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

Sunday Adenrele Adeniyi; Willem Petrus de Clercq; and Adriaan van Niekerk

Dear Topical Editor (Antonio Jordan)

We thank you for your time and effort spent in dealing with our submission. In general, we are pleased by the positive and constructive comments of the four reviewers. Please find the comments of the reviewers attached, along with our responses below each comment (changes made to the manuscript are highlighted in red in the attached manuscript). We believe that we have suitably addressed the reviewers' comments and, by doing so, substantially improved the manuscript. We hope that you agree and that the revised manuscript will be considered for publication in Solid Earth.

Kind regards

Sunday Adeniyi and co-authors

Reviewer#1

Reviewer#1 is thanked for his/her constructive comments. Please find below our responses, along with our suggested amendments to the manuscript. We hope these revisions will address all of Reviewer#1's concerns.

(A) This paper showed great efforts by the authors to assess soil properties and degradation applying soil analysis, PCA on cocoa plantations. Results show alternatives to detect soil indicators and promote strategies during soil sampling and land planning/restorations. In this paper a relevant topic of soil science community is worked in a non-current study area in Nigeria. The methods present clear concepts and tools about soil properties in this potential land degraded area. I find the applied methods are correct and the obtained results are useful to use by the farmers and the soil science community. The results are sufficient to support the interpretation and conclusions, but the authors should work something more in some details. Some descriptions of the soil collected samples (please remark in the figure 1), soil analysis and descriptions (table 1) are not clear for me.

Response:

1. The map (Figure 1) was revised to include the locations of where soil sampling took place.

2. We kept Table 1 as is as a similar approach was followed in other papers published in *Solid Earth*. One example is Parras-Alcántara and Lozano-García, (2014). They also summarized their soil field measurements and analytical techniques in table form. This approach helps to reduce word count and maintain brevity. Advice from the editor is needed on this matter.

3 A reference was added to Table 1 as requested. We thank Reviewer#1 for bringing it to our attention.

(B) General comment

Title: I find the title no clear and no precise. Maybe, if authors considerer it, they would change it as I suggested. 2) Key words: good. Only little changes are suggested. 3) Abstract: good. 4) Introduction: The best part of the text, congratulations. I suggest a couple of references and that the authors put one decimal into the percentages (in all the text, all the figures and tables). 5) Methods: I find really interesting that the authors add pictures about the soil profiles or the plantations with different ages. 6) Discussion: Only, I suggest that add information about the last point of the conclusions. It is really important to discuss this point. Ok, we have an index, maybe the solution are fertilizers: which types? Are expensive? What use other researchers over the world? Only expensive fertilizers? 7) References: actual, complete and international reference list. 8) Figures and Tables: the worst part of the paper. The last three tables are really long and heavy. Please, add them as supplementary materials. Figure 1 would better with photos and the points with the soil samples. Take care with Excel and their graphics. Solid Earth is a high impact factor journal and requires professional graphics (any colours, any lines inside, the same scale. . .). Right now, for me the paper is accepted but with major revisions. I encourage the author to improve all the figures, tables and this point of the discussion (mandatory. . . it is the key of your paper!). Good luck and congratulations for this hard work!

R1.1 I find the title not clear and no precise. Maybe, if authors consider it, they change it as I suggested.

The title was revised to: "Development of a composite soil degradation assessment index for cocoa agro-ecosystems in southwest Nigeria".

R1.2 Key words: good. Only little changes are suggested.

The keywords were modified as suggested by Reviewer#1 and re-arranged in order of importance as suggested by Reviewer #2.

R1.3 Abstract: good.

R1.4 Introduction: The best part of the text, congratulations. I suggest a couple of references

A number of references were added as suggested.

R1.5 Authors put one decimal into the percentages (in all the text, all the figures and tables)

Done.

R1.6 Methods**:** I find really interesting that the authors add pictures about the soil profiles or the plantations with different ages

Given that focus of the study was on soil degradation within the topsoil (rooting layer) of cocoa agro-ecosystems, soil profile photographs were not recorded. Photographs of the plantations were recorded, but these will not add much value to the manuscript as they do not relate to the differences in soil quality. However, we can include some photographs on the editor's advice.

R1.7 Discussion: Only, I suggest that add information about the last point of the conclusions. It is really important to discuss this point. Ok, we have an index, maybe the solution are fertilizers: which types? Are expensive? What use other researchers over the world? Only expensive fertilizers?

The conclusion section was amended accordingly.

R1.8 References: actual, complete and international reference list.

R1.9 Figures and Tables: the worst part of the paper. The last three tables are really long and heavy. Please, add them as supplementary materials.

Most of the figures and tables were improved in the revised manuscript. We attempted to retain the most important figures (eight in total) and tables (seven in total) in the main text of the manuscript, but moved three of the larger tables to the supplementary material section for reference purposes.

R1.10 Figure 1 would better with photos and the points with the soil samples. Take care with Excel and their graphics. Solid Earth is a high impact factor journal and requires professional graphics (any colours, any lines inside, the same scale. . .). Right now, for me the paper is accepted but with major revisions. I encourage the author to improve all the figures, tables and this point of the discussion (mandatory. . . it is the key of your paper!). Good luck and congratulations for this hard work!

We added the location of sample points in Figure 1. The graphics were also improved as suggested.

Reviewer 2

Reviewer#2 is thanked for his/her constructive comments. Please find below our responses, along with our suggested amendments to the manuscript. We hope these revisions will address all of Reviewer#2's concerns.

RC2.1 Title: It sounds good. I like it as in the title the study area is mentioned

RC2.2 Abstract: The abstract was written well.

RC2.3 Keywords: Firstly, I suggest to write the order of key words based on alphabet or their importance. Secondly, I highly suggest to not having more than three words for each key word

The keywords were re-arranged in the revised version of the manuscript as suggested.

RC2.4 The introduction in line 75-97 is quite large, especially the first sentences which are very similar to previous paragraphs. Instead, I have two suggestions. At first, divided this paragraph into two paragraphs that one of them will talk about alteration of soil characteristics, and second one will talk about the statistical approaches, which the authors used. Secondly, I suggest to authors to write a full paragraph regarding multivariate analysis, such as PCA, FA . . ...., and the statistical methods which they have used

The introduction was amended as suggested by the reviewer.

RC2.5 Materials and methods This section was explained very well. However, the authors should mention geographical location of the study area in degrees minutes seconds format. And in the Figure 1, the authors can also add grid using Graticule in ArcGIS desktop

We thank the reviewer for this comment and insightful suggestion. We gave the coordinates of the location of the study area to degrees, minutes and seconds format as suggested. A graticule was also added to Figure 1 as suggested.

RC2.6 Results and Discussion: Results are descripted well; however, Discussion of some parts is weak, especially 3.3 and 3.5 sections

Sections 3.3 and 3.5 were amended as suggested.

RC2.7 Figures and Tables: The quality and performance of figures are not very good, so they should be improved.

The quality of the figures were improved in the revised manuscript.

R2.8 The words "Table" and "Figure" in the text should be capitalized and written completely, no abbreviation

Done.

