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Development of a composite soil degradation assessment index for cocoa agroforests under tropical conditions of southwest Nigeria

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Abstract. Cocoa agroforestry is a major land use type in the tropical rainforest belt of West Africa, reportedly associated with several ecological changes, including soil degradation. This study aims to develop a composite soil degradation assessment index (CSDI) for determining the degradation level of cocoa soils under smallholder agroforests of southwest Nigeria. Plots where natural forests have been converted to cocoa plantations of ages 1-10 years, 11-40 years and 41-80 years, respectively representing young cocoa plantations (YCP), mature cocoa plantations (MCP) and senescent cocoa plantations (SCP) were identified to represent the biological cycle of the cocoa tree. Soil samples were collected at a depth of 0-20cm in each plot and analysed in terms of their physical, chemical and biological properties. Factor analysis of soil data revealed four major interacting soil degradation processes: decline in soil nutrient, loss of soil organic matter, increase in soil acidity and the breakdown of soil textural characteristics over time. These processes were represented by eight soil properties (extractable zinc, silt, SOM, CEC, available phosphorus, total porosity, pH, and clay). These soil properties were subjected to forward stepwise discriminant analysis (STEPDA), and the result showed that four soil properties (extractable zinc; cation exchange capacity; soil organic matter and clay) have the highest power to separate the studied soils into YCP, MCP and SCP. In this way, we hope to have controlled sufficiently for redundancy in the final selection of soil degradation indicators. Based on these four soil parameters, CSDI was developed and used to classify selected cocoa soils into three (3) different classes of degradation. The results revealed that 65% of the selected cocoa farms are moderately degraded, while 18% have a high degradation status. Finally, the value of the CSDI as an objective index of soil degradation under cocoa agroforests was statistically validated.

Keywords: Smallholder cocoa agroforests, age-sequenced plantations, minimum data set, degradation indicators, composite soil degradation assessment index, tropical conditions.

Introduction

Healthy soil is vital to successful agriculture and global food security (Virto, et al., 2014; Lal, 2015). Soil performs several ecosystem functions such as carbon sequestration and regulation (Novara et al. 2011; Brevik et al. 2015); buffering and filtering of pollutants (Keesstra et al. 2012); climate control through the regulation of C and N fluxes (Brevik et al.2015); and home for biodiversity (Schultecoo et al. 2015). Nonetheless, misuse of soils, arising from intensive agricultural production and unsustainable land use practices have resulted in soil degradation, particularly in developing countries with poor infrastructure and financial capacity to manage natural resources (Tesfahunegn, 2016). Statistics show that 500 million hectare (Mha) of land in the tropics (Lal, 2015), and more than 3500 million hectare (Mha) of global land area (Karlen and Rice, 2015) are currently affected by soil degradation, with serious implications for food security and the likelihood of malnutrition, ethnic conflict, and civil unrest (Lal, 2009). In response to these problems, an increasing interest in soil degradation has been observed among researchers and policy makers (Scherr 1999; Adesodun et al. 2008; Baumhardt et al. 2015; Hueso-González et al. 2014; Lal, 2015; Tesfahunegn, 2016).

Soil degradation is a measurable loss or reduction of the current or potential capability of soils to produce plant materials of desired quantity and quality (Chen et al. 2002). Many scientists viewed soil degradation as a decline in soil quality (Lal 2001; Adesodun et al. 2008; Beniston et al. 2015), and soil quality (SQ) as the capacity of a soil to function within ecosystem and land-use boundaries (Doran and Zeiss, 2000; Karlen et al. 2001; Doran, 2002; Yemefack, 2005). Unfortunately, when soil degradation reaches an advance stage, soil quality restoration is practically difficult (Lal and Cummings 1979). Therefore, good knowledge of SQ is important for developing appropriate anti-degradation measures (Tesfahunegn, et al., 2011). Since, soil degradation and soil quality are interlinked through many processes (Lal, 2015), scholars have suggested that soil degradation can be assessed using soil quality assessment strategies (Tesfahunegn, 2014, Pulido et al. 2017). But, an essential step when assessing soil degradation based on soil quality assessment strategies is the need for careful selection of appropriate indicators relevant to degradation processes under investigation.

Degradation of soils is complex, often the consequence of many interacting processes (Prager et al. 2011). However, major processes include accelerated erosion (Cerda et al. 2009; Bravo-Espinosa et al. 2014); deforestation (De la paix et al. 2013); poor pasture management (De Souza Braz et al. 2013); decline in soil structure (Cerda 2000); salinization associated with inadequate irrigation management (Prager et al. 2011; Ganjegunte et al. 2014); alkalinization and sodification (Condom et al. 1999); depletion of soil organic matter (SOM) (Novara et al. 2011); reduction in the activity of soil microorganisms (Lal 2009); and soil compaction (Pulido et al. 2017). For sustainable soil management in agricultural regions, it is essential for farmers and scientists to identify major dominant degradation processes and their indicators.

Cocoa (Theobroma cacao L.) is a major agricultural landuse type in the tropical rainforest belt of West Africa (Tondoh et al. 2015), covering an estimated total area of about 6 million-ha in Côte d'Ivoire, Ghana, Nigeria and Cameroon (Sonwa et al. 2004). Unfortunately, cocoa landscapes are often associated with a range of ecological changes including deforestation, biodiversity loss, destruction of soil flora and fauna from pesticide usage, and accelerated soil degradation (Critchley and Bruijnzeel 1996; Salami 1998, 2001; Rice and Greenberg 2000; Asare 2005; Ntiamoah and Afrane 2008; Mbile et al. 2009; Adeoye and Ayeni 2011; Jagoret et al. 2012;

Akinyemi 2013; Schoneveld 2014; Sonwa et al. 2014, Tondoh et al. 2015). Till date, soil degradation assessments at plot scale in regions undergoing farmland conversion to cocoa agroforests are limited.

Worldwide, agricultural practices have been regarded as one of the major causes of soil degradation (Kessler and Stroosnijder 2006, Rahmanipour, et al. 2014, Karlen and Rice, 2015, Zornoza et al., 2008) It is widely acknowledged that agricultural practices or land use changes in agricultural regions alter key soil properties such as soil organic matter (SOM), total nitrogen (TN), cation exchange capacity (CEC), exchangeable cations, water holding capacity (WHC), bulk density (BD), and total porosity (TP) (Lemenih et al. 2005; Awiti et al. 2008; Trabaquini 2015; Dawoe et al. 2010, 2014; Ameyan & Ogidiolu 1989; Hadgu et al. 2009; Thomaz & Luiz 2012; Zhao et al. 2014; Tesfahunegn 2014). Although, many of these soil properties are regularly used as indicators of soil degradation (Trabaquini 2015), the use of individual soil characteristics often provides an incomplete representation of soil degradation (De la Rosa 2005; Puglisi et al. 2005, 2006). To overcome this shortcoming, an integration of soil properties into numeric indices has been proposed (Doran & Parkin, 1994, Leirós, et al. 1999; Bastida et al. 2006, Gómez et al. 2009, Puglisi et al. 2005, 2006; Sharma et al. 2008; Pulido et al. 2017). Thus, Sánchez-Navarro et al. (2015) developed an overall soil quality index suitable for monitoring soil degradation in semiarid Mediterranean ecosystems. Pulido et al. (2017) developed a soil degradation index for rangelands of Extremadura SW Spain based on six indicators, cation exchange capacity (CEC), available potassium, soil organic matter (SOM), water content at field capacity, soil depth and the thickness of the Ah-horizon. Gomez et al. (2009) developed three soil degradation indexes obtained through a principal component analysis (PCA) of the soils under organic olive farms in southern Spain. One of the index used only three soil properties, organic C, water stable macroaggregates, and extractable P. According to these authors, this index has the highest potential to be used as a relatively easy and inexpensive screening test of soil degradation in organic olive farms in southern Spain. Till date, less attention has been given to development of numeric indices for monitoring soil degradation under crop-specific landuse management systems in tropical countries. Whereas, such indices can serve as the basis for integrating and interpreting several soil measurements, thereby indicating whether a landuse management system is sustainable or not.

