Advances in Crop Science and Technology

Teshome and Kibret, Adv Crop Sci Tech 2015, 3:1
http://dx.doi.org/10.4172/2329-8863.1000159

Research Article

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Characterization of Soil Management Groups of Metahara Sugar Estate in Terms of their Physical and Hydraulic Properties

Zeleke Teshome[1]* and Kibebew Kibret[2]

[1]Sugar Corporation, Research and Training, P. O. Box 15, Wonji, Ethiopia
[2]Haramaya University, P.O.Box 138, Dire Dawa, Ethiopia

Abstract

A study was conducted on soil management groups of Metahara Sugar estate in order to characterize them in terms of their physical and hydraulic properties, and develop pedotransfer functions for estimating water contents at field capacity (FC) and permanent wilting point (PWP). Soils of Metahara were classified in to six textural soil management groups (soil classes) on the basis of soil moisture content at pF2 and texture to determine irrigation intervals. These are class 1, 2, 3, 4, 5, and 6 with pF2 moisture contents of <35, 35-45, 45-55, 55-65, 65-75, and >75%, respectively. pF2 is the water content at -10 kPa matric potentials. Ninety eight disturbed and undisturbed samples were taken from surface and subsurface layers. The soil analyses result indicated that mean values of the estate soils varied from class to class and with depth in which bulk density varied from 1.01 to 1.43 g/cm^3, particle density from 2.23 to 2.76 g/cm^3, total porosity from 40.91 to 61.42%, sand content from 10 to 40%, silt content from 13 to 36%, clay content from 33 to 77%, and organic matter content from 1.18 to 2.69%. The available water holding capacity varied from 99.71 to 212.01 mm/m. The mean saturated hydraulic conductivity varied from 0.96 to 5.95 µm/s while the basic infiltration rate varied from 0.43 to 3.68 cm/hr. The soil water retention characteristic curves (SWRCC) indicate the presence of three distinct groups of soils in the Estate instead of six groups. Water retention at any of the matric potential points considered increased from group 1 (classes 1 and 2) to group 3 (classes 5 and 6). Furthermore, the equation developed using clay content and bulk density as predictor variables was found to be the best equation for predicting gravimetric water content at field capacity and permanent wilting point with reasonable accuracy. Based on the results, the existing irrigation scheduling should be revised for the respective three soil groups.

Keywords: Matric potential; Soil-water retention characteristic curve; Pedotransfer functions

Introduction

Irrigation is the major practice for successful cultivation of sugarcane in all Ethiopian Sugar estates. Rational management of irrigation water is an important aspect not only for successful cane production, but also to ensure a sustainable high sugar yield [1]. For such a reason, the available water should be so planned that the water requirement of the crop is met and at the same time the system does not produce deleterious effects like water logging and salinity [1,2]. Thus, knowledge of soil physical and hydraulic properties is indispensable for solving such soil and water management problems [3].

In Metahara Sugar estate, attempts have been made to improve the irrigation system to minimize water-logging and water deficit in the farm as one of the measures to increase cane productivity. However, old soil classification system has been used by the estate, established based on soil moisture content at pF2 and texture, to group the soils into six classes for the determination of irrigation intervals. Currently, working theoretical irrigation intervals, which were revised about two decades ago, are wider than the ones established at the start of plantation development in late 1960's. In addition, in the production of sugarcane, experiencing different cultural practices and tillage operations for many years, occurrence of such changes is expected [4]. Cultivation practices can alter soil structure and porosity, as well as hydraulic conductivity and moisture retention curves significantly [5].

The characterization of the estate soils in terms of their physical and hydraulic properties is, therefore, expected to provide basic information on the drainage characteristics, water retention and transmission characteristics, and available water holding capacity that are required for various water management activities. Nonetheless, the direct measurement of hydraulic properties is expensive and time consuming, and hence, indirect methods (Pedotransfer functions) are increasingly used to predict hydraulic properties from easily measurable soil properties namely soil texture, organic matter and bulk density. Therefore, this study was initiated with the following specific objectives:

- To characterize soil management groups of Metahara Sugar estate in terms of their physical and hydraulic properties,
- To develop pedotransfer functions for selected hydraulic properties.

