Research Article **AJAR (2020), 5:78**

American Journal of Agricultural Research (ISSN:2475-2002)

Effects of Compaction at Different Moisture Contents on Selected Soil Properties and Sugarcane Growth and Sugar Yield at Metahara Sugar Estate

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ABSTRACT

Although soil compaction has been reported as one of the most serious problems in mechanized sugar cane production, its impacts on soil physicochemical properties and plant growth and sugar yield have not been quantified in the Ethiopian Sugar Estates. A field experiment was conducted in 2016 at Metahara Sugar Estate with the objective of evaluating the effects of initial soil moisture content and number of tractor passes on compaction and resulting impact on selected soil physicochemical properties and sugarcane growth parameters and sugar yield. The field experiment consisted of factorial combinations of compacted soils at three different soil moisture levels (on 4th, 8th and 12th days after irrigation) and six tractor traffic passes (0, 4, 8, 12, 16, and 20 passes) which were replicated three times. The result of the study showed that the highest mean values of dry bulk density and penetration resistance were recorded in plots compacted by twenty to and fro passes of tractor. Both bulk density and penetration resistance showed non-linearly increasing pattern with increasing number of passes. The tallest (196 cm) and shortest (171 cm) cane at the age of 8 months were recorded, respectively, in plots with zero and 20 passes of tractor. Significantly higher values of sugar yield were recorded in plots with zero number of passes (control). Imposing of different number of passes on 4th and 8th days after irrigation gave significantly lower yield than the 12th day after irrigation. Bulk density of the studied farm fields recorded after compaction by 20 traffic passes on the 8th day after irrigation, which corresponded to a gravimetric moisture content of 29.30%, was in excess of the root restriction initiation level. These results imply that it is advisable to avoid field operations involving Magnum 315 tractor on light soils before the 8th day after irrigation and when the gravimetric moisture content of the soils is at/near 29.30%. Management plans should include subsoiling operations to loosen soil in the field only when compaction levels exceed 1.45 g cm-3 (clay texture). There is a need for future study on other areas such as the heavy soils, other tractor passes and moisture levels of soils and other sugar cane varieties at the estates.

Key words: Tractor traffic rates; Sugarcane; Number of passes; Soil moisture

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How to cite this article:
Tesfaye Wakgari, Kibebew Kibret, Bobe Bedadi,Melesse Temesgen, Teklu Erikossa. Effects of Compaction at Different Moisture Contents on Selected Soil Properties and Sugarcane Growth and Sugar Yield at Metahara Sugar Estate. American Journal of Agricultural Research, 2020,5:78.

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INTRODUCTION

Ethiopia is endowed with suitable land, climate and immense water body for sugarcane production. For optimum germination and growth of sugarcane plants the availability of nutrients and loose enough soil for root penetration are crucial [1]. In spite of this, sugarcane production demands a great intensity of vehicular activities. The issue of soil fertility and crop yield reduction due to compaction problem particularly for sugar estates in which tractorization is the mode of all field operations including land preparation, weeding, fertilization, molding, and harvesting is a well recognized problem in many parts of the world [2]. There are two forms of compaction; topsoil and subsoil compaction. Compaction in the top 30 cm of soil is due to ground contact pressure. Compaction in the upper part of the subsoil, from about 30 cm to 50 cm, is caused by a combination of ground contact pressure and axle load. Compaction in the lower subsoil is caused by high axle loads when the soil is wet [3].

There are complex interrelationships among number of passes, bulk density, porosity, penetration resistance, soil water content and soil-plant interactions. These properties are influenced by factors such as soil texture, organic matter content, and the type and magnitude of external force applied [4]. Similarly, study by [5] made on sugarcane growth have demonstrated that compaction affects the growth and yield of the sugarcane crop by affecting primarily the pore space, which in turn affects root development, gas exchange rates, soil strength, nutrient availability, infiltration rate and hydraulic properties of soils. However, in Ethiopian sugarcane fields, where soil compaction is recognized as one of the serious problems, there is no research conducted to examine the effects of soil compaction on soil physicochemical properties and plant growth parameters. It is important to quantitatively know the effects of machinery traffic during the production of sugarcane on soil physicochemical properties and yield of sugarcane under Ethiopian condition in order to improve its productivity. This study was conducted, therefore, to determine the effects of initial soil moisture content and number of tractor passes on compaction and resulting impact on soil physicochemical properties.

MATERIALS AND METHODS

General Description of the Study Areas : The study was conducted at Metahara Sugar Estate which is located in the central part of the East African Rift Valley system at 8^{o} 45' 4.16" to 8^{o} 53' 20.75" N and 39^{o} 49' 10.74" to 40^{o} 0.21' 1.48" E. It has a semi arid climatic condition (Figure 1). The

estate is located at about 200 km southeast of Addis Ababa. The total area under cultivation is about 10, 248 ha with an average cane yield of 165 t ha^{-1} [6] (Figure 1).

The study area is characterized by diverse physiogeographic features. The slope of the field is generally very gentle and regular which makes them suitable for gravity irrigation [7]. The Estate is found at altitude of 950 meter above sea level in the Awash River Basin. The mean annual rainfall in the study area is 539.39 mm. Ten years (2003-2013) climatic data (Figures 2) of the Metahara Estate 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. Average minimum and maximum temperatures of the estate are about 17.73 and 33.24 ^{o}C, respectively [8].

