Changes in Soil Fertility Status under Long-term Intensive Sugarcane Production System at Wonji-Shoa Sugar Estate in Central Ethiopia

Alemayehu Dengia[a], Nigussie Dechassa[b], Lemma Wogi[c] and Berhanu Amsalu[d]
[a]*Ethiopian Sugar Industry Group, Research and Training Division, P. O. Box,15 Wonji/Adama.*
[b]*Haramaya University, College of Agriculture and Environmental Sciences, Africa Center of Excellence for Climate Smart Agriculture and Biodiversity Conservation, P. O. Box 138, Dire Dawa, Ethiopia*
[c]*Haramaya University, School of Natural Resources Management and Environmental Sciences, P. O. Box 138, Dire Dawa, Ethiopia;*
[d]*Ethiopian Institute of Agricultural Research (EIAR), Melkassa Agricultural Research Centre, P.O. Box 436, Adama, Ethiopia; Corresponding author, email:* alexdengia@gmail.com

Abstract

Sugarcane yields at Wonji-Shoa Sugar Estate (WSSE) in central Ethiopia have declined by 48% over the last 70 years. Previous studies suggest that a decline in sugarcane yield is attributed to long-term intensive production system and the subsequent depletion of soil fertility. Hence, it was hypothesized that the soil fertility in the WSSE has been depleted, potentially contributing to the yield decline. To test this hypothesis, a series of bio-sequential soil samples were taken from adjacent cultivated lands (CL) and uncultivated lands (UL) in the two categories of WSSE: the old plantation (OP) and the new plantation (NP) lands, which have been cultivated for 70 and 13 years, respectively. The samples were analyzed for selected soil properties and compared using the t-test statistical tool. The results revealed that the soil organic carbon, total nitrogen, available phosphorus, exchangeable potassium, sulfur, zinc, and EC of the OP have declined significantly by 16%, 13%, 50%, 39%, 82%, 15%, and 58%, respectively, whereas no significant decline was observed in the NP. Calcium, magnesium, sodium, manganese, copper, and boron didn't decline significantly in both plantations. The rating of organic carbon, available phosphorus, sulfur, boron, and EC were below the critical values. The findings confirm that the major soil properties of WSSE have dwindled as a result of the long-term intensive production system and appear to be responsible for the yield decline. Therefore, it is crucial for the sugar estate to design appropriate soil fertility management strategies to arrest the declining yields and produce the crop sustainably.

Keywords: Cultivated land, plantation, soil properties, uncultivated land, yield decline.

Introduction

The sugar industry plays a crucial role in the economic development of tropical and subtropical countries (Zulu *et al.*, 2019). As a result, sugarcane has emerged as one of the top 10 cultivated crops in the world

(Selman-Housein *et al.,* 2000). Sugarcane is used to produce renewable energy, biomaterials, and food or feed, and thus plays a significant role in both rural and urban livelihoods, and the socio-economic transformation of developing countries (Solomon and Shukla, 2019). Given that Ethiopia has suitable agro-climatic conditions for sugarcane cultivation (Berkum *et al.,* 2005; Ming *et al.,* 2006), it is essential for the country to take advantage of the benefits derived from cultivating this crop.

The inception of the sugar industry in Ethiopia dates back to 1951, when a Dutch company called United N.V. Handles Vereeniging Amsterdam (HVA) was granted a concession of 5,000 hectares of land (Kassie, 2022). The establishment of this modern sugarcane plantation showcased Ethiopia's significant potential for sugarcane production, with the capacity to produce up to 10.8 tons ha^{-1} $month^{-1}$, surpassing global productivity by 2.3 tons (ESIG, 2023). Recognizing this potential, the Ethiopian government has prioritized the development of sugar industry since 2010. As a result, the number of sugarcane plantations has increased from four covering 30,000 hectares to 10 encompassing over 102,000 hectares of land (Taye *et al*., 2020).

Despite the expansion of sugarcane plantation, yields have been experiencing a drastic decline over the last 70 years. For instance, at Wonji-Shoa Sugar Estate (WSSE) alone, the yield has decreased by about 48% (Tesfaye, 2021). Therefore, it is crucial to understand, identify, and manage the problem of yield decline to sustain the productivity of the crop and foster the role of the sugar industry in contributing to the economic development of the country.

Soil quality has a strong impact on crop yield, and its degradation has a negative effect on soil fertility, which ultimately causes yield decline (Mendes *et al.,* 2021; Gobinath *et al.,* 2022). The intensive farming system used in sugarcane plantations, which includes monocropping, on-field cane burning for harvesting, excessive tillage, and uncontrolled traffic of heavy machinery is often blamed for causing soil degradation (White *et al*., 2012; Kopittke *et al*., 2019). According to Gomiero (2019), these practices are known to contribute to a phenomenon referred to as "soil fatigue" or "soil sickness", which is characterized by a gradual decline in yields over time, even when optimal management practices are implemented.

Monocropping has been reported as a major cause of the degradation of the physical, chemical, and biological properties of soil with negative repercussions on the beneficial microflora and essential nutrients (Misra *et al.,* 2019; Lei *et al.,* 2020). Moreover, it intensifies the severity of crop pests and plant parasitic nematodes (Chirchir *et al.,* 2010; Aman, 2020). Under continuous monocropping, decaying cane trash and the ratoon cane root system also release allelochemicals into the soil that create unsuitable conditions for plant growth (Sampietro *et al.,* 2007).

One of the major operations in the intensive sugarcane production system is on-field cane burning for harvesting, which eliminates what should be returned back to the soil as organic matter (OM) (Davies, 1998). During burning, the temperature can exeed 400^{o}C (Davis, 1998), which results in the oxidation of carbon and the volatilization of major nutrients, such as nitrogen and sulfur. It also eliminates humus, bacteria, microorganisms, and worms from the soil surface (Vitousek and Sanford, 1986; Chi *et al.,* 2017). Burning also induces salinity as ash contains a considerable amount of soluble ions (Kalra *et al.,* 2000; Khan and Qasim, 2008; An and Park, 2021; Bang-Andreasen *et al.*, 2021). Additionally, calcium oxide (CaO), another major constituent of ash, reacts with water to form $Ca(OH)^2$, resulting in high soil pH (Singh *et al.*, 2007; An and Park, 2021). Since sugarcane is sensitive to salinity (glycophyte) (Wahid *et al.,* 1997; Watanabe, 2020) and high pH (Labajo and Pabiona, 2022), these situations may result in inhibiting growth in the long run.

Excessive tillage and heavy machinery traffic also contribute to soil degradation (Farhate *et al.,* 2022). Tillage deteriorates soil OM content through modifying the soil climate, mixing OM with the soil matrix, and damaging the soil structure. Tillage also exposes OM by removing the protective soil microaggregates (Balesdent *et al.,* 2000). These circumstances increase microbial activity, oxidation rates, and ultimately the biodegradation and liberation of organic compounds in soil solutions.

In spite of the fact that sugarcane has been produced intensively for the last 70 years in the Ethiopian Sugar Estates, there has been a lack of comprehensive studies on the soil-related factors contributing to the decline in sugarcane yields. Since the establishment of the Wonji-Shoa Sugar Estate, only two studies have attempted to address the problem (Alemayehu and Lantinga, 2016; Tesfaye, 2021). However, these studies only considered a few soil parameters, which are insufficient to draw conclusive recommendations. Therefore, a thorough analysis is necessary to comprehend the role of long-term intensive sugarcane production system in depleting major soil properties, especially in the WSSE, where yield decline is the most severe in the country. The hypotheses of this study is that the continuous and intensive production system has led to soil fertility depletion, thereby contributing to the decline of sugarcane yields over the years. The objective of this study was, therefore, to assess and demonstrate changes in selected soil properties under a long-term intensive sugarcane production system in central Ethiopia to explain the declining sugarcane yields in the Wonji-Shoa Sugar Estate.

Material and Methods

Description of study site

Location

The study was conducted from October, 2021 to August, 2022 at Wonji-Shoa Sugar Estate (WSSE), the pioneer sugar estate of Ethiopia. Wonji-Shoa Sugar Estate is situated at a distance of about 110 km from Addis Ababa, in southeasterly direction in Oromia Regional State. The geographical location of the plantation site is within 8°19'54"–8°29'15"N and 39°13'34"–39°19'21"E at an altitude of 1540 to 1650 meters above sea level (Fig. 1).

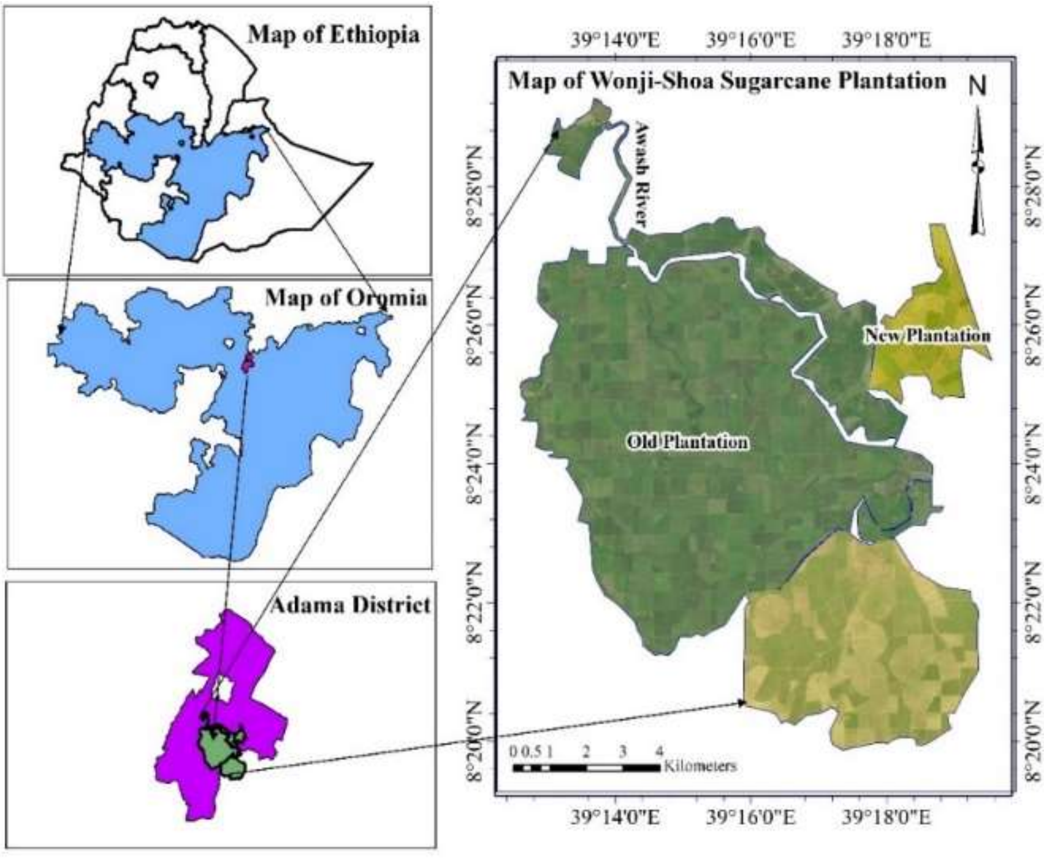

Fig 1. Map of the study site depicting old (green) and new (yellow) plantations of the Wonji-Shoa Sugar Estate

