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Spatial variability and dynamics of soil pH, soil organic carbon and matter content: The case of the Wonji Shoa sugarcane plantation

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Abstract

This study presents the spatial variability and dynamics of soil organic carbon (*SOC*), soil organic matter (*SOM*) and soil pH contents at the Wonji Shoa Sugar Estate (WSSE), Ethiopia. Soil samples were collected immediately after the sugarcane was harvested and then analysed for *SOC*, *SOM* and pH content using standard procedures. The analysis results showed that the pH value varied between 6.7–8.4 (neutral to moderately alkaline) and 7.3–8.5 (neutral to strongly alkaline) for the top and bottom soil profiles, respectively. The *SOM* content is in the range of 1.1–6.7% and 0.74–3.3% for the upper and lower soil layers, respectively. Nearly 45% of the samples demonstrated a *SOM* content below the desirable threshold (<2.1%) in the bottom layer and, hence, inadequate. Moreover, most of the topsoil layer (95%) has an *SOM* content exceeding the desirable limit and hence is categorized within the normal range. Interestingly, the *SOC* content showed a spatial variability in both the surface and sub-surface soil layers. A lower *SOC* and *SOM* content was found for the sub-soil in the south and southwestern part of the plantation. A further decline in the *SOC* and *SOM* content may face the estate if the current waterlogging condition continues in the future for a long period. Overall, the study result emphasizes the need to minimize the pre-harvest burning of sugarcane and action is needed to change the irrigation method to green harvesting to facilitate the *SOC* retention in the soil and minimize the greenhouse emission effect on the environment, hence improving soil quality in the long-term.

Key words: *organic matter content, pH, soil organic carbon, soil quality, sugarcane*

INTRODUCTION

Sugarcane is a commercially produced perennial crop [YADAV *et al.* 2009]. It belongs to a C4 grass family cash crop that is produced in more than seventy countries for sugar production [DINKA, NDAMBUKI 2014; SILVA-OLAYA *et al.* 2014]. Similarly, the production of sugarcane in Ethiopia is also mainly for commercial use as an input for the sugar industries. The first sugar production in Ethiopia started at the Wonji Shoa Sugar Estate (WSSE), which was established more than 60 years ago [DINKA, NDAMBUKI 2014]. The sugar estate uses irrigation and a semi-mechanized harvesting system. Land preparation is completely mechanized.

WSSE uses a pre-harvest sugarcane burning system. Pre-harvest sugarcane burning is common practice during sugarcane harvesting globally prior to transportation to the factory [SOUZA *et al.* 2012]. The long-term irrigation and fertilizer application might lead to the deterioration of soil quality [KARLEN *et al.* 2013]. Moreover, several researchers reported that regardless of commercial production, the soil organic matter (*SOM*) content and its natural resources are being degraded and the productivity of the land is declining in the long-term irrigation system [NACHIMUTHU, Hulugalle 2016]. This could largely be attributed to the inappropriate resource utilization and management of the sugarcane plantation over the long-term [Anaya, Huber-Sannwald 2015; Beza, Assen 2016].

Quantifying soil organic carbon (*SOC*), *SOM* contents and soil pH is crucial to understanding the variability in the soil quality and the effect of the components on the environment i.e. the greenhouse gas emission (GHG) effect [Anaya, Huber-Sannwald 2015; He *et al.* 2017; Silva-Olaya *et al.* 2014]. Understanding the dynamic nature of the soil systems (such as *SOC* and *SOM*) might help to explain changes in soil quality that are taking place in the landscape [Shi, Jin 2016]. Soil is a renewable natural resources that can be affected by several factors that inexorably move the soil towards eventual deterioration, and reversal of these processes cannot take place without the onset of a new cycle of geological erosion [Firehun, Tamado 2006].

