

CACAO PRODUCTIVITY AND SOIL CARBON STORAGE IN TWO CROPPING SYSTEMS WITH SELECTED SOIL AMENDMENTS APPLIED IN KABACAN LOAM SOIL

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ABSTRACT

Rising demand for cacao requires nature-based solutions and improved cropping systems to enhance yields, improve soil health, and store carbon. This study assessed the influence of different cacao cropping systems and soil amendments on the yield of 14-year-old cacao (*Theobroma cacao* L.) trees and soil carbon storage, conducted at the University of Southern Mindanao in Kabacan, Cotabato, Philippines (2023-2024). Using a split-plot design and 2-way ANOVA, the trial evaluated two cacao cropping systems: cacao-rubber-coconut (CS 1) and cacao-rubber (CS 2); and soil amendments (control-C, inorganic fertilizer-RR, lime-L, organic fertilizer-OF, and lime + organic fertilizer-L+OF). Two seasons trials, wet (2023) and dry (2024) seasons, revealed that CS 2 significantly increased the yield of cacao (763.82 g/tree dried beans), elevated stored C in the soil, and maintained light intensity within the range limit for cacao. The application of lime and organic fertilizer further enhanced yield by 60%, improved soil organic carbon (SOC) levels, and stored soil C at 80.22 t/ha and 71.33 t/ha, respectively. The increased CN ratio observed in these plots indicated enhanced stabilized carbon. The study demonstrated that lime and organic fertilizer applications in a cacao-rubber system (CS 2) serve as an effective management strategy for improving both cacao productivity and soil health.

Key words: rubber, coconut, light intensity, organic fertilizer, lime

INTRODUCTION

Proper agricultural soil management could be the most effective strategy for reducing the sector's contribution to global carbon emissions. Soils, among other natural resources, sequester and store a significant amount of carbon (C), the primary agent of global warming, and transform it from one form to another, which benefits the ecosystem. C sequestration is the process of capturing CO₂, which can be stored in the soil as soil organic carbon (SOC) (Corning et al. 2016).

Agricultural soils containing around 5% organic matter (OM) or 3% organic carbon (OC) are considered healthy soils capable of sustaining food production, soil microflora, and fauna (Brady and Weil, 2008). However, the intensive and continuous practice of unsustainable farming decreases the

ability of the soil to store C and sustain life. Employing tillage in soil has a negative impact on its OC content (Szostek et al. 2022; Haddaway et al. 2017) as tillage hastens the decomposition process through soil aggregate disruption, increasing aeration, and accelerating the SOC oxidation, resulting in the loss of C in soil (Farahani et al. 2022; Lu et al. 2016; Toth et al. 2025). The rampant use of chemical fertilizers is one of the drivers of greenhouse gas emissions in the atmosphere (Wang et al. 2017). The synthetic nitrogen fertilizer supply chain alone is responsible for 2% of global heat-trapping gas emissions, which is greater than the emissions from all aviation (Heimsoth 2023). If left unattended and the land is degraded, it will impact food security, water availability, and ecosystem health, as well as the loss of ecosystem services that will directly affect humanity (United Nations n.d.). Thus, investment must be made to restore the health of the soil through sustainable land management practices, such as the use of organic inputs and other nature-based solutions for production and the practice of various cropping systems.

One of the strategies to improve soil fertility is through the continuous cycle of nutrients and C and C storage in the soil by effective cropping systems and soil management. All simplifications in tillage, reducing interference in the soil, and the use of organic fertilizers contribute to the improvement of soil properties (Szostek et al. 2022), which assists in the assimilation of carbon and nutrients from plants into the soil, affecting plant-soil interactions. Soil litter production is a major source of SOC and plant nutrient cycles (Novara et al. 2015). As a perennial crop, cacao naturally produces litter and stores C in the soil. Different soils grown with cacao in Davao City, Philippines, stored a considerable amount of SOC, ranging from 1.18 to 3.34% (Novara et al. 2015). Similarly, cacao agroforest cropping systems showed improved soil organic matter content (Monroe et al. 2016; Mustari et al. 2020; Schneidewind 2022; Silue et al. 2024), soil microbial activity (Schneidewind 2022), and soil carbon storage (Araujo et al. 2013; Asigbaase et al. 2021; Miharza et al. 2023; Monroe et al. 2016; Mustari et al. 2020; Schneidewind 2022; Silue et al. 2024; Somarriba et al. 2013), and improved soil quality compared to cacao monoculture. Furthermore, the utilization of soil for perennial crops, such as cacao, improves soil quality. The soil quality, SOC, and nutrient availability in the soil increased progressively with the age of cacao in Ghana (Arthur et al. 2022).

With the continuously increasing demand for cacao beans, information on the effectiveness of various cropping systems and nature-based solutions in improving the yield of cacao and its effect on soil health, as well as on storing carbon (C), is becoming important for sustainability. In Mindanao, Philippines, the productivity per hectare of cacao is declining at a fast rate of 5% from 0.4 to 0.2 tons/ha from 2010 to 2023, and so with the level of income of the smallholder cacao families. A similar trend was observed for the entire country based on cacao statistics (Sales 2025).

Cropping systems have a direct effect of the productivity of cacao where cacao yield under different cropping system is correlated to shade trees associated. In cacao-cropping systems, cacao yield is positively correlated to the amount of light received by the cacao trees (Asitoakor et al. 2022; Chowdary et al. 2024; Koko et al. 2013; Saj et al. 2025). This can be influenced by the crop species (Asitoakor et al. 2022; Jadán et al. 2015; Mattalia et al. 2022), its crop morphology (Ariza-Salamanca et al. 2024), crop density (Koko et al. 2013; Silue et al. 2024), and planting distance (Koko et al. 2013; Notaro et al. 2021). The legume tree *Albizia lebbek* is a compatible shade tree for cacao intercropping compared to *Acacia mangium* (Silue et al. 2024). There was an increase in cacao yield with *Cedrela odorata*, *Khaya ivorensis*, *Terminalia superba*, and *Millicia excelsa* tree shades as compared to the unshaded cacao plots (Asitoakor et al. 2022). The complementary effect of shade trees to cacao is a result of the tree structure of these species that allows light penetration to cacao trees. The four species mentioned in the study of Asitoakor et al. (2022) have morphological structures that allow higher light penetration. Cacao yield and incident light are logistic functions of the distance between fruit trees and cacao (Koko et al. 2013). Higher yield was observed in cacao cropping system with lower shade tree density and cacao crops in full sun produced higher yield as compared to agroforest cacao cropping systems (Chowdary et al. 2024; Jadán et al. 2015; Koko et al. 2013; Niether et al. 2017; Saj et al. 2025).

Other than the amount of light received, competition for water and soil nutrients, species compatibility (Ariza-Salamanca et al. 2024; Notaro et al. 2021; Silue et al. 2024) and the interaction of organism diversity have influenced the cacao productivity (Ntsoli et al. 2025). Due to this range of factors which vary across locations, assessment and management should be site specific (Mattalia et al. 2022). Given this, it is essential to evaluate the cacao productivity in different cacao cropping systems in a site-specific approach.

In the Philippines, cacao is the major crop planted under coconut trees, but some areas have already established cacao-rubber systems, especially in North Cotabato, Central Mindanao, Philippines (Mag-aso and Garcia, 2021). Given the rising trend of intercropping cacao to rubber and coconut, research into these cropping systems is critical. An earlier published study on cacao-rubber was conducted in Brazil, requiring validation to ensure the feasibility of cacao-rubber combinations (Alvim and Nair 1986). The influence of cacao-rubber cropping systems on cacao productivity and C stocks remains scarce. Also, no prior studies were conducted on the effect of soil amendment application in cacao-rubber cropping systems, specifically for Kabacan loam soil. Therefore, this study was conducted to assess and compare the effects of two cacao-cropping systems (cacao-coconut-rubber and cacao-rubber) and selected soil amendments (control, recommended rate of inorganic fertilizer RR, lime L, organic fertilizer OF and lime + organic fertilizer L + OF) applied within the cacao-cropping system on the productivity of cacao, SOC content and stored C in the soil.

MATERIALS AND METHODS

Experimental design. Experiments were conducted in two (2) different cropping systems of cacao planted in *Typic Hapludpts* (Carating et al. 2014) with the Kabacan loam type located in the experimental field of the Philippine Industrial Crops Research Institute (PICRI), University of Southern Mindanao Agricultural Research and Development Center (USMARDC), University of Southern Mindanao, Kabacan, Cotabato, Philippines, from January 2023 to May 2024. The experiment was done in a split-plot design having two (2) cacao-cropping systems: cacao-rubber-coconut (CS 1) and cacao-rubber (CS 2) as the mainplot factor, and five (5) soil amendments (control, inorganic fertilizer-RR, lime-L, organic fertilizer-OF, and lime + organic fertilizer-L + OF) as subplots. A two-way ANOVA was used to determine the significant difference between the two cacao-cropping systems and among different soil amendments applied within the cacao-cropping systems.

