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Extent of Soil Compaction under Mechanized Sugarcane Cultivation at Wonji-Shoa Sugar Estate

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Abstract: Ethiopian sugarcane estates use heavy machinery at all growth stages of cane crop from soil preparation to harvest although there is no well documented information on the effect of these heavy machineries on status of soil compaction. A study was conducted at Wonji-Shoa Sugar Estate to assess the status of soil compaction under mechanized sugarcane cultivation in 2017. Disturbed composite and undisturbed soil samples were collected from 0-30 and 30-60 cm depths from selected soil management units in the estate for laboratory analysis of some soil physical and chemical properties. The results indicated that the mean textural class of all the soils is clay (more than 40% clay). The dry bulk density values recorded vary from 1.15 to 1.42 gcm^{-3} indicating that most of the soils ranged from some too compact (1.2-1.4 gcm^{-3}) to very compact (1.4-1.6 gcm^{-3}) state. The penetration resistance tests that ranged from 0.54 to 2.46MPa indicated that the soils were medium (0.5-1.25 MPa) to very dense (2-3 MPa). The relative bulk density values also reveal that the soils were in the low (< 50%) to very high (> 70%) levels of soil compaction. The relative penetration resistance tests also confirmed that the sugarcane field soils of the estate were in little or none (< 30%) to severe (> 75%) levels of compaction. The soils were moderately to highly susceptible to compaction. In general, soil compaction assessments made using different indices indicate that soils of the estate fields were under different levels of compaction in which some are still unaffected, while others are in the process of being affected and some considerable proportions of their fields are already affected by soil compaction. Therefore, management interventions that sustain the conditions of the unaffected ones and alleviate the problems of the already affected ones are required in order to increase sugarcane production on a sustainable basis.

Key words: Mechanized Cultivation · Level of Compaction · Susceptibility · Vulnerability

INTRODUCTION

Sugarcane production in Wonji-Shoa Sugar Estate is heavily mechanized. Mechanized cropping system, characterized by the use of an increasing weight of agricultural machinery, has increased the occurrence of soil compaction and its detrimental effects on sugarcane production [1, 2]. Soil compaction occurs when soil particles are pressed together and pore space between particles reduced. The reduction in pore space restricts root growth, infiltration of water, increasing runoff leading to the loss of valuable nutrients and inefficient fertilizer and water use, restriction of gas exchange and reduced yields [3, 4].

The main causes of soil compaction in sugar estates are the forces from tyres of heavy agricultural machines during seed bed preparation, fertilization, molding, weeding and harvesting operations particularly in moist to wet soil conditions when the soil organic matter is low [5]. In mechanized cropping systems the continual use of tillage implements, especially disc ploughs, disc harrows, mould-board ploughing at the same depth over long periods of time frequently results in the formation of dense plough pans (compacted layers) just below the depth to which the soil is tilled, containing few pores large enough to be penetrated by crop roots [6].

The extent of compaction depends on the pressure exerted by the implements and total axle load of the machinery on the soil. Often visual observation of both the soil and crops can give clues as to the extent of soil compaction [7]. To guarantee that the observations are associated with compaction, soil investigations to

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measure soil compaction are necessary. Different approaches have been developed in agriculture and related disciplines to measure soil compaction. But an easily diagnostic tool to measure the extent and depth of subsoil compaction are relative bulk density and penetration resistance. Further, this tool can help producers to determine if subsoiling might be beneficial and at what depth the subsoiler should be set [8].

In Wonji-Shoa Sugar Estate, characterized by more than six decades of heavily mechanized sugarcane mono cropping with an average cycle of three ratoon crops and agricultural practices with limited nutrient recycling, soil compaction is inevitable. There is, therefore, a dire need to identify the current state of compaction in soils of the estate that have been under mechanized agriculture for different number of years. This is required not only for identifying appropriate measures for its avoidance but also to determine the extent and severity of soil compaction as well as susceptibility of soils in the estates to compaction.

The status of soil compaction within Wonji-Shoa Sugar Estate in Ethiopia has not been quantified adequately although the use of mechanised infield loading and transport has developed rapidly and there has also been a significant increase in the use of tractors for other field operations such as fertilizer application and weed control. Since the establishment of this estate, the size of infield vehicles has increased and haulage units of bigger capacity have been in use to extract cane from fields [9]. In other parts of the world, the use of these heavy vehicles has necessitated research into ways of reducing their destructive effects, leading to the development of various wheel and axle configurations, different types of tyres and management guidelines to minimize compaction. Nevertheless, this has never been done in the estate. Although it is widely perceived that traffic-induced soil compaction is a problem that has developed wherever agriculture has become highly mechanized [10] its effect on plants and soil properties has never been consistent. The assessment of the status of soil compaction in fields under long-term mechanization is, therefore, a pre-requisite for developing sound compaction management strategies.

