Is soil fertility the limiting factor of yield in agroforestry cocoa (*Theobroma cacao*) in Haiti?

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ABSTRACT: *This study was carried out to evaluate the response of cocoa in agroforestry to organic fertilizer. Prior to experiments, individual surveys were carried out to estimate farm yield. Soil samples were taken and analyzed. Field trials were conducted to measure the effect of compost on yield. Laboratory analyses showed that the soil characteristics met the minimum requirements of suitability for the crop. The field trials yield varied from 981 to 1458 kg/ha in Grand'Anse and from 485.5 to 1113 kg/ha in Nord with no significant difference among the compost doses. These results mean that there was no significant effect of compost application on the yield and soil fertility is not the limiting factor of agroforestry cocoa yield in Haiti. Future researches are needed to investigate other factors, including plant age, planting density, plant protection, light control and genetic material. In the meantime, farmers are encouraged to compost cocoa pods and other crop residues to fertilize their plots, maintain the current level of soil fertility and avoid soil degradation.*

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1. INTRODUCTION

Cocoa is an important cash crop that provides income to millions of smallholder farmers in Africa, Latin America, Asia and Oceania. (Goudsmit *et al*. 2023). Annual global production has reached 4.5 million tons since 2016 (Poelmans and Swinnen 2019). About 90% of overall production is ensured by around 5 million small farms with between 1 and 5 ha on average, particularly in Africa and Asia and the global market for the cocoa-chocolate sector generates 100 billion dollars annually (Gavrilova 2021). Yields are on average very low compared to the yield potential of the plant (Aneani and Ofori-Frimpong 2013). Producers and development experts agree that plots are deteriorating and need fertilization to replenish soil nutrients and increase yields and income (Snoeck *et al*. 2016). In large cocoa producing countries, fertilizer is frequently recommended as a strategy to increase yields (Abdulai *et al*. 2020). However, on the one hand, the response of cocoa to fertilization is very variable, ranging from doubling the yield to no effect (Dossa *et al*. 2018). On the other hand, most cocoa producers are small farmers with limited access to inputs and who use little or no fertilizer. Additionally, many smallholders appear to be unconvinced about the need for and effect of fertilizers on cocoa bean yield (Kenfack Essougong *et al*. 2020).

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In Haiti, cocoa production is estimated at around 7 500 t of which 98% are exported according to United Nations Program for Environment (PNUE 2016). Ministry of Agriculture, Natural Resources and Rural Development (MARNDR 2012) estimated that the plantations cover about 20,000 ha in agroforestry located mainly in the departments of Grand'Anse at 55% and Nord at 40% and about 20,000 rural families are involved in production. Chemical fertilizers are not used in cocoa plots because the Haitian production is sold under the label of fine flavor organic cocoa. Soil fertility is only ensured by decomposition of crop residues produced by cocoa-based agro-forestry system and most of the plantations are more than 40 years old. As farmers do not replenish the nutrients removed by crops, a question arises as to whether the decomposition of cover crop leaves and other crop residues adequately and sustainably guarantees soil fertility and yields.

The hypothesis of this study is that the leaves of cover crops and crop residues partially replenish soil fertility. However, the nutrients removed by crops are not fully replenished. Consequently, crop yields are limited by low soil fertility.

The main objectives of this study are to investigate whether soil fertility is a limiting factor in cocoa yield in agroforestry in Haiti, and generate data that can help to improve soil fertility, yields, and farmers' incomes. Specifically, it aims to analyze the response of cocoa in terms of yield to organic fertilization in agroforestry in Haiti; identify the optimal application rate of compost.

2. MATERIALS AND METHODS

Characteristics of the study area

The study was conducted in Grand'Anse and Nord where cocoa production is concentrated in Haiti (Figure 1). The average rainfall is 1800 mm in Grand'Anse and 1500 mm in Nord. The monthly mean, maximum and minimum temperatures are respectively 28.09, 30.07 and 26.47 °C in Grand'Anse. They are respectively 26.92, 31.23 and 23.87 °C in Nord.

