsequent cuttings. While, at Finchaa Estate, 150-400 kg ha<sup>-1</sup> of urea and 250 kg ha<sup>-1</sup> of diammonium phosphate fertilizers are used [27].

#### **2.1.6. Irrigation Water Source and Management**

The irrigation water source for Wonji-Shoa and Metahara plantations is the Awash River, while that of Finchaa plantation is the Finchaa River. Blocked-end furrow irrigation system and furrow irrigation using 425 mm plastic fluming (hydroflume) is used to irrigate sugarcane fields in the Wonji-Shoa and Metahara Estates, respectively. In Metahara water applied to each furrow is cutoff as it reaches the end of the furrow, which is blocked and ponds up within the furrow. In Finchaa plantation, movable sprinklers are employed for water application in the sugarcane fields. In the sprinkler irrigation method the irrigation water is applied to the land in the form of spray, somewhat as an ordinary rain. This overhead irrigation manually move from place to place in the field based on the demand for irrigation. Each sprinkler serves 15 positions on an 18 m \* 18 m grid. The laterals are spaced 90 meters and are designed to provide a gross application rate of 134.4 mm per irrigation cycle [28].

Irrigation application volume and intervals vary according to the type of the soil in the scheme. The gross irrigation depth ranges from 165 to 215 mm at Wonji-Shoa and at Metahara Estate. The application rates vary from less than 550 m<sup>3</sup>/ha for light to more than 1,500 m<sup>3</sup>/ha for heavy soils. Furthermore, the irrigation interval which depends on the soil types of the estates varies from 10 days for light soil to 28 days for heavy soils and 7 days for light to 22 days for heavy soils, respectively, for Wonji-Shoa and Metahara Plantations. However, in Finchaa, independent of the soil types irrigation application rate and interval for both soil types is the same and is applied every 15 days for length of 24 hrs. The feel method is used to recognize the need for irrigation. A test is conducted at two depths (30 and 60 cm) a few days before the expected date of irrigation, and irrigation is scheduled when the test results indicate dry soil [29].

### **2.2. Method of Study**

#### **2.2.1. Soil Sampling and Sample Preparation**

The experiment was conducted on light and heavy soil management unit groups at Wonji-Shoa and Metahara, and on Luvisols and Vertisols at Finchaa. Three stages stratified random soil sampling method was used. In the first stage each estate was stratified in to two soil management units. In

second stage each soil management unit was categorized into two land use types (cultivated and uncultivated). In the third stage each land use was represented by six sampling sites so that soil samples from each stratum provided good representation of study area soils. Furthermore, qualitative soil compaction diagnosis at field level was undertaken in order to select the final soil sampling sites.

Accordingly, 6 cultivated sugarcane fields with records of recurrent reduced yield and 6 adjacent uncultivated bare fields were identified for both soil management units of each estate. The uncultivated fields were identified per each existing management unit groups and most of them were located between the main drains and access roads. According to information from station officers of each estate, these soils have not been cultivated for about fifteen years, thirty years, and forty years, respectively, at Finchaa, Metahara, and Wonji-Shoa, respectively. The fields were sampled by replicating three times. Accordingly, 18 sampling sites for each soil management unit was assigned. Global Positioning System (GPS) data was taken from each of the sampling sites.

A representative composite soil samples with three replications per each cultivated and uncultivated bare fields was collected from the surface layer only. Composite and undisturbed (for bulk density) samples were collected from 0-30 cm soil depths using auger and core samplers, respectively. Twenty sub-samples were collected from each sampling site using the X-pattern of sampling technique to make one composite sample per depth. Three undisturbed samples per each cultivated and uncultivated bare field was taken using core sampler into which 5 cm height and diameter cores were fitted. On the basis of this, a total of 108 composite and undisturbed samples were collected from plantation fields of the three estates.

About 500 g of the composite soil samples were properly weighed, labeled and kept in plastic bag, and transported to Debrezeit Research Center, Wonji Central Laboratory, Metahara, and Finchaa station soil laboratories. In the laboratory, sufficient amount of soil samples were air dried and ground to pass through 2 mm diameter sieve for further laboratory analysis of selected soil physicochemical properties except organic carbon and total nitrogen in which case the samples were crushed further to pass through 0.5 mm diameter sieve.