Majority soils of Metahara Estate is 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 [9]. Soils of the estate are classified as Calcaric Cambisols [10]. Moreover, the estate is grouped into a total of six soil management units. This grouping of soil management approach was adopted from [11] 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 the estate. The first three soil groups (Class-$_4$, Class-$_5$, and Class-$_6$) of the estate are heavy textured soils; while the last three soil types (Class-$_1$, Class-$_2$ and Class-$_3$) are light textured soils [12]. Furthermore, the light textured soils require frequent but light irrigation, while the heavy textured ones require less frequent but heavy irrigation [13].

The average land productivity of the estate is about 165 tonnes of cane per hectare. These make the Ethiopian Sugarcane plantation farms one of the highest cane producing farms in the world [14]. 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 in the estate. The most widely used fertilizer in the study area is ammonium sulfate nitrate (26% N) with the application rates of 300 kg ha^{-1} for planting sugarcane, 500 kg ha^{-1} for the second and third cuttings and 650 kg ha^{-1} for the fourth and subsequent cuttings [15]. 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.

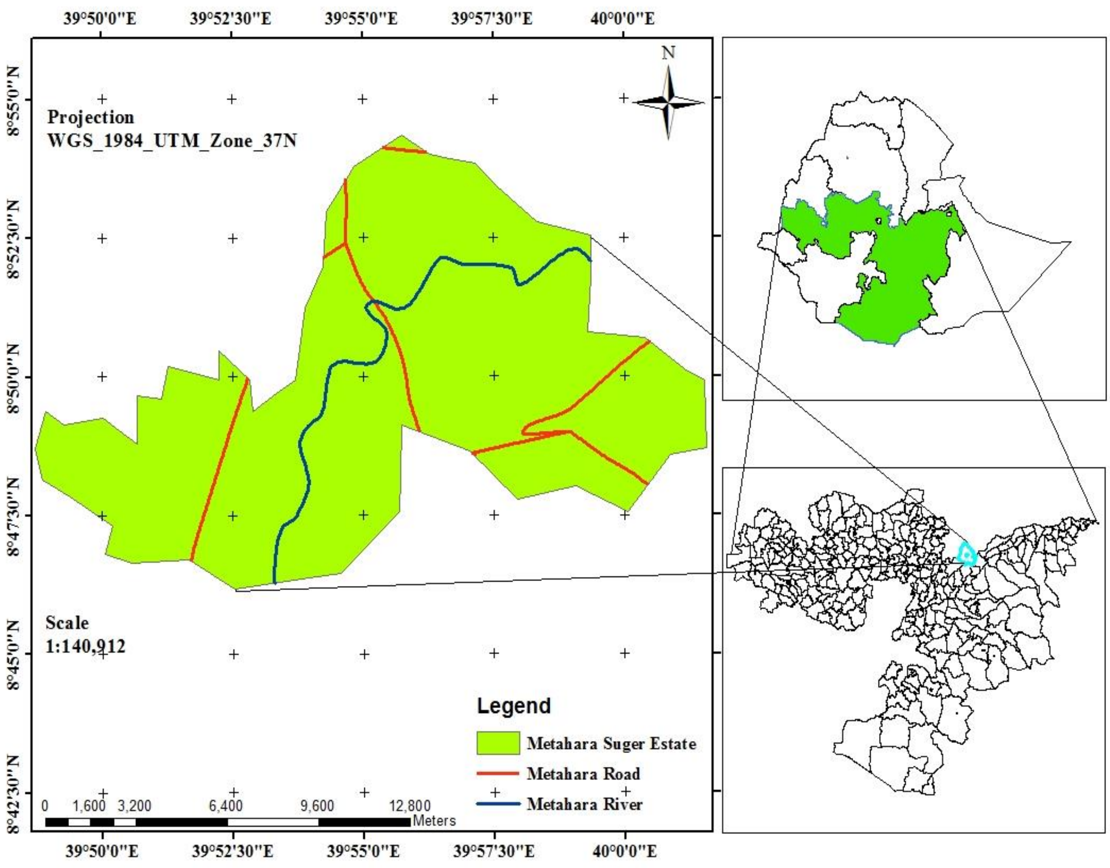


Figure 1. Location Map of the Metahara Sugar Estate in Ethiopia

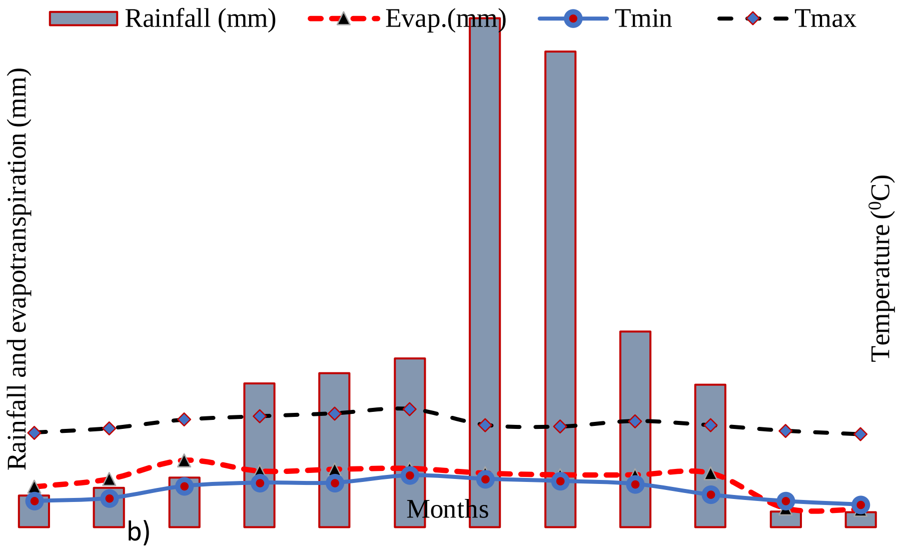


Figure 2. Ten years mean monthly rainfall, evapotranspiration (Evap), and monthly minimum (Min) and maximum (Max) temperatures of Metahara Estate