In the absence of comprehensive management guide based on inherent properties of the soils, monocropping culture with tillage operations at the same depth for long time, tillage operation during inappropriate ranges of soil water content and limited application of organic amendments the soils of the estate is expected to be affected by soil compaction. To what extent the soils could be affected, nevertheless, has never been quantified. This study was, therefore, conducted to assess the status of soil compaction in long term cultivated fields of Wonji-Shoa Sugar Estate.

MATERIALS AND METHODS

General Description of the Study Areas: The study was conducted in 2017 at the commercial sugarcane production fields of Wonji-Shoa, Sugar Estate. The study areais found at a distance of 107 km from Addis Ababa within Oromia National Regional State (ONRS). Moreover, Wonji-Shoa Estateis located at 8° 21' 3.84?? to 8° 27' 25.86?? N and 39^{o} 12' 13.28 ?? to 39^{o} 18' 34.46 E in the central part of the East African Rift Valley at an altitude of 1540 and 950 meters above sea level in the Awash River Basin(Figure 1). The total area of land covered with cane was about 7050 ha[11].

The climate at Wonji-Shoais semiarid and the slope of the farm is generally very gentle and regular, which makes it suitable for gravity irrigation [12]. The rainfall distribution has a bimodal nature with the first and second rainfall occurring during February to April and mid May to September, respectively. The February to April rain is small rainy season, while the June to September is the main rainy season contributing significant proportion of the total annual rainfall. The mean annual rainfall in the study area is 831.47 [13]. Average annual maximum and minimum temperature of the estate is about 15.19 and 27.57°C, respectively (Figure 2).

The major geologic materials of Wonji-Shoa Estate 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 developed from materials laid down by river systems [14]. Vertisols and Fluvisolssoil types cover the major part of the estate [15]. At Wonji-Shoa Estate soils have been grouped for a long time according to their moisture content at pF2, i.e. at 0.1 bar or 10 kPa matrix potential. This grouping of soil management approach was adopted from Kuiper [16] though there is no documented information about the exact methodology, depth of sampling, number of measurements of samples and types of sampling for pF_2 soil classification of this estate. There are five pF2 classes at Wonji-ShoaEsate. The first three soil groups (A_1, A_2 and BA_2) are heavy textured soils; while the last two soil types ($B_{1.4}$ and C_1) are light textured soils [17].