Materials and Methods

Metahara Sugar estate is located in Oromia region at about 200 km southeast of the capital city, Addis Ababa. It is situated at 80 53' N and 39^0 52' E with an altitude of 950 meters above sea level (m.a.s.l). The area has a semi arid climatic condition [6]. Six textural soil management groups or "soil classes" have been identified on the basis of soil moisture content at pF2 and texture to determine irrigation intervals. These are class 1, 2, 3, 4, 5, and 6 with pF2 moisture contents of <35, 35-45, 45-55, 55-65, 65- 75, and >75%, respectively [1].

***Corresponding author:** Zeleke Teshome, Sugar Corporation, Research and Training, P. O. Box 15, Wonji, Ethiopia, Tel: +251911361151; E-mail: zeleketeshome@gmail.com

Received October 16, 2014; **Accepted** December 19, 2014; **Published** December 21, 2014

Citation: Teshome Z, Kibret K (2015) Characterization of Soil Management Groups of Metahara Sugar Estate in Terms of their Physical and Hydraulic Properties. Adv Crop Sci Tech 3: 159. doi:10.4172/2329-8863.1000159

A total of 98 undisturbed core samples, 98 disturbed samples, and 13 composite samples were collected for determinations of soil-water retention characteristic curve and bulk density, particle size distribution and organic matter, and particle density, respectively. The samples were taken from surface and subsurface horizons in duplicate at each sampling site. The surface layer was considered up to the end of the top soils (0-35 cm) and the underlying layer (35 - 80 cm in most cases) as subsurface layer. Soil-water retention characteristic curve (SWRCC) data were obtained using sand box and pressure plate apparatus. Saturated hydraulic conductivity (Ksat) was measured in situ in the surface layer using Guelph permeameter (Model 2800 KI) while basic infiltration rate using double ring infiltrometer. Available water capacity (AWC) between field capacity and permanent wilting point (PWP) were calculated using Equation 1.

$$\mathrm{AWC} = \theta_{\mathrm{FC}} - \theta_{\mathrm{PWP}} \quad (1)$$

where: $\theta_{FC=}$water content at FC (v/v) and $\theta_{PWP=}$water content at PWP(v/v)

For a given soil depth (D, in mm), the available water was calculated as:

$$AW = AWC \times D \quad (2)$$

The soil physical properties that were measured include particle size distribution, bulk density, and particle density. Particle size distribution was determined using the Bouyoucos hydrometer method [7], bulk density (ρ_b) was measured by the core method, and particle density (ρ_s) was measured by the pycnometer method. Porosity was also estimated from bulk density and particle density data. Organic carbon was determined by the Walkley-Black method (19). Point pedotransfer functions were developed to estimate gravimetric water contents at field capacity and permanent wilting point from salient soil properties. Regression equations, using the predictor variables and their combinations, were used to develop the best equation for predicting water contents at the two potentials with reasonable accuracy for Metahara Sugar estate soils. The best equation was then tested and validated using an independent data set. Fifty two paired measurements of independent and dependent variables were used for developing the equations for both FC and PWP. Multiple regression techniques were used to work out the coefficients in the equations and evaluate the relative importance of the soil properties on water content at FC and PWP. To see the relations among soil properties, correlation analysis was made using SPSS.

Results and Discussion

Soil physical properties and organic matter

The mean bulk density values, for the different soil management classes, varied from 1.01 (class 4) to 1.43 g/cm^3 (class 1) and 1.06 (class 6) to 1.43 g/cm^3 (class 1) for surface and subsurface layers, respectively. In general, though not consistent, bulk density increased with depth for most of the management classes. In addition to the anticipated variations in bulk density values among the different management classes, there were some differences among the chosen sampling sites within the same class. For example, the bulk density values were slightly higher than previous study. Bulk densities were 1.1 g/cm^3 for classes 1 to 4 and 1.0 g/cm^3 for classes 5 and 6 [8]. This variation could be attributed to the differences in management practices that have been in operation over the years and spatial variability of the sampling sites. Soil compaction, caused by wheel traffic, is generally perceived as a problem in sugarcane cultivation [9].

The particle density of soils in the different management classes varied from 2.54 (class 4) to 2.76 g/cm^3 (class 2) for the surface layers and 2.23 (Class 6) to 2.64 g/cm^3 (class 3) for the subsurface layers, respectively, as presented in Table 1. The particle density values did not show any consistent trend with class. Nonetheless, with the exception of class 4, it decreased with depth. Different literature sources [10,11] indicated that particle density depends on mineralogical composition, crystal structure of the mineral particles and organic matter content. However, the results of particle density did not show any consistent trend with organic matter.