Site selection, soil moisture calibration curve of site, experimental design and procedures: A field experiment was conducted under both laboratory and field conditions in 2016 on land owned by Metahara Sugar Estate, Awash section of light soil representative field, based on its yield status and drainage. The experimental site was selected based on the available pF_2 soil map, harvesting scheme and previous history of the estate (free of drainage and salinity problems) field in consultation with the Metahara Research Station and sugarcane plantation department offices.

Soil moisture levels were calibrated using tensiometer readings by installing two tensiometers in the field representing light soil per depths of 30 and 60 cm after the fields are saturated by irrigation as described by [16] and using ideal irrigation interval of Metahara Estate. The main emphasis has been the effect of field traffic in causing compaction under wet, moist and dry conditions. As mentioned in [17] wet condition of soil is when the soil matrix potential is less than 1 kPa. This condition was only until 4th day after irrigation (Figure 3). According to report by [18] field capacity (40 kPa) is the moisture content at which a soil holds the maximum amount of water it can against the force of gravity after irrigation. This suction (40 kPa) was attained after 8 days of soil moisture depletion after irrigation (Table 2). According to [19] 50% of available water depleted and irrigation is required for growth when soil tension reaches 50-1000 kPa (refill soil moisture levels). This range of soil water tension was reached 12th days after irrigation (Figure 3). Further for this soil management groups the ideal (theoretical) irrigation interval of the estate was also scheduled to be 13 days [20]. Based on this indicative investigation, 4th, 8th and greater or equal to 12th day after irrigation were taken as days on which the wet, moist, and refill (dry) soil moisture levels, respectively, were attained (Figure 3).

Three levels of moisture content (wet, moist and dry or refill) were differentiated for light soil management unit from calibrated soil moisture depletion pattern of the soils determined using tensiometer reading. Land preparation sequences used (uprooting, subsoiling, ploughing, leveling, and furrowing) were the actual land preparation procedures as per management practices of Metahara Estate.

The field was irrigated up to saturation using irrigation practice of the estate. According to calibrated days, soil compaction was imposed on 4th, 8th and 12th days after irrigation using 12 t tractor. The 4th, 8th and 12th day after irrigation corresponds to the wet, moist and dry or refill moisture levels, respectively. Model Magnum case III 315 tractor was passed with 4, 8, 12, 16 and 20 number of passes through plots of the field based on the design of the experiment on light soils at a speed of 5.6 km hr^{-1} (speed recommended for farm machineries) for all treatments. Four weeks after applying compaction, composite and core samples were collected from 0-30 and 30-60 cm depth per each plot followed by penetration resistance measurement per each plot in the field.

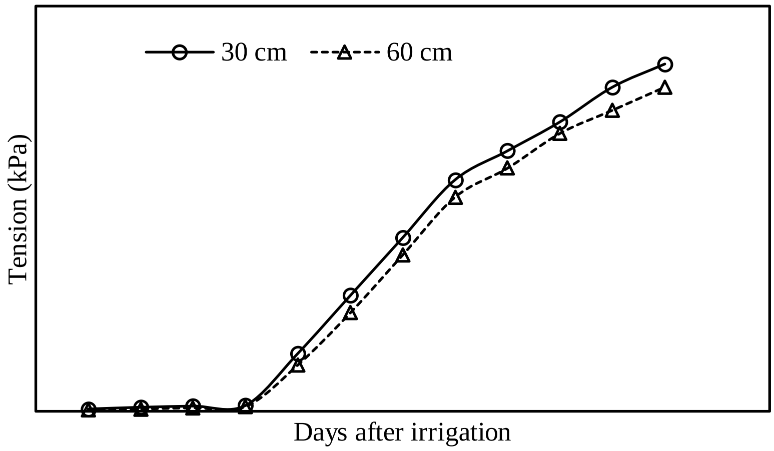


Figure 3 Soil moisture calibration curve for the study site

After completing furrow reshaping and soil sampling were completed, sugarcane was planted on the back ground. Planting was executed using healthy two budded equal number of setts of test variety (NCO 334). After planting, the setts were covered with soil immediately and each plot was irrigated lightly. Water was applied by furrow irrigation (using hydroflume), which is a popular method for 80% of Metahara sugarcane production. The experiment was arranged in randomized complete block lay out with three replication. The plots consisted of 4 furrows, each 15 m length, 1.45 m width and the spacing between two consecutive plots was 2.9 m. The area of single experimental plot was 87 m^2. The experiment consisted of a factorial combination of six tractor pass levels (0, 4, 8, 12, 16 and 20 passes) and three moisture content levels (wet on 4th, moist on 8th and dry or refill on 12th days after irrigation). The treatment combinations were arranged in a randomized complete block design and replicated three times. All management aspects (land preparation, planting, weeding, molding, fertilization and harvesting) were done according to the Metahara Sugarcane Estate practices.

