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Development of a composite soil degradation assessment index for cocoa agroecosystems in southwestern Nigeria

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Abstract. Cocoa agroecosystems are 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 agroecosystems of southwestern Nigeria. Plots where natural forests have been converted to cocoa agroecosystems of ages 1–10, 11–40, and 41–80 years, respectively representing young cocoa plantations (YCPs), mature cocoa plantations (MCPs), and senescent cocoa plantations (SCPs), were identified to represent the biological cycle of the cocoa tree. Soil samples were collected at a depth of 0 to 20 cm 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 nutrients, 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 content). 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, and clay content) are the most useful in separating the studied soils into YCP, MCP, and SCP. In this way, we have sufficiently eliminated redundancy in the final selection of soil degradation indicators. Based on these four soil parameters, a CSDI was developed and used to classify selected cocoa soils into three different classes of degradation. The results revealed that 65 % of the selected cocoa farms are moderately degraded, while 18 % have a high degradation status. The numerical value of the CSDI as an objective index of soil degradation under cocoa agroecosystems 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.

1 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; Muñoz-rojas et al., 2017), buffering and filtering of pollutants (Keesstra et al., 2012), climate control through the regulation of C and N fluxes (Brevik et al., 2015; Zornoza et al., 2015; Al-Kaisi et al., 2017), and supporting biodiversity (Schulte et al., 2015). Nonetheless, misuse of soils, arising from intensive agricultural production and unsustainable land use practices has resulted in soil degradation, particularly in developing countries with poor infrastructure and financial capacity to manage natural resources (Tesfahunegn, 2016). Studies have re-

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ported that 500 Mha of land in the tropics (Lal, 2015), and more than 3500 Mha of global land area (Karlen and Rice, 2015), is 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 policymakers (Scherr, 1999; Lal, 2001; Bindraban et al., 2012; Baumhardt et al., 2015; Lal, 2015; Krasilnikov et al., 2016; Nezomba et al., 2017).

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 (SQ; Lal, 2001; Adesodun et al., 2008; Beniston et al., 2016), and, in turn, SQ as the capacity of a soil to function within ecosystem and land use boundaries (Doran and Parkin, 1994; Doran and Zeiss, 2000; Doran, 2002). Unfortunately, when soil degradation reaches an advanced stage, soil quality restoration is difficult (Lal and Cummings, 1979). Therefore, good knowledge of SQ is important for developing appropriate conservation 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). However, an essential step when assessing soil degradation based on soil quality assessment strategies is the 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 (Lal, 2001; Cerda et al., 2009; Bindraban et al., 2012; Rodrigo Comino et al., 2016a, 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; Jordán et al., 2010), reduction in the activity of soil microorganisms (Lal, 2009), 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.) agroecosystems are a major agricultural land use 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., 2014). 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). Until present, soil degradation assessments on a plot scale in regions undergoing farmland conversion to cocoa agroecosystems have been limited.

Worldwide, agricultural practices have been regarded as one of the major causes of soil degradation (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 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 et al., 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 et al., 2015), the use of single soil characteristics often provides an incomplete representation of soil degradation (De la Rosa, 2005; Puglisi et al., 2005, 2006; 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; Sione et al., 2017; Biswas et al., 2017; Renzi et al., 2017; Khaledian et al., 2017). These statistical techniques can assist researchers in selecting important soil quality indicators that are useful for developing 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, Sione et al. (2017) used a soil quality index (SQI) to evaluate the impact of rice production systems that use irrigation with groundwater on soil degradation on 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 (Sione et al., 2017). In South Asia, Biswas et al. (2017) combined PCA and multiple regression analysis to create MDSs of physical, chemical, and biological indicators, which were integrated to develop a unified SQI for rice–rice cropping systems. Thus, Sánchez-Navarro et al. (2015) developed an overall SQI suitable for monitoring soil degradation in semi-arid Mediterranean ecosystems. Pulido et al. (2017) developed a soil degradation index for rangelands of Extremadura southwestern Spain based on six indicators, namely CEC, available potassium, SOM, water content at field capacity, soil depth, and the thickness of the Ah horizon. Another example is Gómez et al. (2009), who developed three soil degradation indexes (obtained through a PCA) of soils under organic olive farms in southern Spain. One of the indices used only three soil properties, namely organic C, water stable macroaggregates, and extractable P. According to these authors, this index had the highest potential to be used as a relatively easy and inexpensive screening test of soil degradation. Very little attention has been given to the development of numeric indices for monitoring soil degradation under crop-specific land use management systems in tropical countries. Such indices can serve as the basis for integrating and interpreting several soil measurements, thereby indicating whether a particular land use management system (e.g agroecosystems) is sustainable or not.

