Soil aggregate stability of forest islands and adjacent ecosystems in West Africa

Plant and Soil

Bougma, Amelie Baomalgré; Ouattara, Korodjouma; Compaore, Halidou; Nacro, Hassan Bismarck; Melenya, Caleb et al

https://doi.org/10.1007/s11104-022-05302-x

This publication is made publicly available in the institutional repository of Wageningen University and Research, under the terms of article 25fa of the Dutch Copyright Act, also known as the Amendment Taverne. This has been done with explicit consent by the author.

Article 25fa states that the author of a short scientific work funded either wholly or partially by Dutch public funds is entitled to make that work publicly available for no consideration following a reasonable period of time after the work was first published, provided that clear reference is made to the source of the first publication of the work.

This publication is distributed under The Association of Universities in the Netherlands (VSNU) 'Article 25fa implementation' project. In this project research outputs of researchers employed by Dutch Universities that comply with the legal requirements of Article 25fa of the Dutch Copyright Act are distributed online and free of cost or other barriers in institutional repositories. Research outputs are distributed six months after their first online publication in the original published version and with proper attribution to the source of the original publication.

You are permitted to download and use the publication for personal purposes. All rights remain with the author(s) and / or copyright owner(s) of this work. Any use of the publication or parts of it other than authorised under article 25fa of the Dutch Copyright act is prohibited. Wageningen University & Research and the author(s) of this publication shall not be held responsible or liable for any damages resulting from your (re)use of this publication.

For questions regarding the public availability of this publication please contact openscience.library@wur.nl

Plant Soil
https://doi.org/10.1007/s11104-022-05302-x

REGULAR ARTICLE

Soil aggregate stability of forest islands and adjacent ecosystems in West Africa

Amelie Baomalgré Bougma · Korodjouma Ouattara · Halidou Compaore · Hassan Bismarck Nacro · Caleb Melenya · Samuel Ayodele Mesele · Vincent Logah · Jamiu Oladipupo Azeez · Elmar Veenendaal · Jonathan Lloyd

Received: 4 May 2021 / Accepted: 13 January 2022

Abstract

Purpose In the mesic savannas of West Africa, areas around villages of relatively tall and dense forest vegetation are often found. These 'forest islands' are presumably the direct outcome of human activity. To better understand these patches with relatively luxuriant vegetation, our study focused on how they influence soil aggregate stability- a key indicator of soil resilience to degradation through erosion. We compared the proportion of stable soil aggregates of the forest islands with nearby croplands and natural savanna vegetation across a precipitation transect in West Africa for which mean annual precipitation at the study sites ranges from 0.80 to 1.27 m a^{-1}.

Methods Soil samples were taken from 0–5 cm and 5–10 cm depths and stability of soil aggregate groups with diameters: > 500 µm, 500–250 µm and 250–53 µm (viz. "macroaggregates", "mesoaggregates"

Responsible Editor: Feike A. Dijkstra

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11104-022-05302-x.

A. B. Bougma · K. Ouattara · H. Compaore
Institut de l'Environnement et de Recherches Agricoles (INERA), Burkina Faso, 04 BP 8645 , 04 Ouagadougou, Burkina Faso

H. B. Nacro
Université Nazi BONI (UNB), 01 BP 910, 01 Bobo, Burkina Faso

C. Melenya · V. Logah (✉)
Kwame Nkrumah University of Science and Technology, Kumasi, Ghana
e-mail: vlogah@yahoo.co.uk

S. A. Mesele · J. O. Azeez
Federal University of Agriculture, Abeokuta (FUNAAB), PMB 2240, Abeokuta, Nigeria

E. Veenendaal
Nature Conservation and Plant Ecology Group, Wageningen University and Research, Droevendaalsesteeg 3a, 6700 AA Wageningen, Netherlands

J. Lloyd
Department of Life Science, Imperial College London, Silwood Park Campus, Buckhurst Road, Ascot SL5 7PY, UK

J. Lloyd
School of Tropical and Marine Sciences and Centre for Terrestrial Environmental and Sustainability Sciences, James Cook University, Cairns, 4870, Queensland, Australia

J. Lloyd
Universidade de São Paulo, Faculdade de Filosofia Ciências e Letras de Ribeirão Preto, Av Bandeirantes, 3900, CEP 14040-901, Bairro Monte Alegre, Ribeirão Preto, SP, Brazil

and "microaggregates" respectively) determined using the wet sieving method.

Results The results showed significantly ($p < 0.05$) higher proportion of stable soil meso- and macro-aggregates in forest islands and natural savanna than in agricultural soils. Although there was no effect of land-use type on microaggregate stability, there was a strong tendency for the stable microaggregates across all land use types to increase with increasing precipitation. Soil organic carbon and iron oxides contents were the most important factors influencing meso and macro-aggregate stability in the West African ecosystems.

Conclusion We conclude that formation of stable soil microaggregates in the West African ecosystems was climate or precipitation driven whereas the more labile and larger-size groups of meso-and macro-aggregates was land-use driven. The study provides first insights in soil quality processes in a poorly studied but unique phenomenon of man-made forest islands in West Africa.

Keyword Land use, Stable soil macroaggregates, Stable soil microaggregates, Vegetation, West Africa

Introduction

In West Africa, both natural and human dominated ecosystems are often affected by land degradation processes, with soil erosion usually considered a major threat to long-term sustainability (Bashagaluke et al. 2019). The erosion process itself results from a complex combination of climatic and anthropogenic factors (Zombré 2003). In general, soil aggregate stability is a key metric for assessing soil susceptibility to erosion (Barthès and Roose 2002) as it strongly influences the rates of water infiltration and runoff, and plays a key role in the dynamics and stabilization of soil organic matter (Six et al. 2000a).

Earlier studies have shown that soil aggregate formation and stabilization is a complex process influenced by intrinsic soil propeties inter alia soil organic matter content and clay mineralogy, climatic conditions and land use patterns (Larvee et al. 1991; Six et al. 2000b; Barthès et al. 2008; Ouattara et al. 2008; Mataix-Solera et al. 2011; Erktan et al. 2015). Tillage, for example, mixes the soil surface layers and exposes soil aggregates to wet-dry cycles (Roose 1981; Beare et al. 1994; Whalen et al. 2003). As a result, decomposition of organic matter is increased, weakening soil aggregate stability (Hadas 1990). Soil organic matter is a main element in the cohesion and hydrophobicity of soil aggregates (Igwe and Nwokocha 2006). Labile organic matter and microorganisms sustain water stable macroaggregates, which becomes vulnerable to unsustainable agricultural practices.

Recently, several studies showed the role of soil organisms and vegetation structure and/or species composition as additional factors influencing the stability of soil aggregates (Six et al. 2000a; Chartier et al. 2011; Berendse et al. 2015; Gould 2016; Kamau et al. 2020; Morlue et al. 2021). Their attention focused on diverse aspects of above- and below-ground biotic-soil interactions influencing soil physical and chemical characteristics. Of particular importance may be the influence of vegetation formations of different plant functional types, which influence the soil physical environment, increase and stabilize soil structure and enhance the pore system (Le Bissonais et al. 2018; Boonman et al. 2020). However, the impact of the unique man-made 'forest islands' (FI) in West Africa on soil aggregate stability has not been studied. This is despite the potential implication for land mangement as the forest islands could be useful in minimizing soil erosion at the landscape scale and in the provision of other ecoystem services.