In contrast to bulk density, except for class 5, the total porosity for the surface layers increased from class 1 (46.62%) to class 6 (61.42%) whereas no specific trend with class was found for the subsurface layers. Generally, the total porosity decreased with an increase in depth. The decreasing in total porosity is apparently due to increasing bulk density with depth. Except for extreme layer of class 1 (40.91%) which had a slightly lower porosity than it should normally deserve for clay loam and clay texture, the total porosity values of the different classes were in the range of values that do not affect soil properties and, hence, root growth. The range of porosity to affect soil properties and root growth depends on texture. For instance, sands with a total pore space less than about 40% are liable to restrict root growth due to excessive strength whilst, in clay soils, limiting total porosities are higher, and less than 50% can be taken as the corresponding approximate value [12] (Table 1).

The particle size distribution showed marked differences between lower and higher classes. For example, the mean sand content varied from 14% (class 6) - 40% (class 1) and 10% (class 6) to 39% (class 1) for surface and subsurface layer, respectively. The mean silt content of the surface layer varied from 15% (class 6) to 26% (class 2 soils). In the subsurface layer, it varied from 13% to 36%. The lowest (33%) and highest (77%) mean clay contents were found in the subsurface layers of classes 2 and 6 soils, respectively. The mean clay content of the surface layers increased consistently from class 1 through 6. The texture, four out of six soil management classes, both at the surface and subsurface, was clay. For classes 1 and 2, it varied from silt loam, sandy clay loam, silt clay loam, and clay loam to clay.

The average organic matter content of the surface soils of the management groups (classes) ranged from 1.82 in class 1 to 2.69% in class 4 soils (Table 1). It varied from 1.18 (class 2) to 1.47% (class 3) in the subsurface layer. Except for classes 5 and 6, the average organic matter content for the surface layers increased with class number. Soil

Class	Depth (cm)	Particle size distribution (%)			ρ_b (g/cm^3)	ρ_s (g/cm^3)	Porosity (%)	OM (%)
		Sand	Silt	Clay				
1	0-35	40	23	37	1.43	2.66	46.62	1.82
	35-80	39	22	39	1.28	2.46	47.97	1.42
2	0-35	36	26	38	1.15	2.76	58.33	2.08
	35-80	31	36	33	1.21	2.57	52.92	1.18
3	0-35	25	19	56	1.08	2.70	60.00	2.39
	35-80	26	15	59	1.32	2.64	50.00	1.47
4	0-35	17	20	63	1.01	2.54	60.24	2.69
	35-80	19	18	63	1.09	2.60	58.08	1.19
5	0-35	17	16	67	1.04	2.60	60.00	2.67
	35-80	16	14	70	1.15	2.33	50.64	1.26
6	0-35	14	15	71	1.03	2.67	61.42	2.56
	35-80	10	13	77	1.06	2.23	52.47	1.26

Table 1: Range of selected physical and chemical properties of surface and subsurface layers of the soil management classes of Metahara Sugar estate.

organic matter tends to increase as the clay content increases. The organic matter content showed a decreasing pattern with depth [13]. The result revealed that all the soil management classes had very low organic matter content.

The results of the correlation analysis (Table 2) indicated bulk density had significant negative correlation with water content at field capacity (r=-0.439**) and permanent wilting point (r=-0.351*). This negative correlation implies that water retention at these two points increases as bulk density decreases and vice versa. As it can be seen from the correlation matrix, the effect of bulk density on water content at permanent wilting point was less strong. This is because at this point, it is the surface property (specific surface) which is more important than pore size distribution. Similarly, sand and silt contents showed significantly negative correlation with water content at FC and PWP whereas clay and silt plus clay (Si+Clay) contents revealed significantly positive correlation with water content at FC and PWP. Organic matter content, on the other hand, showed significantly positive correlation with water content at FC only. Soil organic matter enhances soil water retention because of its hydrophilic nature and its positive influence on soil structure [14].