## 2.2.2. Laboratory Analysis of Soils

Particle size distribution was determined by the Bouyoucos hydrometer method as described by Okalebo *et al.* [30]. After determining sand, silt, and clay separates; the soil was assigned to textural classes using the USDA soil textural triangle (Soil Survey Staff, 1999). Bulk density was determined using the core method as described by Jamison *et al.* [31]. Particle density (pp) was determined using the pycnometer method following procedures described in Rao *et al.* [32]. Total porosity was calculated from the values of bulk density and particle density using the method described by Rowell [33].

To develop soil water retention characteristic curves, water retention was determined at 0, -5, -8, -10, -33, -60, -100, -300, and -1500 kPa matric potentials for the 36 soil samples collected only from the 0-30 cm layer. For the higher matric potentials ranging from 0 to -10 kPa, suction table (sand box apparatus) was used to apply the predetermined suctions. The same undisturbed samples were resaturated and used in a pressure plate extractor for measuring water content at -33, -60, -100, -300, and -1500 kPa matric potential. From these samples, disturbed subsamples were taken to determine water contents at -33, -60, -100, -300, and -1500 kPa. The equilibrium moisture content at -33, -60, -100, -300, and -1500 kPa matric potential points was determined gravimetrically as described in Reynolds [34]. The gravimetric water content was converted into volume wetness by multiplying it with the ratio of dry bulk density to density of water (assumed to be 1 g cm<sup>-3</sup>) [35].

The pH of the soils was measured in water (1:2.5 soil: water ratio) by glass electrode pH meter [36]. Soil organic carbon was determined by the wet digestion method following the procedure of Walkley and Black [37]. The total nitrogen was determined by the Kjeldal method as described by Jackson [38]. Relative amount of carbon to nitrogen was determined by taking the ratio of soil organic carbon to total nitrogen. Available phosphorus was extracted according to Olsen's method [39] for all estate soils except Bray II [40] for Finchaa (pH < 6) extraction methods. The P extracted with different methods was measured by spectrophotometer following the procedures described by Murphy and Riley [41].

**Table 1.** Selected chemical properties of the soils in the three Ethiopian Sugar Estates.

Estates	SMUG	Land uses	pH	SOC (%)	TN (%)	P (mg kg <sup>-1</sup> )
Wonji-shoa	Light	Cultivated	8.10	0.70	0.06	3.06
		Uncultivated	8.11	1.18	0.06	4.83
	Heavy	Cultivated	7.57	1.09	0.06	3.84
		Uncultivated	8.19	1.24	0.08	5.89
Metahara	Light	Cultivated	8.27	1.07	0.06	3.63
		Uncultivated	8.29	1.33	0.07	3.85
	Heavy	Cultivated	8.24	1.21	0.09	3.08
		Uncultivated	8.35	1.60	0.09	4.25
Finchaa	Luvisol	Cultivated	6.25	0.95	0.06	2.51
		Uncultivated	5.35	1.07	0.08	6.34
	Vertisol	Cultivated	6.63	1.02	0.07	3.24
		Uncultivated	6.00	1.32	0.10	8.63

SMUG=soil management unit groups, pH=soil pH, SOC=soil organic carbon content, TN=total nitrogen, P=available soil phosphorus

### 2.2.3. Field Measured Parameters

Infiltration rate was determined as outlined by Castellano and Valone [42] at twelve representative field sites of the three estates with three replications per each land use. Mean value of tests was taken as infiltration rate value of the respective land uses per management units. About 36 tests including uncultivated fields were under taken for six management unit groups of soil types.

### 2.2.4. Data Analysis and Interpretation

A randomized complete block design (RCBD) with three replications was used to analysis the variance of soil parameters. Analytically determined soil physical and hydraulic parameters for each soil management unit group land uses were tested using the general linear model procedure of the SAS computer package [43]. For statistically different parameters ( $P < 0.05$ ), means were separated using the Fisher's least significant difference (LSD) comparison. Pearson correlation analysis was also executed to reveal the magnitudes and directions of relationships between the selected soil physicochemical properties.

## 3. Results and Discussion

### 3.1. Effects of Land Uses on Selected Soil Physical Properties

#### 3.1.1. Particle Size Distribution

Particle size distribution is the amount of the various soil

separates expressed as weight percentages in a soil sample. Data pertaining to the soil particle size distribution as influenced by land uses is presented in Table 2. Clay and sand particles were significantly ( $P < 0.05$ ) affected by land uses (Table 2). The maximum value of clay percentage (57.15%) was recorded from heavy cultivated Wonji-Shoa Estate, while, minimum clay percentage (34.08%) was recorded from light uncultivated Wonji-Shoa Estate (Table 2).