Climate

The long-term mean annual (1980–2020) maximum and minimum temperatures of the study site are 14.5°C and 27.4°C, respectively (Fig. 2). The area experiences a bimodal and unpredictable distribution of rainfall, with an average annual precipitation of 768 mm. The main rainy season occurs from June to September.

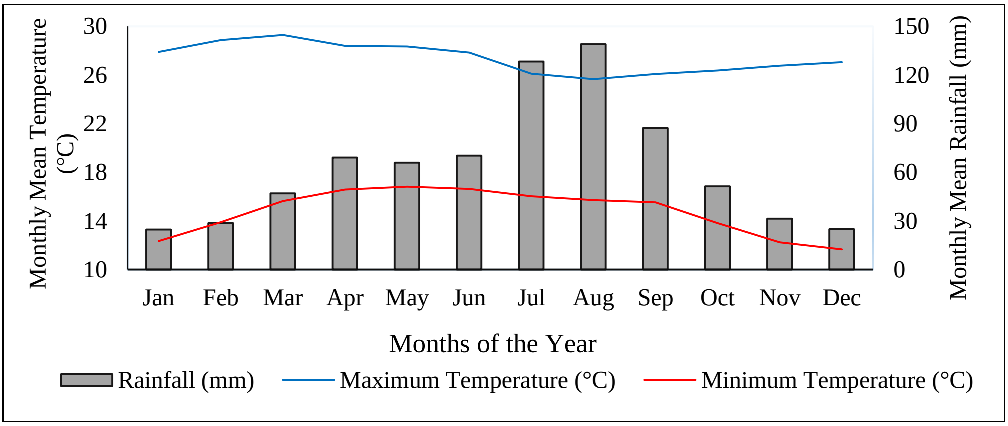

Fig 2. Monthly mean rainfall, and maximum and minimum temperature of the study area.

Establishment of Wonji-Shoa Sugar Estate

Prior to the development of the sugarcane plantation, the Wonji plain and its environs were covered in abundant vegetation (Megersa Olumana and Ndambuki, 2014) which was registered as government land and mainly used as grazing lands by semi-pastoralists (Kassie, 2022). Following the inception of WSSE, the land use/cover of the area was significantly changed.

Sugarcane production at Wonji-Shoa began in 1954 on 5000 ha of land, and an additional 1170 ha of land (out-grower scheme) was included in 1975. The land was developed using furrow irrigation system which was abstracted from Awash River. In 2006, a new expansion project was started in the eastern part of the old plantation (in a place called Waketio) (Fig. 1), which was formerly under cereal cultivation (Booker Tate and MCE, 2003). The project was successfully completed, and sugarcane production commenced in 2009 on a 750-ha land area. This new sugarcane plantation was developed with an over-head (sprinkler) irrigation system (Taye *et al.*, 2020).

Geology and soils of the study area

Located in the main Ethiopian Rift Valley, the geology of the WSSE resulted from the volcanic activity and rift tectonics. The main geological units of the site are dominated by basalts, silicics, tuffs, ash-flows, trachytes, and other volcanic rocks. The age of lacustrine rift sediment is contemporaneous with the Wonji volcanics, which largely include volcano clastic sediments and tuffs with silts, clays, and diatomites. In some parts of the plantation, alluvial deposits are also common (Megersa Olumana and Ndambuki, 2014).

Table 1. Soil type of Wonji-Shoa Sugar Estate fields

Soil Types	Group (FAO classification)	Extent
Vertisols	Haplic Vertisols	70%
Cambisols	Cambisols, clayic	26%
	Cambisols, ruptic	4%

Source: BRLi and GIRDC (2013)

The Wonji plane consists of thick stratified sediments of predominately fluvatile origin (Mukherji, 2000). Clay soils as well as sandy and loamy soils are generally associated with old channels, levees, sandbanks, and meander scars of the present and old courses of the Awash River. They have a sinuous distribution throughout the sugarcane plantation, but all together occupy only 30% of the plantation (Table 1). The remaining 70% of the land is covered by vertisols, which are widely spread throughout the plantation. Vertisols occupy the lowest parts of the alluvial landscape and represent extensive plains/back swamps behind old levees (Table 1). The soil textural class and slope of both the new and the old plantation are presented in table 2.

Table 2. Soil texture and slope of the new and the old plantation of Wonji-Shoa Sugar Estate.

Description	Old Plantation	New Plantation
Sand (%)	12.36	40.33
Silt (%)	21.00	25.67
Clay (%)	66.64	34.00
Textural Class	Clay	Clay Loam
Slope (%)*	0.02 – 0.05	1–4

Old Plantation (Started in 1954); New Plantation (Started in 2009).
*Source; Megersa Olumana and Ndambuki (2014); Booker Tate and MCE (2003).

Methods of soil sampling

The changes (decline) in soil fertility were studied following the definition and procedures outlined by Hartemink (2006), which employ the bio-sequential sampling method. Bio-sequential sampling is a method where paired soil samples are collected simultaneously from cultivated and uncultivated lands that are adjacent to each other (Sanchez *et al*., 1985). Then, the samples are analyzed separately and the results are compared to examine the extent of change in soil properties. The basic assumption in this type of sampling is that the soils of the cultivated and uncultivated lands are similar, and that any changes in soil properties emanate from the adopted farming systems and the associated management.

Selection of sampling sites

The sites for the soil sampling were selected from the two categories of plantation ages of the WSSE, i.e., the old plantation (OP) and new plantation

(NP) (Fig 1). For the sampling, 14 (eleven from the OP and three from the NP) representative cultivated fields were systematically selected in such a way that the sampling sites were evenly distributed across the entire plantation. Meanwhile, from the adjacent field of each selected cultivated field, the second category of sampling sites, namely the corresponding uncultivated land (primarily grasslands) with similar topography and local soil-forming factors, was chosen. This selection ensured that the disparities between the two soils were solely attributable to the cultivation practices of sugarcane. The lands were confirmed to be uncultivated for sugarcane production, from the plantation map of WSSE, which was prepared during the inception of the sugar factory and from the historical satellite images of the site. In total, 28 sites were selected for the soil sampling.

Collection of soil samples

Since most sugarcane roots are found in the top 0–40 cm of soil (Otto *et al*., 2009), soil samples from this layer was used for the analysis. About 20–30 core samples were taken in an X-shape pattern from each field/site and then composited. Afterwards, from each of the composited sample, duplicate sub-samples were taken. Then, a total of 54 soil samples were sent to Wonji Research Center laboratory.

Soil samples preparation and analysis

The collected soil samples were air-dried and ground to pass through a 2 mm size sieve. For analyzing total N (N) and organic carbon (C), the subsamples were again passed through a 0.5 mm sieve. Then, the samples were analyzed for the parameters listed in Table 3 following the standard method (Lemma *et al*., 2021).

After preparing the soil samples at Wonji Research Center laboratory, analysis was carried out for OC, total N, available phosphorus (P), pH, electrical conductivity (EC), exchangeable bases and cation exchangeable capacity (CEC) as indicated in table 3. The samples were additionally sent to the Horticoop PLC-Ethiopia (Bishoftu) Soil and Water Analysis Laboratory, for the analysis of soil micronutrients (Copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), boron (B), and molybdenum (Mo)) and available sulfur (S) (Table 3).