The *SOM* content has a major impact on the quality and productivity of the soil and ecosystem [Raiesi, Riahi 2014]. It contains abundant compounds that are spatially varied and is characterized by the soil microbial function [Baldrian *et al.* 2010; Tian *et al.* 2015]. The *SOC* is the key soil quality that is an indicator of the GHG emission level [Stockmann *et al.* 2013]. The *SOC* dynamics can be affected by the pre-harvest burning of sugarcane during the harvesting process and by farming systems such as tillage [Stockmann *et al.* 2013]. Bordonal *et al.* [2017] reported that there was a reduction of 60% in *SOC* when burning was not practiced. The study indicated that *SOC* is the principal component and plays an important role in improving soil quality and management as affected by the farming system and practices in sugarcane plantation. The short-term application of organic matter that reduces the oxidation level of *SOM* on sugarcane plantations was found to contribute little to the improvement of *SOC* accumulation [Bordonal *et al.* 2017; Selim *et al.* 2016]. Bordonal *et al.* [2017] recommended that further study is required at sub-soil levels for *SOC* budget that affected by farming mechanisms in sugarcane farm. Moreover, Alba [2003] reported that tillage operations affected soil degradation and erosion in the long-term farming process. The tillage processes expose the *SOC* to oxidation, which exposes the C depletion and this contributes to the high level of GHG emission [Brandani *et al.* 2017; Brandao *et al.* 2011; Karlen *et al.* 2013; Sheng *et al.* 2015]. In addition, soil spatial variability appears after its formation and continues after the soil reaches its dynamic balance [Fiener *et al.* 2012].

Long-term intensive sugarcane farming using chemical fertilizers, a farming system and harvesting approaches has an effect on *SOM* and brings about a decline in the *SOM* content in the soil and this will continue to increase in the coming decades [Anaya, Huber-Sannwald 2015]. Moreover, factors such as agricultural practices, land use, fertilization applications, tillage and irrigation systems were reported to affect the *SOC* stoke [Paustian *et al.* 1997]. Long-term farming systems and pre-harvest processes such as burning of sugarcane might affect the soil quality indirectly by influencing dynamics/changes in *SOC*, *SOM* and the pH of the soil [Karlen *et al.* 2013; Marzaioli *et al.* 2010; Rachid *et al.* 2013]. Souza *et al.* [2012] and Galdos *et al.* [2009] also reported that the pre-harvest burning of sugarcane could affect the soil microbial biomass which represents an important and strategic reservoir of plant nutrients that can be quickly altered due to different soil and crop management practices.

However, there is limited information about the *SOC*, *SOM* and soil pH content at WSSE. The production of sugarcane from the estate was reported to have decreased by 40–50% since the 1960s [Dinka *et al.* 2013]. That means the sugar estate is achieving about 50–60% of the production potential. The decline in production in the area might be attributed to many factors such as waterlogging, soil fertility decline and others. The reduction of *SOC*/*SOM* might have an effect on the sugarcane production and productivity. The purpose of this study was, therefore, to identify the status and dynamics of *SOC*, *SOM* and soil pH at WSSE as affected by long-term irrigation, pre-harvest burning, and sugarcane farming management practices.

METHODS

This study was conducted at WSSE (8° to 12° N; 38° to 41.8° E). The sugar estate is located within the Upper Awash River basin, in the regional state of Oromia. It is located at a distance of approximately 110 km South-East of Addis Ababa and approximately 10 km South-West of Adama town. The sugar estate has an estate proper (approximately 6,100 ha excluding the current area under expansion) and out-growers (3,200 ha). There are two sugar factories located at Wonji and Shoa with a total crushing capacity of 3,500 TCD (ton of cane per day). The state-owned lands are divided into nine management sections, classified based on the soil textural classes. The area has a semi-arid climate. Detailed information about WSSE can be obtained from different documents [Dinka *et al.* 2013; Dinka, Ndambuki 2014].

