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Evaluation of soil properties of sugarcane zones and cropping systems for improved productivity in Western Kenya

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Abstract

Unsuitable soil properties can adversely affect sugarcane productivity. The role of soil chemical, physical and biological properties on low productivity has not been evaluated. Soil nutrient survey was conducted to evaluate effects of soil properties of sugarcane zones and cropping systems on productivity in western Kenya. The survey involved 200 soil samples from sugarcane farms in Western (n=100) and Nyando (n=100) Sugar Zones, fallow sugarcane cropping systems (FS) (n=94) and successive sugarcane cropping systems (SS) (n=106). Undisturbed soil samples were also collected from the same selected farms for bulk density (BD) determination. Sugarcane yields (n= 144) were obtained from the selected farms for plant crop and two ratoons. A portion of soil samples was used for chemical analysis while another for parasitic nematodes identification and quantification. Soil test results were subjected to statistical analysis (SAS) and means were separated by student's t-test at 5 %. The test results were further correlated with respective sugarcane yields by multiple regression models. Soils of Western Zone were consistently high in parasitic nematode counts and were strongly acidic, moderate in organic C but low in all nutrients except P content. Nyando Zone soils were moderately acidic, adequate in P and K but low in N, C and Mg. However, N was the most limiting factor to sugarcane production in Nyando Zone and on the FS farms. The study recommends the need for appropriate nutrient replenishment for soils in the two zones while N management is critical in Nyando Zone and under the FS farms.

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Introduction

Typical sugarcane yields ranged from 100 to 140 t ha^{-1} (irrigated) under commercial conditions but achievable dry land yields were much lower and more variable due to rainfall distribution and the length of the wet season than the yields under irrigated conditions (Meyer and Clowes, 2011). But in western Kenya, the yields ranged between 60 and 90 t ha^{-1} over a decade in all growing zones [Kenya Sugar Board (KSB), 2010]. Low sugarcane productivity has persisted despite the release of improved sugarcane varieties (Korir *et al*., 2006; Jamoza, 2005), continued fertilizer use and opening new land. Declining soil nutrients and/or nutrient imbalances have been reported as some of the possible factors constraining sugarcane productivity in Kenya (Marabu, 2013; Wawire *et al.,* 2006). However, other reports indicated that sugarcane yields were mostly related to levels of organic matter, soil pH, calcium (Ca), magnesium (Mg) and sum of bases and silt, independent of sampling depth (De Menezes Rodrigues *et al*., 2016). Similar studies indicated significant relationships between labile carbon (C) with crop yields (Stine and Weil, 2002). But other studies identified no significant relationships between soil organic fractions with wheat (*Triticum aestivum*) yields (Datta *et al*., 2010; Moharana *et al*., 2012), attributing this to incomplete oxidation during analysis (Moharana *et al*., (2012). It has not been established if soil C content may be contributing to low sugarcane yields.

Soil is a living, dynamic system made up of different mineral particles, organic matter and diverse community of microorganisms (Meyer and Clowes, 2011). It is a medium for plant growth since it provides water, nutrients and anchorage to the growing plant (Meyer, 2011). Soil fertility comprises a complex range of chemical, physical and biological properties that should be optimized as a basis of good management practices (Meyer and Clowes, 2011). Thus, maintenance of these properties is necessary for achieving higher growth, yield and quality of sugarcane (Meyer and Wood, 2000; Morgan, 1986). Sugarcane requires moderate to high fertility, deep and well drained sandy clay loam soils with bulk density (BD) of 1.1 – 1.2 g cm^{-3} (1.3 – 1.4 g cm^{-3} in sandy soils) and an optimal soil water pH of 6.5 [Kenya Sugar Research Foundation (KESREF), 2010]. Its cultivation for many decades has resulted in nutrient mining, depletion of soil organic matter, low cation exchange capacity (CEC), exchangeable cations and increases in soil acidity, resulting in soil degradation (Meyer and van Antwerpen, 2010; Haynes and Hamilton, 1999; Meyer *et al*., 1996; Meyer and Wood, 1985). However, mechanisms and factors causing these changes have not been properly explained.