In CS 1, cacao plants were established as a rectangular double row, with distances within cacao rows were 3 m x 3 m and 15 m between double rows (559 trees/ha). Coconut was intercropped 7.5 m x 18 m in a rectangular design (74 trees/ha). While rubber is intercropped in a rectangular double row, the distance within cacao rows were 5 m x 2.5 m and 13 m in between double rows (444 trees/ha). Meanwhile, cacao plants in CS 2 were established in 3-row triangular design with 3 m distance between plants having a double row with 10 m distance in between (864 trees/ha). Similarly, rubber in CS 2 was intercropped in rectangular double row plants with 5 x 4 m distance and 10 m distance between double row (329 trees/ha) (Table 1, Fig. 1).

Table 1. Planting distance and layout design of the two cropping systems in PICRI Research Area, USMARDC, USM, Kabacan, Cotabato.

Cropping System	Crops	Age of the crops (years)	Planting Distance (m)	Planting Design	Planting density of crops (trees/hectare)	Planting Density of the cacao-cropping system (trees/hectare)
Cacao + Coconut + Rubber (CS 1)	Cacao	14	15 x 3 double row 3 x 3	Rectangular double rows	559	1, 077
	Coconut	14	7.5 x 18	Rectangular	74	
	Rubber	14	13 x 2.5, double row 5 x 2.5	Rectangular double rows	444	
Cacao + Rubber (CS 2)	Cacao	14	3 x 3 10	Triangular Double row	864	1, 193
	Rubber	14	10 x 4 double row 5 x 4	Rectangular double rows	329	

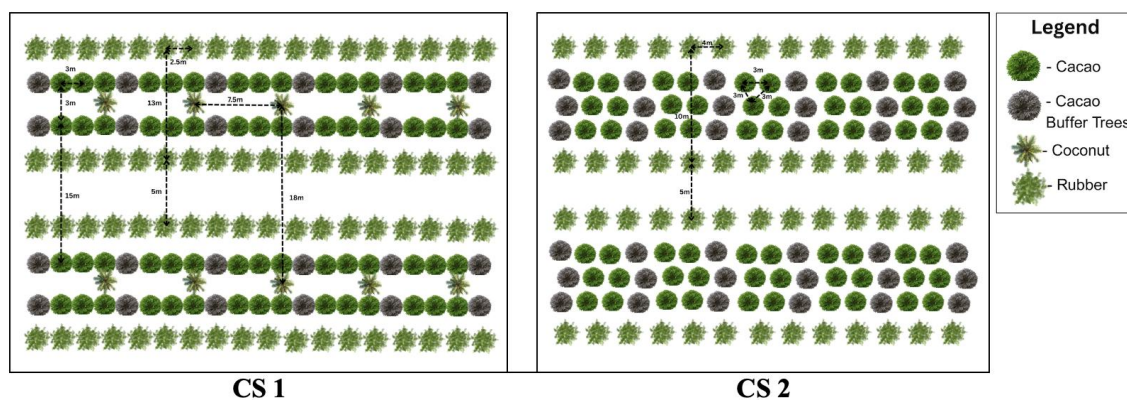


Figure 1. Planting design of the two cropping systems, cacao-coconut-rubber (CS 1) and cacao-rubber (CS 2) in PICRI Research Area, USMARDC, USM, Kabacan, Cotabato.

Liming and fertilization. Application of lime and soil amendments started in October 2022 and was done annually in the month of October for two (2) consecutive years (2022-2023). The lime (L) application rate was 1 kg/tree. Inorganic fertilizer (RR) rate applied was 160g N - 60g P₂O₅ - 120g K₂O/tree, and organic fertilizer application (OF) rate was 2,000 g/tree (Table 2).

Table 2. Treatments and the types of fertilizer applied in the different cacao (*Theobroma cacao* L.) cropping systems in PICRI Research Area, USMARDC, USM, Kabacan, Cotabato.

Treatments	Application Rate (kg/tree)	Time of Application
T1- Control	No fertilizer application	
T2- RR	160g N - 60g P ₂ O ₅ - 120g K ₂ O/tree	Fertilization was done annually starting October 2022.
T3- Lime (L)	1000 g/tree of lime	Liming was done annually starting October 2022.
T4- Organic Fertilizer (OF)	2000 g/tree of organic fertilizer	Fertilization was done annually starting October 2022.
T5- Lime + Organic Fertilizer (L + OF)	1000 g/tree lime + 2000 g/tree organic fertilizer	Liming and fertilization were done annually, starting in October 2022.

Soil analysis. Soil samples were collected from the experimental area before the application of each treatment. One (1) composite sample, composed of 15 subsamples, was collected at a depth of 20 cm. The samples were submitted to the USMARDC-Central Laboratory, where soil pH (1:2.5 soil: water), organic C% (Walkley-Black method), total N% (Kjeldahl method), available P (Bray P2 method), exchangeable K (Ammonium Acetate 7 method), cation exchange capacity (CEC Ammonium Acetate 7 method), and texture (Hydrometer method) were analyzed.

Chemical analysis of fertilizers. The organic fertilizer and lime used were also submitted to the USMARDC-Central Laboratory for analysis. Organic C content (Walkley-Black method), P₂O₅% (colorimetric method), and K₂O (AAS determination) were determined for the organic fertilizer. For the calcic lime, total Ca and CaCO₃ (acid digestion method) were determined.

Cacao yield. Data were collected at the onset of harvest from September 2023 to March 2024 (peak season of cacao). A sample of six cacao trees per plot were used to estimate the number of cacao pods, the bean weight per pod, and the bean weight (wet and dry) per tree. The number of pods per tree were counted, bean weight per pod was recorded and the total bean weight per tree was calculated by aggregating the bean weight in each sample tree. The beans were oven-dried at 70°C until a constant weight was achieved. Both fresh and dried weights of cacao beans per tree were expressed in grams.

Soil C storage assessment. The soil samples were collected and prepared for each experimental plot. Each soil sample was a composite of ten (10) subsampling points randomly selected within the experimental plots, and collected using an auger to a depth of 20 cm. These were analyzed for soil organic C (OC%) following the Walkley-Black chromic acid wet oxidation method (GLOSOLAN 2019) and bulk density using the core method (Jabro et al. 2020). Carbon stored in soil (t/ha) was estimated using the C storage formula (Araujo et al. 2013; Morgan and Ackerson 2022; Tadiello et al. 2022) as follows:

$$\text{Soil C storage} \left(\frac{\text{t}}{\text{ha}} \right) = \text{OC}\% \times \text{layer thickness} \times \text{bulk density} \times (1 - \text{RF}) \times 10^4$$

where OC is the organic carbon content and RF is the rock fragment content fraction.

Total N (%) in the soil was also determined using the Kjeldahl method (GLOSOLAN 2021) to determine the CN ratio.

Light intensity (lux). Light intensity was determined using the lux light meter, collected at 10:00 am and 2:00 pm on March 2024. The collection of light intensity using the light meter was done five times, at a height of 1.5 m from the ground, within the experimental plots.

Litterfall production (t/ha). Litterfall production was gathered following the modified procedure of Pitman et al. 2010. A litterfall trap was established by setting-up one (1) meter square mesh net with a distance of 10 cm from the ground for litterfall collection in the center of each experimental unit. The plant litterfall samples were collected monthly during the wet season 2023 (May to October 2023) and the dry season 2024 (November 2023 to April 2024). Dry weight of leaf litter was determined using a convection oven, and monthly data were consolidated for each season.

Statistical analysis. Two-way ANOVA was used to determine the differences between cropping systems and among soil amendments. The difference between the two cropping systems was tested using Least Significant Difference (LSD) at 5% level, and the differences among soil amendments were separated using Tukey’s Honest Significant Difference (HSD). The Statistical Tool for Agricultural Research (STAR 2013) was used to analyze the data.