Forest islands are dense vegetation typically of 0.1 to 10 ha area, constituting a unique phenomenon surrounding many village areas in the West African mesic savanna zones with a species and structural composition more typical of forest stands found in more humid regions. It has been realised that these ecosystems result at least in part, from the actions of the nearby village occupants (Jones 1963; Fairhead and Leach 1995). However, there have been few studies on their role and unique ecological characteristics (Kokou and Sokpon 2006), apart from the descriptive analyses of few soil profiles (Sobey, 1978; Fairhead and Leach 1998). The potential impacts of the FIs apart from soil erosion control, are relevant with regard to many aspects related to soil hydrological system and in preserving and sustaining soil biodiversity conservation, soil carbon storage, and may provide a valuable insights for the massive tree planting drives in the Sudano-Sahelian zone (https://www.greatgreenwall.org/). Thus, further understanding of FI function is of main importance.

This study contributes to the knowledge of the edaphic properties of FIs through assessing soil aggregate stability in comparison with adjacent natural savannas and cultivated fields in West Africa. Considering the recent studies on the importance of biodiversity and vegetation cover on soil quality (Chartier et al. 2011; Berendse et al. 2015; Gould 2016), we hypothesize that soil aggregate stability is higher under forest islands than in adjacent savanna or agricultural field.

Material and methods

Sampling locations and site descriptions

The study was carried out in 2016 and 2017 in 11 locations across Burkina Faso, Ghana and Nigeria (Fig. 1, Appendices S1, S2). The study sites were distributed across three agro-ecological zones (AEZ) as defined by Ker (1995). At each of the eleven locations, three land-use types were selected for sampling as follows:

Forest island (FI) plots consisted of patches of forests around villages with open landscape mosaic of relatively open savanna vegetation and agricultural fields. The trees are tall, being 15 to 20 m high with typically more than 400 individuals per hectare with diameter at breast height (*D*) greater than 10 cm. Selection of the forest islands was based on prior knowledge and ground-based survey. Forest islands created as a result of anthropogenic activities of the villagers (e.g. dumping of refuse or household wastes, animal excreta, etc.) were selected.

Savanna (SA) plots may be considered as natural vegetation type from all three agro-ecological zones (AEZ). Trees were typically between 5 to 10 m high

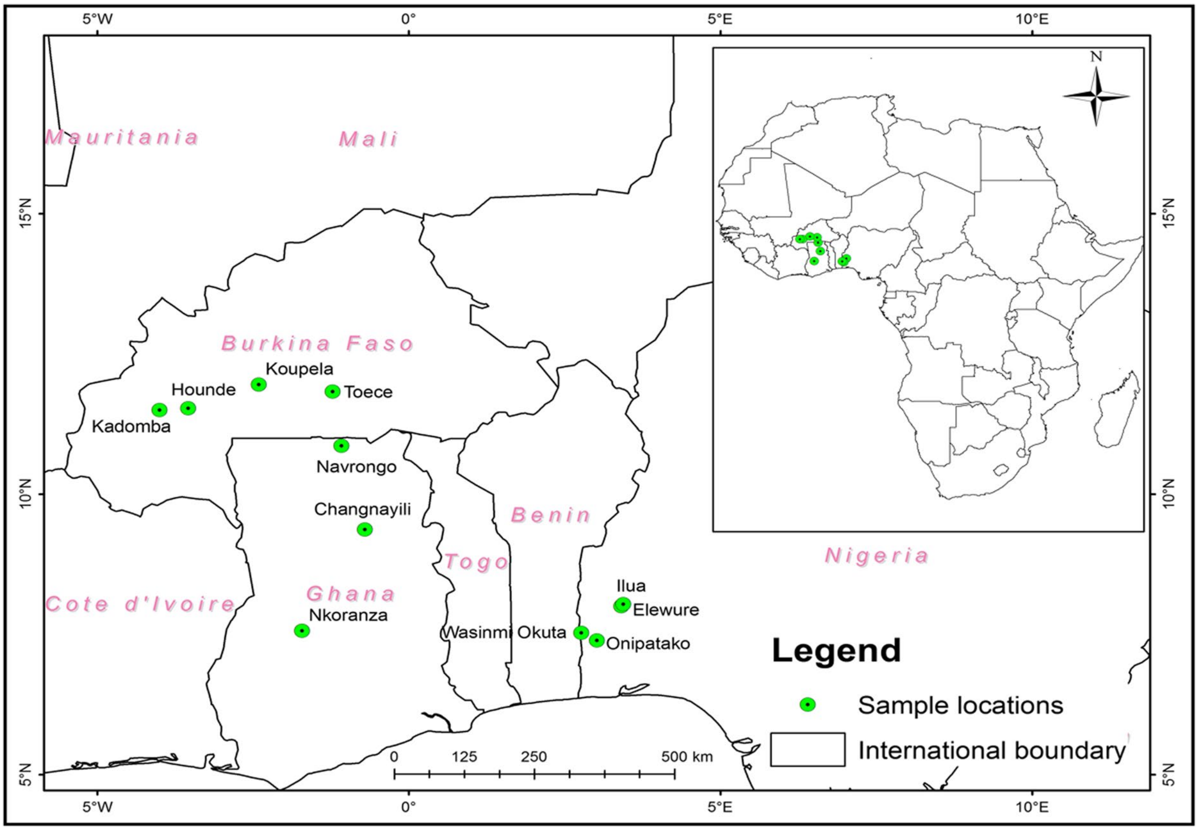

Fig. 1 Location of study areas. Although Ilua and Elewure forest islands were quite close (< 10 km apart), each generally possessed unique features of biodiversity, hence their selection for the study

and with a density of 50 to 100 trees ($D > 10$ cm) per hectare. Due to their open nature, these savanna formations were typically with an abundant ground layer of grasses and herbs.

Agricultural field plots (AF) were selected as close as possible to the FI and SA plots and, from discussions with local village inhabitants, had been cropped for 10 years or more. In Burkina Faso, the cropland study sites were cotton based or cereal-based fields. In Ghana, the cropping areas were monocultures of maize. In Nigeria, they were maize or mixture of maize/cassava or legumes.

Proximity of the land-use systems at each location: In Nigeria, the three land-use systems at each location were within 0.13 to 0.60 km radius. In Ghana and Burkina Faso, the forest islands and agricultural plots at a location were within 0.10 to 0.70 km radius except the Nkoranza cropland, which was ca. 3.1 km from the forest island. The savanna plots in Ghana were generally within 10 km radius from the forest islands whereas in Burkina Faso, they were a little bit further apart.

Soil sampling

At each of the 11 locations, soil samples were collected from FI, SA and AF during the periods July to August, 2016 and August, 2017. Soil sampling on agricultural fields was done at peak vegetative phase and in few cases, at crop physiological maturity. The size of the sampling area was 0.16 ha which was divided into four 20 × 20 m subplots for soil sampling. Within each subplot, five samples were taken randomly from each of 0–5 and 5–10 cm depths using an undisturbed soil-sampling auger (Eijkelkamp Agrisearch Equipment BV, Giesbeek, The Netherlands). The five samples were composited and subsample taken, representative of each subplot. The soil samples were subsequently air-dried and stored for laboratory analysis.

Soil aggregate stability

The wet sieving method (Mathieu 1998) was used to determine soil aggregate stability. This method consists of passing air-dried soil samples through 4000 µm, 500 µm, 250 µm and 53 µm sizes sieves (not sequentially) to obtain three aggregate groups defined as "macroaggregates" (4000–500 µm), "mesoaggregates" (500–250 µm) and "microaggregates" (250–53 µm). To measure the stability of each aggregates group, 3.0 g of soil sample previously moistened by spraying with distilled water was placed, accordingly, on the sieves which were then placed on the wet sieving equipment, and shaken slowly backwards and forward for one hour. Thus, the unstable soil aggregates passed through the sieve mesh. At the end of the sieving procedure, stable soil aggregates remained in the sieve were collected in a cup, oven dried at 105 °C for 24 h and then weighed. The sand fraction of each aggregate group was then determined after destruction of organic matter through addition of 3 ml of hydrogen peroxide and heating until all bubbles disappeared from the soil–water mixture. Thereafer, the solution was made up to 75 ml with distilled water and the soil particles dispersed using sodium hexametaphosphate. Afterwards, samples were washed on a 0.5 mm sieve and then dried and weighed. The stable soil aggregates (Φ_A) was then calculated using the following formula (Bloin et al., 1990).

$$\Phi_A = (P_{ag} - P_s)/(P_e - P_s) \quad (1)$$

where P_{ag} = the dried total soil remaining in the sieve, P_e = the weight of soil sample used and P_s = weight of the sand in the sample.