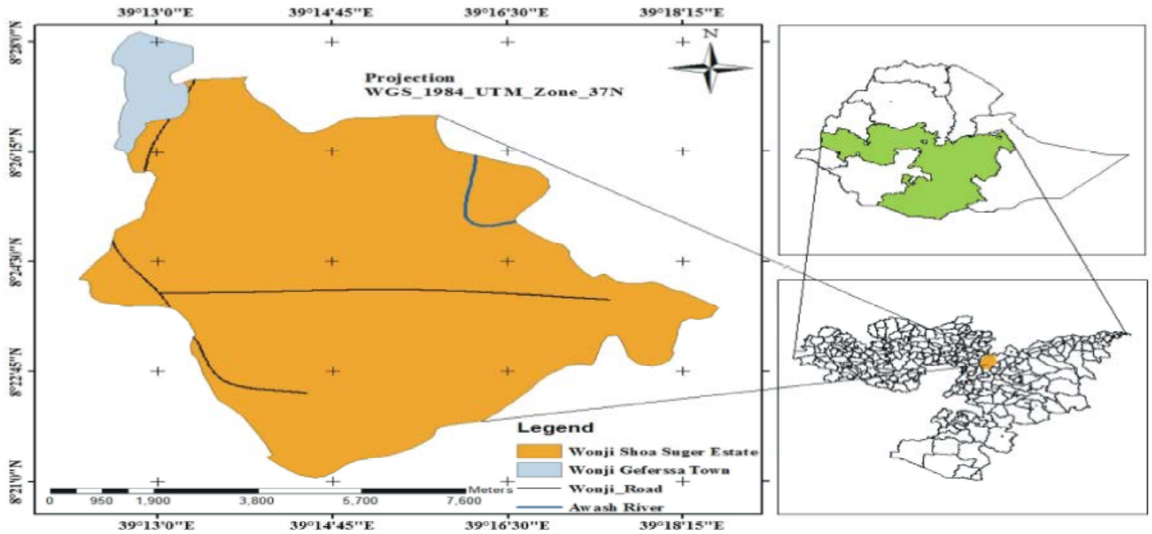

Fig. 1: Location maps of Wonji-Shoa Sugar Estate

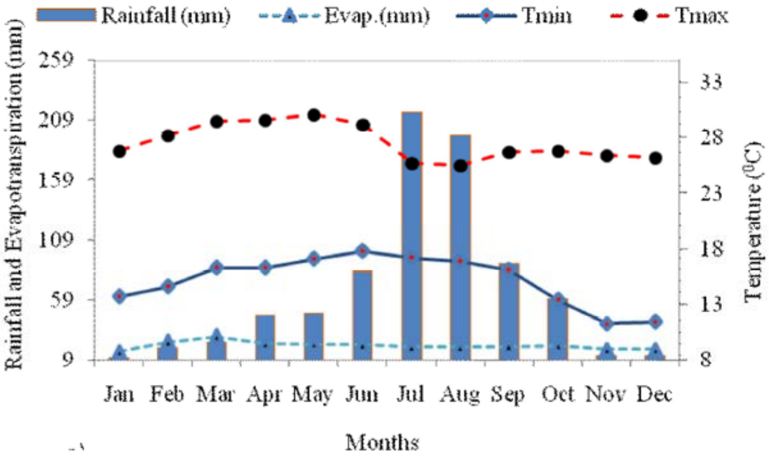

Fig. 2: Ten years mean monthly rainfall, evapotranspiration (Evap) and monthly minimum (Min) and maximum (Max) temperatures of Wonji-ShoaEstate

The inferred correlation between pF2 values and soil types assumes that water holding capacity is related primary to soil clay content, heavy, clayey soils hold more water than light, sandy soils. Soils holding least water C_1 of Wonji-Shoa, require more frequent but lighter applications than do the soils holding most water of A_1 of Wonji-Shoa Estate. The data are used to define the irrigation interval and the application rate of each field.

The estate's sugarcane production is undertaken with irrigation [18]. The source of irrigation water is the Awash River. The major crop of the estate is sugarcane, while haricot bean and crotalaria are minor crops. The average length of growing period of sugarcane (plant cane) in the estate is 22 months.

Sampling Site Selection, Soil Sampling and Sample Preparation: Field observations and soil sampling were carried out during the winter of 2016 at Wonjo-Shoa Estate that has been under sugarcane cultivation for more than 60 years. From the estate 45 sugarcane fields with records of recurrent reduced yield were identified for first step for field observation. The report of Girma [19] indicates that the yield reduction was due to soil related constraints such as soil compaction. Furthermore, qualitative soil compaction diagnosis at field level, based on set of criteria indicated in Duiker [20] was undertaken in order to select the final soil sampling fields. In accordance with these 15 fields representing the different soil management units (A_1, A_2, BA_2, $B_{1.4}$ and C_1)

with three replications were selected. By replicating each field, representing soil management unit, three times 45 soil sampling sites were identified.

From identified soil sampling sites disturbed and undisturbed soil samples were collected from top layer (0-30 cm) and sub layer (30-60 cm) of these selected sites by replicating each sampling field representing management unit three times.Both disturbed and undisturbed samples were collected from both depths. The undisturbed samples were collected using core sampler into which 5 cm height and diameter cores were fitted, while, the disturbed samples were collected using auger. For disturbed soil samples ten sub-samples were collected from each field using the X-pattern of sampling technique to make one composite sample per depth. On the basis of this, a total of 90 composite and undisturbed samples each were collected from the selectedsoil sampling sites' both layer of the estate. Further, ten soil samples of 50 kg each were collected from both layers of the estate soil management units for proctor test laboratory analysis.

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. The analysis for proctor test was carried out in the Transport and Construction Share Company Soil Test Laboratory in Addis Ababa. 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. The samples were crushed further to pass through 0.5 and 4.75 mm sieve diameter sieve for analysis of organic carbon or total nitrogen and for proctor test, respectively. The selected soil properties analyzed in the laboratory include particle size distribution, bulk and particle densities, proctor test density, soil pH, organic carbon, total nitrogen, available phosphorus.

Laboratory Analysis of Soils: Particle size distribution was determined by the Bouyoucos hydrometer method as described by Okalebo *et al.* [21]. The textural class was determined using the USDA soil textural triangle. Moreover, bulk density was computed from the values of oven dry soil mass and volume of core sample as described by Jamison *et al.* [22]. Particle density of the soils was determined using the pycnometer method following the procedure described in Rao *et al.* [23]. Total porosity was calculated from the values of bulk density and particle density using the method described by Rowell [24]. The soil moisture in the samples was also determined gravimetrically as described by Reynolds [25]. Proctor test was determined following the procedures outlined by American Society of Testing Materials [26]. For analysis for proctor test in the laboratory, a modified proctor test was applied at different water contents to obtain the maximum dry density of the soils. The samples were compacted by dropping a 4.5 kg rammer 125 times from a height of 45 cm.