RESULTS AND DISCUSSION

Soil initial analysis. Soil pH, available P, and cation exchange capacity had sufficient levels for cacao production; however, soil OC, total N, and exchangeable K were deficient when compared to the cacao nutrient threshold established by Snoeck et al. (2016) (Table 3). The soil of the experimental area was moderately acidic (pH 5.62), which was within the optimal threshold of cacao. The available P content was higher than the cacao threshold level (6-15 ppm) with a value of 77.91 ppm. Cation exchange capacity (CEC) was slightly higher than the cacao threshold (12-30 cmol₊ kg⁻¹ soil), which was 30.43 cmol₊ kg⁻¹ soil. The soil organic C content, total N, and exchangeable K analysis were lower than the range for cacao threshold with values 1.24%, 0.17% and 0.09 cmol₊ kg⁻¹ soil, respectively. The soil texture was loam.

Table 3. Initial soil analysis of the experimental area, PICRI research area, USMARDC, USM Kabacan, Cotabato.

Soil analysis	Value
Soil pH	5.62 S
Soil organic carbon (%)	1.24 D
Total nitrogen (%)	0.17 D
Available phosphorus (ppm)	77.91 S
Exchangeable potassium (cmol ₊ kg ⁻¹ soil)	0.09 D
CEC (cmol ₊ kg ⁻¹ soil)	30.43 S
Soil texture	Loam (46.08% sand, 29.18% clay, and 24.75% silt)

S – sufficient and D-deficient for cacao based on Snoeck et al. 2016

Chemical analysis of organic fertilizer and calcic lime. The organic C and organic matter content of the organic fertilizer was 8.26 and 14.20%, respectively. The total N content was 1.69%, P₂O₅ and K₂O were 0.70 and 0.84%, respectively. The lime used in the experiment had 35.6% total Ca and the total CaCO₃ was 89.1% (Table 4).

Table 4. Chemical analysis of organic fertilizer and calcic lime used in the field trials experiment.

Chemical analysis	Organic Fertilizer	Calcic Lime
Organic carbon (%)	8.26	
Organic matter (%)	14.20	
N (%)	1.69	
P ₂ O ₅ (%)	0.70	
K ₂ O (%)	0.84	
Total Ca (%)		35.7%
Total CaCO ₃ (%)		89.1%

Yield of cacao

Cropping system. Significant interactions between the cropping system and soil amendment were recorded in cacao yield, where liming under CS 2 resulted in the highest yield. Moreover, it was observed that cropping system significantly increased the cacao yield which was notably higher in CS 2, having higher cacao plant density and a lower rubber population per unit area. Number of cacao pod, weight of beans per pod and weight of wet beans per tree were significantly higher in CS 2 than in CS 1 (Table 5). The fresh (Table 6) and dried weight (Fig. 2) of beans per tree were also higher in CS 2 as compared to CS 1.

Wider spacing between the cacao under CS 2 provided ideal conditions to produce higher fruit numbers and weights of wet and dried beans. CS 1 has a larger number of tall trees, such as rubber and coconut, which reduces the space for cacao and resulted in lower light received which is 9,510 lux as compared to CS 2 which have 31,636 lux light intensity (Fig. 2). Hence, pod production is lower in CS 1 with an average of 7 pods/tree (Table 5). This indicates that increasing the density and population of rubber and coconut trees and decreasing planting distance will result in lower pod development and reduced bean weight in pods.

Competition for light between tall trees and cacao might have affected cacao yield as light intensity penetrating the CS 1 was lower than CS 2. (Fig. 2). Excessive shade in CS 1 indicated by low light intensity (9,510 lux) is detrimental to the photosynthetic activities (Arévalo-Gardini et al. 2021), resulting in reduced cacao growth and productivity. Although cacao is a shade-tolerant crop, it requires a certain light limit ranging from 27,000 lux (De Santana et al. 2025; Lennon et al. 2021) to 81,000 lux (De Santana et al. 2025), reaching up to 97,200 lux (Galyoun et al. 1996) which may vary depending on the cacao genotype and season (Acheampong et al. 2013; Lahive et al. 2019). Several studies shows that cacao yield in the cacao-cropping system is influenced by the associated shade trees, affecting light inflexion and penetration to cacao. The amount of light received by the cacao trees in the cacao-cropping systems is positively correlated with the cacao tree vigor and yield (Chowdary et al. 2024). Light availability is the critical limiting factor for production in the cacao cropping system (Saj et al. 2025).

These results were consistent with an earlier study on a coconut-cacao system that revealed higher cumulative cacao yield in higher cacao plant density with fewer coconut trees as an intercrop (Osei-Bonsu et al. 2002). Similar findings were also shown by Silue et al. (2024), where cocoa productivity is lower in cacao-*Acacia mangium* agroforests with lower cacao density and reduced

distance between cacao trees and the shade tree *Acacia mangium*. Increasing the shade tree cover from about 20% to 80% in the cacao system resulted in about a 60% decrease in cacao yield (Blaser et al. 2017). Cacao yield is lower in a cropping system having high density shade trees as compared to monocrop cacao (Jadán et al. 2015) . Thus, shade management is key in balancing cocoa productivity and carbon sequestration (Somarriba et al. 2013).

Soil amendments. The application of soil amendments significantly increased the cacao yield which was found to be more effective in CS 2. Under CS 2, cacao trees treated with lime significantly increased the yield of cacao in terms of the number of pods per tree (51 pods/tree), followed by cacao trees treated with OF (37 pods/tree). The combination of L and OF application resulted in a yield output of 30 pods/tree, similar to that of cacao trees treated with RR of inorganic fertilizer (31 pods/tree) (Table 5). Soil amendment can improve the yield of cacao cropping systems by providing nutrients in optimum shade (Acheampong et al. 2015; Goudsmit et al. 2023) and full sunlight (Goudsmit et al. 2023).

Table 5. Number of pods/tree and weight of wet beans of cacao per pod (g/pod) under different cacao cropping systems applied with soil amendments, during the wet 2023 and dry 2024 season.

Soil Amendments	Number of pods/tree ^{1/}		Weight of wet beans per pod (g/pod) ^{1/}	
	CS 1	CS 2	CS 1	CS 2
T1- Control	0 ± 0.00 a	3 ± 1.22 c	0.00 ± 0.00 c	99.09 ± 8.23 c
T2- RR	7 ± 4.18 a	31 ± 4.33 b	112.10 ± 7.04 b	111.39 ± 13.38 bc
T3- Lime (L)	9 ± 3.93 a	51 ± 10.68 a	116.04 ± 1.00 b	124.73 ± 4.33 b
T4- Organic Fertilizer (OF)	13 ± 2.31 a	37 ± 9.24 ab	139.32 ± 4.68 a	151.09 ± 8.86 a
T5- Lime + Organic Fertilizer (L + OF)	5 ± 2.52 a	30 ± 4.37 b	109.76 ± 168.83 b	127.14 ± 0.06 b
Pr (>F) _a	0.0115		0.0159	
Pr (>F) _b			0.0004	0.0000
Pr (>F) _{axb}			0.0255	0.0000

^{1/}In a column, means followed by the same letter are not significantly different at the 5% level according to Tukey's HSD test.

Soil amendment applications significantly increased the weight of wet beans per pod in both CS employed (Table 5). The application of OF recorded the highest bean weight per pod in both CS 1 (139.32g) and CS 2 (151.09g). This was followed by the bean weight per pod applied with L (CS 1 - 116.04 g and CS 2 124.73 g) and L + OF (CS 1 - 109.76 and CS 2 – 124.14 g), which did not differ significantly from the results of RR (112.10g and 111.39g).

The wet bean yield of the cacao trees also increased significantly following the application of soil amendments. Under CS 1, the highest wet bean yield per tree was observed in cacao trees treated with OF (1,086.70 g/tree). The application of lime alone resulted in the wet bean weight increase of 36.72% relative to RR; however, the L + OF application resulted in a lower bean weight output of 331.37 g/tree as compared to L (653.02 g/tree) and OF (1,086.70 g/tree) application, which was not significantly different from bean weight output of cacao applied with RR inorganic fertilizer (413.20 g/tree) (Table 6).

