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RESEARCH ARTICLE

Medium-term effect of fertilizer, compost, and dolomite on cocoa soil and productivity in Sulawesi, Indonesia

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Abstract

In Indonesia, management practices that reduce soil fertility could be limiting cocoa (*Theobroma cacao* L.) production. To address this, we investigated the effects of fertilizers and organic amendments comprising different combinations of NPK + urea, dolomite, and manure-based compost on soil properties and cocoa productivity. We extended an existing field experiment in South Sulawesi, Indonesia, to assess these treatments' effects on cocoa trees from the age of 2.9 years to 7.4 years. The treatments were first applied 5 months after planting and subsequently twice a year. Soil analyses were performed before planting, after 3 years, and finally after 7 years. Productivity was assessed yearly between the age of 3.5 and 7.4 years. The highest yields were obtained from the plots receiving compost, although the yield benefits diminished over time. Inorganic fertilizer alone doubled the yield compared to the control, while the yields with compost and compost + fertilizer were three times that of the control. With dolomite alone, the yield cumulated over 4 years was 41% higher than the control. The positive effect of compost on cocoa yields can potentially be attributed to (1) physical changes increasing soil water availability, (2) the chemical improvement of nutrient availability, and (3) biologically, by promoting the activity of beneficial organisms. The application of dolomite increased soil pH, Ca, and Mg contents. Soil organic carbon greatly declined in the composted treatments, even though 10 kg of compost was applied per tree per year, probably because of the low C:N ratio of the compost. Future studies should assess different fertilizer formulations and combinations with organic inputs and explore the mechanisms by which compost promotes cocoa productivity.

Keywords: Compost; Soil fertility; Cocoa

Introduction

Cocoa (*Theobroma cacao* L.) is a major cash crop for millions of farmers, particularly in developing countries. Indonesia is the third-largest cocoa-producing country in the world, after Ghana and Ivory Coast, with about 50 to 75% of its output coming from Sulawesi. From 1990 to 2010, the land allocated for cocoa production in Indonesia increased 10-fold, reaching a plateau of approximately 17 000 km^2 in 2010 (FAOSTAT, 2020). However, the gross production of cocoa has decreased since 2010 because of declining yields per hectare that started in the early 1990s (FAOSTAT, 2020). Because of the limited availability of land, productivity per hectare will need to increase if Indonesia is to contribute to the increasing global demand for cocoa.

The decline of productivity of cocoa plantations has been related to inadequate management leading to problems such as lower soil fertility and increased levels of pests and disease

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(Asare *et al.*, 2018). Due to a lack of resources to improve the fertility and health of existing farms, low profits have often pushed farmers to move cultivation to forested areas (Ruf, 2001). To prevent deforestation, many public and private stakeholders in the cocoa industry are seeking to improve crop productivity on existing farms (Carodenuto, 2019; Weber, 2017). The revitalization of cocoa farms is being implemented through improved planting material, the integrated control of pests and diseases, optimal shade control, and the long-term management of soil fertility (Asare *et al.*, 2018; Wood & Lass, 2008).

Soil fertility often deteriorates on cocoa farms (Adeniyi *et al.*, 2017). Typically, cocoa trees planted on a freshly cleared forest initially benefit from high fertility due to high organic matter levels and well-developed soil structure. However, the subsequent removal of the harvested pods and beans can reduce nutrient levels (Boyer, 1973; Fassbender *et al.*, 1988; Hartemink, 2005; Thong & Ng, 1978; van Vliet *et al.*, 2015), and soil fertility declines if they are not replenished with organic or mineral/inorganic fertilizers (Aikpokpodion, 2010; Hartemink, 2005). Degradation can also occur due to the acidification of the soil from the use of acidifying fertilizers, like urea, organic matter decay, the removal and leaching of basic cations (Goulding, 2016), and an increased availability of toxic elements (Lal *et al.*, 1989).

To maintain soil fertility, farmers typically apply amendments and fertilizers to replenish nutrients stocks and correct soil acidity. Few peer-reviewed studies have evaluated their effects both on cocoa productivity and soil properties, and where there is research, it often focuses on short-term effects on seedlings or young cocoa trees (Ahenkorah *et al.*, 1987; van Vliet *et al.*, 2015; Wessel, 1971). Verlière (1981) reported that only a few fertilizer experiments with cocoa had provided significant results, and there was a need to determine the interactions between shade management, cocoa nutritional needs, and productivity. Fewer fertilizer studies have been conducted in South-East Asia than in West Africa, and the work completed in Sulawesi is scarce (Mulia *et al.*, 2019). In addition, there have been few studies examining the combined effects of fertilizers, organic inputs (e.g., compost or manure), and other amendments (e.g., lime dolomite).

To address this lack of information for Indonesia, Mulia *et al.* (2019) reported the responses for the first 4 years of a cocoa field trial established in 2011 with various combinations of fertilizers and amendments (organic and inorganic). Because the treatments were continued after the first 4 years, this study aims to evaluate the effects of the treatments on soil properties, growth, and yield on more mature cocoa plants in order to develop fertilizer recommendations based on organic amendments.

Methodology

Experimental site

The experimental area has been described in detail by Mulia *et al.* (2019), but the main points are repeated here for clarity. The plot is located in Bone-Bone, South Sulawesi, Indonesia (2.605833°S, 120.612333°E). The principal activities carried out between 2011 and 2018 on the experiment are presented in Table S1, Table S2, and Table S3. Cocoa plants of clone PBC123, also known as Sulawesi 1, were planted at a 3 m x 3 m spacing in December 2011, that is, 1111 trees per hectare. Shade trees of *Gliricidia sepium* were planted at the same time as the cocoa trees, as well as existing coconuts. In January 2016, after the completion of Mulia's study, new cocoa trees were planted to replace the ones that died during the first phase of the experiment. However, after this replanting, productivity was not recorded on those trees. Monthly precipitation for the 2011–2018 period (Table S4 in supplementary material) was obtained from Mars's Cocoa Research Station, located in Tarengge, approximately 20 km from the site (South Sulawesi, Indonesia).

Treatments

Initially, the experiment followed a randomized block design repeated four times, with 16 cocoa trees for each repetition (Table 1). As described in Mulia *et al.* (2019), there was a control treatment

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Table 1. Breakdown of the treatments applied between 2012 and 2018 (adapted from Mulia et al., 2019)

Rates in g tree^{-1} year$^{-1,}$ equivalent to kg ha^{-1} year^{-1} (considering a density of 1000 cocoa trees per hectare)								
Treatment		C	N	P	K	Ca	Mg	S
A	**No amendment**	0	0	0	0	0	0	0
B	**Mineral fertilizer**	0	120.5	24.5	46.6	0	0	Trace
C	**Compost (10 kg)**	930	130	37	45	551	15	18
D	**Dolomite (5 kg)**	650	0	0	0	1100	650	0
E	**B + C**	930	250.5	61.5	91.6	551	15	18
F	**B + D**	650	120.5	24.5	46.6	1100	650	Trace
G	**C + D**	1580	130	37	45	1651	665	18
H	**B + C + D**	1580	250.5	61.5	91.6	1651	665	18

Soil amendments and fertilizers were applied twice per year and per tree to provide total quantities as follows: 374 g NPK ('Phonska') and 250 g urea (mineral fertilizer), 5 kg dolomite, and 10 kg compost. Combinations (Treatments E–H) were additive. The values represent the total quantities of elements (g) provided per tree each year in each treatment. Phonska is a subsidized compound fertilizer made from three raw materials: urea, DAP (diammonium phosphate), rock phosphate, MOP (potassium chloride), and 'other macronutrients' according to the manufacturer (https://www.pupukkaltim.com/en/distribution-product-product-knowledge). At the time of planting, mineral fertilizer, 100 g NPK (Phonska) and 150 g triple superphosphate (36%), was added to each tree in equal amounts to provide adequate and uniform nutrient conditions for the establishment of all plants in the first few months after planting out (Mulia *et al.*, 2019).

with no fertilizers or amendments (Treatment A), and treatments comprising either the application of NPK fertilizer + urea (Treatment B), compost (Treatment C), and dolomite (Treatment D). Then four possible combinations of the three primary inputs were implemented with cumulated application rates (Treatments E to H). There were eight treatments in total, coded from A to H (one control + three with individual inputs + four with combinations of inputs). The treatments described in Table 1 were split into two applications applied at a 6-month interval. The inorganic fertilizer applied to each tree was a mix of 374 g of Phonska (15% N, 15% $P_2O_{5,}$ and 15% K_2O with traces of S) and 250 g of urea. The compost was locally made of 60% cow manure, 15% empty oil palm bunches, 10% rice straw, 10% diverse leaves (banana, grass, *Gliricidia,* and maize), and 5% cocoa pod husks. A microorganism mix (EM4) was also applied. The compost treatments comprised the application of 5 kg of compost to each tree twice a year (10 kg per year, distributed in six small pits located at 1 m from the trunk, Table S2), and the full chemical composition is described by Mulia *et al.* (2019). The dolomite amendment comprised 18–22% of MgO, but the content for other constituents such as carbonates or calcium oxide CaO was unknown, but typical contents are around 22% Ca, 13% Mg, 13% C, and 52% O in elemental terms (Mineralogical Society of America, 2003).