Soil pH was determined in soil to water ratio of 1:2.5 by glass electrode pH meter [27]. Organic carbon was determined using the wet digestion and oxidation method as described by Walkly and Black [28]. Total N content in the soils was determined using the Kjeldahl procedure [29]. Soil available phosphorus was determined according to the Olsen's method [30] except for Finchaa Estate where Bray II extraction method was used for soils withpH < 6 [31]. The P extracted with different methods was measured by spectrophotometer following the procedures described by Murphy and Riley [32]. The laboratory soil analysis results were summarized in to mean at soil management unit (SMU) levels.

Field Measured Parameters: Penetration resistance was measured using a manually operated soil cone penetrometer ASAE [33] with a cone base diameter of 11.28 mm and 15.96 mm with cone angle of 30° per each selected sampling site. The cone was hand-pushed into the soil at a uniform rate of 2 cm sec^{-1}. Six penetration resistance measurements were taken from each sampling site and the parallel values at each depth were expressed as an average. As a reference, maximum penetration resistance value of 3 MPa was used as described in equation 2.

Furthermore, roots of randomly selected cane plants from each of the sampling sites of the estate were carefully removed and immersed into a container filled with water and kept for about 3 hours in order to remove soil lumps from the roots gradually. After washing the roots, dry root biomass was measured using digital balance by cutting the roots into 10 cm pieces along the root depth (to 60 cm depth) and dried at 70°C to constant weight for about 24 hours. This was done in order to evaluate the likely impacts of compaction on root proliferation and biomass [34].

Assessment of Soil Compaction: To characterize the levels of soil compaction, the approach proposed by Bennie and Van Antwerpen [35] for semi arid and arid regions was used (Eq. 1):

$$R_d = \frac{B_d - B_{d\,\min}}{B_{d\,\max} - B_{d\,\min}} \tag{1}$$

were: R_d is relative bulk density (unit less), B_d = measured bulk density (Mg m^{-3}). B_{dmax} is maximum bulk density measured by proctor test method per each soil management unit, B_{dmin} is minimum bulk density.

Furthermore, the method used by Murdock *et al.* [36] was applied to characterize the status of soil compaction using relative penetration resistance data (Eq. 2):

$$PPR = \frac{PR(measured)}{PR_{\max}} \quad (2)$$

where: RPR = relative penetration resistance (unit less). To relate values of the RPR to level of compaction and to categorize soils according to their different compaction levels, a reference maximum penetration resistance was used regardless of clay type and texture as proposed by Bennie and Burger [37].

where PR = penetration resistance (MPa) measured, PR_{max} = maximum penetration resistance (MPa). Maximum penetration resistance is the critical penetration resistance beyond which extension of root is strictly limited.

Data Analysis and Interpretation: The soil parameters measured in the laboratory and field were compared using their mean values and critical levels for all surveyed fields of the estate.

RESULTS AND DISCUSSION

Status of Selected Soil Properties in Wonji-shoa Sugar Estate

Particle Size Distribution: The particle size distribution data of soils of the estate indicates the existence of particle size distribution difference among the management units within the estate. In general terms, the heavy textured management units of Wonji-Shoa have greater clay content than the light-textured management units. Furthermore, the management units are also different in their sand content. Accordingly, the heavy-textured management units at Wonji-Shoa have relatively lower sand content than the other respective management units in the estate (Table 1). The highest clay percent (87.3%) was found in Wonji-Shoa A_1 subsoil layer.Nevertheless, the difference in particle size distribution is not fully reflected in the textural class names. Accordingly, soil samples collected from all the management units have a mean clay content that is greater than 40%, sand ≤ 45% and silt < 40%, which means that the textural class is all clay. This makes the present classification of the soils into different management units questionable. The soils may have differences in clay mineralogy. The classification, therefore, requires revisiting for better management of soils in the estate.

The slight differences observed in particle size distribution among the management units could be associated with differences in topographic position. Topography affects particle size distribution in such a way that soils at the bottom of slopes generally have higher clay contents [40]. According to the report by Michael and Seleshi [41], Wonji-Shoa farms have generally very gentle and regular slope (less than 1%). Similar to this Mohammed *et al.* [42] reported variation of textural class with slopes of the fields.Furthermore, the trend of particle size distribution with depth indicates a general increase with soil depth of clay content and decrease in silt and sand contents. The increase in clay content with soil depth could be attributed to downward translocation of clay from the upper layers. In consent with this finding, Zeleke [43] reported increase of clay content with depth in soils of Metahara Estate and attributed this to downward translocation of clay from the upper soil layers.