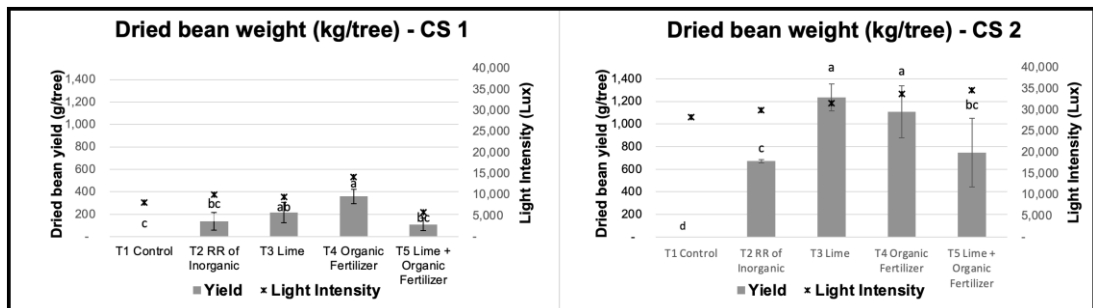
In CS 2, the wet bean weight output of cacao trees treated with L was significantly higher than those applied with RR. Wet bean weight of cacao applied with L was 3,743 g/tree, which was 84% higher than that of cacao trees subjected to RR (2,034 g/tree). The application of OF produced a bean weight yield output of 3,359.31 g/tree, which was at par with the output of cacao trees applied with L (3,743.36 g/tree). However, the combination of L and OF resulted in a significantly lower wet bean weight output of 2,263.28 g/tree compared to wet bean weight treated with L alone or OF alone (Table 6).

The dried bean yield per tree of cacao increased significantly when the soil amendments were applied. Under CS 1, the OF application resulted in the highest dried bean yield (355.61 g/tree), which was not significantly different from the dried bean yield obtained from cacao trees treated with L (215.50 g/tree). However, significantly lower dried bean yield was obtained when lime and organic fertilizer were combined (109.35 g/tree). Under CS 2, the application of lime resulted in a higher dried bean yield (1,235.31 g/tree), which was at par with those that were applied with OF (1,108.57 g/tree) (Fig. 2).

Table 6. Weight of wet beans (g/tree) under two cacao cropping systems applied with soil amendments, during the wet 2023 and dry 2024 seasons.

Soil Amendments	Weight of wet beans per tree (g/tree) ^{1/}	
	CS 1	CS 2
T1- Control	0.00 ± 0.00 a	172.91 ± 49.24 d
T2- RR	413.20 ± 235.40 a	2,034.09 ± 358.25 c
T3- Lime (L)	653.02 ± 277.61 a	3,743.36 ± 700.17 a
T4- Organic Fertilizer (OF)	1,086.70 ± 190.10 a	3,359.31 ± 918.60 ab
T5- Lime + Organic Fertilizer (L + OF)	331.37 ± 168.83 a	2,263.28 ± 334.10 bc
Pr (>F) _a	0.0132	
Pr (>F) _b		0.0003
Pr (>F) _{axb}		0.0276

^{1/}In a column, means followed by the same letter are not significantly different at 5% level Tukey's HSD test.



*Cropping system significantly different at p -value < 0.05 LSD

^{1/}Within the cropping systems, bars followed by the same letter are not significantly different at the 5% level according to Tukey's HSD test.

Figure 2. Dried bean weight of cacao (kg/tree) in different cropping systems* and soil amendments.

Both organic fertilizer application and liming significantly increased the wet and dry bean yield of cacao. OF application improved the cacao yield by providing nutrients to the plants and increasing nutrient uptake and efficiency (Muda et al. 2021; Mulia et al. 2019), contributed by the effect of organic fertilizer on enhancing soil microbial activity, improving soil structure, and increasing nutrient availability (Fungenzi et al. 2021). Furthermore, liming soil improves the pH of the soil and the availability of nutrients, which increases yield (Ejigu et al. 2023; Qaswar et al. 2020) and is necessary for application in acidic soils (Snoeck et al. 2016). Rosas-Patiño et al. (2019) showed that liming increases the yield of cacao. However, combining lime to organic fertilizer did not significantly increase the wet and dry bean yield of cacao. Similar results were found in the study of Islam et al. (2021) where the combination of lime and organic manure (cow dung) resulted to lower first crop (T. aman) yields compared to lime alone, with result comparable to control (no application). Ca in lime may form inner and outer sphere complexes with OC (Adusei-Gyamfi et al. 2019; Galicia-Andrés et al. 2021). These forms dense agglomerates which enhances OM stability and protect SOM from further degradation (Galicia-Andrés et al. 2021). Stable OM from agglomeration through Ca-SOM complexation might reduce the mineralization of nutrients making it temporarily unavailable for crop uptake, hence, reducing cacao yield.

Soil pH

Cropping system. Soil pH was not significantly influenced by the different cropping systems and soil amendments during wet season (2023), however, a significant difference was recorded during dry season (2024) (Table 7).

Soil amendments. Soil pH was increased significantly in soil applied with OF in CS 2 (pH 5.95) and L + OF in CS 1 (pH 5.90). However, liming soil in CS 1 (pH 5.40) and CS 2 (pH 5.55) did not significantly increase the soil pH, while L + OF applied in CS 2 resulted in a lower soil pH (pH 5.27). Soil applied with OF in CS 1 has a soil pH value (pH 5.59) similar to soil applied with RR under CS 1 (pH 5.56) and CS 2 (pH 5.58), and control in CS 2 (pH 5.65) (Table 7).

OF application in CS 2 and L + OF in CS 1 have shown to increase the soil pH attributed to the mechanism of organic matter decomposition that includes decarboxylation, where reaction products may consume proton (Yan et al. 1996) and the release of basic ions and salts which are products of mineralization. Similar results were also found in the study of Islam et al. (2021) and Regasa et al. (2025) where application of lime combined with organic amendment significantly increased the soil pH as compared to lime alone. Liming soil without OF application did not significantly increase the soil pH, as the amount of lime applied might be insufficient to increase the pH in soils. Factors affecting the change in pH with liming application rate, other than the type of liming material, timing, and method (Jouichat et al. 2024). A low application rate of lime below the buffering capacity of the soil will not effectively increase the soil pH (Fageria and Baligar 2008; Fageria and Nascente 2014). Similar results were also found in an earlier study wherein application of lime at a rate of 0.5 to 1 ton per hectare in wheat resulted in soil pH similar to control (without lime) (Ejigu et al. 2023).

It was also observed that soil pH in dry season (2024) was higher than the soil pH recorded during wet season 2023 noticeable in CS 2. Soil pH was recorded as higher during the dry season than in wet season based on the laboratory analysis of Solonchaks soil in Yinbei region, China (Jia et al. 2021). This difference is attributed to the intensified leaching of basic ions by rainfall during the wet season, which is reduced in the dry season, thereby maintaining a higher pH.

Table 7. Soil pH under two cacao cropping systems applied with soil amendments during the wet 2023 and dry 2024 seasons.

Treatments	Wet Season (2023) ^{ns}		Dry Season (2024) ^{1/}	
	CS 1	CS 2	CS 1	CS 2
T1- Control	5.38 ±0.08 a	5.07 ±0.03 a	5.31 ±0.03 b	5.65 ±0.08 ab
T2- RR	5.51 ±0.04 a	5.43 ±0.16 a	5.56 ±0.04 ab	5.58 ±0.16 ab
T3- Lime (L)	5.37 ±0.01 a	5.13 ±0.09 a	5.40 ±0.04 ab	5.55 ±0.09 ab
T4- Organic Fertilizer (OF)	5.55 ±0.13 a	5.47 ±0.09 a	5.59 ±0.03 ab	5.95 ±0.09 a
T5- Lime + Organic Fertilizer (L + OF)	5.37 ±0.19 a	5.37 ±0.13 a	5.90 ±0.14 a	5.27 ±0.13 b
Pr (>F) _a	0.1716		0.6943	
Pr (>F) _b			0.1005	0.0684
Pr (>F) _{axb}			0.6870	0.0013

Ranges of soil pH as follows: very strongly acid (4.5–5.0), strongly acidic (5.1–5.5), moderately acidic (5.6–6.0), slightly acidic (6.1–6.5) (Ditzler et al. 2017)

^{1/}In a column, means followed by the same letter are not significantly different at 5% level Tukey's HSD test.
^{ns} - Not significantly different

