Experimental Agriculture (2024), vol. 60, e27, 1–14
doi:10.1017/S001447972400019X

CAMBRIDGE UNIVERSITY PRESS

RESEARCH ARTICLE

Soil fertility indices in cocoa agroforests under organic and conventional management in Suhum, Eastern Region of Ghana

Deogratias Kofi Agbotui[1], Mariko Ingold[1], Rainer Georg Joergensen[2] and Andreas Buerkert[1]

[1]Organic Plant Production and Agroecosystems Research in the Tropics and Subtropics (OPATS), Universität Kassel, Witzenhausen, Germany; and [2]Soil Biology and Plant Nutrition, Universität Kassel, Witzenhausen, Germany
Corresponding author: Mariko Ingold; Email: tropcrops@uni-kassel.de

(Received 13 January 2024; revised 08 May 2024; accepted 10 July 2024)

Abstract

Deforestation and declining soil fertility are major obstacles for productive cocoa production in West Africa. To improve sustainability of this production system, countries like Ghana promoted agroforestry technologies and introduced organic certification of cocoa agroforests. However, for West Africa, which produces 70% of the world's cocoa, studies comparing soil fertility under conventional and organic management, which is an important factor for sustainable cocoa production, are rare. Hence this study aimed at investigating differences in soil physico-chemical and microbial properties at 0–10 cm and 10–30 cm depth of traditional cocoa agroforests under organic *versus* conventional management in four villages with each three farms in Suhum Municipality, Eastern Region of Ghana. Electrical conductivity, soil organic carbon (SOC), total nitrogen (N), SOC/total N, and extractable potassium (K) in the topsoil were 51%, 35%, 30%, 11%, and 47% respectively, lower ($p < 0.05$) under conventional than under organic management. On average, topsoil under conventional management recorded 29% higher NH_4^+-N concentration and 27% lower NO_3^--N concentrations than topsoil under organic management. Microbial biomass carbon and nitrogen in the topsoil of farms under organic management were 48% and 57%, respectively, greater than under conventional management. Contrarily, conventional management significantly increased the metabolic quotient (qCO_2) in topsoil compared with organic management, indicating a higher demand of soil micro-organisms for maintenance energy due to the use of herbicides and pesticides. In cocoa agroforests, conventional management has adverse effects on soil chemical and microbial properties. Hence transitioning from conventional management to organic management is beneficial to maintain soil fertility.

Keywords: Cocoa production; Organic management; Soil quality; Sustainable agriculture; Microbial indicators

Introduction

Cocoa (*Theobroma cacao* L.) is a globally important crop cultivated in many parts of humid, tropical Africa, Southeast Asia, and South America (Wessel and Quist-Wessel, 2015). During the last decades, increasing demand for cocoa beans motivated farmers to cultivate the crop in monoculture to increase yield (Andres *et al.*, 2016), which has often enhanced deforestation and soil degradation. Typically initial yield after intensification decline over time, as soil nutrients deplete, diseases such as witches' broom (*Moniliophthora perniciosa*) increase and soil fertility is exhausted, particularly when sufficient nutrient input is lacking (Andres *et al.*, 2016). This often forces farmers to abandon their farms and establish new plantations in existing forests (Arévalo-Gardini *et al.*, 2015). Such shifting cultivation systems considerably contribute to forest degradation in cocoa producing countries (Arévalo-Gardini *et al.,* 2015). In West Africa declining soil fertility is among the most limiting factors in cocoa production (Wessel and Quist-Wessel, 2015), which is a major threat to farmers' livelihoods in countries whose economy is highly reliant on cocoa (Kolavalli and Vigneri, 2011). In Ghana, attempts to prevent declining soil fertility and to boost yields by enhancing farmers' adoption of chemical inputs have been largely unsuccessful (Gockowski and Sonwa, 2011). This is due to the relatively high cost of mineral fertilizers and pesticides in addition to lacking knowledge about their efficient utilisation (Wessel and Quist-Wessel, 2015).

Agroforestry technologies have been proposed to counter some of these problems (Alfaro-Flores *et al.,* 2015). Cocoa can be easily cultivated under the shade of forest trees and be intercropped with other perennials (Snoeck *et al.,* 2013) and food crops (Obiri *et al.,* 2007). Traditional agroforests mimic the forest ecosystem and are known to allow soil fertility restoration (Suárez *et al.,* 2021). Increased plant diversity within such traditional cocoa agroecosystems may provide a diversification of litter quantity and quality, root architecture, and other physiological traits, which can improve substrate quality for soil microorganisms (da Silva Moço *et al.,* 2009). Furthermore, nutrient losses from erosion and leaching can be reduced by litter covering the soil surface and nutrient pumping capacity of trees with deep roots (Hartemink, 2005).

To increase the sustainability and profitability of traditional cocoa agroforests, organic certification was introduced in Suhum Municipality, Eastern Region of Ghana in 2005 (Glin *et al.,* 2015). By certification, agroforesters must prove a mineral fertilizer- and pesticide-free production to benefit from a premium price for their cocoa beans. Certified organic farmers are also supported by the provision of free tree and cocoa seedlings, organic fertilizer and pesticides, mechanised spraying machines, extension service, and training on sustainable agronomic practices. Several studies compared soil fertility of traditional agroforestry systems under conventional and organic management (Alfaro-Flores *et al.,* 2015; Haggar *et al.,* 2011; Sauvadet *et al.,* 2019), however, results have been inconclusive. For example, Haggar *et al.* (2011) reported higher soil fertility under organic management than under conventional management in coffee agroforests of Costa Rica. In contrast, in traditional agroforests under cocoa in Bolivia (Alfaro-Flores *et al.,* 2015) and coffee in Costa Rica (Sauvadet *et al.,* 2019) no difference in soil fertility was observed between organic and conventional management. The disparity between the results of Haggar *et al.* (2011) and those of Sauvadet *et al.* (2019) was likely due to the high amount of organic fertilizers used by the former. All of these studies were conducted in systems with moderate to high fertilizer inputs ranging from 46 to 300 kg N ha^{-1}, 2 to 205 kg P ha^{-1}, and 44 to 326 kg K ha^{-1}. In West Africa, where most of the world´s cocoa is produced (Wessel and Quist-Wessel, 2015), input levels of farmers are much lower due to their low investment capacities. Due to organic certification being in its developmental stages for West African cocoa, studies comparing soil fertility in traditional cocoa agroforests under conventional and organic systems are rare. Understanding the impact of management systems on soil fertility is of particular importance as it affects nutrient cycling, carbon sequestration, and sustainable yields as key factors to promote sustainable cocoa agroforestry systems. Hence this study compared (a) the soil physical, chemical, and microbial properties under conventional and organic cocoa agroforests in Ghana, (b) the rate of nitrogen (N) mineralisation and potential N mineralised under conventional and organic cocoa agroforests, and (c) the physical and chemical properties regulating microbial properties in these cocoa agroforests.