R2.9 Reference: Unfortunately, the review literature is not new, just one reference in the year 2016, while there a great number of publication regarding soil degradation in 2016 and 2017. Therefore, I highly suggest to add new references from very good journals, such as Land Degradation & Development, Catena, Geoderma and so forth.

We added recent literature as recommended. Some of these sources are from *Soil, Solid Earth, Land Degradation & Development, Catena, Geoderma; Soil and Tillage Research* and so forth.

RC2.10 To sum up, to me the paper needs major revision before publishing. I hope my comments contribute the authors to improve the manuscript

We sincerely thank the reviewer for his suggestions and word of encouragement on our re-submission.

Reviewer#3

Reviewer#3 is thanked for his/her constructive comments. Please find below our responses, along with our suggested amendments to the manuscript. We hope these revisions will address all of Reviewer#3's concerns.

RC3.1. I consider the title of the paper adequate except the use of agroforests. I suggest the word "ecosystems" instead.

The title was revised to: "Development of a composite soil degradation assessment index for cocoa agro-ecosystems in southwest Nigeria" to accommodate this insightful suggestion.

RC3.2 The abstract is well written. The introduction of the paper is comprehensive highlighting the major aspects of soil degradation such as processes, factors and consequences. Furthermore, it shows the familiarity of the authors to the issues of soil degradation under tree crops in the tropical areas with up-to-date literature.

RC3.3 The study area is clearly indicated

RC3.4 Methodology, in terms of sampling, data collection, data analytical procedures and statistical analyses, is quite adequate. Data collection, analytical procedures and statistical analyses, is quite adequate

RC3.5 The presentation of results and discussion is academic and of value and relevance to future management of cocoa ecosystems and similar plant systems especially in the tropical areas

RC3.6 General Line 67: Theobroma cacao should be in italics.

Agreed. Theobroma cacao was changed to *Theobroma cacao* throughout.

RC3.7 Line 143: Phytophthora Sp. should be in italics.

Agreed. We apologize for this oversight. Phytophthora Sp. was changed to *Phytophthora Sp.* throughout.

RC3.8 Line 150: YCP, MCP and SCP to be defined.

YCP, MCP and SCP were defined earlier in lines 102 and 103.

RC3.10 9 Lines 159, 160 and 161: The word quadrant should be quadrat.

Thank you for this correction**.** The word quadrant has been changed to quadrat.

RC3.11 Line 180: fig.2 should be Fig.2

Corrected.

RC3.12 Line 369: Result…indicate to be Result…indicates

Corrected.

Reviewer#4

Reviewer#4 is thanked for his/her constructive comments. Please find below our responses, along with our suggested amendments to the manuscript. We hope these revisions will address all of Reviewer#4's concerns.

RC4.1 Introduction part is written comprehensively.

RC4.2 Materials and Methods, Results and Discussions, and Conclusions need some revision particularly in the selection of minimum data set (MDS) and its statistical correlation part. The paper has thoroughly been reviewed and observed that, in its present form it may not finds its suitability for publication hence, may be asked to submit after incorporating following specific comments

Specific comments

RC4.3 Site selection/Soil sample collection for laboratory analysis: Line 146, 154 & 159: Statement given contradicts each other. Because, reconnaissance soil survey was done during March-April 2013, whereas soil sampling was done in May 2013. Further, research plots were visited several times: for what and when?

The term "reconnaissance" was not intended to be understood as being part of the actual soil sample collection activities. The "reconnaissance" survey was merely a visit to the area to better understand where soil samples should be taken. We recognize that the way it was previously formulated in the manuscript was misleading. We consequently deleted the statement "reconnaissance soil survey was done during March-April 2013" and replaced it with "The study area was visited in March and April 2013 to identify suitable cocoa agroecosystem and locate candidate sample sites".

RC4.4 Line 149: Cocoa stands of different ages is not clear

The word "stands" was substituted with "agro-ecosystems" for clarity.

RC4.5 Line 150: Size of each plot not mentioned. No information provided about spacing between cocoa plants in each plot and is there and inter crop or vegetation exists in the study plots

For the purpose of this study, cocoa agro-ecosystems were conceived as areas where cocoa trees co-exist with other (fruit and timber) tree species on the same plot of land. These trees are of economic importance to the farmers. They also provide shade to the cocoa trees. The selected cocoa agro-ecosystems are between 2 and 3 ha in size, with a tree spacing of 3 x 3 meters as recommended for good agricultural practices (GAP) for sustainable cocoa production in West Africa sub region. This information was added to our revised manuscript under the site selection section.

RC4.6 Line 162 & 166: The cacao tree can be as tall as 8-12 m with tap-roots about 1.5 to 2 m deep. Hence, soil sampling should be for both surface soil (0-30 cm) & sub-surface soil (30-60 cm).

We restricted our soil sample to topsoil (i.e. 0 to 20 cm) because several studies (e.g. Isaac et al 2007) demonstrated that the cacao tree tends to have shallow root activity within the topsoil (0-20 cm). Also, the soil degradation index developed in this study is expected to be used by farmers and extension officers in rehabilitation of degraded cocoa plantations in the study area and similar environments. By confining the samples to the topsoil the likelihood of adoption by the farmers and extension officers is greater. This aspect is now better explained in the revised manuscript.

RC4.7 As cocoa plantation was developed under Slash & Burn (shifting cultivation) area having humid tropical climate in rain forest area with more than 1400 mm rainfall, parameter related to soil erosion is essential to assess the soil degradation processes due to surface soil losses every year

The word “slash & burn” was erroneously used in the manuscript as it is not the practice in the study area (although it does occur in other cacao producing areas). The paragraph was reworded to reflect the actual practice of establishing cocoa agroforests in the study area. We also added an explanation that the floors of the cocoa agro-ecosystems in the study area are usually covered with leaves and plant litter to prevent soil erosion. During the field visits no evidence of substantial soil erosion was observed.

RC4.8 Nitrogen, potassium and base saturation are important parameters which reflect the nutrient status of the soil in relation to plant growth. Changes in these indicator reflected the combined effects of soil quality. These parameters have PC value more than >0.60 as per Table 1 and need to be included as minimum data set (MDS) in addition to Fe for better reflection of soil degradation scenario.

We agree that nitrogen, potassium and base saturation are important parameters for reflecting the nutrient status of soil in relation to plant growth. However, these soil properties were not included in the final MDS because our data analysis (Principal Component Analysis) did not support their inclusion. The criterion for selecting minimum data set (MDS) of soil quality and degradation indicators was described in lines 188 to 191. This criterion is in line with standard practices found in the literature (e.g. Andrews et al. 2002). In addition, including these parameters in the MDS would have introduced redundancy owing to their strong correlation with SOM, Ex Zn, Clay and CEC. For example, a strong and positive correlation (0.717; correlation coefficients were added to the supplementary material section) between Nitrogen and Extractable Zinc was observed in our data.

RC 4.9 Table 2, Table 3 and Table 4 should be rearranged in the order of (i) physico-chemical properties (BD, WHC, porosity, Base saturation, pH, EC & clay content), (ii) chemical properties (N, P, K, Ca, Mg, Fe, Zn, Cu, Mn & Na), and (iii) biological properties (org. C, Earthworm population)

The table was re-arranged as suggested.