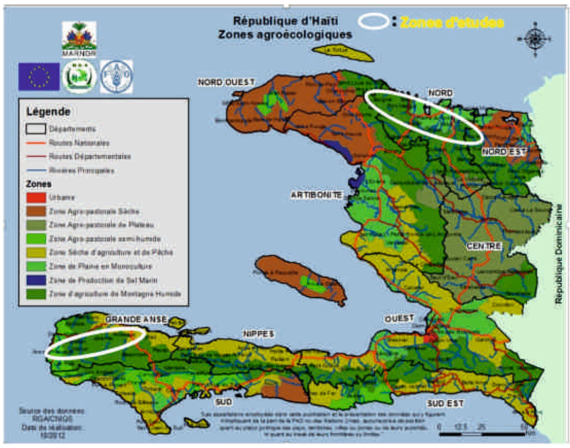

Figure 1. Haiti map showing location of the departments of Grand'Anse and Nord

Geologically, the subsoil of the sites is dominated by two categories of rock: limestone and basalt. These rocks are the origin of the different types of soil found throughout the sites (MARNDR, 2005; FAO, 2015). In plains and valleys, the soil is alluvial, gray or brown in color and deep (150 cm or more). In mountains, the dominant rock is limestone, but basalt is also observed. On the hills, the soil depth is less; in some cases, portions of the bedrock are observed at the soil surface, indicating soil loss through erosion. Agriculture is rainfed and cocoa (*Theobroma cacao* L.) is grown in agroforestry under shade of trees in association with yam (*Dioscorea sp.*) although other species such as taro (*Xanthosoma sagittifolium* L.) are often present in the same space. The main cover tree species are breadfruit (*Artocarpus altilis* L.), mango (*Mangifera indica* L.), avocado (*Persea americana* Mill), cedar (*Cedrera odorata* L.), mahogany (*Swietenia mahogani* L.), saman (*Albizia saman* L.), coconut palm (*Cocos nucifera* L.) and oak (*Catalpa longissima* L).

Farm yield assessment by farmer's individual surveys

Individual surveys to estimate farm yield were carried out in five communes in the department of Grand'Anse (Abricots, Anse-d'Hainault, Chambellan, Dame-Marie and Moron) and three in the department of Nord (Borgne, Grande-Rivière and Port- Margot).

The choice of the communes was made purposefully to cover the areas where cocoa production is concentrated. From a sampling base of 400 farmers across the two departments, 40 women and 120 men were randomly selected. A total of 124 farmers including 30 women (24%) and 94 men (76%) agreed to participate to the surveys (Table 1), representing a response rate of 78%. The sample size of 124 respondents made it possible to make the expected estimate with an error margin of 8.8% and a confidence level of 95%. Collected data included area under cocoa and harvested quantity during the last 12 months preceding the surveys. The yield was obtained by dividing the declared harvested quantity by the harvested area.

Soil sampling and compost collection

Prior to field trials, a total of 30 plots, 15 in each department, were used to take soil samples. The average plot sizes were 0.83 ha in Grand'Anse and 0.61 ha in Nord. In each plot, a sampling point was selected and two soil samples were taken at 0-30 and 30-60 cm depth, respectively. Compost made from the cocoa agroforestry system crop residues was collected in the study area.

Compost and soil analyses

Soil and compost samples were packaged in polyethylene zip bags, labeled and transferred to the

Table 1. Sample composition for individual farmer surveys

Department	Commune	Men	Women	Total/commune
Grand'Anse	Abricots	15	5	20
	Anse-d'Hainault	9	5	14
	Chambellan	15	2	17
	Dame-Marie	12	7	19
	Moron	7	1	8
Nord	Borgne	19	3	22
	Grande-Rivière du Nord	7	4	11
	Port-Margot	10	3	13
Total	-	94	30	124

soil laboratory of the College of Agriculture and Veterinary Medicine (FAMV) of the State University of Haiti (UEH) for analyses. The analyses were carried out according to the protocol in use in the laboratory. pH was measured using an electronic pH meter in a soil-distilled water mixture (ratio 1:2.5). Organic matter (%) and organic carbon (%) were assessed by the method of Walkley and Black; total nitrogen, (%) by the Kjeldahl method; and available phosphorus (mg/kg), by the Olsen method. CEC and exchangeable potassium were measured using a flame spectrophotometer after extraction with ammonium acetate at pH 7. The results were obtained in milliequivalent/100 g (meq/100 g), then converted to mg/kg using the coefficient conversion of 1 meq/100 g = 390 mg/kg. The percentages of clay, silt and sand were determined by the Bouyocos method and texture, using a texture triangle calculator from Agricultural Technology Centre (ATC). Reference values provided by Snoeck *et al*. (2016) and Villason and Olguera (2020) were used for results interpretation of soil analysis by the selected methods in cocoa farm.

Plant material

Cocoa production in the study area is dominated by phenotypes resulting from crosses involving the Trinitario, Criollo and other types. Boccara *et al.* (2017) reported different genetic origins of Grand'Anse cocoa trees. These include Criollo and Trinitario, but also other types such as Amelonado, Matina 2/8, Iquitos, Namay, Marañon, Contamana, and Refractario. Plots with proximate planting density of 1111 plants/ha (planting distances 3 m x 3 m) were used for the field trials. Some farmers prune cocoa trees in their plots, others don't. Both plot types were used in the field trials.

