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Soil Quality Assessment for Sustainable Land Use and Management

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Authors' contributions

This work was carried out in collaboration between the two authors. Author ODA designed the study with input from author AOO. Author ODA carried out the field study, handled the laboratory and statistical analysis, wrote the protocol and wrote the first draft of the manuscript with the guidance of author AOO. Author AOO managed the literature searches and read through the draft many times to make necessary corrections. Both authors read and approved the final manuscript.

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ABSTRACT

Tropical soils are generally fragile and hence highly degraded due to such factors as low organic matter content, dominance of low activity clay, high susceptibility to erosion etc. Coupled with this, there is population pressure on the limited land and this has become a great challenge for land management and agricultural production. It is therefore imperative to adopt science-based and efficient approach for monitoring the impact of land use on land resources. This study has assessed soil quality under two land use types to establish the effect of land use on soil quality and demonstrate the kind of assessment necessary to arrest land degradation before it progresses too far. It was conducted within Oluyole Local Government Area in Oyo State, Southwestern Nigeria under two agricultural land use types (cacao and maize). For each of the two land uses, two farmlands were chosen for the study. In each of the farmlands, five sampling points were located and soil samples were collected at 0 – 15 cm and 15 – 30 cm depths. The samples were processed and analyzed for selected indicators, following standard methods. Soil quality was assessed using Soil Management Assessment Framework. Sustainability assessment was carried out on a scale of

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< 20 (highly sustainable) to > 40 (not sustainable) - i.e. 'less is better'. The relationship between soil quality and sustainability was established using regression analysis. Soil quality index was 85 – 87% under cacao and 60 – 77% under maize. Sustainability index ranged from 14 – 19 (highly sustainable) under cacao to 25 – 28 (moderately sustainable) under maize. High positive linear relationship (R^2 = 0.86 and 0.94) was obtained between soil quality and sustainability. The results thus indicate that the land use and management systems in the farms studied are sustainable, although the arable land use requires closer monitoring.

Keywords: Soil quality; land use type; sustainability; land management.

1. INTRODUCTION

Globally, for about three decades, there has been a progressive and deliberate emphasis on sustainability of any production system including agriculture. Almost every aspect of modern agriculture is now under scrutiny from producers to the consumers and policy makers; agricultural sustainability is on the agenda. This development has increased the demand for agricultural management systems that balance the needs for production of food and fibre with those of maintenance of the environment. i.e, production on a sustainable basis.

Soil is a critically important component of the earth's biosphere. It serves a multitude of functions and plays important roles in maintaining environmental quality. Inherent capacity of the soil to support crops varies and depreciates with use. The rate of depreciation also varies depending on the type of use and the soil properties mostly affected. Soil quality assessment deals with the dynamic capacity of the soil. It enables land users to assess the sustainability of management or cropping systems in addition to capacity of the soil itself to function. Soil quality is conceptualized as the major linkage between the strategies for agricultural conservation management practices and achievement of major goals of sustainable agriculture [1,2]. Soil quality assessment is essential to development, performance and evaluation of sustainable land management systems. In short, the assessment of soil quality and direction of change with time is the primary indicator of sustainable land management [3].

Soils of Southwestern Nigeria is characterized by high erosion risk, rapid leaching, high rate of organic matter decomposition, low activity clay, low fertility status among others. The traditional shifting cultivation/bush fallow system of management can no longer sustain production due to population expansion which has virtually removed the fallow period. Thus, farmers adopt various types of management systems. Thus soil quality as well as sustainability of the land use/management needs to be assessed so as to know the impact of the land use on soil quality.

This study aimed to: (i) assess the quality of the soils under cacao and maize and sustainability of land use and (ii) establish the relationship between the two parameters.

2. MATERIALS AND METHODS

2.1 Study Site

The study was conducted in Oluyole Local Government Area of Oyo State, Southwestern Nigeria under two agricultural land use types (cacao and maize) in year 2009. The study locations fall within longitudes 3°45" E and 3°55" E and latitudes 7°10" N and 7° 20" N of the equator (Fig. 1).