RC4.10 In case of micronutrients, only Zn, Cu & Mn were included. What is the reason of excluding iron (Fe) which is most important micronutrients besides Zn. Cu and Mn may not be very important as soil is acidic

We fully agree that micronutrients (Zn, Cu, Mn, Fe, B and Mo) often limit crop growth, especially in soils that are continuously cropped without returning these nutrients. Fe was deliberately not included because:

(i) A recent review of the literature on mineral nutrition (e.g. Van Vliet and Giller, 2017) indicated that Fe is not a limiting micronutrient in cocoa based farming systems. Similar observation was made by Ogeh and Ipinmoroti (2013).

(ii) Rousseau et al. (2012) showed that Fe was not a candidate soil property for inclusion in an MDS used in cacao-based agroforestry systems (AFS).

(iii) Several studies have highlighted Zn deficiency African soils (Vanlauwe et al. 2015); and in cocoa soils (Van Vliet and Giller, 2017; Ogeh and Ipinmoroti, 2013). Consequently Zn is a more appropriate micronutrient to include.

RC4.11 Correlation coefficient given in Table is not appropriate as per relationship of different physico-chemical properties of soils. Correlation required to be done in following manner to get a real relationship: - Micronutrients (Fe,Zn,Cu, Mn), P and Ca Vs pH - CEC and Porosity Vs Clay and Org. C

The table under reference was deliberately included to show the strength of relationship among the eight (8) “highly important” soil parameters identified using PCA. This is common practice in the literature. However, we agree that it is important to include the correlation coefficients of all the 22 soil quality parameters investigated. A table with this information was consequently added to the supplementary material for reference.

RC4.12 Information on average value (in range) of all the parameters analysed/studied is not provided for checking the actual fertility status of soil of the study area. This need to be included

A table with this information is now included in the supplementary material.

RC4.13 Fig 4 may be deleted

The figure was deleted as suggested.

RC4.14 Table 1: In sand, silt and clay analysis (%): write International Pipette method. This is very old method and reference given is of year 2002.

The international Pipette Method (Piper, 1966) is well known to us. However, analysis of particle size distribution (% sand, silt and clay) using pipette method as described by Gee & Or (2002) was used in this study. A similar approach was used by Fisher et al. (2017).

RC4.15 Please check all the references and its style as per journal again

Done.

RC4.16 Keeping in view the relevance and dimensions of the study, Results & Discussion, Conclusions & Abstract need to be revised. Author(s) may be asked to resubmit it after taking care of all the grey areas

The results & discussion, conclusions & abstract were revised.

Additional references

(a) Fisher, K.A., Yarwood, S.A. & James, B.R. (2017). Soil urease activity and bacterial ureC gene copy numbers: Effect of pH. *Geoderma*. 285:1–8.

(b) Isaac, M. E.Timmer, V. R. and Quashie-Sam, S. J. Shade tree effects in an 8-year-old cocoa agroforestry system: Biomass and nutrient diagnosis of Theobroma cacao by vector analysis; Nutrient Cycling in Agroecosystems, 78, 155-165, 2007

(c) Ogeh, J S and Ipinmoroti, R R,.: Micronutrient assessment of cocoa , kola , cashew and coffee plantations for sustainable production at Uhonmora , Edo State , Nigeria, Journal of Tropical Soils, 18, 2; 1-5, 2013.

(d) Parras-Alcántara l., and Lozano-García, B.: Conventional tillage versus organic farming in relation to soil organic carbon stock in olive groves in Mediterranean rangelands (southern Spain), Solid Earth, 5, 299–311, 2014

(e) Rousseau, G.X., Deheuvels O., Rodriguez Arias I., and Somarriba E.: Indicating soil quality in cacao-based agroforestry systems and old-growth forests: The potential of soil macrofaunal assemblage, Ecological Indicators 23, 535-543, 2012

(f) Snoeck, D Afrifa, A AK, Ofori-Frimpong, Boateng, E, Abekoe, M K,: Mapping Fertilizer Recommendations for Cocoa Production in Ghana Using Soil Diagnostic and GIS Tools West African Journal of Applied Ecology, 17, 97-107, 2010

(g) Vanlauwe, B., Descheemaeker, K., Giller K. E., Huising, J., Merckx, R., Nziguheba1, G., Wendt, J., and Zingore, S.: Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation SOIL, 1, 491–508, 2015

(h) Van Vliet, J. A., and Giller, K, E.: Mineral nutrition of cocoa: A review, Advances in Agronomy, 141, 185-270, 2017

Development of a composite soil degradation assessment index for cocoa agro-ecosystems~~forests under tropical conditions of~~ in southwest Nigeria

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Abstract. Cocoa agro-ecosystems ~~forestry~~ 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 agro-ecosystems ~~forests~~ of southwest Nigeria. Plots where natural forests have been converted to cocoa agro-ecosystems ~~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 to -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, soil organic matter (SOM), cation exchange capacity (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; SOM ~~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~~ sufficiently eliminated 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,~~ Tthe numerical value of the CSDI as an objective index of soil degradation under cocoa agro-ecosystems~~forests~~ was statistically validated. The results of this study reveal that soil management should promote activities that help to increase organic matter and reduce Zn deficiency over the cocoa growth cycle. Finally, the newly developed CSDI can provide an early warning of soil degradation processes and help farmers and extension officers to implement rehabilitation practices on degraded cocoa soils.

Keywords: ~~Smallholder~~ cocoa agro--ecosystems~~forests~~, age-sequenced plantations, minimum data set, degradation indicators, ~~composite soil~~ degradation assessment index, tropical conditions, southwest Nigeria.

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). Studies have reported 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) Krasilnikov et al., 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; Rodrigo Comino et al., 2016 a&b; Xu et al., 2016); 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) (Jordan et al., 2010; Novara et al., 2011); reduction in the activity of soil microorganisms (Lal, 2009); and soil compaction (Pulido et al., 2017); and unsustainable agricultural practices (Krasilnikov et al., 2016). 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.) agroecosystem 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;

Salami, 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 agro-ecosystems~~forests~~ 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), CEC ~~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 and Ogidiolu, 1989; Hadgu et al., 2009; Thomaz and 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; María José Sione et al., 2017). To overcome this shortcoming, an integration of soil properties into numeric indices has been proposed (Doran and Parkin, 1994; Leirós et al., 1999; Bastida et al., 2006, Gómez et al., 2009; Puglisi et al., 2005, 2006; Sharma et al., 2008; Xu et al. 2016;Pulido et al., 2017).