Factors, factors' level and experiment design

In each department, six farmers' plots, including three with pruned trees (PTP) and three with unpruned trees (UTP), were chosen. Of the three PTPs, one was chosen in plain, one in valley and one in hilly area, considered as three complete blocks. Likewise, of the three UTPs, one was chosen in plain, one in valley and one in hilly area. Each farmer's plot was subdivided into five subplots of 9 m x 9 m (81 m^2) containing nine cocoa trees to receive five doses of compost (0, 1, 2, 3 and 4 t/ha). "Plot type" and "compost doses" were arranged into split plot combination with plot type as main factor and compost doses as subsidiary factor. Table 2 shows the composition of the compost and the quantities of organic matter, organic carbon, total nitrogen, available phosphorus and exchangeable potassium it brought in each dose.

Yield assessment in field trials

For each subplot, harvests were measured and recorded for two years of experiment after compost application. For each year, the yield in g/m^2 was calculated by dividing the sum of harvested quantities in g by the harvested area (81 m^2). The obtained yield in g/m^2 was converted into kg/ha using the conversion coefficient of 1 g/m^2=10 kg/ha.

Data analysis

Survey yield data were subjected to descriptive statistical analyses in Excel. Results were presented as mean ± standard error, skewness and median ± semi-interquartile range (IQR/2). For soil analysis data, mean of 15 observations was computed and reported for each department and each sampling depth. Field trials yield data were submitted to analysis of variance at alpha=0.05 in R (R Core Team. 2016). To separate effects of department, plot type, block, and year fluctuations from those of compost on yield, the following model was used:

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Means associated with compost doses of 1 to 4 t/ha were compared to that of the control (0 t/ha) using the

Table 2. Organic matter, organic carbon, nitrogen, phosphorus and potassium content (%) of the compost and corresponding quantities (kg) of these nutrients in the different treatments

Parameter	Content (%)	Compost doses (t/ha)				
		0	1	2	3	4
Organic matter	32.140	0	321.40	642.80	964.2	1285.6
Organic carbon	18.670	0	186.70	373.40	560.1	746.8
Total nitrogen	1.330	0	13.30	26.60	39.9	53.2
Available phosphorus*	0.015	0	0.15	0.30	0.45	0.60
Exchangeable potassium**	0.080	0	0.80	1.60	2.40	3.20

*Content in lab unit : 149 mg/kg ˜ 0.015 %

**content in lab unit: 2.05 meq/100 g; as 1 meq/100 g K = 390 mg/kg, 2.05 meq/100 g =799.5 mg/kg ˜ 0.08 %.

Dunnett method (Steel and Torrie, 1980). The results were presented as mean ± standard error and mean (95% confidence interval (95%CI)). Significant difference was set 95%CI on difference excluding zero or p-value < 0.05. Small Latin letters were used to indicate significant differences as appropriate.

3. RESULTS AND DISCUSSION

Farm yield estimated by individual farmer surveys

Yield estimates from farmer surveys varied from 192 kg/ha to 1523 kg/ha (Table 3), with the overall average being 563 kg/ha. The variation was quite large and the dissymmetry coefficients high. Thus, the median yield was also computed. It varied from 98 kg/ha to 590 kg/ha. The overall median yield was low, 241 kg/ha. The low yields were attributed to insufficient soil fertility.

Potential cocoa yields are estimated at more than 5,000 kg/ha (Zuidema *et al.* 2005) and should reach 2,125 kg/ha on farm, but yield gaps are significant (Abdulai *et al*. 2020). In Ivory Coast and Ghana, responsible for more than 60% of global cocoa production (Fountain and Huetz-Adams 2020), the average annual yield ranges from 450 to 550 kg/ha (Goudsmit *et al*. 2023). In agroforestry cocoa in Cameroon, the average yield is 300 kg/ha (Wessel and Quist-Wessel 2015). Our findings add to a body of international literature on cocoa farm yield that needs to increase to improve farmers' revenues.