Particle size analysis

The distribution of the sand, silt and clay fractions were done using Robinson-Köhn method. This method consists of destruction of organic matter by hydrogen peroxide followed by particle dispersion with sodium hexametaphosphate, with subsequent separation of silt and clay particles by sedimentation with sands by sieving (Mathieu, 1998).

Chemical analysis

For chemical analyses, soil samples were air-dried and sieved on 2-mm mesh. Soil pH was measured using the electrode method in a ratio of soil / water of 1: 2.5. Soil organic carbon content was determined in an automated elemental analyzer (Vario MACRO cube, Elementar Germany).

Free iron and aluminium oxides were determined according to the procedure of Mehra and Jackson (1960), using the dithionite-citrate-bicarbonate (DCB) after destruction of organic matter in a mixture of concentrated nitric acid and perchloric acid. The digest was analyzed colorimetrically for Fe (o-phenanthroline) and Al (aluminium).

The oxalic acid-extractable Fe and Al, the amorphous forms of Fe and Al, were extracted using ammonium oxalate (McKeague et al. 1971). Determination of Al and Fe in all the digests was done by the xylenol–orange colorimetric method (McKeague 1971).

Statistical analysis

Here, we used generalized linear mixed models (GLMMs) to evaluate the potential joint effects of mean annual precipitation amount (v), land-use (L) and sampling depth (d) (independent variables) on soil aggregate stability (dependent variable) according to:

$$\log_{10}\left[\arcsin\left(f_{\mathrm{dcp}}\right)\right] = \alpha_{000} + \alpha_{001}P_{\mathrm{A00p}} + \gamma_{\mathrm{i}}L_{\mathrm{00p}} + \gamma_{j}d_{\mathrm{0cp}} + U_{\mathrm{00p}} + V_{\mathrm{0cp}} + R_{\mathrm{dcp}} \tag{2}$$

where f_{dcp} is the stable soil aggregate fraction f as measured at depth d of core c in subplot p; α_{000} is the overall mean value of f at 0–5 cm depth for agricultural fields (AF) across the dataset (intercept term with all model input centered on the dataset mean annual precipitation amount (P_A) of 1.01 m a^{-1}), α_{001} is a fitted variable describing the response of f to P_A, γ_i is the response of f to the land use indicator variable L (for which AF = 0, forest island (FI) = 1 and savanna (SA) = 2); γ_j is the difference in f between the upper and lower sampling depths for core c within subplot p; U_{00p} represents the variance associated with subplot location (i.e. the systematic component of the subplot variation that is not accounted for by the precipitation and land use terms); V_{0cp} is the within-plot variation (i.e. the variance associated with the sampling of replicate cores within individual subplots) and R_{dcp} is the residual variance.

The arcsine transformation of f_{dcp} was incorporated so as to allow for the binomial-type distribution of proportions with the logarithmic transformation making the covariates multiplicative rather than additive. The latter effect can easily be seen through a rewriting of (Eq. 2) as (ignoring subscripts where possible for convenience)

$$f = \sin\left(10^{\left[\alpha_0+\alpha_1 P_{\mathrm{A}}+\gamma_{\mathrm{i}}L+\gamma_j d\right]=\sin\left(10^{[\alpha_0+P_{\mathrm{A}}]}10^{\gamma_i L}10^{\gamma_j d}\right)}\right) \tag{3}$$

In terms of precipitation sensitivities, Eq. 3 may also be differentiated as (taking the indicator variables γ_0 and γ_i as zero (= AF) for simplicity)

$$\frac{df}{d\langle P_{\mathrm{A}}\rangle} = \alpha_1 \bullet \cos\left(10^{\left[\alpha_0+\alpha_1 P_{\mathrm{A}}\right]}\right) \bullet 10^{\left[\alpha_0+\alpha_1 P_{\mathrm{A}}\right]} \bullet \log(10) \tag{4}$$

Note that for the fitting of the mixed model, the input precipitations were centered on the dataset mean of 1.01 m a^{-1}. This means that, once appropriately back transformed, the fitted intercept gives an estimate of f at the dataset mean precipitation rather than the (relatively meaningless) $P_A = 0$ m a^{-1}. Further, from generalized linear mixed-effects models, Nakagawa and Schielzeth (2010; 2013), have derived two easily interpretable values of R^2. The first is called the marginal R^2m and describes the proportion of variance explained by the fixed factor(s) alone. The second is the conditional R^2c, which describes the proportion of variance explained by both the fixed and random factors.

Results

Effects of rainfall amount and land use on soil aggregate stability

Here we evaluated the variations in soil aggregate stability with land-use type and precipitation amount at 0–5 cm depth only (Fig. 2) with the fitted lines coming from the mixed model analysis of Table 1. For the stable microaggregates (Fig. 2a), there was a strong increase in proportion with precipitation amount ($p < 0.001$) but no effect of land use ($p > 0.1$). Due to the centering of $P_{A,}$ the intercept of -0.030 equates to a predicted f_{micro} of 0.80 for agricultural fields (AF) at the dataset mean of 1.01 a^{-1}. Although the fitted equation is linear in form, due to the data transformations, f_{micro} is

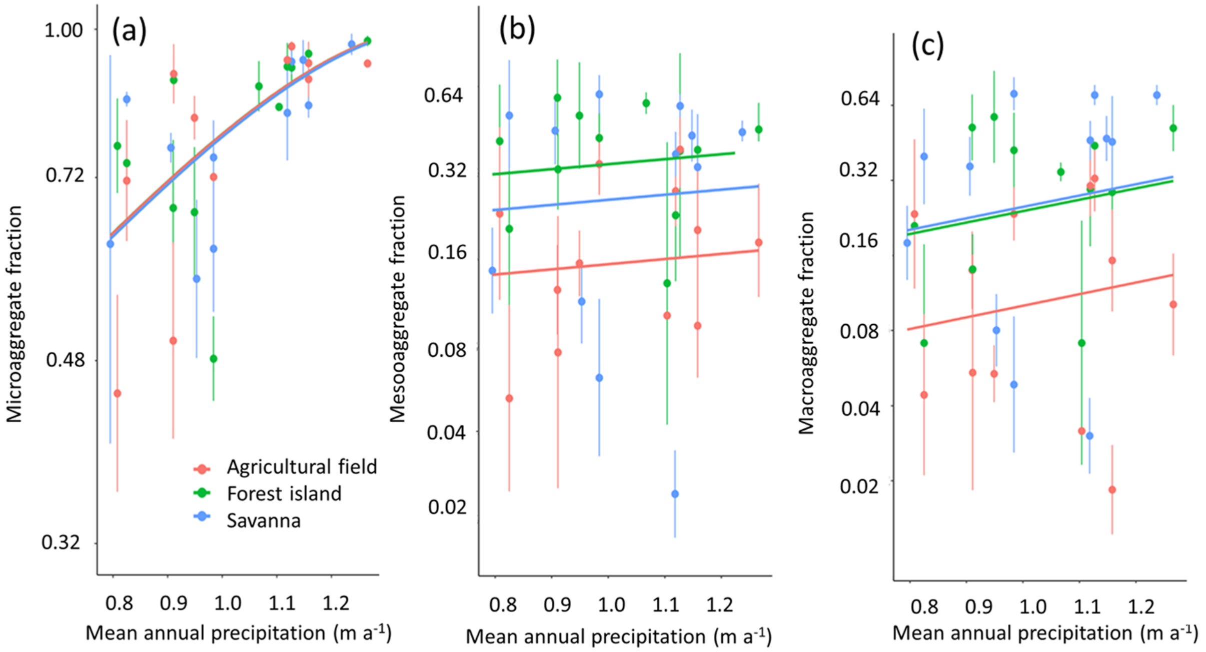

Fig. 2 Effect of land-use and mean annual precipitation on soil aggregate fractions at 0–5 cm depth. **a** microaggregates; **b** mesoaggregates; **c** macroaggregates. Symbol and line colours are as indicated in panel (a), with the fitted lines representing the fixed component of the model fits as summarised in Table 1. Bars represent standard deviations