Multivariate statistical techniques such as- principal component analysis (PCA), canonical discriminant analysis (CDA), cluster analysis (CA), partial least squares (PLS), principal component regression (PCR), ordinary least squares regression (OLS) and multiple linear regression analysis (MLRA) have been applied to assess soil quality (Parras-Alcántara and Lozano-García, 2014; Xu et al., 2016; María José Sione et al., 2017; Biswas et al., 2017; Renzi et al., 2017; Khaledian et al., 2017). These statitical techniques can assist researchers to select important soil quality indicators that are useful to develop an overall soil quality or degradation index for effective land resource management and planning (Khaledian et al., 2017). Regardless of the techniques used, the selection of a minimum data set (MDS) of soil quality and degradation parameters has been widely supported in the literature (Biswas et al., 2017). For instance, María José Sione et al. (2017) used a soil quality index to evaluate the impact of rice production systems that use irrigation with groundwater on soil degradation at the field scale in Argentina. They selected six soil quality indicators including aggregate stability, water percolation, SOM, exchangeable sodium content (ESC), pH, and electrical conductivity in saturated paste extract. Their results showed that the use of soil quality indicators can provide an early assessment of soil degradation processes and help land managers to implement soil conservation practices (María José Sione et al., 2017). In South Asia, Biswas et al., (2017) combined PCA and multiple regression analysis to create MDS of physical, chemical and biological indicators which were integrated to develop a unified soil quality index (SQI) for rice-rice cropping systems. Thus, Sánchez-Navarro et al., (2015) developed an overall SQI ~~soil quality index~~ suitable for monitoring soil degradation in semi-arid Mediterranean ecosystems.(Pulido et al., (2017) developed a soil degradation index for rangelands of Extremadura ~~SW~~ Southwest Spain based on six indicators, namely CEC ~~cation exchange capacity (CEC)~~, available potassium, SOM ~~soil organic matter (SOM)~~, water content at field capacity, soil depth and the thickness of the Ah-horizon. Another example is Gomez et al., (2009) who developed three soil degradation indexes (obtained through a PCA ~~principal component analysis (PCA)~~) of ~~the~~ soils under organic olive farms in southern Spain. One of the indicesex used only three soil properties, namely organic C, water stable macroaggregates, and extractable P. According to these authors, this index ~~has~~ had the highest potential to be used as a relatively easy and inexpensive screening test of soil degradation ~~in organic olive farms in southern Spain.~~ Very little ~~Till date, less~~ attention has been given to the development of numeric indices for monitoring soil degradation under crop-specific landuse management systems in tropical countries. ~~Whereas,~~ ~~s~~Such indices can serve as the basis for integrating and interpreting several soil measurements, thereby indicating whether a particular landuse management system (e.g agro-ecosystems) is sustainable or not.

Therefore, ~~T~~the aim of the present study is to develop a CSDI ~~composite soil degradation assessment index (CSDI)~~ for shaded cocoa ~~agroforests~~ agro-ecosystems under tropical conditions in southwest Nigeria. This area is currently suffering from soil degradation arising from low input cocoa agro-ecosystems. ~~cocoa based agroforests under a "slash and burn" farming system.~~ Soil conditions under age-sequenced peasant cocoa ~~agroforests~~ agro-ecosystems are investigated. The cocoa agro-ecosystem ~~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 goals ~~specific objectives~~ are to: (i) ~~to~~ identify the most important soil degradation processes ~~associated with shaded cocoa agroforestry in the study area~~; (ii) ~~to~~ select a MDS ~~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 rehabilitating ~~on of~~ degraded cocoa soils in southwest Nigeria (and similar environments).

2.0 Materials and ~~M~~methods

2.1 Study area

This study was carried out in the Ife region, southwest Nigeria between $6^0$50' 27''N –7^0 38'33''N and 4^0 21'33'E–4^0 45'55''E (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~~ 2014)~~,~~ or Luvisols (WRBSR, 2014) (~~World Soil Reference, 2006)~~ and locally known as Egbeda Association (Smyth and ~~&~~ Montgomery, 1962). The area of study lies within the Egbeda soil series, characteriz~~s~~ed 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 farmers ~~agroforests~~ in the region ~~were~~ traditionally established ~~using "slash and burn" approach (Tondoh et al. 2015; Ngo-mbogba et al. 2015),~~ their cocoa farms by planting cocoa trees where primary or secondary forests are selectively cleared. Cocoa trees are then ~~burned and cocoa is~~ planted along with understory food crops and a range of forest or fruit tree species (Isaac et al., 2005; Jagoret et al., 2017). Although some ~~F~~farmers have recently shifted towards full-sun cocoa plantations ~~agroforestry~~, particularly in areas where natural forest is scarce (Oke and Chokor, 2009), ecological changes associated with such land use transitions are yet to attract research attention. Cocoa trees in agro-ecosystems 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~~ The study area was visited in March and April 2013 to identify suitable cocoa agro-ecosystems and locate candidate sample sites. ~~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 agro-ecosystems ~~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). For the purpose of this study, cocoa agroecosystems are conceived as areas where cocoa trees co-exist with other tree species on the same plot of land. Some tree species identified within selected cocoa agro-ecosystems include kola (*Cola acuminata and Cola nitida*) and oil palm (*Elaeis guineensis). These trees are of economic importance to the farmers. They also provide shade to the cocoa trees. The selected cocoa agro-ecosystems are between 2 and 3 ha in size, with a tree spacing of 3 x 3 meters as recommended by the good agricultural practices (GAP) for sustainable cocoa production in West Africa sub-region. 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 at least once ~~several times~~ before soil sampling. During the field visits no evidence of substantial soil erosion was observed on any of the plots, as the floors of the selected cocoa agro-ecosystems are covered with leaves and plant litter. ~~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~~ quadrat measuring 1000 m^2 was demarcated at the centre of each cocoa agro-ecosystem~~plantation~~. Each ~~quadrant~~ quadrat was subdivided into ten 100 m^2 ~~sub-quadrants~~ sub-quadrats and serially labelled. Soil samples were drawn at the centre of the even-numbered ~~sub-quadrants~~ sub-quadrats, resulting in a total of five soil samples per plot. Measurements were deliberately restricted to a depth of ~~the top~~ 0 to –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; Tondoh et al., 2015); (ii) these depths cover the main distribution of roots and soil nutrient stocks of cocoa plantations (Hartemink, 2005), and is therefore usually used in soil surveys for fertilizer recommendations in West Africa cocoa-based agro-ecosystem (Snoeck et al., 2010); (iii) several studies (e.g. Isaac et al, 2007) demonstrated that cacao trees tend to have shallow root activity within the topsoil (0-20 cm); (i~~ii~~v) biological processes, such as earthworm activities are restricted to 0-10 cm layer of tropical soils; (~~iv~~v) to facilitate future replication of the methodology as routine soil samples are usually taken from ~~kept at~~ the topsoil ~~top-soil~~ layer (plough layer); and (vi) the soil degradation index developed in this study is expected to be used by farmers and extension officers for rehabilitating degraded cocoa plantations in the study area and similar environments, by confining the samples to the topsoil the likelihood of adoption by the end users is greater.

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 BD ~~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 BD ~~bulk density (BD),~~ WHC ~~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, and average values (in range) of all the soil degradation parameters considered are provided in Table S1(supplementary material).