Sampling and analyses

Soil

In each plot, one soil sample was collected, at the center of the plot, 1 m from a cocoa trunk, at a depth of 0–20 cm, below the scraped surface litter, using an auger. The same day, samples were air-dried before being ground and sieved to 2 mm. The core ring method was used to collect bulk density samples on each plot, next to the soil sample, at a 0–5 cm depth. These were later air-dried at 60°C for 48 hours before weighing. In total, 32 soil samples were collected for soil analyses and bulk density measurement, corresponding to eight treatments with four repetitions each. The samples were then split with one sample sent to Asian-Agri Laboratory in North Sumatra, Indonesia, and the second sample was sent to Cranfield University in the United Kingdom. The analytical methods corresponding to each soil property are listed in Table 2 (Asian-Agri analyses) and Table 3 (Cranfield University analyses). A difference must be noted between the term 'extractable', referring to Asian-Agri analyses (using HCl at 25% v/v as an extractant), and the term 'total' which refers to Cranfield analyses (using microwave-assisted aqua regia digestion).

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Table 2. Soil bulk density, pH, organic carbon, and nitrogen content and extractable and exchangeable nutrient contents in December 2018, 6.5 years after Treatments A–H were first applied

Treatment	○ Bulk density (g cm^{-3})	* pH (water)	† Org. C (%)	‡ N (%)	C/N	†† CEC (cmol kg^{-1})
A	1.12 a (0.01)	5.36 c (0.58)	1.26 a (0.17)	0.138 ab (0.01)	9.13	6.65 ab (1.04)
B	1.10 a (0.08)	5.30 c (0.38)	1.21 a (0.11)	0.123 b (0.03)	9.84	5.89 b (1.25)
C	1.12 a (0.03)	5.21 c (0.46)	1.22 a (0.10)	0.140 ab (0.02)	8.68	7.37 ab (0.83)
D	1.06 a (0.06)	6.83 a (0.17)	1.35 a (0.11)	0.138 ab (0.03)	9.80	8.36 a (0.58)
E	1.08 a (0.10)	5.79 bc (0.25)	1.40 a (0.18)	0.153 ab (0.02)	9.15	8.11 a (0.90)
F	1.09 a (0.06)	6.87 a (0.35)	1.17 a (0.33)	0.153 a (0.02)	7.69	6.94 ab (0.90)
G	1.10 a (0.06)	6.75 a (0.19)	1.24 a (0.22)	0.135 ab (0.02)	9.19	7.16 ab (0.20)
H	1.06 a (0.09)	6.25 ab (0.43)	1.17 a (0.19)	0.128 ab (0.04)	9.16	6.82 ab (0.61)
Average	1.09	6.04	1.25	0.138	9.08	7.16
Stat sign.	0.839	<0.001	0.641	0.511 (K–W)	na	0.010

	§ Extractable (ppm)				
Treatment	P	Ca	Mg	K	‡‡ Exch. Al (ppm)
A	18.4 b (1.4)	95.8 e (5.2)	334 e (18)	666a (57.6)	705 a (24.3)
B	33.8 ab (15.8)	95.9 e (10.4)	329 e (11.2)	641a (61.1)	743 a (59.4)
C	32.1 ab (19.7)	117 d (13.6)	383 d (24.7)	715a (76.1)	720 a (4.4)
D	38.4 ab (22.8)	947 a (64.0)	980 a (63.7)	704a (88.1)	20.9 c (1.4)
E	68.4 a (24.6)	167 c (32.3)	427 d (41)	745a (18.8)	678 a (99.5)
F	48.3 ab (16.6)	2010 a (2438.3)	1540 a (1280)	699a (53.1)	27.0 c (18.3)
G	33.4 ab (15.1)	630 b (118)	804 b (65.1)	678a (68.7)	30.4 bc (6.8)
H	37.2 ab (29.6)	386 bc (201)	620 c (71.9)	716a (75.5)	141 b (111)
Average	38.8	556	677	696	383
Stat sign.	0.076	<0.001 (K–W)	<0.001 (K–W)	0.457	<0.001 (K–W)

		†† Exch. Bas. Cation (ppm)					
Treatment	Available P (ppm)	Ca	Mg	K	Na	Total (cmol kg^{-1})	¥ B.S. (%)
A	3.66 bc (1.15)	85.2 d (29.7)	20.1 d (6.4)	39.1 a (9.03)	12.6 a (2.97)	0.45	6.77
B	4.83 ab (0.61)	81.2 d (23.7)	21.9 d (5.3)	37.1 a (7.14)	13.8 a (3.75)	0.45	7.60
C	8.12 a (2.69)	150 c (51.6)	40.1c (12.6)	37.1 a (3.48)	12.6 a (1.33)	0.69	9.36
D	1.90 c (0.20)	1840 a (219.8)	813 a (126.3)	34.2a (4.05)	13.8 a (1.88)	8.07	96.5
E	12.6 a (7.33)	247 c (91.6)	84.5 c (52.3)	40.1 a (2.58)	13.8 a (0.00)	1.13	13.9
F	9.53 b (12.34)	1860 a (708.6)	931 a (343.0)	41.1 a (7.14)	15.5 a (4.35)	8.66	125
G	3.95 b (1.13)	1190 b (187.0)	651 ab (121.8)	45.0 a (8.95)	15.5 a (2.20)	5.83	81.4
H	4.48 b (1.71)	884 b (255.3)	490 b (186.3)	39.1 a (2.20)	14.4 a (2.89)	4.39	64.3
Average	6.13	792	382	39.1	14.0	3.71	50.6
Stat sign.	0.006 (K–W)	<0.001 (K–W)	<0.001 (K–W)	0.757	0.713	na	na

Soil treatments were applied twice per year, beginning in May 2012. Soil properties were determined in the soil laboratory of the Asian-Agri Laboratory in North Sumatra, Indonesia (samples collected in December 2018). Soil treatments are: A, control; B, mineral; C, compost; D, dolomite; E, mineral/compost; F; mineral/dolomite; G, compost/dolomite; H, all amendments. Means are calculated on four samples and given with three significant figures. Numbers in brackets are standard deviations. Treatments with the same letter are not statistically different ($P > 0.05$). K–W attached to a statistical significance refers to the p-value of Kruskal–Wallis test, used if ANOVA assumptions were not met. Methods: ♠After Fahmy (1977); ○Core ring method; ▣pH determined by AIAT Soil Laboratories, Maros; †Walkley–Black method; ‡Kjeldahl method; §25% HCl extraction; ¶Bray-I method; ††Ammonium acetate (pH 7) extraction; and ‡‡KCl (1 N) extraction. 'na' stands for not applicable (calculated data). ¥ B.S. refers to base saturation.