Texture is typically permanent as well as an intrinsic attributes of the soil, the significant differences in individual separates modified the textural classes only in light uncultivated Wonji-Shoa Estate. The textural classes of the cultivated and uncultivated land uses in most of the estates is clay, but the texture of uncultivated light of Wonji-Shoa and Metahara soils are sandy clay loam and clay loam, respectively. The relatively increase in clay percentage of cultivated over the uncultivated land uses and the reverse for sand percentage could be attributed to the mixing of soils during normal tillage activities and sub soiling operations of sugarcane cultivation field. In line with this Bengough *et al.* [44] and Negesse and Tesfaye [45] also reported the variation in particle size distribution due to the removal of soil particles through erosion and mixing of the surface and subsurface soils during deep tillage activities.

Table 2. Effects of land use on selected physical properties of the soils in the three Ethiopian Sugar Estates.

Estates	SMUG	Land use types	Particle size distribution (%)			pb (g.cm <sup>-3</sup> )	pp (g.cm <sup>-3</sup> )	f(%)
			Sand	Silt	Clay			
Wonji-Shoa	Light	Cultivated	29.12 <sup>b</sup>	19.85	51.03 <sup>a</sup>	1.36 <sup>a</sup>	2.26	39.89 <sup>b</sup>
		Uncultivated	46.34 <sup>a</sup>	19.58	34.08 <sup>b</sup>	1.29 <sup>b</sup>	2.27	42.80 <sup>a</sup>
		LSD	4.31	ns	4.24	0.04	ns	2.40
	Heavy	Cultivated	24.58 <sup>b</sup>	18.27	57.15 <sup>a</sup>	1.32 <sup>a</sup>	2.10	38.19
		Uncultivated	33.00 <sup>a</sup>	20.08	46.92 <sup>b</sup>	1.26 <sup>b</sup>	2.14	40.03
		LSD	2.11	ns	2.56	0.01	ns	ns
Metahara	Light	Cultivated	24.03 <sup>a</sup>	29.31	46.66 <sup>a</sup>	1.35 <sup>a</sup>	2.58	47.73
		Uncultivated	27.09 <sup>b</sup>	33.08	39.83 <sup>b</sup>	1.27 <sup>b</sup>	2.48	48.77
		LSD	0.77	ns	1.71	0.04	ns	ns
	Heavy	Cultivated	19.02 <sup>a</sup>	27.17	53.81 <sup>b</sup>	1.32 <sup>a</sup>	2.64	50.17 <sup>b</sup>
		Uncultivated	10.50 <sup>b</sup>	34.65	54.85 <sup>a</sup>	1.22 <sup>b</sup>	2.64	54.83 <sup>a</sup>
		LSD	2.13	ns	0.52	0.06	ns	4.12
Finchaa	Luvisols	Cultivated	38.50 <sup>b</sup>	18.59	42.91 <sup>a</sup>	1.54 <sup>a</sup>	2.62	39.61 <sup>b</sup>
		Uncultivated	40.84 <sup>a</sup>	17.50	41.66 <sup>b</sup>	1.51 <sup>b</sup>	2.55	42.48 <sup>a</sup>
		LSD	0.59	ns	0.31	0.008	ns	2.70
	Vertisols	Cultivated	34.09 <sup>b</sup>	20.14	45.77 <sup>a</sup>	1.47 <sup>a</sup>	2.47	39.94 <sup>b</sup>
		Uncultivated	36.00 <sup>a</sup>	19.83	44.17 <sup>b</sup>	1.39 <sup>b</sup>	2.45	43.65 <sup>a</sup>
		LSD	0.48	ns	0.40	0.01	ns	0.93

SMUG=soil management unit groups, LSD=least significant difference, pb=bulk density, pp=particle density, f=total porosity, and means with the same letters are not significantly different

#### 3.1.2. Bulk Density and Total Porosity

Bulk density is a dynamic soil property, altered by cultivation, systems of land use, ameliorative measures such as subsoiling or soil mixing, and by loss of organic matter.