The climate of the study sites is humid to sub-humid tropical with distinct dry and wet seasons. The dry season runs from early November to the end of March or early April, while the wet season is from end of March or early April to about middle of November. The rainfall pattern is bimodal, with two rainfall peaks in June and September with a dry spell in August (August break). The average annual rainfall is 1279 mm. The mean annual temperature range between 26°C and 32°C, relative humidity is high and range between 60% and 90% at 16.00 hrs. [4]

The soils of the study sites are formed on Crystalline Basement Complex rocks with granite gneiss as dominant parent rock. There is a very strong geological and geomorphological influence on the pattern of soil distribution in the study sites. Vegetation of the study site is forest, and also contributes to the pattern of soil development in the area.

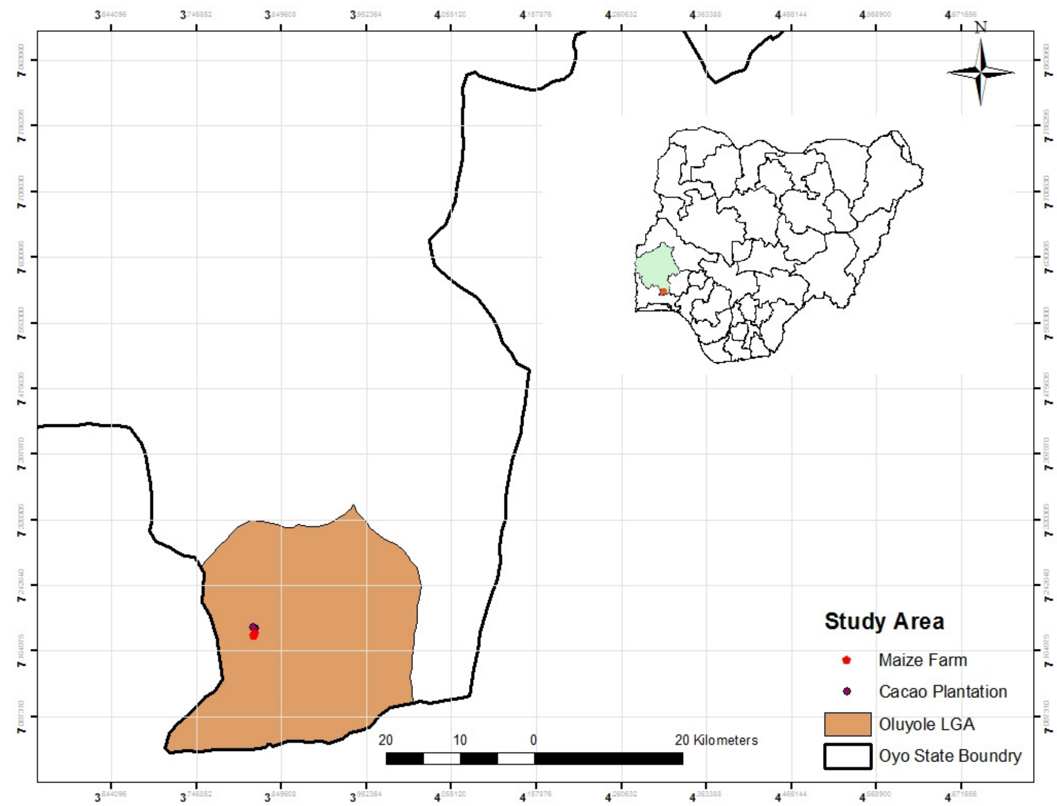

Fig. 1. Map of Oluyole local government showing the study locations

2.2 Selection of Indicators

The indicators used for soil quality assessment were selected by modifying the approach of Cameron et al. [5] for selecting soil quality indicators for crop production function. The approach is based on the equation:

$$A = (S+ U+ M+ I+ R) \quad (1)$$

where,

- A = Acceptance score for indicators
- S = Sensitivity of the indicator to degradation or remediation process.
- U = Ease of understanding of indicator value.
- M = Ease and / or cost effectiveness of measurement of soil indicator.
- I = Predictable influence of properties on soil, plant and animal health, and productivity.
- R = Relationship to ecosystem processes (especially those reflecting wider aspects of environmental quality and sustainability).

Each parameter in the equation is given a scores from 1 to 5 based on previous studies [5]. The sum of individual scores gives the level of Acceptance (A) score, which is ranked in comparison to other potential indicators to aid the selection of indicators for a site.

2.3 Field Study

Two farmlands were chosen for the study on each of the land use types. In each of the locations, ten sampling points were located and soil samples were collected at 0 – 15 cm and 15 – 30 cm depth. The samples were processed and analyzed for the selected indicators.