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~~. Figure 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 PCA ~~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, BD ~~bulk density~~, pH, soil aggregate stability, CEC ~~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 ($r^2 > \pm 0.70$; $p<0.05$), the one with the highest factor loading (absolute value) was retained (Andrews and 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:

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

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 SL 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~~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 (CDA). ~~(CANDA)~~. CDA ~~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 CDA ~~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 (see supplementary Table S2 for detail). 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, CDA~~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~~ 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 TN ~~total nitrogen~~, 77% in silt, 83% in magnesium, 83% in sand, and 58% in BD~~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 TP ~~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 4 ~~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 TN ~~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~~ Figure 5 represents the percentage contributions of the investigated soil properties in selected cocoa plantation chronosequence (CPC).

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

The PCA results presented thus far suggest that eight indicators (extractable zinc, silt, SOM, CEC, available phosphorus, TP ~~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 STEPDA ~~stepwise discriminant analysis (STEPDA)~~ to determine which of them are most important for soil degradation monitoring in the study area. ~~Figure 7~~ Figure 6 and Table 4 show that STEPDA separated CPC ~~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 CPC ~~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 CPC ~~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 MDS ~~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 agro-ecosystems~~forests~~ as:

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

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

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

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.

One significant result from this study is that Zn was identified as the most important degradation indicator and play a key role in maintaining soil quality in the study area. Zn deficiency has been widely reported in agricultural soils in Africa (Vanlauwe et al., 2015), and cocoa is highly sensitive to Zn deficiency (Ogeh and Ipinmoroti, 2013; Van Vliet and Giller, 2017). Our results suggest that there is a Zn deficiency in the study area with potential effect on the growth and yield of cocoa over time.

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~~ Table 5 (modified from Gómez et al., 2009). Most ~~(65%)~~ of the selected cocoa agro-ecosystems~~farms~~ (65%) 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; Table not shown). ~~Fig 8~~ Figure 7 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 YCP ~~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-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 agro-ecosystems ~~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 CDA ~~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~~ Figure 8 and Table 6 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 CEC ~~cation exchange capacity~~ significantly contributed to the distinction among soil degradation classes and were positively associated with the first canonical function (Table 6) . Clay also contributed significantly to the distinction among soil degradation classes, but was positively associated with the second canonical function (Table 6).

~~CANDA~~ CDA classification results in Table 7 reveals that the CSDI model performs reasonable well, showing a low level of misclassification. The table shows that for the original grouped cases, the CDA ~~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~~ CDA 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 indicates 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). Nevertheless, the results of this study confirm that composite indicators, which are intended as tools for assessing the state and evolution of complex and multifaceted environmental phenomena (OECD,2008), are generally easier to interpret than an array of individual indicators (Renzi et al., 2017). Therefore, the CSDI developed in this study represents a promising methodology for assessing soil degradation in cocoa agro-ecosystem. More work is needed to apply and evaluate the index on different soil types from different cocoa producing regions ~~or~~ and 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 agro-ecosystems ~~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 MDS ~~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 agro-ecosystem~~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 agro-ecosystems ~~production~~. The implications are serious for sustainability of cocoa agro-ecosystem ~~production sustainability~~ on acidic Alfisols. While, d~~D~~egradation of physical components of these soils portends serious risks to crop yields, degradation ~~. 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 (organic) fertilizers, particularly underYCP ~~young cocoa plantations~~. Obviously, ~~Although the~~ application of organic fertilizers will substantially improve the soil structure and nutrient conditions of cocoa soils (Van Vliet and Giller, 2017) but 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. Therefore, alternative fertilizers in term of organic residues, with potential of increasing organic matter has been proposed in recent times (Van Vliet & Giller, 2017). Studies have reported that addition of organic plant residues to crop soils helps to improve soil structure (Jordan et al.2010). In addition, animal manures can be added to cocoa soils, but the potential effect on cocoa yield is yet to be reported in the literature. Although this study sets a basis for soil quality monitoring, more work is needed to improve our knowledge of changes in soil quality/health under cocoa agro-ecosystem of different ages. Hopefully this will lead to much-needed evidence-based recommendations for rehabilitation of degraded cocoa soils in West Africa.

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Supplementary data associated with this article are also provided

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Figure 1: Location map of the study area