Materials and methods

Study sites

Our study was conducted in Suhum Municipality, an area of 359 km^2 (6°2‘3.84“N and longitude 0° 27‘8.64“W) in the Eastern Region of Ghana, West Africa. Suhum Municipality has a long history

https://doi.org/10.1017/S001447972400019X Published online by Cambridge University Press

Table 1. Structural characteristics and yield of cocoa agroforests under organic and conventional management in Suhum Municipality, Eastern Region of Ghana

	Cocoa tree density (stems.ha)	Shade tree density (stems.ha)	Annual litterfall (t ha^{-1})	Standing litter (t ha^{-1})	Cocoa yield (kg ha^{-1})
Organic	1299	389	9	2	500
Conventional	1395	283	8	2	619
CV (%)	18	60	10	14	27

Note: CV = mean coefficient of variation between replicates within management ($n = 6$).

of cocoa production as it is climatically and ecologically well suited for this crop. Since 2005 farmers in some villages produce certified organic cocoa (Glin et al. 2015), so that conventionally and organically managed farms exist under similar environmental conditions. Human activities such as agricultural expansion, lumbering, and fuelwood extraction have changed the vegetation of Suhum from natural semi-deciduous forests to secondary forests and regrowth thickets (MOFA, 2017). The area has a bi-modal rainfall pattern, whereby between 2005 and 2020 annual mean rainfall ranged from 1270 to 1651 mm and annual mean temperature from 23 to 32 °C (World Weather Online, 2021). The soils in the study area are classified as Lixisols (IUSS Working Group WRB, 2015), which is the dominating soil type in the humid and subhumid regions of West Africa (Bationo *et al.* 2006) where most cocoa is grown. Although Lixisols are highly weathered, they are well-suited for cocoa production because of a high saturation with cations, medium to high pH and no aluminium toxicity (Bationo *et al.,* 2006). In the study area two types of Lixisol exist, Ferric and Haplic Lixisols, which were used as one criterion for selecting our study villages. The second selection criterion was to choose a pair of villages, one dominated by certified organic cocoa farms and one dominated by conventional farms, within a 6 km radius. This led to the selection of Nsuta (Haplic Lixisol) and Adimediem (Ferric Lixisol) for organic management whereas Kuano (Haplic Lixisol) and Oboadeka (Haplic Lixisol) represented conventional management.

Organic farms selected for this study (Agbotui *et al.,* 2023) have not received any form of fertilizer in the past two years. Mirids (*Distantiella theobroma*) were controlled by using Pyrethrum (Pyrethrum 5EW™) at the rate of 400 ml ha^{-1} once a year between August and September. Black pod disease (caused by *Phytophthora palmivora* and *Phytophthora megakarya*) was controlled by integrated system management. Weed control was done by slashing them with cutlasses 2–3 times per year.

Mirids and blackpod disease in conventional farms were controlled using Bifenthrin (Akate Master™; 500 ml ha^{-1}) and Imidacloprid (Confidor™; 150 ml ha^{-1}) twice a year between August and September. It is recommended that fertilization in these farms is done using the compound mineral fertilizer Asaase wura™ (Yara, Ghana; NPK 0–22–8 + 9CaO + 7S + 6MgO) at the rate of 300 kg^{-1} ha^{-1} yr^{-1}, but typical farmers only use 50% of this amount. Weed is controlled through a combination of manual weeding and Roundup™ (glyphosate at 225–300 ml ha^{-1}) 2–3 times yearly. Structural characteristics of cocoa agroforests used in this study (Table 1) were typical for the area with a mix of non-N-fixing fruit and timber trees (Asase and Tetteh, 2010; Agbotui *et al.* 2024).

Soil sampling

Within each village, three farms were selected using farm management information obtained from a farmer survey (Agbotui *et al.* 2024). Farms with the most productive tree age ranging from 8 to 25 years (Obiri *et al.,* 2007) were randomly selected ensuring that routine sanitary maintenance such as pruning, weeding, disease, and pest control was guaranteed. Each field was divided into 3–5 sub-plots sized from 1000 to 4000 m^2 for sample collection to account for heterogeneity of the

https://doi.org/10.1017/S001447972400019X Published online by Cambridge University Press

topography. Criteria used for sub-plot delineation was natural occurring slopes based on the farmers' knowledge of their field topography. Within each sub-plot, ten soil samples per depth were taken diagonally in a zig-zag manner at 0–10 cm and 10–30 cm using a soil auger, pooled per sub-plot and depth, and air dried for determination of physico-chemical and microbiological properties.

Soil physico-chemical properties

Bulk density (BD) was measured at each depth using metal cylinders with an inner diameter of 3 cm and a length of 10 cm at a point randomly selected in each field. Soils sampled with the metal cylinders were oven dried at 105 °C until constant weight and soil dry weight was divided by the inner volume of the metal cylinder. After adding 10% H_2O_2 and 2 M HCl to remove organic matter and carbonate, respectively, soil texture was determined by wet sieving for sand and gravitational sedimentation for silt and clay according to Glendon and Dani (2017). Air-dry soil samples were sieved to 2 mm mesh prior to further analysis. Total C and N were determined by a Vario Max CN analyser (Elementar Analysensysteme GmbH, Langenselbold, Germany) after soil was grinded with a ball mill and oven dried at 60 °C for 24 h. Soil pH was assessed at a soil to water ratio of 1:2.5 using a glass electrode (pH 3110, Xylem Analytics Germany GmbH, Weilheim, Germany). Electrical conductivity (EC) was determined at a soil to water ratio of 1:5 with a digital conductivity meter (GMH3430, Seneca Germany GmbH, Remscheid, Germany). Carbonate concentration was measured gas volumetrically by adding 10% HCl to soil following the Scheibler method (Loeppert and Suarez, 1996). Soil organic carbon (SOC) was calculated as the difference between total C and carbonate C.

Potassium was extracted by mechanical shaking of 10 g soil in 100 mL 0.0125 M $CaCl_2$ for 1 hr. The extracts were filtrated through P-free filters (MN280 ¼, Macherey-Nagel GmbH & Co. KG, Düren, Germany) and K was quantified using the flame photometry (BWB Technologies, Newbury, United Kingdom; Toth and Prince 1949). Available soil P was colorimetrically measured using a spectrophotometer (Hitachi U-2000, Hitachi Ltd. Corp., Tokyo, Japan; Bray and Kurtz 1945) in Bray P2 extracts made of 2.5 g soil in 25 mL Bray P2 solution with 0.1N HCl, shaken for 15 min. and centrifuged at 2000 rpm before filtration through P-free filters. For N mineralisation, 20 g air dried soil was incubated at 25 °C and 60% water holding capacity in the dark for 28 days. Ammonium (NH_4^+-N) and nitrates (NO_3^--N) were determined at time intervals of 1, 7, 14, and 28 days after distilled water addition. NH_4^+-N and NO_3^--N were extracted with 0.0125 M $CaCl_2$ and measured with a Continuous Flow Analyzer (Evolution II, Alliance Instruments GmbH, Freilassing, Germany).