Soil Bulk and Particle Densities, Total Porosity, Penetration Resistance and Dry Root Biomass: Differences in dry soil bulk density among management units within the estate were recorded (Table 2). Furthermore, the bulk density of the top soils was slightly lower than the corresponding subsoils in all soil management units of the estate. Also, in the estate, the soils of the light textured management units generally had slightly higher bulk density values than the heavy textured ones. The bulk density values , except for C_1 and $B_{1.4}$ soil management units, were below the critical bulk density value (< 1.40 gcm^{-3}) for plant growth at which root penetration is likely to be severely restricted in a clayey soil [44]. On the other hand, Reichert *et al.* [45] explaining the effects of bulk density on soil conditions, indicated that, for a clay soil, bulk density values in the range of 1.2-1.4 g cm^{-3} imply that the soils are in a state of some to too compact, while bulk density values between 1.4 -1.6 g cm^{-3} indicate that the soils are very compact. Based on this assessment, the soils of the estate are under some to too compact and very compact conditions.

The results obtained indicate that, although the soils have been under long-term mechanized agriculture, soil compaction of detrimental and permanent nature has not

Table 1: Variation of particle size distribution among soil management units in Wonji-Shoa Estate

	Particle size distribution (%)						Textural class	
	Sand		Silt		Clay			
SMU	0-30	30-60	0-30	30-60	0-30	30-60	0-30	30-60
A1	7.47	3.03	14.83	9.67	77.70	87.30	C	C
A2	9.17	8.03	15.83	9.67	75.00	82.30	C	C
BA2	8.30	7.80	17.00	14.00	74.70	78.20	C	C
B1.4	16.00	16.50	27.00	24.00	57.00	59.50	C	C
C1	26.00	27.13	28.00	21.67	46.00	51.20	C	C

SMU = soil management unit; A1, A2, BA2, B1.4 and C1 are letters to designate the first second, third, fourth and fifth soil management units, respectively;C=Clay

Table 2: Bulk density and penetration resistance values of the different soil management units in the Wonji-Shoa Sugar Estate

	ρb (gcm^{-3})		ρ_p (gcm^{-3})		f (%)		PR (MPa)	
SMU	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
A1	1.15	1.16	2.02	2.03	43.10	42.90	0.70	0.84
A2	1.18	1.19	2.08	2.13	43.30	44.00	0.54	0.77
BA2	1.2	1.21	2.12	2.03	43.40	40.4	0.60	0.74
B1.4	1.23	1.42	2.04	2.42	39.71	42.00	1.04	2.46
C1	1.28	1.40	2.17	2.36	41.00	40.70	0.97	1.31

SMU = soil management unit; A1, A2, BA2, B1.4 and C1 are letters to designate the first second, third, fourth and fifth soil management units, respectively; MPa = Mega Pascal; ñb = bulk density; $ñ_p$ = particle density; f = total porosity, PR = penetration resistance

occurred in most soils of the estate. The probable reason could be that the soils have natural ability to heal themselves from compaction through, for instance, swelling following irrigation. Furthermore, the slightly higher bulk density values in the subsurface soils might be due to compaction resulting from continuous cultivation at the same depth for long time in addition to the commonly known effects of the overlying soil material and generally low levels of organic matter and the resulting poor aggregation. In support of the findings in this study, Botta *et al*. [46] reported the existence of subsoil compaction as a result of number of passes of heavy machines at the same depth. Moreover, the slight differences in soil bulk density among the soil management units might reflect the differences in inherent properties of the soils, which cause them to respond to external forces differently. In agreement with this, Barzegar *et al*. [47] reported that heavy machines of different weights caused different degrees of bulk density increases in different soils.

The penetration resistance tests made using cone penetrometer indicate that the highest penetration resistance was recorded for $B_{1.4}$ (2.46 MPa or very dense) in subsoil layers, while the lowest penetration resistance value (0.54 MPa or medium) was determined for A_2 top soil layer as per rating by Whalley *et al.* [48] (Table 2). As pointed out by Passioura [49] and Lipiec and Hatano [50] the medium compaction indicates a soil condition whereby root growth of sugarcane plants may be restricted. Similarly, the dense and very dense compaction indicate soil conditions in which root growth of sugarcane will be badly restricted and very few roots penetrate the soil, respectively. Therefore, majority of the soil conditions in the estate are in a state where the growth of cane roots may be restricted. However, some of the soils have also reached a stage where root penetration may be very difficult (soil management unit $B_{1.4}$). This indicates the increasing difficulty to penetrate the soil beyond these layers.