Critical soil nitrogen (N) and C contents for any crop production, inclusive of sugarcane, were reported as 1.1 and 1.5 % respectively (Tekalign *et al*., 1991). Nitrogen (N) is required for both above and below ground biomass production (Sharma *et al*., 2008; Accoe *et al*., 2004). Adequate soil nutrient levels for phosphorous (P), potassium (K), Ca and Mg are 20, 50, 1000 and 40 ppm respectively (Okalebo *et al*., 2002). Phosphorous (P) is for root growth and development while K is for enzyme activation in plant metabolism such as in photosynthesis, protein synthesis, starch formation and translocation of proteins and sugars (Filho, 1985). However, in old sugarcane farms high P levels tend to develop due to long history of P application (Chapman *et al*., 1981). Sugarcane is mainly produced in humid zones of western Kenya. Under these conditions, Ferralsols and Acrisols (Jaetzold *et al*., 2007) are major soil types with low content of plant nutrients due to leaching of bases (Jaetzold *et al*., 2007; Kuile, 1975). Since principal degradation process in the humid zone is leaching and soil acidification, which leads to toxicities and nutrient imbalances (Meyer, 2011), inadequate soil N contents is attributed to these processes (Kuile, 1975). Increased soil acidification (pH < 7) caused reduced availability of important nutrients such as N, P, K, Ca, Mg and sulphur (S) while micronutrients such as copper (Cu) and zinc (Zn) became more available (Meyer, 2011). Thus, long term use of acidifying fertilizers such as di-ammonium phosphate (DAP) and urea contributes to

low sugarcane yields through increased soil acidity in the following process of nitrification:

$NH_4^+ + 2O_2 \longrightarrow NO_3^- + H_2O + 2H^+$ (active acidity).

Other reports indicated that soil acidity also promoted nematode infestation up to soil pH_w 4, below which infestation was limited (Fischer and Fuhrer, 1990). Soil pH range less than 5.0 limited crop yields due to excess aluminum (Al) and Ca deficiency (Fox *et al*., 1991). Furthermore, the authors reported that excess manganese (Mn) and Ca deficiency limited yields in the soil pH range of 5.0 to 5.7; and that the yields became stable when soil pH was in the range of 5.7 to 6.0 as Ca and P contents remained constant. However, the authors reported that yields abruptly increased in the soil pH range 6.0 to 6.3, and this was attributed to elevated Ca concentration in soil solution. It has not been established if the humid zone soils are degraded with increased acidity and low nutrients, thus constraining sugarcane productivity. Furthermore, repeated use of acidifying fertilizers such as DAP and urea in this zone with limited soil tests (Jamoza *et al*., 2013) may have contributed to increased soil acidity but impacts on sugarcane yields have not been established.

Sugarcane production has also targeted sub-humid climate whose soils are characterized with less leaching of bases due to low rainfall. However, major limitation to crop production under this zone is lack of adequate soil moisture due to long periods of drought (Kuile, 1975). Drought is one of the most important environmental stresses limiting sugarcane production worldwide (Venkataramana *et al*., 1986). Four distinct growth stages (germination, tillering, grand growth, and maturity) have been identified in sugarcane (Gascho and Shih, 1983). The tillering and grand growth stages (also referred to as sugarcane formative growth phase) have been identified as the most critical water demand period (Ramesh, 2000), mainly because 70 to 80 % of cane yield is produced in this phase (Singh and Rao, 1987). Other reports indicated that evapo-transpiration and water use efficiency were strongly influenced by soil water availability, resulting in high sugarcane productivity (Da Silva *et al*., 2013). Furthermore, availability of soil water and adequate N supply were factors that influenced nutrient accumulation and storage in plants, resulting in crop growth and development (Da Costa *et al*., 2016). The availability of water in the soil was crucial to the growth and development of crops (Lawlor and Cornic, 2002), affected the efficiency of fertilization and promoted solubility and the subsequent release of nutrients to the plant (Da Costa *et al*., 2016).

Soils of the sub-humid zone are mainly Cambisols, Planosols and Vertisols (Jaetzold *et al*., 2007). Some soil types such as the Planosols and Vertisols are prone to water logging during wet seasons but they are not highly weathered as the humid zone soils. However in Kenya, it has not been established whether there may be sugarcane yield differences between humid and sub-humid zones. Regardless of the growing zones, low inherent soil fertility was reported as one of the casual factors to low sugarcane productivity [Kenya National Assembly (KNA), 2015; KESREF, 2011; Nyongesa, 1992; Odada, 1987; Wawire *et al*., 1987]. But the authors never evaluated the specific soil components constraining sugarcane productivity in the growing zones.