Soil bulk density of three estates range from 1.22 to 1.54 g.cm<sup>-3</sup>. According to rating suggested by Jones [46] the bulk density of Finchaa Luvisols were within the range that causes restriction to root penetration ( $> 1.40 \text{ g cm}^{-3}$ ). While, the bulk density of the uncultivated light soils of Wonji-Shoa and

cultivated Vertisols of Finchaa were in the range of close to the root restriction initiation bulk density values. On the other hand, the bulk density values of all the other soils of three estates were within the normal range suggested for the respective textural class.

The dry bulk density values of the cultivated fields were significantly ( $P < 0.05$ ) higher than the bulk density values of the adjacent uncultivated fields (Table 2). This could be due to soil compaction induced in the soil of cultivated fields. The negative and significant correlation between organic matter and bulk density in soils of the estates (Table 5) confirms the favorable effects of soil organic matter on bulk density in the cultivated soils. Similarly, Rao *et al.* [47] also reported increasing of bulk density due to soil compaction and the negative correlation between soil organic matter and bulk density, respectively. Due to induced soil compaction in sugarcane fields; the dry bulk density of most sampled sites was out of optimum values (1.10 to 1.20 g.cm<sup>-3</sup> for both clay and loam soils, and 1.30 to 1.40 g.cm<sup>-3</sup> for sandy soils [48]) for sugarcane production.

The different land uses showed significant ( $P < 0.05$ ) effect on total porosity of soils except for Wonji-Shoa heavy and Metahara light soil management unit groups (Table 5). The total porosity of soils of the estates ranges between 39.61 and 54.83%. The highest value of total porosity was obtained from uncultivated land and the lowest value was recorded from cultivated land for all soil management unit groups of estates. As suggested by Tesfaye *et al.* [49] total porosity required for good growth of sugarcane is 50%. Moreover, the total porosity of most soils lie between 30 and 70%. Landon [50] also reported that in clay textured soils total porosity less than 50% can be taken as critical value for root restriction. Based on these values it can be suggested that porosity values for cultivated lands were in the range of root growth restriction.

The higher total porosity values in the uncultivated fields might be attributed to the higher amount of organic matter contents and lower bulk density values of uncultivated land uses (Tables 1-2). In line with this, Brady and Weil [51] reported that the low total porosity was the reflection of the low organic matter content and the high bulk density. This could be evidenced from the negative correlation between bulk density and total porosity as well as positive correlation between total porosity and organic matter in most soils of the estates (Table 5).

### 3.2. Effects of Land Uses on Soil Hydraulic Properties

#### 3.2.1. Available Water Holding Capacities

The range of water available to plants and microorganisms (difference between field capacity and permanent wilting point) is between  $150.8 \frac{mm}{m}$  (for Wonji-Shoa heavy uncultivated land use) and  $197.60 \frac{mm}{m}$  (for Finchaa cultivated vertisol). As per rating by miller and Donahue [52] for available water holding capacity all the uncultivated soil management unit groups as well as cultivated were categorized in medium class

except that of cultivated Luvisols and Vertisols which were in the high category class (Table 3).

Available water holding capacity of greater or equal to 15% (15 cm per meter depth of soil) or more is considered to be ideal for sugarcane cultivation [53]. As per this critical value, all the fields under sugarcane in the three estates have AWC that is well above this threshold value for sugarcane production. According to recommendation by Hazelton and Murphy [54] Volumetric water content ranges from 10 to 50% and 2 to 30% for agricultural soils, respectively, at field capacity and permanent wilting points depending on clay content and type. In this respect, the volumetric water content at FC and PWP of the three estates are within this range and it implies the potential sugarcane plantation fields have for better productivity of sugarcane.

For all the sampled sites, soils under sugarcane had higher available water holding capacity than the uncultivated soils for all soil management unit groups (Table 3). The difference between cultivated land and uncultivated land in available water holding capacity might be due to higher bulk density of cultivated land use and the dominance of the clay fraction in affecting the available water holding capacity (Table 3). This is in agreement with the findings of Hillel [55] and Dang [56] who stated that the water content can be affected by percentage of the clay present in the soil since they tightly hold large amount of water in their large surface area. Mehta and Wang [57] also reported increase of available water holding capacity with increasing clay content.