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Table 3. Total contents of some soil elements of the experiment in December 2018

	‡ Total (%)		♠ Total (ppm)
Treatment	C	N	P
A	1.64 a (0.152)	0.139 a (0.0101)	283 b (37.7)
B	1.52 a (0.143)	0.128 a (0.00465)	285 ab (23.2)
C	1.58 a (0.0837)	0.133 a (0.00767)	320 ab (35.2)
D	1.75 a (0.117)	0.140 a (0.011)	296 ab (27.5)
E	1.82 a (0.219)	0.147 a (0.016)	366 a (57.7)
F	1.70 a (0.161)	0.136 a (0.0118)	340 ab (37.3)
G	1.64 a (0.284)	0.134 a (0.020)	289 ab (20.2)
H	1.54 a (0.139)	0.130 a (0.00804)	296 ab (23.6)
Average	1.65	0.136	309
Stat. sign.	0.253	0.424	0.021

	♠ Total (ppm)			
Treatment	Ca	Mg	K	Na
A	98.4 e (27.3)	352 d (43.7)	667 a (70.0)	94.1 ab (26.8)
B	98.7 e (21.3)	398 cd (57.3)	800 a (212)	114 ab (23.6)
C	134 de (41.5)	460 c (65.6)	913 a (258)	136 a (23.1)
D	1120 a (94.9)	1020 a (80.9)	776 a (196)	127 ab (33.1)
E	177 d (81.9)	406 cd (74.1)	684 a (193)	94.5 b (16.4)
F	1850 ab (1890)	1500 ab (1280)	584 a (131)	85.4 b (2.19)
G	758 bc (128)	754 ab (164)	569 a (355)	102 b (78.2)
H	481 c (130)	635 b (88.1)	797 a (259)	120 ab (48.7)
Average	589	691	724	109
Stat. sign.	<0.001 (K–W)	<0.001 (K–W)	0.386	0.150 (K–W)

	♠ Total (%)		♠ Total (ppm)			
Treatment	Al	Fe	Cu	Zn	Mn	B
A	1.98 a (0.223)	1.83 a (0.245)	2.38 a (0.660)	5.76 a (1.24)	55.3 ab (11.0)	1.92 ab (0.272)
B	2.08 a (0.286)	1.85 a (0.221)	2.42 a (0.409)	6.17 a (1.54)	67.0 ab (9.12)	1.99 ab (0.664)
C	2.11 a (0.185)	1.83 a (0.152)	2.66 a (0.96)	7.82 a (2.35)	81.2 a (11.2)	2.46 a (0.696)
D	2.17 a (0.347)	2.00 a (0.304)	2.39 a (0.792)	6.64 a (1.07)	63.1 ab (13.9)	2.19 ab (0.737)
E	2.01 a (0.170)	1.86 a (0.135)	3.33 a (0.661)	7.66 a (1.88)	57.9 ab (14.0)	1.28 bc (0.402)
F	1.75 a (0.133)	1.75 a (0.175)	2.70 a (0.750)	9.12 a (5.57)	49.3 ab (11.2)	0.889 c (0.530)
G	1.77 a (0.479)	1.73 a (0.130)	2.43 a (0.568)	6.42 a (1.33)	46.7 b (22.1)	1.35 bc (1.80)
H	1.99 a (0.451)	1.84 a (0.364)	3.29 a (0.221)	10.4 a (7.15)	63.2 ab (14.6)	1.68 abc (0.740)
Average	1.98	1.84	2.7	7.5	60.5	1.72
Stat. sign.	0.476	0.812	0.242	0.671 (K–W)	0.047	0.091 (K–W)

Soil treatments were applied twice per year, beginning in May 2012. These soil properties were determined at Cranfield University laboratory (samples collected in Indonesia in December 2018). Soil treatments are: A, control; B, mineral; C, compost; D, dolomite; E, mineral/compost; F; mineral/dolomite; G, compost/dolomite; and H, all amendments. Means are calculated on four samples and given with three significant figures. Numbers in brackets are standard deviations. Treatments with the same letter are not statistically different ($P > 0.05$). K–W attached to a statistical significance refers to the p-value of Kruskal–Wallis test, used if ANOVA assumptions were not met. ‡ The total soil contents of these elements were determined after dry combustion (SOP based on ISO 10694:1995), while the total contents marked by ♠ were analyzed by ICP-MS after using an HCl/HNO3 extractant (SOP based on ISO 11047:1998).

Growth of cocoa

Mulia *et al.* (2019) reported the height of each cocoa tree height. In this study, the cocoa growth was determined from the circumference of the trunks (30 cm from the soil surface) because the bushes had recently been pruned. These measurements were converted to mean basal areas per treatment (formula and results available in Table S5). Both the soil sampling and the trunk measuring occurred at the same time in December 2018. The number of dead cocoa trees was used to calculate average survival rates per treatment and is presented in the supplementary material (Table S6).

Productivity and bean quality

From January 2015 to December 2018, cocoa tree productivity was assessed by counting the total number of pods produced per tree over a year, and measuring the weight of pods and the annual yield of cocoa beans per plot, as described in Mulia *et al.* (2019). A pod index (*PI*, number of pods required to produce 1 kg of dry beans) for each treatment was derived from the pod counts and the mean pod weights ($PI = 1000 \div$ average yield per pod in grams) (Table S7). The number of healthy and infected pods was also recorded. The pods were categorized as being uninfested or infested following the method previously described in McMahon *et al.* (2015). A sample of the harvested beans was also collected in November 2017 to determine the waste fraction and the average weight of the fresh beans. Harvest quality results were obtained from Mars Laboratory in Makassar. The mean pod count per tree, yield per pod, pod index, and proportion of infected pods for each year and treatment are presented as supplementary material (Table S7). In Mulia's study, productivity data covered the second semester of 2014 and the first of 2015, whereas this study recorded the annual yields from January 2015 to December 2018.

Statistical analyses

Basal areas, dry bean yields, and pod counts were averaged *per surviving tree* (≤ 16) and then extrapolated to 1000 trees to provide a per hectare value (as in Mulia *et al.*, 2019). Additionally, the average yield *per planted tree* was also calculated, this time dividing the yield per plot by the number of initial trees, 16, and then multiplying by 1000 to derive the adjusted yield per hectare. Averaging per surviving tree minimizes treatment differences due to mortality rates. However, it can lead to the confounding effect in that trees with lower competition (i.e., where the mortality is high) could show greater growth rates and higher yields on a per tree basis.

Means and standard deviations of the four replicates were calculated for each variable (growth, productivity, and the soil analyses) and each treatment. Statistical differences between the treatments were evaluated by submitting the individual observations to an ANOVA followed by a Tukey HSD test in R 3.6.0 using the package 'agricolae' (at $P = 0.05$). If ANOVA assumptions were not met, the Kruskal–Wallis test was applied using the 'kruskal' function (at $P = 0.05$), and multiple comparisons between the treatments were obtained by using Fischer's least significant difference post hoc test (with a level of significance at 0.05). Because of the lack of dispersion data in 2014, we used Welch one-sample t-tests to estimate the statistical difference between the two soil sampling periods, 2014 and 2018. In this case, we had to assume that the 2014 result was equal to the true mean (Table S8).

Results

Tree basal areas and survival rates

Tree basal areas and survival rates in December 2018, 7 years after planting, are presented in Figure 1a. Compared to the control (Treatment A) and the mineral fertilizer-only plots (Treatment B), we found significantly higher mean basal areas where compost and dolomite together (Treatment G) and the full combination were applied (Treatment H). The observed basal areas (of surviving trees only) were relatively heterogeneous for all treatments, with coefficients of variation ranging from 25 to 41% (Table S5). Treatment B had the lowest survival rate (41%),

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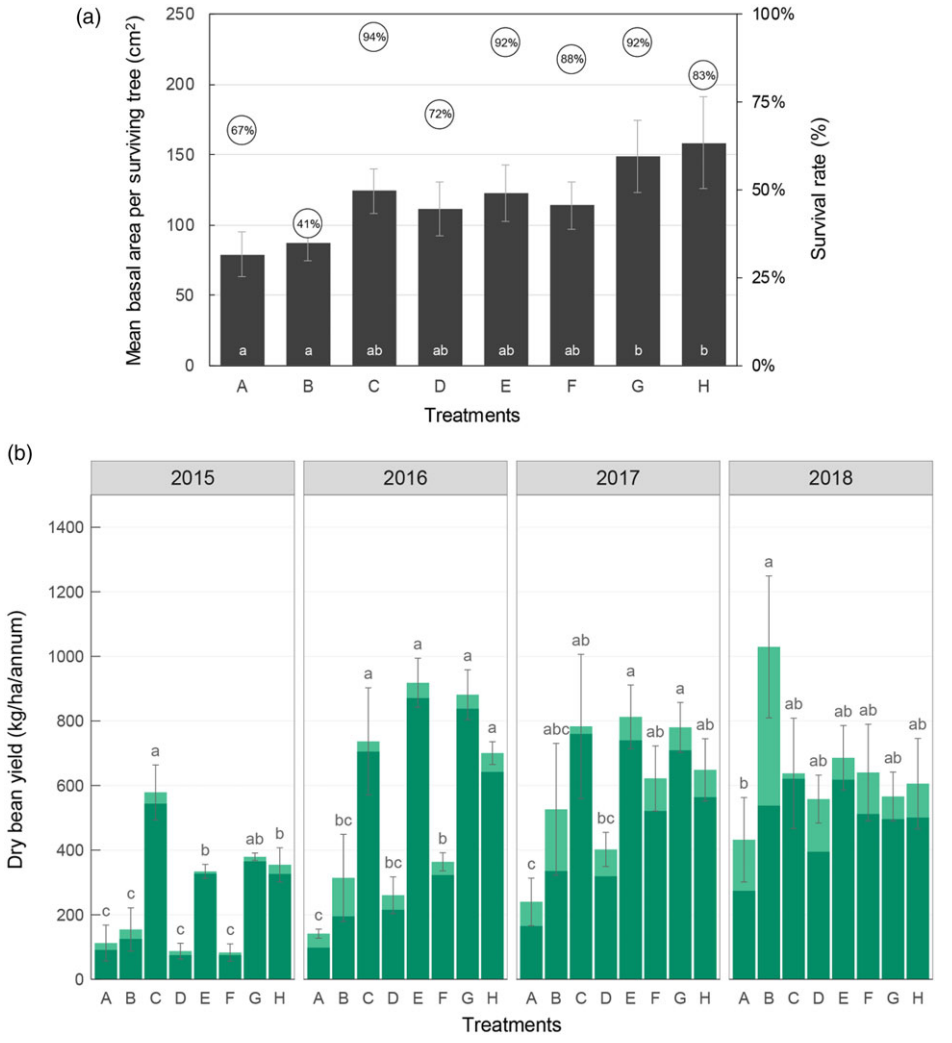