The aim of the present study is to develop a composite soil degradation assessment index (CSDI) for shaded cocoa agroforests under tropical conditions in southwest Nigeria. This area is currently suffering from soil degradation arising from cocoa based agroforests under a "slash and burn" farming system. Soil conditions under age-sequenced peasant cocoa agroforests are investigated. The agroforest ages of 1-10 years, 11-40 years and 41-80 years – hereafter referred to as young cocoa plantation (YCP), mature cocoa plantation (MCP) and senescent cocoa plantation (SCP) respectively – were targeted as this is in line with the biological cycle of the cocoa tree (Isaac et al. 2005; Jagoret et al. 2011, 2012; Saj et al. 2013). The specific objectives are: (i) to identify the most important soil degradation processes associated with shaded cocoa agroforestry in the study area; (ii) to select a minimum data set (MDS) of soil degradation indicators using multivariate statistical techniques; (iii) to integrate the MDS into a CSDI; and (iv) to statistically validate CSDI and evaluate to what extent the CSDI can be used as a tool by researchers, farmers, agricultural extension officers and government agencies involved in rehabilitation of degraded cocoa soils in southwest Nigeria (and similar environments).

2.0 Materials and Methods

2.1 Study area

This study was carried out in the Ife region, southwest Nigeria (Figure 1), where most of the soils have been under cocoa plantations for more than eighty years (Abiodun, 1971; Berry, 1974). The climate is humid tropical with a mean daily minimum temperature of 25°C and a mean maximum temperature of 33°C. The mean annual rainfall ranges between 1400 mm and 1600 mm, with a long- wet season lasting from April to October, and a relatively short dry season that lasts from November to March. The natural vegetation is dominated by humid tropical rainforests of the moist evergreen type, characterized by multiple canopies and lianas. The area is underlain by rocks from the Basement complex of Pre-Cambrian Age, which are exposed as outcrops in several areas. The soils are mainly Alfisols, classified as Kanhaplic Rhodustalf in the USDA Soil Taxonomy (Soil Survey Staff, 2006), or Luvisols (World Soil Reference, 2006) and locally known as Egbeda Association (Smyth & Montgomery 1962). The area of study lies within the Egbeda soil series, characterised by sandy loam soils, with increasing clay content in the lower horizons. The soils are slightly acidic to neutral in reaction (pH 6.5). With the exception of the areas set aside as forest reserves, the natural vegetation has been replaced with perennial and annual crops. Cocoa agroforests in the region were traditionally established using "slash and burn" approach (Tondoh et al. 2015; Ngo-mbogba et al. 2015), where primary or secondary forests are selectively cleared, burned and cocoa is planted along with understory food crops (Isaac et al. 2005). Farmers have recently shifted towards full-sun cocoa agroforestry, particularly in areas where natural forest is scarce (Oke and Chokor 2009). Cocoa trees are regularly sprayed with chemicals to combat black pod disease (Phytophthora sp), but farmers depend entirely on the natural fertility of the soil without application of inorganic fertilizers or organic manure.

2.2 Site selection

A reconnaissance survey of Ife region was carried out between March and April 2013. Considering soil variability and heterogeneity, five settlements of cocoa farmers (Mefoworade, Omifunfun, Aye Coker, Aba Oyinbo and Kajola-Onikanga) in the southern Ife area were randomly selected as study sites. In each site, a total of eight (8) cocoa stands of different ages (since site clearance) were randomly selected and assigned to three cocoa plantation age categories: YCP (10 plots), MCP (15 plots) and SCP (15 plots). All sampled plots were restricted to upper slope positions of a catena where the slope angle did not exceed 2° to ensure that catenary variation in soil properties between the farms studied was minimal. Local farmers served as the main source of information on the age distribution of the cocoa plantations and their permission was also sought to use their farms as research plots. Each research plot was visited several times and notes were made on the physical characteristics of the fields, their approximate sizes, presence of other crops and neighbouring trees, levels of farm maintenance and evidence of soil erosion.

2.3 Soil sample collection for laboratory analysis

Soil sampling was conducted in May 2013. A quadrant measuring 100 m^2 was demarcated at the centre of each cocoa plantation. Each quadrant was subdivided into ten 100 m^2 sub-quadrants and serially labelled. Soil samples were drawn at the centre of the even-numbered sub-quadrants, resulting in a total of five soil samples per plot.

Measurements were confined to the top 0–20 cm soils for the following reasons: (i) most significant changes in soil characteristics in any vegetation (especially in a tropical environment) are confined to the topmost layer of the soil profile (Aweto 1981; Aweto and Iyanda 2003); (ii) these depths cover the main distribution of roots and soil nutrient stocks of cocoa plantations (Hartemink 2005); (iii) biological processes, such as earthworm activities are restricted to 0-10 cm layer of tropical soils; (iv) to facilitate future replication of the methodology as routine soil samples are usually kept at top-soil layer (plough layer). Two categories of soil samples were taken at each sampling point to promote a detailed investigation of soil-property differences. The first was an undisturbed sample using a bulk-density ring measuring 5 x 5 cm (diameter and height), whereas the other sample was taken using a soil auger. The first sample was used to determine bulk density (BD), water-holding capacity (WHC) and saturated hydraulic conductivity (SHC), and the second sample was used to determine the other studied soil properties. The soil samples were stored in labelled polythene bags and taken to the laboratory for analysis. The composite soil samples aggregated from the five samples collected in each plot were air-dried for two weeks, hand ground in a ceramic mortar, passed through a 2 mm sieve and analysed for chemical properties and particle-size distribution. Twenty-two soil properties were selected for analysis. The analytical methods are summarized in Table 1.

2.4 Statistical analyses and index development

Based on extensive review of literature on soil quality and degradation assessment indexing, CSDI was developed using a range of statistical techniques and procedures. The methodology consisted of eight steps as shown schematically in fig. 2. Each of these steps is outlined below.

Step 1) involved selection of relevant indicators of soil degradation. Here, we selected twenty-two (22) analytical soil properties widely acknowledged as soil quality and degradation indicators.