2.4 Soil Quality Assessment

The quality of soils for crop production was assessed using the framework for evaluating indicators of soil quality by [6] called Soil Management Assessment Framework (SMAF). This technique is based on the principle that soil quality can only be assessed by a combination of different properties or indicators using the critical values of the indicators and the soil processes relevant to crop productivity [7]. In this study, six soil processes relating to crop productivity (nutrient availability, nutrient retention, root penetration, biotic environment, water entry capacity and ability to resist degradation) were identified; relative weights were also assigned based on the level of importance. Soil quality indicators related to each process were identified and given weights as well [7]. All weights within each level summed up to 1.0 and 100% equivalent. The different processes and indicators were combined using Standard Scoring Functions (SSF) which enables users to convert numerical or subjective ratings to unitless values on a scale of 0 – 1. All indicators affecting a particular process were grouped together, given scores and relative weights based on relative importance. After scoring each indicator, the value was multiplied by the appropriate weight, producing an equation for soil quality rating for crop productivity as follows:

$$Q = \sum_{i=1}^{n} q.na \text{ x } wt. + q.nr. \text{ x } wt. + q.rp \text{ x } wt. + q.be \text{ x } wt + q.wc \text{ x } wt + q.dr \text{ x } wt \quad (2)$$

where,

Q = Overall soil quality index for crop productivity expressed as percentage
q.na = soil quality rating for nutrient availability process
q. nr = soil quality rating for nutrient retention process
q.rp = soil quality rating for root penetration process
q.be = soil quality rating for biotic environment process
q.wc = soil quality rating for water entry capacity process
q.dr = soil quality rating for degradation resistance process
wt = relative weight.

2.5 Sustainability Assessment

The sustainability of the soil quality values was assessed to know if the current soil quality can be sustained by the current land use. Relative weighting factors [1–5] were assigned to each of the soil quality indicators selected for sustainability assessment based on their critical values. The limitation ranges with relative weighting factors of 1 to 5 are as follows:

1= No limitation; the negative effect of the indicator on sustainability of land use is nil;
2= Slight limitation; the negative effect of the indicator on the sustainability of land use is slight;
3= Moderate limitation; the negative effect of the indicator on sustainability of land use is moderate.
4= Severe limitation; the negative effect of the indicator on sustainability of land use is severe.
5= Extreme limitation; the negative effect of the indicator on sustainability of land use is extreme.

The data were later combined into a cumulative rating index as follows:

$$SI = SQI_1 + SQI_2 + \text{---------} + SQI_n. \quad (3)$$

where,

SI = Sustainability index.
SQI_1 = weight score of the first soil quality indicator.
SQI_n. = weight score of the nth soil quality indicator.

The sustainability rating adopted is the 'less is better' system [8]. Table 1 shows an example of the sustainability rating of a land use in relation to the cumulative rating index based on 10 soil quality indicators.

The relationship between soil quality and sustainability was established using regression analysis.

Table 1. Sustainability rating of land use based on less is 'better' approach on a scale of < 20 to > 40

Sustainability rating	Cumulative rating index
Highly sustainable	< 20
Sustainable	20 - 25
Sustainable with high input	25 - 30
Sustainable with another land use	30 - 40
Unsustainable	>40

Source: Lal, (1994)

3. RESULTS

The values of soil quality indicators under the two cacao plantations are shown on Table 2. The soils are slightly acidic to near neutral with pH in water ranging between 5.7 and 6.9, and the soil acidity increased with depth. Active carbon which is the portion of the total carbon available as energy source for microorganism is moderate and decreased with depth. Total carbon, total nitrogen, potentially mineralizable nitrogen, base saturation (which is high) and cation exchange capacity (low to moderate) also followed the same trend. The bulk density is moderate and also increased with depth. Water holding capacity, aggregate stability, texture, porosity and infiltration rate are all high and adequate.