Soil microbial properties

Prior to analysis of microbial properties, soil moisture was adjusted to 60% field capacity and samples were incubated at 25 °C for 7 days in the dark to restore microbial population to mimic those in fresh soils (Zornoza *et al.*, 2007). Microbial biomass C (MBC) and N (MBN) were determined by the chloroform fumigation method (Brookes *et al.*, 1985; Vance *et al.*, 1987) in 0.5 M K_2SO_4 extracts (10 g soil in 40 mL extracting solution). Organic C and total N in the fumigated and non-fumigated soil extracts were measured with a C/N analyzer (Multi N/C 2100s, Analytic Jena GmbH, Jena, Germany). MBC was calculated as E_C/k_{EC}, where E_C = (extracted organic C from fumigated soil samples) – (extracted organic C from non-fumigated soil samples) and $k_{EC} = 0.45$ (Wu *et al.*, 1990). MBN was calculated as E_N/k_{EN}, where E_N = (extracted organic N from fumigated soil samples) – (extracted organic N from non-fumigated soil samples) and $k_{EN} = 0.54$ (Brookes *et al.*, 1985). The microbial quotient was calculated as the proportion of MBC in SOC. *In situ* soil respiration was measured using a closed chamber system as described by Predotova *et al.* (2010) in the months of November 2019 and January 2020. The system consisted

https://doi.org/10.1017/S001447972400019X Published online by Cambridge University Press

of a photo-acoustic infrared multi gas analyser (INNOVA 1312-5, Lumasense Technologies A/S, Ballerup, Denmark) connected to a cuvette *via* a 1.5 m long and 3.3 mm diameter Teflon tube®. The cuvette was made up of 0.3 m diameter and 0.11 m high PVC cylinder combined with a 0.3 m diameter and 0.07 m high base ring pushed 0.05 m into the soil. During measurements, the system was kept closed for 10 minutes and air temperature inside the cuvette was monitored with a data logger (Onset HOBO data logger U12-012, USA). To eliminate carry-over contamination in-between measurements, the cuvette was opened and ventilated for 2 min. before the next measurement. Measurements were carried out in the morning (6–10 am) and afternoon (12–3 pm) to capture diurnal changes of CO_2 emissions.

Basal respiration under laboratory conditions was determined using a LGR 915-0011 (Los Gatos Research, Los Gatos, CA, USA) ultra-portable greenhouse gas analyser. To this end, 20 g of pre-incubated moist soil was poured into a 100 ml PET bottle. The bottle was placed into a 1.6 L Mason jar connected to the gas analyser via inlet and outlet tubes of 0.6 m length in a closed chamber system. The gas analyser measured through-flowing air continuously for an accumulation period of 5 min. CO_2 flux rates in both the *in situ* soil and basal respiration were calculated using the 'gasfluxes' package of the R software (Fuss *et al.*, 2020). The metabolic quotient (qCO_2) was estimated as the ratio of basal respiration and MBC.

Statistical analysis

Data were analysed using nested one-way analysis of variance with management as the fixed factor and Lixisol type as the random factor. Using a first order equation ($Nmin = N_0\ (1 - e^{-xt})$), the potential nitrogen mineralisation (N_0) and nitrogen mineralisation rate constant (X) were estimated (Stanford and Smith, 1972). The Pearson correlation was used to analyse the relationship between physico-chemical and microbial properties. Redundancy analysis (RDA) was employed to determine the relationships between soil physico-chemical and microbial properties. Data failing the assumptions of ANOVA (normality and homogeneity of variance) were transformed using the 'bestNormalize' package in R. All statistical analyses were performed using R 4.0.3 software (R Core Team, 2020).

Results

Average BD in the topsoil of conventional farms was 19% higher than in organic farms but this difference was not significant (Table 2). However average sand content in topsoil under conventional management was 14% greater ($p < 0.01$) than topsoil under organic management, whereas clay was 1.5 times greater ($p < 0.01$) under organic management than in conventional management. In the subsoil there was no significant management effect on physical properties.

Management significantly affected chemical properties in topsoil, except for extractable P despite 78% higher extractable P in organic than conventional management (Table 3). Average EC in topsoil of conventionally managed farms was two-folds lower ($p = 0.03$) than their organic counterparts. SOC, total N, SOC/total N, and extractable K in the topsoil were 35%, 30%, 11%, and 47% respectively, lower ($p < 0.01$) under conventional management than under organic management. In the subsoil both physical and chemical properties were not significantly affected by management.

Before incubation, NH_4^+-N concentration was highest in conventionally managed soils, which was 46% greater ($p < 0.01$) than in organically managed ones (Figure 1A). Day 7 yielded a peak in all management systems, but NH_4^+-N concentrations under conventional management was 48% higher ($p < 0.05$) than in organic counterparts. On day 28, NH_4^+-N concentration in organically managed farms was 25% lower ($p = 0.03$) than their conventional counterparts. The concentrations of NO_3^--N on days 7 and 14 were 1.7- and 1.6-folds respectively, greater ($p < 0.01$) under organic management than under conventional management (Figure 1B). For

https://doi.org/10.1017/S001447972400019X Published online by Cambridge University Press

Table 2. Soil physical properties at different depths of cocoa agroforests under organic and conventional management in Suhum Municipality, Eastern Region of Ghana

	Bulk density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)
0–10 cm				
Organic	0.89	50.82	20.10	26.07
Conventional	1.06	57.75	21.77	17.15
CV (%)	31.00	30.75	42.05	40.45
p value	0.06	<0.01	0.50	<0.01
10–30 cm				
Organic	1.10	50.66	21.23	25.25
Conventional	1.30	58.64	17.92	20.20
CV (%)	26.10	32.80	40.80	50.60
p value	0.06	0.11	0.22	0.14

Note: CV = mean coefficient of variation between replicates within management ($n = 6$).

Table 3. Soil chemical properties at different depths of cocoa agroforests under organic and conventional management in Suhum Municipality, Eastern Region of Ghana

	pH	EC (µS cm^{-1})	SOC (mg g^{-1})	Total N (mg g^{-1})	SOC/total N	Extractable P (µg g^{-1})	Extractable K (µg g^{-1})
0–10 cm							
Organic	6.83	66.42	19.60	2.11	9.34	36.17	62.44
Conventional	6.44	32.79	12.83	1.47	8.34	20.37	32.79
CV (%)	8.40	45.85	47.85	42.37	11.35	150.50	74.30
p value	0.02	0.03	<0.01	<0.01	<0.01	0.10	<0.01
10–30 cm							
Organic	6.48	40.37	8.86	1.07	8.07	14.94	30.57
Conventional	6.23	38.27	6.99	0.89	7.01	14.77	25.57
CV (%)	8.80	36.70	56.65	43.25	23.45	180.30	81.55
p value	0.21	0.60	0.19	0.07	0.10	0.59	0.08

Note: CV = mean coefficient of variation between replicates within management ($n = 6$).

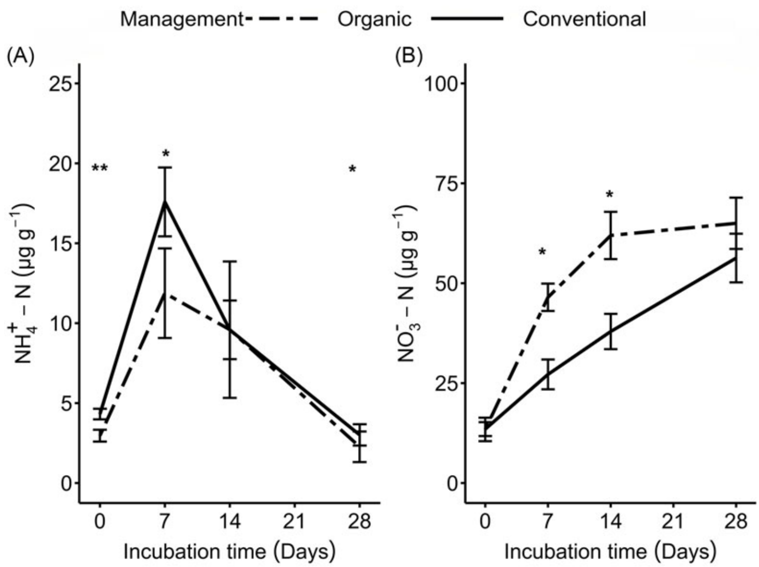

Figure 1. Ammonium (A) and nitrate (B) dynamics of topsoil in cocoa agroforests of villages under organic and conventional management in Suhum Municipality, Eastern Region of Ghana. Soil was incubated under laboratory conditions for 28 days at 25 °C and 60% WHC. Error bars show +/− one standard error of the mean. * and ** indicate *p* values of 0.05 and 0.01, respectively.

