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The carbon storage potential of selected ultramafic soils in Puerto Princesa City and Bataraza, Palawan, Philippines

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ABSTRACT. The primary environmental challenge of this 21st century is climate change, induced by carbon dioxide, with limited research focusing on the soil carbon-trapping potential of forest formations such as ultramafic. However, understanding the physicochemical properties of soil is essential to determine the carbon storage potential of soil organic matter, which is investigated in the mineral-rich ecosystem in Palawan Island. Ultramafic forests from Brgy. Rio Tuba, BatarazaW and Sitio Magarwak, Brgy. Sta. Lourdes, Puerto Princesa City, Philippines, was considered for the present study. Pearson and Kruskal-Wallis tests were used to establish a hierarchy of soil physicochemical parameters, such as carbon, pH, texture, particle and bulk density, porosity, and organic matter (OM) about carbon storage potentials. Most ultramafic soils were sandy loam or sandy clay loam with low bulk BD and clayey, which stores more carbon than sandy soils. Among the soil properties, soil texture, particularly clayey soil, has more influence ($p = 1.46E^{-13}$) in the soil organic carbon (SOC) pool than soil pH ($p = 0.59$), soil porosity (0.39), bulk density (0.37), and particle density (0.32). SOC was inversely proportional to BD, with soil porosity directly affected by soil depth. SOC and organic matter decreased at a depth with higher carbon sequestration at the rhizosphere layer, ranging from 4–7 % in the topsoil to 3–5% in the subsoil. The ultramafic area of Puerto Princesa City stored higher organic carbon (99.05 tons ha^{-1}) than that of Bataraza (85.68 tons ha^{-1}).

Keywords: carbon sequestration, physicochemical properties, soil organic carbon, soil organic matter

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INTRODUCTION

The potential for sequestering carbon and eventual storage in soil organic matter is one field that needs to be explored, particularly since soils can hold almost half of the atmosphere's carbon dioxide (European Union, 2011). Soil carbon sequestration is a process of removing carbon dioxide (CO_2) from the atmosphere and storing it in the soil's carbon pool, while carbon stock is the sum of annual leftovers from each intake, and it is directly dependent on incoming carbon fluxes, biotransformations, and stabilization time (Basile-Doelsch *et al*., 2020). The quantity of carbon in passive soil carbon pools or organic matter tightly fixed on mineral surfaces with millennia-long turnover periods is determined by soil maturity, mineralogy, and overall soil properties, reflecting long-term climatic conditions (Trumbore, 1997). Thus, having positive trends from those factors, particularly from the soil properties (*e.g.*, soil texture and clay mineralogy), will increase the soil organic matter (SOM) content, which in return also increases the soil's capacity to store carbon (Barré *et al*., 2017). However, studies examining the carbon sequestration in ultramafic rocks (Kelemen *et al*., 2019; Cutts *et al*., 2021) are rather rare, and studies available are looking at either carbon sequestration in ultramafic rocks or solely only in minerals themselves.

The effect of ultramafic soil properties on SOM and CO_2 sequestration potential is focused only on soil attributes. Subsequently, ultramafic soils contain a high amount of magnesium, which improves soil aggregation and stability. This process enhances soil quality and helps store organic carbon. Serpentine minerals, like serpentine and talc, found in ultramafics can also retain carbon and have layered structures that protect against microbes' breakdown of organic matter. However, these effects have only been studied and proven in the context of carbon mineralization in rocks and minerals (Reeves *et al*., 2007).

Studies on ultramafic soils and their carbon sequestration potential and capacity remain limited (Angst *et al*., 2018; Wiesmeier *et al*., 2019). Hence, this study aimed to characterize selected ultramafic soils in Palawan Island with known ultramafic rock exposures (Labis *et al*., 2020). Also, focus was placed on various factors, such as the soil's physicochemical qualities that influence SOM's ability to store carbon. Consequently, the study identified and built a hierarchy for the most influential edaphic properties affecting the SOM potential to store carbon. Findings from the study also identified the potential factors that directly affect the soil organic carbon (SOC) storage capacity between non-ultramafic and ultramafic soils.

METHODOLOGY

Study area

Palawan is a long, narrow island that connects the main Philippine islands to the southwest and west, located explicitly at N 9° 29 '59.99" and E 118° 29' 59.99". The study was conducted in ultramafic formations in Palawan, namely, Rio Tuba, Bataraza (samples reported as RTB) located within the Mineral Production Sharing Agreement tenement of Rio Tuba Nickel Mining Corporation, and in Sitio Magarwak at the boundary, Brgys. Sta. Lourdes and Bacungan, Puerto Princesa City (samples reported as PPC) (**Figure 1A and 1B**). The two sites were selected based on the difference in land use; Rio Tuba, Bataraza is located inside an active mining site, while the Magarwak area in Puerto Princesa City was not subjected to any mining activity. The sampling site in RTB is currently untouched and classified as a secondary forest, while the PPC site is also a secondary forest.