Table 3. Extraction and determination methods of the selected soil parameters

Soil parameter	Unit	Extraction Method	Determination Method
Soil pH	–	Soil:Water ratio 1: 2.5	Potentiometric
Soil EC	dSm^{-1}	Soil:Water ratio 1: 2.5	Conductivity meter
OC	%	Walkley and Black wet digestion	Titration
TN	%	Kjeldahl procedure	Titration
Av-P	ppm	Olsen	Spectrophotometer
Fe, Mn, Zn, Cu	$mg\ kg^{-1}$	DTPA extraction	ICP-OES
B	$mg\ kg^{-1}$	DTPA-sorbitol	ICP-OES
Exc-K^+, Exc-Na^+	$cmol_{(+)}kg^{-1}$	Ammonium acetate (pH = 7)	Flame photometric
Exc-Ca, Exc-Mg	$cmol_{(+)}kg^{-1}$	Ammonium acetate (pH = 7)	EDTA titrimetric
CEC	$cmol_{(+)}kg^{-1}$	Na acetate method	Flame photometric
Av-S, Mo	$mg\ kg^{-1}$	Mehlich-III	ICP-OES

EC, Electrical Conductivity; OC, organic Carbon; TN, total Nitrogen; Av-P, available Phosphorus; Av-S, available Sulfur; Exc-K^+, Exchangeable Potassium; Exc-Na^+, Exchangeable Sodium; Exc-Ca, Exchangeable Calcium; Exc-Mg, Exchangeable Magnesium; Fe, Iron; Mn, Manganese; Zn, Zinc; Cu, Cupper; B, Boron; Mo, Molybdenum; CEC, cation exchangeable capacity; DTPA, Diethylene Triamine Pentaacetic Acid

Exchangeable Sodium Percentage (ESP) (Equation 2.5.1) and percent Base Saturation (BS) (Equation 2.5.2) were calculated as described by Hazelton and Murphy (2016).

$$\mathrm{ESP}=\frac{\mathrm{ExcNa}}{\mathrm{CEC}}*100 \qquad (2.5.1)$$

$$\mathrm{BS}=\frac{\Sigma(\mathrm{Basic\ Cations})}{\mathrm{CEC}}*100 \qquad (2.5.2)$$

Data analysis and interpretation

Laboratory results of the bio-sequential soil samplings were compared by applying t-test analysis ($P < 5\%$) using Genstat 2018 (VSN International, 2015). The results were also compared with established classes of deficiency and sufficiency (ratings) as well as critical values. Accordingly, soil organic C, total N (Tekalign *et al*., 1991), available P (Cottenie, 1980) and Cu, Fe, Mn and Zn (Lindsay and Norvell, 1978), extractable S (Bashour and Sayegh, 2007), pH (Murphy, 1968), exchangeable bases (FAO, 2006), CEC (Landon, 1991), B (Jones, 2003), Mo (FAO, 1982), BS and ESP (Hazelton and Murphy, 2016) were rated and categorized into different ranks as determined in the literature.

The relative changes (RC) in the soil properties were also determined by computing the difference between the mean values of individual soil properties of the bio-sequentially sampled soils and dividing by the value of the uncultivated land (Mesfin and Mohammed, 2020), using the equation indicated below;

$$\mathrm{RC}\ (\%) = \frac{\mathrm{CL-UL}}{\mathrm{UL}}\mathrm{x}100\% \qquad (2.5.3)$$

Where, RC is the relative change of soil properties, CL is the mean of soil properties in cultivated lands; UL is the mean of soil properties in uncultivated lands.

Results and Discussion

Soil pH

For the old plantation (OP) fields, there were no significant differences in soil reaction between the cultivated land (CL) and the uncultivated land (UL) (Table 4). However, for the new plantation (NP) fields, the soil reaction was significantly ($P < 0.05$) higher in the CL than in the UL. Furthermore, both the CL and UL showed a significant ($P < 0.05$) differences in soil reaction, between the NP and OP fields, with the NP fields showing more alkalinity than the OP fields.

Murphy (1968) categorizes Ethiopian soils as slightly alkaline for pH values ranging from 7.4 to 7.8 and moderately alkaline for pH values ranging from 7.9 to 8.4. Therefore, both the CL and UL in the OP are mildly alkaline, while the NP is moderately alkaline. Furthermore, the current pH levels of both the OP and NP were 18% and 24% higher than the optimum value for sugarcane (6.5) (Labajo and Pabiona, 2022).

The stable pH in the OP and the decreased pH in the NP might be due to the differences in the soil texture between the two plantations i.e. the OP has a high clay content while the NP has a low clay content (Table 2). According to Curtin *et al.* (2013), soils with high clay contents have better buffering capacity (the capacity of a soil to resist changes in the soil pH in the presence of acidifying or alkalizing factors) for change in the soil pH. This finding is also in agreement with Chi *et al.* (2017) who reported that soil with high clay contents showed no significant change in the soil pH under long-term cultivation. However, the higher pH in the NP compared to the OP might be attributed to the pedogenesis of the soil in each plantation. Therefore, to gain a deeper understanding of this phenomenon, additional investigation is necessary.

Generally, the slightly elevated pH observed at the study site, exceeding the optimum value, could potentially hinder nutrient availability, particularly for micronutrients and phosphorus (Neina, 2019). These trends may have a negative impact on cane yield in the future, therefore, it is important to promote management measures.

Soil Electrical conductivity

In the old plantation fields (OP), soil electrical conductivity (EC) was significantly ($P < 0.05$) lower (58%) in the cultivated land (CL) than in the uncultivated land (UL), whereas in the new plantation fields (NP), no significant difference was obtained (Table 4). Furthermore, the EC in the OP was significantly ($P < 0.05$) higher than in the NP in both land types. The soils in both plantations and land types were found to be in non-saline range as the soil EC was < 4, which is rated as non-saline by Richards (1954). This has important implications for the plantations, as sugarcane is a typical glycophyte plant that grows poorly on high EC soil (Wahid *et al.,* 1997).

Despite the long term practices of furrow irrigation systems and pre-harvest cane burning, the observed lower EC levels compared to the critical value were unpredicted. Remarkably, the current EC value was also 51% lower than the soil analytical result of the OP, which was done 22 years ago (Mukherji, 2000). This result also contradicts the findings of other researchers, such as Le Roux *et al.* (2007), who observed an increase in EC in an irrigated farm. Khan and Qasim, (2008) also stated that the ash left after pre-harvest cane burning adds enormous amounts of cations such as Fe, Mn, Zn, Cu, Ca, Mg, Na, S, K, and P to a soil, which can increase the soil EC. Similarly, Wong and Lai (1996) and Kalra *et al.* (2000) stated that ash in a soil can result in the precipitation of soluble cations with a concomitant increase in the soil EC.

The decline in soil EC observed in this study might result from the quality and quantity of irrigation water used in the WSSE. According to Zeyede and Mulate (2021), the EC of irrigation water used at WSSE (0.51 Sm^{-1}) is in the safe category. This, coupled with the furrow irrigation method in the OP, may have leached down the cations and thus kept the EC within an optimum range. This is also consistent with Chang and Oosterveld (1981), who found similar results on lands irrigated for 65 years.

The higher EC in the OP than the NP in both land types may be attributed to the difference in soil texture, where the soil of the NP has relatively higher sand contents (Table 2) compared to OP. Because soil with a higher sand proportion has a relatively limited ability to retain and hold cations, it loses nutrients more quickly than soil with a higher clay proportion. Thus, cations that are responsible for increasing soil EC might be leached from the soil of the NP, which ultimately led to the lower EC. In line with this finding, Kim *et al.* (2017) also found a strong correlation between clay content and soil EC.

Table 4. Soil Organic Carbon (%), Soil pH, and EC (dS m^{1}) of soils of Wonji-Shoa Sugar Estate and their relative change (%)

Soil Parameter	Plantation Age	Cultivated Land	Uncultivated Land	Relative Change	P-value
pH (1:2.5)	OP	7.65	7.51	1.88	0.136
	NP	8.09	7.98	1.42	0.021
	P-value	0.034	0.001		
EC (1:2.5)	OP	0.15	0.37	-57.86	0.012
	NP	0.12	0.13	-10.46	0.083
	P-value	0.019	0.015		
OC	OP	1.19	1.42	-15.68	0.008
	NP	0.69	0.59	17.22	0.180
	P-value	0.187	0.041		

OP, Old Plantation (Started in 1954); NP, New Plantation (Started in 2009); OC, Organic Carbon; EC, Electrical Conductivity. The sampling depth was 0-40cm.

Organic carbon

A significant ($P < 0.05$) difference in soil organic carbon (C) content was obtained between the cultivated land (CL) and the uncultivated land (UL) of the old plantation (OP), with the organic C content of the UL exceeding that of the CL by about 16% (Table 4). However, no significant difference was observed in the new plantation (NP). The ratings of Tekalign *et al*. (1991) categorize soils with percent organic C contents ranging from 0.5 to 1.5 as "low." Accordingly, for all land types, whether CL or UL, NP or OP, the soil organic C contents are low.

Regarding the two categories of plantation ages, the soils of OP fields were exceeding that of NP fields by about 24% and 58% in the CL and in the UL, respectively. However, the change was significant ($P < 0.05$) only in the case of the CL.

In the OP, the significant decline in the organic C could be attributed to the long-term (70 years) excessive tillage practices and the pre-harvest cane burning. Prior studies indicate that the organic C contents of a soil can be depleted by increased disturbance of the soil during land preparation (tillage) (Morrison and Gawander, 2016; Mesfin and Mohammed, 2020). Tillage enhances soil aeration and eventually mineralization of labile organic matter, aggregate breakdown, and removal of topsoil. Furthermore, the pre-harvest cane burning practiced in the study site removes plant residues, which would be returned to the soil as organic matter (OM). During burning, the high temperature that exceeds $400^{o}C$ also negatively affects the organic C through oxidation of the organic matter (Chi *et al.*, 2017).

In contrast to the OP, the organic C did not show significant ($P < 0.05$) differences between the CL and the UL in the NP, which might be due to the relatively shorter period of cultivation (13 years) of sugarcane. On the other hand, the significantly higher OC in the OP than the NP might relate to the gentler land slopes and the higher clay contents in the OP than in the NP (Table 2). In areas with steeper slopes, geomorphic processes of erosion preclude the deposition of organic C (Mesfin and Mohammed, 2020). Furthermore, soils with low clay contents have generally low organic C due to the lack of occlusion of particulate organic matter (Schweizer *et al.,* 2021). Similarly, Bechtold and Naiman (2006) reported a significant and positive relationship between organic C and clay concentrations.

The observed depletion and the low ratings of the organic C in the plantations might contribute to the yield decline encountered in WSSE. Therefore, in light of the roles that organic C plays in soil fertility and cane productivity, the current study calls for immediate management measures to be implemented to improve the level of organic C. Crop rotation (green manuring), trash retention, traffic control, and minimum tillage are among the best solutions currently being used in the major sugarcane-producing countries of the world (Franco *et al*., 2018). Further research is warranted to determine the role of these practices in increasing soil organic C at WSSE.