actually a saturating function of P_A. For example, at a lower $P_A = 0.80$ a^{-1} then $f_{micro} = 0.56$ with the relative increase in f_{micro} per 10 mm of P_A of 1.9%. On the other hand, at the higher $P_A = 1.20$ a^{-1} then the model pedicts a f_{micro} of 0.99 and with each 10 mm increase in rainfall being associated with a relative increase in f_{micro} of just 0.2%. It is also evident that there is an effect of depth ($p < 0.05$) with the regression coefficient of -0.086 ± 0.029 m^{-1} suggesting that f_{micro} were typically 13.7% lower at 5–10 cm depth than was the case for the upper 0–5 cm (Table 1).

For both the stable mesoaggregates (Fig. 2b) and macroaggregates (Fig. 2c), very different patterns of

Table 1 Estimates for linear mixed effects models relating variation in log × arcsine transformed aggregate fractions to precipitation and land-use type. For this analysis, Mean Annual Precipitation P_A estimates for each site have been centred on the dataset mean value of 1.01 m a^{-1}

	Microaggregates $R^2_m = 0.17$, $R^2_c = 0.59$			Mesoaggregates $R^2_m = 0.14$, $R^2_c = 0.82$			Macroaggregates $R^2_m = 0.14$, $R^2_c = 0.82$		
Fixed effect	Coef	S.E	T	Coef	S.E	T	Coef	S.E	t
Intercept (Agricultural field)	-0.030	0.0036	-0.82	-0.805	0.101	-7.94	-0.990	0.127	-7.82
P_A(m)	0.976	0.272	3.58	0.180	0.418	0.43	0.467	0.522	0.89
Forest island	0.007	0.093	0.07	0.354	0.141	2.50	0.383	0.177	2.17
Savanna	-0.003	0.095	-0.04	0.227	0.142	1.60	0.401	0.177	2.27
Sampling depth	-0.086	0.029	-2.97	-0.141	0.024	-5.90	-0.106	0.029	-3.62
Random Component	Parameter			Parameter			Parameter		
Within plot variance	0.0097			0.0190			0.0177		
Between plot variance	0.0387			0.1086			0.1735		
Residual variance	0.0474			0.0337			0.0528		

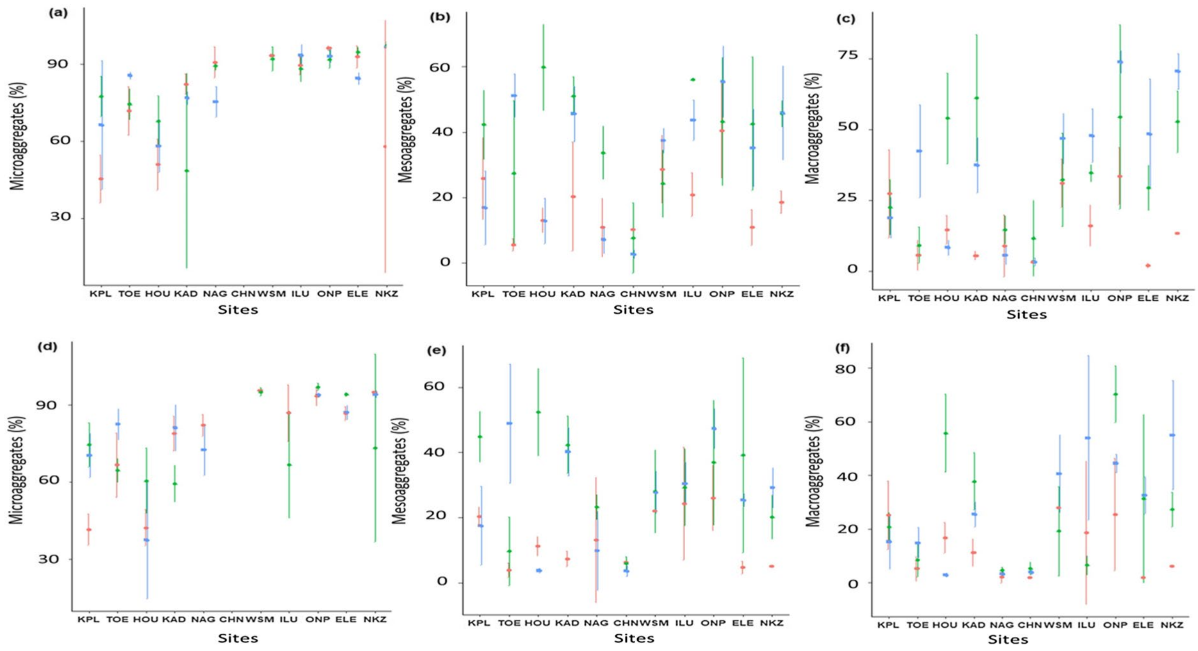

Fig. 3 Site-specific variations in water stable aggregate distribution at 0–5 cm (a-c) and 5–10 cm (d-f) depths. Legend same as for Fig. 2. KPL = Koupela (BNF), TOE = Toece (BNF), HOU = Hounde (BNF), KAD = Kadomba (BNF), NAG = Navrongo (GHA), CHN: Changnayili (GHA); WSM = Wasinm Okuta (NGA), ILU: Ilua (NGA), ONP = Onipatako (NGA), ELE = Elewure (NGA), NKZ = Nkoranza (GHA); BNF = Burkina Faso, GHA = Ghana, NGA (Nigeria). Bars represent standard deviations

variation were observed with there being no dependence of soil aggregate stability on P_A but with effects of land-use being observed in both cases. For example, again calculating at the data set average $P_A = 1.01$ m a^{-1} , we obtain estimates for $f_{meso} = 0.15$ for AF and with forest island (FI) and savanna (SA) modelled to have f_{meso} that were, on average, 122% and 67% higher respectively. The FI-AF difference here was significant only at $p < 0.05$. As for f_{micro}, there was an effect of sampling depth on f_{meso} with values of the 5–10 cm depth modelled as being 26% lower than is observed at 0–5 cm depth. Overall, the patterns observed for f_{macro} were as for f_{meso} (Fig. 2c), but with the effect of sampling depth being a little less marked (Table 1).

Site-and depth-specific variation in water stable aggregate distributions

With respect to site-specific aggregate stability, some trends were observed at both 0–5 and 5–10 cm depths (Fig. 3). There were generally more stable mesoaggregates and macroaggegates in the forest islands and savannas at both depths than agricultural fields across locations. As an example, all agricultural fields in Nigeria (Elewure, Onipatako, Illua and Wasinm Okuta) showed the least distribution of water stable mesoaggregates at 5–10 cm depth (Fig. 3e) and also at 0–5 cm depth except at Wasinm Okuta. Similarly, all agricultural fields in Ghana (Changnayili, Navrongo and Nkoranza) had the least water stable macroaggregates at 5–10 cm depth (Fig. 3f). In both Nigeria and Burkina Faso, at least 50% of the sites showed agricultural fieds as having the least proportions of stable macroaggregates at both depths (Figs. 3c and 3f). For microaggregate distribution, no clear trend was observed among the land use types, as precipitation was rather a controlling factor already established in Fig. 2a.