In Step 2) a factor analysis was performed to group all the soil data into statistical factors with principle component analysis (PCA) as the method of factor extraction (Tesfahunegn et al., 2011). Factors were subjected to varimax rotation with Kaiser normalization in order to generate factor patterns that load highly significant variables into one factor, thereby producing a matrix with a simple structure that is easy to interpret (Ameyan and Ogidiolu 1989; de Lima et al. 2008; Momtaz et al. 2009). Factors with eigenvalues of less than one (1) were ignored. The order in which the factors were interpreted was determined by the magnitude of their eigenvalues. Under each factor, soil properties regarded as highly important were retained. These were defined as those that had a loading value within 10% of the highest loading within an individual factor (Andrews et al. 2002). Soil properties that are widely acknowledged as good indicators of soil quality, but with factor loading scores ≤ 0.70, were also retained. Soil physical, chemical and biological properties that have been suggested as important soil quality indicators include soil organic carbon, available nutrients and particle size, bulk density, pH, soil aggregate stability, cation exchange capacity and available water content (Doran and Parkin, 1994; Larson and Pierce, 1994; Karlen et al., 1997; Zornoza et al., 2007; García-Ruiz et al., 2008; Qi et al., 2009; Marzaioli et al., 2010; Fernandes et al., 2011; Lima et al., 2013; Merrill et al., 2013; Rousseau et al., 2013; Singh et al., 2014; Zornoza et al.2015). In cases where more than one soil property was found to be of high importance under a single PC, Pearson's correlation coefficients were used to determine if any of these variables are redundant (Qi et al. 2009). When two highly important variables were found to be strongly correlated ($r^2 > \pm0.70$; $p<0.05$), the one with the highest factor loading (absolute value) was retained (Andrews & Carroll 2001; Andrews et al. 2002; Montecchia et al. 2011).

In Step 3) of the CSDI development, the highly important soil properties under each factor were subjected to stepwise discriminant analysis (STEPDA) to select key soil properties (variables). In principle, stepwise discriminant analysis generates two or more linear combinations of the discriminating variables, often referred to as discriminant functions (Tesfahunegn et al., 2011). Whereas, the discriminant functions can be represented as:

$$D_i = d_{i1}Z_1 + d_{i2}Z_2 + \ldots . d_{iP}Z_P. \qquad \text{(eq 1)}$$

where D_i is the score on discriminant function i, the d's are weighting coefficients, and the Z's are the standardized values of the p discriminating variables used in the analysis (Awiti et al. 2008). In this study, STEPDA was used to select variables with the highest power to discriminate between the treatments. The validity of the result was evaluated using the Wilk's Lambda value. This value is an index of the discriminating power ranging between 0 and 1 (the lower the value, the higher the discriminating power). At each step of STEPDA, the variable that minimizes the overall Wilks' Lambda was selected. One of the advantages of STEPDA is that the final model contains the variables that are considered useful. The result of this process was an MDS consisting of the most important variables for quantifying soil degradation in the selected plantations.

Step 4) involved the normalisation of the MDS variables to numerical scores between 0 and 1 using a linear scoring function (Masto et al. 2008; Ngo-mbogba et al. 2015). The "more is better" scoring curve was used to determine the linear score of soil variables:

$$S_L = \left(\frac{x-l}{h-l}\right) \qquad \text{(eq 2)}$$

where, S_L is the linear score (between 0 and 1) of a soil variable, x is the soil variable value, l is the minimum value and h is the maximum value of soil variable.

During Step 5), the normalized MDS values were transformed into degradation scores (D) as described by Gómez et al. (2009) and obtained from:

$$\mathrm{D} = 1 - S\mathrm{L} \qquad \text{(eq 3)}$$

where D is the degradation score and $S\mathrm{L}$ is the normalized MDS value. Here, a score of 1 signifies the highest possible soil degradation score and 0 represents complete absence of degradation for a particular soil property.

In Step 6) the degradation scores (D) were integrated into an index using the weighted additive method:

$$\mathrm{CSDI} = \sum_{i=1}^{n} (\mathrm{W_i}\ \mathrm{D_i}) \qquad \text{(eq 4)}$$

where CSDI represents the composite soil degradation index, W_i is the weight of variable i, D_i represents the degradation scores of the parameters in the MDS for each of the cocoa farms, and n is the number of indicators in the MDS. W_i in eq. [4] was derived by the percentage of the total variance explained by the factor in which the soil property had the highest load divided by the total variance explained by all the factors with eigenvalues ≥ 1 (Masto et al. 2008; Armenise et al. 2013).

In Step 7) CSDI values were categorized into number of desired (3) classes of degradation using their Z-score value as obtained by:

$$z = \frac{x-\mu}{\sigma} \qquad \text{(eq 5)}$$

where, Z is the z-score, x is the CSDI value of each plot, μ is the mean value and σ is the standard deviation. In principle, z-scores explain the standard deviations of input values from the mean (Hinton 1999). For this purpose, a Z values between -1 and 1 were regarded as having a *moderate* degradation status, while values of more than 1 was regarded as *high* and less than -1 as *low* (see results section for further explanation on this categorization). In Step 8) the CSDI classification was statistically validated using a canonical discriminant analysis (CANDA). Canonical discriminant analysis is a multivariate statistical technique whose objective is to discriminate among pre-specified groups of sampling entities. The technique involves deriving linear combinations of two or more discriminating variables (canonical variates) that will best discriminate among the *a priori* defined groups. In this study, we used the "leave-one-out" cross validation procedure of CANDA. Using this procedure, a given observation is deleted (excluded) and the remaining observations are used to compute a canonical discriminant function that is used to assign the observation into a degradation class with the highest probability. For instance, a sample with a probability of 0.003, 0.993 and 0.004 belonging to low, moderate and high degradation class respectively was assigned to medium. This procedure is repeated for all observations and the result is a "hit ratio" or confusion matrix, which indicates the proportions of observations that are correctly classified. Additionally, CANDA was used to confirm the significance of the explanatory variables that discriminate between the three soil degradation classes. In this study, the threshold (T) for the selection of variables correlating significantly with the canonical discriminant functions was taken as T= 0.2/√ (eigenvalue) as suggested by Hadgu et al. (2009). Scoring and indexing were performed using Microsoft Excel 2013. All statistical analyses were performed using XLSTAT version 2016 (Addinsoft New York, USA).

3.0 Results and discussion

3.1 Identification of soil degradation processes using factor analysis

Table 2 shows the results of the factor analysis and reveals that the first five PCs had eigenvalues > 1 as illustrated by the scree test (figure 3). Each PC explained 5% or more of the variation of the dataset. The first five PCs jointly accounted for more than 77% of the total variance in the data set. In addition, it explained 68% of the variance in available phosphorus, 84% in SOM, 76% in calcium, 65% in pH, 87% in clay, 90% in total nitrogen, 77% in silt, 83% in magnesium, 83% in sand, and 58% in bulk density. The high communalities among the soil properties suggests that variability in selected soil properties is well accounted for by the extracted factors (Tesfahunegn *et al.*, 2011).