https://doi.org/10.1017/S001447972400019X Published online by Cambridge University Press

Table 4. Nitrogen mineralisation of soils at different depths from cocoa agroforests under organic and conventional management in Suhum Municipality, Eastern Region of Ghana incubated for 28 days

	N_0 (μg g^{-1})	X (day^{-1})	R^2
0–10 cm			
Organic	88.20	0.25	0.84
Conventional	77.16	0.24	0.84
CV (%)	68.50	74.90	16.65
p value	0.24	0.98	
10–30 cm			
Organic	33.89	0.39	0.81
Conventional	25.99	0.44	0.80
CV (%)	47.60	53.65	17.85
p value	0.15	0.54	

Note: $Nmin = N_0 (1 - e^{-xt})$; *Nmin* is nitrogen (*N*) mineralised, N_0 is *N* mineralisation potential, *X* is *N* mineralisation rate constant in days, *t* is time, and R^2 is goodness of fit of the exponential curve. CV = mean coefficient of variation between replicates within management ($n = 6$).

Table 5. Soil microbial properties at different depths of cocoa agroforests under organic and conventional management in Suhum Municipality, Eastern Region of Ghana

	MBC (μg g^{-1})	MBN (μg g^{-1})	MB-C/N	Basal respiration (mg CO_2-C g^{-1} d^{-1})	MBC/SOC (%)	qCO_2 (mg CO_2-C g^{-1} d^{-1})
0–10 cm						
Organic	103.88	21.23	5.21	41.71	0.53	133.50
Conventional	70.38	13.54	5.70	49.83	0.57	205.45
CV (%)	48.20	56.97	26.50	64.65	23.05	48
p value	<0.01	<0.01	0.17	0.36	0.50	<0.01
10–30 cm						
Organic	48.79	6.79	7.86	15.64	0.59	88.74
Conventional	48.23	7.83	6.66	11.51	0.79	66.55
CV (%)	41.75	51.00	34.15	79.20	30.95	65
p value	0.76	0.40	0.13	0.16	0.02	0.22

Note: CV = mean coefficient of variation between replicates within management ($n = 6$).

both N mineralisation potential and rate, there was no significant difference between management systems in the top- and subsoil (Table 4).

For MBC and MBN, the topsoil of farms under organic management were 48% and 57% respectively, greater ($p < 0.01$) than under conventional management (Table 5). Contrarily the qCO_2 of the topsoil under conventional management was 54% higher ($p < 0.01$) than under organic management. For microbial properties in the subsoil, it was only MBC/SOC that was 34% greater ($p < 0.05$) under conventional than under organic management. The average *in situ* soil respiration in November 2019 was 41% greater than in January 2020. In both months, management had no effect on *in situ* soil respiration (Figure 2).

Pairwise correlation showed a strong positive relationship for SOC and N with MBC and MBN in topsoils regardless of the management system (Figure 3). The explanatory physico-chemical properties (SOC, pH, BD, and sand) used in the RDA model significantly ($p < 0.01$) explained 70% of the variation in soil microbial properties (MBC, MBN, and BR) in the topsoil (Figure 4). Together the first two axes explained ($p < 0.01$) 72% of the variation. The significant explanatory variables were SOC ($p < 0.01$) which accounted for 64% of the variance, pH ($p < 0.05$) which accounted for 2.4% of the variance and, BD ($p < 0.05$) which accounted for 5.2% of the variance in the model. But SOC and pH were highly correlated with the first RDA axis and BD with the second RDA axis. SOC was positively correlated with MBC and MBN, whereas sand was negatively correlated with SOC, MBC, and MBN. On the other hand, basal respiration correlated with BD and soil pH.

https://doi.org/10.1017/S001447972400019X Published online by Cambridge University Press

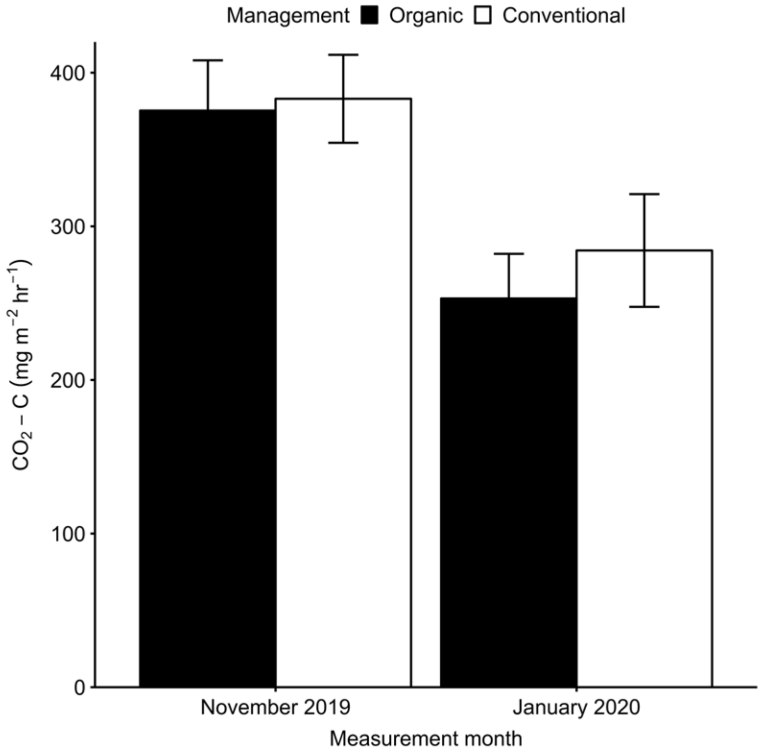

Figure 2. *In situ* soil respiration in cocoa agroforests under organic and conventional management in Suhum Municipality, Eastern Region of Ghana. Error bars indicate +/– one standard error of the mean.

Discussion

Management system's effect on soil selected physico-chemical properties

Cocoa agroforests are known to have high SOC given high continuous supply of organic material via litterfall and turnover of fine roots (Dawoe *et al.*, 2010). The average SOC of the investigated soil was similar to values reported for cocoa agroforests in the Ashanti Region of Ghana (Dawoe *et al.*, 2014), in Cameroon (Sauvadet *et al.*, 2020), and in Bolivia (Alfaro-Flores *et al.*, 2015) ranging from 0.7 to 2.6% and in the lower range of SOC reported for cocoa agroforests in Brazil (Zaia *et al.*, 2012). SOC positively correlated with pH, EC, total N, and extractable K, as SOC is an important regulator of the cation exchange capacity and nutrient buffering. Niether *et al.* (2019) also reported higher soil N and extractable K concentrations in organic agroforest soils compared with conventional agroforest soils in Bolivia, whereby the latter differences were not significant. Soil organic C and soil nutrient pools represent a balance of inputs and outputs. Decomposition processes lead to CO_2 respiration and mineralisation of nutrients, which can leave the soil pool by plant uptake or leaching. While C inputs are coming from dead roots and litterfall, nutrients in organic systems are difficult to replace and the only N source is often coming from legumes (Sauvadet *et al.*, 2020). Despite lacking nutrient input from fertilizers or legumes in the investigated organic farms, total N, extractable P, and K were higher than in conventional farms, which received some mineral fertilizer inputs. While a higher output of plant nutrients by higher yields of cocoa beans, though not significant, in conventional farms is one explanation for this discrepancy, higher leaching losses in the SOC-depleted soils of conventional farms may be another explanatory factor. The composition of shade trees affects C litter quantity and quality, and thus C sequestration as SOC (Sauvadet *et al.*, 2020). Although shade tree composition and

https://doi.org/10.1017/S001447972400019X Published online by Cambridge University Press