Soil factors underlying aggregate stability

Using Kendall's τ and taking mean values per subplot at 0–5 cm depth only, Table 2 details the strength of associations between the soil macro-, meso and micro-aggregate stability. It also shows

Table 2 Strength of association between the studied covariates as estimated by Kendall's τ (soil data for the 0 to 5 cm depth only). Symbols used: f_{micro} = micoaggregate fraction, f_{meso} = mesoaggregate fraction, f_{macro} = macroaggregate fraction, [Fe_o] = oxalate extractable iron concentration, [Al_o] oxalate extractable aluminium concentration,[Fe_d] = dithionite extractable iron concentration, [Ald] = dithionite extractable aluminium concentration, [Fe_c] = pyrophosphate extractable iron concentration, [Al_c] pyrophosphate extractable aluminium concentration, [C] = soil carbon concentration, P_A = mean annual precipitation. Relationships significant at $p < 0.01$ are shown in bold (with grey background) with those for which $0.01 \leq p \lesssim 0.05$ are shown in italics

f_{meso}	0.21									
f_{macro}	0.17	0.70								
[Fe_o]	-0.13	0.11	0.18							
[Al_o]	-0.11	*-0.24*	-0.16	0.23						
[Fe_d]	-0.16	*0.24*	*0.25*	0.32	-0.30					
[Al_d]	-0.16	-0.28	-0.19	0.00	0.70	-0.33				
[Fe_c]	-0.17	0.21	0.19	-0.03	-0.52	0.64	-0.40			
[Al_c]	*-0.26*	-0.17	-0.15	-0.28	0.19	-0.22	0.49	0.00		
[C]	0.00	*0.26*	0.42	0.19	0.01	0.18	-0.02	0.07	-0.05	
P_A	0.50	0.18	0.06	-0.13	-0.19	-0.18	-0.23	-0.13	-0.22	0.03
	f_{micro}	f_{meso}	f_{macro}	[Fe_o]	[Al_o]	[Fe_d]	[Al_d]	[Fe_c]	[Al_c]	[C]

the correlations with and between measures of soil citrate-, dithionate- and pyrophosphate-extractable aluminum and iron, soil carbon and mean annual precipitation amount.

As expected for $f_{\text{micro},}$ there was a strong positive association with P_A ($\tau = 0.50$; $p < 0.0001$), and with a weaker negative association with pyrophosphate-extractable aluminum also of note ($\tau = -0.26$; $p = 0.051$) (Table 2). For f_{meso}, it was the dithionate-extractable aluminum [Al_d] that showed the strongest (negative) correlation ($\tau = -0.28$; $p = 0.032$), and with both dithionate-extractable iron [Fe_d] ($\tau = 0.24$; $p = 0.068$) and soil [C] being positively associated ($\tau = 0.26$; $p = 0.047$). Overall, across sites, there was a very strong association between f_{meso} and f_{macro} ($p < 0.0001$), with soil [C] appearing to be a much stronger determinant of the latter ($\tau = 0.42$; $p = 0.0012$). Also of note, [Fe_d] also showed a modestly strong correlation with f_{macro} ($\tau = 0.25$; $p = 0.053$).

In order to separate out the potentially causative versus correlative factors, partial Kendall correlation coefficients τ_P were subsequently employed. For example, for f_{meso} – testing for [Al_o], [Al_d], [Fe_d] and [C] separately (whilst in each case controlling for variation in the other three covariates) – all of [Al_o], [Al_d] and [Fe_d] were found to be with $|\tau_P| < 0.22$ and with $p > 0.1$. The best of the four tested predictors was [C] for which $\tau_\text{P} = 0.23$ and $p = 0.093$. Although this result for f_{meso} must be regarded as negative, a similar analysis confirmed an unequivocal strong role for [C] in accounting for site-to-site variations in f_{macro} ($\tau_\text{P} = 0.39$; $p = 0.004$). However, all three other tested variables have $|\tau_P| < 0.2$ and with an associated $p > 0.2$. For f_{micro}, the same partial Kendall's analysis suggested nothing other than a strong role for P_A in accounting for the variations observed as already indicated (Table 1) with the f_{micro} *vs.* P_A association already shown in Fig. 2a.

Discussion

Our data show a strong influence of precipitation amount on stable soil micro-aggregates (Fig. 2) whereas land use-type influenced the stable meso- and macro-aggregates in West Africa. Also, soil organic carbon content and iron oxides influenced the stability of soil meso- and macro-aggregates in the region. Here, we discuss these findings and their implications for maintenance of forest islands in the West-African savanna landscapes.

Soil micro-aggregate stability

The strong influence of precipitation amount on the stable soil microaggregates (Fig. 2) is consistent with other studies reporting increased aggregate stability with increasing precipitation amounts (Imeson and Vis, 1982; Lavee et al. 1991; Cerdà 2000; Sarah 2005). This observation was presumably a result of high soil microbial activity. Precipitation has often been reported to increase soil microbial biomass (Logah et al. 2010, 2013; Huang et al. 2015; Anokye et al. 2021), which serves as binding agent in soil aggregate formation (Chotte, 2005). Apart from this, increased precipitation amount enhances microbial decomposition of fresh organic matter (Schaefer 1973; Lavee et al. 1996) leading to production of polysaccharides (Sarig and Steinberger 1993), which enhance the formation of microaggregates (Amezketa 1999; Totsche et al., 2018). The effectiveness of the polysaccharides in the aggregation process (Robert and Chenu 1992) has been attributed to their macromolecular structure, enabling them to be adsorbed on clay particles and also as gluing agent, binding particles together (Chote 2005). Tisdall (1994) showed that microbial debris and bacteria fit in pores within microaggregates and contribute to stability through their extracelluar polysaccharides.

Soil microaggregates may initially form by the progressive bonding of primary particles of clay, soil organic matter and cations, with fungal and bacterial debris giving rise to extremely stable soil microaggregates (Bongiovanni and Lobartini 2006; Bouajila and Gallali 2008).

In some earlier studies (e.g. Utomo and Dexter 1982; Denef et al. 2001; Nsabimana et al. 2020), the extent of soil aggregate stability has been associated with variation in soil moisture and soil drying-wetting cycles which impact on soil microbial biomass. As a result of shrinking and swelling arising from wet-dry cycles, soils with large proportions of macro-aggregates develop more fissures along the plane of weakness (Kay 1990), consequently resulting in breakdown of such aggregates into smaller aggregate-sized groups including microaggregates. The wetting–drying cycles are also known to influence soil strength and hydraulic stability, resulting in cracking and stability failure (Tang et al. 2016).

Drivers of meso and macro-aggregate stability

Land-use type influenced stable soil mesoaggregates and macroaggregates across locations. This results corroborate previous works highlighting the effect of land use on soil agregate stability (Le Bissonnais and Arrouays 1997; Chenu et al. 2000; Erktan et al. 2015). The observation is attributable to management benefits through differences in soil organic carbon content and vegetation, explaining to some extent the positive correlations observed between soil organic carbon content and stable soil aggregates (Table 2). Here, key impacts of vegetation on soil aggregation are advanced. First, vegetation cover moderates the impact of drying-wetting cycles (Cerdà 1998) with the tree litter protecting the soil from the splash effect of rains, preventing disruption of aggregates and the phenomena of sudden drying-wetting of the soil (Le Bissonnais et al. 2018; Pawarda and Tol 2019). For example, Rhoades (1997) reported that improved micro-environmental conditions beneath savanna trees improved soil physical conditions. The influence of vegetation on soil aggregate stability also stems from carbon inputs from leaf litter decomposition and root exudation or rhizo-deposition resulting in binding effects. Though we did not measure the impact of root exudates in this study, it is important to note that they have potential key roles in driving the soil aggregation process as previously demonstrated (Amezketa, 1999; Baumert et al. 2018).