Total Nitrogen

In the OP, total nitrogen (N) content of the CL was significantly ($P < 0.05$) lower (13%) than the UL, while in the NP no significant ($P < 0.05$) difference was observed between the two land types (Table 5). On the other hand, a significant ($P < 0.05$) difference was observed in the total N content between the OP and NP only for the UL, whereby the soils of the OP exceeded the soils of the NP by about 40%. However, in the CL, no significant difference was observed between the two plantations. In addition, the total N contents of soils from OP sampled from the cultivated and uncultivated fields are 0.12 and 0.14%, which are in the category of “medium” and "high", respectively according to the rating of Tekalign *et al.* (1991). However, the total nitrogen contents of soils in NP from both cultivated and uncultivated lands range from 0.09 to 0.10%, which are of "medium" status according to the rating of the same authors (ibid).

Table 5. Total Nitrogen, available Phosphorus and available Sulfur contents of soils of Wonji-Shoa Sugar Estate (WSSE) and their relative change (%).

Soil Parameter	Plantation Age	Cultivated Land	Uncultivated Land	Relative Change	P-value
Total N (%)	OP	0.12	0.14	-12.58	0.001
	NP	0.09	0.10	-9.68	0.063
	P-value	0.077	0.022		
Av-P (mg kg^{-1})	OP	5.64	9.96	-50.12	0.014
	NP	2.10	1.97	6.86	0.306
	P-value	<0.001	<0.001		
Av-S (mg kg–1)	OP	22.64	128.36	-82.36	0.019
	NP	10.08	15.14	-33.41	0.152
	P-value	<0.001	<0.001		

OP, Old Plantation (Started in 1954); NP, New Plantation (Started in 2009), N, Nitrogen, Av-P, Available Phosphorus, Av-S, Available Sulfur.

In the CL, the fast mineralization of the organic substrates during intense cultivation may be responsible for the significant drop in total nitrogen as compared to the UL (Morrison and Gawander, 2016). Additionally, the high temperature during pre-harvest cane burning causes nitrogen to volatilize and oxidize, which ultimately decreases soil N concentrations (Vitousek and Sanford, 1986; Chi *et al.,* 2017). In contrast to the sprinkler irrigation system employed in the NP fields, the uncontrolled irrigation practices in the OP, often leading to waterlogging (Megersa Olumana and Ndambuki, 2014), could also contribute to the substantial decline in total N. According to Hamonts *et al.* (2013), waterlogging causes root anoxia and excessive denitrification, which results in a substantial loss of soil N. Furthermore, as organic carbon is a surrogate for total nitrogen (Murage *et al.,* 2000), the observed decline in total nitrogen content could be attributed to the decline noticed in the OC content (Table 4).

In the UL, the significantly higher total N in the soils of the OP than the NP as well as the high rating of the OP and the medium rating of the NP might be due to the difference in soil texture and the land slope among the two plantations (Table 2). Since clay soils have a fine texture and more persistent aggregates, it may operate as a medium for higher levels of total N concentrations (Raiesi, 2006). Unlike soils with a high sand content, the leaching losses in a soil with a high clay content are very low (Wang *et al.*, 2022). Areas with steep slopes are highly susceptible to soil erosion, leading to the leaching of N and other soluble elements, consequently reducing total N concentrations in the soil. Hence, the steeper slope (1–4%) and the lower clay content (35%) in the NP, while the gentler slope (0.02 to 0.05%) and the higher clay content (60%) in the OP (Table 2) could be responsible for the observed result. In agreement with this finding, Bechtold and Naiman (2006) reported a positive correlation between N and clay concentration.

However, the non-significant difference between the total N contents of the OP and the NP in the CL may be associated with the same trends noticed in the organic carbon (Table 4). Despite the lower clay content of the NP, the roots and stubbles biomass of sugarcane and its gradual decomposition in the CL might maintain the total N level of both plantations to the same level.

Available Phosphorus

In the old plantation (OP), the available phosphorus (P) content of the cultivated land (CL) was significantly lower ($P < 0.05$) than the uncultivated land (UL), exhibiting a 50% decline (Table 5). In contrast, no significant difference was observed between the two land types of the NP. Additionally, the available P contents of the OP fields of both the CL and the UL ranged between 5.64 and 9.96 mg kg soil^{-1}, which are classified as "low" according to the rating of Cottenie (1980). Furthermore, the available P contents of the NP fields under both CL and UL ranged between 1.97 and 2.10 mg kg soil^{-1}, which are in the category of "very low" according to the rating of the same author (ibid). This means the sugarcane plants are predisposed to P deficiency and require ample fertilization with P-containing fertilizers, particularly in the NP fields. What is more, significant ($P < 0.05$) differences occurred in the available P contents between the OP and NP under both the CL and UL. Notably, the available P content of soils in the OP under the CL exceeded the available P content of soils in the NP fields under the same cultivation condition by more than threefold. For the UL, this difference exceeded fivefold. Generally, the finding clearly indicated that the long-term intensive production systems severely depleted the available P content of the OP below the critical value (8 mg kg^{-1}) (Tekalign *et al*., 1991).

In the OP, the significant decline in available P in the CL compared to the UL can be attributed to P uptake by the sugarcane crop without the application of P-related fertilizers in the Sugar Estate. This depletion of available P is consistent with findings from other studies (Belayneh and Eyasu, 2020; Mesfin and Mohammed, 2020) that have documented similar declines in areas without P fertilizer application. This is because sugarcane requires a significant amount of P, with an estimated 34 kg ha^{-1} of P needed to produce 100 ton ha^{-1} of sugarcane (Calheiros *et al*., 2018). On the other hand, the lower available P levels in the NP than the OP are probably caused by the geomorphic processes of erosion in the NP due to its steeper land gradient. The higher proportion of sand in the soils of the NP may also exacerbates the leaching losses of available P, as this type of soil has poor nutrient retention capacity. Additionally, the higher pH in the NP (8.09) than the OP (7.65) (Table 4) might result in fixation of P.

Available Sulfur

The old plantation (OP) had significantly ($P < 0.05$) lower available sulfur (S) content in the cultivated land (CL) than in the uncultivated land (UL), with the available S content of the UL being 82% higher than that of the CL (Table 5). However, in the new plantation (NP) no significant difference was observed between the CL and the UL. On the other hand, the available S content of the OP was significantly ($P < 0.05$) higher than the NP, with the OP fields surpassing that of the NP fields by nearly twofold and eightfold in the CL and UL, respectively. Bashour and Sayegh's (2007) classify soils with available S concentrations between 10 and 20 mg kg^{-1} in the low category and greater than 45 mg kg^{-1} in the very high category. Accordingly, the CL and UL of the NP and OP are both classified as low, whereas the UL of the OP is classified as very high. Furthermore, the available S concentrations of the CL were 25% and 66% lower than the threshold level (30 mg kg^{-1}) in the OP and NP, respectively (Havlin *et al*., 1991).

The drastic decrease (82%) in available S in the OP and its subsequent low rating indicate that S is the nutrient most adversely affected by the long-term intensive production system of sugarcane. This might be due to the fact that sulfur is a nutrient mineralized from organic matter that is not bound to clay or organic particles and hence leaches easily (Calcino *et al*., 2018). Sulfur is also among the largest constituents of the sugarcane plant (47 kg SO_4 per 100 tons of sugarcane) (Hamid and Dagash, 2014) and is taken up by the crop in a large amount (30 kg S per 100 tons of sugarcane) (Shukla *et al*., 2022). Therefore, the excessive tillage and furrow irrigation system coupled with the high uptake of the crop, have led to a significant decrease in available S in the OP. In line with this finding, Zhang *et al*. (2019) also observed a significant decrease in available S when a land use transformed from uncultivated to a sugarcane plantation.

The fact that the available S in the OP is substantially greater than the available S in the NP may be related to the higher clay content in the OP than in the NP (Table 2). Evidently, soils with a low clay content are poor in organic matter content (Schweizer *et al.,* 2021) and thus low in S concentration (Calcino *et al*., 2018). In addition, leaching losses are extremely high in soils with a high sand content (Wang *et al*., 2022) and steeper land gradient (Mesfin and Mohammed, 2020). In this context, the sand content and the gradient of the land are higher in the NP than the in the OP (Table 2) and soil erosion is relatively more severe in the NP, and thus resulting in the observed low ratings of available S.

According to Shukla *et al*. (2022), after N, P, and K, S is being widely recognized as the fourth key nutrient for plants. Sulfur plays a significant role in lowering soil pH, boosting micronutrient availability, and enhancing metabolic and physiological processes (Hamid and Dagash, 2014). However, S management in the WSSE has received scant attention. Hence, the current finding revealed the possible roles of S in the decline of yield that utmost attention should be given for management of soil sulfur in the sugarcane plantation.

Exchangeable bases

Exchangeable Potassium

In the OP, the exchangeable potassium (K) content was significantly lower ($P < 0.05$) in the cultivated land (CL) than the uncultivated land (UL), where a 39% decline was observed (Table 6). Contrastingly, no significant difference was observed among the two land types in the NP. In the case of the two categories of plantation ages, no significant differences were observed between the OP and NP in both the UL and CL. Soils with exchangeable K contents greater than 1.2 $cmol_{(+)}kg^{-1}$ are considered very high (FAO, 2006) and the critical level is 0.38 $cmol_{(+)}kg^{-1}$ (Barber, 1984). Accordingly, for all land types, whether CL or UL, NP or OP, the exchangeable soil K contents are in the category of "very high" and above the critical level.