Immediately after the sugarcane harvest and the pre-harvest burning of the fields, composite soil samples were collected at two depths of soil profiles (0–40 cm and 40–100 cm). The locations of the sampling sites were registered by GPS. Then, the soil samples were immediately taken to the central laboratory of the Research Directorate located at Wonji. The *SOC*, *SOM* and soil pH were analyzed in the laboratory using the method mentioned in FAO [2006]. The *SOC* (Eq. 1–2) was determined by the methods described by Gattinger *et al.* [2012] and Benbi *et al.* [2015]. The *SOM* (Eq. 3) was determined from the value of *SOC* ($\mathrm{Mg{\cdot}C\ ha^{-1}}$).

$$SOC_{\mathrm{stock}} = BD \cdot SOC_{\mathrm{conc}} \cdot D \tag{1}$$

$$BD = \frac{100}{\frac{SOM_{\mathrm{conc}}}{0.244} + \frac{100 - SOM_{\mathrm{conc}}}{1.64}} \tag{2}$$

$$SOM_{\mathrm{conc}} = 1.72 SOC_{\mathrm{conc}} \tag{3}$$

Where the *BD* is the soil bulk density ($\mathrm{Mg{\cdot}m^{-3}}$), *D* is the soil thickness layer (m), SOM_{conc} is the concentration of *SOM* (%) and SOC_{conc} is the *SOC* concentration of the soil.

The values 0.244 and 1.64 represent the bulk density of the *SOM* and soil mineral matter, respectively.

The pH value of the soil samples was measured with a glass electrode pH-meter (A211, Thermo Scientific) with a one to one soil-water ratio as indicated in LIANG *et al.* [1994]. Finally, the spatial maps of the *SOM* and soil pH were produced in GIS (ArcMap 9.3) using the spatial mapping (IDW – inverse distance weight) available in GIS. The samples were collected randomly from the sugarcane fields by considering the two major soil types (vertisol and luvisols) as well as the nine soil management units. All the fundamental principles of experimentation including repetition and randomization were met. The experiment was performed in triplicate. In addition, all the samples were collected from the same soil type and the same sugarcane cultivator, which was treated similarly with fertilizers and pesticides.

RESULTS AND DISCUSSION

Table 1 summarizes the statistical summary of *SOC*, *SOM* and pH values. The top soil layer shows more variation compared to the bottom layer. All the soil samples are positively skewed, except pH for the bottom layer. The pH values of the soil samples at the considered soil depths are presented in Table 2. The result show that the pH value varied between 6.6–8.4 (the topsoil profile) and 7.3–8.5 (the bottom soil profile). Approximately 31% and 72% of the samples have pH > 7.8 for the top and the bottom profiles, respectively. The soil pH value is the measure of acidity or alkalinity of the soil, also called the soil reaction. It controls soil microbial enzymatic efficiencies in the mineralization process of *SOM* [XIAO 2015]. It also influences the availability of soluble nutrients, and affects the activity of microorganisms responsible for breaking down organic matter and most chemical transformations in the soil [LIANG *et al.* 1994]. The optimum pH for the rapid decomposition of organic matter is 6.7 [XIAO 2015]. Accordingly, the topsoil layer is classified as neutral to moderately alkaline, while the subsurface soil layer is in the range of neutral to strongly alkaline, which is similar to the report made by ASMAMAW *et al.* [2018] for the Tendaho Sugar Plantation, located within the lower Awash Basin. At pH ≥ 7.8, Ca and Mg are abundant. A high soil pH level in the study area might affect the availability of Fe, Mn, Co, Zn, P and B in the burnt soil as well as long-term irrigation in the estate farm.

Table 1. Statistical summary of soil properties

Parameter	Layer (cm)	Range	Min.	Max.	Mean	*SD*	Skewness	Kurtosis
pH	0–40	1.8	6.6	8.4	7.6	0.36	0.10	0.89
	40–100	1.2	7.3	8.5	8.0	0.35	–0.13	–0.69
Organic matter	0–40	5.6	1.1	6.7	3.6	1.18	0.79	1.79
	40–100	2.5	0.7	3.3	2.0	0.63	0.13	–0.22
Organic carbon	0–40	1.9	0.4	2.2	1.2	0.38	0.89	2.15
	40–100	0.9	0.3	1.2	0.7	0.23	0.23	–0.29

Source: own study.

Table 2. Classification of soil pH

pH range	Category	Sample (%)	
		0–40	40–100
6.6–7.3	neutral	13.9	5.6
7.4–7.8	slightly alkaline	55.6	22.2
7.9–8.4	moderately alkaline	30.6	69.4
8.5–9.0	strongly alkaline	0.0	2.8

Source: own study.