Four weeks after imposing compaction, penetration resistance was measured using a manually operated soil cone penetrometer [21] with a cone base diameter of 11.28 mm and 15.96 mm with cone angle of 30°. The cone was hand-pushed into the soil at a uniform rate of 2 cm sec^{-1} [22]. Penetration resistance measurements were taken from the center of tyre truck at 10 cm increments to a depth of 60 cm. Six penetration resistance measurements were taken from each plot and the parallel values at each depth were expressed as an average.

Soil Sampling and Sample Preparation: To determine soil physicochemical properties of study area composite and undisturbed soil samples were drawn from top layer (0 to 30 cm) and subsoil layer (30 to 60 cm) of each experimental plot before and after planting. Prior to sugarcane planting, soil sample was collected by auger from eleven plots and thoroughly mixed to make one composite sample per each block from both layers. A total of three composite samples were collected from the three blocks per each layer. At the same time, one undisturbed core sample per block from both top and subsoil layers were also randomly collected using core method to determine soil bulk density (Table 1).

For soil sampling after applying treatments from each plot an auger was used to sample five randomly selected spots per plot from both top and subsoil layers. These five subsample soils from each layer combined into one composite soil sample per each plot for investigating soil properties. Similarly, undisturbed core samples from both layers was also collected to determine soil bulk density of each plot. After imposing compaction, 108 core samples (5 cm height and 5 cm diameter) and 108 composite samples were collected from 0-30 and 30-60 cm depth of 54 experimental plots. The composite soil samples were placed in a polyethylene plastic bag labeled with the required information. In the laboratory, the collected composite soil samples were air-dried, ground and sifted to pass through a 2 mm sieve except 0.5 mm sieve for analysis of soil total nitrogen.

Laboratory Analysis: Soil samples that were collected from experimental plot before and after planting or imposing compaction were subjected to laboratory analysis to determine selected soil physical properties (bulk density, particle density, total porosity, and soil moisture content) and chemical properties (total N, soil available P, and soil available K). Particle size distribution was determined by the hydrometer method as described by [23]. The textural class was determined using the USDA soil textural triangle. Bulk density was determined using core method and computed from the values of oven dry soil mass and volume of core samples as described by [24]. Particle density (ρd) of soil was determined using the pycnometer method following the procedures described by [25]. Total porosity was calculated from the values of bulk density and particle density using the method described by [26]. The soil moisture in the soil sample was also determined gravimetrically as described by [27]. Soil pH of the soil was determined in soil to water ratio of 1:2.5 by glass electrode pH meter [28]. Organic carbon was determined using the wet digestion method as described by [29]. The total N content in soils was determined using the Kjeldahl procedure as described in [30]. Soil available P was determined using Olsen method [31]. The P extracted with Olsen method was measured by spectrophotometer following the procedure described by [32]. The result of soil analysis for prior to sugarcane planting is presented in Table 2 below.

Agronomic Data Collection, Plant Sampling and Analysis: The central two rows of each plot were used for data collection. Plant height was measured by taking the average lengths of five randomly taken canes per experimental plot measured from the ground level to the top of the sugarcane at the age of eight months. Moreover, number of tillers per m^2 was recorded by counting the number of tillers /per individual shoots in 1 m^2 area at four months from planting date at five random spots within the middle two rows of the plots and average was worked out. At harvest (at the age of 22 months), from plot consisting of four furrows twenty millable samples of stalks were randomly taken from the middle two furrows to avoid any influence from adjacent plots for measuring stalk weight and juice quality parameters (polarization, brix, purity and recoverable sugar). The products of millable stalk population count per hectare and mean weight of the millable stalks was used to compute cane yield, while sugar yield was determined following the procedures out lined by [33].

Data Analysis and Interpretations: Analysis of variance was carried out on soil physicochemical properties determined after imposing the treatments and growth parameters of sugarcane to determine the effects of treatments using GLM procedures of the Statistical Analysis System software [34]. For significantly ($P < 0.05$) different parameters, the means were separated using Fisher's Least Significant Difference (LSD) test and correlation analysis was also conducted to identify useful associations among key soil and plant variables.

Table 1. Selected physicochemical properties of soils of the study site prior to field traffic

Parameters	Mean	
	0-30	30-60
Sand (%)	24.69	20.67
Silt (%)	19.67	20.33
Clay (%)	55.67	59.00
Texture	Clay	Clay
Soil classification(FAO, 1990)	Fine	Fine
Particle density(g/cm^3)	2.47	2.49
Bulk density (g/cm^3)	1.24	1.29
Total porosity (%)	49.00	48.00
Soil pH	7.49	7.54
Soil organic carbon (%)	0.65	0.49
Total nitrogen (%)	0.08	0.06
Carbon to nitrogen ratio	8.00	7.80
Available P (ppm)	5.00	3.29

RESULTS AND DISCUSSIONS

Effects of Pass Number at Different Soil Moisture Levels on Selected Soil Physicochemical Properties and Sugarcane Yield and growth parameters

Responses of soil physical properties to pass number and different moisture levels

Soil bulk density and total porosity: High bulk density is an indicator of low soil porosity and soil compaction. Imposing compaction with different number of tractor passes at different moisture content significantly ($P < 0.05$) affected top and subsoil layers bulk density as well as total porosity (Tables 3). The highest mean values of dry bulk density (1.43 and 1.40 g cm^{-3}, respectively, for top layer at 29.30% and subsoil layer at 32.74% gravimetric moisture content) were recorded in plots compacted by 20 to and fro passes of tractor. The minimum mean values of bulk density (1.32 and 1.31 g cm^{-3} for both layers) were exhibited by zero traffic pass. The increase in soil bulk density with increase in number of passes from 0 to 20 could be attributed to the more packing together of soil particles, thus increasing cohesion and reducing the pore space of the clay soil as the number of passes increase (Table 2).