Very slight variations in AWC among the cultivated soil management unit groups were observed. This may indicate that the existing soil management unit groups of the three estates are poorly related with soil physicochemical parameters including AWC. Similarly, different researchers verified the problems related to the soil management unit groups presently in use based on pF 2 classes [58]. Thus, irrigation interval, frequency and the amount of water for irrigation presently in use in the three estates are in question. This may call for periodic revision of the soil management groups based on their soil available water characteristics of the top 0.6 m wherein most cane root populations exist.

#### 3.2.2. Soil Water Retention Characteristic Curves

Soils at the three estates relatively high in clay content as well as silt plus clay, consequently, the release of water due to successive increment in matric potential points was very gradual in almost all the soil management unit groups (Figure 2). Nevertheless, in terms of their average volumetric water contents of each land use the presence of two distinct groups of soils were identified in each estate with respect to their water retention characteristic curves. At Wonji-Shoa Estate light cultivated, heavy cultivated, heavy uncultivated and light uncultivated; at Metahara Estate heavy cultivated, light uncultivated, light cultivated and heavy uncultivated; at Finchaa Estate vertisol cultivated, vertisol uncultivated and luvisol cultivated,



luvisol uncultivated showed nearly identical water retention characteristic curves.

**Table 3.** Average percent volumetric water contents at 33 and 1500 kPa matric potential points and available water of the three sugar estates.

Estates	SMUG*	Land use	Water retained (%v/v) at Pot.(kPa)		AWC (mm/m)*	Rating class
			-33	-1500		
Wonji-Shoa	Light	Un cultivated	41.48	25.62	158.60	Medium
		cultivated	35.88	19.32	165.60	Medium
	Heavy	Un cultivated	41.76	26.68	150.80	Medium
		cultivated	44.22	26.80	174.20	Medium
Metahara	Light	Un cultivated	47.50	31.25	162.50	Medium
		cultivated	54.18	37.41	167.70	Medium
	Heavy	Un cultivated	45.85	28.82	170.30	Medium
		cultivated	47.16	28.82	183.40	Medium
Finchaa	Luvisols	Un cultivated	43.21	25.33	178.80	Medium
		cultivated	46.69	27.37	193.20	High
	Vertisols	Un cultivated	41.60	24.70	169.00	Medium
		cultivated	50.16	30.40	197.60	High

\*SMUG=soil management unit groups; AWC=available water holding capacity

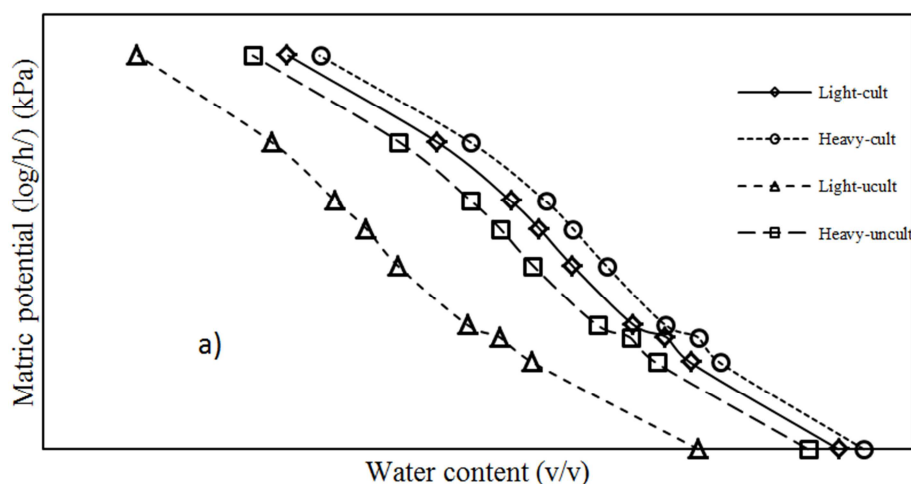
Beside this, at any suction point cultivated land use showed higher amount of water than uncultivated land use except in Metahara Estate greater for uncultivated heavy. The variation in water retention between cultivated and uncultivated land uses might be due to the differences in bulk density and clay contents. Moreover, this high retention of water of cultivated land use at the respective matric potential points could be related to good soil structure, which affects release of water in the wet range and the high specific surface of the clays which gives rise to high adsorptive forces at the dry range of the curve of cultivated land use. In agreement with this, Zeleke [59] also reported dependence of water retained at respective matric potential points on bulk density and clay content.