Sugarcane production under successive sugarcane cropping systems (SS) was where sugarcane was continuously produced for at least 20 years with few weeks or months break (Glaz and Ulloa, 1995). The SS farms were perceived to be unsustainable due to degraded soils (Wood, 1985). Reports indicated that soils of the SS farms had high BD values, low soil pH, low labile organic C, low CEC and manganese (Mn), low Cu and Zn but high exchangeable Al (Antwerpen *et al*., 2007). High BD values developed on compacted soils due to repeated use of heavy machinery for land preparation and cane haulage (Wood, 1985). High BD values of the inter rows of sugarcane reported under SS farms were due to wheel traffic (Hartemink, 1998). The high BD values affected sugarcane productivity through increased resistance to root penetration, reduced air supply

(Otto *et al*., 2011) and water permeability (Meyer, 2011) regardless of climatic conditions. As the BD increased, total porosity decreased and penetration resistance (Pr) increased (Otto *et al*., (2011). Significant effects of BD values in inter rows on sugarcane were due to wheel traffic but the effects of BD values within the sugarcane rows were not significant (Hartemink, 1998). Sugarcane root growth was not affected below penetration resistance of 0.75 Megapacals (Mpa), but decreased significantly between 0.75 - 2.0 MPa, and was severely restricted at Pr greater than 2.0 MPa. Critical BD value of 1.7 Mg m^{-3} (1.7 g cm^{-3}) for sugarcane productivity under Alfisol soil type was reported in Brazil (Reichert *et al*., 2009). But only one soil type was studied and it was unknown whether these BD values were from sugarcane inter rows or within the rows. However, no significant differences in BD values between adjoining natural grassland and within sugarcane rows was reported (Hartemink, 1998). Thus, soil compaction within sugarcane rows had greater impact on yields than that of the inter rows (Meyer and van Antwerpen, 2010). In Kenya, repeated use of heavy machinery for land preparation and cane haulage may have caused soil compaction, resulting in possible high BD values of top soils, but the impact on sugarcane yields has not been evaluated.

Soils of the SS farms also harbored deleterious fungi and nematodes which retarded plant establishment and early growth leading to decline in sugarcane productivity (Pankhurst *et al*., (2005). Several detrimental soil micro-organisms associated with sugarcane yield decline such as fungal root pathogen (*Pachymetra chaunorhiza*, lesion nematode (*Pratylenchus zeae*) (Pankhurst *et al*., 2003) and root-knot nematodes (*Meloidogyne incognita* and *M. javanica*) have been reported (Cadet and Spaull, 2005). The two parasitic nematode genera, *Pratylenchus* and *Meloidogyne* species were wide spread in sugarcane farming systems (Pankhurst *et al*., 2005), and affected sugarcane growth and development by attacking the sett- and shoot roots (Cadet and Spaull, 2005). Whereas the *Pratylenchus* species were dominant in clay soils (Mehta, 1992), the *meloidogyne* species dominated the sandy soils (Blair *et al*., 1999 a, b). Individual threshold values of 50 per 100 g dry soil significantly affected sugarcane yields (Stirling and Blair, 2001). Sugarcane yield reduction up to 50 % was reported on sandy soils (Spaull, 2011). However, in Kenya, 22 genera of plant parasitic nematodes existed and their distribution varied with soil types in South Nyanza sugar (SonySugar) belt (Nzioki, 2007). But the nematodes were neither quantified nor their impacts on sugarcane yields evaluated. It has not been established whether the production under the SS systems has contributed to the perennial problem of low productivity, thus specific soil components under these systems have not been studied.

Sugarcane production under fallow sugarcane cropping system (FS) has periods of rest when no fertilizers are applied, though the rest period varies from weeks to months. These were systems where sugarcane was introduced to farms in the first 5 years or previous sugarcane farms were rotated with legume crops for 8 – 12 months (Glaz and Ulloa, 1995). They were also previous sugarcane farms left under natural vegetation (natural fallows) for few months to years. Soils of the FS farms had moderate to neutral soil pH, high sugarcane yields; and few or absence of parasitic nematodes (Pankhurst *et al*., 2004; Glaz and Ulloa, 1995), hence they were perceived to be less degraded than the SS farms. A pasture break for 7 years increased biological suppression of soil organisms associated with yield decline compared to soil that had been under continuous sugarcane (Pankhurst *et al*., 2005).