Potassium is a nutrient most abundantly taken up by sugarcane, accounting for 332 kg ha^{-1} per 100 ton ha^{-1} of biomass (Calheiros *et al*., 2018), as well as it is accumulated in sugarcane in the highest proportion (150 kg ha^{-1} K per 100 ton ha^{-1} of harvestable culms) (Oliveira *et al*., 2018). Thus, one of the major causes of the significant depletion of the exchangeable K in the current study may be attributed to such an enormous uptake of the nutrient by the crop over several years. In addition, the mobile nature of the nutrient that leads to excessive leaching, coupled with the absence of K fertilization in WSSE, may exacerbate the depletion. On the contrary, such a significant depletion was not observed in the NP, perhaps due to the short period of cultivation (13 years) and the sprinkler irrigation system. Unlike the furrow irrigation system in the OP, the irrigation system in the NP is a sprinkler, where water is applied only to the optimum level. As a result, the amount of the nutrient leached from the CL of the NP may be minimal.

Exchangeable Calcium and Magnesium

Both the exchangeable Calcium (Ca) and exchangeable Magnesium (Mg) did not show significant variation among the CL and the UL (Table 6). In addition, exchangeable Ca in both land types and exchangeable Mg in the UL did not significantly differ between the OP and the NP. Nevertheless, exchangeable Mg was significantly higher in the CL of the OP than the NP. The exchangeable Ca contents range between 20.4 and 32.84 $cmol_{(+)}kg^{-1}$, in both categories of plantation ages and in both land types. As a result, it is classified as "very high" based on the rating of FAO (2006). Furthermore, under both land types, the exchangeable magnesium (Mg) contents in the OP and in the NP range between 3.33 and 7.16 $cmol_{(+)}kg^{-1}$ which is in the category of "high" according to the rating by the same literature (ibid). Furthermore, as per the designation of Landon (1991), exchangeable Ca and Mg are above the critical values, which are 0.2 $cmol_{(+)}kg^{-1}$ and 0.5 $cmol_{(+)}kg^{-1}$, respectively.

The non-significant difference between the CL and the UL as well as the very high and high ratings of exchangeable Ca and Mg, respectively, imply that these nutrients may not be affected by long-term sugarcane cultivation. This might be due to pre-harvest cane burning, which adds significant amounts of ash back to the soils. It is evident that ash is a major source of cations (Nkana *et al.*, 1998). Similar findings were also reported by Hartemink (1998); Tellen and Yerima (2018); Belayneh and Eyasu (2020); Mesfin and Mohammed (2020), where they found no significant difference between CL and UL in exchangeable Ca and Mg. Therefore, the role of these cations in the yield decline problem of WSSE might be of minor importance.

Erosion and leaching, which are problematic under the steep slope and light-textured soil conditions of the NP (Table 2) coupled with the high susceptibility of Mg for leaching (Fan *et al.*, 2021), may be the causes of the significantly lower exchangeable Mg observed in the CL of the NP. However, the non-significant difference observed in exchangeable Ca content among the CL and UL as well as among the OP and the NP may be related to the fact that exchangeable Ca is more tightly held on soil colloids than the other cations (Gavrilescu, 2014) and hence less susceptible to leaching losses.

Table 6: Exchangeable bases ($\text{cmol}_{(+)}\text{kg}^{-1}$), cations exchangeable capacity (CEC) ($\text{cmol}_{(+)}\text{kg}^{-1}$) and related properties of soils, of Wonji-Shoa Sugar Estate and their relative change (%)

Soil Parameter	Plantation Age	Cultivated Land (CL)	Uncultivated Land (UL)	Relative Change	P-value
Exc-K	OP	1.39	2.28	-39.35	<0.001
	NP	1.79	2.21	-18.66	0.138
	P-value	0.061	0.302		
Exc-Na	OP	1.82	1.75	3.70	0.283
	NP	0.58	0.59	-1.59	0.333
	P-value	0.006	0.005		
Exc-Ca	OP	32.84	32.84	<0.001	0.500
	NP	20.40	27.07	-24.63	0.117
	P-value	0.154	0.184		
Exc-Mg	OP	7.16	6.47	10.67	0.153
	NP	3.33	4.40	-24.24	0.104
	P-value	0.022	0.129		
CEC	OP	45.56	44.72	1.90	0.245
	NP	34.19	35.60	-3.95	0.346
	P-value	0.233	0.054		
BS	OP	97.65	98.47	-0.83	0.401
	NP	81.47	100	-18.53	0.116
	P-value	0.339	0.457		
ESP	OP	3.87	3.87	0.00	0.550
	NP	1.78	1.71	4.32	0.224
	P-value	0.071	0.010		

OP, Old Plantation (Started in 1954); NP, New Plantation (Started in 2009), Exc-Na, exchangeable Sodium; Exc-K, exchangeable Potassium; Exc-Ca, exchangeable Calcium; Exc-Mg, exchangeable Magnesium (%); CEC, Cation Exchangeable Capacity; BS, Base Saturation; ESP, Exchangeable Sodium Percentage (%)

Cation exchangeable capacity, base saturation and exchangeable sodium percentage

Cation Exchangeable Capacity (CEC) and percent base saturation (BS) showed no significant differences ($P < 0.05$) among the CL and UL as well as among the OP and NP (Table 6). Exchangeable sodium percentage (ESP) in the CL did not also significantly vary among the OP and NP, whereas in the UL, it was significantly ($P < 0.05$) higher in the OP than in the NP. According to Landon's (1991) classifications, soils having Cation Exchangeable Capacity (CEC) values between 25 and 40% and over 40% are classified as "high" and "very high", respectively. Thus, the soil CEC of the CL and UL is rated as "very high" in the OP and "high" in the NP. In addition, as per the rating of Hazelton and Murphy (2016), the soil BS values are classified as "very high" (>80%) and the ESP values are within the non-sodic category (< 6%) in both categories of plantation ages.

The reasons for the very high rating of the OP and the high ratings of the NP in CEC could be related to the differences in soil texture. As shown on table 2, the percentage of clay in the OP is higher than in the NP. Thus, the soils in the OP contain a lot of surface negative charges that attract and hold cations, leading to greater CEC (Tomašic *et al*., 2013). Wang *et al*. (2005) also discovered a positive correlation between soil CEC and soil clay content.

The higher concentrations of exchangeable cations (Table 6), the slightly alkaline soil pH (Table 4), and the good quality of irrigation water (Zeyede and Mulate, 2021) might be responsible for the non-significant differences observed in CEC levels between both land types. This a stable CEC, in turn, maintained the BS and ESP within permissible ranges. Previous research showed that when soil pH is high, the levels of CEC, BS, and ESP are also high (Kabala and Labaz, 2018; Chowdhury *et al*., 2021; Mohiuddin *et al*., 2022). This is mainly due to the precipitation of the two major cations, Ca^{2+} and Mg^{2+}, out of the solution by CO_3^{2-} and HCO_3^- ions (Hazelton and Murphy, 2016). It was also well reported that CEC is an inherent soil characteristic that is hardly possible to significantly change, particularly in highly reactive clay soil (Havlin, 2005; Chowdhury *et al.*, 2021). This is also consistent with the soil survey conducted in the OP of the WSSE (Mukherji, 2000), where the CEC (38.7 $cmol_{(+)}kg^{-1}$), BS (93.3%), and ESP (3.7%) values were very close to the current result. Several studies elsewhere also indicate that CEC is not much affected by long-term intensive production system (Kopittke and Menzies, 2017; Tellen and Yerima, 2018). Nevertheless, some studies reported declining trends in CEC after long-term intensive production system, which they attributed to the acidification of the soil and the decline of SOM (Hartemink, 1998; Mesfin and Mohammed, 2020).

Micronutrients

In the old plantation (OP), zinc (Zn) level was significantly ($P < 0.05$) lower (15%) in the cultivated land (CL) compared to the uncultivated land (UL), whereas molybdenum (Mo) level was significantly ($P < 0.05$) higher (4.2%) in the CL than in the UL. However, no significant differences were observed in the new plantation (NP) in both micronutrients. On the other hand, iron (Fe) levels were significantly ($P < 0.05$) higher in the CL than in the UL in the NP, but there were no significant variations in the OP (Table 7). In both the OP and the NP, copper (Cu), manganese (Mn), and boron (B) showed no significant ($P < 0.05$) differences among the two land types. In the case of the two categories of planation ages, except for Fe and Mo, the OP was significantly ($P < 0.05$) higher than the NP in all the micronutrients under both land types (Table 7).

Table 7. Micronutrient contents (mg kg^{-1}) of soils of Wonji-Shoa Sugar Estate and their relative changes (%)

Soil Parameter	Plantation Age	Cultivated Land (CL)	Uncultivated Land (UL)	Relative Change	P-value
Cu	OP	3.41	3.55	-3.73	0.187
	NP	1.47	1.45	1.68	0.114
	P-value	<0.001	<0.001		
Fe	OP	5.19	4.57	13.56	0.157
	NP	5.19	4.53	14.68	0.043
	P-value	0.427	0.275		
Mn	OP	17.12	13.68	25.15	0.133
	NP	6.12	5.36	14.27	0.215
	P-value	<0.001	<0.001		
Zn	OP	1.36	1.60	-14.74	0.025
	NP	1.15	1.12	2.42	0.428
	P-value	0.003	0.039		
B	OP	0.57	0.59	-3.27	0.221
	NP	0.40	0.39	3.53	0.244
	P-value	0.012	0.006		
Mo	OP	0.25	0.24	4.18	0.031
	NP	0.24	0.25	-1.47	0.364
	P-value	0.217	0.455		

OP, Old Plantation (Started in 1954); NP, New Plantation (Started in 2009), Cu – Copper; Fe – Iron; Mn – Manganese, Zn – Zinc; B – Boron, Mo – Molybdenum

In the OP, the Cu contents of both the CL and the UL range from 3.41 to 3.55 mg kg soil^{-1} while in the NP it ranges from 1.45 to 1.47 mg kg soil^{-1}, which are in the statuses of "very high" and "high", respectively (Lindsay and Norvell, 1978). Furthermore, the soil Zn, Fe, Mn, B, and Mo contents for all land types, whether CL or UL, NP or OP recorded 1.12 to 1.6 mg kg^{-1}, 4.53 to 5.19 mg kg^{-1}, > 5.36 mg kg^{-1}, and 0.39 to 0.59 mg kg^{-1}, and 0.24–0.25 mg kg^{-1}, respectively. Thus, Zn and Fe contents are rated as “medium” and Mn is rated as “very high”, based on the classification of the same authors (ibid). Additionally, Mo and B are rated as “high” and “low”, as per the rating of FAO (1982) and Jones (2003), respectively.