Table 3 shows the values of soil quality indicators under maize farms. The values of most of the soil quality indicators follow the same trend with that of cacao plantations but they are lower than under cacao plantations. Percentage aggregate soil quality indices under cacao and maize farms are shown on Table 4. The values ranged from 85 to 87% under cacao plantations and ranged from 60 to 77% under maize farms. Relative weighting of sustainability indicators for cacao plantations and maize farms are shown on

Table 2. Values of soil quality indicators for cacao plantations

Indicators	Farm 1		Farm 2	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm
pH (H_2O)	6.9	6.5	5.9	5.7
pH (KCl)	6.2	6.0	4.8	5.1
Active C (g/kg)	10.1	4.2	8.6	3.5
PMN (g/kg)	1.1	0.8	1.4	0.9
Avail.P (mg/kg)	0.8	1.7	4.6	2.4
Total C (g/kg)	19.0	10.1	20.1	8.5
Total N (g/kg)	2.0	1.1	2.1	1.4
Base Sat. (%)	97.5	95.6	98.3	97.5
CEC (cmol/kg)	12.8	3.7	14.2	9.8
Bulk density(g/cm^3)	1.3	1.4	1.3	1.4
WHC (m^3/m^3)	0.4	0.3	0.4	0.3
Aggt. Stab. (%)	86.4		80.5	
Texture	SL	SCL	LS	LS
Porosity(m^3/m^3)	0.6	0.5	0.5	0.5
Infiltration rate(cm/min)	2.3		2.1	

Note: PMN = Potentially Mineralizable Nitrogen, WHC = Water Holding Capacity, CEC = Cation Exchange Capacity, Avail. P = Available Phosphorus, Aggt. Stab. = Aggregate Stability, Base Sat. = Base Saturation

Table 3. Values of soil quality indicators for maize farms

Indicators	Farm 1		Farm 2	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm
pH (H_2O)	6.0	5.6	6.7	6.4
pH (KCl)	5.1	4.5	6.2	6.2
Active C (g/kg)	5.3	3.3	9.5	5.3
PMN (g/kg)	0.9	0.7	2.0	0.9
Avail.P (mg/kg)	3.2	1.9	1.6	0.6
Total C (g/kg)	10.7	8.7	17.8	15.2
Total N (g/kg)	1.1	0.9	3.9	1.6
Base Sat. (%)	95.5	95.0	97.3	85.0
CEC (cmol/kg)	2.8	2.5	9.0	2.7
Bulk density(g/cm^3)	1.5	1.5	1.3	1.5
WHC (m^3/m^3)	0.3	0.2	0.3	0.2
Aggt. Stab.(%)	62.1		60.5	
Texture	LS	SC	LS	LS
Porosity (m^3/m^3)	0.4	0.4	0.5	0.4
Infiltration rate (cm/min)	2.4		2.0	

Note: PMN = Potentially Mineralizable Nitrogen, WHC = Water Holding Capacity, CEC = Cation Exchange Capacity, Avail. P = Available Phosphorus, Aggt. Stab. = Aggregate Stability, Base Sat. = Base Saturation.

Tables 5 and 6. Sustainability indices ranged from 14 to 19 under cacao plantations and 25 to 28 under maize farms. Figs. 2 and 3 show the relationship between soil quality and sustainability under cacao plantations and maize farms. R^2 values are 0.86 (for maize farms) and 0.94 (for cacao plantations).

4. DISCUSSION

Soil quality index ranges from moderate (60% to 77% for maize farms) to high (85% to 87% for cacao plantations) (Table 4). The high values recorded under the tree crop may be due to the fact that tree crops produce debris (leaves, twigs,