Moreover, mean bulk density in subsoil layer showed inconsistent pattern with increase in days after irrigation (1.38, 1.40, and 1.33 g/cm^3 on the 4th, 8th and 12th days, respectively, after irrigation). For the top soil layer maximum mean bulk density value of 1.43 g/cm^3 was recorded on the 8th day after irrigation (Table 3). The difference in values of bulk density recorded on the three days after irrigation could be due to the difference in degree of inert-particle bonding when the soil dries and wets. Results in present study revealed that bulk density increases with increase in tractor passes at different initial moisture contents. This is also in consent with [35] who reported increase in bulk density with increasing number of passes and values of moisture content. Similarly, [36] also noted that bulk density increased and soil porosity decreased as soils became more compacted.

Porosity depends on the extent of soil compaction. Increase in soil compaction caused increase in bulk density and decrease in soil porosity and vice versa. Increase in bulk density resulted in decrease in total porosity from 50 to 44 (for top soil layer) and 50 to 45 (for subsoil layer). The maximum porosity (50%) was recorded in the control plot, which progressively decreased to the minimum (44%) in plots compacted by 20 to and fro passes of tractor (Table 3). The linear and inverse relationship between bulk density and total porosity may be attributed to the decrease in soil pore spaces as a result of increase in levels of soil compaction. Moreover, the decrease in total porosity with increase in traffic intensity could be attributed to the adverse effect of compaction on the clay soil which resulted in decreased pore space. [37] also reported that porosity depends on the extent of soil compaction.

Table 2. Effects of number of passes of tractor on soil physical properties and sugar yield

parameters	Number of passes (NP)						LSD
	0	4	8	12	16	20	
ρbt (g/cm^3)	1.32^c	1.34^c	1.37^b	1.39^{ab}	1.40^{ab}	1.43^a	0.05
ft (%)	50.00^a	48.00^{ab}	47.00^{bc}	46.00^{bc}	45.00^{bc}	44.00^c	0.03
PRt (MPa)	1.70^c	1.80^{bc}	1.91^{bc}	1.96^b	2.00^b	2.25^a	0.23
H(cm)	1.96^a	1.90^{ab}	1.92^{ab}	1.89^{ab}	1.81^{bc}	1.71^c	0.12
Yield (t/ha)	17.87^a	17.20^{ab}	16.05^c	16.80^{bc}	16.40^{bc}	15.97^c	0.90
ρbs (g/cm^3)	1.31^c	1.33^c	1.35^{bc}	1.38^{ab}	1.39^{ab}	1.40^a	0.04
fs (%)	50.00^a	49.00^a	48.00^{ab}	47.00^{ab}	46.00^{ab}	45.00^b	0.02
PRs (MPa)	1.39^d	1.49^{bc}	1.41^{cd}	1.60^{bc}	1.70^{ab}	1.78^a	0.22

ρbt = top soil bulk density; ft = top soil total porosity; PRt = top soil penetration resistance; H = height; yield = yield of sugar; ρbs = sub soil bulk density; fs = subsoil total porosity; PRs = sub soil penetration resistance. Figures in the same column followed by the same lower case letter are not significantly different

Soil penetration resistance: Soil penetration resistance was significantly ($P < 0.05$) affected by number of passes of tractor as well as by soil moisture levels. Maximum and minimum values of penetration resistance (2.25 MPa, 1.70 MPa) and (1.78 MPa, 1.39 MPa) were recorded for plots compacted under twenty to and fro passes of tractor and control, respectively, for top and subsoil layers at 28.50 and 30.31%, and 31.46 and 33.86% gravimetric moisture contents. The difference in the mean values of penetration resistance for different number of passes and moisture content may be attributed to difference in level of compaction due to different number of passes imposed to soils at different initial moisture contents of the plots.

The mean penetration resistance values at the top 30 cm depth were 1.68, 1.95 and 2.16 MPa, on the 4th, 8th and 12th days, respectively, after irrigation. This demonstrates that penetration resistance of the surface layer increased progressively with increase in days after irrigation which is in line with [38] who reported consecutive decrease of penetration resistance mean values with increase of moisture content.

Furthermore, for each level of compaction, penetration resistance decreased with increase in soil moisture content. The maximum penetration resistance was obtained at the lowest moisture content level, which was on 12th day after irrigation (Table 2). This might be due to the fact that at the lowest moisture content level the cohesive forces of the soil particles were greater than that of the highest moisture content level and therefore more resisting forces were developed by the soil particles and more energy is required to push the probe in the soil profile on 12th day after irrigation. This is in agreement with the report by [39] who indicated increasing of penetration resistance with increasing of resisting forces of soil. The subsoil layer mean penetration resistance values also showed progressive decrease with increase in soil moisture level. The maximum subsoil layer penetration resistance (1.52 MPa) was also recorded on 12th day after irrigation (Table 3).