The absence of a significant decline in most of the micronutrient concentrations might be due to the miner uptake of these nutrients by the crop. In a 100 ton ha^{-1} sugarcane plant, the accumulations in a plant shoot are only about 8.0, 3.0, 0.6, 0.4, and 0.3 kg for Fe, Mn, Zn, Cu, and B, respectively (Kingston, 2013; Oliveira *et al.*, 2018). Furthermore, pre-harvest cane burning returns back a significant amount of micronutrients to plantation soils. For instance, a study conducted by Vallejo-Torres and López-Hernández (2001) indicated that the amount of micronutrients added to a soil after pre-harvest cane burning accounts for about 281 g Zn ha^{-1} year^{-1}; 127 g Cu ha^{-1} year^{-1}; 611 g Mn ha^{-1} year^{-1}; and 6662 g Fe ha^{-1} year^{-1}.

Unlike the other micronutrients, Zn in the OP was found to be the only micronutrient significantly depleted (15%). This suggests that Zn is the micronutrient most profoundly impacted by the long-term intensive production system of sugarcane. The exceptional decline of Zn observed in this case may be attributed to the fact that Zn is the most mobile element in the soil and thus susceptible to leaching (Kicińska, 2020).

The clay percentage is higher (Table 2), and the slope is gentle in the OP, which is contrariwise in the NP. As a result, nutrient leaching is more prevalent in the NP, while nutrient adsorption is higher in the OP (Tomašic *et al*., 2013). This situation could be the possible reason for the significantly higher levels of B, Cu, Mn, and Zn in the OP than in the NP. However, the non-significant differences between the two plantations in Fe and Mo are unexpected, and thus need further research.

Tropical soils are typically deficient in B and Zn due to the low natural fertility of the soils, brought about by high levels of weathering and poor management of corrective measures (Franco *et al*., 2011). This could explain why the WSSE soils have a low B rating and a medium Zn rating. Similarly, according to a study conducted on a Brazilian sugarcane plantation, Zn and B are the most limiting micronutrients (Marangoni *et al*., 2019). Furthermore, the medium rating observed in Fe might result from the fact that Fe is the largest micronutrient taken up by the sugarcane plant (6 kg per 100 ton ha^{-1}) (Oliveira *et al.*, 2018). It is also crucial to consider that in the WSSE, the slightly alkaline nature of the soils (Table 4) might depress the solubility of the micronutrients and thereby responsible for the low or medium rating of these micronutrients. According to Selman-Housein *et al.* (2000), increasing a pH by one unit results in a tenfold decrease in metal solubility.

Previous studies confirmed that micronutrient deficiencies diminish crop yield and quality, expose the plant to a number of pests, and reduce nutrient use efficiency (Neina, 2019). Thus, the deficiency of micronutrients may contribute to the yield decline encountered in the WSSE. Hence, considering the low organic matter contents and the moderately alkaline pH (Table 4) of the WSSE soils, further study is required in relation to plant tissue analysis and crop responses. Particularly, the low and medium ratings observed in B, Fe, and Zn should be given priority attention.

In general, this study has several notable strengths that contribute to its robustness. Firstly, it includes a thorough comparison of the soil properties against standard ratings, allowing for an assessment of the soil health and fertility. Additionally, the study examines fields cultivated for different periods (OP vs. NP), in reference to uncultivated land. This approach enables a more comprehensive understanding of the changes in soil properties over time. As a result, it is anticipated that this study will provide valuable insights into the extent of alterations in soil properties, fostering a clearer understanding of the soil dynamics in the study site. However, the limitations of this study that warrant further investigation include the need for plant response studies and tissue analysis to better understand how sugarcane responds to different soil fertility conditions. Additionally, assessing soil biological properties would provide valuable insights into the microbial activity and nutrient cycling processes. Another aspect worth exploring is the evaluation of the individual soil fertility indicators in relation to sugarcane yield, as this can help prioritize and fine-tune management practices. It is also important to address similar issues in other sugar estates across the country to gain a broader perspective on the challenges and potential solutions in the industry. In spite of these limitations, this study provides compelling evidences on the existence of one of the potential causes of yield decline in WSSE, i.e., depletion of soil fertility.

Conclusions

The results of this study have demonstrated that the long-term intensive production system has led to the depletion of major soil fertility indicators. This depletion is evident from the significantly lower values of soil fertility indicators in the cultivated land compared to the adjacent uncultivated land in the old plantation, but there is no significant difference in the new plantation for most of the parameters. Particularly, organic C, total N, available P, exchangeable K, available S, Zn, and B are among the most exhausted soil nutrients. Soil pH is also above the optimum level for sugarcane. An additional but not unexpected finding, not considered in the original research aim, was that the slope and soil texture of a farm play a significant role in dictating soil properties. In light of the heavy feeding nature of the sugarcane plant, the current findings have revealed that the depleting soil nutrients are the most likely causes of the drastic decline in sugarcane yields in Wonji-Shoa Sugar Estate over the last 70 years. Therefore, this problem calls for soil fertility enhancement strategies, such as breaking the monoculture system of sugarcane cultivation through green manuring, minimizing tillage practices, regulating machinery traffic, and retaining cane residue. Future studies should focus on these issues along with establishing a minimum data set for soil properties in relation to sugarcane yields.

References

Alemayehu Dengia and Lantinga, E.A. 2016. Impact of long-term conventional cropping practices on some soil quality indicators at Ethiopian Wonji sugarcane plantation. *Advances in Crop Science and Technology,* 4(3). DOI:10.4172/2329-8863.1000224.

Aman, M. 2020. Impact of Monocropping for

Crop Pest Management : Review. *Academia Research Journal*, 8(5). DOI: 10.14662/ARJASR2020.340.

An, J.Y. and Park, B.B. 2021. Effects of wood ash and N fertilization on soil chemical properties and growth of Zelkova serrata across soil types. *Scientific Reports*, 11(1): 1–13. DOI.org/10.1038/s41598-021-93805-5.

Balesdent, J., Chenu, C. and Balabane, M. 2000. Relationship of soil organic matter dynamics to physical protection and tillage. *Soil and Tillage Research*, 53(3–4): 215–230. DOI.org/10.1016/S0167-1987 (99)00107-5.

Bang-Andreasen, T., Peltre, M., Ellegaard-Jensen, L., Hansen, L.H., Ingerslev, M., Rønn, R., Jacobsen, C.S. and Kjøller, R. 2021. Application of wood ash leads to strong vertical gradients in soil pH changing prokaryotic community structure in forest top soil. *Scientific Reports*, 11(1): 1–10.

Barber, S. 1984. *Soil Nutrient Bioavailability Mechanistic Approach*. J. Wiley and Sons. Inc., New York. 398p.

Bashour, I.I. and Sayegh, A.H. 2007. *Methods of analysis for soils of arid and semi-arid regions*. FAO. Rome.

Bechtold, J.S. and Naiman, R.J. 2006. Soil texture and nitrogen mineralization potential across a riparian toposequence in a semi-arid savanna. *Soil Biology and Biochemistry*, 38(6): 1325–1333. DOI:10.1016/j.soilbio.2005.09.028.

Belayneh Bufebo and Eyasu Elias. 2020. Effects of land use/land cover changes on selected soil physical and chemical properties in Shenkolla watershed, south central Ethiopia. *Advances in Agriculture*, 2020. DOI.org/10.1155/2020/5145483.

Berkum, S., Roza, P. and Tongeren, F. 2005. Impacts of the EU Sugar Policy Reforms on Developing Countries. Agric.

Booker Tate and MCE. 2003. Review and Updating of the Feasibility Study on Irrigation and Agricultural Land Extention, Wonji/Shoa Sugar Factory. Final Report, Volume III, Wonji, Ethiopia.

BRLi and GIRDC. 2013. Detailed studies on the status of ground water rise at WSSF Cane Plantation. Interim Report, Ethiopian Sugar Corporation. Wonji.

Calcino, D., Schroeder, B., Panitz, J., Hurney, A., Skocaj, D., Wood, A. and Salter, B. 2018. Australian sugarcane nutrition manual. BSES Limited, Sugar Research Australia Limited, Indooroopilly.

Calheiros, L.C., Freire, F.J., Moura Filho, G., Oliveira, E.C., Moura, A.B., Costa, J.V., Cruz, F.J., Santos, A.S. and Rezende, J.S. 2018. Assessment of nutrient balance in sugarcane using DRIS and CND methods. *Journal of Agricultural Science*, 10(9): 164–79. DOI:10.5539/jas.v10n9p164

Chang, C. and Oosterveld, M. 1981. Effects of long-term irrigation on soil salinity at selected sites in southern Alberta. *Canadian Journal of Soil Science*, 61(3): 497–505. DOI:10.4141/cjss81-056.

Chi, L., Mendoza-Vega, J., Huerta, E. and Álvarez-Solís, J.D. 2017. Effect of long-term sugarcane (*Saccharum* spp.) cultivation on chemical and physical properties of soils in Belize. *Communications in Soil Science and Plant Analysis*, 48(7): 741–755. DOI.org/10.1080/00103624.2016.1254794.

Chirchir, A. K., Kimenju, J. W., Olubayo, F. M. and Mutua, G. K. 2010. Abundance and Distribution of Plant Parasitic Nematodes Associated with Sugarcane in Western Kenya. *Asian Journal of Plant Pathology*, 4(1). DOI: 10.3923/ajppaj.2008.48.53.