Therefore, the aim of the present study is to develop a CSDI for shaded cocoa agroecosystems under tropical conditions in southwestern Nigeria. This area is currently suffering from soil degradation arising from low input cocoa agroecosystems. Soil conditions under age-sequenced peasant cocoa agroecosystems are investigated. The cocoa agroecosystem ages of 1–10, 11–40, 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). Our goals are to (i) identify the most important soil degradation processes, (ii) select a MDS of soil degradation indicators using multivariate statistical techniques, (iii) integrate the MDS into a CSDI, and (iv) statistically validate the 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 degraded cocoa soils in southwestern Nigeria (and similar environments).

2 Materials and methods

2.1 Study area

This study was carried out in the Ife region of southwestern Nigeria between 6°50′27″–7°38′33″ N and 4°21′33″–4°45′55″ E (Fig. 1), where most soils have been under cocoa plantations for more than 80 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 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, which are exposed as outcrops in several areas, of the Precambrian age. The soils are mainly Alfisols, classified as Kanhaplic Rhodustalf (Soil Survey Staff, 2014) or Luvisols (IUSS Working Group WRB, 2015) and locally known as the Egbeda association (Smyth and Montgomery, 1962). The area of study lies within the Egbeda soil series, characterized 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 in the region traditionally established their cocoa farms by planting cocoa trees where primary or secondary forests are selectively cleared. Cocoa trees

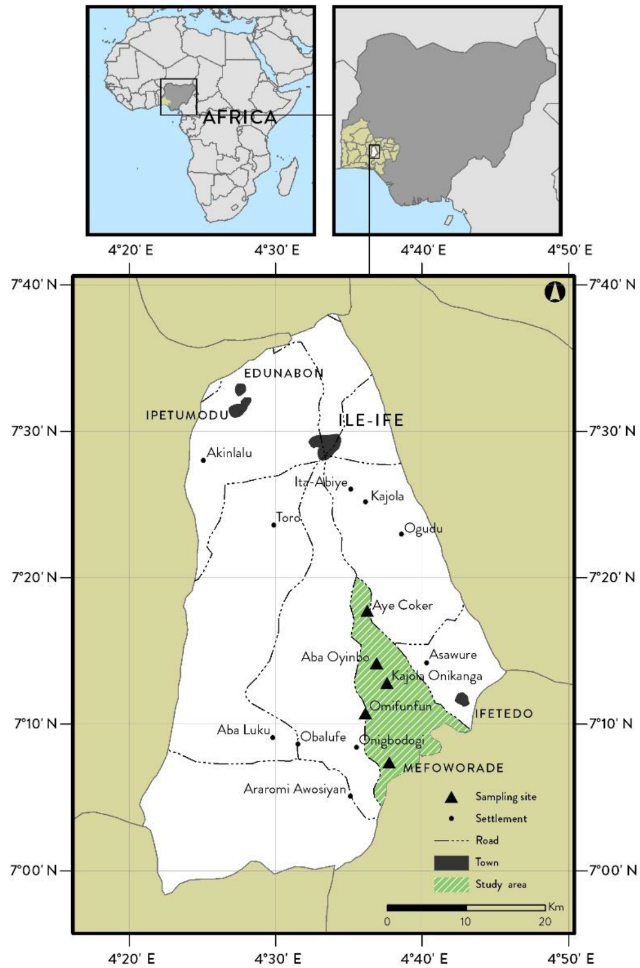

Figure 1. Location map of the study area.

are then 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 farmers have recently shifted towards full-sun cocoa plantations, 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 agroecosystems 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

The study area was visited in March and April 2013 to identify suitable cocoa agroecosystems and locate candidate sample sites. 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. At each site, a total of eight cocoa agroecosystems 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 coexist with other tree species on the same plot of land. Some tree species identified within selected cocoa agroecosystems 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 agroecosystems are between 2 and 3 ha in size, with a tree spacing of 3 × 3 m as recommended by good agricultural practices for sustainable cocoa production in the West African subregion. 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 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 agroecosystems are covered with leaves and plant litter.