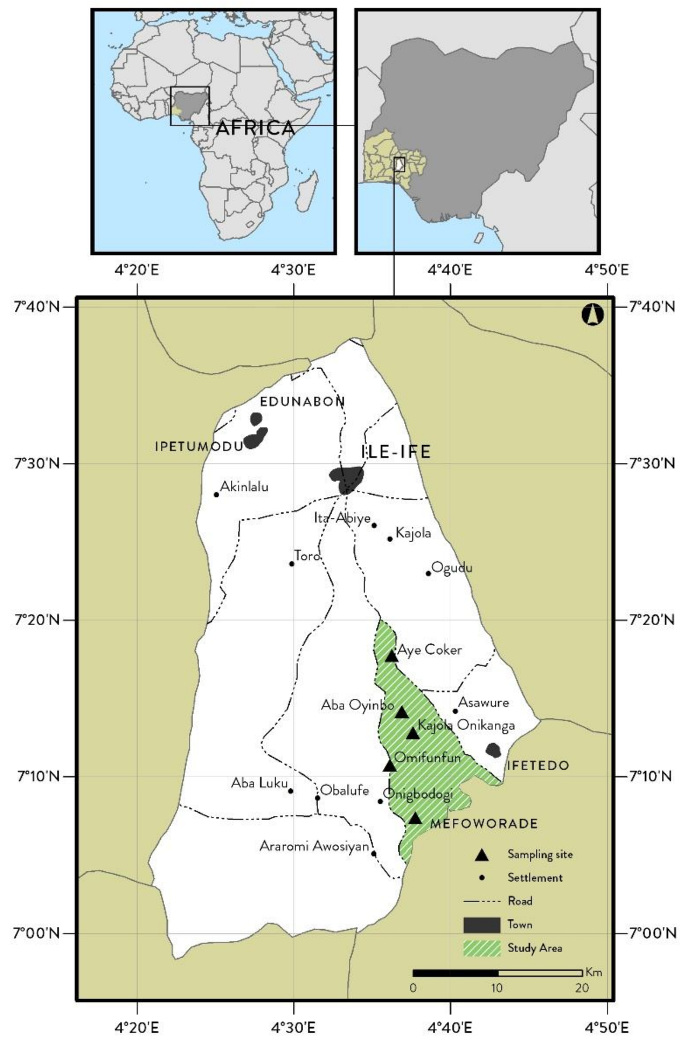


Figure 2. Analytical framework for development of CSDI

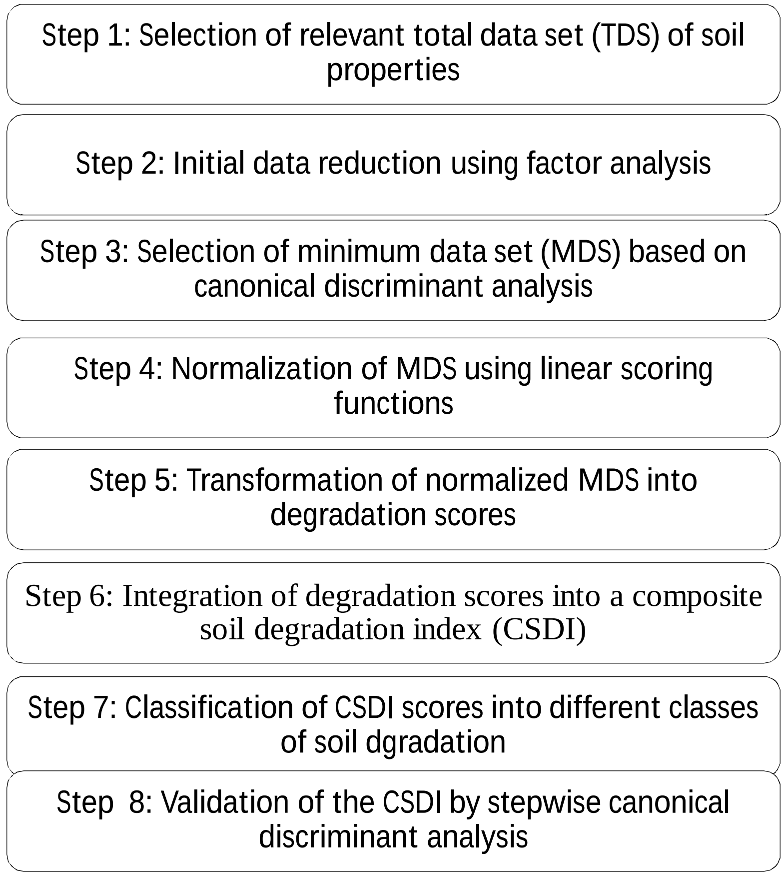
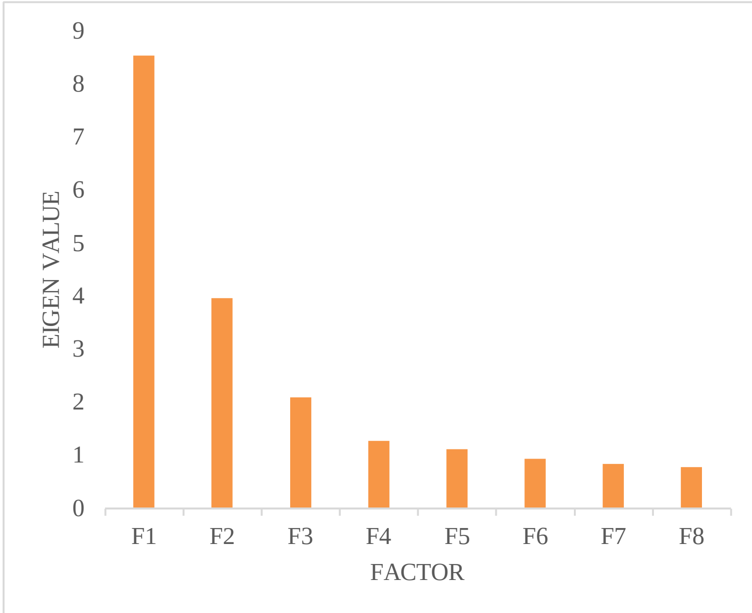


Figure 3: Scree test result from factor analysis



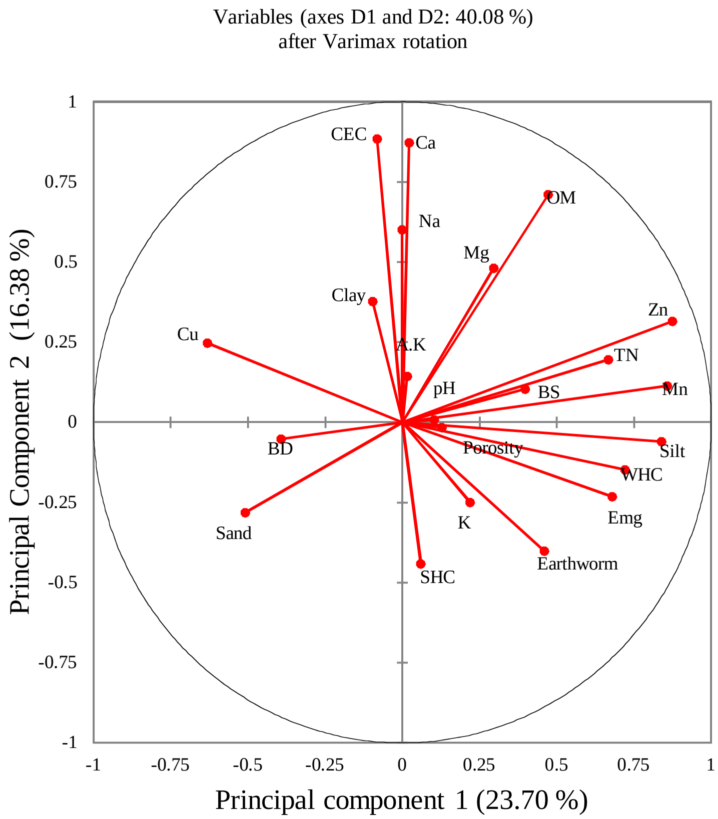


Figure 4~~5~~: Principal Components' distribution of the investigated soil properties in age-sequenced peasant cocoa plantations. BD- Bulk density; WHC- Water holding capacity; SHC- Saturated hydraulic conductivity; OM- Organic matter; A.P – Available phosphorus; TN-Total nitrogen; Ca-Exchangeable calcium, 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.

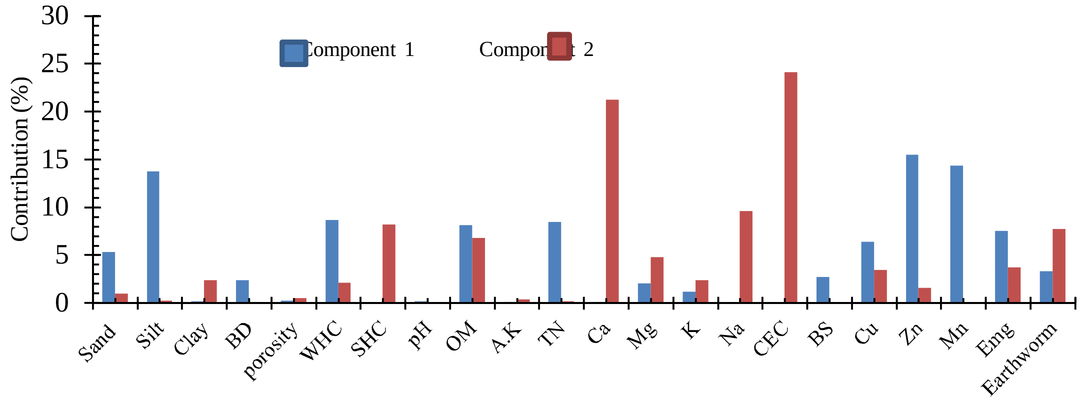


Figure 5. Percentage contributions of the investigated soil properties in age-sequenced peasant cocoa plantations.BD- Bulk density; WHC- Water holding capacity; SHC- Saturated hydraulic conductivity; OM-Organic matter; A.P – Available phosphorus; TN-Total nitrogen; Ca-Exchangeable calcium, Mg- Exchangeable 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.