Soil organic C and litterfall

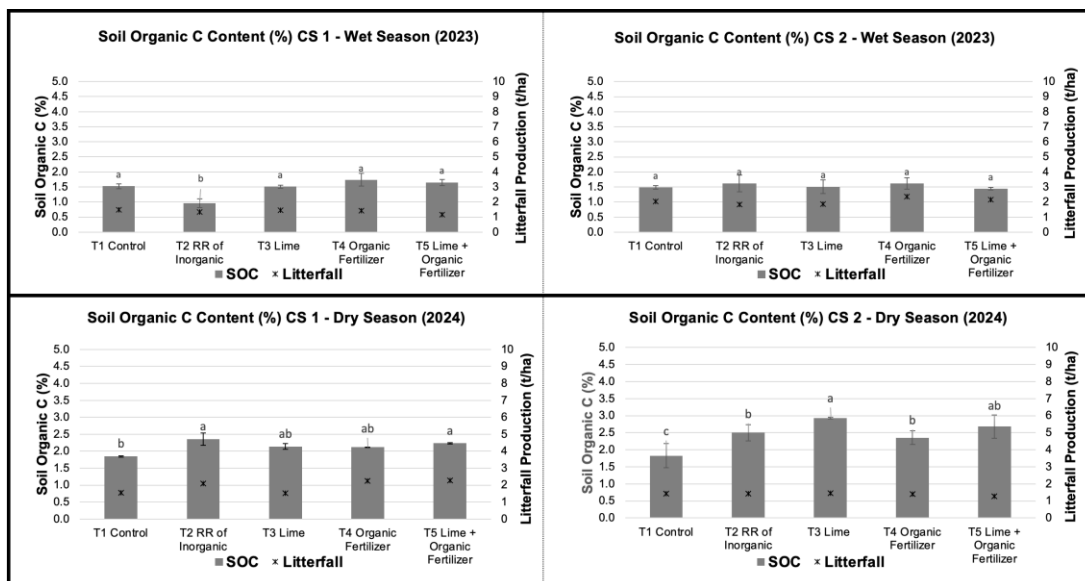
Cropping system. Significant interaction was recorded between the cropping system and soil amendments on their effect on the soil organic carbon content. The organic C (OC) content in the soil increased significantly with the application of soil amendment in both cropping systems - CS 1 and CS 2. Over time, a noticeable increase in OC was observed, indicating an accumulation of OC in the soil. The SOC content between cacao cropping systems tends to be higher under CS 2 compared to CS 1, specifically during DS 2024 (Fig. 3). The higher SOC accumulation observed in CS 2 might be attributed to the higher biomass from total litterfall production in the system, owing to its higher cacao plant density than CS1. The overall litterfall production tends to be higher in CS 2, where relatively higher litterfall accumulated in CS 2 during the wet season (2023) (Fig. 3). Higher litterfall production was observed in CS 2 in wet season (2023) brought about by cacao litter as CS 2 had higher cacao density. Whilst, during the dry season (2024), higher litterfall was observed in CS 1, as this period was wintering for rubber, where CS 1 had greater rubber density. Overall, CS 2 recorded relatively higher litterfall production.

In a cacao agroforest system, the biomass and density of cacao trees were the determinants of biomass production (Silue et al. 2024). The sources of this biomass in cacao were litterfall and litter from cacao management, such as pruning, and the abundance of roots and fine root biomass (Monroe et al. 2016).

Soil amendments. Soil organic C content is also significantly influenced by the application of soil amendments. The highest significant increase in soil organic C content was achieved in CS 2 with L and L + OF amendments (Fig. 3).

During the wet season of 2023, the application of soil amendments to CS 1 significantly influenced the soil organic matter content. The lowest SOC content (0.96 %) was recorded in soils treated with inorganic fertilizer. Statistically, the application of L, OF, and L + OF gained SOC content similar to the control. However, the application of OF recorded 14% higher SOC content (1.74%) relative to control (1.52%) and was 58% higher than the application of RR. Under CS 2, soil organic C content applied with soil amendment was not significantly different (Fig. 3).

During the dry season (2024), the addition of soil amendments increased soil organic C content. Under CS 1, the SOC content of the soil subjected to RR (2.36%) increased, which was not statistically different from the SOC content of the soil treated with L + OF (2.23%). An increase in SOC was also observed in soils treated with OF (2.12%) and L (2.14%) relative to the control. Similarly, a significant increase in SOC was also observed under CS 2. The highest SOC was observed in the soil treated with L (2.93%), which was similar to the SOC level of the soil treated with L + OF (2.68%). SOC content was also significantly higher in soil applied with OF (2.36%) as compared to control where SOC content applied with OF was statistically similar to SOC content applied with RR (2.50%) (Fig. 3).



^{1/}Within the cropping systems, bars followed by the same letter are not significantly different at the 5% level according to Tukey's HSD test.

Figure 3. Soil organic carbon (%) under two cacao cropping systems after application of selected soil amendments during the wet 2023 and dry 2024 seasons.

The increase in OC content in soil treated with OF is attributed to the OC content of the amendment, which might be stable (Yilmaz and Sönmez 2017). Furthermore, a noticeable decline in OC was observed in soil treated with RR, which might be attributed to the low C:N ratio (6.11) and faster rate of SOC oxidation (Fig. 4). The retention of C in soil with inorganic fertilizer is much lower (Ndung'u et al. 2021). Liming alone did not increase the amount of OC in the soil during the wet season of 2023, as liming delayed the effect of increased litter and other sources of C in increasing SOC levels. The effect of liming on SOC was observed in the succeeding season (dry season, 2024) (Fig. 3).

The addition of L + OF and OF to the soil effectively increases the SOC in soil, as these soil amendments might improve the conversion of litterfall to stable SOC, acted by decomposers (Paradelo

et al. 2015). Additionally, Ca from the applied lime formed complexes with OC, flocculated the soil, and stabilized SOC (Rowley et al. 2018).

Stored carbon (C) in soil

Cropping system. Cropping systems influenced the stored C in soil in two different seasons, wherein higher stored C was noted in CS 2, having a high cacao tree density that distributes more leaf litter in the soil (Fig. 4).

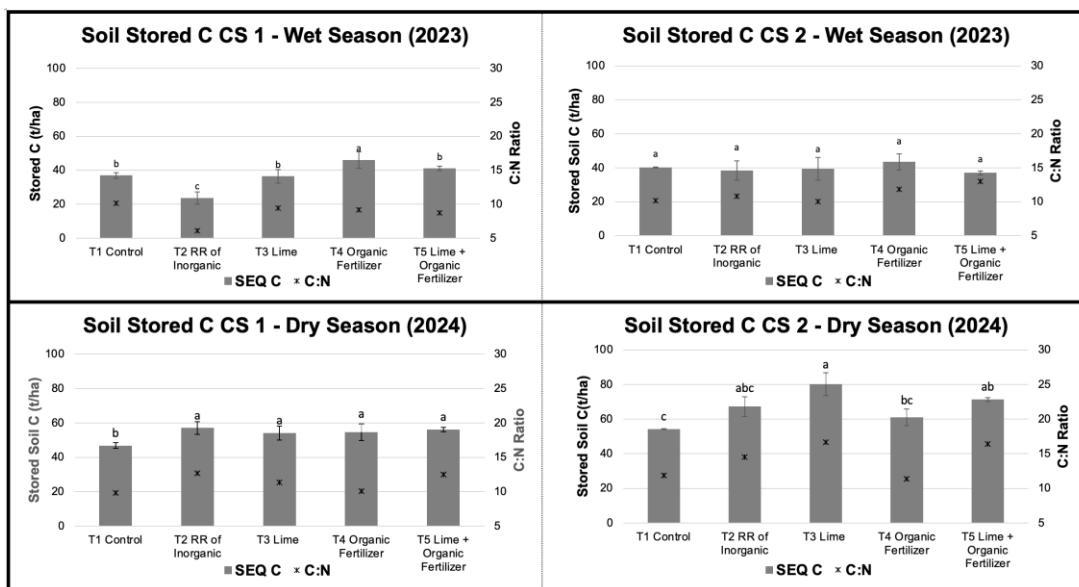
The density of cacao trees is a major determinant of the biomass in agroforest systems. This is attributed to the reduced competition for light among cacao trees, increased photosynthetic activity, and C assimilation, which results in higher biomass production (Silue et al. 2024). Furthermore, in the cacao-rubber system, soil C storage was greater in the cacao rows than in the rubber rows, which is attributed to the deposition of cacao litter and root biomass in the system (Monroe et al. 2016). In addition, the addition of coconut, in a dense rubber-cacao system in CS 1, resulted in low turnover, as coconut fronds are composed of a high percentage of lignin components (18-21%) and low N content (Mohamad Aziz et al. 2018), making it resistant to decomposition.

Soil amendments. The application of soil amendments increased the stored C within the different cropping seasons. The highest significant increase in stored C content was achieved in CS 2 with L amendments (Fig. 4).

During the wet season of 2023 under CS 1, the highest C stored was observed in soil applied with OF (46.10 tons/ha), which was not statistically different from soil applied with L + OF (41.04 t/ha), having a noticeable difference of 9.19 tons/ha of C stored in soil against the control (Fig. 4). The application of L alone did not significantly increase the stored carbon (36.42 tons/ha), while RR application decreased the stored C in soil by 13.19 tons/ha relative to the control. This implies that the addition of organic fertilizer in CS 1 provided additional C in the soil, which is more stable, while inorganic fertilizer resulted in greater OC release. This might be attributed to the faster rate of mineralization as reflected in the low C:N ratio of the soil treated with inorganic fertilizer. Furthermore, under CS 2, the level of stored C in the soil was not statistically different when soil amendments were applied. Stored C in soil ranged from 37.07 t/ha (L + OF) to 43.48 t/ha (OF).