Soil characteristics in the study areas

Soil samples pH varied between 6.4 and 6.7 (Table 4), complying with the crop requirements of 5 to 7 (Snoeck *et al*. 2016; Villason and Olguera 2020). Organic matter content at 0-30 cm depth exceeded the

Table 3. Variation in cocoa yield estimated by individual farmer surveys

Commune	Yield (kg/ha)		
	Moyenne±SE	CD	Median ±IRQ/2
Abricots	405.81±118.96	1.32	155.71±191.25
Anse-d'Hainault	260.24±89.40	1.57	98.22±97.99
Chambellan	325.54±64.66	1.35	243.33±109.59
Dame-Marie	214.96±39.42	0.31	160.79±133.85
Moron	191.59±55.73	0.38	151.33±120.75
Borgne	1522.61±504.09	1.74	406.00±416.79
Grande-Rivière-du-Nord	305.89±84.45	0.77	227.04±161.91
Port-Margot	1066.11±300.81	0.86	590±554.39
All communes	562.98±10.70	4.46	241.19±191.25

NB. SE = standard error, CD = Coefficient of Dissymmetry, IQR/2 = semi-interquartile range

Table 4. Contents of major nutrients and organic matter in soil samples from the study areas

Param	0-30 cm depth		30-60 cm depth		LA	Ref.
	GA	NO	GA	NO		
pH	6.4	6.6	6.4	6.7	5.0-7.0	1; 2
OM	3.8	2.6	2.6	1.5	>3.5	2
OC	2.1	1.5	1.5	0.9	1.7–3.2	1
N	0.26	0.14	0.18	0.08	0.09-0.4	1; 2
C/N	8	11	8	11	12	1
P	48	47	52	52	10–25	1; 2
CEC(1)	33	18	32	18	12-30	1 ; 2
CEC(2)	12870	7020	12480	7020	4680-11700	
K(1)	0.2	0.2	0.2	0.2	0.2–1.2	1 ; 2
K(2)	78	78	78	78	78-468	
S/A/L	40/51/9	65/25/10	38/53/8	62/28/10	50/30-40/10-20	2
Texture	Clay	SCL	Clay	SCL	Sandy clay	2

NB. Param= parameter, LA= limit of adequacy, Ref= reference, GA= Grand'Anse, NO= Nord, OM= organic matter (%), OC= organic carbon (%), N= total nitrogen (%), C/N= carbon to nitrogen ratio, CEC(1)= cation exchange capacity (meq/100g), CEC(2)= cation exchange capacity (mg/kg), P= available phosphorus (mg/kg), K(1)= exchangeable potassium (meq/100g), K(2)= exchangeable potassium (mg/kg), S/A/L= sand/clay/silt ratio (%), SCL=sandy clay loam. References: 1=Snoeck *et al.* 2016 ; 2=Villason and Olguera 2020.

3.5% critical minimum limit of adequacy (Villason and Olguera 2020) in Grand'Anse (3.7%), but it was slightly lower in Nord (2.6%). Similarly, organic carbon content at 0-30 cm depth reached the 1.7 to 3.2% critical range of adequacy (Snoeck *et al*. 2016) in Grand'Anse (2.1%), but it was lower in Nord (1.5%). Total nitrogen content (0.14 to 0.26%) reached the 0.09- to 0.4% critical range of adequacy (Villason and Olguera 2020; Snoeck *et al*. 2016) in both departments. However, carbon to nitrogen ratio with measured values ranging from 8 to 11 against critical minimum limit of 12 was insufficient in both departments.

Soil samples content of available phosphorus (47 to 52 mg/kg) and CEC level (18 to 33 meq/100 g) largely exceeded critical ranges of adequacy set at 10 to 25 mg/kg and 12 to 30 meq/100 g, respectively. Exchangeable potassium content (0.2 meq/100 g or 78 mg/kg) was at the border of the 0.2 to 1.2 meq/100 g critical range of requirements. The soils were clay in Grand'Anse (38% to 40% of sand) and sandy clay loam in Nord (62% to 65% of sand) while sandy clay with approximately 50% of sand is the recommended texture. The results showed that the soil organic matter content needs to be improved, particularly in the department of Nord. However, the soil characteristics do not confirm the hypothesis that low yields in agroforestry cocoa in Haiti are due to lack of soil fertility.

Field trials yield as affected by department, year and plot type

Significant interaction was observed between year and department (p-value=0.0024). The interannual variation in yield was significant in Nord, but not in Grand'Anse (Table 5). Likewise, the difference between the two departments was significant in 2023, but not in 2022. The results did not show any significant difference between the pruned cacao trees and unpruned cacao trees plots (Table 6; p-value=0.9176).