Figure 1 shows the *SOM* and the pH levels of soil samples. *SOM* is a key component of soils that affects many reactions that take place in the soil system [SPAIN *et al.* 1983]. Moreover, BENBI *et al.* [2015] reported that *SOM* has a key function in maintaining soil quality and the functionality of the ecosystem. It adds organic carbon to the soil by decomposition and hence reduces the emission of CO_2 into the atmosphere, which reduces the GHG effect on the environment [GATTINGER *et al.* 2012; XIAO 2015]. The results show that the pH and *SOC* vary with soil sample percentage and soil depth (Fig. 1). The pH values of the topsoil (0–40 cm) were found to be higher than that of the lower depth (40–60 cm). The results are consistent with the results reported by KELLOGG [1993]. As per the classification by KELLOGG [1993], several parts of the topsoil depth have pH values of 7.4–7.8, which is categorized as a slightly alkaline soil. On the other hand, several portions of the bottom soil depth have a pH value in the range of 7.9–8.4, which is categorized as moderately alkaline. Moreover, the result show that some *SOM* samples displayed less than 2% for the bottom soil profile than the upper soil profile while the reverse result was displayed for *SOC* of 2–4%. Furthermore, the higher level of *SOM* content (4–7%) was observed only for the topsoil layer. The concentration of the *SOM* content in soils generally ranges from 1–6% of the total topsoil mass for most upland soils [PERIE, OUIMET 2008]. Since the majority (58%) of *SOM* is due to *SOC*, the content of *SOM* is directly proportional to that of *SOC*.

The spatial variability of the *SOM* and pH are displayed in Figures 2–3. The *SOC* and pH values showed a spatial variability in both surface and sub-surface soil layers (Figs. 2–3). The *SOC* is a complex of organic carbon compounds that are generated from *SOM* including that of biological origin [XIAO 2015]. These include plant and animal remains in a state of decomposition, cells and tissues of soil organisms, material from plant roots and soil microorganisms [XIAO 2015]. The *SOM* content obtained in the area is in the range of 1.1–6.7% (upper) and 0.74–3.3% (lower) soil layers The *SOM* content obtained in the study area is in the range of 1.1–6.7% (upper soil layer) and 0.74–3.3% (lower soil layer), with an average value of 3.6% and 2.0%, respectively. Almost half (45%) of the soil samples have an *SOM* content below the desirable limit (<2.1% for clay loam/clay soil) in the subsurface soil layer, and hence are inadequate. On the other hand, the majority (95%) of the soil samples have an *SOM* exceeding the desirable limit in the topsoil profile and approximately 8% of the samples have *SOM* > 5%. The ex-Awash route, which is in the topsoil, is relatively rich in *SOC* compared to the others. This may be due to the deposition of fertile soil

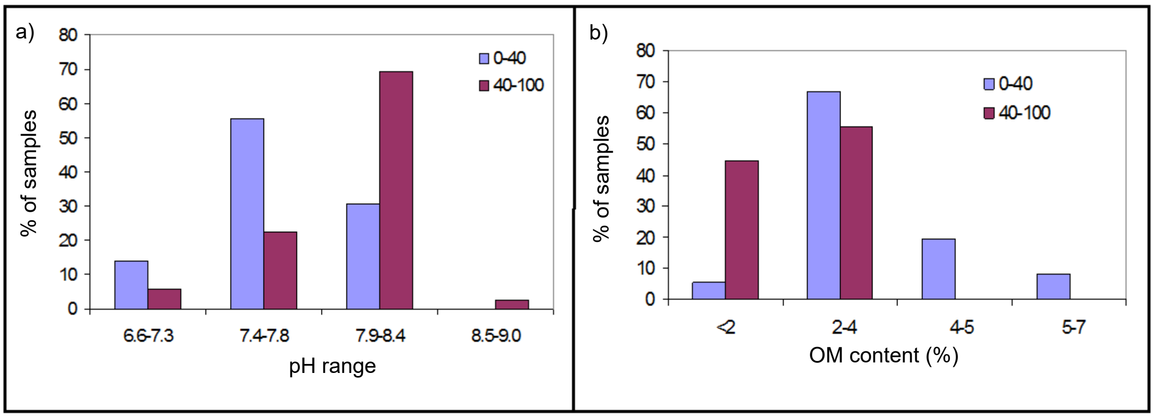

Fig. 1. Distribution of chosen soil parameters for the two soil layers per percentage of soil samples: a) pH value, b) organic matter (OM) content; source: own study