The soil organic carbon improves soil aggregate stability through key organo-mineral mechanisms. These include ligand exchange arising from inner sphere interaction between the carboxyl groups and cations of the mineral structure (Mikutta et al. 2011). The soil organic matter comprises hydrophilic (e.g. carboxyl and C-O-alkyl groups) and hydrophobic structures of aliphatic and aromatic groups (Hanke and Dick 2017). The soil organic matter zonal model (Wershaw et al. 1996; Kleber et al. 2007) suggests that organo-mineral interactions occur between the mineral surface and the organic hydrophilic groups, whilst the aliphatic and aromatic components enhance hydrophobic interaction with other soil organic matter micelles (Hanke and Dick 2017). The mechanism of other organo-mineral interactions such as cation bridges, cation and anion exchange and Van der Waals interactions may also enhance aggregation (Hanke et al. 2015; Hanke and Dick 2017). Because mineral soil surfaces and organic materials are polyanions, they are bridgeable by polyvalent cations namely Ca, Mg, Fe and Al (Oades, 1984). These cations play a crucial ecological role, serving as reversible crosslinking agents (Aquino et al. 2010). Formation and disruption of such cation bridges may close or open sorption sites on soil organic matter (Aquino et al. 2010) with consequences for aggregate stability.

We found that macroaggregates and organic carbon are closely linked in the West African ecosystems ($\tau = 0.42$, Table 2) and may act mutually in a loop cycle. Increasing soil stable aggregates may therefore sustain sequestration of organic carbon by offering physical protection via occlusion from decomposing agents (Guan et al. 2019). Better water stable soil aggregates observed in the forest islands (Fig. 3) may impact sustainability of carbon storage and serve as a step to achieving the goal of better adaptation and mitigation to climate hazards in West Africa. The higher proportion of stable soil macroaggregates in forest islands and natural savanna than in the cultivated soils (Fig. 3c and 3f) indicated negative effects of cultivation on soil aggregation. Similar results have been reported by Cerdà (2000) who found higher soil aggregate stability in scrubland than in cropland in southern Bolivia. Duchicela et al. (2013) observed a decrease in soil aggregate stability in cropland after decline in vegetation cover due to intensive cultivation. In cropland, disaggregation of macroaggregates due to tillage (Ouattara 2007; Six et al. 2000a) is known as key factor leading to less stable soil aggregates. This is by virtue of the fact that annual or seasonal ploughing leads to physical disruption of soil aggregates (Six et al. 2004). Due to its adverse impacts including soil compaction, mechanical tillage increases runoff which overall, enhances susceptibility to soil aggregate breakdown (Kahlon et al. 2013). Moreover, ploughing in agricultural land causes loss of soil organic matter through increased mineralization with negative implications on soil aggregate stability.

Our results show strong positive relationship ($\tau = 0.70$) between meso- and macroaggregates (Table 2), which seem to suggest soil aggregate hierarchy (Barthès et al. 2008) under the land use systems of West Africa. This implies that macroaggregates resulted mainly from bounding of mesoaggregate and in the event of disruption by disaggregating factors, macroaggregate could release mesoaggregates (Barthès et al. 2008). We also observed a positive but lower strength of relationship between meso- and microaggregates ($\tau = 0.21$, Table 2) suggesting a likely hierarchy between these two aggregate groups as well. Though aggregate hierarchy has not often been reported for low activity clay (LAC) soils typical of our study region, Feller et al. (1996) reported the likelihood for an aggregate hierarchy on Ultisol, Inceptisol and Oxisol. Conversely, Oades and Waters (1991) and Six et al. (2000b) reported aggregate hierarchy on soils dominated by 2:1 clay mineralogy. There were greater proportions or dominance of micro-aggregates than macro- and meso-aggregates in the land use systems (Fig. 3) depicting clearly the light-textured nature of the soils in the West African ecosystems (Appendix S1). On tropical soils, high proportion of soil stable macroaggregates has usually been observed on clayey LAC (Albrecht et al. 1998; Six et al. 2000b) but less frequently for less stable coarse-textured soils (Dalal and Bridge 1996; Spaccini et al. 2001).

Iron oxides mainly Fe_d significantly influenced ($p = 0.05$) meso and macroaggregates stability in order of 24 and 25%, respectively (Table 2). In an earlier study, Igwe et al. (2013) reported the dithionite or the crystalline iron ($Fe_{d)}$ forms having a positive influence on the stability of soil aggregates. Positive effects of iron oxides content on soil stability have also been reported in other tropical soils (Ouattara 2008; Demenois et al. 2017). The role of iron oxides or sequioxides in soil aggregation is ascribable to their 1) flocculation ability, 2) effect in binding of clay particles to organic molecules, and 3) potential precipitation on clay surfaces as gels, with these mostly considered as modulating meso-aggregation (Amézketa 1999, Barthès et al. 2008). Besides, electrostatic interactions between clays and the oxides account for aggregation but due to their limited range of action, these mostly result in rather less stable macroaggregates to slaking (Six et al. 2002). Though Barthès et al. (2008) indicated the importance of Al-containing crystalline sesquioxides in modulating macroaggregate stability in some tropical soils, this observation has not been widely reported in literature. Our results rather emphasized, a strong dominance of iron oxides and showed negative correlation of aluminium oxides with aggregate stability (Table 2).

Conclusions

We conclude that the primary stage of stable soil aggregate formation (i.e. microaggregates) in the west African ecosystems was climate (precipitation) driven whereas the more labile and larger-size groups (meso-and macro-aggregates) were land-use driven, the latter arising principally from protection of vegetation cover in the more dense forest islands and the natural savanna with relatively higher carbon inputs than adjacent croplands. We also found soil organic carbon content and iron oxides as key determinants of meso- and macro-aggregate stability in the region. The study provides first insights in soil quality processes in a poorly studied but unique phenomenon of man-made forest islands in West Africa. It also has implication for land mangement as the forest islands could be useful in the prevention of soil erosion at the landscape scale, enhancement of soil biodiversity and in the provision of other ecoystem services.

Acknowledgements The authors are grateful to the Royal Society-DFID for funding the study through the Soil of Forest Island in Africa (SOFIIA) ACBI project. We also thank the local village occupants for their collaboration and field assistance.

Funding This work was funded by the Royal Society-DFID Africa Capacity Building Initiative (ACBI) through the SOFIIA project.

Data Availability The datasets used during the current study are available from the corresponding author on reasonable request.

Code availability R statistics.

Declarations

Competing interests The authors declare that they have no competing interests.