Yield improvements of 20 - 30 % were achieved when sugarcane monoculture was broken with soybean (*Glycine max*), pasture and bare fallow (Garside *et al*., 1999, 2000, 2002). Furthermore, the yield improvements were associated with improvements on chemical and physical soil properties (Braunack *et al*., 2003) and biological (Stirling *et al*., 1996, 1999, 2001; Pankhusrt *et al*., 1999, 2000, 2003) soil properties, particularly the latter. Use of legumes in rotation to sugarcane not only provide a source of fixed nitrogen

but also improve soil health (Garside *et al.*, 1996, 1997c, 1998; Noble and Garside, 2000). Simulation studies suggested that legume N was available to the sugarcane crop up to the fourth ratoon, resulting in potential reductions in fertilizer application rate that could be approximately 100 % in the first ratoon, and 60 %, 25 % and 10 % in the subsequent ratoons (Sarah *et al.*, 2010). Traditionally, long duration natural fallows (at least 7 years) were practiced by farmers to restore soil fertility (Amadalo *et al.*, 2003). But in western Kenya, well defined rotational breaks (improved legume fallows) and long duration natural fallows under sugarcane cropping systems are scarce due to limited land occasioned by population pressure. However, it is unknown whether sugarcane yield differences may occur between the SS and FS farms, and that the specific soil components constraining the productivity have not been determined.

Materials and methods

Study area

Western Kenya comprises 12 sugarcane growing Counties namely: Mumias, Busia, Kakamega, Bungoma, Kisumu, Siaya, Kisii, Nyamira, Migori, Homabey, Kericho and Narok. The area lies between latitude 1° 8' N and 1° 24' S and between longitude 34° and 35° E. The elevation ranges from 1000 to 1600 m above the sea level; and occupies an area of 20,719 km² (Amadalo *et al.*, 2003). The study area comprised humid zone (Western Sugar Zone) namely: Mumias/Busia, Nzoia and West Kenya and sub-humid zone (Nyando Sugar Zone) namely: Kibos, Miwani, Chemelil, Muhoroni and Soin. The former zone has mean annual rainfall ranging from 1600 – 2000 mm while that of the latter zone ranges from 1000 – 1600 mm. (Jaetzold *et al.*, 2007). The rainfall occurs in two seasons namely: March to June (long rainy season) and September to November (short rainy season) (Amadalo *et al.*, 2003). Ten year mean daily temperatures range from 21 to 22 ° C (Jaetzold *et al.*, 2007). The Authors further reported that main soil types of Western Sugar Zone are: Ferralsols, Nitosols and Acrisols while major soil types of Nyando Sugar Zone are: Cambisols, Vertisols, Planosols and Gleysols.

Farm Sample Size

Soils were sampled once from 200 sugarcane farms in western Kenya, of which 94 farms were under the FS while 106 were under the SS farms. In the process, 100 farms fell within humid climatic zone while another 100 farms fell within the sub-humid climatic zone.

Farm sample size (Ss) required was calculated using the following formula:

$$Ss = \frac{Z^2 \times P(1-P)}{C^2}$$ (Cochran, 1977)

Where Z= reliability coefficient, fixed at 1.96 for 95% confidence level.

P= proportion of the sugarcane farms whose owners were likely to pick a choice; a choice was the number of sugarcane farms whose owners were likely to agree that indeed low sugarcane productivity was a problem (90 % was assumed since the problem was widespread). At least 50 % is chosen when population is big [Statistical Services Centre (SSC), 2000]; but to control the number of samples to manageable levels 90 % was arbitrary chosen for the current study.

C= confidence interval (5 % is chosen as confidence interval)

For the current study, $Ss = \frac{(1.96)^2 \times 0.9 \times 0.1}{(0.05)^2} = 138$ sugarcane farms

Soil sampling and analysis

From sample size calculation at least 138 farms were required but 200 farms were used to safe guard against possible rejection of farmers that soils should not be sampled from their farms. The farms were selected according to the current cropping systems, namely the FS and the SS farms. The FS farms were those that had sugarcane for the first time in 5 years or farms that previously had sugarcane but were left under natural vegetation for one or two years. The SS farms were those that had been with continuous sugarcane for at least 20 years with a few weeks or

months break under natural fallow. Soil sampling was randomly undertaken between November and December, 2008 at a depth of 0 - 25 cm using a scoop sampling method according to Byrnes *et al.*, (1994). The sampling was undertaken once in two zones namely; Western and Nyando Sugar Zones. Three or more sampling points were sampled per farm to provide a composite soil sample. For each farm from which soil sample was taken, mean sugarcane yields for three crop cycles (plant crop, first and second ratoons) were recorded after farm record verification using cane delivery receipts. Sugarcane yields in tones cane (tc) per acre were then converted to tones cane per hectare (t ha^{-1}). The samples were transported in small brown paper bags (size 2) to laboratory for analyses at KESREF in Kisumu county.