Extractable zinc, extractable manganese and silt had high positive loadings on PC1 (0.875, 0.857, and 0.838 respectively). Because a significant correlation exists between extractable zinc and extractable manganese (r=0.834, p<0.001; Table 3), the latter variable was excluded. For ease of association, PC1 was labelled ***soil micronutrient degradation factor***. PC2 was loaded highly by CEC (0.884) and exchangeable calcium (0.871), but given that the correlation analysis showed a strong relationship (r=0.870, p<0.001; Table 3) between CEC and exchangeable calcium, the latter was also excluded. SOM, with a relatively high factor loading (0.711), was retained owing to its relevance in monitoring soil quality degradation (Brejda et al. 2000; Sharma et al.2009; Masto et al. 2008; 2009; Zornoza, et al., 2015). Because the correlation coefficient between SOM and CEC was relatively low (r=0.578; p<0.001; Table 3), both were retained as highly important variables. Given that SOM was significantly correlated with several of the eliminated soil properties in the group, the second component factor was labelled the *soil organic matter degradation factor*.

The third component factor (PC3) was highly loaded on available phosphorus (0.810) and total porosity (0.801). Because the correlation coefficient between the two variables is relatively low (r=0.578; p<0.001; Table 3), both properties were retained. The group of variables associated with the third factor was termed the *available phosphorus degradation factor.* The fourth factor was labelled as *soil acidity degradation factor* because it was highly loaded on pH (0.791) only. Similarly, the fifth factor was labelled *soil textural degradation factor* because it was dominated by clay (0.812).

So far, the PCA result suggests that soil degradation in the study region is mainly linked to four degradation processes, namely 1) decline in soil nutrient, 2) loss of soil organic matter, 3) increase in soil acidity and 4) the breakdown of soil textural characteristics arising from differences in clay eluviation (Figure 4). Figure 5 summarises the results of the interrelationship among the 22 soil properties as a correlation circle. The figure shows that the first two PCA axes jointly accounted for 40.08 % of the total variance, with the first axis (eigenvalue = 8.545) representing mainly micronutrients with extractable manganese, zinc, silt and total nitrogen in contrast to bulk density, copper and sand. The second axis (eigenvalue = 3.96) is represented by CEC and exchangeable calcium as opposed to the pH content of the soils. Figure 6 represents the percentage contributions of the investigated soil properties in selected cocoa plantation chronosequence (CPC).

3.2 Selecting a minimum dataset (MDS) of soil degradation indicators

The PCA results presented thus far suggest that eight indicators (extractable zinc, silt, SOM, CEC, available phosphorus, total porosity, pH, and clay) can be used to assess soil degradation in the study area. However, the collection and analysis of such a large number of indicators is not viable for monitoring programmes covering extensive areas and the identification of key soil degradation indicators will be very useful. The eight soil properties were consequently subjected to forward stepwise discriminant analysis (STEPDA) to determine which of them are most important for soil degradation monitoring in the study area. Figure 7 and Table 4 show that STEPDA separated cocoa plantation chronosequence (CPC) into three groups (YCP, MCP and SCP), based on the explanatory variables (8 soil parameters) included in the model. The first discriminant function separates the MCP from YCP and SCP, while the second discriminant function separates YCP from MCP and SCP. The overall Wilks' lambda test (lambda=0.047; p<0.001) confirms that the means of the cocoa plantation chronosequence (CPC) were significantly different for the two discriminant functions.

Table 4 shows that the first discriminant function which accounts for more than 80% of the variance in soil properties is positively correlated with organic matter (0.952; p<0.001), extractable zinc (0.806; p<0.001), CEC (0.611; p<0.001), thus it is labelled *soil organic matter and macro nutrients* dimension. This result suggests that the plots in MCP have higher concentrations of soil nutrients than YCP and SCP. Similarly, the second discriminant function, which accounts for more than 19% of the variance in soil properties is positively correlated with CEC (0.622; p<0.001) and SOM (0.096), but negatively correlated with silt (0.520), clay (0.139), porosity

(0.309), zinc (0.527), and available phosphorus (0.035). This suggests that the YCP cases have poor physical soil properties compared to MCP and SCP. This function is labelled *soil physical and micronutrient dimension*.

The result of STEPDA confirmed that only four soil properties are significant in discriminating between the cocoa plantation chronosequence (CPC). These soil properties and their partial regression (R^2) are SOM (R^2=0.797, p<0.001; Wilks' Lambda=0.203), extractable zinc (R^2=0.548, p<0.001; Wilks' Lambda=0.259), CEC (R^2=0.379, p<0.001; Wilks' Lambda=0.432) and clay (R^2=0.169, p<0.05; Wilks' Lambda=0.866). The relative importance of these variables, as indicated by the length of their eigenvectors, is (in decreasing order) SOM, extractable zinc, CEC, and clay. Consequently, these four soil properties constitute a minimum dataset (MDS) of soil degradation indicators in our study area.

3.3 MDS normalization, transformation and integration into CSDI

The four selected indicators of the MDS were normalized and transformed into degradation scores (D) as described in Section 2.4. Weights were assigned to each degradation score using the result of the factor analysis (Table 2). As an example, the procedure to calculate the weighting factor for extractable zinc was as follows: the individual percentage variance for PC1 (23.70), was divided by 77.15%, the cumulative percentage of variation explained by all the retained PCs (Table 3), to yield the weight of 0.31. After assigning different weights to each parameter, they were integrated into a CSDI. This index is the sum of the normalised and weighted values of each parameter. CSDI was computed for each cocoa agroforests as:

$$\text{CSDI}= 0.21\ (\text{DSOM}) +0.31\ (\text{DZn}) + 0.21\ (\text{DCEC}) + 0.17\ (\text{DClay}) \qquad \text{(eq 6)}$$

Ordering the variables included in the equation as a function of the loading of the coefficient gave:

$$\text{CSDI}= 0.31\ (\text{DZn}) +0.21\ (\text{DSOM}) + 0.21\ (\text{DCEC}) + 0.17\ (\text{DClay}) \qquad \text{(eq 7)}$$

where, CSDI is the composite soil degradation index and DZn, DSOM, DCEC and DClay are the degradation scores of extractable zinc, organic matter, CEC and clay respectively.