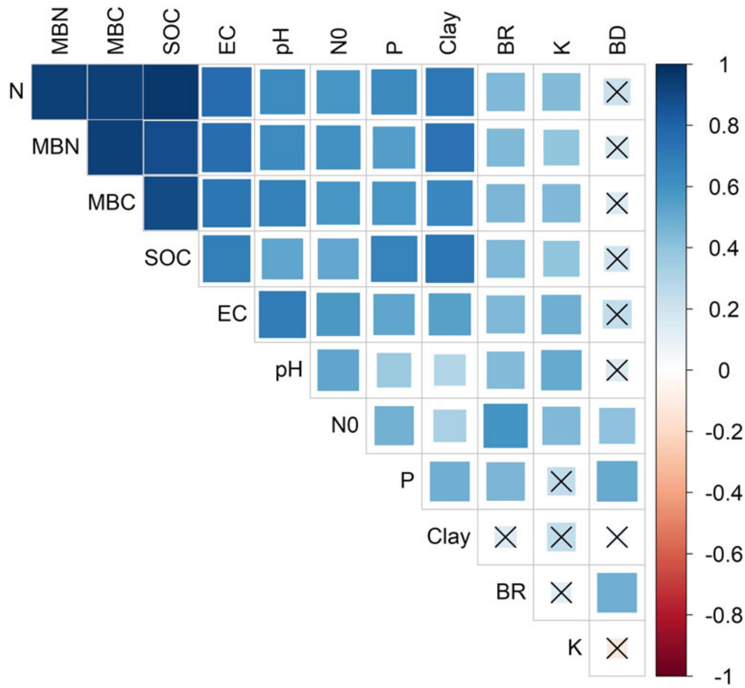

Figure 3. Pearson correlation of soil physico-chemical and microbial properties in the topsoils of cocoa agroforests from the Eastern Region of Ghana. × shows no significant difference at $P > 0.05$. *N*0 refers to the nitrogen mineralisation potential, BD = bulk density, and BR = basal respiration.

density varied between the investigated farms, litterfall quantity was not affected by the management system (Agbotui *et al.* 2024). Therefore, it is likely that decomposition processes were affected by litter quality and/or the use of pesticides, leading to higher SOC sequestration and higher nutrient contents in organically managed soils. However, SOC often correlates with the clay content of soils, which was significantly higher in the organic soils used in current study. High clay content is known to stabilise SOC by absorbing as well as occluding organic materials within aggregates, thereby protecting it from fast decomposition (Singh *et al.*, 2018).

Management system effect on soil N mineralisation

Typically for cocoa agroforests, the NH_4^+-N concentration of all investigated soils were low compared with the NO_3^--N concentration due to the rapid conversion of NH_4^+-N into NO_3^--N (Isaac *et al.* 2005). This demonstrates that irrespective of management in the topsoil (0-10 cm) of cocoa agroforests there is no N limitation for nitrification due to high availability of organic matter. In general, the average N mineralisation rate constant in our soils was ten-fold higher than that reported for cocoa agroforests in Brazil (Zaia *et al.*, 2012). It must be stated that in the current study N mineralisation was determined in a laboratory incubation approach with sieved soils, which can lead to higher mineralisation rates due to the disruption of the natural soil structure (Hassink, 1992). Thus, our values rather represent the potential N mineralisation. However, high clay contents in the Brazilian soil may also explain the observed discrepancy, as soils with high clay content generally have low N mineralisation rates (Soinne *et al.*, 2021). A peak in NH_4^+-N on day 7 during incubation in soils of both management systems is indicative of a quick onset of ammonification, which is the first step of N mineralisation. The decline of NH_4^+-N thereafter and

https://doi.org/10.1017/S001447972400019X Published online by Cambridge University Press

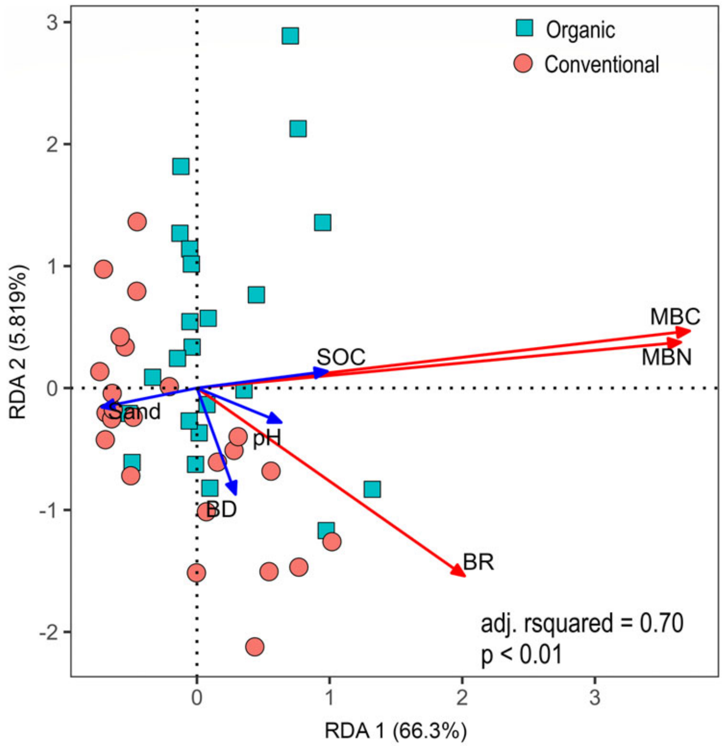

Figure 4. Redundancy analysis biplot using microbial properties as response variables (red arrows) and physico-chemical properties as explanatory variables (blue arrows). Correlations between variables are indicated by angle between arrows i.e. an angle <90° between two arrows imply positive relationship, equal to 90° imply no relationship, and > 90° imply negative relationship. The length of the arrow depicts the strength of association between a variable and the ordination axis in the biplot.

the simultaneous increase in NO_3^--N results from nitrification of NH_4^+-N (Islam et al., 2021). Temporarily and significantly higher NH_4^+-N and lower NO_3^--N in conventional management observed in this study may have resulted from a stimulation of ammonifying bacteria (Demanou *et al.*, 2004) and an inhibition of nitrifying ones (Zhang *et al.*, 2017) by pesticides. The overall N mineralisation potential was numerically higher in organically managed top- and subsoil compared with conventionally managed soils, and may indicate a better N availability for cocoa trees under organic management.

Management system effect on soil microbial properties

Average MBC and MBN were close to 125 μg C g^{-1} and 22 μg N g^{-1} reported for rice (Oryza sativa)-based agroforestry in India (Kaur *et al.*, 2000), but 79% for MBC and 84% for MBN lower than reported for cocoa agroforests in Bolivia (Alfaro-Flores *et al.*, 2015) and Brazil (Zaia *et al.*, 2012). SOC was strongly correlated to the microbial biomass (Figures 3 and 4), as it serves as an energy and nutrient source, and habitat for soil microorganisms and explains the significantly lower MBC and MBN in the topsoil under conventional management. Several authors have reported an inhibitory effect of pesticides on MBC (Mukherjee *et al.*, 2016; Perucci *et al.*, 2000), which are toxic to soil microorganisms, especially those that have low ability for pesticide breakdown (Yang *et al.*, 2009). Additionally, commonly used pesticides such as glyphosate and endosulfan indirectly affect microbial biomass by reducing soil pH (Bueno de Mesquita, *et al.*

https://doi.org/10.1017/S001447972400019X Published online by Cambridge University Press

2023; Manson *et al.* 2022). This can lower microbial growth efficiency leading to reduced microbial biomass and a decline in SOC accumulation (Malik *et al.* 2018).