The BD values were determined according to Anderson and Ingram (1993) method. Core rings were inserted into already sampled points to collect un-disturbed samples at 30 cm depth and were transported to an oven and dried at 80 ^{o}C for 24 hours to a constant weight. For soil chemical analysis, the samples were air dried and ground to pass through 2 mm sieve for the analysis of the following parameters: pH_w and exchangeable acidity (pH_{KCl}) (Mehlich, 1960), total N (Bremner, 1960), available nutrients P, K, Ca, Mg, Na and Mn (Mehlich *et al.*, 1962) and organic C (Walkley and Black, 1934). Soil sub-samples from each farm were also used to determine the population of parasitic nematodes which were extracted [Centre for Agricultural Biosciences International (CABI), 2005; Hooper *et al.*, 2005], and identified by Mai and Lyon (1975) methods then quantified.

Statistical analysis

Analysis of variance (ANOVA) was adopted using statistical analysis systems (SAS) version 9.1 (SAS, 2007) to investigate differences in soil properties in the growing zones and also per the cropping system. A student's t-test was used to separate means at 5 %, assuming equality of variance. However, when the equal variance assumption was violated, the t-test used individual variances to approximate t - values and the degrees of freedom according to satterthwaite method (Hildebrand *et al.*, 2005). Furthermore, multiple regression model of SAS software was used to relate soil properties of the growing zones and cropping systems to respective sugarcane yields.

Results

Whereas soils of Western Sugar Zone were consistently high in parasitic nematode counts and were strongly acidic, moderate in organic C but low in all nutrients except soil P content, Nyando Sugar Zone soils were moderately acidic, adequate in P and K but low in N, C and Mg (Table 1). However, there were no significant differences in BD and sugarcane yields in the two growing zones (Table 1).

Table 1. Comparison of soil properties and sugarcane.

Variable	Zone	n†	Mean	Standard error	Pr > |t|
BD, g cm^{-3}	1	96	1.6	0.01	(0.13)
BD, g cm^{-3}	2	100	1.5	0.02	
Nematode count, per 100g dry soil	1	99	39	3.59	(<0.00)**
Nematode count, per 100g dry soil	2	99	16	0.87	
pH_w	1	100	5.2	0.04	(<0.00)**
pH_w	2	100	6.0	0.06	
pH_{KCl}	1	100	4.4	0.04	(<0.00)**
pH_{KCl}	2	100	5.0	0.05	
Organic C, %	1	96	1.5	0.06	(0.00)**
Organic C, %	2	96	1.8	0.06	
N, %	1	100	0.1	0.01	(<.00)**
N, %	2	100	0.2	0.01	
P, ppm	1	98	35.5	4.09	(0.01)*
P, pmm	2	94	55.1	6.78	
K, ppm	1	99	7.8	1.81	(<0.00)**
K, ppm	2	99	54.9	3.92	
Ca, ppm	1	99	9.8	2.87	(<0.00)**

Ca, ppm	2	98	48.3	2.92	
Mg, ppm	1	100	1.3	0.12	(<0.00)**
Mg, ppm	2	95	5.8	0.56	
Na, ppm	1	100	0.8	0.05	(<0.00)**
Na, ppm	2	99	10.1	0.85	
Yields (t ha^{-1})	1	66	79.5	4.14	(0.73)
Yields (t ha^{-1})	2	74	81.4	4.20	

yields (t ha^{-1}) of the two growing zones.

†Varying sample numbers indicated loss of some samples due to undetectable trace values; ** Significant at 1%; * significant at 5%; Zone 1- Western Sugar Zone (n = 100); Zone 2- Nyando Sugar Zone (n=100).

Whereas soil Mn and N contents significantly ($p \leq 0.05$) affected sugarcane yields in Western and Nyando Sugar Zones respectively (Table 2; Table 3), the N effects were marginal in the former zone (Table 2).

Table 2. Impact of soil properties on sugarcane yields (t ha^{-1}) in Western Sugar Zone.