3.4 Classification into degradation classes

Table 5 shows the soil degradation classification of CSDI scores by solving equation 5. In our case, μ and σ were calculated as 0.289 and 0.094 respectively, resulting in CSDI values of 0.195 when Z = -1 and 0.383 when Z = 1. Consequently, the CSDI classes are *Low* (<0.0195) and *High* (>0.383). CSDI values between 0.195 and 0.383 were regarded as *Moderate*. The interpretations of these classes is shown in table 6 (modified from Gómez et al. 2009). Most (65%) of the selected cocoa farms are moderately degraded, while 18% have a high degradation status (Table 5). A significant difference was observed in the degradation status of YCP, MCP and SCP (ANOVA test, $F_{2,39}$=57.59; P<0.001). Fig 8 shows that 30% of YCP, 53.33% of MCP, and 100% of SCP are moderately degraded. However, 70% of YCP is highly degraded and 47% of MCP show no sign of degradation. This implies that MCP plots are less degraded compared to YCP and SCP. This result is consistent with other studies in West Africa. For instance, Dawoe et al. (2014) reported that, in humid lowland Ghana, soil properties and quality parameters of a ferric lixisol improved under cocoa plantations that have been operating for 15-30 years and were better than that of young cocoa plantations with a three-year production age. Similar results were obtained by Tondoh et al. (2015), who reported that, in Côte d'Ivoire, there was a steady degradation of soil quality over time in full-sun cocoa stands planted on ferralsols for 10 years, but the degradation value was less pronounced in 20-

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year-old plantations. Comparing our results with those of Dawoe et al. (2014) and Tondoh et al. (2015) highlights the effects of poor and unsustainable land management practices on soil degradation in peasant cocoa agroforests in West Africa. Traditionally, cocoa plots are cultivated with food crops in the first three to five years of development until the canopies have formed. Given that smallholder cacao farmers in the study area do not use chemical fertilizers to improve soil quality, degradation of the physical, chemical and biological properties of cocoa soils are imminent during this phase of plantation establishment.

3.5 Statistical validation of CSDI

A canonical discriminant analysis (CANDA) was used to validate the CSDI classification. The values of the four soil properties (organic matter, extractable zinc, CEC and clay) were used as data input. Fig. 9 and Table 7 show that the three soil degradation classes (*low*, *moderate* and *high*) were significantly separated on the first and second canonical functions (Wilk's Lambda=0.156, $F_{6,68}$=13.04, p<0.0001). Of the total variance, 93.46% was accounted for by the first canonical function, which was significant at p<0.001. The second canonical function accounted for 6.54% of the total variance and was significant at P<0.005. Extractable zinc, organic matter and cation exchange capacity significantly contributed to the distinction among soil degradation classes and were positively associated with the first canonical function (Table 7). Clay also contributed significantly to the distinction among soil degradation classes, but was positively associated with the second canonical function (Table 7).

CANDA classification results in Table 8 reveals that the CSDI model performs reasonable well, showing a low level of misclassification. The table shows that for the original grouped cases, the CANDA correctly classified 6 of the 7 (85.7%) low, 23 of 26 (88.4%) moderate and all of the high cases. The implication of the CANDA accuracy assessment is that the proposed classes of soil degradation (*Low*, *Moderate* and *High*) were significantly separated by the four canonical variables included in the model and that the model can consequently be used with a high degree of confidence. Result from this study indicate that the CSDI can effectively be used to monitor and evaluate the degree of soil (Alfisols) degradation under cocoa plantation in the study area (and similar environments). However, more work is needed, to apply and evaluate the index on different soil types from different cocoa producing regions or countries.

4.0 Conclusions

In this study, we developed a composite soil degradation index (CDSI) to cost-effectively assess the status of soil degradation under cocoa agroforests. Of the initial twenty-two (22) soil properties evaluated, multivariate statistical analyses revealed that four (4) soil properties (extractable zinc, SOM, CEC and clay) were the main indicators of soil degradation. This minimum dataset (MDS) of soil degradation indicators was used to produce a CSDI, which was classified into three classes of degradation. According to this classification 65% of the selected cocoa farms are moderately degraded, 17.5% have a high degradation status and 17.5% show no sign of degradation. This classification corresponded well with a CANDA classification performed on the same dataset.

The findings suggest that the selection of a small set of relevant indicators will be more cost-efficient and less time consuming than using a large number of soil properties that may be irrelevant to the processes of degradation. They also suggest that soil degradation under cocoa agroforests (in this region at least) is mainly attributed to a decline in soil nutrient, loss of soil organic matter, increase in soil acidity and the breakdown of soil textural characteristics over time. This study shows that both physical and chemical soil properties are degraded under long-term cocoa production. The implications are serious for cocoa production sustainability on acidic Alfisols. Degradation of physical components of these soils portends serious risks to crop yields. Degradation of chemical soil properties, coupled with non-application of fertilizers, will likely exacerbate soil degradation processes. To prevent smallholder cocoa production from becoming unsustainable in the long-term, it is critical to advise farmers of the need for the application of artificial fertilizers, particularly under young cocoa plantations. Although the application of fertilizers will substantially improve the soil structure and nutrient conditions of cocoa soils, the poor transportation system in rural areas and prohibitive costs associated with artificial fertilizer application in cocoa groves remains a challenge to both farmers and government.

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Figure 1: Location map of the study area