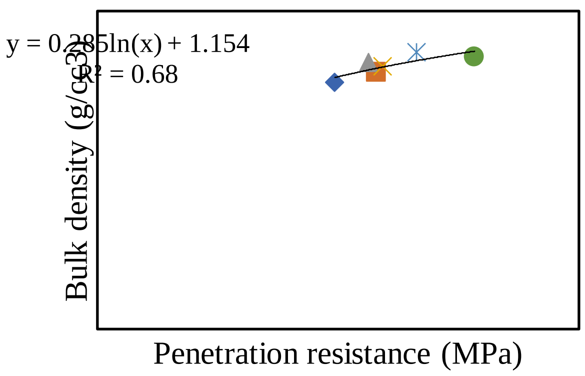
Table 3. Effects of soil moisture at the time of compaction on selected soil physical properties and sugar yield

Parameters	Soil moisture levels			LSD
	SM1	SM2	SM3	
ρbt (g/cm^3)	1.41^a	1.42^a	1.37^b	0.03
ft (%)	47.00^{ab}	45.00^b	48.00^a	0.02
PRt (MPa)	1.68^c	1.95^b	2.16^a	0.16
H(cm)	1.83^b	1.81^b	1.95^a	0.08
Yield (t/ha)	16.50^b	16.21^b	17.43^a	0.70
ρbs (g/cm^3)	1.38^{ab}	1.40^a	1.33^b	0.04
fs (%)	47.00^b	46.00^b	49.00^a	0.01
PRs (MPa)	1.25^b	1.51^a	1.52^a	0.17

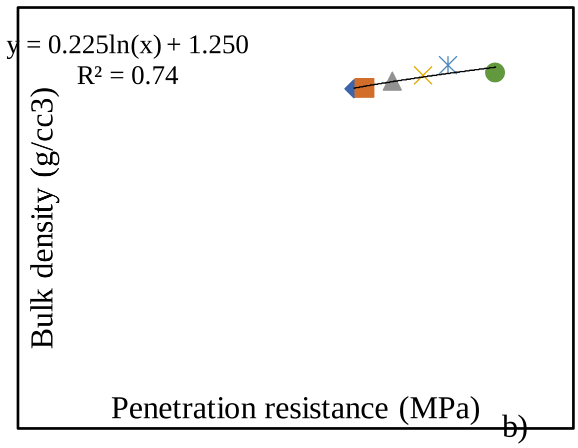
ρbt = top soil bulk density; ft = top soil total porosity; PRt = top soil penetration resistance; H = height; yield = yield of sugar; ρbs = sub soil bulk density; fs = subsoil total porosity; PRs = sub soil penetration resistance; SM1 = soil moisture on 4th day; SM2 = soil moisture on 8th day; SM3 = soil moisture on 12th. Figures in the same column followed by the same lower case letter are not significantly different.

In general, bulk density, penetration resistance, and total soil porosity changed due to the soil compaction imposed by different number of tractor passes. Compaction increased bulk density and penetration resistance values in the depth range of 0 to 30 cm by 2 to 8.53% and 12.50 to 32.35%, respectively, above the control. However, for the depth from 30-60 cm, bulk density increased by 0.74 to 7% and penetration resistance by 4.70 to 28.06%, respectively, above the control (Table 2). The difference between subsoil bulk density and penetration resistance of different number of passes with respect to the control plot were smaller than top soil layer. This may indicate that the increase in both penetration resistance and bulk density were greatly dependent on ground pressure and less on the axle load which is in agreement with [40] who stated the differences between values of penetration resistance due to different number of passes with respect to control plots were small for depth range from 30-60 cm than top layer (Table 2).

Relationships between bulk density and penetration resistance: Knowledge of the relationships between penetration resistance, bulk density and soil moisture for cultivated soils can assist in understanding of root growth responses to cultivation and compaction, and the ability of soil to resist compaction [41]. There was positive but non-linear (logarithmic) association between soil strength in terms of penetration resistance and bulk density (Figure 4). Logarithmic function fitted the data points with coefficient of determination (R^2) of 0.68 for topsoil and 0.74 for subsoil layers (Figure 4). Similar to this, [42] also reported logarithmic relationship between bulk density and penetration resistance. Penetration resistance was positively correlated with bulk density and negatively varied with soil moisture for all soils (Tables 3 and 4). Moreover, the rate of change in penetration resistance with bulk density was greater at lower soil moisture level (Table 3).



a)



b)

Figure 4. Relationship between bulk density and soil penetration resistance in response to soil compaction (a) for topsoil layer and (b) for subsoil layer

Effects of Pass Numbers and Soil Moisture Content on Sugarcane yield and Growth Parameters

Height: The height of sugarcane was significantly ($P < 0.05$) affected by both number of tractor passes and soil moisture levels (Tables 2 and 3). The average tallest cane reached at the age of 8 months was 196 cm in plots with zero tractor pass, whereas the lowest average height (171 cm) was recorded in plots with 20 passes of tractor. [43] also reported that the tallest sugarcane in the field for every month of measurement was in plot with zero tractor pass. The highest height of zero pass may be attributed to the low bulk density of this plot which helps in better root development and increased soil porosity as well as better soil aeration, water and nutrient availability in the root zone (Figure 5). Moreover, topsoil bulk density and penetration resistance had significant and negative associations ($r = -0.38^{**}$ and $r = -0.35^{**}$) respectively with sugarcane height. However, top and subsoil total porosity had positive correlation ($r = 0.38^{**}$ and $r = 0.45^{***}$, respectively) with sugarcane height. It implies that increase in compaction levels resulted in decreased pore spaces and reduced availability of water and nutrients required by the crop for its growth and, thus, reduced sugarcane height. Correlation analysis further showed that sugarcane height had positive association with sugar yield (Table 4).