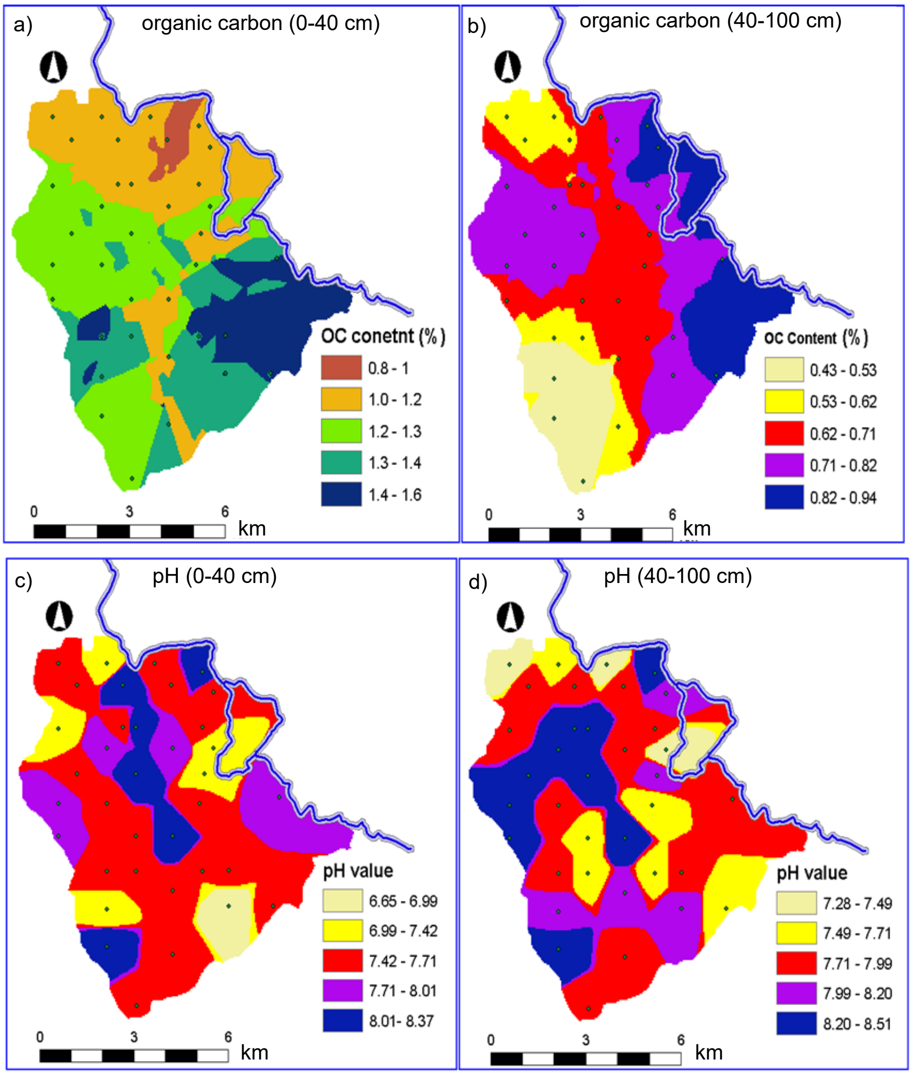

Fig. 2. The spatial distribution of chosen soil parameters in the surface (0–40 cm) and subsurface (40–100 cm) layer: a) organic carbon, 0–40 cm, b) organic carbon, 40–100 cm, c) pH, 0–40 cm, d) pH, 40–100 cm; source: own study

coming from the surrounding escarpment. In the sub-soil layer, the *SOC* is low on the South and southwestern side of the plantation.