Hydraulic properties

The soil water retention characteristic curves for the six management classes, mean of the mean surface and subsurface volumetric water contents, were plotted against the specific matric potential values as indicated in the Figure 1. The differences were more distinct in the wet range of the curve, reflecting the differences in structural conditions of the classes, than in the dry range. These groups of water retention curves indicate that those classes that had about the same water retention characteristic curve near the wet range and dry range also have the same drainage requirement and irrigation water management scenarios. Hence, the six soil management groups can be reduced to three groups.

As the soils of the estate are dominantly clay in texture, the water release characteristics of the soils showed slight changes in water content for successive applications of matric suctions. In a clayey soil, the pore-size distribution is more uniform, and more of the water is adsorbed, so that increasing the suctions causes a more gradual decrease in water content [15,16]. More generally, the slow and gradual release behavior of clay could be an asset for the estate because it reduces irrigation

	OM	ρ_b	Sand	Silt	Clay	Si+Clay	FC	PWP	AWC
OM	1								
ρ_b	-0.408**	1							
Sand	-0.208*	0.647**	1						
Silt	-0.186	-0.031	0.193	1					
Clay	0.279**	-0.437**	-0.813**	-0.714**	1				
Si+Clay	0.233*	-0.637**	-0.983**	-0.183	0.818**	1			
FC	0.211*	-0.439**	-0.763**	-0.447**	0.800**	0.756**	1		
PWP	0.201	-0.351*	-0.621**	-0.594**	0.774**	0.620**	0.770*	1	
AWC	0.101	-0.275*	-0.633**	-0.178	0.550**	0.636**	0.800*	0.234	1

* = significant at p < 0.05; ** = significant at p< 0.01; and FC, PWP, and AWC are volumetric water content

Table 2: The Pearson's correlation matrix among measured properties of the six soil management classes.

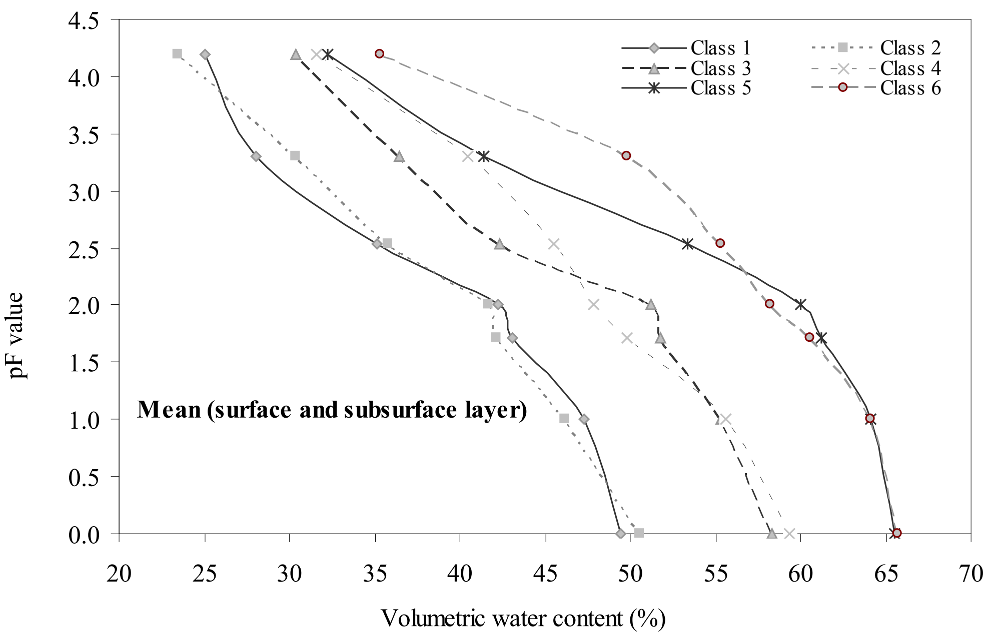

Figure 1: Soil-water retention characteristic curves of the six soil management classes.

frequencies by increasing the irrigation intervals that has direct cost implications. Similarly, abundance of clayey soils in the plantation is an advantage to ensure higher productivity provided that due effort is made to properly manage the accompanying limitations like water logging and difficulty in tillage operations [1].