Both bulk density and penetration resistance values showed similar pattern so that highest values were recorded for light soils of Wonji-Shoa Estate. While, the lowest bulk density and penetration resistance values were recorded for heavy Wonji-Shoa. Similarly, research reports showed both linear [51] and non linear logarithmic relationship [52] between bulk density and penetration resistance. It is also important to note that soils with relatively high clay content in Wonji-Shoa, such as A_1, A_2 and BA_2, showed least penetration resistance as well as bulk density. Furthermore, the very dense compaction recorded in the subsoil layer of soil management unit $B_{1.4}$ in Wonji-Shoa is attributed to the presence of a 5 cm thick hard pan observed during soil sample collection.

Relatively higher values of penetration resistance and bulk density were recorded at the subsoil than top soil layers. The relatively higher values of penetration resistance as well as bulk density recorded in the subsoil layers than top soil layers of the soil management units could be attributed to subsoil compaction or presence of some clay pans in the subsoil layers resulting from continuous cultivation at the same depth and inevitable moisture content differences at the time of measurement. In line with this, Etana *et al.* [53] reported high penetration resistance value for compacted subsoils and hard pans and dependence of penetration resistance on soil moisture content at the time of measurement. The slight differences in penetration resistance and bulk density values among the management units could also be reflections of differences in their level of compaction, differences in moisture retention and structure, among others.

The particle density of all the soil management units studied is below the average particle density of 2.65 g cm^{-3}, which indicates that the soils are composed of light minerals (Table 2). Furthermore, in all the soil management units studied, the particle density values of the top soils are slightly higher than the values in the subsoils. This might be attributed to the relatively higher soil organic matter content in the top soils (Table 4), which weighs less per unit volume.

The total porosity of the different soil management units, both in the top and subsoils, was between 39.71 and 44%. Except in A_2 and $B_{1.4}$ management units in Wonji-Shoa, the total porosity of the topsoils was slightly higher than the corresponding subsoils in the estate. The variation of the total porosity with depth is in line with the variation of bulk and particle densities.

From the measurement of the maximum root length of the largest root, restriction of roots in the upper 60 cm soil depth was observed. In consent with this finding, BAI [54] reported that 90% of the root population was found in the upper 60 cm of the soils in Ethiopian Sugarcane Estates. The data presented in Table 3 reveals a sharp decline in dry root mass with an increase in penetration resistance from 0.54 (little) to 2.46 MPa (severe) in Wonji-Shoa Estate investigated sites. It seems that root penetration is poor when the resistance exceeds 2.41 MPa as a result of which the roots of sugarcane plant were found concentrated in the upper 40 cm of the soils in all the surveyed fields (Table 3) and decreases with increase of soil depth and levels of compaction. Li *et al.* [55] also correlated dry root weight with penetration resistance and found an inverse relationship.

The critical penetration resistance of soil at which root elongation stopped was a function of clay content and ranged from 2.41 to 2.46 MPa in clay textured soils of the estate. This is in agreement with the finding of Mcphee *et al.* [56] who reported low critical penetration resistance for fine soils. Grand total dry root weight was maximum for heavy-textured soils of Wonji-Shoa where levels of compaction varied from little to moderate. On the other hand, the lowest grand total dry root weight was determined for $B_{1.4}$ soil management unit for which compaction level was severe (Table 3).

Selected Soil Chemical Properties: Differences in soil pH among the management units were also noted (Table 4). The pH of both the surface and subsurface layers of soils at Wonji-Shoa Estate was in the range of moderately to strongly alkaline [57]. As reported in Arain *et al.* [58], the optimum pH required for sugarcane cultivation should be between 6.50 –7.0 and most of the primary nutrients like nitrogen; phosphorus and potassium and secondary nutrients like calcium and magnesium are best utilized by sugarcane crop when the soil pH ranges between 5.50 to 7.90. In this regard, the pH of some soils of the sugar estate was within the range that does not limit the availability of these nutrients. However, few of soil pH values of the estate were out of the optimum ranges. The strongly alkaline reaction recorded in some management units of Wonji-Shoa Estate require serious attention as the pH range recorded in those soils is considered not suitable for sugarcane production.

Limited leaching due to impeded internal drainage associated with the high clay content and also compaction might be among the reasons for accumulation of base-forming cations in these soils. On the other hand, the variation in soil pH with soil depth was not consistent albeit some general increases were observed in some management units. In consent with this finding, Ambachew *et al.* [59] reported high pH values in soils with impeded internal drainage in soils of Wonji-Shoa Estate and attributed this to limited leaching of base-forming cations (Table 4). Therefore, soil management practices that reduce high pH value of soils at Wonji-ShoaEstate have positive effect in improving sugarcane production.