In general, the *SOC* was higher in the topsoil layer compared to the bottom soil layer. Similar results were obtained by other studies elsewhere in the world [GATTINGER *et al.* 2012]. Cited authors obtained higher *SOC* on the top profile and indicated that the increased concentration in the topsoil is due to organic farming. The *SOC* content of irrigation or farming soil is usually less than 5% and inversely proportional to soil depth [XIAO 2015]. As discussed earlier, these areas experience the shallowest water table throughout the year and are identified as problematic soils (poor drainage). WU *et al.* [2016] reported that the *SOC* content was inversely proportionated with that of the biochar level of the soil.

It is evident from Figure 2 that the topsoil has a normal range of *SOM* content compared with the bottom layer. The results obtained reveal the reduction of *SOM* with soil depth, which is as reported by different researchers for the Ethiopian context [BELACHEW, ABERA 2011] and other parts of the world [XIAO 2015]. The relatively higher *SOM* content in the upper profile, as also suggested by DINKA [2010] for the Matahara Sugar Plantation, may be due to the partial decomposition of parts of the cane (such as the cane top and underground biomass – roots) as well as the amendments of filter cake into the soil. Despite this fact, the WSSE soil, especially the subsurface soil layer, is experiencing a lower amount of *SOC* and *SOM*. The lower amount of *SOC*/*SOM* in the subsurface soil layer is common for all the sugar estates in Ethiopia [DINKA 2010]. As suggested by DINKA [2010], dry harvesting (pre-harvest burning of sugarcane), burning residues that add dry ash into the soil and removing plant products (increasing bare fallow), is probably the cause of the decline of *SOC*/*SOM* in Ethiopian sugar estates.

BLAIR [2000] indicated that green waste releases more active liable C from crop residues than the burnt treatment. This author further indicated that the burnt sugarcane residue/waste remaining on the soil surface most likely had a higher lignin content and a lower decomposition rate than the higher quality, readily decomposable, green residues. Moreover, the low *SOM* is even true for most cultivated Ethiopian soils due to the low organic materials applied to the soil; the complete removal of plant biomass from the field [YIHENEW 2002], and the geographical/biophysical and climatic condition [DINKA 2010]. High rainfall and the warm temperature (tropical climate) are one of the factors affecting soil *SOM* levels that results in the rapid breakdown of organic materials, in contrast to low rainfall and a cool climate [BLAIR 2000].

It is also well documented that continuous cultivation of soils results in the reduction of *SOM* and the associated structural degradation [BLAIR 2000]. Furthermore, *SOM* can be lost through erosion processes (detachment and transport of topsoil). Also it is utilized by soil microorganisms as energy and nutrients to support their own life processes; some of the material is incorporated into the microbes, but most is released as CO_2 and H_2O, some are released (nitrogen) in gaseous form, and some are retained along with most of the phosphorus and sulphur [USDA 1995–96]. Soil tilth is also one factor in the decline of *SOM*. When soils are tilled, *SOM* decomposes faster because of changes in water, aeration, and temperature conditions [USDA 1995–96]. Drainage and fertilization (especially with excess N) also increase the rate of decomposition. *SOM* breaks down more quickly in moist soil than in dry soil.

Several studies have well documented lower *SOM* content conditions in soils cultivated with sugarcane in Brazil, Australia and many others [SILVA *et al.*]. The *SOM* is a sensitive indicator of the effects of management practices on soil *SOM* [SILVA *et al.* 2007] and probably the clearest indicator of unsustainable land management [GREENLAND, SZABOLCS 1994]. Higher levels of *SOM* are generally associated with improved physical integrity, higher soil productivity, and enhanced environmental quality [e *SOM* enhances the soil-water relation because of its hydrophilic nature and its positive influence on soil structure [HUNTINGTON 2008. The *SOM* content expresses the relationships between the sources of the organic materials and the decomposing factors (soil biota) [GREENLAND, NYE 1959]; both factors depend, to a large extent, on climate and lithology factors that control the texture, structure, moisture content and temperature [SARAH 2006]. Furthermore, *SOM* serves as one of the major reservoirs for (biospheric) carbon on the earth's surface [POST, MANN 1990].