Figure 1. Effect of soil amendments on (a) mean basal area per cocoa tree and survival rates in December 2018 and (b) annual yield of dry beans in each year from 2015 to 2018. In December 2018, cocoa trees were 7.4 years old (89 months). For each variable, means correspond to an average of the four replicates. Error bars represent standard errors of the mean based on surviving trees (light bars). Upper case letters on the X-axis refers to each treatment, namely: A is control; B is mineral fertilizer; C is compost; D is dolomite; E is mineral fertilizer and compost; F is mineral fertilizer and dolomite; G is compost and dolomite; and H is the full combination. Treatments with the same lower-case letter are not statistically significant ($P > 0.05$). For (b), the dark bars represent the harvest averaged for 16 initially planted trees, while the addition of light bars shows the average yield calculated per surviving tree (i.e., excluding dead trees, excluding mortality). From 2016, one replicate of Treatment B was excluded from the average calculation, as all trees were dead, leaving three replicates instead of four.

followed by the control (67%) and dolomite Treatment D (72%). All the other treatments had a survival rate higher than 80%.

Yields and harvest quality

Dry bean yield

Dry bean yields for each treatment from 2015 to 2018 are shown in Figure 1b and detailed in Table S9. Productivity was very low in 2015, with a pattern similar to Mulia *et al.*'s results for 2014–2015

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(low for A, B, D, and F; high for C, E, G, and H). In 2015, the treatments receiving no compost (Treatments A, B, D, and F) provided the lowest annual yields of only 110 kg ha^{-1} on average. In 2016, the mean level of yields increased, but the treatments without compost (A, B, D, and F) again produced less than the composted treatments (C, E, G, and H). The following year, differences between treatments were less marked. Finally, in 2018, only the yield in the mineral fertilizer treatment (B) was greater than the yield in the control treatment (A); the other treatments' yields were similar. The coefficients of variation associated with a given year declined from 69% in 2015 to 27% in 2018 (Table S9). Over the 4 years, the compost-only treatment (C), the fertilizer and compost treatment (E), and the compost and dolomite treatment (G) produced the highest cumulative yields (2600–2750 kg ha^{-1}; Table S9).

Pod count and yield per pod

The pattern for pod counts in 2015 and 2016 (Table S7) was similar to dry bean yields: treatments with compost (C, E, G, and H) had high pod counts (27–47), the treatments without compost (A, B, D, and F) had low counts (5–16). From 2017, the pod counts between treatments seemed to converge in a similar way as the yields.

The mean yield of dry beans per harvested pod was highly variable across treatments over the years (Table S7), ranging from a minimum of 10.8 g attained by Treatment D in 2015 to a maximum of 30.3 g (for pod-producing replicates) attained by the mineral fertilizer Treatment B in 2017. The low yields obtained in 2015 were associated with the smallest mean yield per pod of 12.4 g across all the treatments. Mean yields of dry beans per pod increased to 23.2 g in 2016 and 26.8 g in 2017, before declining to 19.1 g in 2018.

Yield index

To partially account for the differences in competition caused by the replanting in 2016, a yield index was calculated for each treatment (Table S10). It was determined as the ratio of the yield of dry beans per hectare (kg) divided by the basal area (cm^2). On average, the mineral fertilizer treatment had the highest yield index of around 10 g cm^{-2}, while the value for the other treatments ranged from 3.8 to 5.6 g cm^{-2}.

Pod index

The dolomite treatment attained the highest pod index in 2015 (Table S10), reaching 96 pods kg^{-1}, equating to a very small mean pod size of 10.8 g. The lowest pod index of 33 pods kg^{-1} was attained by the mineral fertilizer treatment (B) in 2017 when the mean pod weight reached 30.3 g. In 2016 and 2017, the pod indices were uniform across treatments with a mean value of 44 and 38 pods kg^{-1}. Even though yields were more uniform in 2018, pod indices differed, ranging from 43 pods kg^{-1} (Treatment B) to 70 pods kg^{-1} (Treatment G).

Proportion of infected pods, dry bean weight, and fraction of waste beans

The proportion of infected pods was high, ranging from 0.62 to 0.97 for individual treatments per year (Table S7), and there was no consistent treatment effect. The analysis of a production sample, collected in November 2017, revealed differences between average dry bean weights (Table S11). The smallest beans were obtained for Treatment B (1.25 g), which were lower than the control (1.30 g). The largest beans were found for Treatment D (1.59 g). Compared to the mineral fertilizer Treatment B, Treatments C to H produced beans that were, on average, 18% heavier, while those in the control were only 65% of the weight of those in the mineral fertilizer treatment. The fraction of waste beans ranged from 8% (Treatment E) to 18% (Treatment F), with the others between 10 and 14%.

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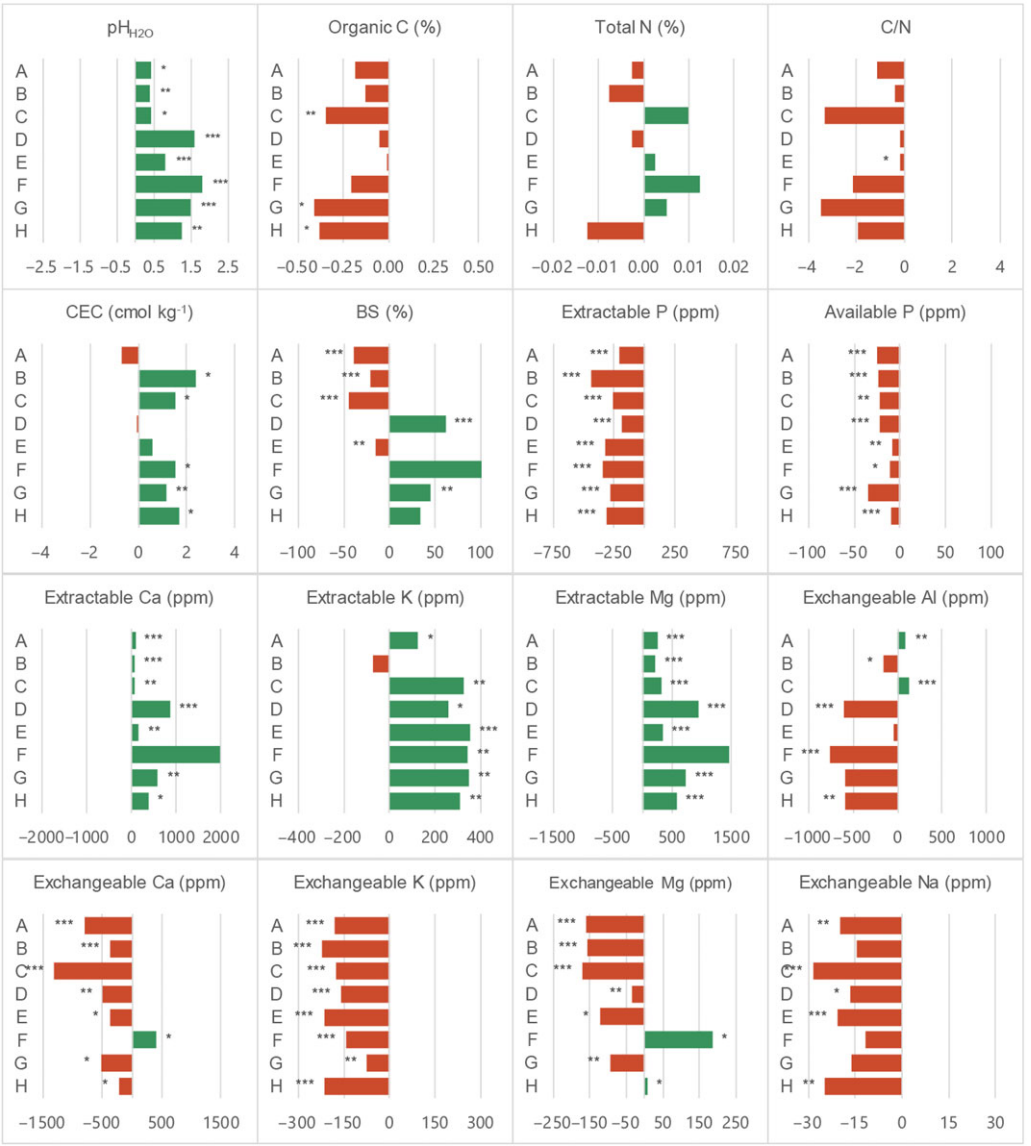