During the dry season of 2024, adding soil amendments to CS 1 increased the amount of C stored in the soil compared to the control (46.81%). The increase was about 7.39 t/ha (L) to 10.27 t/ha (RR). Similarly, a significant increase in stored C with applied soil amendments was observed in CS 2. The highest stored C was recorded in soil treated with lime (80.22 t/ha), which was statistically similar to that in soil treated with L + OF (71.33t/ha). The stored C applied with OF (60.97 t/ha) was comparable to the stored C in soil applied with RR (67.29 t/ha), which increased stored C by 13 t/ha and 6.67 t/ha, respectively, relative to the control (54.30 t/ha).

The addition of fertilizers and soil amendments improves the growth of crops in the system, which effectively utilizes atmospheric CO₂, sequestering it in the crops, and a portion of the C is stored in the soil. L and L + OF applications resulted in a significant increase in stored C. Liming promotes microbial activity that decomposes organic materials; however, over time, the decomposition process provides more stable C, that is, humus, which is resistant to destruction and hence stored as stable carbon (Greff et al. 2022; Rowley et al. 2018).



^{1/}Within the cropping systems, bars with the same letter are not significantly different at the 5% level according to Tukey's HSD test.

*Significantly different at p -value < 0.05 LSD test.

Figure 4. Stored C in soil under the different cacao cropping systems* as influenced by the application of soil amendments^{1/} during wet season 2023 and dry season 2024.

CONCLUSION

Cacao-cropping systems and soil amendment application influenced significantly the yield of cacao, organic carbon content and the carbon storage of Kabacan loam soil. The cacao-rubber system increased significantly the yield of cacao, elevated stored carbon in the soil, and maintained light intensity within the acceptable light intensity limit. The application of lime, particularly in combination with organic fertilizers, increased yield by 60%. This amendment strategy specifically improved soil organic carbon (SOC) levels and elevated stored soil carbon. The improved C:N ratio observed in these plots indicated enhanced stabilized carbon. Consequently, the study highlighted that the cacao-rubber system, combined with lime and organic fertilizer applications, serves as an effective management strategy for improving both cacao productivity and soil health. Similar research in other cacao-producing areas in the Philippines would be worth considering for broader recommendations. Further studies are needed to determine the best planting densities for rubber, coconut, and cacao intercropping and to optimize the application rates of soil amendments to achieve maximum yield.

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REFERENCES CITED

- Acheampong, K., P. Hadley, A. Daymond and P. Adu-Yeboah. 2015. The influence of shade and organic fertilizer treatments on the physiology and establishment of *Theobroma cacao* clones. *American Journal of Experimental Agriculture*. 6(6): 347–360. <https://doi.org/10.9734/AJEA/2015/15206>
- Acheampong, K., P. Hadley and A. J. Daymond. 2013. Photosynthetic activity and early growth of four cacao genotypes as influenced by different shade regimes under West African dry and wet season conditions. *Experimental Agriculture*. 49(1): 31–42. <https://doi.org/10.1017/S0014479712001007>
- Adusei-Gyamfi, J., B. Ouddane, L. Rietveld, J.P. Cornard and J. Criquet. 2019. Natural organic matter-complexation and its impact on water treatment: A critical review. *Water Research*. 160: 130–147. <https://doi.org/10.1016/j.watres.2019.05.064>
- Alvim, R. and P. K. R. Nair. 1986. Combination of cacao with other plantation crops: An agroforestry system in Southeast Bahia, Brazil. *Agroforestry Systems*, 4(1): 3–15. <https://doi.org/10.1007/BF01834698>
- Araujo, Q. R., G. A. H. A. Loureiro, S. O. Santana and V. C. Baligar. 2013. Soil classification and carbon storage in cacao agroforestry farming systems of Bahia, Brazil. *Journal of Sustainable Forestry*. 32(6): 625–647. <https://doi.org/10.1080/10549811.2013.799037>
- Arévalo-Gardini, E., A. Farfán, F. Barraza, C. O. Arévalo-Hernández, L. B. Zúñiga-Cernades, J. Alegre and V. C. Baligar. 2021. Growth, physiological, nutrient-uptake-efficiency and shade-tolerance responses of cacao genotypes under different shades. *Agronomy*. 11(8): 1536. <https://doi.org/10.3390/agronomy11081536>
- Ariza-Salamanca, A. J., R. M. Navarro-Cerrillo, J. Crozier, C. Stirling, A. Mancini, W. Blaser-Hart and P. González-Moreno. 2024. Drivers of cocoa yield and growth in young monoculture and agroforestry systems. *Agricultural Systems*. 219: 104044. <https://doi.org/10.1016/j.agsy.2024.104044>
- Arthur, A., S. Acquaye, W. Cheng, J. A. Dogbatse, S. Konlan, O. Domfeh and A. K. Quaye, 2022. Soil carbon stocks and main nutrients under cocoa plantations of different ages. *Soil Science and Plant Nutrition*. 68(1): 99–103. <https://doi.org/10.1080/00380768.2022.2029219>
- Asigbaase, M., E. Dawoe, B. H. Lomax and S. Sjøgersten. 2021. Biomass and carbon stocks of organic and conventional cocoa agroforests, Ghana. *Agriculture, Ecosystems and Environment*. 306: 107192. <https://doi.org/10.1016/j.agee.2020.107192>
- Asitoakor, B. K., P. Vaast, A. Ræbild, H. P. Ravn, V. Y. Eziah, K. Owusu, E. O. Mensah and R. Asare. 2022. Selected shade tree species improved cocoa yields in low-input agroforestry systems in Ghana. *Agricultural Systems*. 202: 103476. <https://doi.org/10.1016/j.agsy.2022.103476>
- Blaser, W. J., J. Oppong, E. Yeboah and J. Six. 2017. Shade trees have limited benefits for soil fertility in cocoa agroforests. *Agriculture, Ecosystems and Environment*. 243: 83–91. <https://doi.org/10.1016/j.agee.2017.04.007>
- Brady, N. C., and R. R. Weil. 2008. *The Nature and Properties of Soils*. 14th ed., Pearson Prentice Hall, Upper Saddle River, New Jersey. 965 p.
- Carating, R. B., R. G. Galanta and C. D. Bacatio. 2014. *The Soils of the Philippines*. Springer Netherlands. <https://doi.org/10.1007/978-94-017-8682-9>

- Chowdary, G. S., M. Kalpana, L. N. Naidu, D. S. Suneetha and V. Sekhar. 2024. Assessing the performance of cocoa grown under different cropping systems in various soils of coastal Andhra Pradesh. *International Journal of Research in Agronomy*. 7(10): 28–31. <https://doi.org/10.33545/2618060X.2024.v7.i10a.1692>
- Corning, E., A. Sadeghpour, Q. Ketterings and K. Czymmek. 2016. The carbon cycle and soil organic carbon. <http://nmsp.cals.cornell.edu/publications/factsheets/factsheet91.pdf>
- De Santana, E. N., K. T. Kuhlcamp, J. Crasque, B. Cerri Neto, V. D. S. Oliveira and S. Dousseau-Arantes. 2025. Photosynthetic light response curve and photosynthetic performance of cacao (*Theobroma cacao* L.) genotypes grown under full sun field conditions. *Plants*. 14(23): 3555. <https://doi.org/10.3390/plants14233555>
- Ditzler, C., K. Scheffé and H. C. Monger. 2017. *Soil Survey Manual*. United States Department of Agriculture. Government Printing Office.
- Ejigu, W., Y. G. Selassie, E. Elias and E. Molla. 2023. Effect of lime rates and method of application on soil properties of acidic Luvisols and wheat (*Triticum aestivum*, L.) yields in northwest Ethiopia. *Heliyon*. 9(3): e13988. <https://doi.org/10.1016/j.heliyon.2023.e13988>
- Fageria, N. K. and V. C. Baligar. 2008. Chapter 7 Ameliorating soil acidity of tropical oxisols by liming for sustainable crop production, vol 99, pp 345-399. In D. L. Sparks. *Advances in Agronomy* 4078. Elsevier. [https://doi.org/10.1016/S0065-2113\(08\)00407-0](https://doi.org/10.1016/S0065-2113(08)00407-0)
- Fageria, N. K. and A. S. Nascente. 2004. Management of soil acidity of South American soils for sustainable crop production, vol 128, pp 221-275. In D. L. Sparks. *Advances in Agronomy* 284. Elsevier. <https://doi.org/10.1016/B978-0-12-802139-2.00006-8>
- Farahani, E., H. Emami, and M. Forouhar. 2022. Effects of tillage systems on soil organic carbon and some soil physical properties. *Land Degradation and Development*. 33(8): 1307–1320. <https://doi.org/10.1002/ldr.4221>
- Fungenzi, T., R. Sakrabani, P. J. Burgess, S. Lambert and P. McMahon. 2021. Medium-term effect of fertilizer, compost, and dolomite on cocoa soil and productivity in Sulawesi, Indonesia. *Experimental Agriculture*. 57(3): 185–202. <https://doi.org/10.1017/S0014479721000132>
- Galicia-Andrés, E., Escalona, Y., Oostenbrink, C., Tunega, D. and M. H. Gerzabek. 2021. Soil organic matter stabilization at molecular scale: The role of metal cations and hydrogen bonds. *Geoderma*, 401: 115237. <https://doi.org/10.1016/j.geoderma.2021.115237>
- Galyoun, I. K. A., C. R. McDavid, F. B. Lopez, and J. A. Spence. 1996. The effect of irradiance level on cocoa (*Theobroma cacao* L.): Growth and leaf adaptations. *Tropical Agriculture*. 73(1): 23–27.
- GLOSOLAN. 2019. Standard operating procedure for soil organic carbon: Walkley-Black method, titration and colorimetric (Version 1). <https://openknowledge.fao.org/server/api/core/bitstreams/e498d73e-1711-4d18-9183-aa8476387e2c/content>
- GLOSOLAN. 2021. Standard operating procedure for soil nitrogen Kjeldahl method (Version 1). FAO. <https://openknowledge.fao.org/server/api/core/bitstreams/17a0e476-f796-4608-a869-295a367c0b56/content>