Moreover, the two land uses under different soil management unit groups have distinct difference in shape of the soil water retention characteristic curve at low suction range and dry range of the curve might be due to difference in degree of compaction and clay percentage of soils, respectively. In line with this Lipiec *et al.* [60] reported the dependence of water retained at low suction range and dry

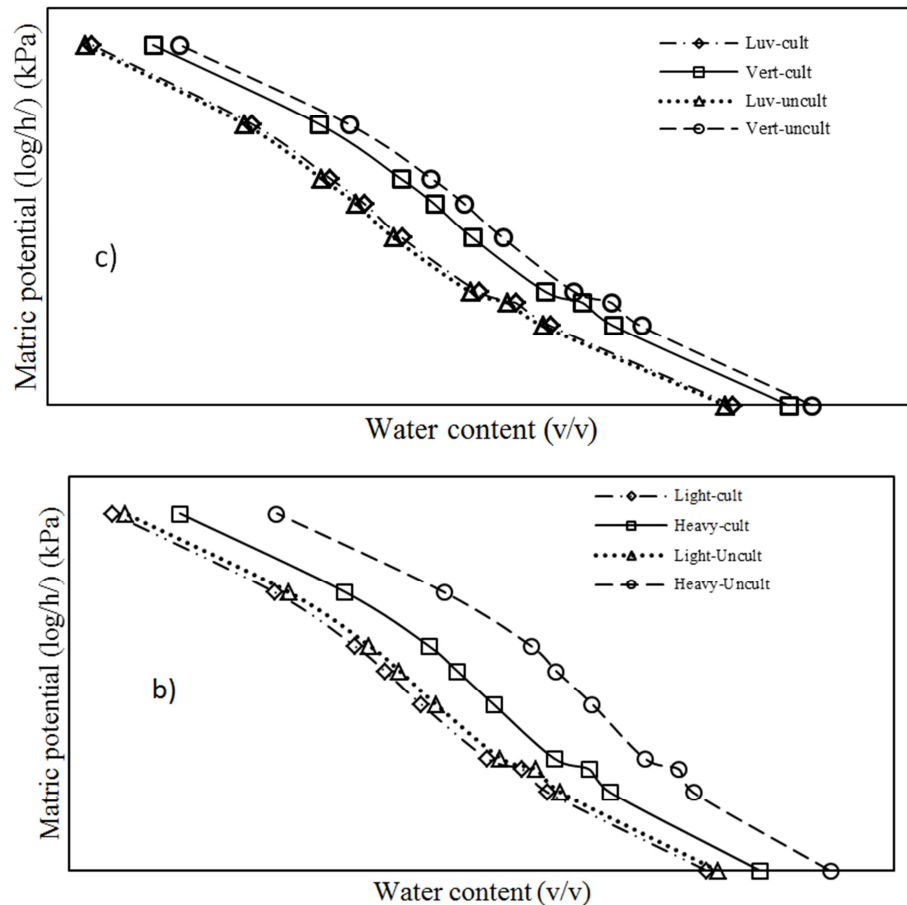
range of the curve on dry bulk density and clay content, respectively. It is also supported by the finding of Zhang *et al.* [61] which stated that clay percentage affects the shape of the soil water retention characteristic curve at lowest potential points (large negative tension values).

Long term cultivation of sugarcane induces soil compaction which decreases the total pore space of a soil mainly by increasing fineness of the soils and also number of meso and micropores in all the estates. As the fineness of texture increases, there is a general increase in the available moisture storage. This indicates that bulk density has a greater effect on water retention at low matric potential (matric potentials higher than -33 kPa).

The gradual releasing behaviors manifested by clay soils of Ethiopian Sugar Estates could be considered as an asset in cost benefit (by increasing the irrigation intervals) and to increase yield per fields of the estates if accompanied by good soil water managements. In line with this, Firehun *et al.* [62] +reported advantages of the estates clayey soils in increasing productivity of sugarcane under good management.