Figure 2. Summary of the differences observed in the soil properties between 2014 and 2018. Each difference was calculated by taking 2014 as the initial value and 2018 as the final one. Stars rating correspond to the following rule, calculated after a Welch one-sample t-test: $P \leq 0.001$, ***; $P \leq 0.01$, **; $P \leq 0.05$, *. Bars with no stars indicate no statistical difference between the 2 years ($p = 0.05$). Please refer to Table S8 in the supplementary material for the exact p-values). For extractable Ca and Mg, F had the largest effect, but the difference is not significant, only because the variability was very high. The mean annual rate of change for each element in kg ha^{-1} year^{-1} is shown in Table S12.

Soil properties

The results of the soil analyses are presented in Table 2 and Table 3, and the soil changes that occurred in 4 years are shown in Figure 2 (arranged in terms of soil property) and Figure S1 (arranged in terms of the treatments). The mean annual rates of change for each element in kg ha^{-1} year^{-1} are presented in Table S12.

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Bulk density and pH

The mean surface bulk density of the soil was statistically similar for each treatment, with a mean value of 1.09 g cm^{-3}. For all treatments, soil pH values increased between 2014 and 2018 (Figure 2). Treatments A, B, and C, which did not receive dolomite, were the most acidic in 2018 with a value of 5.21–5.36 (Table 2). The pH was about neutral (6.75–6.87) for D, F, and G, where dolomite was applied. The pH of E and H were intermediate (respectively 5.79 and 6.25).

Carbon (C)

Despite the addition of compost, the organic C contents across the treatments in 2018 were statistically similar, with a mean value of 1.25% (Table 2). The organic C content in Treatments C, G, and H appeared to have significantly declined since 2014 (Figure 2). Subsequent analyses of the total C after dry combustion (following ISO 10694:1995, in Table 3) determined with an Elementar Analyzer at Cranfield University on sample duplicates also showed no statistical difference between treatments. However, the mean total carbon content of 1.65% was about 30% higher than the organic carbon values. Possible reasons for the higher reading could be the presence of inorganic forms of C (included in the Cranfield measurement) or a systematic difference between the Elementar and Walkley–Black methods.

Nitrogen (N)

Despite the different treatments, there was no statistical difference between treatments in the level of soil nitrogen, determined within either the Kjeldahl method (Table 2) or the Elementar Analyzer (Table 3). The nitrogen values reported in 2018 of 0.123–0.153% were broadly similar to measurements made in 2014 and reported by Mulia *et al.* (2019). In 2018, the C:N ratios based on the measurements with the Asian-Agri's dataset were approximately around 9:1. The C:N ratio determined using Cranfield University's data also indicated similar results between treatments, but the higher carbon measurement resulted in a higher mean C:N ratio of 12:1.

Phosphorus (P)

In 2018, the extractable P content in the control Treatment A (18.4 ppm) was lower than that (68.4 ppm) in Treatment E receiving mineral fertilizer and compost (Table 2). The other treatments were not statistically different. The total P contents also followed the same pattern, with the value (283 ppm) for Treatment A being less than that (366 ppm) for Treatment E; the rest were statistically similar (Table 3). The extractable P contents measured in 2018 (18–68 ppm) were substantially lower than those measured in 2014 (227–471 ppm; Figure 2).

In 2018, the mean value for available P (Bray 1) for each treatment ranged from 1.9 to 12.6 ppm (Table 2). These values were lower than those (10–40 ppm) in 2014 and those (13 ppm) in 2011 prior to planting. The fraction of available P relative to total P ranged from 5% (Treatment D) to 25% (Treatment C). The higher pH observed for Treatment D was not associated with a noticeable increase in P availability (lowest available P at 1.9 ppm), nor did the addition of compost affect P availability (higher for Treatments C and E, 10.3 ppm on average, but not G and H, 4.2 ppm on average).

Potassium (K)

There were no statistical differences for exchangeable, extractable, and total K between the treatments in 2018 (Table 2). However, the measured exchangeable K decreased in all treatments from 2014 to 2018 (Figure 2). In 2018, the mean value across all treatments was below adequate levels (between 117 and 235 ppm, according to Nelson *et al.*, 2011). By contrast, between 2014 and 2018, extractable K increased with all the treatments, except in Treatment B, where it decreased, and in the control for which the change was negative but not significant (Figure 2).

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Calcium (Ca)

In 2018, there were treatment differences in the level of extractable and total Ca (Table 2 and Table 3). Treatments D and F, which received dolomite, had the highest concentrations. The lowest levels were found in the control (Treatment A) and the plots receiving only mineral fertilizer (Treatment B). Extractable Ca increased significantly in the limed treatments, with a peak at 2 g kg^{-1} for Treatment F. The treatment effects on exchangeable and total Ca were similar to those for extractable Ca. The highest value occurred where dolomite was applied. Again, there was potentially an outlier in Treatment F, where a reading reached 5.7 g kg^{-1}, perhaps due to the presence of incompletely dissolved dolomite. After 2014, the Ca contents of all the treatments which did not receive dolomite decreased to low levels.

Magnesium (Mg)

In 2018, there was no treatment effect on the level of extractable Mg (Table 2), but the exchangeable (Table 2) and total Mg (Table 3) showed a similar treatment response to Ca. The highest contents corresponded to the treatments with dolomite application; the lowest values were observed for the control and mineral fertilizer-only plots. There was again a peak for Treatment F, possibly due to an outlier, while the other observations were closer to 900 ppm. The lowest values were found for Treatments A and B, slightly exceeded by Treatments C and E. For exchangeable Mg, a pattern similar to Ca was found: highest where dolomite was applied, peaks for Treatments F and D and minimums for the control and the mineral fertilizer Treatments A and B. As for Ca, one very high Mg measurement was found for one of the samples, suggesting the presence of high concentrations of dolomite. As with Ca, the Mg contents have decreased since 2014 in the plots without dolomite, while it increased where it was applied.

Sodium (Na)

In 2018, no statistical differences were found between the treatments for exchangeable Na contents (Table 2). However, between 2014 and 2018, the Na contents decreased for all treatments (Figure 2). Sodium adsorption ratios were all very low (<1), suggesting no degradation risks of soil structure (USDA NRCS, 2017).

Aluminum (Al)

Distinctively, the lowest exchangeable Al contents were recorded in the treatment with the application of dolomite, which also decreased compared to 2014. Overall, total Al contents were statistically the same for all treatments, around 2%.

CEC and base saturation

The treatments did not appear to influence the cation exchange capacity (CEC), which was low in all the treatments. The treatments showed distinct base saturations. Treatment F attained 125% of saturation, possibly due to very high Ca and Mg found in the samples, themselves probably coming from the dolomite.

Discussion

Recontextualization

The aim of extending the study by Mulia *et al.* (2019) was to determine if the yield responses of 7-year-old cocoa trees to different soil amendments were similar to those reported for 3-year-old trees and if the differences in responses could be related to soil chemical properties. This information was then used to develop fertilizer recommendations.

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The initial study highlighted the beneficial effects of compost in increasing cocoa trees' height, increasing flowering and yields, and pod quality. There were no obvious treatment effects on leaf nutrient contents and pest and disease incidence. The initial study also highlighted that mineral fertilizer and dolomite application to the young cocoa trees were associated with high mortality rates. Soil-wise, it was suggested that the high yields in the compost treatments were associated with increased nutrient availability and uptake. Mulia *et al.* (2019) also suggested that the mineral fertilizer application could have resulted in nutritional deficiencies in Ca and Mg. This discussion examines how an additional 4 years of measurements improves our understanding of the medium-term effects of the different soil amendments.

Soil response to treatments

The effect of the treatments on soil properties is considered in terms of the effect of the compost, the mineral fertilizer, and the dolomite.