Although some slight variations in soil organic carbon content among the management units were noted, the organic carbon content of all the soils was within the range of very low (< 2%) following the Landon [60] rating of soil organic carbon. The lowest soil organic carbon content (1.1%) was found in the topsoil layer

Table 3: Effects of penetration resistance and level of compaction on total dry root biomass in soils of selected management units

	PR (Mpa)		RPR (%)		TDRM (g)		
SMU	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	GTDRM (g)
A_2	0.54	0.78	23.00	31.00	68.40	31.95	100.35
Levels of comp			Little	Little			
B1.4	1.04	2.46	50.00	90.00	54.20	0.20	54.40
Levels of comp			Moderate	Severe			

SMU= soil management units; A2= heavy soil management unit; B1.4 = light soil management unit; TDRM = total dry root mass, GTDRM = grand total dry root mass, PR = penetration resistance, Comp = compaction, RPR = relative penetration resistance

Table 4: Selected soil chemical properties of the Wonji-Shoa Estate

	pH		SOC (%)		TN (%)		Available P (ppm)	
SMU	0-30	30-60	0-03	30-60	0-30	30-60	0-30	30-60
A1	7.62	7.60	1.40	1.23	0.08	0.08	4.82	4.32
A2	7.60	7.51	1.33	1.13	0.09	0.08	6.20	5.20
BA2	7.60	7.50	1.43	1.20	0.07	0.07	9.20	7.50
B1.4	7.80	8.20	1.30	1.10	0.07	0.06	6.50	5.71
C1	8.29	8.31	1.10	0.90	0.06	0.06	7.30	3.20

SMU = soil management unit; A1, A2, BA2, B1.4 and C1 are letters to designate the first second, third, fourth and fifth soil management units, respectively; SOC = soil organic carbon; TN = total nitrogen; P = phosphorus

of Wonji-Shoa C_1 soil management unit. The highest soil organic carbon content was recorded for heavy soil management unit groups than light. This may be attributed to higher clay content of heavy than light soils. Clay helps to protect organic matter from breakdown, it causes environmental conditions that favor higher organic matter content by forming physical barriers such as higher soil moisture content and less aeration which limits microbial access, thus, decomposition occurs slowly. Similarly, Maunuksela *et al.* [61] reported higher content of organic carbon due to limitation to microbial access formed by high clay content.

On the other hand, the organic carbon content of the top soils was slightly higher than the subsurface soils of all the selected soil management units in the estate (Table 4). The very low organic carbon content in the subsoils could mean low biological activity, due to limited energy sources for microorganisms in the soils and, thus, poor soil physical and chemical conditions in the soil system. These poor soil conditions (e.g., poor soil structure) may create unfavorable conditions (e.g., increased susceptibility to compaction) for optimum growth of sugarcane. Moreover, a decline in soil organic carbon is probably the clearest indicator of unsustainable land management. Such very low organic carbon content in estate could be due to intensive long term cultivation under hot climate since tillage introduces oxygen and breaks aggregates to expose SOC that was formerly protected from decomposition. In line with the findings of this study, Usaborisut and Niyamapa [62] reported decline in soil organic matter with continuous sugarcane production. Thus, to maintain higher sugarcane production in Wonji-Shoa Sugar Estate, the low level of soil organic carbon should be improved by introducing soil management practices that can increase organic carbon in soils.

In line with the very low level of soil organic carbon in soils of the estate, the total nitrogen content was also in the range of very low [63] (Table 4). This is expected since more than 90% of the total nitrogen is contained in soil organic matter. Although there is no established empirical relationship between total nitrogen and plant available forms of nitrogen for Ethiopian soils, the results of this study clearly indicate that soils of the estate are likely to have nitrogen deficiency. In line with this lowest total N content due to intensive cultivation in was also reported by [64]. The variation of total nitrogen with soil depth also closely followed the trend of soil organic carbon in which case the total nitrogen content of the top soils was relatively higher than the corresponding subsoil layers.