2.3 Soil sample collection for laboratory analysis

Soil sampling was conducted in May 2013. A quadrat measuring 1000 m^2 was demarcated at the centre of each cocoa agroecosystem. Each quadrat was subdivided into 10 sub-quadrats of 100 m^2 and serially labelled. Soil samples were drawn at the centre of the even-numbered sub-quadrats, resulting in a total of five soil samples per plot. Measurements were deliberately restricted to a depth of 0 to 20 cm 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 African cocoa-based agroecosystems (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); (iv) biological processes, such as earthworm activities, are restricted to 0–10 cm layer of tropical soils; (v) measurements were restricted to facilitate future replication of the methodology as routine soil samples are usually taken from the topsoil 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, and 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 ring measuring 5 × 5 cm (diameter and height), whereas the other sample was taken using a soil auger. The first sample was used to determine BD, 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 2 weeks, hand ground in a ceramic mortar, passed through a 2 mm sieve and analysed for chemical properties and particle-size distribution. For analysis 22 soil properties were selected. 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 (Supplement).

2.4 Statistical analyses and index development

Based on an extensive review of literature on soil quality and degradation assessment indexing, the CSDI was developed using a range of statistical techniques and procedures. The methodology consisted of eight steps as outlined below:

Step (1) involved selection of relevant indicators of soil degradation. Here, we selected 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 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

Table 1. Methods and field analysis of soil data.

Soil properties	Method of determination and reference
*Particle size distribution (Sand, silt, and clay content (%))	Pipette method (Gee and Or, 2002)
Bulk density ($g\,cm^3$)	Core method (Grossman and Reinsch, 2002)
Total porosity (%)	Computed from value of bulk density (Vomocil, 1965)
Water-holding capacity (%)	Oven-dry method
Saturated hydraulic conductivity ($cm\,h^{-1}$)	Determined in the laboratory using a constant head permeameter (Reynolds and 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 and 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 H_2O_2 (6 %) to remove organic matter (OM) as described by Parras-Alcántara et al. (2015).

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	
	Principal component, PC					
Soil degradation indicators	PC 1	PC 2	PC 3	PC 4	PC 5	Communalities
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 content (%)	−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 ($cm\,h^{-1}$)	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

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

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 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, pH, soil aggregate stability, CEC, and available water content (Doran and Parkin, 1994; Larson and Pierce, 1994; Karlen et al., 1997; Zornoza et al., 2007, 2015; 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., 2012, 2013; Singh et al., 2014). In cases in which 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, 2004; 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). Conversely, the discriminant functions can be represented as

$$D_i = d_{i1}Z_1 + d_{i2}Z_2 + d_{iP}Z_P, \tag{1}$$

in which D_i is the score on discriminant function i, d's are weighting coefficients, and 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 Wilks' 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 normalization 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:

$$S_L = \left(\frac{X - l}{h - l}\right), \tag{2}$$

in which 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 the 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

$$\mathrm{D} = 1 - S_L, \tag{3}$$

in which D is the degradation score and S_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:

$$\mathrm{CSDI} = \sum\nolimits_{i=1}^{n} (W_i D_i), \tag{4}$$

in which 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

$$z = \frac{x - \mu}{\sigma}, \tag{5}$$

in which 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, Z values between -1 and 1 were regarded as having a moderate degradation status, while values of more than 1 were regarded as high and less than -1 as low (see the results section for further explanation on this categorization).

In Step (8) the CSDI classification was statistically validated using a CDA. CDA 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. 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, or 0.004 belonging to the low, moderate, or high degradation classes, respectively, was assigned to medium (see 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 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 $T = 0.2/\sqrt{}$ (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).