Effect of the compost

Despite the addition of almost 1 Mg of organic carbon (OC) per hectare per year from 2012 to 2018, compost inputs did not result in significantly higher surface bulk density, CEC, and soil C contents than the control. Several factors could explain this.

First, although the mean value of OC in the treatments ranged from 1.17% to 1.40%, these differences were not statistically different. A difference of 0.33% OC over one hectare to a depth of 20 cm and assuming a bulk density of 1.09 g cm^{-3} is equivalent to 7 Mg per hectare. Hence, the level of replication (four per treatment) described in this paper would be insufficient to identify a statistically significant difference from the addition of approximately 6 Mg of OC per hectare over 6 years. Such analysis highlights the very high levels of replication needed to detect soil changes because of the innate spatial variability in soil properties (Upson *et al.*, 2016).

A second factor relates to the mode of compost application. Compost was applied in six small pits, surrounding the cocoa trees (Table S2). However, even though we sampled soil at the same distance from the trunk, the location of our samples was randomly positioned. Moreover, since we only collected one sample per treatment, it is easy to miss one of those little pits and therefore miss the local effect of compost on those spots.

A third factor is that the compost had a low C:N ratio (7:1), suggesting that it was prone to rapid mineralization instead of being turned into more 'passive' and recalcitrant forms of soil organic matter through humification (Nicolardot *et al.*, 2001; Tian *et al.*, 1992; Weil & Brady, 2017). By contrast, the use of more recalcitrant organic matter (e.g., higher C:N or lignin:N ratios) could be a more promising method to raise soil organic matter levels (Talbot & Treseder, 2012).

Various authors have argued that a key benefit of compost addition is the increase in soil water holding capacity (Adugna, 2016; Blanco-Canqui & Lal, 2007; Nguyen, 2013; Smith, 2018; Zemánek, 2011). This is useful as cocoa yield is strongly affected by soil water regimes (Abdulai *et al.*, 2020; Dada, 2018; Kotei, 2019). Improving soil water storage, it may have served as a water reserve which may have resulted in different levels of drought stress between the composted and non-composted treatments.

Effect of dolomite

Over the 4 years, the dolomite (without compost) plots received about 4950 kg Ca ha^{-1} and 2900 kg Mg ha^{-1}; the changes in measured soil contents were equivalent to 1820–4300 kg Ca ha^{-1} and 2006–3074 kg Mg ha^{-1}. Seven years after the experiment's start, the pH in the top 20 cm of the four treatments receiving dolomite was 6.25–6.83, compared to 5.21–5.79 in the treatments receiving no dolomite. Although the addition of dolomite alone increased yields relative to the control (+40%; presumably because of the higher pH increasing nutrient availability), the increase

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was less than that for the addition of compost alone (+195%) and the addition of mineral fertilizer alone (+118%; Figure 1b). The effect of dolomite on soil pH may also have contributed to reduce the availability of Al (Figure 2).

Effect of mineral fertilizer

In the initial study, mineral fertilizer alone did not have a beneficial effect on yield, but 7 years after planting, the mineral fertilizer treatment was the only treatment producing a statistically higher yield than the control plot. However, if yields including mortality rates are considered (dark bars in Figure 1), this improved performance is no longer apparent. Mineral fertilizer addition to young tree crops can be problematic, and high rates can lead to toxicities and root scorching (Gauthier *et al.*, 2014). This is less of a problem once a tree has established a robust root system. Also, regularly harvesting cocoa pods removes nitrogen, phosphorus, and potassium and can create deficiencies for these nutrients. For example, a yield of approximately 1000 kg ha^{-1} described in Treatment B would represent the removal of approximately 40 kg of nitrogen, 6 kg of phosphorus, and 62 kg of potassium per hectare (Singh *et al.*, 2019). Compared to the control plot, the mineral fertilizer treatment led to higher yields in 2016, 2017, and 2018. Despite this, there was no significant measurable difference in the soil properties between the control and the mineral fertilizer plot.

Calcium and Magnesium availability

Mulia *et al.* (2019) reported that the poor initial yields in the fertilizer treatment were due to the low availability of soil Ca and Mg. By contrast, in 2018, the soil analyses detected low Ca and Mg contents (both total and exchangeable) for the compost (alone) and the mineral fertilizer + compost treatments (C and E). The Treatments C and E were among the most productive plots, while their soil Ca, and Mg contents were similar to controls. These new results suggest that point measurements of soil Ca and Mg contents may not be good indicators of crop productivity because low-nutrient contents may also be a result of increased plant uptake. Presumably, by promoting the activity of beneficial microorganisms (Bünemann *et al.*, 2006), compost could enhance the availability of nutrients like Ca. This could have resulted in similar soil Ca and Mg contents between the composted and non-composted plots. The difference would simply be that plants absorbed more nutrients under the influence of compost, therefore resulting in similar levels to other treatments. Determining the tissue contents of these elements would be necessary to confirm this hypothesis.

Exchangeable Aluminum

Mulia *et al.* (2019) also associated low initial yields with high concentrations of exchangeable Al and low pH. The exchangeable Al contents at year 7 ranged from 21 to 30 ppm for Treatments D, F, and G, which received dolomite, up to 705–743 ppm for Treatments A, B, and C, which did not. In both cases, the soil Al concentrations are substantially below the levels reported by Shamshuddin *et al.* (2004). Our results showed that high productivity was obtained for the compost (Treatment C) and the compost + mineral fertilizer (Treatment E) plots, which featured high exchangeable Al contents (720 and 678 ppm; also reported for Treatment C by Mulia *et al.*, 2019), comparable to the control and mineral fertilizer-only treatments (A and B; 705 and 743 ppm). On the other hand, we found low exchangeable Al concentrations for two low-yield treatments, dolomite-only and dolomite + mineral fertilizer (D and F; Table 3). These observations imply that exchangeable Al, even though it may affect yields, was not a determining factor. The presence of organic matter may still offset Al toxicity, but the soil analyses revealed no difference in C contents across all treatments. Nevertheless, with the same C contents, differences in the

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microbiological profiles and the type of organic compounds present could play a role in mitigating Al toxicity.

Cocoa response to treatments

Seven years after field planting, the highest cumulative yields were still achieved from those treatments that had received compost (e.g., Treatments C, E, G, and H). The most effective single treatment to improve cocoa productivity was compost (C). The treatment including compost alone (C) led to higher survival rates, basal areas, and dry bean yields than the control (A), mineral fertilizer (B), and dolomite (D) alone treatments (except in 2018 for dry bean yields). Of the combined treatments, the treatment without compost (F) resulted in lower yields than those with compost (E, G, and H).

From year 4 to 7, the yield benefits of compost tended to decline relative to the other treatments. In 2015, which was a particularly dry year (Table S4), the benefit from compost was particularly strong. However, by 2018, the cocoa yields had become similar within all the treatments receiving additions, although they remained greater than the control treatment yields. Hence, as the cocoa bushes became more established, the benefits of adding organic material declined, and the benefits of supplying specific nutrients such as nitrogen (removed during harvesting) became more important.

The results indicate that the basal area of 7-year-old cocoa plants was not a good predictor of yield, since the largest cocoa trees were not the most productive (Figure 1). Verlière (1981) suggested that the positive relationship between basal area and yield is only significant for younger trees (Jones & Maliphant, 1958; Longworth & Freeman, 1963), and this was observed in the initial phase of this experiment (Mulia *et al.*, 2019).

Despite the various soil measurements, no immediately obvious relationship was found between soil nutrient levels and yields. For example, although yields varied between treatments in 2018, soil nitrogen levels across the treatments were similar. By contrast, there was evidence of the yield benefits of organic matter and an increase in pH. Nevertheless, it appeared that yield benefits from compost and/or dolomite addition had declined by years 6 and 7. The benefits of compost may have been particularly pronounced in 2015 because of the low rainfall in that year (Table S4). Another factor related to compost application could be the quantity of organic P provided by the compost (50% more than the fertilizer input). For example, a strong positive correlation ($r = 0.85$) between organic P and cocoa yields was reported for Southern Nigeria (Omotoso, 1971).

One difficulty limiting the results' interpretation is that soil characteristics were only measured at the beginning of year 4 and the end of year 7, whereas the yields were measured continuously. In addition, the lack of significant differences between treatments in many chemical soil properties also constrained the identification of relationships. One possible way of addressing this is to construct models describing the inputs and outputs of nutrients.