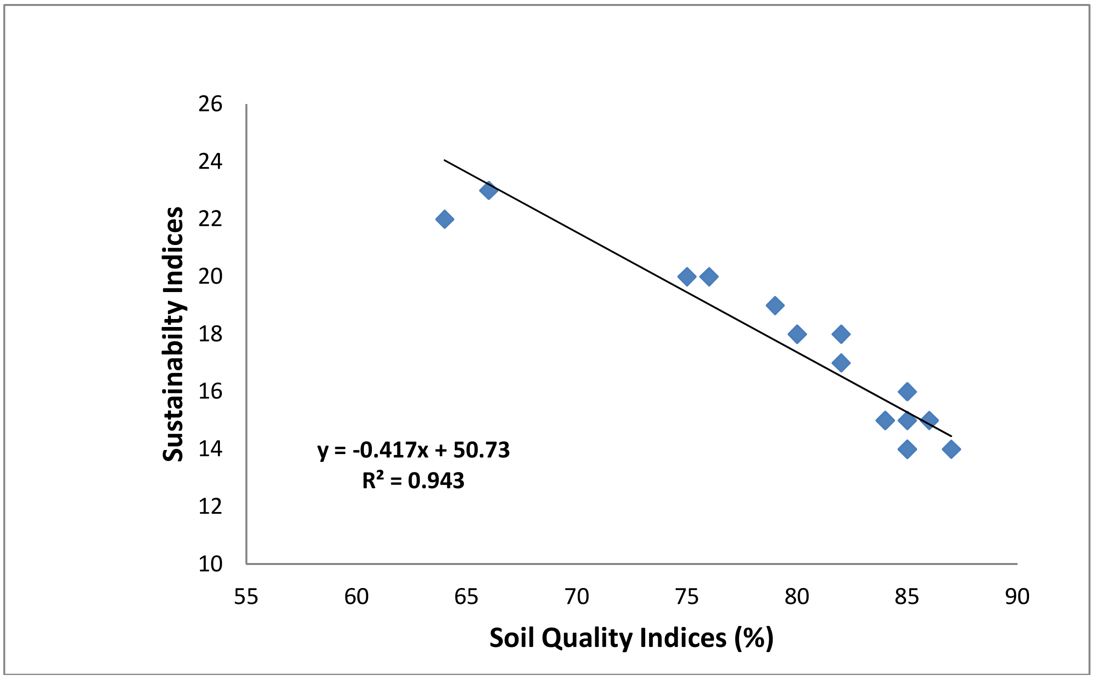

Fig. 2. Relationship between soil quality and sustainability of land use under cacao plantation

Table 4. Aggregate soil quality index for each of the farms (%)

Land use	Farm 1		Farm 2	
	0 – 15 cm	15 – 30 cm	0 – 15 cm	15 – 30 cm
Cacao plantations	85	85	87	86
Maize farms	60	77	61	64

Table 5. Relative weighting of sustainability indicators for cacao plantations

Indicators	Farm 1		Farm 2	
	0 – 15 cm	15 – 30 cm	0 – 15 cm	15 – 30 cm
pH	1	2	1	2
Active Carbon	1	2	1	1
PMN	2	2	2	2
Avail.P	4	3	3	4
Total Carbon	2	2	2	2
CEC	1	1	1	1
Aggt. Stab.	2	2	2	2
WHC	1	1	1	1
Bulk Density	1	1	2	2
Porosity	1	1	2	2
Sustainability Index	16	17	17	19

Table 6. Relative weighting of sustainability indicators for maize farms

Indicators	Farm 1		Farm 2	
	0 – 15 cm	15 – 30 cm	0 – 15 cm	15 – 30 cm
pH	2	2	3	3
Active Carbon	4	5	4	4
PMN	4	4	4	4
Avail.P	2	4	3	4
Total Carbon	3	3	2	2
CEC	4	4	2	3
Aggt. Stab.	2	2	2	2
WHC	2	2	1	1
Bulk Density	2	1	2	2
Porosity	2	1	2	2
Sustainability Index	27	28	25	27