Chowdhury, S., Bolan, N., Farrell, M., Sarkar, B., Sarker, J.R., Kirkham, M., Hossain, Z. and Kim, G.H. 2021. Role of cultural and nutrient management practices in carbon sequestration in agricultural soil. pp. 131–196. *In*: Donald, L.S., (ed.), *Advances in Agronomy*, Academic Press, Amsterdam, Netherlands. Doi.org/10.1016/bs.agron.2020.10.001.

Cottenie, A. 1980. *Soil and plant testing as a* *basis of fertilizer recommendations*. FAO soil bulletin 38/2. Food and Agriculture Organization of the United Nations, Rome.

Curtin, D. and Trolove, S. 2013. Predicting pH buffering capacity of New Zealand soils from organic matter content and mineral characteristics. *Soil Research*, 51(6): 494-502. DOI.org/10.1071/SR13137.

Davies, J. 1998. The causes and consequences of cane burning in Fiji's sugar belt. The Journal of *Pacific Studies,* 22, 1–25.

ESIG (Ethiopian Sugar Industry Group). 2023. Ethiopian Sugar Industry Profile. http://etsugar.com/esig/2023/01/31/ethiopian-sugar-industry-profile/ Accessed on March, 7 2023.

Fan, B., Zhao, L., Feng, Z., Liu, D., Yin, W., Long, Z. and Huang, X. 2021. Leaching behaviors of calcium and magnesium in ion-adsorption rare earth tailings with magnesium sulfate. Transactions of Nonferrous Metals. *Society of China*, 31(1), 288–296. DOI.org/10.1016/s1003-6326(21)65495-x.

FAO (Food and Agriculture Organization of the United Nations). 1982. Micronutrients and the Nutrient Status of Soils: A Global Study, Soil Bulletin 63, Rome.

FAO (Food and Agriculture Organization of the United Nations). 2006. Plant nutrition for food security: A guide for integrated nutrient management. FAO, Fertilizer and Plant Nutrition Bulletin 16, Rome.

Farhate, C.V.V., Souza, Z.M.D., Cherubin, M.R., Lovera, L.H., Oliveira, I.N.D., Guimarães Júnnyor, W.D.S. and La Scala Junior, N. 2022. Soil physical change and sugarcane stalk yield induced by cover crop and soil tillage. *Revista Brasileira de Ciência do Solo*, 46. DOI:10.36783/18069657rbcs20210123.

Franco, H.C.J., Castro, S.G.Q., Sanches, G.M., Kölln, O.T., Bordonal, R.O., Borges, B.M.M.N. and Borges, C.D. 2018. Alternatives to Increase the Sustainability of Sugarcane Production in Brazil under High Intensive Mechanization. pp. 350–379. *In:* Singh P. and Tiwari, A.K. (eds.), *Sustainable Sugarcane Production,* Apple Academic Press, Oakville, Canada and Waretown, USA.

Gavrilescu, M. 2014. Colloid-mediated transport and the fate of contaminants in soils. pp. 397–451. *In:* Fanun, M. (ed), *The role of colloidal systems in environmental protection*. Elsevier, Amsterdam, Netherlands. DOI.org/10.1016/B978-0-444-63283-8.00017-X.

Gobinath, R., Ganapathy, G.P., Gayathiri, E., Salunkhe, A.A. and Pourghasemi, H.R. 2022. Ecoengineering practices for soil degradation protection of vulnerable hill slopes. pp. 255-270. *In:* Pourghasemi, H. (ed.), *Computers in Earth and Environmental Sciences,* Elsevier, Amsterdam, Netherlands.

Gomiero, T. 2019. Soil and crop management to save food and enhance food security. pp. 33–87. *In:* Galanakis, C.M. (ed.), *Saving Food.* Academic Press, Treviso, Italy.

Hamid, A.M. and Dagash, Y.M. 2014. Effects of sulfur on sugarcane yield and quality at the heavy clay soil vertisols of Sudan. *Universal Journal of Applied Science,* 2(3). DOI:10.13189/ujas.2014.020303.

Hamonts, K., Clough, T.J., Stewart, A., Clinton, P.W., Richardson, A.E., Wakelin, S.A., O'Callaghan, M. and Condron, L.M. 2013. Effect of nitrogen and waterlogging on denitrifier gene abundance, community structure and activity in the rhizosphere of wheat. *FEMS Microbiology Ecology*, 83(3): 568–584, DOI.org/10.1111/1574-6941.12015.

Hartemink, A.E. 1998. Soil chemical and physical properties as indicators of sustainable land management under sugarcane in Papua New Guinea. *Geoderma*, 85(4): 283–306. DOI: 10.1016/S0016-7061(98)00048-2.

Hartemink, A.E. 2006. Assessing Soil Fertility Decline in the Tropics Using Soil Chemical Data. *Advances in Agronomy*, 89: 179–225. DOI.org/10.1016/S0065-2113(05)89004-2.

Havlin, J. L. 2005. Fertility. pp. 10–19. *In:* D. Hillel (ed.), *Encyclopedia of Soils in the*

Environment, Oxford, Elsevier.

Hazelton, P. and Murphy, B. 2016. *Interpreting soil test results: What do all the numbers mean?* CSIRO publishing.

Jones, J.B. 2003. *Agronomic Handbook: Management of Crops, Soils, and Their Fertility.* CRC Press LLC, Boca Raton, FL, USA. 482p.

Kabała, C. and Łabaz, B. 2018. Relationships between soil pH and base saturation–conclusions for Polish and international soil classifications. *Soil Science Annual,* 69(4): 206–214. DOI:10.2478/ssa-2018-0021.

Kalra, N., Harit, R.C. and Sharma, S.K. 2000. Effect of fly ash incorporation on soil properties of texturally variant soils. *Bioresource Technology*, 75(1): 91–93. DOI:10.1016/S0960-524(00)00036-5.

Kassie, A. 2022. African Labour and Foreign Capital: The Case of Wonji-Shewa Sugar Estate in Ethiopia, 1951–1974. *Social Sciences*, 11(5): 245–253. DOI: 10.11648/j.ss.20221105.11.

Khan, M.J. and Qasim, M. 2008. Integrated use of boiler ash as organic fertilizer and soil conditioner with NPK in calcareous soil. *Songklanakarin Journal of Science and Technology*, 30(3). 281–289.

Kicińska, A. 2020. Lead and zinc in soils around a Zinc-Works – presence, mobility and environmental risk. *Journal of Ecological Engineering*, 21(4): 185–198. https://doi.org/10.12911/22998993/119815.

Kim, K., Sim, J. and Kim, T.H. 2017. Evaluations of the effects of soil properties and electrical conductivity on the water content reflectometer calibration for landfill cover soils. *Soil and Water Research*, 12(1): 10–17. DOI:10.17221/158/2015-SWR.

Kingston, G. 2013. Mineral nutrition of sugarcane. pp. 85–120. *In*: Moore, P.H. and Botha, F.C. (eds.), *Sugarcane: Physiology, biochemistry, and functional biology*, John Wiley & Sons, Inc., New Delhi, India.

Labajo, J.R.N. and Pabiona, M.G. 2022. Physical and chemical properties of soil on selected sugarcane farms in Mt. Nebo, Valencia City, Bukidnon, Philippines. Asian Journal of Agriculture, 6(2). DOI.org/10.13057/asianjagric/g060204.

Landon, J.R. 1991. *Booker Tropical Soil Manual: A hand book for soil survey and Agricultural Land Evaluation in the Tropics and Subtropics.* Longman Scientific and Technical, Essex, New York. 474p. OR John Wiley & Sons Inc., New York.

Lei, H., Liu, A., Hou, Q., Zhao, Q., Guo, J. and Wang, Z. 2020. Diversity patterns of soil microbial communities in the Sophora flavescens rhizosphere in response to continuous monocropping. *BMC Microbiology*, 20(1): 1–12. DOI: 10.1186/s12866-020-01956-8.

Lemma Wogi, Nigussie Dechassa, Bereket Haileselassie, Fikre Mekuria, Ayele Abebe and Lulseged Tamene. 2021. A guide to standardized methods of analysis for soil, water, plant, and fertilizer resources for data documentation and sharing in Ethiopia. CIAT Publication No. 519. International Center for Tropical Agriculture (CIAT). Addis Ababa, Ethiopia. 41 p.

Le Roux, P.A.L., du Preez, C., Strydom, M., van Rensburg, L. and Bennie, A. 2007. Effect of irrigation on soil salinity profiles along the Lower Vaal River, South Africa. *Water SA*, 33(4). DOI: 10.4314/wsa.v33i4.52942.

Lindsay, W.L. and Norvell, W.A. 1978. Development of DTPA soil test for zinc, iron, manganese and copper. *Soil Science Society of America Journal*, 42: 421–428. DOI.org/10.2136/sssaj1978.03615995004200030009x.

Marangoni, F.F., Otto, R., de Almeida, R.F., Casarin, V., Vitti, G.C. and Tiritan, C.S. 2019. Soluble sources of zinc and boron on sugarcane yield in Southeast Brazil. *Sugar Tech*, 21(6): 917–924. DOI.org/10.1007/s12355-019-00716-x.

Mavrogenis, M. 2019. Analysis of DTPA Extracted Soils per Chinese Standard HJ

804-2016. Agilent Technologies, Inc. USA.

Megersa Olumana and Ndambuki J.M. 2014. Identifying the Potential Causes of Waterlogging in Irrigated Agriculture: The Case of Wonji-Shoa Sugarcane Plantation (Ethiopia). *Irrigation and Drainage*, 63: 80–92. DOI.org/10.1002/ird.1791.

Mendes, I.C., Sousa, D.M.G., Dantas, O.D., Lopes, A.A.C., Junior, F.B.R., Oliveira, M.I. and Chaer, G.M. 2021. Soil quality and grain yield: A win–win combination in clayey tropical Oxisols. *Geoderma*, 388: 114880. DOI: 10.1016/j.geoderma.2020.114880.