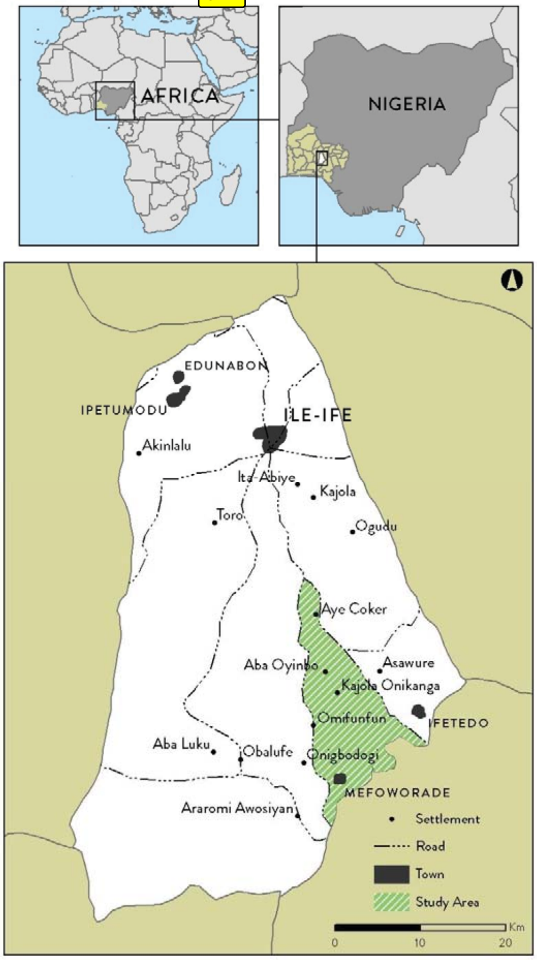

FIG 2. Analytical framework for development of CSDI

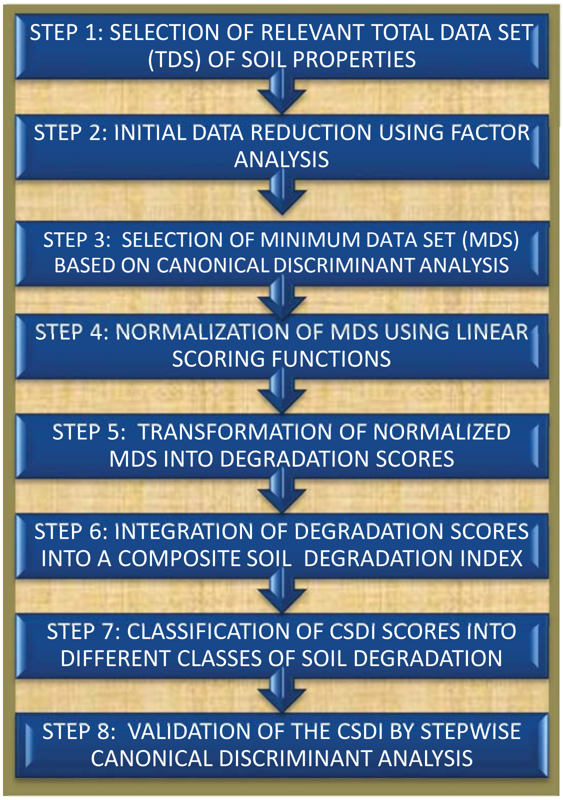

Figure 3: Scree test result from factor analysis

Solid Earth Discuss., doi:10.5194/se-2016-175, 2017
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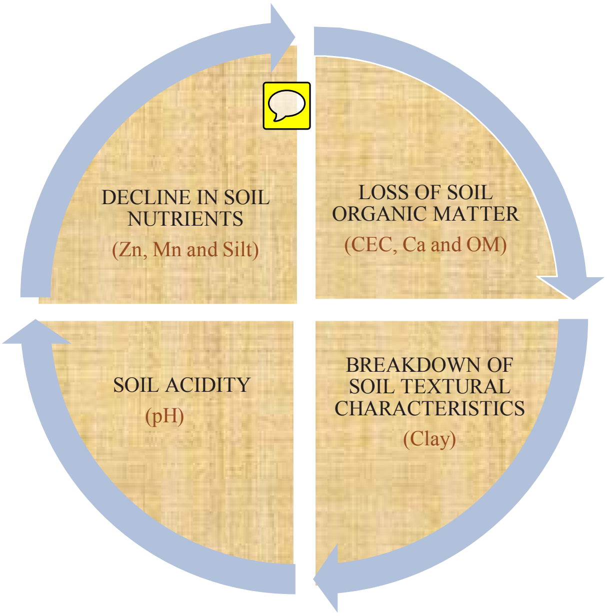
719 Fig 4. Soil degradation processes and indicators under cocoa agroforests in southwest

720



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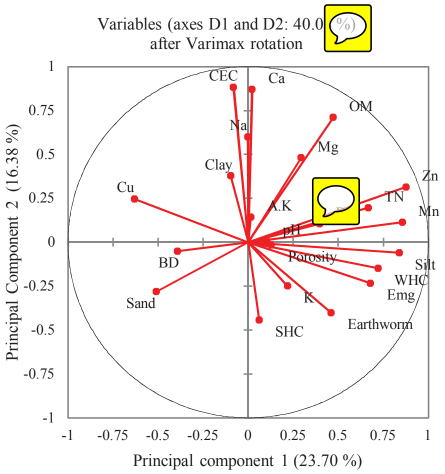

Figure 5: Principal Components' distribution of the investigated soil properties in age-sequenced peasant cocoa plantations. BD- Bulk density; WHC- Water holding capacity; SHC- Saturated hydraulic conductivity; OM- Organic matter; A.P – Available phosphorus; TN- Total nitrogen; Ca-Exchangeable calcium, Mg- Exchangeable magnesium; K- Exchangeable potassium; .Na- Exchangeable sodium; CEC- Cation exchange capacity; BS- Base saturation; Cu – Extractable copper; Zn- Extractable zinc; Mn- Extractable manganese ; EMg – Extractable magnesium; Earthworm population.

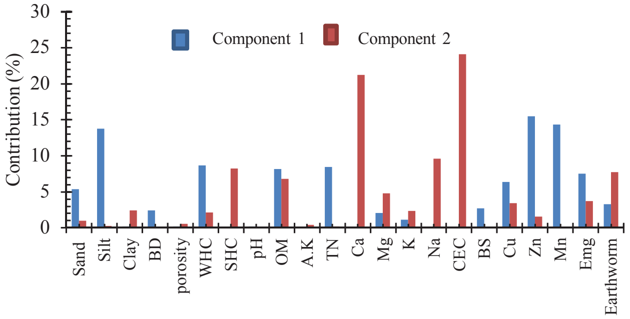

Figure 6. Percentage contributions of the investigated soil properties in age-sequenced peasant cocoa plantations.
BD- Bulk density; WHC- Water holding capacity; SHC- Saturated hydraulic conductivity; OM- Organic matter; A.P – Available phosphorus; TN-Total nitrogen; Ca- Exchangeable calcium, Mg- Exchangeable magnesium; K- Exchangeable potassium; .Na- Exchangeable sodium; CEC- Cation exchange capacity; BS- Base saturation; Cu – Extractable copper; Zn- Extractable zinc; Mn- Extractable manganese ; Emg – Extractable magnesium; Earthworm population

Figure 7: First and second discriminant function separating different cocoa plantations in southwest Nigeria

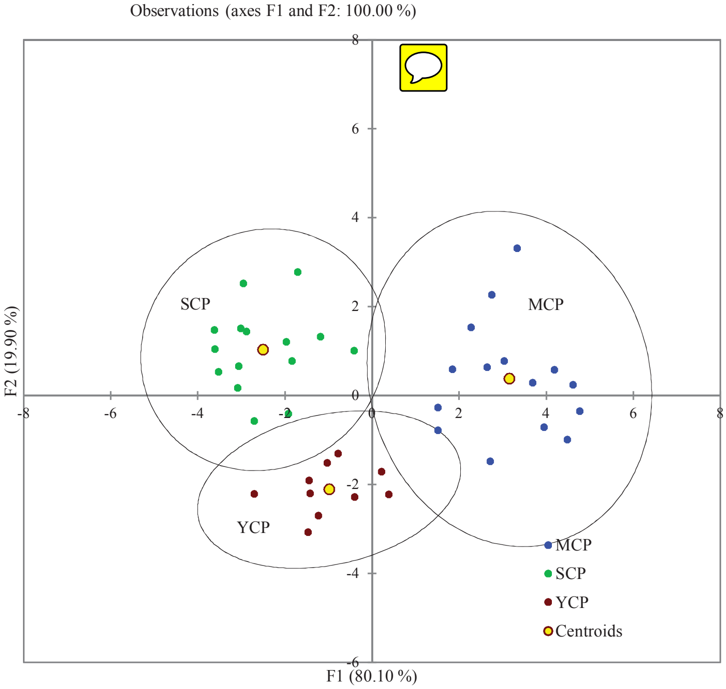

Figure 8 Percentages of degraded farms across cocoa chronosequence plantations (YCP, MCP and SCP)