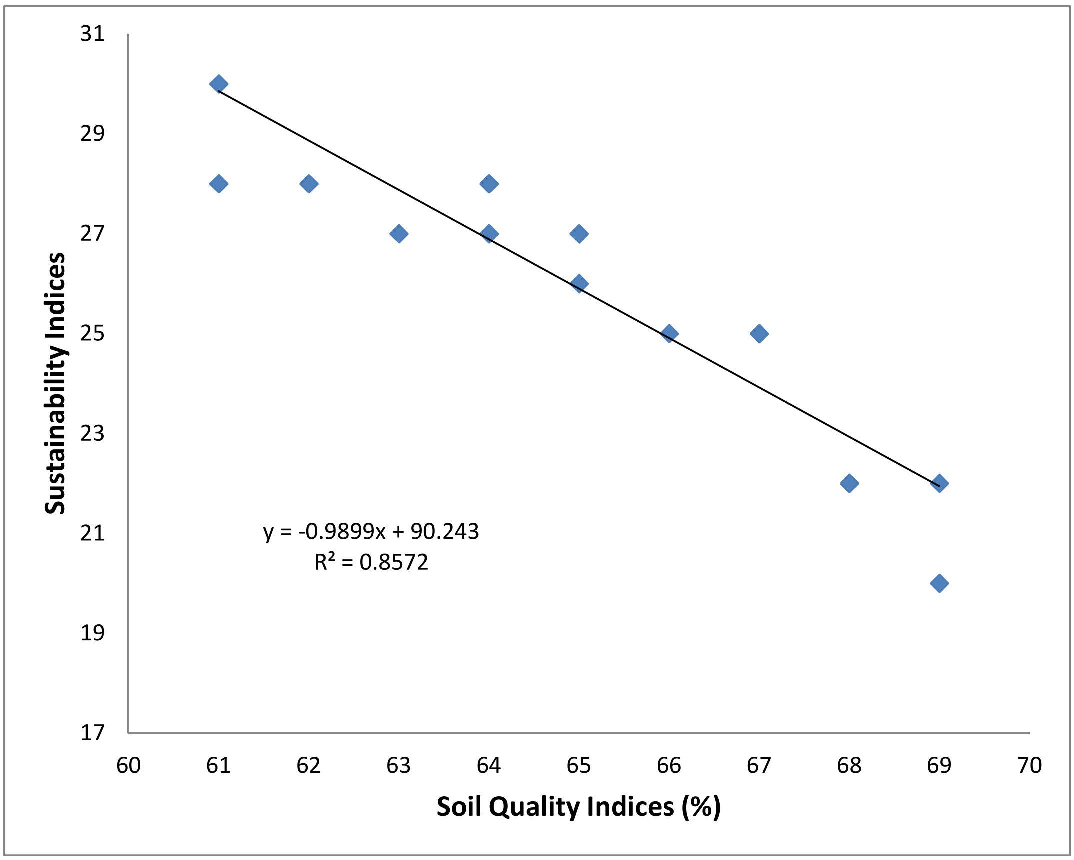

Fig. 3. Relationship between soil quality and sustainability of land use under maize farm

pods) which when decomposed helps to improve the levels of some of the soil quality indicators. For instance, organic matter is improved, and will positively influence aggregate stability, water holding capacity, and reduce compaction and erosion [9]. [10,11] also reported that a change in organic matter content of the surface soil significantly influenced other key soil properties. Soil organic matter plays key roles in soil function, determining soil nutrient status, water holding capacity and susceptibility of soil to degradation [12,13]. In addition, soil organic matter may serve as a source or sink to atmospheric CO_2 [14] and an increase in the soil carbon content is indicated by a higher microbial biomass and elevated respiration [15]. It is also the principal reserve of nutrients particularly N in the soil, some tropical soils are known to contain large quantities of mineral N in the top 2 m depth [16]. Arable crops on the other hand are noted for nutrient mining and will require very high quality soils for good productivity. In most farms, residue incorporation in the soil after maize harvesting, which is helps to improve soil fertility is not common. It is not practiced in the maize plots used for this study. This explains the lower values of soil quality index in the maize farms.

The sustainability indices follow the same trend with soil quality indices. Cacao plantations which have higher soil quality indices are also highly sustainable (values less than 20) while maize farms which have relatively lower soil quality are sustainable only with high inputs (values ranging from 25 to 28) (Tables 5 and 6). From all the results, soil quality and sustainability indices seem to have the same direction and magnitude indicating that when soil quality is high, sustainability is also high and vice versa. This may be due to the fact that the same sets of indicators were used for the two assessments. However, the same method was not used to integrate the indicators into indices. This, invariably, is pointing to the fact that there is a direct relationship between soil quality and sustainable land management [2]. This is supports the submission of [3] that assessment of soil quality and direction of change with time is the primary indicator of sustainable land management. Similarly, [17] also stated that soil quality indicators are a means towards the development of sustainable management systems. It is also a critical component of sustainable agriculture, and a farming system can only be sustainable when soil quality is maintained or improved [18]. If soils become degraded, more resources in terms of time, money, energy, and chemicals will be needed to produce less-abundant crops of a lower quality, and the goal of sustainable agriculture will not be met.

Sustainability was generally higher under cacao plantations than the maize farms. This could be due to the fact that cacao tree produces large amount of biomass which covers the soil surface and prevents the direct impact of raindrops on the soil surface in addition to being good source of organic materials that enriches the soil. This is in line with the submission of [19] that perennial vegetation enhances soil organic matter accumulation and minimizes topsoil disturbance. Also, the canopies produced by tree crops can also protect the topsoil from the direct impact of raindrops which can detach the soil particles and result in soil erosion. It has been established that continuous cultivation for arable crops especially maize degrades the soil faster than tree crops [20].