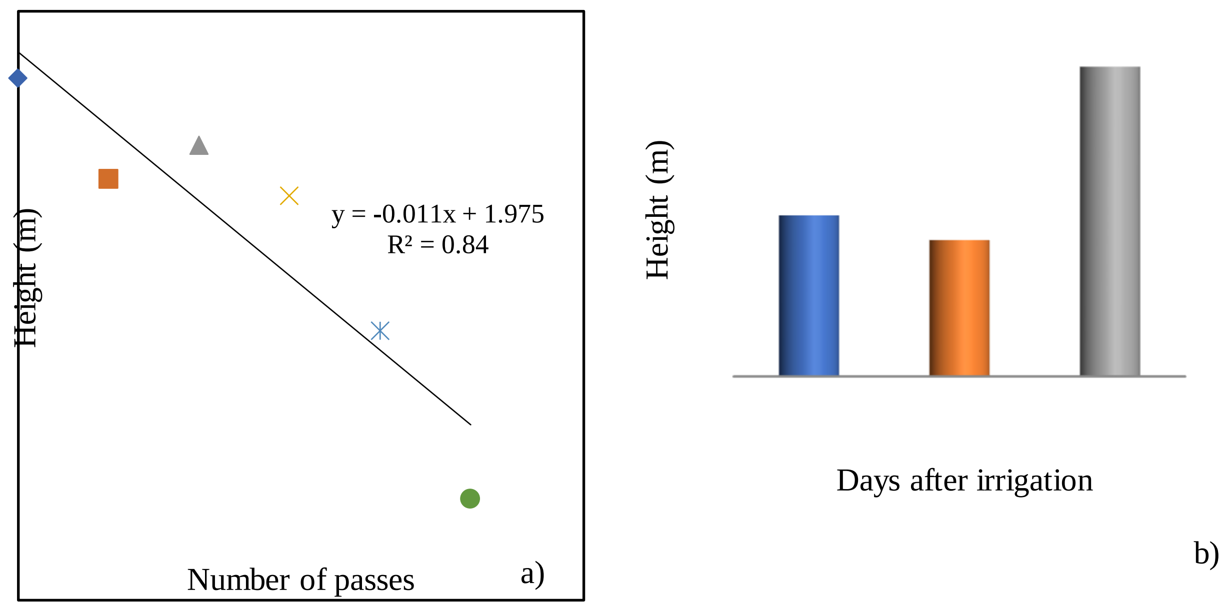


Figure 5. Sugarcane height as affected by number of tractor passes (a) and soil moisture levels (b)

The mean sugarcane heights were 183, 181, and 195 cm on soils compacted after 4th, 8th and 12th day after irrigation showing that the maximum height of sugarcane was attained at the dry moisture level. The highest height in soils compacted on 12th day after irrigation may be because at the lowest moisture content level the cohesive forces of the soil particles were greater than at the highest moisture content level and, therefore, more resisting forces were developed by the soil particles against compacting force. This is consistent with the finding of [44] who reported decreased compaction with decrease in moisture levels.

Sugar yields: Figure 5 shows the average yield from plots subjected to different levels of soil compaction. Imposing different levels of soil compaction at different moisture levels significantly ($P < 0.05$) affected average sugar yield. Significantly higher sugar yield was recorded for plots with zero number of pass (control), whereas the plots with 20 number of passes produced the lowest yield (Figure 6). The statistically significant sugar yield response to different number of passes at three different moisture levels might be ascribed to the variation of levels of compaction among the plots. Moreover, the significant variation of bulk density and sugarcane height with compaction treatments might have contributed to the variation of yield, which can be evidenced by the negative and positive correlation, respectively, between sugar yield and bulk density as well as sugar yield and height (Figure 6 and Table 4).

On the other hand, the lower yield in the plots treated with higher number of passes could be due to less nutrient and water availability in the soil to the crop and the difficulty of roots to go deeper into the soil at higher compaction levels. This can be evidenced by the positive correlation (r = 0.34* and r = 0.27*) of sugar yield with available soil phosphorus in both top and subsoil layers respectively (Table 4). This may indicate that high sugar yield was obtained from plots that have better soil available phosphorus. Moreover, restriction of roots might have limited the nutrient uptake in these plots, which resulted in a reduction of growth in terms of height and finally reduction in sugar yields. This is in agreement with the report by [45] that sugar yield and sugarcane yield components decrease as number of tractor passes increase. The soil compaction reduced yield by 10.63% in the plots with 20 number of passes. Furthermore, there were also lower number of stalks in plots with 20 number of tractor passes, whereas stalk population is a key component in determining sugar yield.