Over the first 7 years, one of the lowest cumulative yields was achieved in the plots where only mineral fertilizer was applied. These results do not mean that mineral fertilizers should be avoided. Instead, one of the largest cumulated yields was obtained from the compost + fertilizer (E; three times the control), and fertilizer alone led to double the yield of that from the control treatment. Furthermore, the rate at which productivity was increasing during the last 3 years for the fertilizer-only treatment (B) suggests that productivity could continue to rise substantially as the cocoa matures. Conversely, the average yield of the four composted treatments all declined during the last 3 years, while the non-composted increased. Another argument in favor of fertilizer is the high-yield index reached for this treatment, surpassing the others.

As described before, it appears that the yield response was different between the composted and non-composted treatments. In 2015 (dry year), the response to treatments was strong for the composted treatment and less for the non-composted ones. In the following years, the yields slowly

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declined for the composted treatment, while the non-composted gradually increased. In 2018, productivity was equivalent for all, except for the control (lowest average yield) and the fertilizer treatment (highest average yield). We could hypothesize that in the long run, fertilizer can be particularly helpful in maintaining productivity, while compost is useful in encouraging high yields during establishment and particularly during drought. Continuing the analysis during more years as the cocoa further matures could support or contradict these trends.

It is also important to note that we did not observe additional effects on yields when combining the treatments. For example, the yields of the treatment combinations with compost were approximately at the same level as compost alone. In Treatment E, there was no benefit from using the fertilizer as compared to compost alone. The fertilizer + dolomite treatment was slightly lower than fertilizer alone, suggesting that the addition of dolomite reduced the benefits of fertilizer application. The full combination did not give the highest yields. However, we should add that, if we consider the productivity including mortality rates (averaging per 16 trees), dolomite + fertilizer showed an improvement. The cumulated productivity of Treatment F (dolomite + fertilizer) was also 1.27 times Treatment B (fertilizer alone). In addition, average survival rates were also increased by adding dolomite. The survival rate of Treatment F (88%) was more than double that of Treatment B (41%) and showed an improvement as compared to the control. Treatment A had a survival rate of 67%, which means that adding dolomite approximately halved the mortality rate of the control treatment (33% for A and 12% for F).

A secondary cause suggested by Mulia *et al.* (2019) for the response to the treatments was the young age of the cocoa trees. We can presume that young cocoa trees are more sensitive to environmental factors than older trees. In our study, cocoa age seems to be an essential factor since yields increased over time but also became almost homogenous the last year. The explanation behind the harmonization of yields by 2018 across the trial is uncertain. The positive effects of amendments may have been only useful in the first years of cocoa growth and development, but yield disparities between treatments had narrowed after 7 years. One reason could be as simple as the design of the trial itself. A block size of 16 trees separated spaced by 3 m may not be enough. Belowground, root systems may now be accessing adjacent plots and therefore blending the responses. Expansion of the root zone, possibly resulting in access to soil nutrition sources in adjacent plots, may have been influential.

Developing fertilization and amendment recommendations

The mean annual rate of change of soil nutrients can provide insights into the quantity of each element that is either taken up or lost by leaching or volatilization (Table S12) and into appropriate cocoa fertilization rates. There were major differences in the contents of certain soil nutrients between those reported for 2014 by Mulia *et al.* (2019) and those reported here for 2018 (Figure 2 and Figure S1). For example, available P and exchangeable K declined drastically in 4 years. This could result from substantial leaching associated with the low-nutrient retention capacity of the soil. However, total N concentrations were maintained over 4 years. Another explanatory factor for the decline in nutrients is the uptake by cocoa trees and the associated shade trees at a rate higher than the rate of inputs. Based on those averages, the stock of extractable K, Ca, and Mg, declined, even in the control plot, suggesting that the supply of these nutrients may be insufficient for this plot. Considering organic C, the statistically significant changes that occurred over 4.5 years for Treatments C, G, and H correspond respectively to annual rates of change of 1671, 1986, and 1853 kg of C ha^{-1} yr^{-1}, while 930, 1580, and 1580 kg ha^{-1} of C were applied yearly. About 896 kg of C ha^{-1} yr^{-1} were lost on average in the control plot, almost equivalent to the compost treatment inputs. However, for the composted treatments, the loss of C was 1.5 to 2 times that in the control treatment. This could suggest that the application of compost with a low C:N ratio was associated with increased decomposition of the preexisting soil organic matter (Kuzyakov, 2010), whereas the incorporation of more recalcitrant forms of organic inputs could

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have resulted in greater organic matter stability. The reported rate of change of extractable P was extremely large, and initially assuming a technical error, the Asian-Agri laboratory manager double-checked the 2018 results, and the analysis of total P at Cranfield University was repeated three times. In theory, 'extractable' (Asian-Agri) (Table 2) and 'total' (Cranfield) contents (Table 3) should be similar (i.e., 'pseudo-total'), but on this occasion, the quantities varied widely. Unfortunately, the 2014 and 2018 soil samples were not stored by Asian-Agri, preventing additional analyses. Because Cranfield's results were consistent, it is possible that there is a technical error in the values of extractable P reported from Asian-Agri in 2018. This issue raises the question of the consistency and comparability of chemical analyses between different laboratories, methods, and years. The soil analyses presented by Mulia *et al.* (2019) were produced by ICCRI (Indonesian Coffee and Cocoa Research Institute) and AIAT (Assessment Institute of Agricultural Technology), while ours came from Asian-Agri and Cranfield University laboratories.

The above analysis demonstrates the difficulty in developing appropriate fertilizer and amendment recommendations based on soil nutrient measurements alone. However, soil measurements can provide insights within an experiment examining yield responses. Two other tools for developing fertilizer recommendations are analysis of plant tissue and nutrient budgets. A nutrient budget requires considering the flows in terms of inputs and the quantity of nutrients being removed either as harvested pods or stored in the cocoa and shade trees' accumulated biomass. Nitrogen can illustrate this issue since additional inputs may have increased yields but did not lead to a measurable change in 2018.

Conclusions

The effects of the treatments on soil properties were variable, with distinct changes for some variables (such as organic C, pH, and extractable nutrients) and little to no response for others (such as total N). Composted treatments resulted in the highest cocoa cumulative yields (on average, 2.8 times the control). In contrast, the addition of mineral fertilizer or dolomite without compost provided yields that were 1.6 times the control. The composted treatments yielded significantly more pods than the other treatments. The relative benefits from compost (with a low C:N ratio) compared to fertilizer applications were greatest in the initial years of establishment, gradually declining as the cocoa matured. Furthermore, soil C contents were similar between treatments despite the inputs and were not adequate to raise soil C levels. This issue raises questions about the feasibility of improving soil carbon storage in cocoa systems. The effect of altering the C:N ratio of the compost could be an area for further study, as well as experimenting with other combinations of organic inputs. The results also demonstrate that developing a site-specific soil fertility management strategy cannot be based on soil nutrient analysis alone, but soil nutrient analysis can be useful when integrated with experimental yield results and the analysis of nutrient flows. While it seemed that adding compost was sufficient to support cocoa productivity, the applications may be unattainable to many farmers. For this reason, future research should evaluate other combinations of compost + fertilizer + dolomite, with lower compost application rates than our experiment, combined with other organic inputs, to determine which ones are the most cost-effective to meet cocoa's needs.

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Supplementary materials. For supplementary material for this article, please visit https://doi.org/10.1017/S0014479721000132

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References

Abdulai I., Hoffmann M.P., Jassogne L., Asare R., Graefe S., Tao H.H., Muilerman S., Vaast P., Van Asten P., Läderach P. and Rötter R.P. (2020). Variations in yield gaps of smallholder cocoa systems and the main determining factors along a climate gradient in Ghana. *Agricultural Systems*, **181**(February), 102812. https://doi.org/10.1016/j.agsy.2020.102812

Adeniyi S.A., de Clercq W.P. and van Niekerk A. (2017). Development of a composite soil degradation assessment index for cocoa agroforests under tropical conditions of southwest Nigeria. *Solid Earth Discussions*, 1–37. https://doi.org/10.5194/se-2016-175

Adugna G. (2016). A review on impact of compost on soil properties, water use and crop productivity. *Academic Research Journal of Agricultural Science and Research*, **4**(3), 93–104. https://doi.org/10.14662/ARJASR2016.010

Ahenkorah Y., Halm B.J., Appiah M.R., Akrofi G.S. and Yirenkyi J.E.K. (1987). Twenty years' results from a shade and fertilizer trial on amazon cocoa (theobroma cacao) in Ghana. *Experimental Agriculture*, **23**(1), 31–39. https://doi.org/10.1017/S0014479700001101

Aikpokpodion P.E. (2010). Nutrients dynamics in cocoa soils, leaf and beans in Ondo State, Nigeria. *Journal of Agricultural Sciences* **1**(1), 1–9. https://doi.org/10.1080/09766898.2010.11884647

Asare R., Afari-Sefa V., Muilerman S. and Anim-Kwapong G.J. (2018). *Good Agronomic Practices in Cocoa Cultivation: Rehabilitating Cocoa Farms*. Burleigh Dodds Science Publishing.