Ethics approval and consent to participate Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

References

Albrecht A, Angers DA, Beare MH, Blanchart E (1998) Déterminants organiques et biologiques de l'agrégation : implications pour la recapitalisa- tion de la fertilité physique des sols tropicaux. Cah Agric 7:357–363

Amezketa E (1999) Soil aggregate stability: a review. J Sustain Agric 14(2):83–151

Anokye J, Logah V, Opuku A (2021) Soil carbon stock and emission: estimates from three land-use systems in Ghana. Ecol Process 10(1):1–13

Aquino AJA, Tunega D, Schaumann GE, Haberhauer G, Gerzabek MH, Lischka H (2010) The functionality of cation bridges for binding polar groups in soil aggregates. Int J Quantum Chem 111(7–8):1532–1542

Bach EM, Hofmockel KS (2015) A time for every season: soil aggregate turnover timulates decomposition and reduces carbon loss in grasslands managed for bioenergy. Glob Change Biol 8(3):588–599

Barthès BG, Kouakoua E, Larré-Larrouy M-C, Razafimbelo TM, de Luca EF, Azontonde A, Carmen NCSVJ, de Freitas PL, Feller CL (2008) Texture and sesquioxide effects on water-stable aggregates and organic matter in some tropical soils. Geoderma 143:14–25

Barthès B, Roose E (2002) Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. CATENA 47(2):133–149

Baumert VL, Vasilyeva NA, Vladimirov AA, Meier IC, Kogel-Knabner I, Mueller CW (2018) Root exudates induce soil macroaggregation facilitated by fungi in subsoil. Front Environ Sci 6:140

Beare M, Hendrix PF, Coleman DC (1994) Water-stable aggregates and organic matter fractions in conventional and no-tillage soils. Soil Sci Soc Am J 58:777–786

Bashagaluke JB, Logah V, Opoku A, Tuffour HO, Sarkodie-Addo J, Quansah C (2019) Soil loss and runoff characteristics under different soil amendments and cropping systems in the semi-deciduous forest zone of Ghana. Soil Use Manage 35(4):617–629

Berendse F, van Ruijven J, Jongejans E, Keesstra S (2015) Loss of plant species diversity reduces soil erosion resistance. Ecosyst 18(5):881–888

Bloin M, Philippy R, Bartoli F (1990) Dossier de valorisation d'un prototype de désagrégation des sols. Institut National de la Propriété Industrielle, Paris, p 16

Bongiovanni M, Lobartini J (2006) Particulate organic matter, carbohydrate, humic acid contents in soil macro and microaggregates as affected by cultivation. Geoderma 136(3–4):660–665

Boonman CC, van Langevelde F, Oliveras I, Couédon J, Luijken N, Martini D, Veenendaal EM (2020) On the importance of root traits in seedlings of tropical tree species. New Phytol 227(1):156–167

Borggaard O (1983) Iron Oxides in Relation to Aggregation of Soil Particles Acta Agric Scand 33(3):257–260

Bouajila A, Gallali T (2008) Soil organic carbon fractions and aggregate stability in carbonated and no carbonated soils in Tunisia. J Agron 7(2):127–137

Cerdà A (2000) Aggregate stability against water forces under different climates on agriculture land and scrubland in southern Bolivia. Soil till Res 57(3):159–166

Cerdà A (1998) Soil erodibility under different Mediterranean vegetation types. CATENA 32:73–86

Chartier M, Rostagno C, Pazos G (2011) Effects of soil degradation on infiltration rates in grazed semiarid rangelands of northeastern Patagonia. Argentina J Arid Environ 75(7):656–661

Chenu C, Le Bissonnais Y, Arrouays D (2000) Organic matter influence on clay wettability and soil aggregate stability. Soil Sci Soc Am J 64:1479–1486

Chote JL (2005) Importance of microorganisms in soil aggregation. In: Buscot F, Varma A (eds) Soil Biology, vol 3. Springer-Verlag, Berlin Heidelberg, pp 107–119

Dalal RC, Bridge BJ (1996) Aggregation and organic matter storage in sub- humid and semi-arid soils. In: Carter MR, Stewart BA (eds) Structure and organic matter storage in agricultural soils. Lewis Publishers, Boca Raton, FL, Advances in Soil Science, pp 263–307

Demenois J, Carriconde F, Rey F, Stokes A (2017) Tropical plant communities modify soil aggregate stability along a successional vegetation gradient on a Ferralsol. Ecol Eng 109:161–168

Denef K, Six J, Bossuyt H, Frey SD, Elliott ET, Merckx R, Paustian K (2001) Influence of dry-wet cycles on the interrelationship between aggregate, particulate organic matter, and microbial community dynamics. Soil Biol Biochem 33:1599–1611

Duchicela J, Sullivan T, Bontti E, Bever J (2013) Soil aggregate stability increase is strongly related to fungal community succession along an abandoned agricultural field chronosequence in the Bolivian Altiplan. J Appl Ecol 50:1266–1373

Erktan A, Cécillon L, Graf F, Roumet C, Legout C, Rey F (2015) Increase in soil aggregate stability along a Mediterranean successional gradient in severely eroded gully bed ecosystems: combined effects of soil, root traits and plant community characteristics. Plant Soil 398(1–2):121–137

Fairhead J, Leach M (1998) Reframing deforestation. Global analyses and local realities: studies in West Africa. Routledge, London and New York

Fairhead J, Leach M (1995) False forest history, complicit social analysis: Rethinking some West African environmental narratives. World Dev 23(6):1023–1035

Feller C, Albrecht A, Tessier D (1996) Aggregation and organic matter storage in kaolinitic and smectitic tropical soils. In: Carter MR, Stewart BA (eds) Structure and organic matter storage in agricultural soils. Lewis Publishers, Boca Raton, FL, Advances in Soil Science, pp 309–359

Gould IJ, Quinton JN, Weigelt A, De Deyn GB, Bardgett RD (2016) Plant diversity and root traits benefit physical properties key to soil function in grasslands, edited by E. Seabloom Ecol Lett 19(9):1140–1149

Guan S, Liu S, Liu R, Zhang J, Ren J, Cai H, Lin X (2019) Soil organic carbon associated with aggregate-size and density fractions in a Mollisol amended with charred and uncharred maize straw. J Integr Agric 18(7):1496–1507

Hadas A (1990) Effect of management practices on soil physical properties. Soil till Res 15(4):393–394

Hanke D, Melo V, Dieckow J, Dick D, Bognola I (2015) Influência da Matéria Orgânica no Diâmetro Médio de Minerais da Fração Argila de Solos Desenvolvidos de Basalto no Sul do Brasil. Rev Bras Ciênc Solo 39(6):1611–1622

https://www.greatgreenwall.org/. The great green wall: growing a world wonder. Accessed 20 July 2020

Hanke D, Dick D (2017) Aggregate stability in soil with humic and histic horizons in a toposequence under Araucaria Forest. Rev Bras Ciênc Solo 41(0), https://doi.org/10.1590/18069657rbcs20160369

Huang G, Li Y, Su YG (2015) Effects of increasing precipitation on soil microbial community composition and soil respiration in a temperate desert, Northwestern, China. Soil Biol Biochem 83:52–56

Igwe CA, Nwokocha D (2006) Soil organic matter fractions and microaggregation in a Ultisol under cultivation and secondary forest in south-eastern Nigeria. Aust J Soil Res 44:627–635

Igwe CA, Zarei M, Stahr K (2013) Stability of aggregates of some weathered soils in south-eastern Nigeria in relation to their geochemical properties. J Earth Syst Sci 122(5):1283–1294

Imeson AC, Vis M (1982) Factors influencing the aggregate stability of soils in natural and semi-natural ecosystems at different altitudes in the Central Cordillera Colombia. Zeitschrift fqr Geomorphologie. N.F. Supplementband 44:94–105

Jones EW (1963) The Forest outliers in the Guinea zone of northern Nigeria. J of Ecol 51(2):415

Kahlon M, Lal R, Ann-Varughese M (2013) Twenty two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. Soil till Res 126:151–158

Kamau S, Barrios E, Karanja NK, Ayuke FO, Lehmann J (2020) Dominant tree species and earthworms affect soil aggregation and carbon content along a soil degradation gradient in an agricultural landscape. Geoderma 359(2020):113983

Kay BT (1990) Rates of change of soil structure under different cropping systems. Adv Soil Sci 12:1–41

Ker A (1995) Farming Systems in the African Savanna. A Continent in Crisis. International Development Research Centre (IDRC), Ottawa. 1st edn. IDRC, Ottawa, pp 166

Kleber M, Sollins P, Sutton R (2007) A conceptual model of organo-mineral interactions in soils: self-assembly of organic molecular fragments into zonal structures on mineral surfaces. Biogeochemistry 85:9–24

Kokou K, Sokpon N (2006) Les forêts sacrées du Couloir Du Dahomey. Bois Et Forêts Des Tropiques 288(2):15–23