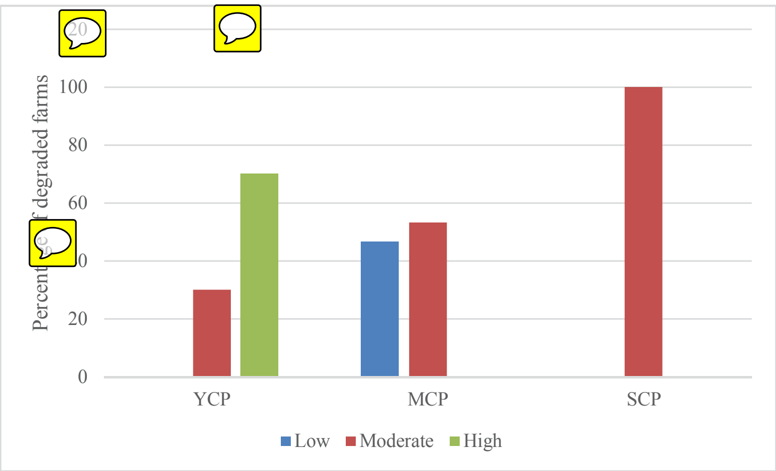

Figure 9. First and second canonical function of canonical discriminant analysis separating studied soils into three degradation classes (*Low, Moderate and High*)

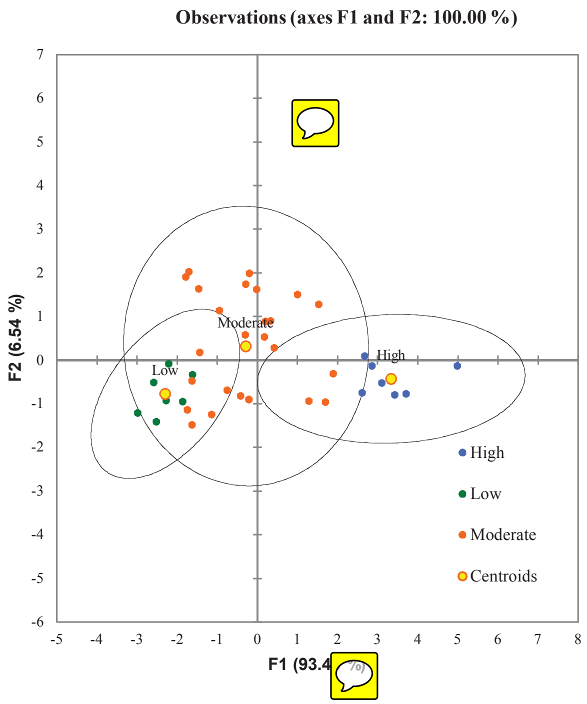

Table 1. Methods and field analysis of soil data

Soil properties	**Method of determination and reference**
Sand, silt and clay (%)	Pipette method (Gee & Or 2002)
Bulk density (g/cm^{-3}).	Core method (Grossman & Reinsch 2002)
Total porosity (%)	Computed from value of bulk density (Vomocil, 1965)
Water-holding capacity (%)	Oven dry method
Saturated hydraulic conductivity (cm hr^{-1})	Determined in the laboratory using a constant head permeameter (Reynolds & Elrick 2002)
pH (KCl)	Potentiometrically in 0.1 M $CaCl_2$ solution (Peech 1965)
Organic matter (%)	Walkley and Black (1934)
Available phosphorus (mg kg^{-1})	Olsen and Sommer 1982
Total nitrogen (%)	Kjeldahl method
Exchangeable Ca and Mg (mg kg^{-1})	Atomic absorption spectrophotometer
Exchangeable Na and K (mg kg^{-1})	Flame photometer
Cation exchange capacity (cmol$_c$ kg^{-1})	Summation method (Juo, *et al.* 1976)
Base saturation (%)	Calculated as the percentage of the CEC occupied by basic cations
Extractable Zn, Mn, Mg and Cu (mg kg^{-1})	Atomic absorption spectrophotometer
Earthworm population (per m^2)	Anderson & Ingram 1993

Ca= calcium; Mg= magnesium; Na = sodium; K= potassium; Zn= zinc; Mn= manganese; Cu= copper.

Table 2: Rotated factor loadings for the first five factors including proportion of variance, eigenvalues and communalities of measured soil properties

Eigenvalue	8.545	3.964	2.088	1.265	1.113	
Total Variance (%)	23.702	16.382	14.642	9.131	13.300	
Cumulative variance	23.702	40.083	54.725	63.856	77.155	

Soil degradation indicators	**Principal component, PC**					**Communalities**
	PC 1	**PC 2**	**PC 3**	**PC 4**	**PC 5**	
Sand (%)	-0.510	-0.282	-0.093	-0.094	-0.688	0.830
Extractable zinc (mg kg^{-1})	**0.875**	0.315	0.037	0.062	0.162	0.896
Extractable manganese (mg kg^{-1})	**0.857**	0.114	0.152	-0.007	0.313	0.868
Silt (%)	**0.838**	-0.060	-0.154	0.217	-0.014	0.777
Cation exchange capacity (cmol$_c$ kg^{-1})	-0.081	**0.884**	-0.124	-0.094	-0.067	0.816
Exchangeable calcium (mg kg^{-1})	0.022	**0.871**	-0.007	0.028	0.084	0.767
Organic matter (%)	0.472	**0.711**	0.142	-0.209	0.231	0.846
Available phosphorus (mg kg^{-1})	0.016	0.144	**0.810**	0.063	0.075	0.686
Total porosity (%)	0.128	-0.016	**0.801**	-0.087	0.233	0.719
pH (KCl)	0.104	0.008	-0.029	**0.791**	0.143	0.658
Clay (%)	-0.097	0.378	0.235	-0.070	**0.812**	0.871
Bulk density (g cm^{-3}).	-0.393	-0.051	-0.143	-0.633	0.055	0.582
Water-holding capacity (%)	0.721	-0.147	0.358	0.367	0.278	0.882
Saturated hydraulic conductivity (cm hr^{-1})	0.060	-0.442	0.603	0.480	0.204	0.835
Total nitrogen (%)	0.667	0.196	0.583	0.187	0.225	0.908
Exchangeable magnesium (mg kg^{-1})	0.295	0.481	0.260	0.079	0.508	0.650
Exchangeable potassium (mg kg^{-1})	0.219	-0.249	0.099	0.094	0.624	0.518
Exchangeable sodium (mg kg^{-1})	-0.001	0.601	0.032	0.289	0.393	0.600
Base saturation (%)	0.397	0.104	0.355	0.272	0.661	0.806
Extractable copper (mg kg^{-1})	-0.632	0.247	-0.382	-0.463	-0.168	0.849
Extractable magnesium (mg kg^{-1})	0.679	-0.232	0.518	0.210	0.078	0.834
Earthworm population (per m^2)	0.459	-0.401	0.552	0.144	0.282	0.776

Rotation method: Varimax with Kaiser normalization.
Boldface factor loadings are considered highly weighted;
Extraction method: principal component analysis.