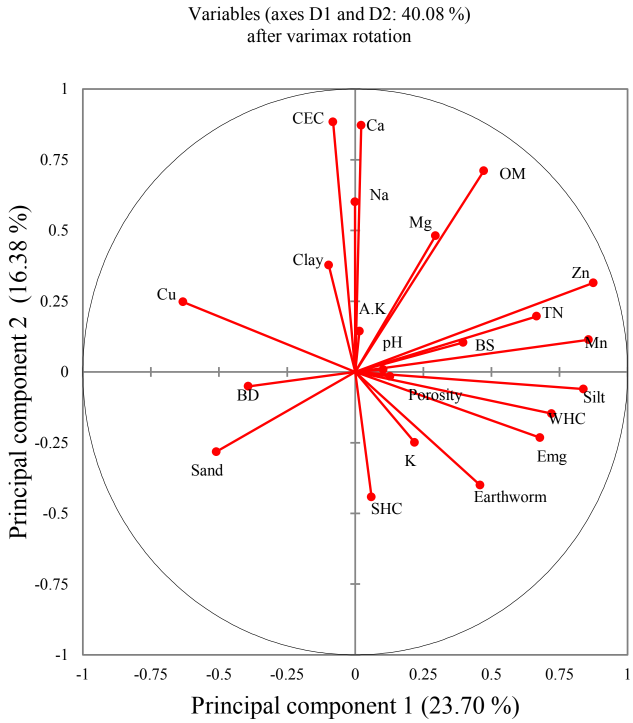

Figure 2. Principal component distribution of the investigated soil properties in age-sequenced peasant cocoa plantations. BD – bulk density; Clay – clay content; WHC – water-holding capacity; SHC – saturated hydraulic conductivity; OM – organic matter; AP – available phosphorus; TN – total nitrogen; 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; earthworm population.

3 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. Each PC explained 5 % or more of the variation in the data set. The first five PCs jointly accounted for more than 77 % of the total variance in the data set. In addition, they explained 68 % of the variance in available phosphorus, 84 % in SOM, 76 % in calcium, 65 % in pH, 87 % in clay content, 90 % in TN, 77 % in silt, 83 % in magnesium, 83 % in sand, and 58 % in BD. The high communalities among the soil properties suggest 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 (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 the soil acidity degradation factor because it was highly loaded on pH (0.791) only. Similarly, the fifth factor was labelled as the soil textural degradation factor because it was dominated by clay content (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 nutrients, (2) loss of soil organic matter, (3) increase in soil acidity, and (4) the breakdown of soil textural characteristics arising from differences

Table 3. Correlation coefficient between highly weighted variables under PCs with high factor loading.

PC1 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 content		
Clay content	1.000		

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

in eluviation of clay content. Figure 2 summarizes 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 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 3 represents the percentage contributions of the investigated soil properties in selected cocoa plantation chronosequence (CPC).

3.2 Selecting a MDS of soil degradation indicators

The PCA results presented thus far suggest that eight indicators (extractable zinc, silt, SOM, CEC, available phosphorus, TP, pH, and clay content) 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 to determine which of them are most important for soil degradation monitoring in the study area. Figure 4 and Table 4 show that STEPDA separated CPC into three groups (YCP, MCP, and SCP), based on the explanatory variables (eight 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 were significantly different for the two discriminant functions.

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 coefficient correlation	
Silt	0.353	−0.520
Clay content	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 $p < 0.05$. ** Significant at $p < 0.001$.

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, $p < 0.001$), and CEC (0.611, $p < 0.001$); thus, it is labelled as the soil organic mat-

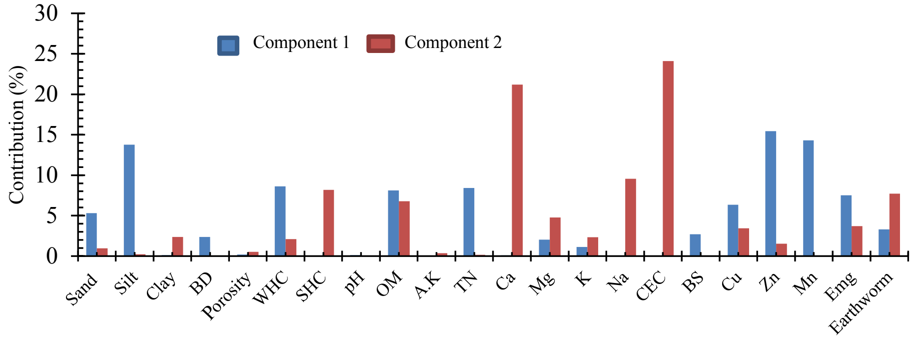

Figure 3. Percentage contributions of the investigated soil properties in age-sequenced peasant cocoa plantations. Clay – clay content; BD – bulk density; WHC – water-holding capacity; SHC – saturated hydraulic conductivity; OM – organic matter; AP – available phosphorus; TN – total nitrogen; Ca – exchangeable 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; earthworm population.