The available water holding capacity, between FC and PWP, of the surface layers increased consistently with class except for class 3 soils ranging from 109.79 mm/m for class 1 soils to 216.88 mm/m for class 6 soils (Table 3). This implies that the potentially plant available water increased as the texture of the soils become finer. On the other hand, the AW of the subsurface layers varied inconsistently with class ranging from 91.86 mm/m for class 1 to 211.70 mm/m for class 5 soils. Surprisingly enough, for the subsurface layers it was not the class with the highest clay content that had the highest total available water. This could indicate the existence of threshold value for clay content beyond which available water does not increase with further increase in clay content.

Depth of the soil is a key parameter affecting its available water. To show the differences in available water for the six classes, the available water capacity per the entire sampling depth for each class were considered. This was done by calculating the AWC for the upper 80 cm of each class and then converting the values into mm/m. This AW increased inconsistently with class ranging from 99.71 mm/m for class 1 to 212.01 mm/m for class 5 soils. According to established ratings AW for irrigation suitability [16], class 1 was grouped in to low, classes 2, 3 and 4 to medium, and classes 5 and 6 to high.

The saturated hydraulic conductivity varied from 0.96 µm/s for class 6 soils to 5.95 µm/s for class 1 soils. Also, except for class 3 soils, saturated hydraulic conductivity decreased as class number increases. The general decrease in saturated hydraulic conductivity with class could be the result of decrease in the proportion of macro pores in the higher classes. As a result, when saturated the coarse textured soils have high conductivity than the finer textured soils. In few areas of the Sugar estate, soils where class 5 and 6 are found, shallow water table accompanied with low Ksat, are already giving some indications of drainage needs. On the basis of saturated hydraulic conductivity ratings established [17], the six classes can be categorized in to slow (class 6), moderately slow (classes 2, 4 and 5) and moderate (classes 1 and 3).

The basic infiltration rate, alike the saturated hydraulic conductivity values, showed a decreasing trend with class except for class 3 soils (Table 4). Class 1 had the highest basic infiltration rate (3.68 cm/hr) followed by class 3 soils (2.73 cm/hr) whereas class 6 soils had the lowest basic infiltration rate (0.43 cm/hr). On the basis of basic infiltration, the six soil classes can be grouped in to three rating classes of slow (class 6), moderately slow (classes 2, 4 and 5) and moderate (classes 1 and 3). Some of the classes showed greater infiltration rate regardless of their texture. Report indicated that infiltration rate varies greatly with soil structure and stability, even beyond the normal ranges [18].

Point pedotransfer functions

Of the different equations developed, which are shown in Table 5, the use of clay content and bulk density as predictor variables produced statistically significant ($P<0.01$) coefficients. However, the use of all or more than two variables produced better R^2 values indicating that the use of more number of soil properties can explain large proportion of the variations in soil water content at these two matric potential points. From the R^2 values in Table 5, about 86% of the variations in soil water content at FC were explained by the variations in soil texture, bulk density and organic matter content. On the other hand, about 85% and 81% of the variations in water content at FC and PWP, respectively, were explained by the variations in clay content and bulk density alone. From this, the improvement in precision by using all the variables was only 5% for FC. These equations show the strong impact of bulk density on water retention at FC and PWP.

From the different regression equations developed for predicting water content at FC and PWP, the following pedotransfer functions were established:

$$\theta_{FC} = 58.849 + 0.408(\%clay) - 36.198 \times \rho_b \quad R^2=0.849 \quad (3)$$

$$\theta_{PWP} = 38.431 + 0.244(\%clay) - 22.433 \times \rho_b, \quad R^2=0.811 \quad (4)$$

Soil Class	Depth (cm)	Percent volumetric water retained at matric potential (kPa)							AW (mm/m)
		0	-1	-5	-10	-33	-200	-1500	
1	0-35	47.25	45.77	42.21	41.45	37.17	28.49	26.19	109.79
	35-80	51.63	48.78	43.94	43.02	33.10	27.56	23.91	91.86
2	0-35	49.90	44.25	39.84	39.26	34.65	30.50	23.19	114.56
	35-80	51.27	48.12	44.48	44.04	36.89	30.27	23.66	132.34
3	0-35	62.32	58.30	52.66	51.86	41.85	34.87	30.46	113.90
	35-80	54.32	52.40	50.87	50.59	42.90	38.05	30.38	125.18
4	0-35	59.44	55.94	48.86	46.64	44.72	39.41	31.14	135.87
	35-80	59.25	55.31	50.73	48.98	46.40	41.59	32.06	143.39
5	0-35	67.24	65.46	61.76	60.18	53.85	42.97	32.61	212.40
	35-80	63.88	62.73	60.59	59.74	52.88	39.81	31.73	211.70
6	0-35	67.31	66.19	61.25	58.15	55.45	49.93	33.76	216.88
	35-80	64.05	62.02	59.83	58.30	55.24	49.72	36.83	184.10