Variable	Parameter Estimate *beta* (β)	Standard Error	Type II SS	F Value	Pr > F
Intercept	-110.47	58.99	2426.99	3.51	(0.07)
BD, g cm^{-3}	20.29	24.10	490.66	0.71	(0.40)
Nematode count, per 100 g dry soil	0.20	0.17	902.22	1.30	(0.26)
Soil pH_water	20.67	18.72	843.55	1.22	(0.28)
Soil pH_KCl	-0.47	18.43	0.45	0.00	(0.98)
Organic C, %	0.90	6.59	12.92	0.02	(0.89)
N, %	158.18	80.88	2646.49	3.82	(0.06)
P, ppm	0.22	0.22	695.29	1.00	(0.32)
K, ppm	0.61	0.47	1139.32	1.65	(0.21)
Ca, ppm	-0.02	0.43	1.25	0.00	(0.97)
Mg, ppm	3.71	4.31	512.22	0.74	(0.39)
Na, ppm	-12.73	10.30	1056.14	1.53	(0.22)
Mn, ppm	14.40	6.53	3368.93	4.87	(0.03)*

*Significant at 5%; confidence interval (CL) = 95%; P≤ 0.0001; $R^2 = 0.47$.

Soil BD, parasitic nematode counts, N, K and Mn did not change with the cropping systems (Table 4). However, the FS decreased soil organic C but increased soil P, Ca, Mg and sugarcane yields (Table 4). Under FS farms, only soil N significantly ($p \leq 0.05$) affected sugarcane yields (Table 5) while under the SS farms, only soil Ca marginally affected the yields (Table 6).

Discussion

The strongly acidic soils and low nutrients except for P in Western Sugar Zone was expected (Table 1). In this zone, the strongly acidic soils were not only attributed to humid conditions (Kuile, 1975) but also the commonly used acidifying fertilizers such as DAP and urea (KESREF, 2011). The effects of soil Mn content on sugarcane yields were significant ($p \leq 0.05$) while that of N was minimal (Table 2).

The finding was in agreement with Fox *et al.*, (1991) who reported that the yields were limited by excess Mn and Ca deficiency at soil pH range of 5.0 – 5.7. Although parasitic nematodes were higher in this zone than in Nyando Sugar Zone, there were no significant effects on sugarcane yields because threshold values were not yet reached as reported by Stirling and Blair (2000).

Table 3. Influence of soil properties on sugarcane yields (t ha^{-1}) in Nyando Sugar Zone.

Variable	Parameter Estimate (β)	Standard Error	Type II SS	F Value	Pr > F
Intercept	-59.79	105.09	190.74	0.32	(0.58)
BD, g cm^{-3}	19.79	33.89	201.05	0.34	(0.57)
Nematode count, per 100 g dry soil	0.23	0.31	317.10	0.54	(0.48)
Soil pH_water	21.43	44.57	136.19	0.23	(0.64)
Soil pH_KCl	-23.19	34.53	265.84	0.45	(0.51)
Organic C, %	20.59	16.99	865.11	1.47	(0.23)
N, %	460.16	158.73	4952.82	8.40	(0.01)*
P, ppm	0.15	0.42	76.46	0.13	(0.73)
K, ppm	0.17	0.79	27.12	0.05	(0.83)
Ca, ppm	-0.13	0.87	13.47	0.02	(0.88)
Mg, ppm	0.69	11.45	2.14	0.00	(0.95)
Na, ppm	19.40	17.76	703.12	1.19	(0.30)

*Significant at 1%; CL = 95%; P≤ 0.0001; R^2 = 0.47.

Similarly, there were no significant effects of BD on sugarcane yields because critical values were not yet reached as reported by Reichert *et al.*, (2009). However, high P levels were attributed to long history of P application as reported by Chapman *et al.*, (1981). But lack of significant effects of P on sugarcane yields in this zone was attributed to the soils being high P fixing given that the soils were strongly acidic (Table 1).

Despite adequate soil P and K in Nyando Sugar Zone due to less leaching occasioned by low rainfall (Kuile, 1975), sugarcane yields were not different from that of Western Sugar Zone (Table 1). This is because the zone is characterized by Cambisols, Vertisols, Planosols and Gleysols which are richer than Ferralsols and Acrisols characterizing Western Sugar Zone (Jaetzold *et al.*, 2007).

Table 4. Comparison of soil properties and sugarcane yields (t ha^{-1}) of the two cropping systems.