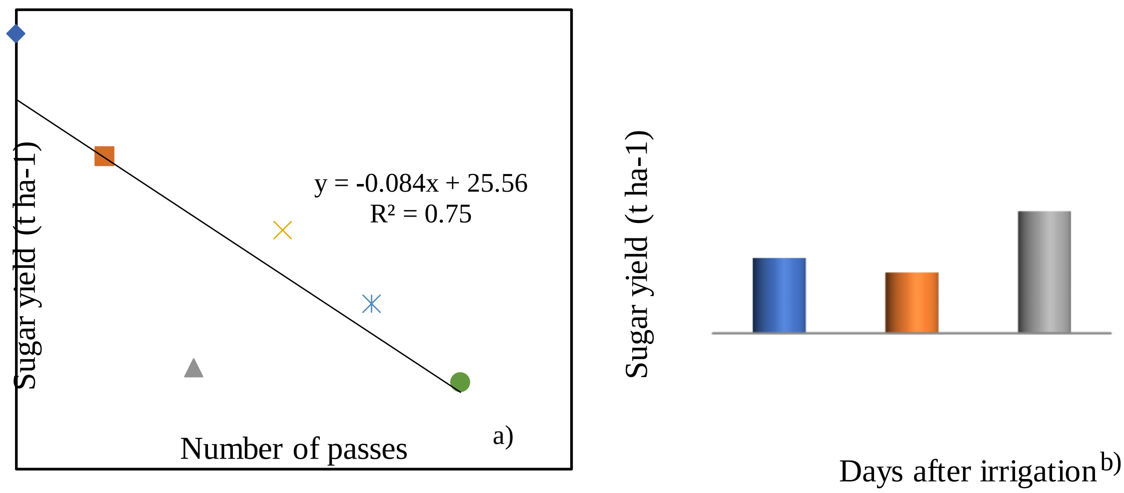


Figure 6. Sugar cane yields as affected by number of tractor passes (a) and soil moisture levels (b)

Table 4. Pearson correlation analysis of soil physicochemical properties with plant growth and sugar yield

	ρb	f	PR	H	P	Yield
ρb	1	-0.98^{***}	0.31^{*}	-0.38^{**}	-0.18^{ns}	-0.24^{ns}
f		1	-0.31^{*}	0.38^{**}	0.18^{ns}	0.24^{ns}

PR	1	-0.35^{**}	-0.14^{ns}	-0.01^{ns}
H		1	0.03^{ns}	0.04^{ns}
P			1	0.34^{*}
Yield				1

ρb = soil bulk density, f = soil total porosity, PR = soil penetration resistance, H = height; P = soil available phosphorus, and ***, ** and * = Significant at P < 0.001, p< 0.01 and P < 0.05, respectively; ns = not significant.

Imposing different number of passes on 4th and 8th days after irrigation gave significantly lower yield than the 12th day after irrigation. The highest yield on 12th day might be due to low soil compaction level as a result of low moisture and due to highest growth (height) on 12th day which is evidenced by the positive correlation between height and sugar yield (Figure 5 and Table 4).

Establishing Soil Compaction Threshold for Magnum 315 Tractor: According to NRCS (2008) for clayey soils (>45% clay) root extension 'restriction' is initiated at a dry bulk density value of 1.39 g/cm^3 and that dry bulk density values ≥ 1.45 g/cm^3 are considered root extension limiting [46]. Accordingly, Metahara light soils compacted by 20 passes on 8th day and 16 passes on 4th day after irrigation resulted in mean bulk density values that were higher than the 1.39 g/cm^3 root restriction initiation level and close to the root-limiting ≥ 1.45 g/cm^3 value for both the top and subsurface layers. For the 0-30 cm layer, these above root restriction initiation level bulk density values were attained when the soils were compacted by 20 and 16 passes at gravimetric moisture contents, respectively, of 30.31 and 29.30%. The values recorded for 20 numbers of passes are even greater than the critical value of bulk density for plant growth at which root penetration is likely to be severely restricted as noted in [47]. In summary, the values of bulk density on 8th days after irrigation for 20 traffic passes were in excess to the root restriction initiation level value that can affect sugarcane root growth [48]. This value for 20 passes was recorded when gravimetric soil moisture content was close to 29.30% (0.93 PL). This implies that the management should decide field operations using Magnum Case III 315 tractor on light soil fields not to be before 8th day after irrigation and when gravimetric moisture content for clay soils are at/near 29.30%. Furthermore, management plans should include subsoiling operations to loosen soil in the field only when compaction levels exceed 1.45 g/cm^3.

CONCLUSSION AND RECOMMENDATION

The study showed that imposing of compaction with different number of passes at different moisture content produced bulk density and penetration resistance which were in excess of the root restriction initiation level value that can affect sugarcane root growth of soil for high number of passes on 8th day after irrigation at/near 29.30% (0.93 PL) moisture content. This may indicate the need for an appropriate selection of traffic timing for agricultural production efficiency and profitability. It is therefore necessary to stop any field operation using Magnum case III 315 before 8th day after irrigation when the gravimetric moisture content of Metahara light soils are at/near 29.30% (0.93 PL). Management plans should include subsoiling operations to loosen soil in the field only when compaction levels exceed 1.45 g cm^{-3}. The current study is limited to light soil management unit group at Metahara Estate only. There is a need for further study on other soil management unit groups at other estates and heavy soil management unit group at Metahara Estate. Furthermore, few tractor passes and moisture levels were considered. Therefore, future studies should consider more tractor passes at different moisture levels. Only one type of tractor and sugarcane variety are considered. Therefore, the ability of sugarcane varieties to grow under high soil density situations and other tractor types in use in the estates should be considered.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this paper.

ACKNOWLEDGMENTS

This work was supported by a grant from the Ministry of Education through Ambo and Haramaya Universities. The authors of this article would like also to acknowledge staff members of Metahara and Wonji Stations for providing us laboratory facilities, laboratory analysis, labour and technical support during the implementation of this experiment.

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