High positive linear relationship was observed between sustainability and soil quality (Figs. 2 and 3). This confirms the findings of [21] that a positive linear relationship exists between soil quality and sustainability such that as one increases, the other also increases and vice versa. Thus with soil quality assessment in place, sustainability evaluation which embraces principles of specificity of land use, multidisciplinary activity and land suitability can be predicted with a high degree of accuracy [22]. Sustainable soil management is part of the effort to achieve sustainable agriculture. The soil quality indices under maize field is low to moderate according to the criteria of [23], similarly, the sustainability indices are also high on the scale of less is better [8]. This indicates that for soil quality to be and remain high under maize field and similar arable land uses, high-input management practices that will encourage organic matter build-up must be put in place. Alternatively, high rate of commercial fertilizer application may have to be adopted. Even then, the physical properties of the soil cannot be improved due to lack of organic matter.

Soil degradation is better prevented than 'cured', so there is need to be pro-active by assessing and monitoring soil quality before land use and management is imposed so as to have a reference point. For soil quality to be meaningful, it must relate to sustainability of land use/management system. [24] submitted that the most effective way to maintain soil quality is to provide enough soil organic matter, or increase soil organic carbon pool in the soil. Planting of cover crops or green manuring is a way of protecting and improving organic matter in the soil [25-27]. These practices have the potential for recycling nutrients which otherwise would be lost through leaching during off-season periods. Cover crops with shallow fibrous root systems, such as grasses, rapidly build soil aggregation in the surface layer. Cover crops with deep roots can help break-up compacted layers, and bring nutrients from deeper soil layers to make them available for the crop that follows.

Leguminous cover crops have the additional benefit of fixing atmospheric nitrogen for the benefit of crop that follows in the rotation [25,26]. Other benefits from cover crops include protection of the soil from water and wind erosion, improved soil tilth and suppression of soil-borne pathogens [23]. [27] also reported that vegetative cover crop is necessary to protect the soil surface from raindrop impact, runoff, erosion and rapid desiccation. Another way of soil protection or nutrient build-up through organic matter is by agroforestry where food crops are grown with permanent tree crops before the canopy is closed up.

Traditional cropping system has been found to be effective in maintaining soil quality and needs to be emphasized in our farming systems. Due to the method of land preparation which encourages minimum tillage, observations have shown a reduced erosion incidence, improved soil structure, increase in microbial activities especially earthworm cast formation, improved organic matter content, as well as increase in infiltration rate and reduced bulk density [28,29]. However, in large-scale farming, where the use of traditional hoe and cutlass for land preparation is inadequate, a shallow tillage operation where the depth of tillage is not beyond 15 cm is required. Here, harrowing/ploughing alone especially in soils of basement complex origin should be advocated for most crops except root and tubers that require ridges/heaps. A conventional tillage system of multiple ploughing and harrowing should be discouraged due to low resilience ability of tropical soils.

5. CONCLUSION

Tropical soils are generally fragile in nature due to low organic matter content, dominance of low activity clay, high erodibility and low resilience. It is imperative to adopt science-based approach for sustainable land use in order to manage this resource to avoid degradation. To do this, there is need to put in place efficient assessment method that will make monitoring of land use impact on land resources possible. This study was set out to: Conduct assessment of soil quality under a tree and arable crop production, determine the sustainability of land use/management systems and establish the relationship between soil quality and sustainability.

The study was conducted in Oluyole local government area of Oyo State in Southwestern Nigeria under two agricultural land use types (Cocoa and Maize). Soil quality and sustainability of the land use systems were assessed. The following results were obtained:

1. Soil quality indices ranged from moderate to high with the highest value occurring under cocoa plantation while the lowest value occurred in maize field.
2. Sustainability indices follow the same trend with the soil quality indices. Cacao plantations soils which have higher soil quality indices are also highly sustainable for cacao production; and maize fields which have relatively lower soil quality are sustainable with input of high management practices.
3. Soil quality has high positive linear relationship with sustainability of land uses. Therefore, with soil quality assessment in place, sustainability of land uses can be predicted with high degree of accuracy.

In conclusion, soil quality assessment is highly essential for sustainable land use and management and hence sustainable agriculture.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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