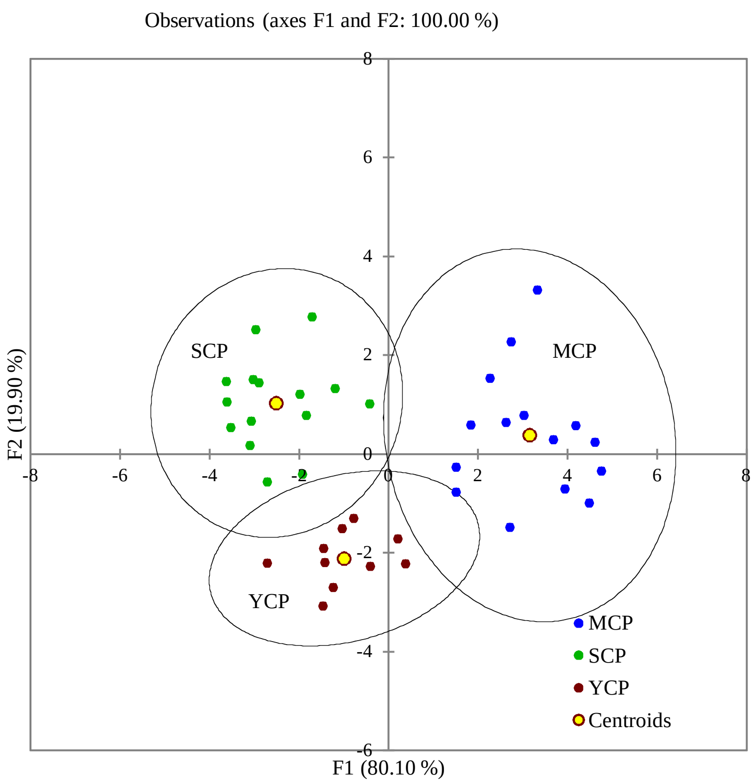
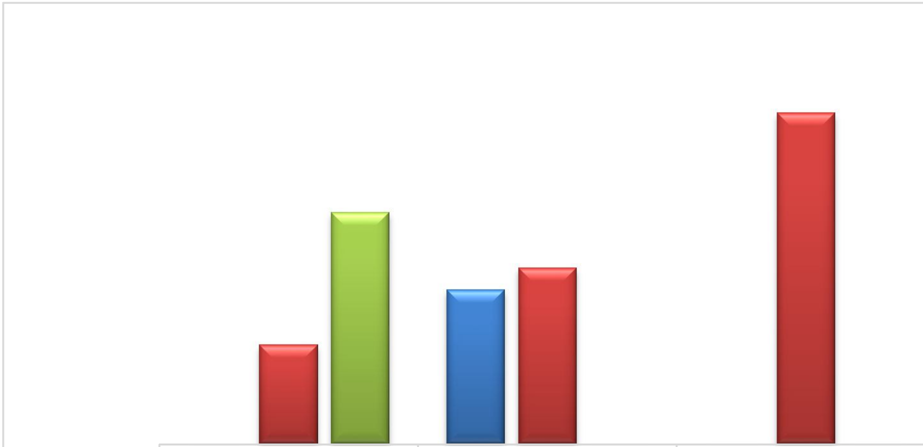


Figure 6: First and second discriminant function separating different cocoa plantations in southwest Nigeria



	YCP	MCP	SCP
Low	0	46.67	0
Moderate	30	53.33	100
High	70	0	0

Figure 7 Percentages of degraded farms across cocoa chronosequence plantations (YCP, MCP and SCP)

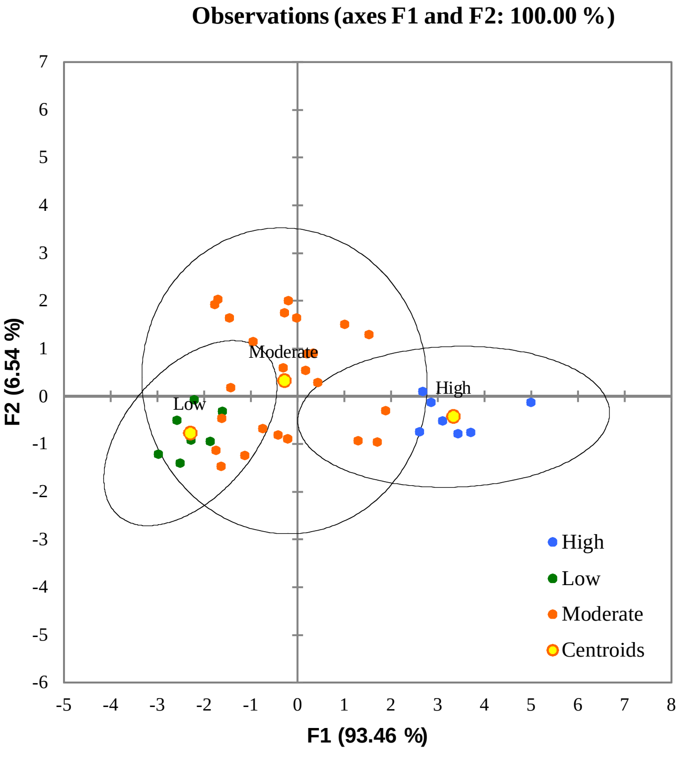


Figure 8. First and second canonical function of canonical discriminant analysis separating studied soils into three degradation classes (*Low, Moderate and High*)

Table 1. Methods and field analysis of soil data

Soil properties	Method of determination and reference
*Particle size distribution [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 (Bremner,1996)
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.

∗ For determining the particle size distribution, samples were treated with H2O2 (6 %) to remove organic matter (OM). Particles larger than 2 mm were determined by wet sieving and smaller particles were classified according to Gee & Or (2002)

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

Soil degradation indicators	PC 1	PC 2	PC 3	PC 4	PC 5	Communalities
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	
Sand (%)	-0.510	-0.282	-0.093	-0.094	-0.688	0.830
Silt (%)	**0.838**	-0.060	-0.154	0.217	-0.014	0.777
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
Total porosity (%)	0.128	-0.016	**0.801**	-0.087	0.233	0.719
Base saturation (%)	0.397	0.104	0.355	0.272	0.661	0.806
pH (KCl)	0.104	0.008	-0.029	**0.791**	0.143	0.658
Cation exchange capacity ($cmol_c$ kg^{-1})	-0.081	**0.884**	-0.124	-0.094	-0.067	0.816
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
Available phosphorus (mg kg^{-1})	0.016	0.144	**0.810**	0.063	0.075	0.686
Exchangeable potassium (mg kg^{-1})	0.219	-0.249	0.099	0.094	0.624	0.518
Exchangeable calcium (mg kg^{-1})	0.022	**0.871**	-0.007	0.028	0.084	0.767
Exchangeable magnesium (mg kg^{-1})	0.295	0.481	0.260	0.079	0.508	0.650
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
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
Exchangeable sodium (mg kg^{-1})	-0.001	0.601	0.032	0.289	0.393	0.600
Organic matter (%)	0.472	**0.711**	0.142	-0.209	0.231	0.846
Earthworm population (per m^2)	0.459	-0.401	0.552	0.144	0.282	0.776

Principal component, PC (PC 1–PC 5)

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
Porosity	0.158	-0.309
pH	0.029	-0.211
Cation exchange capacity	0.611*	0.622
Available Phosphorus	0.186	-0.035
Extractable Zinc	0.806*	-0.527
Organic matter	0.952*	0.096

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

Table 5: 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 6: 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 $0.2/\sqrt{3.506} = 0.106$; F2is $0.2/\sqrt{0.426} = 0.30$

* Significant;

^{ns} Not Significant

Table 7: 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

Table S1(supplementary material).