The available P content of the different soil management units of the estate also exhibited some degree of variation. Furthermore, in all the soil management units, the available P content of the top soils was relatively higher than the corresponding subsurface soils (Table 4). The available P content of the soils was in the range of low (< 5 ppm) to medium (5-15 ppm) following the rating suggested by Tekalignand Haque [65]. This indicates that P could also be among the

Table 5: Levels of soil compaction versus soil management units using relative bulk density of the Wonji-ShoaEstate

	Proctor Bd_{max} (gcm^{-3})		Rd (%)		Levels of compaction	
SMU	0-30	30-60	0-30	30-60	0-30	30-60
A1	1.25	1.32	23.00	11.00	Low	Low
A2	1.30	1.34	29.00	27.00	Low	Low
BA2	1.33	1.32	32.00	42.00	Low	Low
B1.4	1.43	1.44	31.00	86.00	Low	Very high
C1	1.56	1.57	30.00	58.00	Low	Medium

SMU = soil management unit; A1, A2, BA2, B1.4 and C1 are letters to designate the first second, third, fourth and fifth soil management units, respectively; Proctor Bd_{max} = maximum bulk density determined by Proctor test method; Rd = relative bulk density

Table 6: Levels of soil compaction of the soil management units based on relative penetration resistance

	PR (MPa)		RPR (%)		Levels of compaction	
SMU	0-30	30-60	0-30	30-60	0-30	30-60
A1	0.70	0.84	26.00	27.00	Little or none	Little
A2	0.54	0.78	23.00	31.00	Little or none	Slight
BA2	0.60	0.74	23.00	28.00	Little or none	Little
B1.4	1.04	2.46	50.00	90.00	Moderate	Severe
C1	0.98	1.31	36.00	44.00	Slight	Slight

SMU = soil management unit; A1, A2, BA2, B1.4 and C1 are letters to designate the first second, third, fourth and fifth soil management units, respectively; PR = penetration resistance; RPR = relative penetration resistance

yield-limiting nutrients in soils of the estate. In line with this finding Ademe [66] also reported the yield limiting case of soil available P. The results of the selected soil chemical analysis indicated that soils of the estate are constrained by strongly alkaline soil reaction and, low levels of soil organic carbon, total nitrogen and available phosphorus.

Levels of Soil Compaction Based on Relative Bulk Density and Relative Penetration Resistance: The values of relative bulk density indicate that soils of the estate were under different levels of compaction (Table 5). Based on relative bulk density measurement interpretations suggested by Hazelton and Murphy [67] (Table 5), Wonji-Shoa soils were under low soil compaction level except subsoil layers of B1.4 and C1 which were under very high and medium compaction levels, respectively. Although the soils had low level of compaction for some management units, for fine textured soils with low density, with very limited macro-porosity only a small reduction in this porosity would have a very significant adverse effect on their physical properties [68].

The results of assessment of soil compaction based on relative penetration resistance also indicate that the different soil management units in the estate experienced different levels of compaction (Table 6). As per relative penetration resistance measurement interpretation (Table 6), soils of Wonji-Shoa were under little or none to slight levels of compaction except in soils of $B_{1.4}$ management unit where the compaction was moderate in the topsoils and severe in the subsoils (Table 6). The results obtained based on relative penetration resistance also indicate that some of the soils in the estate are already affected by soil compaction, while others are potentially under threat.

In general terms, the results in Wonji-Shoa were slightly different with results obtained using relative bulk density. The difference in levels of compaction in terms of bulk density and penetration resistance especiallyin the top layer of $B_{1.4}$ in Wonji-Shoa is attributed to the presence of a 5 cm thick hard pan that can be detected only by penetrometer. Variation in levels of compaction using the values of the two parameters for all management units may be attributed to disparity in soil conditions under which the measurements were made for the two parameters such as water content and soil structure. Similarly, Silva *et al.* [69] reported that in cultivated soils higher bulk density and greater soil depth result in higher penetration resistance, while the rate of change in penetration resistance with bulk density was greater at lower soil moisture content.

On the other hand, the few contrasting results obtained using relative bulk density and relative penetration resistance reflect the existence of differences in soil conditions under which the measurements were made and highlight the need for standardizing the measurement conditions, such as soil moisture content.

CONCLUSIONS AND RECOMMENDATION

Results of the present study indicate that soils of the study area generally have high clay content (> 40%) with a clay textural class. Soils of some management units at Wonji-Shoa Estate have problems related to high pH level. Soils of the estate are generally low in their organic carbon and total nitrogen level and also available phosphorus. The results of the compaction assessment made using various indices indicated that some of the soil management units in the estate are still free from compaction, while others are being compacted and still some others are already affected by compaction seriously. the results of the study clearly indicate that soil compaction is among the constraints affecting sugarcane production in the Wonji-Shoa Sugar Estate and, thus, require serious attention in order to maintain favorable soil conditions for sugarcane production. To avoid the contrasting results obtained using the different indices from two tools, the most robust index should be selected to critically evaluate the status of soil compaction for designing management strategy. Selection of the correct index should be taken as an important aspect in the compaction evaluation process in the future.

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