Lavee H, Imeson AC, Pariente S, Benyamini Y (1991) The response of soils to simulated rainfall along a climatological gradient in an arid and semi-arid region. Catena Supplement 19:19–37

Lavee H, Sarah P, Imeson AC (1996) Aggregate stability dynamics as affected by soil temperature and moisture regimes. Geogr Ann 78 A(1):7

Le Bissonnais Y, Prieto I, Roumet C, Nespoulous J, Metayer J, Huon S, Villatoro M, Stokes A (2018) Soil aggregate stability in Mediterranean and tropical agro-ecosystems:

effect of plant roots and soil characteristics. Plant Soil 424(1–2):303–317

Le Bissonnais Y, Arrouays D (1997) Aggregate stability and assessment of soil crustability and erodibility: II. Application to humic loamy soils with various organic carbon contents. Eur J Soil Sci 48:39–48

Logah V, Ewusi-Mensah N, Tetteh EN, Quansah C, Danso I (2013) Seasonal variations of soil microbial biomass under different nutrient management and cropping systems on a Ferric Acrisol in Ghana. J Trop Agric 51(1–2):98–104

Logah V, Safo EY, Quansah C, Danso I (2010) Soil microbial biomass carbon, nitrogen and phosphorus dynamics under different amendments and cropping systems in the Semi-deciduous forest zone of Ghana. West Afr J Appl Ecol 17:121–133

Mataix-Solera J, Cerdà A, Arcenegui V, Jordán A, Zavala L (2011) Fire Effects on Soil Aggregation: A Review Earth Sci Rev 109(1–2):44–60

Mathieu C (1998) Pieltain F (1998) *Analyse Physique Des Sols: Methodes Choisies*. Lavoisier, Paris

McKeague J, Brydon J, Miles N (1971) Differentiation of Forms of Extractable Iron and Aluminum in Soils. Soil Sci Soc Am J 35(1):33–38

Mehra OP, Jackson ML (1960) Iron oxide removal from soils and clay by a dithionite-citrate system buffered with sodium bicarbonate. Clays Clay Miner 7:317–327

Morlue B, Kamau S, Ayuke FO, Kironchi G (2021) Land use change, but not soil macrofauna, affects soil soil aggregates and soil aggregate-associated C content in central highlands of Kenya. J Soil Sediment 21(3):1360–1370

Mikutta R, Zang U, Chorover J, Haumaier L, Kalbitz K (2011) Stabilization of extracellular polymeric substances (Bacillus subtilis) by adsorption to and coprecipitation with Al forms. Geochimi Cosmochim AC 75(11):3135–3154

Nakagawa S, Schielzeth H (2013) A general and simple method for obtaining R^2 from generalized linear mixed-effects models. Methods Ecol Evol 4:133–142

Nakagawa S, Schielzeth H (2010) Repeatability for Gaussian and non-Gaussian data: a practical guide for biologists. Biol 85:935–956

Nsabimana G, Bao Y, He X, Nambajimana JD, Wang M, Yang L, Li J, Zhang S, Khurram D (2020) Impacts of water level fluctuations on soil aggregate stability in the three Gorges Reservoir. China Sustainability 12:9107

Oades JM (1984) Soil organic matter and structural stability: mechanisms and implications for management. Plant Soil 76:319–337

Oades JM, Waters AG (1991) Aggregate hierarchy in soils. Aust J Soil Res 29:815–828

Ouattara K (2007) Improved soil and water conservatory managements for cotton-maize rotation system in the western cotton Area of Burkina Faso. Swedish University of Agricultural Sciences Umeå, PhD-thesis

Ouattara K, Ouattara B, Nyberg G, Sédogo M, Malmer A (2008) Effects of ploughing frequency and compost on soil aggregate stability in a cotton–maize (Gossypium hirsutum-Zea mays) rotation in Burkina Faso. Soil Use Manage 24(1):19–28

Pagliai M, Vignozzi N, Pellegrini S (2004) Soil structure and the effect of management practices. Soil till Res 79(2):131–143

Parwada C, Van Tol J (2019) Influence of litter source on soil splash rates and organic carbon loss in different soil horizons. Water SA 45(1):12–19

Rhoades CC (1997) Single-tree influences on soil properties in agroforestry: lessons from natural forest and savanna ecosystems. Agrofor Syst 35:71–94

Robert M, Chenu C (1992) Interactions between soil minerals and microorganisms. In: Stotzky G, Bollag JM (eds) Soil Biochemistry, vol 7. Dekker, New York, pp 307–404

Roose E (1981) Dynamique actuelle des sols ferrallitiques et ferrugineux tropicaux d'Afrique Occidentale. Etude expérimentale des transferts hydrologiques et biologiques de matières sous végétations naturelles ou cultivées. Orléans ORSTOM, Paris

Sarah P (2005) Soil aggregation response to long- and short-term differences in rainfall amount under arid and Mediterranean climate conditions. Geomorphology 70:1–11

Sarig S, Steinberger Y (1993) Immediate effect of wetting event on microbial biomass and carbohydrate production mediated aggregation in desert soil. Geoderma 56:599–607

Schaefer R (1973) Microbial activity under seasonal conditions of drought in Mediterranean climates. In: Castri F, Harold MA (eds) Mediterranean type ecosystems, origin and structure Ecological Studies 7. Springer-Verlag, Berlin, pp 191–198

Six J, Elliott E, Paustian K (2000a) Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol Biochem 32(14):2099–2103

Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil till Res 79(1):7–31

Six J, Feller C, Denef K, Ogle SM, de Moraes Sá JC, Albrecht A (2002) Soil organic matter, biota and aggregation in temperate and tropical soils -effect of no-tillage. Agronomie 22:755–775

Six J, Paustian K, Elliott ET, Combrink C (2000b) Soil Structure and Organic Matter. Soil Sci Soc Am J 64(2):681

Sobey DG (1978) Anogeissus groves on abandoned village sites in theMole National Park, Ghana. Biotropica 10:87–99

Spaccini R, Zena A, Igwe CA, Mbagwu JSC, Piccolo A (2001) Carbohydrates in water-stable aggregates and particle size fractions of forested and cultivated soils in two contrasting tropical ecosystems. Biogeochemistry 53:1–22

Tang C-S, Cui Y-J, Shi B, Tang A-M, An N (2016) Effect of wetting-drying cycles on soil desiccation cracking behavior. Web of Conferences 9:12003

Tisdall JM (1994) Possible role of soil microorganisms in aggregation in soils. Plant Soil 159:115–121

Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates in soils. J Soil Sci 33(2):141–163

Totsche KU, Amelung W, Gerzabek MH, Guggenberger G, Klumpp E, Knief C et al (2018) Microaggregates in soils. J Plant Nutr Soil Sci 181(1):104–136

Utomo WH, Dexter AR (1982) Changes in soil aggregate water stability induced by wetting and drying cycles in non-saturated soil. J Soil Sci 33:623–631

Wershaw RL, Llaguno EC, Leenheer JA, Sperline RP, Song Y (1996) Mechanism of formation of humus coatings on mineral surfaces 2. Attenuated total reflectance spectra of hydrophobic and hydrophilic fractions of organic acids from compost leachate on alumina. Colloids Surf a: Physicochem Eng Aspects 108:199–211

Whalen JK, Hu Q, Liu A (2003) Compost applications increase water-stable aggregates in conventional and no-tillage systems. Soil Sci Soc Am J 67:1842–1847

Zombré NP (2003) Les sols très dégradés (Zipella) du Centre Nord du Burkina Faso: Dynamique, Caractéristiques morpho-bio- pédologiques et impacts des techniques de restauration. Thèse de Doctorat ès Sciences Naturelles, Université de Ouagadougou, p 374