Soil Properties	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**	**Coefficient of Variation (%)**
Sand (%)	64.40	78.00	68.22 (±0.49)	3.07	5.50
Silt (%)	6.90	16.80	12.11 (±0.34)	2.17	17.91
Clay (%)	10.80	26.00	19.68 (±0.42)	2.64	13.41
Bulk density (g cm^{-3})	1.15	1.81	1.41 (±0.02)	0.14	9.92
Total porosity (%)	0.45	0.73	0.60 (±0.01)	0.06	10.00
Water-holding capacity (%)	9.70	26.80	16.76 (±0.76)	4.81	28.69
Saturated hydraulic conductivity (cm hr^{-1})	2.93	9.90	5.71 (±0.29)	1.83	32.00
pH (KCl)	4.60	6.50	5.74 (±0.06)	0.40	6.90
Organic carbon (%)	0.58	2.32	1.34 (±0.08)	0.54	40.29
Available phosphorus (mg kg^{-1})	6.10	15.50	10.55 (±0.58)	3.25	30.80
Total nitrogen (%)	0.50	1.44	1.00 (±0.05)	0.31	31.00
Exchangeable calcium (mg kg^{-1})	4.70	10.00	6.62 (±0.22)	1.39	20.99
Exchangeable magnesium (mg kg^{-1})	1.90	4.50	3.48 (±0.10)	0.64	18.30
Exchangeable potassium (mg kg^{-1})	0.10	0.90	0.44 (± 0.04)	0.24	54.54
Exchangeable sodium (mg kg^{-1})	0.10	0.40	0.17 (± 0.01)	0.09	52.94
Cation exchange capacity (cmolc kg^{-1})	9.50	16.30	12.28 (±0.28)	1.77	14.41
Percent Base saturation (%)	70.68	98.18	86.79 (±1.41)	8.90	10.25
Extractable copper (mg kg^{-1})	4.00	13.20	8.65 (±0.38)	2.39	27.63
Extractable zinc (mg kg^{-1})	4.70	17.70	10.36 (±0.58)	3.67	35.42
Extractable manganese (mg kg^{-1})	13.20	23.90	18.98 (±0.56)	3.52	18.54
Extractable magnesium (mg kg^{-1})	4.30	16.90	8.83 (±0.51)	3.19	36.12
Earthworm population (per m^2)	3.20	11.10	6.20 (±0.30)	1.90	30.64

Table S2(supplementary material). 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 S2 continue (supplementary material). 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 S2 continue (supplementary material). Pearson correlation coefficient among soil quality indicators

Variables	Sand	Silt	Clay	BD	Porosity	WHC	SHC	pH	SOC	AP	TN	Ca	Mg	K	Na	CEC	BS	Cu	Zn	Mn	Emg
Silt	**-0.539**																				
Clay	**-0.720**	-0.197																			
BD	0.309	**-0.465**	0.024																		
Porosity	**-0.333**	0.032	**0.360**	-0.135																	
WHC	**-0.593**	**0.575**	0.214	**-0.520**	**0.391**																
SHC	-0.152	0.034	0.146	**-0.408**	**0.447**	**0.596**															
pH	-0.178	0.273	-0.020	-0.300	0.034	**0.336**	0.268														
SOC	**-0.545**	0.262	**0.419**	-0.137	0.209	0.224	-0.272	-0.021													
AP	-0.208	0.029	0.218	-0.205	**0.579**	0.228	**0.364**	0.079	0.293												
TN	**-0.650**	**0.480**	**0.359**	**-0.446**	**0.536**	**0.803**	**0.446**	0.217	**0.533**	**0.536**											
Ca	-0.281	-0.110	**0.417**	-0.033	-0.035	0.003	**-0.331**	0.053	**0.619**	-0.003	0.168										
Mg	**-0.647**	0.275	**0.528**	-0.151	**0.337**	0.305	0.126	0.197	**0.586**	**0.397**	0.563	0.339									
K	**-0.345**	0.119	**0.304**	-0.275	0.194	**0.405**	**0.334**	0.179	0.151	0.225	0.270	-0.108	0.258								
Na	**-0.440**	0.008	**0.505**	-0.117	0.097	0.167	-0.038	0.185	**0.433**	0.170	0.298	0.443	**0.436**	0.013							
CEC	-0.102	-0.190	0.276	0.074	-0.164	-0.234	**-0.457**	-0.084	**0.523**	-0.063	0.006	0.870	**0.333**	-0.150	**0.350**						
BS	**-0.713**	**0.351**	**0.541**	**-0.321**	**0.450**	**0.644**	**0.399**	**0.370**	**0.439**	**0.388**	**0.644**	0.217	**0.650**	**0.452**	**0.392**	-0.142					
Cu	**0.432**	**-0.531**	-0.063	**0.506**	**-0.346**	**-0.850**	**-0.684**	**-0.395**	-0.090	-0.296	**-0.744**	0.219	**-0.322**	**-0.341**	-0.124	**0.354**	**-0.546**				
Zn	**-0.605**	**0.653**	0.167	**-0.423**	0.191	**0.642**	0.009	0.161	**0.658**	0.079	**0.717**	0.283	**0.526**	0.278	0.276	0.199	**0.494**	**-0.556**			
Mn	**-0.625**	**0.612**	0.222	-0.267	**0.314**	**0.752**	0.161	0.173	**0.601**	0.163	**0.733**	0.122	**0.485**	**0.382**	0.282	-0.007	**0.577**	**-0.661**	**0.834**		
Emg	**-0.382**	**0.465**	0.059	**-0.367**	**0.443**	**0.877**	**0.596**	0.229	0.169	**0.314**	**0.748**	-0.053	0.183	0.284	-0.018	-0.300	**0.560**	**-0.790**	**0.556**	**0.657**	
EP	-0.308	0.288	0.120	-0.210	**0.509**	**0.749**	**0.638**	0.291	0.052	**0.353**	**0.630**	-0.153	0.190	**0.497**	-0.158	**-0.407**	**0.618**	**-0.644**	**0.339**	**0.508**	**0.823**

Values in bold are different from 0 with a significance level alpha=0.05; BD=Bulk density; WHC= Water hydrolic capacity; SHC=Saturated hydraulic conductivity; SOC = soil organic carbon; AP= 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; EP= Earthworm Population;