Table 3: Average percent volumetric water contents at different matric potential points and available water (mm/m) of the six soil management classes.

pF2 Soil class	Infiltration rate (cm/hr)	Rating class	Ksat (µm/s)	Rating class
1	3.68	Moderate	5.95	Moderate
2	1.87	Moderately slow	5.14	Moderately slow
3	2.73	Moderate	5.73	Moderate
4	1.96	Moderately slow	3.94	Moderately slow
5	1.38	Moderately slow	1.47	Moderately slow
6	0.43	Slow	0.96	Slow

Table 4: Basic infiltration rate and saturated hydraulic conductivity of the six soil management classes.

Predicted variables	Intercept	Predictor variables						R^2
		Sand	Silt	Clay	Si+clay	OM	ρ_b	
FC	74.447	-0.347	-0.217	0.079	0.092	0.782	-30.096	0.86071
	76.398	-0.367	-0.297	-	0.151	0.797	-30.08	0.86069
	74.377	-0.346	-0.125	0.172	-	0.766	-30.106	0.86068
	62.301	-0.226	-	0.294	-	0.746	-30.134	0.86056
	64.451	-0.203	-	0.307	-	-	-31.97	0.85854
	58.849	-	-	0.408	-	-	-36.198	0.84937
	86.412	-0.596	-	-	-	-	-27.943	0.80476
	60.043	-0.849	-	-	-	-	-	0.69466
PWP	75.000	-0.310	-0.294	-	-0.113	0.247	-23.637	0.81902
	63.771	-0.199	-0.293	-	-	0.244	-23.683	0.81867
	75.956	-0.305	-0.297	-	-0.111	-	24.241	0.81845
	68.339	-	-	0.296	-0.332	-	-24.155	0.81805
	45.615	-	-	0.296	-0.102	-	-24.434	0.81652
	38.431	-	-	0.244	-	-	-22.432	0.81087
	6.9489	-	-	0.343	-	-	-	0.57281

Table 5: Pedotransfer functions developed for predicting water content at field capacity and permanent wilting point from basic soil properties for the six soil management classes.

Where: $\theta_{FC=}$water content at field capacity (% by weight), $\theta_{PWP\ 4}$= water content at permanent wilting point (% by weight), and $\rho_{b=}$bulk density (g/cm^3)

Conclusion

The soil analyses result indicated that the mean values of the estate soils varied from class to class and with depth in which bulk density varied from 1.01 to 1.43 g/cm^3, particle density from 2.23 to 2.76 g/cm^3, total porosity from 40.91 to 61.42%, sand content from 10 to 40%, silt content from 13 to 36%, clay content from 33 to 77%, and organic matter content from 1.18 to 2.69%.

The pertinent physical and hydraulic properties were determined using standard laboratory and/or field procedures. The similarity of soil water retention characteristic curves between some classes of the six soil management classes indicated that the six management groups can be reduced to three groups (classes). It is, therefore, the existing irrigation scheduling should be revisited taking the present findings of the soil-water relations into account. The developed equation through pedotransfer functions can be used to predict gravimetric water contents at field capacity and permanent wilting point to obtain available water capacity with reasonable accuracy for the estate soils and other similar areas with soil properties in the range where the model equation developed. Periodic revision of the soil classes is important as there will be cumulative effects due to cultural practices, tillage operations and addition of amendments that cause changes in chemical, physical, and hydraulic properties of the estate soils. Additional information including other chemical and physical properties of the estate soils are required to fully understand the potentials and limitations of the soils and use according to their suitability for a given land use.

Acknowledgments

The authors would like to thank the staff of Soil and Water Management Department of the former Ethiopian Sugar Development Agency the then Sugar Corporation, particularly Ato Abiy Fantaye, for their assistance, professional comments and suggestions. Great appreciation also goes to W/ro Sintayehu Temesgen from Haramaya University for her unreserved support during the physical soil laboratory analysis. Our special gratitude is also extended to the Ethiopian Sugar Development Agency (ESDA) for sponsoring the study.

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