Variable	Cropping systems	n†	Mean	Standard error	Pr > |t|
BD, g cm^{-3}	1	90	1.5	0.02	(0.59)
BD, g cm^{-3}	2	106	1.5	0.02	
Nematode count, per 100g dry soil	1	94	29	3.41	(0.56)
Nematode count, per 100g dry soil	2	104	26	2.30	
pH_w	1	94	5.7	0.06	(0.03)*
pH_w	2	106	5.5	0.06	
pH_{KCl}	1	94	4.8	0.06	(0.09)
pH_{KCl}	2	106	4.6	0.05	
Organic C, %	1	94	1.5	0.06	(0.01)*
Organic C, %	2	98	1.8	0.07	
N, %	1	94	0.1	0.01	(0.71)
N, %	2	106	0.1	0.01	
P, ppm	1	91	54.4	6.65	(0.03)*
P, pmm	2	101	36.6	4.47	
K, ppm	1	93	31.1	3.25	(0.93)
K, ppm	2	105	31.6	4.29	
Ca, ppm	1	93	36.0	3.97	(0.01)*
Ca, ppm	2	104	22.7	2.90	
Mg, ppm	1	94	4.5	0.57	(0.00)*
Mg, ppm	2	101	2.5	0.30	
Na, ppm	1	94	5.8	0.85	(0.47)
Na, ppm	2	105	5.0	0.68	
Mn, ppm	1	49	1.1	0.09	(0.29)
Mn, ppm	2	55	1.0	0.07	
Yields (t ha^{-1})	1	62	94.8	4.39	(<0.00)*
Yields (t ha^{-1})	2	78	69.1	3.50	

† Varying sample numbers indicated loss of some samples due to undetectable trace values; * significant at 5%; cropping system 1- fallow sugarcane cropping systems; cropping system 2- successive sugarcane cropping systems.

Ferralsols and Acrisols are among the soil groups with low content of plant nutrient elements (Jaetzold *et al.*, 2007). Furthermore, the zone has sub-humid climate with low rainfall (Jaetzold *et al.*, 2007), and this is affecting the productivity. Inadequate soil moisture influences evapo-transpiration and water use efficiency which are necessary for high sugarcane productivity (Da Silva *et al.*, 2013). In addition, low soil moisture also affects tillering and grand growth sugarcane stages which contributes 70 – 80 % of the yields and affects soil N availability (Da Costa *et al.*, 2016).

Table 5. Effects of soil properties on sugarcane yields (t ha^{-1}) under fallow sugarcane cropping systems.

Variable	Parameter Estimate (β)	Standard Error	Type II SS	F Value	Pr > F
Intercept	-59.79	105.09	190.74	0.32	(0.58)
BD, g cm^{-3}	19.79	33.89	201.05	0.34	(0.57)
Nematode count, per 100g dry soil	0.23	0.31	317.10	0.54	(0.48)
Soil pH_water	21.43	44.57	136.19	0.23	(0.64)
Soil pH_KCl	-23.19	34.53	265.84	0.45	(0.51)
Organic C, %	20.59	16.99	865.11	1.47	(0.25)
N, %	460.16	158.73	4952.82	8.40	(0.01)*
P, ppm	0.15	0.42	76.46	0.13	(0.73)
K, ppm	0.17	0.79	27.12	0.05	(0.83)
Ca, ppm	-0.13	0.87	13.47	0.02	(0.88)
Mg, ppm	0.69	11.45	2.14	0.00	(0.95)
Na, ppm	19.40	17.76	703.12	1.19	(0.30)
Mn, ppm	1.20	9.36	9.64	0.02	(0.90)

*Significant at 5 %; confidence interval (CL) = 95%; P≤ 0.0001; R^2 = 0.71.

This is confirmed by significant (p≤ 0.05) effects of soil N on sugarcane yields in this zone (Table 3). Furthermore, significant effects of N on sugarcane yields indicated that N was a major limiting factor to sugarcane production in this zone. Similar findings on the importance of N in sugarcane production were also reported by Sharma *et al.*, (2008); Accoe *et al.*, (2004).

Table 6. Influence of soil properties on sugarcane yields (t ha^{-1}) under successive sugarcane cropping systems.

Variable	Parameter Estimate (β)	Standard Error	Type II SS	F Value	Pr > F
Intercept	-122.36	107.82	698.08	1.29	(0.27)
BD, g cm^{-3}	-51.50	48.01	623.52	1.15	(0.30)
Nematode count, per 100g dry soil	0.11	0.21	153.54	0.28	(0.60)
Soil pH_water	43.21	27.61	1327.27	2.45	(0.13)
Soil pH_KCl	2.23	30.61	2.89	0.01	(0.94)
Organic C, %	1.22	7.98	12.69	0.02	(0.88)
N, %	161.47	132.86	800.58	1.48	(0.24)
P, ppm	-0.13	0.35	70.79	0.13	(0.72)
K, ppm	-0.99	1.62	204.66	0.38	(0.55)
Ca, ppm	1.21	0.62	2100.84	3.88	(0.06)
Mg, ppm	9.67	5.77	1522.18	2.81	(0.11)
Na, ppm	-30.22	22.85	948.25	1.75	(0.20)
Mn, ppm	18.31	11.03	1492.92	2.75	(0.11)

Confidence interval (CL) = 95%; P≤ 0.0001; R^2 = 0.50.