**Figure 3.** Matrix potentials (kPa) versus volumetric moisture content (v/v) of Wonji-Shoa (a), Metahara (b) and Finchaa Estates (c)

Light uncult.=light uncultivated, Heavy uncult.=heavy uncultivated, Light cult.=light cultivated, Heavy cult.=heavy cultivated, Log=logarithm; Luv.uncult.=Luvisol uncultivated, Luv. cult.=Luvisol cultivated, Vert. Uncult.=Vertisol uncultivated, Verti cult.=Vertisol cultivated

### 3.2.3. Infiltration Characteristics

The rate of infiltration of water in the soil is important factor that limits the water economy of plant communities and the amount of surface runoff. The results of analysis of variance showed that infiltration rate was significantly ( $P < 0.05$ ) affected by the land use types at all the soil management unit groups (Table 4). The basic infiltration rate was decreased with increasing of clay percentage except Metahara heavy soil management unit group (Table 4). Finchaa uncultivated Luvisol soils had the highest basic infiltration rate ( $4.73 \text{ cm. hr}^{-1}$ ) followed by Finchaa Vertisol uncultivated soils ( $4.30 \text{ cm hr}^{-1}$ ), whereas, Wonji-Shoa heavy cultivated soils had the lowest basic infiltration rate ( $0.99 \text{ cm hr}^{-1}$ ).

Accordingly, the mean basic infiltration rate value of uncultivated land was significantly ( $P < 0.05$ ) greater than the mean infiltration rate of the cultivated lands in all the soil management unit groups (Table 4). The results further indicated that long term cultivation decreased the basic infiltration rate by 56.06, 49.75, 19.21, 36.49, 45.67 and 48.14% as compared to the uncultivated sites, respectively, at light and heavy Wonji-Shoa, light and heavy Metahara, and Luvisols and Vertisols of Finchaa Estate. The lower

basic infiltration rate recorded in the cultivated sites could possibly be due to subsoil compaction of the cultivated fields during sugarcane cultivation using heavy machinery. The highest infiltration rate in Finchaa land uses might be indicated the presence of more porous surface conditions in Finchaa Estate soil management units than the other soil management unit groups. This is in resonance with the finding by Tullberg and Freebairn [63] who reported higher infiltration rate in uncultivated land than cultivated ones. Moreover, Dikinya [64] also reported infiltration rate of 55.37% more for uncompacted relative to compacted soils.

For Metahara Estate, the results were contrary to what was recorded at Wonji-Shoa for light and heavy soil management units in that the basic infiltration rate increased from light to heavy (Table 4). The relatively high infiltration rate recorded in the heavy soil management units of Metahara Estate could be attributed to the coarse pumic materials found in subsoil layer of most of the heavy soils in Metahara observed during soil sampling and field data collection as well as hidden subsurface cracks at the test sites, which is consistent with BAI [65] and Silva *et al.* [66] who reported highest IR value due to hidden subsurface crack at Metahara Estate.

**Table 4.** Effects of land use on basic infiltration of soils at the three Ethiopian Sugar Estates.

Estates	SMUG	Land uses	IR (cm hr <sup>-1</sup> )	Rating class
Wonji-Shoa	Light	Cultivated	1.45 <sup>b</sup>	Moderately slow
		Uncultivated	3.30 <sup>a</sup>	Moderate
		LSD	0.10	
	Heavy	Cultivated	0.99 <sup>b</sup>	Moderately slow
		Uncultivated	1.97 <sup>a</sup>	Moderately slow
		LSD	0.30	
Metahara	Light	Cultivated	1.43 <sup>b</sup>	Moderately slow
		Uncultivated	1.77 <sup>a</sup>	Moderately slow
		LSD	0.18	
	Heavy	Cultivated	2.14 <sup>b</sup>	Moderate
		Uncultivated	3.37 <sup>a</sup>	Moderate
		LSD	0.32	
Finchaa	Luvisols	Cultivated	2.57 <sup>b</sup>	Moderate
		Uncultivated	4.73 <sup>a</sup>	Moderate
		LSD	0.30	
	Vertisols	Cultivated	2.23 <sup>b</sup>	Moderate
		Uncultivated	4.30 <sup>a</sup>	Moderate
		LSD	0.34	

SMUG=soil management unit groups, LSD=least significant difference, IR=infiltration rate, and means with the same letters are not significantly different

As per basis of basic infiltration ratings established by Tekalign [67], the land uses of soil management units in the three estates can be grouped in to two rating classes, thus moderate (uncultivated light Wonji-Shoa, Metahara heavy soil management unit group both land uses, Finchaa both soil management unit group land uses), while, moderately slow classes include (Wonji-Shoa light cultivated, Wonji-Shoa heavy soil management unit group both land uses, Metahara heavy soil management unit group both land uses) (Table 4).