Table 3: Correlation coefficient between highly weighted variables under PC's with high factor loading

PC 1 variables	Extractable zinc	Extractable manganese	Silt
Extractable zinc	1.000	0.834**	0.653*
Extractable manganese	0.834**	1.000	0.612*
Silt	0.653*	0.612*	1.000

PC2 variables	Cation exchange capacity	Exchangeable calcium	Organic matter
Cation exchange capacity	1.000	0.870**	0.523*
Exchangeable calcium	0.870**	1.000	0.619*
Organic matter	0.523*	0.619*	1.000

PC3 variables	Available phosphorus	Total porosity
Available phosphorus	1.000	0.578*
Total porosity	0.578*	1.000

PC4 variable	pH
pH	1.000

PC5 variable	Clay
Clay	1.000

* Significant difference at P = 0.05. ** Significant difference at P = 0.01.

Table 4: Result of stepwise discriminant analysis (STEPDA) separating YCP, MCP and SCP

	Discriminant function	
	1	**2**
Significance	0.000	0.000
Eigenvalue	6.826	1.696
% of variance	80.101	19.899
Cumulative % variance	80.101	100.000
Canonical correlation coefficient	0.934	0.793
Variables	**Canonical correlation coefficients**	
Silt	0.353	-0.520
Clay	0.373**	-0.139
pH	0.029	-0.211
Organic matter	0.952*	0.096
Cation exchange capacity	0.611*	0.622
Extractable Zinc	0.806*	-0.527
Available Phosphorus	0.186	-0.035
Porosity	0.158	-0.309

*, **, Significant at $p<0.05$ and $p<0.001$ respectively.

Table 5: CSDI value, classification and membership probabilities

CPC	CSDI Value	Z-Score value	Membership probabilities		
			Low	Moderate	High
YCP1	0.3693	0.8543	0.000	0.175	**0.825**
YCP2	0.3982	1.1615	0.000	0.040	**0.960**
YCP3	0.4421	1.6289	0.000	0.001	**0.999**
YCP4	0.4430	1.6379	0.000	0.001	**0.999**
YCP5	0.5261	2.5227	0.000	0.000	**1.000**
YCP6	0.3624	0.7807	0.000	0.209	**0.791**
YCP7	0.4238	1.4337	0.000	0.005	**0.995**
YCP8	0.4034	1.2173	0.000	0.030	**0.970**
YCP9	0.3591	0.7459	0.000	0.389	**0.610**
YCP10	0.3936	1.1131	0.000	0.071	**0.929**
MCP1	0.1916	-1.0359	0.471	**0.529**	0.000
MCP2	0.2175	-0.7604	0.410	**0.590**	0.000
MCP3	0.1977	-0.9715	**0.844**	0.156	0.000
MCP4	0.2333	-0.5931	0.426	**0.574**	0.000
MCP5	0.2386	-0.5359	**0.613**	0.387	0.000
MCP6	0.1757	-1.2051	0.449	**0.551**	0.000
MCP7	0.2790	-0.1068	0.012	**0.988**	0.000
MCP8	0.2669	-0.2347	0.046	**0.954**	0.000
MCP9	0.2584	-0.3256	0.078	**0.922**	0.000
MCP10	0.2564	-0.3463	0.030	**0.970**	0.000
MCP11	0.1187	-1.8117	**0.993**	0.007	0.000
MCP12	0.1836	-1.1217	**0.703**	0.297	0.000
MCP13	0.1645	-1.3246	**0.928**	0.072	0.000
MCP14	0.1476	-1.5039	**0.944**	0.056	0.000
MCP15	0.1367	-1.6203	**0.986**	0.014	0.000

CPC= Cocoa plantation chronosequence = YCP, MCP and SCP

Table 5 continue: CSDI value, classification and membership probabilities

CPC	CSDI Value	Z-SCORE value	Membership probabilities		
			Low	Moderate	High
SCP1	0.2331	-0.5948	0.100	**0.900**	0.000
SCP2	0.2949	0.0625	0.008	**0.977**	0.015
SCP3	0.2733	-0.1668	0.012	**0.988**	0.000
SCP4	0.2802	-0.0938	0.010	**0.989**	0.001
SCP5	0.3326	0.4636	0.000	**0.992**	0.008
SCP6	0.2851	-0.0411	0.003	**0.997**	0.000
SCP7	0.3242	0.3739	0.000	**0.996**	0.003
SCP8	0.2837	-0.0563	0.002	**0.998**	0.000
SCP9	0.3770	0.9365	0.000	**0.995**	0.005
SCP10	0.3520	0.6705	0.000	**0.930**	0.070
SCP11	0.2218	-0.7153	0.078	**0.922**	0.000
SCP12	0.2941	0.0539	0.001	**0.999**	0.000
SCP13	0.2589	-0.3200	0.007	**0.993**	0.000
SCP14	0.2918	0.0302	0.002	**0.998**	0.000
SCP15	0.2551	-0.3611	0.007	**0.993**	0.000

CPC= Cocoa plantation chronosequence = YCP, MCP and SCP

Table 6: Classification of soils into degradation levels and their interpretations modified after Gómez et al. (2009)

Range	Classes of degradation	Interpretation
< 0.195	Low	Farms with little or no form of degradation and their nutrient deficiencies can be restored with moderate effort
0.195 -0.383	Moderate	Farms with moderate soil quality degradation, where some action should be taken to improve soil conditions
> 0.383	High	Farms are currently degraded and their soil quality restoration will require sustained management efforts

Table 7: Standardized and unstandardized coefficient functions of canonical discriminant analysis

	Constant	Zn	OM	CEC	Clay
Function 1 $^{\Psi}$	-11.863	0.599*	1.225*	0.226*	0.054^{ns}
Function 2 $^{\Psi}$	-5.248	-0.326*	0.092 ^{ns}	0.214 ^{ns}	0.365 *
Classes of degradation					
Low	-145.980	6.851	10.885	6.634	3.977
Moderate	-104.651	5.889	7.806	5.776	3.459
High	-74.970	3.359	3.489	5.202	3.564

OM- Organic matter (%); CEC- Cation Exchange Capacity (cmol$_c$ kg^{-1}); Zn - Extractable zinc (mg kg^{-1}); Clay (%).

$^{\Psi}$ Wilks' lambda test of functions ($F_{observed}$ = 22.576 and $F_{critical}$ =2.499) shows that the discriminant model was significant at probability P=0.000, for the two functions, indicating that these functions contributed more to the model.

$^{\Psi}$ Eigen value for F1= 3.506 and F2 = 0.426;

Threshold for F1 is 0.2/√ 3.506 = 0.106; F2is 0.2/√ 0.426 = 0.30

* Significant;

^{ns} Not Significant

Table 8: Cross-validation results by canonical discriminant analysis

Case	Actual group	Discriminant analysis of classification of predicted group membership				
Original group	from \ to	Low	Moderate	High	Total	% correct
	Low	**6**	1	0	7	85.71%
	Moderate	2	**23**	1	26	88.46%
	High	0	0	**7**	7	100.00%
	Total	8	24	8	40	90.00%
Cross-validated						
	from \ to	Low	Moderate	High	Total	% correct
	Low	**6**	1	0	7	85.71%
	Moderate	2	**22**	2	26	84.62%
	High	0	0	**7**	7	100.00%
	Total	8	23	9	40	87.50%

Percent of “grouped” cases correctly classified =87.50%
Boldface figure in each group is number of cases correctly classified by canonical discriminant analysis