Figure 3 presents the plot of clay content, pH and *SOM* for the two soil layers. It is clear to see that the *SOM* tends to increase as the clay content increases and vice versa in both soil profiles. This is due to, as also reported by BOT and BENITES [2005], the bonds between the surface of clay particles and *SOM*, which may retard the decomposition process. This means that heavy clay soils with a high clay content are most likely to be affected by drainage problems. This is because there is the development of the anaerobic condition in poorly drained soils, resulting in retardation of the rate of mineralization of the *SOM*. As per the clay content, the Wonji plantation soils could have been rich in *SOM*, but the lower value may be explained by the waterlogging condition and the resulting drainage problems facing the plantation [DINKA, NDAMBUKI 2014]. A decline in *SOM* may face the estate if the current waterlogging condition continues in the future for a long period. This partially explains how waterlogging is affecting the soil fertility and hence production and productivity in the study area.

CONCLUSION AND RECOMMENDATION

This study presents the effects of long-term sugarcane farming on the soil pH and organic carbon/matter content at Wonji Shoa Sugar Estate (WSSE). The pH for the top profile of the soil is neutral to moderately alkaline (6.7–8.4), while that of the bottom profile is neutral to strongly alkaline (7.3–8.5). The *SOC*/*SOM* contents vary inversely with the depth of the soil. The *SOM* content ranged from 1.1 to 6.7% and from 0.74 to 3.3% for the top and bottom soil profiles, respectively. The majority of the samples taken from the topsoil profile have organic contents greater than the desirable amount, while more than half of the samples in the bottom profile was found to be lower than the desirable amount (<2.1% for clay loam/clay soil).

The result of this study also indicated that the *SOC*/*SOM* contents are lower in the South and Southwestern part of the study area. This was attributed to the fact that these parts having shallower water table throughout the year and consequently having poorer drainage compared with other parts of the study area. The decrease in *SOM* content with increased depth was attributed to dry