- Goudsmit, E., D. M. A. Rozendaal, A. Tosto and M. Slingerland. 2023. Effects of fertilizer application on cacao pod development, pod nutrient content and yield. *Scientia Horticulturae*. 313: 111869. <https://doi.org/10.1016/j.scienta.2023.111869>
- Greff, B., J. Szigeti, Á. Nagy, E. Lakatos and L. Varga. 2022. Influence of microbial inoculants on co-composting of lignocellulosic crop residues with farm animal manure: A review. *Journal of Environmental Management*. 302: 114088. <https://doi.org/10.1016/j.jenvman.2021.114088>
- Haddaway, N. R., K. Hedlund, L. E. Jackson, T. Kätterer, E. Lugato, I. K. Thomsen, H. B. Jørgensen, and P. E. Isberg. 2017. How does tillage intensity affect soil organic carbon? A systematic review. *Environmental Evidence*. 6(1): 30. <https://doi.org/10.1186/s13750-017-0108-9>
- Heimsoth, J. 2023. Nitrogen Fertilizer Releases Greenhouse Gases Throughout Its Life Cycle. Pulitzer Center. <https://pulitzercenter.org/stories/nitrogen-fertilizer-releases-greenhouse-gases-throughout-its-life-cycle>
- Islam, M. R., R. Jahan, S. Uddin, I. J. Harine, M. A. Hoque, S. Hassan, M. M. Hassan and M. A. Hossain. 2021. Lime and organic manure amendment enhances crop productivity of wheat–mungbean - T. Aman cropping pattern in acidic Piedmont soils. *Agronomy*. 11(8): 1595. <https://doi.org/10.3390/agronomy11081595>
- Jabro, J. D., W. B. Stevens and W. M. Iversen. 2020. Comparing two methods for measuring soil bulk density and moisture content. *Open Journal of Soil Science*. 10(06): 233–243. <https://doi.org/10.4236/ojss.2020.106012>
- Jadán, O., M. Cifuentes Jara, B. Torres, D. Selesi, D. A. Veintimilla Ramos and S. Günter. 2015. Influence of tree cover on diversity, carbon sequestration and productivity of cocoa systems in the Ecuadorian Amazon. *Programa de Cambio Climático y Cuencas (PCCC)*. 325(3): 35–47.
- Jia, P., T. Shang, J. Zhang and S. Yuan. 2021. Inversion of soil pH during the dry and wet seasons in the Yinbei region of Ningxia, China, based on multi-source remote sensing data. *Geoderma Regional*. 25: 1–9. <https://doi.org/10.1016/j.geodrs.2021.e00399>
- Jouichat, H., L. Khiari, J. Gallichand and M. Ismail. 2024. Modeling temporal variation of soil acidity after the application of liming materials. *Soil and Tillage Research*. 240: 106050. <https://doi.org/10.1016/j.still.2024.106050>
- Koko, L. K., D. Snoeck, T. T. Lekadou and A. A. Assiri. 2013. Cacao-fruit tree intercropping effects on cocoa yield, plant vigour and light interception in Côte d'Ivoire. *Agroforestry Systems*. 87(5): 1043–1052. <https://doi.org/10.1007/s10457-013-9619-8>
- Lahive, F., P. Hadley and A. J. Daymond. 2019. The physiological responses of cacao to the environment and the implications for climate change resilience. A review. *Agronomy for Sustainable Development*. 39(1): 5. <https://doi.org/10.1007/s13593-018-0552-0>
- Lennon, A. M., V. R. Lewis, A. D. Farrell and P. Umaharan. 2021. Photochemical responses to light in sun and shade leaves of *Theobroma cacao* L. (West African Amelonado). *Scientia Horticulturae*. 276: 109747. <https://doi.org/10.1016/j.scienta.2020.109747>
- Lu, X., X. Lu, S. K. Tanveer, X. Wen and Y. Liao. 2016. Effects of tillage management on soil CO₂ emission and wheat yield under rain-fed conditions. *Soil Research*. 54(1): 38–48. <https://doi.org/10.1071/SR14300>

- Mag-aso, J. and F. G Garcia. 2021. Productivity from the different rubber-based farming system models in Cotabato Province, Philippines. IOP Conference Series: Earth and Environmental Science. 892(1): 012019. <https://doi.org/10.1088/1755-1315/892/1/012019>
- Mattalia, G., A. Wezel, P. Costet, P. Jagoret, O. Deheuevls, P. Migliorini and C. David. 2022. Contribution of cacao agroforestry versus mono-cropping systems for enhanced sustainability. A review with a focus on yield. *Agroforestry Systems*. 96(7): 1077–1089. <https://doi.org/10.1007/s10457-022-00765-4>
- Miharza, T., N. Wijayanto, J. M. Roshetko and I. Z. Siregar. 2023. Carbon stocks and footprints of smallholder cacao systems in Polewali Mandar, West Sulawesi. *Frontiers in Environmental Science*. 11: 680984. <https://doi.org/10.3389/fenvs.2023.680984>
- Mohamad Aziz, N. S., A. Shariff, N. Abdullah and N. Mohamed Noor. 2018. Characteristics of coconut frond as a potential feedstock for biochar via slow pyrolysis. *Malaysian Journal of Fundamental and Applied Sciences*. 14(4): 408–413. <https://doi.org/10.11113/mjfas.v14n4.1014>
- Monroe, P. H. M., E. F. Gama-Rodrigues, A. C. Gama-Rodrigues and J. R. B. Marques. 2016. Soil carbon stocks and origin under different cacao agroforestry systems in Southern Bahia, Brazil. *Agriculture, Ecosystems and Environment*. 221: 99–108. <https://doi.org/10.1016/j.agee.2016.01.022>
- Morgan, C. L. S. and J. P. Ackerson. 2022. Sampling design for quantifying soil organic carbon stock in production ag fields. *Crops and Soils*. 55(1): 28–33. <https://doi.org/10.1002/crso.20156>
- Muda, B., M. Dandan and A. Awang. 2021. Effect of agricultural waste as organic fertilizer on yield and soil properties of cocoa (*Theobroma cacao* L.). *Journal of Agricultural and Food Engineering*. 1(4): 1–4. <https://doi.org/10.37865/jafe.2021.0024>
- Mulia, S., P. J. McMahon, A. Purwantara, H. Bin Purung, F. Djufry, S. Lambert, P. J. Keane and D. I. Guest. 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>
- Mustari, K., L. Asrul and L. Faradilla. 2020. Carbon stock analysis of some cocoa planting systems in South Sulawesi. IOP Conference Series: Earth and Environmental Science. 486(1): 012085. <https://doi.org/10.1088/1755-1315/486/1/012085>
- Ndung'u, M., L. W. Ngatia, R. N. Onwonga, M. W. Mucheru-Muna, R. Fu, D. N. Moriasi and K. F. Ngetich. 2021. The influence of organic and inorganic nutrient inputs on soil organic carbon functional groups content and maize yields. *Heliyon*. 7(8): e07881. <https://doi.org/10.1016/j.heliyon.2021.e07881>
- Niether, W., I. Smit, L. Armengot, M. Schneider, G. Gerold and E. Pawelzik. 2017. Environmental growing conditions in five production systems induce stress response and affect chemical composition of cocoa (*Theobroma cacao* L.) beans. *Journal of Agricultural and Food Chemistry*. 65(47): 10165–10173. <https://doi.org/10.1021/acs.jafc.7b04490>
- Notaro, M., C. Collado, J. K. Depas, D. Dumovil, A. J. Denis, O. Deheuevls, P. Tixier and C. Gary. 2021. The spatial distribution and height of associated crops influence cocoa tree productivity in complex agroforestry systems. *Agronomy for Sustainable Development*. 41(5): 60. <https://doi.org/10.1007/s13593-021-00716-w>