In contrast to our findings, Alfaro-Flores *et al.* (2015) observed no differences in MBC of cocoa agroforests under organic and conventional management in Bolivia. The lack of a management effect in the cited study might be based on the young age (3 years) of the farms and thus the shorter effective duration of pesticides on soil microorganisms. Differences in soil properties between organic and conventional management systems are often observed in the long-term. Average *in situ* soil respiration of 374 mg m^{-2} h^{-1} in our study was close to 302–318 mg m^{-2} h^{-1} reported for various land use systems in Ghana (Anokye *et al.*, 2021). In our study, the average *in situ* soil respiration was approximately 600-times lower than the average basal respiration (214,125 mg m^{-2} h^{-1}), when estimating the basal respiration on m^{-2} basis using 10 cm soil depth and 0.98 g cm^{-3} BD. Disruption of the soil structure during soil sieving for basal respiration determination consequently exposed more organic matter to microbial degradation (Thomson *et al.*, 2010). In addition, basal respiration was determined under ideal temperature and moisture conditions, which might have led to a higher microbial activity compared with field conditions. The *in situ* measurements were conducted during the dry season, which is characterised by low precipitation and high maximum temperatures of up to 55°C. This may have inhibited microbial activity. In spite of these differences between *in situ* soil and basal respiration, both methods detected no management effect on CO_2 emission. However, qCO_2 was significantly lower in the soils under organic than under conventional management. A higher qCO_2 indicates an increased catabolic demand for maintenance energy (Anderson and Domsch, 2010; Araújo *et al.*, 2008). This phenomenon may be caused by the toxicity of pesticides to non-susceptible microbes (Bonfleur *et al.*, 2015) and low SOC (Malik *et al.* 2018).

Pesticides have been found to reduce microbial diversity and enzymatic activity (Wang *et al.*, 2020), although these were not measured in our study. In general, the qCO_2 values found in the investigated cocoa agroforests were within the range of 60–218 mg CO_2-C g^{-1} d^{-1} reported for agroforests in India (Kaur *et al.*, 2000) and Brazil (Notaro *et al.*, 2014). Araújo *et al.* (2008) found that qCO_2 was higher in conventional than organic management, which confirms our findings and showed that qCO_2 is a sensitive indicator for environmental stress factors of soil microorganisms. This stress leads to soil microbes using more C for respiration instead of growth which reduces nutrient cycling in cocoa agroforests under conventional management.

Conclusion

Our study showed that compared to conventional management, organic management of cocoa agroforests had higher pH, SOC, total N, and microbial biomass C and N. Nitrate was the dominant N form in cocoa agroforests due to the rapid conversion of NH_4^+-N into NO_3^--N. Pesticide use might be the cause for temporarily higher NH_4^+-N concentrations and lower NO_3^--N concentrations in soils under conventional management, although it only numerically increased potential N mineralisation. The topsoil of conventionally managed soils recorded higher qCO_2 than of organically managed ones, which indicates higher C demand for maintenance. Our results show a more intensive nutrient cycling in cocoa agroforests under conventional management.

Acknowledgments. We are indebted to Claudia Thieme-Fricke and Eva Wiegard of the OPATS group and Gabi Dormann of Soil Biology and Plant Nutrition at University of Kassel for their laboratory assistance. Lastly, we are grateful to the Suhum cocoa agroforesters for access to their fields and homes during data collection and to my family and friends for their relentless support throughout this study

Financial support. The German Academic Exchange Service (DAAD) supported this study in the form of a PhD research grant to the first author.

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

Authorship. DKA, MI, and AB designed the experiment. DKA, MI, and RGJ selected the soil fertility indicators. Data analysis was done by DKA and MI. DKA, MI, and RGJ revised the manuscript. AB supervised and helped secured funding.

References

Agbotui, D.K., Ingold, M., Wiehle, M., and Buerkert, A. (2023) Can carbon payments improve profitability of traditional conventional and organic cocoa agroforests? A case study in the Eastern Region of Ghana. *Agroforestry Systems* **97**, 813–831. doi: 10.1007/s10457-023-00828-0.

Agbotui, D.K., Mariko, I., and Buerkert, A. (2024) Carbon and nutrient cycling in cocoa agroforests under organic and conventional management. *Nutrient Cycling in Agroecosystems* **129**, 7–20. doi: 10.1007/s10705-024-10349-6.

Alfaro-Flores, A., Morales-Belpaire, I., and Schneider, M. (2015) Microbial biomass and cellulase activity in soils under five different cocoa production systems in Alto Beni, Bolivia. *Agroforestry Systems* **89**(5), 789–798. doi: 10.1007/s10457-015-9812-z.

Anderson, T.-H., and Domsch, K.H. (2010) Soil microbial biomass: The eco-physiological approach. *Soil Biology and Biochemistry* **42**(12), 2039–2043. doi: 10.1016/j.soilbio.2010.06.026.

Andres, C., Comoé, H., Beerli, A., Schneider, M., Rist, S., and Jacobi, J. (2016) Cocoa in monoculture and dynamic agroforestry. In E. Lichtfouse (ed.), *Sustainable Agriculture Reviews*, 19th edn., pp. 121–153. doi: 10.1007/978-3-319-26777-7_3.

Anokye, J., Logah, V., and Opoku, A. (2021) Soil carbon stock and emission: Estimates from three land-use systems in Ghana. *Ecological Processes* **10**(11), 1–13. doi: 10.1186/s13717-020-00279-w.

Araújo, A.S.F., Santos, V.B., and Monteiro, R.T.R. (2008) Responses of soil microbial biomass and activity for practices of organic and conventional farming systems in Piauí state, Brazil. *European Journal of Soil Biology* **44**, 225–230. doi: 10.1016/j.ejsobi.2007.06.001.

Arévalo-Gardini, E., Canto, M., Alegre, J., Loli, O., Julca, A., and Baligar, V. (2015) Changes in soil physical and chemical properties in long term improved natural and traditional agroforestry management systems of cacao genotypes in Peruvian Amazon. *PLoS ONE* **10**(7), 1–29. doi: 10.1371/journal.pone.0132147.

Asase, A. and Tetteh, D.A. (2010) The role of complex agroforestry systems in the conservation of forest tree diversity and structure in southeastern Ghana. *Agroforestry Systems* **79**, 355–368. doi: 10.1007/ s10457-010-9311-1, , , , ,

Bationo, A., Hartemink, A., Lungu, O., Naimi, M., Okoth, P., Smaling, E.M.A., and Thiombiano, L. (2006) African Soils: Their Productivity and Profitability of Fertilizer Use Background Paper for the Africa Fertilizer Summit 9-13th June 2006, Abuja, Nigeria.

Bonfleur, E.J., Tornisielo, V.L., Regitano, J.B., and Lavorenti, A. (2015) The effects of glyphosate and atrazine mixture on soil microbial population and subsequent impacts on their fate in a tropical soil. *Water, Air, and Soil Pollution* **226**(21), 1–10. doi: 10.1007/s11270-014-2190-8.

Bray, R.H., and Kurtz, L.T. (1945) Determination of total organic and available forms of phosphorus in soils. *Soil Science* **59**(1), 39–46.