Mesfin Anteneh and Mohammed Assen. 2020. Effects of land cover changes and slope gradient on soil quality in the Gumara watershed, Lake Tana basin of North–West Ethiopia. *Modeling Earth Systems and Environment*, 6(1): 85–97. DOI.org/10.1007/s40808-019-00660-5.

Ming, R., Moore, P.H., Wu, K., D'Hont, A., Glaszmann, J.C. and Tew, T.L. 2006. Sugarcane Improvement through Breeding and Biotechnology. pp. 15–126. *In:* Janick, J. (ed.), *Plant Breeding Reviews*. John Wiley & Sons, Inc.

Misra, P., Maji, D., Awasthi, A., Pandey, S.S., Yadav, A., Pandey, A., Saikia, D., Babu, C.V. and Kalra, A. 2019. Vulnerability of soil microbiome to monocropping of medicinal and aromatic plants and its restoration through intercropping and organic amendments. *Frontiers in Microbiology*, 10: 2604. DOI: 10.3389/fmicb.2019.02604.

Mohiuddin, M., Irshad, M., Sher, S., Hayat, F., Ashraf, A., Masood, S., Bibi, S., Ali, J. and Waseem, M. 2022. Relationship of Selected Soil Properties with the Micronutrients in Salt-Affected Soils. *Land*, 11(6): 845. DOI.org/10.3390/land11060845.

Morrison, R.J. and Gawander, J.S. 2016. Changes in the properties of Fijian Oxisols over 30 years of sugarcane cultivation. *Soil Research*, 54(4): 418–429. DOI.org/10.1071/SR15173.

Mukherji, J.P. 2000. Rehabilitation, optimization, and expansion of agriculture and factory. Interim Report, Vol. 1, Ethiopian Sugar Industry Sh. Co., Wonji-Shoa Sugar Factory.

Murage, E.W., Karanja, N.K., Smithson, P.C. and Woomer, P.L. 2000. Diagnostic indicators of soil quality in productive and non-productive smallholders' fields of Kenya's Central Highlands. *Agriculture, Ecosystems and Environment*, 79(1): 1–8. DOI.org/10.1016/S0167-8809(99)00142-5.

Murphy, H.F. 1968. A Report on the Fertility Status of Some Soils of Ethiopia. Experimental Bull. No. 1. Imperial College of Agriculture and Mechanical Arts; Alemaya, Ethiopia, 201 p.

Neina, D. 2019. The role of soil pH in plant nutrition and soil remediation. *Applied and Environmental Soil Science*, 2019. DOI: 10.1155/2019/5794869.

Nkana, J.V., Demeyer, A. and Verloo, M.G. 1998. Chemical effects of wood ash on plant growth in tropical acid soils. *Bioresource Technology*, 63(3): 251–260. DOI:10.1016/S0960-8524(97)00134-X.

Oliveira, M.W., Macêdo, G.A.R., Martins, J.A., da Silva, V.S.G. and de Oliveira, A.B. 2018. Mineral nutrition and fertilization of sugarcane. *Sugarcane. Technology and Research*, 1: 169–191. DOI: 10.5772/intechopen.72300.

Otto, R., Trivelin, P.C.O., Franco, H.C.J., Faroni, C.E. and Vitti, A.C. 2009. Root system distribution of sugarcane as related to nitrogen fertilization, evaluated by two methods: Monolith and probes. *Revista Brasileira de Ciência do Solo*, 33*:* 601–611. DOI:10.1590/S0100-06832009000300013.

Raiesi, F. 2006. Carbon and N mineralization as affected by soil cultivation and crop residue in a calcareous wetland ecosystem in Central Iran. *Agriculture, Ecosystems and Environment*, 112(1): 13–20. DOI.org/10.1016/j.agee.2005.07.002.

Richards, L.A. 1954. *Diagnosis and improvements of saline and alkali soils*. USDA. Agriculture Handbook 60. 160 p.

Sampietro, D.A., Soberon, J.R., Sgariglia, M.A., Quiroga E.N. and Vattuone. 2007. Allelopathic plants. 17. Sugarcane (*Saccharum officinarum* L.). *Allelopathy Journal.* 20: 243–250.

Sanchez, P. A., C. A. Palm, C.B. Davey, L.T. Szott and C. E. Russell. 1985. Trees as soil improvers in the humid tropics? *In:* Cannell, M.G.R. and Jackson, J.E. (eds.), *Attributes of trees as crop plants.* Huntingdon, U.K.: Institute of Terrestrial Ecology.

Schweizer, S.A., Mueller, C.W., Höschen, C., Ivanov, P. and Kögel-Knabner, I. 2021. The role of clay content and mineral surface area for soil organic carbon storage in an arable toposequence. *Biogeochemistry*, 156(3): 401–420. DOI.org/10.1007/s10533-021-00850-3.

Selman-Housein, G., Lopez, M.A., Ramos, O., Carmona, E.R., Arencibia, A.D., Menéndez, E. and Miranda, F. 2000. Towards the improvement of sugarcane bagasse as raw material for the production of paper pulp and animal feed. pp. 189–193. *In:* Arencibia A.D. (ed.), *Plant genetic engineering: towards the third millennium:* Proceedings of the International Symposium on Plant Genetic Engineering, Havana, Cuba, 6-10 December, 1999. Elsevier Science Publishers. DOI:10.1016/S0168-7972(00)80030-4.

Shukla, S.K., Sharma, L., Jaiswal, V.P., Dwivedi, A.P., Yadav, S.K. and Pathak, A.D. 2022. Diversification Options in Sugarcane-Based Cropping Systems for Doubling Farmers' Income in Subtropical India. *Sugar Tech,* 1–18. DOI: 10.1007/s12355-022-01127-1.

Singh, K.P., Suman, A., Singh, P.N. and Srivastava, T.K. 2007. Improving quality of sugarcane-growing soils by organic amendments under subtropical climatic conditions of India. *Biology and Fertility of Soils,* 44(2): 367–376. DOI:10.1007/s00374-007-0216-8.

Solomon, S., Quirk, R.G. and Shukla, S.K. 2019. Special issue: green management for sustainable sugar industry. *Sugar Tech,* 21 (2): 183–185.

Taye Alemayehu, Bastiaanssen, S., Bremer, K., Cherinet, Y., Chevalking, S., Girma, M. 2020. Water Productivity Analyses Using WaPOR Database. A Case Study of Wonji, Ethiopia. Water-PIP technical report series. IHE Delft Institute for Water Education, Delft, the Netherlands.

Tekalign Tadese, Haque, I. and Aguayi, E.A. 1991. Soil, plant, water, fertilizer, animal manure and compost analysis. Working Document No. 13. International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia.

Tellen, V.A. and Yerima, B.P. 2018. Effects of land use change on soil physicochemical properties in selected areas in the North West region of Cameroon. *Environmental Systems Research*, 7(1): 1–29. DOI.org/10.1186/s40068-018-0106-0.

Tesfaye Wogari. 2021. Status of selected physicochemical properties of soils under long term sugarcane cultivation fields at Wonji-Shoa Sugar Estate. *American Journal of Agriculture and Forestry,* 9: 397–408. DOI: 10.11648/j.ajaf.20210906.19.

Tomašic, M., Zgorelec, Ž., Jurišic, A. and Kisic, I. 2013. Cation exchange capacity of dominant soil types in the Republic of Croatia. *Journal of Central European Agriculture*, 14(3): 84–98. DOI:10.5513/JCEA01/14.3.1286.

Vallejo-Torres, O. and López-Hernández, D. 2001. Micronutrient content in sugar-cane ash and its effect on a sugar-cane agroecosystem. *Communications in Soil Science and Plant Analysis,* 32(3–4): 409–419. DOI.org/10.1081/CSS-100103017.

Vitousek, P.M. and Sanford, R.L. 1986. Nutrient cycling in moist tropical forest. *Annual Review of Ecology and Systematics,* 17: 137–167.

VSN International. 2015. Genstat for Windows 18th Edition. VSN International, Hemel Hempstead, UK. Web page: Genstat.co.uk.

Wahid, A. and Rasul, E. 1997. Identification of salt tolerance traits in sugarcane lines. *Field Crops Research,* 54(1): 9–17. DOI.org/10.1016/S0378-4290(97)00038-5.

Wang, L., He, Z., Zhao, W., Wang, C. and Ma, D. 2022. Fine soil texture is conducive to crop productivity and nitrogen retention in irrigated cropland in a Desert-oasis ecotone, Northwest China. *Agronomy*, 12(7): 1509.

Watanabe, K. 2020. Sugarcane Grown with Saline Irrigation. Encyclopedia, 10.3390/agronomy10050722.

White, P.J., Crawford, J.W. Díaz Álvarez, M.C. and García Moreno, R. 2012. Soil management for sustainable agriculture. *Applied and Environmental Soil Science*, 2012. DOI:10.1155/2012/850739.

Wong, J.W.C. and Lai, K.M. 1996. Effect of an artificial soil mix from coal fly ash and sewage sludge on soil microbial activity. *Biology and Fertility of Soils,* 23(4): 420-424. DOI: 10.1007/BF00335916.

Zeyede Aregahegn and Mulate Zerihu. 2021. Study on Irrigation Water Quality in the Rift Valley Areas of Awash River Basin, Ethiopia. *Applied and Environmental Soil Science*, 2021. DOI.org/10.1155/2021/8844745.

Zhang, Z., Wang, J.J., Lyu, X., Jiang, M., Bhadha, J. and Wright, A. 2019. Impacts of land use change on soil organic matter chemistry in the Everglades, Florida-a characterization with pyrolysis-gas chromatography–mass spectrometry. *Geoderma*, 338:393–400. DOI.org/10. 1016/j.geoderma.2018.12.041.

Zulu, N. S., Sibanda, M. and Tlali, B. S. 2019. Factors affecting sugarcane production by Small-Scale growers in NDwedwe Local Unicipality, South Africa. *Agriculture*, 9(8): 170. DOI:org/10.3390/agriculture9080170.