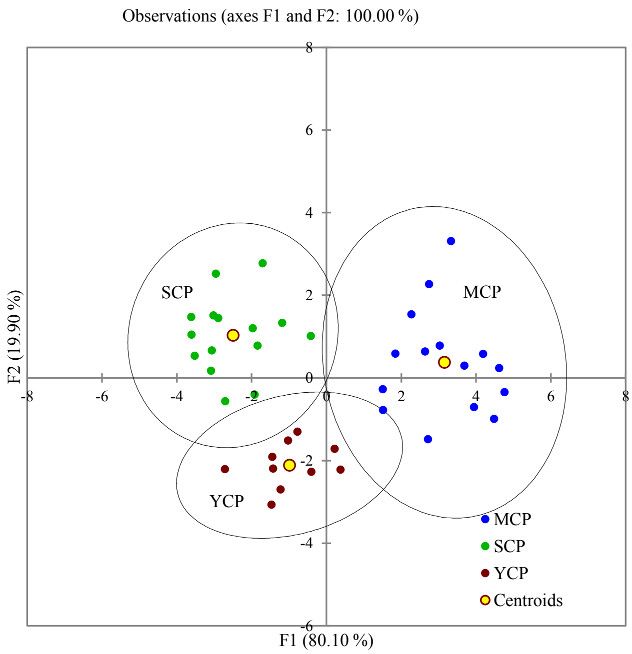

Figure 4. First and second discriminant function separating different cocoa plantations in southwestern Nigeria.

ter and macronutrients 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 content (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 as the soil physical and micronutrient dimension.

The result of STEPDA confirmed that only four soil properties are significant in discriminating between the 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 content ($R^2 = 0.169$, $p < 0.05$; 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 content. Consequently, these four soil properties constitute a 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 Sect. 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 normalized and weighted values of each parameter. CSDI was computed for each cocoa agroecosystems as

$$\mathrm{CSDI} = 0.21(\mathrm{DSOM}) + 0.31(\mathrm{DZn}) + 0.21(\mathrm{DCEC}) + 0.17(\mathrm{DClay}). \tag{6}$$

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

$$\mathrm{CSDI} = 0.31(\mathrm{DZn}) + 0.21(\mathrm{DSOM}) + 0.21(\mathrm{DCEC})$$

Table 5. Classification of soils into degradation levels and their interpretations modified after Gómez et al. (2009).

Range	Classes of degradation 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 content
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 content (%). $^{\Psi}$ 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. $^{\Psi}$ Eigenvalue for F1 = 3.506 and F2 = 0.426; threshold for F1 is $0.2/\sqrt{3.506} = 0.106$; F2 is $0.2/\sqrt{0.426} = 0.30$. * Significant. ^{ns} Not significant.

$$+0.17(\mathrm{DClay}), \tag{7}$$

in which 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 content, respectively.

One significant result from this study is that Zn was identified as the most important degradation indicator and it plays 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 a 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 Eq. (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 5 (modified from Gómez et al., 2009). Most of the selected cocoa agroecosystems (65 %) are moderately degraded, while 18 % have a high degradation status.

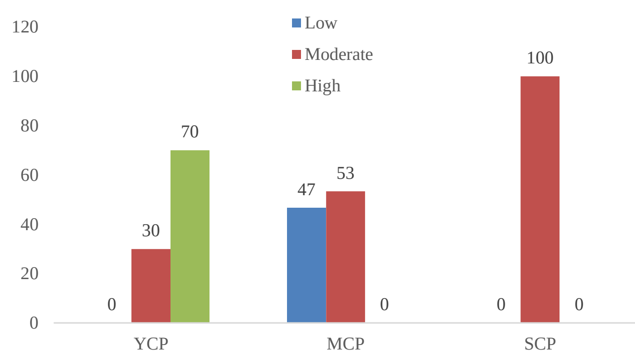

Figure 5. Percentages of degraded farms across cocoa chronosequence plantations (YCP, MCP, and SCP).