Brookes, P.C., Landman, A., Pruden, G., and Jenkinson, D.S. (1985) Chloroform fumigation and the release of soil nitrogen: A direct extraction method to measure microbial biomass nitrogen in soil. *Soil Biology and Biochemistry* **17**(6), 837–842. doi: 10.1016/0038-0717(85)90144-0.

Bueno de Mesquita, C.P., Solon, A.J., Barfield, A., Mastrangelo, C.F., Tubman, A.J., Vincent, K., Porazinska, D.L., Hufft, R.A., Shackelford, N., Suding, K., and Schmidt, S.K. (2023) Adverse impacts of Roundup on soil bacteria, soil chemistry and mycorrhizal fungi during restoration of a Colorado grassland. *Applied Soil Ecology* **185**, 104778. doi: 10.1016/j.apsoil.2022.104778.

da Silva Moço, M.K., da Gama-Rodrigues, E.F., da Gama-Rodrigues, A.C., Machado, R.C.R., and Baligar, V.C. (2009) Soil and litter fauna of cacao agroforestry systems in Bahia, Brazil. *Agroforestry Systems* **76**, 127–138. doi: 10.1007/s10457-008-9178-6.

Dawoe, E.K., Isaac, M.E., and Quashie-Sam, J. (2010) Litterfall and litter nutrient dynamics under cocoa ecosystems in lowland humid Ghana. *Plant and Soil* **330**, 55–64. doi: 10.1007/s11104-009-0173-0.

Dawoe, E.K., Quashie-Sam, S.J., and Oppong, S.K. (2014) Effect of land-use conversion from forest to cocoa agroforest on soil characteristics and quality of a Ferric Lixisol in lowland humid Ghana. *Agroforestry Systems* **88**, 87–99. doi: 10.1007/s10457-013-9658-1.

Demanou, J., Monkiédjé, A., Njiné, T., Foto, S.M., Nola, M., Togouet, S.H.Z., and Kemka, N. (2004) Changes in soil chemical properties and microbial activities in response to the fungicide Ridomil Gold Plus Copper. *International Journal of Environmental Research and Public Health* **1**, 26–34. doi: 10.3390/ijerph2004010026.

Fuss, R, Hueppi, R, and Pedersen, AR (2020) *Greenhouse gas flux calculation from chamber measurements*. Retrieved from https://cran.r-project.org/web/packages/gasfluxes/gasfluxes.pdf

Glendon, W.G., and Dani, O. (2017) Particle size analysis. In Dane, J.H. and Topp, C.G. (eds.), *Methods of Soil Analysis: Part 4. Physical Methods, Madison, Wisconsin, USA*, pp. 255–293. doi: 10.1051/0004-6361/201731731.

Glin, L.C., Oosterveer, P.J.M., and Mol, A.P.J. (2015) Governing the organic cocoa network from Ghana: Towards hybrid governance arrangements? *Journal of Agrarian Change* **15**(1), 43–64. doi: 10.1111/joac.12059.

Gockowski, J., and Sonwa, D. (2011) Cocoa intensification scenarios and their predicted impact on CO_2 emissions, biodiversity conservation, and rural livelihoods in the Guinea rain forest of West Africa. *Environmental Management* **48**(2), 307–321. doi: 10.1007/s00267-010-9602-3.

Haggar, J., Barrios, M., Bolanos, M., Bolaños, M., Merlo, M., Moraga, P., Munguia, R., Ponce, A., Romero, S., Soto, G., Staver, C., and Virginio, E. de M.F. (2011) Coffee agroecosystem performance under full sun, shade, conventional and organic management regimes in Central America. *Agroforestry Systems* **82**, 285–301. doi: 10.1007/s10457-011-9392-5.

Hartemink, A.E. (2005) Nutrient stocks, nutrient cycling, and soil changes in cocoa ecosystems: A review. *Advances in Agronomy* **86**, 227–253. doi: 10.1016/S0065-2113(05)86005-5.

Hassink, J. (1992) Effects of soil texture and structure on carbon and nitrogen mineralization in grassland soils. *Biology and Fertility of Soils* **14**, 126–134. doi: 10.1007/BF00336262.

Isaac, M.E., Gordon, A.M., Thevathasan, N., Oppong, S.K., and Quashie-Sam, J. (2005) Temporal changes in soil carbon and nitrogen in west African multistrata agroforestry systems: A chronosequence of pools and fluxes. *Agroforestry Systems* **65**, 23–31. doi: 10.1007/s10457-004-4187-6.

Islam, M.R., Bilkis, S., Hoque, T.S., Uddin, S., Jahiruddin, M., Rahman, M.M., Rahman, M.M., Alhomrani, M., Gaber, A., and Hossain, M.A. (2021) Mineralization of farm manures and slurries for successive release of carbon and nitrogen in incubated soils varying in moisture status under controlled laboratory conditions. *Agriculture* **11**, 846. doi: 10.3390/agriculture11090846.

IUSS Working Group WRB (2015) *World Reference Base for Soil Resources. World Soil Resources Reports 106 World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.*

Kaur, B., Gupta, S.R., and Singh, G. (2000) Soil carbon, microbial activity and nitrogen availability in agroforestry systems on moderately alkaline soils in northern India. *Applied Soil Ecology* **15**, 283–294. doi: 10.1016/S0929-1393(00)00079-2.

Kolavalli, S., and Vigneri, M. (2011) Cocoa in Ghana: Shaping the success of an economy. In Chuhan-Pole, P. and Angwafo, M. (eds.), *Yes Africa Can: The Success Stories from a Dynamic Continent.* Washington D.C.: World Bank, pp. 201–217.

Loeppert, R.H., and Suarez, D.L. (1996) Carbonate and gypsum. In Bigham, J.M. (ed.), *Methods of Soil Analysis: Chemical Methods.* Madison, Wiscounsin, USA, pp. 437–474.

Malik, A.A., Puissant, J., Buckeridge, K.M., Goodall, T., Jehmlich, N., Chowdhury, S., Gweon, H.S., Peyton, J.M., Mason, K.E., van Agtmaal, M., Blaud, A., Clark, I.M., Whitaker, J., Pywell, R.F., Ostle, N., Gleixner, G., and Griffiths, R.I. (2018) Land use driven change in soil pH affects microbial carbon cycling processes. *Nature Communications* **9**, 3591. doi: 10.1038/s41467-018-05980-1.

Manson, S., Nekaris, K.A.I., Rendell, A., Budiadi, B., Imron, M.A., and Campera, M. (2022) Agrochemicals and shade complexity affect soil quality in coffee homegardens. *Earth* **3**, 853–865. doi: 10.3390/earth3030049.

MOFA (2017) Suhum Municipal Assembly – Ministry of Food and Agriculture. Retrieved March 24, 2019, from http://mofa.gov.gh/site/?page_id=1526

Mukherjee, S., Tripathi, S., Mukherjee, A.K., Bhattacharyya, A., and Chakrabarti, K. (2016) Persistence of the herbicides florasulam and halauxifen-methyl in alluvial and saline alluvial soils, and their effects on microbial indicators of soil quality. *European Journal of Soil Biology* **73**, 93–99. doi: 10.1016/j.ejsobi.2016.01.009.

Niether, W., Schneidewind, U., Fuchs, M., Schneider, M., and Armengot, L. (2019) Below- and aboveground production in cocoa monocultures and agroforestry systems. *Science of the Total Environment* **657**, 558–567. doi: 10.1016/j.scitotenv.2018.12.050.