As in the Western Sugar Zone, the effects of parasitic nemtodes and BD on sugarcane yields were non significant because threshold values were not yet reached as reported by Stirling and Blair, (2001) and Reichert *et al.*, (2009) respectively. However, high P levels were eattributed to long history of P application as reported by Chapman *et al.*, (1981). But lack of significant effects of P on sugarcane yields in this zone was due to inadequate soil moisture. Availability of soil water together with adequate N supply were factors that influenced nutrient accumulation and storage in plants, resulting in crop growth and development (Da Costa *et al.*, 2016), and soil water availability was crucial to the growth and development of crops (Lawlor and Cornic, 2002). Thus, soil water availability affects the efficiency of fertilization and promotes solubility and the subsequent release of nutrients to the plant (Da Costa *et al.*, 2016).

Under the FS farms, the soils were moderately acidic and all nutrients were inadequate except P as reported by Okalebo *et al.*, (2002). This is because under this cropping system, farms do not continuously receive urea as is the case with farms under SS. This was because there are periods of fallows in which no fertilizers are utilized though the period may be short. The higher P, Ca and Mg contents in FS farms than in SS farms might possibly be due to less intensive absorption of these elements by sugarcane plants under FS in contrast to the case under SS farms. Significant ($p \leq 0.05$) high sugarcane yields under the FS farms (Table 4) was attributed to increased Ca content as reported by Fox *et al.*, (1991). However, the yields were still below the potential as reported by Meyer and Clowes (2011), indicating that benefits due to fallowing were minmal. Although there was a significant decrease in organic C under the FS farm (Table 4), the effects on sugarcane yields were not significant (Table 5). This finding was in agreement with Datta *et al.*, (2010); Moharana *et al.,* (2012) who found no effects of organic C on yields, attributing this to incomplete oxidation (Moharana *et al.,* 2012). However, other reports indicated that organic C affects yields (Stine and Weil, 2002). Therefore, lower yields under the FS than the potential may be attributed to moderate organic C levels (Table 4). Although there were no effects of BD and parasitic nematode on sugarcane yields, the critical values for the soils were not determined.

Under the SS farms with the soil pH tending towards strongly acidic conditions, the Ca content was inadequate (Table 4). The finding was in agreement with Fox *et al.*, (1991) who reported that Ca deficiency limited yields in the pH range of 5.0 to 5.7. The tendency towards strong acidity was attributed to repeated use of acidifying fertilizers such as DAP and urea for sugarcane production in these regions (KESREF, 2011). This is because the two fertilizers are of high nutrient analysis (urea and DAP at 46 % N and 46 % P_2O_5 respectively), implying that they are cheaper to transport and apply as opposed to low nutrient analysis fertilizers such as calcium ammonium nitrate (CAN) at 26 % N and other phosphate fertilizers which may be required in large quantities. But with long term use, both DAP and urea fertilizers acidify soils in the process of nitrification as follows:

$NH_4^+ + 2O_2 \longrightarrow NO_3^- + H_2O + 2H^+$ (active acidity)

Although there were no effects of BD and parasitic nematode on sugarcane yields (Table 5; Table 6), the critical values were not determined.

Conclusions and recommendation

Whereas all the determined nutrients, N, K, Ca, Mg with exception of P, were inadequate in Western Sugar Zone, both P and K were adequate but N, Ca and Mg were inadequate in Nyando Sugar Zone. Soil N was the most critical nutrient constraining sugarcane yields in Nyando Sugar Zone and under the FS farms. Although sugarcane yields of the FS farms were better than those of the SS, the yields were still below the potential as reported by Meyer and Clowes, (2011), indicating that benefits due to fallowing practices were minimal. However, both nematode infestations and soil BD values had not reached

threshold levels and, hence, were not a problem on these farms.

There is need for integrated (use of both organic manures and inorganic fertilizers) nutrient replenishment under both sugarcane growing zones and the cropping systems for improved sugarcane productivity.

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