Doses of compost and field trials yield

The field trials yield varied among the doses of compost from 389.0 to 1113.4 kg/ha in Nord and from 981.2 to 1458.8 kg/ha in Grand'Anse (Table 7). Neither the interactive nor the main effect of the compost was significant. None of the observed differences was significant, all p-values higher than 0.05 and all the 95%CI including zero. These results are in concordance with those of the soil analyses and suggest that soil fertility is not the yield limiting factor in agroforestry cocoa in Haiti. Future researches are needed to study other factors including plant protection, plant age, planting density, light control and genetic material. The yields were higher in trials plots than in farm. This difference was partly due to higher planting density in trials plots. Increasing cocoa planting density has already proven beneficial in Indonesia, Malaysia and Brazil (Lockwood and Pang 1996). However, the benefits of high densities are evident in young plantings, but as trees begin to age, disease incidence increases and yield declines (Kowal 1959; Dias *et al*. 2000; Souza *et al*. 2009). It also appears that not all cocoa varieties respond positively to increased density (Lockwood and Pang 1996).

Table 8 shows the year-to-year variation of the yield between pruned and unpruned plots and among five compost doses. Neither the main effects, nor the double and triple interactions among these three variable were significant at alpha = 0.05.

4. CONCLUSION

Soil characteristics met the minimum organic matter, organic carbon, nitrogen, available phosphorus, and CEC requirements for cocoa cultivation. Soil pH and texture were also within the limits. Potassium value was at the lower borderline. Furthermore, field trials

Table 5. Interactive effects of department and year factors on yield

Department	Year	Yield (kg/ha)
Grand'Anse	2022	1001.01±112.82 ab
Grand'Anse	2023	1285.55±108.86 a
Nord	2022	819.62±107.03 b
Nord	2023	448.84±107.03 c

Note: Results are as mean ± standard error; means with same letter are not significantly different at alpha=0.05 according to LSD test (p-value>0.05).

Table 6. Main effects of type of plot on yield (kg/ha)

Type of plot	Mean (95% confidence interval)	p-value
Unpruned trees' plots (UTP)	918.53 (771.20; 1065.86)	-
Pruned trees' plots (PTP)	905.77 (755.79; 1055.75)	-
Difference	12.76 (-256.16; 230.64)	0.9174

N.B. Difference is not significant if 95% confidence interval includes 0 or p-value >0.05.

Table 7. Variation of yield (kg/ha) among doses of compost in the two departments

Doses	Department of Grand'Anse		Department of Nord	
	Mean	Difference*	Mean	Différence*
0 t/ha	1039.8 (703.2 ; 1376.4)	-	389.0 (20.2 ; 757.7)	-
1 t/ha	981.2 (644.6 ; 1317.8)	-58.60 (-716.9 ; 599.7)	1113.4 (744.7 ; 1482.1)	724.4 (-8.62; 1440.2)
2 t/ha	1193.2 (841.6 ; 1544.8)	153.4 (-519.7 ; 826.5)	817.2 (480.6 ; 1153.8)	428.2 (-257.1; 1113.6)
3 t/ha	1458.8 (1090.1 ; 1827.5)	418.98 (-271.4 ; 1109.4)	483.5 (146.9 ; 820.1)	94.5 (-590.8: 779.9)
4 t/ha	1122.1 (770.5 ; 1473.7)	82.30 (-590.8; 755.4)	602.7 (266.1; 939.3)	213.6 (-471.6; 899.1)

Note. *: difference with 0 t/ha mean set as control; a difference is not significant if its 95% confidence interval includes 0 or if the p-value >0.05.

Table 8. Variation of the yield between two plot types, two years and among the compost doses

Year	Plot type	Compost doses					Average
		0 t/ha	1 t/ha	2 t/ha	3 t/ha	4 t/ha	
2022	Pruned	759.76	1303.23	1017.33	737.94	1174.86	999.34
2022	Unpruned	746.79	1094.14	1176.06	852.22	581.74	880.34
Average 2022		752.68	1189.18	1089.50	800.28	851.34	936.59
2023	Pruned	608.23	839.06	959.95	1063.84	678.65	821.88
2023	Unpruned	887.72	958.643	864.59	1044.65	1023.26	958.10
Average 2023		735.27	893.41	912.27	1053.37	850.95	888.80
Overall average		743.98	1041.30	997.03	926.82	851.14	912.30

results showed no effect of organic fertilizer on yield. Then, soil fertility is not the limiting factor of yield in agroforestry cocoa in Haiti. However, although soil characteristics meet the minimum requirements for cocoa cultivation, it is recommended to add organic amendments in soil for sustainability of the production system over a long period of time. Moreover, median farm yield (241 kg/ha) was low. Future researches are needed to investigate other factors, including plant protection, plant age, planting density, light control and genetic material.

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