- Novara, A., J. Rühl, T. La Mantia, L. Gristina, S. La Bella and T. Tuttolomondo. 2015. Litter contribution to soil organic carbon in the processes of agriculture abandon. *Solid Earth*. 6(2): 425–432. <https://doi.org/10.5194/se-6-425-2015>
- Ntsoli, P. G., Kouam, I. D., Titti, R. W., Etame Kossi, G. M., Mouthe, D. B. and A. Yaouba. 2025. Yield, production losses, fertility status, and soil microbial population in three different cocoa (*Theobroma cacao* L.)-based cropping systems in an Oxisol in Southern Cameroon. *International Journal of Agronomy*. 2025(1): 8888362. <https://doi.org/10.1155/ioa/8888362>
- Paradelo, R., I. Virto and C. Chenu. 2015. Net effect of liming on soil organic carbon stocks: A review. *Agriculture, Ecosystems and Environment*. 202: 98–107. <https://doi.org/10.1016/j.agee.2015.01.005>
- Pitman, R., Badtrup-Birk, A.-M., Bréda, N. and P. Rautio. 2010. Sampling and analysis of litterfall. Manual on methods and criteria for harmonized sampling assessment, monitoring and analysis of the effects of air pollution on forests: Part XIII. ICP Forests. <https://hal.inrae.fr/hal-02815080v1><https://hal.inrae.fr/hal-02815080v1>
- Osei-Bonsu, K., Opoku-Ameyaw, K., Amoah, F. M. and F. K. Oppong. 2002. Cacao-coconut intercropping in Ghana: Agronomic and economic perspectives. *Agroforestry Systems*. 55(1): 1–8. <https://doi.org/10.1023/A:1020271608483>
- Qaswar, M., L. Dongchu, H. Jing, H. Tianfu, W. Ahmed, M. Abbas, Z. Lu, D. Jiangxue, Z. H. Khan, S. Ullah, Z. Huimin and W. Boren. 2020. Interaction of liming and long-term fertilization increased crop yield and phosphorus use efficiency (PUE) through mediating exchangeable cations in acidic soil under wheat–maize cropping system. *Scientific Reports*. 10(1): 19828. <https://doi.org/10.1038/s41598-020-76892-8>
- Regasa, A., W. Haile, and G. Abera. 2025. Effects of lime and vermicompost application on soil physicochemical properties and phosphorus availability in acidic soils. *Scientific Reports*. 15(1): 25544. <https://doi.org/10.1038/s41598-025-02053-4>
- Rosas-Patiño, G., Y. J. Puentes-Páramo and J. C. Menjivar-Flores. 2019. Liming effect on macronutrient intake for cacao (*Theobroma cacao* L.) in the Colombian Amazon. *Ciencia y Tecnología Agropecuaria*. 20(1). https://doi.org/10.21930/rcta.vol20_num1_art:1247
- Rowley, M. C., S. Grand and É. P. Verrecchia. 2018. Calcium-mediated stabilisation of soil organic carbon. *Biogeochemistry*. 137(1–2): 27–49. <https://doi.org/10.1007/s10533-017-0410-1>
- Saj, S., E. Somarriba, U. Schneidewind, J. Milz, M. Cotter and M. Schneider. 2025. Shade tree pruning effects on flowering and cacao yields in different cropping systems in a long-term trial in Bolivia. *Experimental Agriculture*. 61: e22. <https://doi.org/10.1017/S0014479725100124>
- Sales, M. C. A. 2025. Adapting cacao farming in Mindanao to soil and climate challenges. *Mindanao Development Authority*. 2025–001: 1–3.
- Sales, M. C. A., S. C. Sales, S. C., R. B. Badayos and P. B. Sanchez. 2024. Land suitability evaluation of cocoa (*Theobroma cacao* L.) production areas in Davao City, Philippines. *Mindanao Journal of Science and Technology*. 22(1). <https://doi.org/10.61310/mjst.v22i1.1952>
- Schneidewind, U. 2022. Above and belowground biomass and nutrient stocks in monoculture and agroforestry cacao production systems in the Alto Beni, Bolivia [Georg-August University School of Science]. <https://ediss.uni-goettingen.de/handle/11858/13913>

- Silue, B. K., A. W. Koné, A. J. A. Kotaix, K. Coulibaly, S. Aïdara, L. Chapuis-Lardy and D. Masse. 2024. Effects of shade tree legumes on cacao biomass and bean yields after 20 years of intercropping in Ivory Coast. *Experimental Agriculture*. 60: e16. <https://doi.org/10.1017/S0014479724000097>
- Snoeck, D., L. Koko, J. Joffre, P. Bastide and P. Jagoret. 2016. Cacao nutrition and fertilization, pp 155-202. In E. Lichtfouse (Ed.). *Sustainable Agriculture Reviews*. 19: 399. Springer International Publishing. https://doi.org/10.1007/978-3-319-26777-7_4
- Somarriba, E., R., Cerda, L. Orozco, M. Cifuentes, H. Dávila, T. Espin, H. Mavisoy, G. Ávila, E. Alvarado, V. Poveda, C. Astorga, E. Say and O. Deheuvelds. 2013. Carbon stocks and cocoa yields in agroforestry systems of Central America. *Agriculture, Ecosystems and Environment*. 173: 46–57. <https://doi.org/10.1016/j.agee.2013.04.013>
- Szostek, M., E. Szpunar-Krok, R. Pawlak, J. Stanek-Tarkowska and A. Ilek. 2022. Effect of different tillage systems on soil organic carbon and enzymatic activity. *Agronomy*. 12(1): 208. <https://doi.org/10.3390/agronomy12010208>
- Tadiello, T., A. Perego, E. Valkama, C. Schillaci, and M. Acutis. 2022. Computation of total soil organic carbon stock and its standard deviation from layered soils. *MethodsX*. 9: 101662. <https://doi.org/10.1016/j.mex.2022.101662>
- Toth, M., J. Davies, J. Quinton, J. Davies, C. Stumpp, A. Klik, B. Mehdi-Schulz, P. Strauss, G. Liebhard, J. Bartmann and S. Strohmeier. 2025. Long-term effects of tillage practices and future climate scenarios on topsoil organic carbon stocks in Lower Austria – A modelling and long-term experiment study. *International Soil and Water Conservation Research*. 13(2): 486–499. <https://doi.org/10.1016/j.iswcr.2025.02.011>
- United Nations. (n.d.). Land—The planet’s carbon sink. United Nations. Retrieved March 24, 2025, from <https://www.un.org/en/climatechange/science/climate-issues/land>
- Wang, Z., J. Chen, S. Mao, Y. Han, F. Chen, L. Zhang, Y. Li and C. Li. 2017. Comparison of greenhouse gas emissions of chemical fertilizer types in China’s crop production. *Journal of Cleaner Production*. 141: 1267–1274. <https://doi.org/10.1016/j.jclepro.2016.09.120>
- Yan, F., S. Schubert, and K. Mengel. 1996. Soil pH increase due to biological decarboxylation of organic anions. *Soil Biology and Biochemistry*. 28(4–5): 617–624. [https://doi.org/10.1016/0038-0717\(95\)00180-8](https://doi.org/10.1016/0038-0717(95)00180-8)
- Yilmaz, E. and M. Sönmez. 2017. The role of organic/bio–fertilizer amendment on aggregate stability and organic carbon content in different aggregate scales. *Soil and Tillage Research*. 168: 118–124. <https://doi.org/10.1016/j.still.2017.01.003>

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