Notaro, K. de A., Medeiros, E.V. de, Duda, G.P., Silva, A.O., and Moura, P.M. de (2014) Agroforestry systems, nutrients in litter and microbial activity in soils cultivated with coffee at high altitude. *Scientia Agricola* **71**(2), 87–95. doi: 10.1590/S0103-90162014000200001.

Obiri, B.D., Bright, G.A., McDonald, M.A., Anglaaere, L.C.N., and Cobbina, J. (2007) Financial analysis of shaded cocoa in Ghana. *Agroforestry Systems* **71**(2), 139–149. doi: 10.1007/s10457-007-9058-5.

Perucci, P., Dumontet, S., Bufo, S.A., Mazzatura, A., and Casucci, C. (2000) Effects of organic amendment and herbicide treatment on soil microbial biomass. *Biology and Fertility of Soils* **32**, 17–23. doi: 10.1007/s003740000207.

Predotova, M., Gebauer, J., Diogo, R.V.C., Schlecht, E., and Buerkert, A. (2010) Emissions of ammonia, nitrous oxide and carbon dioxide from urban gardens in Niamey, Niger. *Field Crops Research* **115**(1), 1–8. doi: 10.1016/j.fcr.2009.09.010.

R Core Team (2020) *R: A Language and Environment for Statistical Computing.* Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/.

Sauvadet, M., Saj, S., Freschet, G.T., Enock, S., Becquer, T., Tixier, P., and Harmand, J.-M. (2020) Cocoa agroforest multifunctionality and soil fertility explained by shade tree litter traits. *Journal of Applied Ecology* **57**, 476–487. doi: 10.1111/1365-2664.13560.

Sauvadet, M., Van den Meersche, K., Allinne, C., Gay, F., de Melo Virginio Filho, E., Chauvat, M., Becquer, T., Tixier, P., and Harmand, J.-M. (2019) Shade trees have higher impact on soil nutrient availability and food web in organic than conventional coffee agroforestry. *Science of the Total Environment* **649**, 1065–1074. doi: 10.1016/j.scitotenv.2018.08.291.

Singh, M., Sarkar, B., Sarkar, S., Churchman, J., Bolan, N., Mandal, S., Menon, M., Purakayastha, T.J., and Beerling, D.J. (2018) *Stabilization of Soil Organic Carbon as Influenced by Clay Mineralogy Advances in Agronomy*, 1st edn, Vol. **148**, Elsevier Inc. doi: 10.1016/bs.agron.2017.11.001.

Snoeck, D., Lacote, R., Kéli, J., Doumbia, A., Chapuset, T., Jagoret, P., and Gohet, É. (2013) Association of hevea with other tree crops can be more profitable than hevea monocrop during first 12 years. *Industrial Crops and Products* **43**(1), 578–586. doi: 10.1016/j.indcrop.2012.07.053.

Soinne, H., Keskinen, R., Räty, M., Kanerva, S., Turtola, E., Kaseva, J., Nuutinen, V., Simojoki, A., and Salo, T. (2021) Soil organic carbon and clay content as deciding factors for net nitrogen mineralization and cereal yields in boreal mineral soils. *European Journal of Soil Science* **72**(4), 1497–1512. doi: 10.1111/ejss.13003.

Stanford, G., and Smith, S.J. (1972) Nitrogen mineralization potentials of soils. *Soil Science Society of America Proceedings* **36**, 465–472. doi: 10.2136/sssaj1972.03615995003600030029x.

Suárez, L.R., Salazar, J.C.S., Casanoves, F., and Bieng, M.A.N. (2021) Cacao agroforestry systems improve soil fertility: Comparison of soil properties between forest, cacao agroforestry systems, and pasture in the Colombian Amazon. *Agriculture, Ecosystems and Environment* **314**, 107349. doi: 10.1016/j.agee.2021.107349.

Thomson, B.C., Ostle, N.J., Mcnamara, N.P., Whiteley, A.S., and Grif, R.I. (2010) Effects of sieving, drying and rewetting upon soil bacterial community structure and respiration rates. *Journal of Microbiological Methods* **83**, 69–73. doi: 10.1016/j.mimet.2010.07.021.

Toth, S.J., and Prince, A.I. (1949) Estimation of cation-exchange capacit yand exchangeable Ca, K, and Na contents of soils by flame photometer techniques. *Soil Science*, **67**(6), 439–446. doi: 10.1097/00010694-194906000-00003.

Vance, E.D., Brookes, P.C., and Jenkinson, D.S. (1987) An extraction method for measuring soil microbial biomass C. *Soil Biology and Biochemistry* **19**(6), 703–707. doi: 10.1016/0038-0717(87)90052-6.

Wang, X., Lu, Z., Miller, H., Liu, J., Hou, Z., Liang, S., Zhao, X., Zhang, H., and Borch, T. (2020) Fungicide azoxystrobin induced changes on the soil microbiome. *Applied Soil Ecology* **145**, 103343. doi: 10.1016/j.apsoil.2019.08.005.

Wessel, M., and Quist-Wessel, P.M.F. (2015) Cocoa production in West Africa, a review and analysis of recent developments. *NJAS - Wageningen Journal of Life Sciences* **74–75**(1), 1–7. doi: 10.1016/j.njas.2015.09.001.

World Weather Online (2021) Suhum monthly climate averages. Retrieved March 4, 2021, from https://www.worldweatheronline.com/suhum-weather-averages/ashanti/gh.aspx

Wu, J., Joergensen, R.G., Pommerening, B., Chaussod, R., and Brookes, P.C. (1990) Measurement of soil microbial biomass C by fumigation - extraction - an automated procedure. *Soil Biology and Biochemistry* **22**(8), 1167–1169. doi: 10.1016/0038-0717(90)90046-3.

Yang, Q., Zhang, J., Zhu, K., and Zhang, H. (2009) Influence of oxytetracycline on the structure and activity of microbial community in wheat rhizosphere soil. *Journal of Environmental Sciences* **21**(7), 954–959. doi: 10.1016/S1001-0742(08)62367-0.

Zaia, F.C., Gama-Rodrigues, A.C., Gama-Rodrigues, E.F., Moço, M.K.S., Fontes, A.G., Machado, R.C.R., and Baligar, V.C. (2012) Carbon, nitrogen, organic phosphorus, microbial biomass and N mineralization in soils under cacao agroforestry systems in Bahia, Brazil. *Agroforestry Systems* **86**(2), 197–212. doi: 10.1007/s10457-012-9550-4.

Zhang, M., Wang, W., Wang, J., Teng, Y., and Xu, Z. (2017) Dynamics of biochemical properties associated with soil nitrogen mineralization following nitrification inhibitor and fungicide applications. *Environmental Science Pollution Research* **24**, 11340–11348. doi: 10.1007/s11356-017-8762-6.

Zornoza, R., Guerrero, C., Mataix-Solera, J., Arcenegui, V., García-Orenes, F., and Mataix-Beneyto, J. (2007) Assessing the effects of air-drying and rewetting pre-treatment on soil microbial biomass, basal respiration, metabolic quotient and soluble carbon under Mediterranean conditions. *European Journal of Soil Biology* **43**, 120–129. doi: 10.1016/j.ejsobi.2006.11.004.

Cite this article: Agbotui DK, Ingold M, Joergensen RG, and Buerkert A. Soil fertility indices in cocoa agroforests under organic and conventional management in Suhum, Eastern Region of Ghana. *Experimental Agriculture*. https://doi.org/10.1017/S001447972400019X