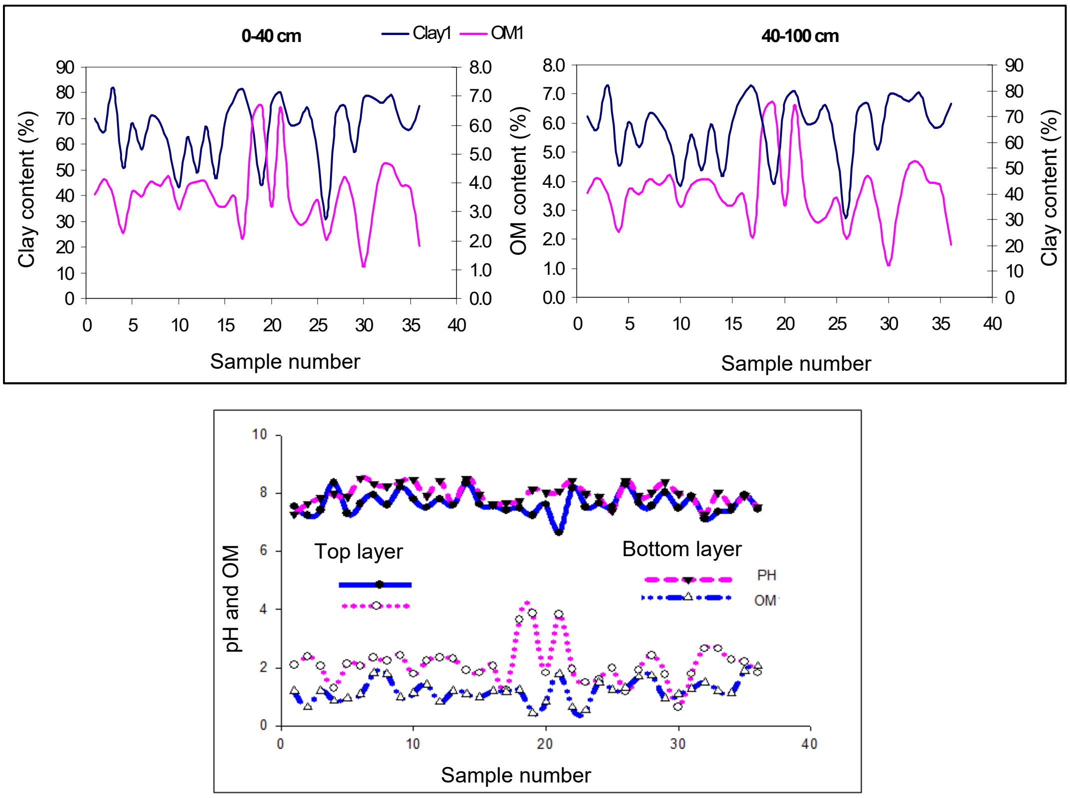

Fig. 3. The contents of soil organic matter (OM), clay and pH at two soil layers; source: own study

harvesting and poor drainage of the clay soil, which cause waterlogging. The implication of this finding is that fewer soil nutrients from organic matter will be available for absorption by the roots of plants, which consequently decreases the soil fertility and the yield in the study area. Columns of gravel or other coarse aggregates can be constructed within the soil profile to facilitate the migration of organic matter to the bottom profile of the soil in the study area.

Based on the findings of this study, the authors would like to emphasize the need for feasible management measures to increase the organic contents of the study area. Attention should be focused on the need to minimize pre-harvest burning of the sugarcane and action is needed to change the irrigation method to green harvesting to facilitate the soil organic carbon retention in the soil and to minimize the greenhouse emission effect on the environment, hence improving soil quality in the long-term. Moreover, the authors of this paper would like to urge the concerned bodies to find a feasible management measure for the waterlogging and its associated problems in the study area.

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Przestrzenne zróżnicowanie i dynamika pH gleby oraz zawartości węgla organicznego i materii organicznej: Przykład plantacji trzciny cukrowej Wonji Shoa

STRESZCZENIE

W pracy przedstawiono przestrzenną zmienność i dynamikę węgla organicznego w glebie (SOC), materii organicznej (SOM) i pH na plantacji Wonji Shoa Sugar Estate (WSSE) w Etiopii. Próbki gleby były pobierane bezpośrednio po zbiorze trzciny cukrowej. Analizowano w nich wymienione wyżej składniki według standardowych procedur. Wartość pH zmieniała się od 6,7 do 8,4 w powierzchniowej warstwie gleby i od 7,3 do 8,5 w głębi profilu glebowego. Zawartość materii organicznej wynosiła od 1,1 do 6,7% w górnej i od 0,74 do 3,3% w dolnej warstwie gleby. Około 45% próbek zawierało materię organiczną w ilościach mniejszych niż pożądana (2,1%) w głębszych warstwach gleby. Większość próbek powierzchniowych zawierała materię organiczną w ilościach przekraczających tę granicę, co klasyfikuje te gleby jako normalne. Co ciekawe, zawartość węgla organicznego cechowała zmienność przestrzenna zarówno w powierzchniowych, jak i podpowierzchniowych warstwach gleby. Mniejszą zawartość materii organicznej i węgla organicznego stwierdzono w podpowierzchniowych warstwach gleby z południowej i południowozachodniej części plantacji. Gleby na plantacji mogą doświadczać dalszego spadku zawartości SOC i SOM, jeśli obecne wysycenie gleby wodą będzie występowało w przyszłości. Podsumowując, wyniki badań wskazują na potrzebę minimalizowania opalania trzciny cukrowej przed zbiorem oraz podejmowania działań zmierzających do zmiany metod nawadniania, aby usprawnić retencję węgla organicznego w glebie i łagodzić środowiskowe skutki emisji gazów cieplarnianych, a przez to polepszyć jakość gleb w dłuższej perspektywie czasowej.

Słowa kluczowe: *jakość gleb, pH, trzcina cukrowa, węgiel organiczny w glebie, zawartość materii organicznej*