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). Figure 5 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 shows 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 a YCP with a

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 %

Percentage of grouped cases correctly classified is 87.50 %. Bold font in each group is the number of cases correctly classified by canonical discriminant analysis.

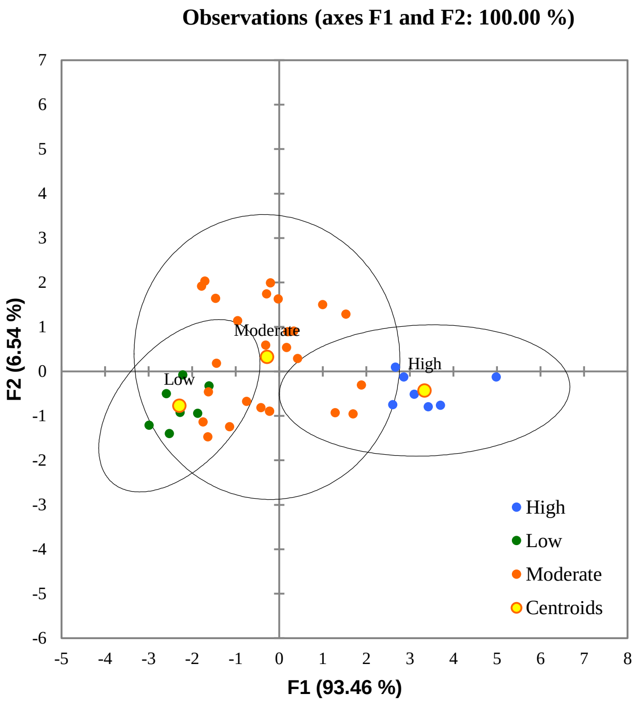

Figure 6. First and second canonical function of canonical discriminant analysis separating studied soils into three degradation classes (low, moderate, and high).

3-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 agroecosystems in West Africa. Traditionally, cocoa plots are cultivated with food crops in the first 3 to 5 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 was used to validate the CSDI classification. The values of the four soil properties (organic matter, extractable zinc, CEC, and clay content) were used as data input. Figure 6 and Table 6 show that the three soil degradation classes (low, moderate, and high) were significantly separated on the first and second canonical functions (Wilks' 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 significantly contributed to the distinction among soil degradation classes and were positively associated with the first canonical function (Table 6). Clay content also contributed significantly to the distinction among soil degradation classes, but was positively associated with the second canonical function (Table 6).

CDA classification results in Table 7 reveal that the CSDI model performs reasonable well, showing a low level of misclassification. The table shows that for the original grouped cases, the CDA 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 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. Results from this study indicate that the CSDI can effectively be used to monitor and evaluate the degree of soil (Alfisols) degradation under cocoa plantations in the study area (and similar environments). The results of this study also 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 agroecosystems. More work is needed to apply and evaluate the index on different soil types from different cocoa-producing regions and countries.

4 Conclusions

In this study, we developed a composite soil degradation index to cost-effectively assess the status of soil degradation under cocoa agroecosystems. Of the initial 22 soil properties evaluated, multivariate statistical analyses revealed that four soil properties (extractable zinc, SOM, CEC, and clay content) were the main indicators of soil degradation. This 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 CDA classification performed on the same data set.

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 agroecosystems (in this region at least) is mainly attributed to a decline in soil nutrients, 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 agroecosystems. The implications are serious for sustainability of cocoa agroecosystems on acidic Alfisols. While degradation of physical components of these soils poses 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 (organic) fertilizers, particularly under YCP. Obviously, 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 governments. Therefore, alternative fertilizers in terms of organic residues, with the potential of increasing organic matter have been proposed in recent times (Van Vliet and Giller, 2017). Studies have reported that the addition of organic plant residues to crop soils helps to improve soil structure (Jordán et al., 2010). In addition, animal manure 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 and health under cocoa agroecosystems of different ages. Hopefully this will lead to much-needed evidence-based recommendations for rehabilitation of degraded cocoa soils in West Africa.

Data availability. Data associated with this study are provided in the Supplement.

The Supplement related to this article is available online at https://doi.org/10.5194/se-8-827-2017-supplement.

Competing interests. The authors declare that they have no conflict of interest.

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