Moreover, interpretation of infiltration measurements for furrow irrigation as per ratings of El Ramlawi [68] showed that all of the land uses in the three estates are in suitable class for furrow irrigation. Nevertheless, according to Lozon *et al.* [69] rule of thumb for surface irrigation (surface

irrigation should be limited to soils having basic infiltration rates less than 3.6 cm hr<sup>-1</sup>); Finchaa sugarcane plantation soil management unit groups basic infiltration values are out of this range which might indicate unsuitability of Finchaa soils for furrow irrigation.

The time required to reach the basic infiltration rate varied between the land uses of soil management unit groups. The difference in time required to reach basic infiltration between land uses might be due to difference in initial moisture content and clay content of the soil. Soils with relatively high initial water content was reached basic infiltration rate within short period and long time (> 5 hrs) was taken for the soils with high clay percentage.

**Table 5.** Pearson correlation analysis of some selected soil physicochemical parameters.

	pb	F	Cl	SOC	TN	P
Wonji-Shoa Estate						
pb	1.00	-0.67***	-0.30 <sup>ns</sup>	-0.51*	-0.44*	-0.59**
f		1.00	0.09 <sup>ns</sup>	0.17 <sup>ns</sup>	0.15 <sup>ns</sup>	0.19 <sup>ns</sup>
Cl			1.00	0.77***	0.42*	0.69***
SOC				1.00	0.62**	0.81***
TN					1.00	0.70***
P						1.00
Metahara Estate						
pb	1.00	-0.69***	-0.04 <sup>ns</sup>	-0.01 <sup>ns</sup>	-0.02 <sup>ns</sup>	-0.09 <sup>ns</sup>
f		1.00	0.49*	0.05 <sup>ns</sup>	0.05 <sup>ns</sup>	0.50*
Cl			1.00	0.28 <sup>ns</sup>	0.41*	0.33 <sup>ns</sup>
SOC				1.00	0.79***	0.55**
TN					1.00	0.41*
P						1.00
Finchaa Estate						
pb	1.00	-0.77***	-0.29 <sup>ns</sup>	-0.31 <sup>ns</sup>	-0.50*	-0.47*
f		1.00	0.34 <sup>ns</sup>	0.11 <sup>ns</sup>	0.33 <sup>ns</sup>	0.45*
Cl			1.00	0.68**	0.34 <sup>ns</sup>	0.19 <sup>ns</sup>
SOC				1.00	0.84***	0.72***
TN					1.00	0.79***
P						1.00

Cl=clay content, San=sand content, Bd=bulk density, f=total porosity, N=total nitrogen, P=soil available P, SOC=soil organic carbon, and \*\*\*, \*\* and \*=Significant at P < 0.001, P < 0.01 and P < 0.05, respectively; ns=not significant.

## 4. Conclusion and Recommendation

The results of the study indicated that soils under sugarcane cultivation had higher clay contents than uncultivated soils at all the soil management unit groups. The bulk density and total porosity values were not optimum for sugarcane cultivation. For all the sampled sites, soils under sugarcane had higher available water holding capacity. Available water holding capacity of the three estates is above the threshold AWC value ideal for sugarcane cultivation. Very close variations were observed in AWC among the cultivated soil management unit groups. The mean basic infiltration rate value of uncultivated land was greater than the cultivated lands in all the soil management unit groups. Subsoil compaction induced in cultivated fields increased bulk density and decreased basic infiltration rate. Interpretation of infiltration measurements in terms of suitability for furrow irrigation indicated that Finchaa soils are not suitable for furrow irrigation.

From these findings one can conclude that long term cultivation of sugarcane induced soil compaction which decreased the total pore space of a soil mainly by increasing fineness of the soils and also number of meso and micropores in all the estates. The existing soil management groups of the three estates are poorly related with soil physical and hydraulic parameters. The gradual water releasing behaviors manifested by clay soils of Ethiopian Sugar Estates could be considered as an asset in increasing yield per fields of the estates if accompanied by good soil water managements.

Based on the findings and conclusions of this study the following recommendations were given as to maintain sustainability of sugarcane production in the three estates soil management practices that can protect/ ameliorate soil compaction is important. Nevertheless, to develop a concrete recommendation and to measure the long term effects further research studies are needed.

## Conflict of Interests

The authors declare that they have no competing interests.

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