Blanco-Canqui H. and Lal R. (2007). Soil structure and organic carbon relationships following 10 years of wheat straw management in no-till. *Soil and Tillage Research* **95**(1–2), 240–254. https://doi.org/10.1016/j.still.2007.01.004

Boyer J. (1973). Cycles de la matière organique et des éléments minéraux dans une cacaoyère Camerounaise. *Café Cacao Thé* **XVII**(1), 3–24.

Bünemann E.K., Schwenke G.D. and Van Zwieten L. (2006). Impact of agricultural inputs on soil organisms - A review. *Australian Journal of Soil Research* **44**(4), 379–406. https://doi.org/10.1071/SR05125

Carodenuto S. (2019). Governance of zero deforestation cocoa in West Africa: New forms of public–private interaction. *Environmental Policy and Governance* **29**(1), 55–66. https://doi.org/10.1002/eet.1841

Dada E. (2018). Rainfall variation: Implication on Cocoa Yield in Ondo State, Nigeria. *American International Journal of Agricultural Studies* **1**(1), 16–25. Available at www.acseusa.org/journal/index.php/aijas

Fassbender H.W., Alpízar L., Heuveldop J., Fölster H. and Enríquez G. (1988). Modelling agroforestry systems of cacao (Theobroma cacao) with laurel (Cordia alliodora) and poro (Erythrina poeppigiana) in Costa Rica III. Cycles of organic matter and nutrients. *Agroforestry Systems* **6**(1), 49–62. https://doi.org/10.1007/BF02344745

Food and Agriculture Organization of the United Nations. (2020). *FAOSTAT Statistical Database - Cocoa*. Available at http://www.fao.org/faostat/en/#search/cocoa

Gauthier N.W., Kaiser C.A., Dockery J. and Goodin K. (2014). *Stress and Decline in Woody Plants*. Agriculture and Natural Resources Publications.

Goulding K.W.T. (2016). Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. *Soil Use and Management* **32**(3), 390–399. https://doi.org/10.1111/sum.12270

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

Jones T.A. and Maliphant G.K. (1958). Yield variations in tree crop experiments with specific reference to cacao. *Nature* **182**, 1613–1614. https://doi.org/https://doi.org/10.1038/1821613b0

Kotei R. (2019). Influence of the water levels on the yield parameters of cocoa in the forest savannah-transition zone of Ghana. *International Journal of Agriculture, Environment and Bioresearch* **4**(6), 1689–1699. https://doi.org/10.1017/CBO9781107415324.004

Kuzyakov Y. (2010). Priming effects: interactions between living and dead organic matter. *Soil Biology and Biochemistry* **42**(9), 1363–1371. https://doi.org/10.1016/j.soilbio.2010.04.003

Lal R., Hall G.F. and Miller F.P. (1989). Soil Degradation: 1. basic processes. *Land Degradation & Rehabilitation* **1**(January), 51–69.

Longworth J.F. and Freeman G.H. (1963). The use of trunk girth as a calibrating variate for field experiments on cocoa trees. *Journal of Horticultural Science* **38**(1), 61–67. https://doi.org/10.1080/00221589.1963.11514060

McMahon P., Purung H. bin, Lambert S., Mulia S., Nurlaila**, Susilo A.W., Sulistyowati E., Sukamto S., Israel M., Saftar A., Amir A., Purwantara A., Iswanto A., Guest D. and Keane P.** (2015). Testing local cocoa selections in three provinces in Sulawesi: (i) Productivity and resistance to cocoa pod borer and Phytophthora pod rot (black pod). *Crop Protection* **70**(April), 28–39. https://doi.org/10.1016/j.cropro.2015.01.001

Mineralogical Society of America. (2003). Handbook of mineralogy - Dolomite. *Mineral Data Publishing* **39**(5), 177–178. https://doi.org/10.1021/ac60249a025

Mulia S., McMahon P.J., Purwantara A., Bin Purung H., Djufry F., Lambert S., Keane P.J. and Guest D.I. (2019). Effect of organic and inorganic amendments on productivity of cocoa on a marginal soil in Sulawesi, Indonesia. *Experimental Agriculture* **55**(1), 1–20. https://doi.org/10.1017/S0014479717000527

Nelson P., Webb M., Berthelsen S., Curry G., Yinil D., Fidelis C., Fisher M., Oberthur T. and Oberthür T. (2011). Nutritional status of cocoa in Papua New Guinea. *Better Crop* **95**(2), 18–20.

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Nguyen T.T. (2013). *Compost Effects On Soil Water Content, Plant Growth Under Drought and Nutrient Leaching*. University of Adelaide.

Nicolardot B., Recous S. and Mary B. (2001). Simulation of C and N mineralisation during crop residue decomposition : a simple dynamic model based on the C : N ratio of the residues Author (s): B. Nicolardot, S. Recous and B. Mary Source : Plant and Soil, Vol. 228, No. 1, THE 10TH INTERNA. *Plant and Soil* **228**(i), 83–103.

Omotoso T.I. (1971). Organic phosphorus contents of some cocoa growing soils of Southern Nigeria. *Soil Science* **112**(3), 195–199.

Ruf F. (2001). Tree crops as deforestation and reforestation agents: the case of cocoa in Côte d'Ivoire and Sulawesi. In *Agricultural Technologies and Tropical Deforestation* (pp. 291–315).

Shamshuddin J., Muhrizal S., Fauziah I. and Husni M.H.A. (2004). Effects of adding organic materials to an acid sulfate soil on the growth of cocoa (Theobroma cacao L.) seedlings. *Science of the Total Environment* **323**(1–3), 33–45. https://doi.org/10.1016/j.scitotenv.2003.10.003

Singh K., Sanderson T., Field D., Fidelis C. and Yinil D. (2019). Soil security for developing and sustaining cocoa production in Papua New Guinea. *Geoderma Regional* **17**, e00212. https://doi.org/10.1016/j.geodrs.2019.e00212

Smith C. (2018). *Effects on Soil Water Holding Capacity and Soil Water Retention Resulting from Soil Health Management Practices Implementation. March*, 1–30.

Talbot J.M. and Treseder K.K. (2012). Interactions among lignin, cellulose, and nitrogen drive litter chemistry-decay relationships. *Ecology* **93**(2), 345–354. https://doi.org/10.1890/11-0843.1

Thong K.C. and Ng W.L. (1978). *Growth and nutrients composition of monocrop cocoa plants on inland Malaysian soils.*

Tian G., Kang B.T. and Brussaard L. (1992). Biological effects of plant residues with contrasting chemical compositions under humid tropical conditions-Decomposition and nutrient release. *Soil Biology and Biochemistry* **24**(10), 1051–1060. https://doi.org/10.1016/0038-0717(92)90035-V

Upson M.A., Burgess P.J. and Morison J.I.L. (2016). Soil carbon changes after establishing woodland and agroforestry trees in a grazed pasture. *Geoderma* **283**, 10–20. https://doi.org/10.1016/j.geoderma.2016.07.002

USDA NRCS. (2017). Sodium Adsorption Ratio (SAR). *United States Department of Agriculture*, 13–14.

van Vliet J.A., Slingerland M. and Giller K.E. (2015). *Mineral Nutrition of Cocoa. A Review*. https://doi.org/10.1016/bs.agron.2019.08.005

Verlière G. (1981). *Etude par la méthode du diagnostic foliaire de la fertilisation et de la nutrition minérale du cacaoyer (Theobroma cacao L.) en Côté d'Ivoire*.

Weber H. (2017). *Joining forces to protect fragile forests in West Africa*. Available at https://www.cocoalife.org/progress/joining-forces-to-protect-fragile-forests-in-west-africa

Weil R.R. and Brady N.C. (2017). *Nature and Properties of Soils*, 15th Edn. Pearson.

Wessel M. (1971). *Fertilizer Requirements of Cacao (Theobroma Cacao L.) in South-Western Nigeria*. Koninklijk Instituut voor de Tropen.

Wood G.A.R. and Lass R.A. (2008). *Cocoa*. John Wiley & Sons.

Zemánek P. (2011). Evaluation of compost influence on soil water retention. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis* **59**(3), 227–232. https://doi.org/10.11118/actaun201159030227

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