Field methods

The study is part of the research aimed to compare the morpho-anatomical properties of selected nickel hyperaccumulator plants thriving in two ultramafic soils. Part of the study was the floral biodiversity assessment to measure the species richness and the most important species in the two

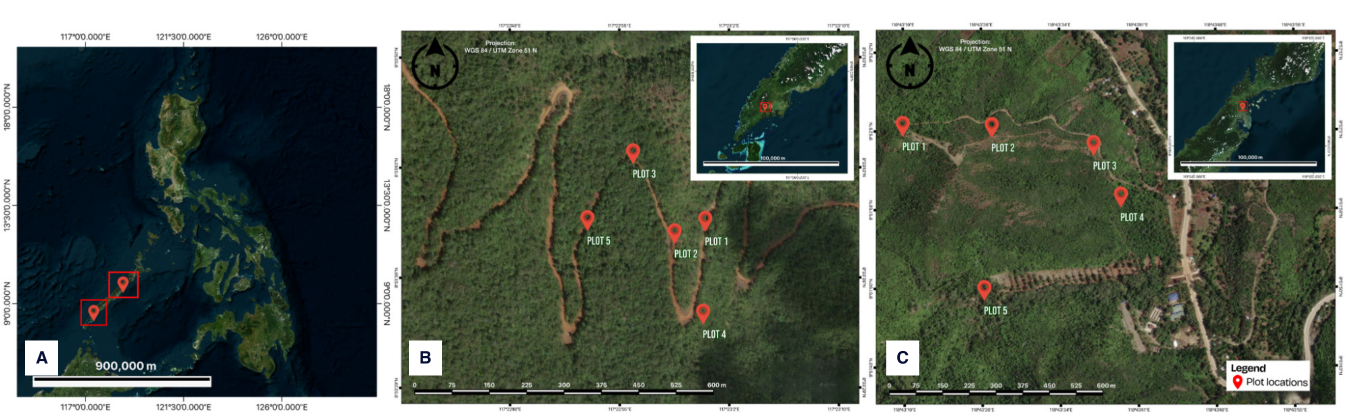

Figure 1. (A) Location of sampling areas in Palawan Island; (B) Specific sampling points in Brgy. Rio Tuba Bataraza, Palawan; (C) Brgy. Sta. Lourdes Puerto Princesa, Palawan.

study sites. It was done following the Biodiversity Assessment and Monitoring System method prescribed for protected areas (BMB, 2017), but with modification. In particular, nested plots measuring 10 m x 10 m were established 250 m apart in a 1 km transect line following the trail or road network. Five nested plots were established in each study site, and in each plot, 10 composite soil samples were collected at depths ranging from 0–20 cm (topsoil) and 21–50 cm (subsoil), respectively. The composite samples were mixed, and approximately 1 kg representative sample was brought for several laboratory analyses. Characterization of soil horizons through soil profiling and soil color were determined onsite using the Munsell color chart.

Soil analysis

Soil samples were air-dried, pulverized, oven-dried, and divided into several types of analysis. These include soil texture using the hydrometer method (Germaine & Germaine, 2009), undisturbed core method for bulk density (BD), approximation method for particle density (PD), and Walkley-Black method for SOC and SOM determination (Walkley & Black, 1934). Soil pH was measured using the Thomas's potentiometric method (1996). The % carbon to % organic matter was converted with the empirical factor of 1.72.

Data analysis

R studio software analyzed the data collected from the two sites. The Pearson R Correlation, Kruskal-Wallis Test, and Confidence Interval level were employed in this study. Parametric variables, including %SOM, soil porosity, BD, and PD, used Pearson R Correlation to test the significant values of SOC (p-value = 0–1, > 0.5 / > –0.5 strong positive or negative statistical significance). Since soil texture is a nonparametric variable, the Kruskal-Wallis Test was performed to determine its importance to percentage organic carbon changes (p-value < α to be statistically significant; α = 0.5) to its related SOC (Minitab Statistical Software, 2002). Significant differences in ultramafic SOC with other settings based on land cover, lithology, and farming system types were compared and analyzed using the Wilcoxon Signed Rank Test in R studio. Since the samples from different locations did not follow a normal distribution, the Wilcoxon Signed Rank Test validated the significant difference of %OC values with α = 0.05 to indicate significant median values (LaMorte, 2017).

RESULTS AND DISCUSSION

Characterization of the ultramafic soils

Generally, the soil properties of the two ultramafic forests in Palawan did not exhibit a common trend. Soils in ultramafic forests at RTB exhibit a deeper profile of up to 80 cm with significant color variations (**Figure 2A**). The values ranged from 7.5 YR 6/6 (0–10 cm depth); 2.5 YR 6/6 (11–20 cm depth); 5 YR 5/6 (21–30 cm depth); 7.5 YR 5/6 (31–35 cm depth); 5 YR 5/4 (36–40 cm depth); 5 YR 6/8 (41–50 cm depth); 5 YR 6/6 (51–60 cm depth); 5 YR 6/6 (61–70 cm depth); and 5 YR 5/6 (71–80 cm depth), respectively. The topsoil is more granular, while the subsoil is granular to blocky. It was also observed that the color becomes darker red as depth increases. On the other hand, the soil profile at PPC exhibits a shallower depth of up to 40 cm before reaching the bedrock. There was also an observable difference in the structure and texture with the changing depth. The topsoil is granular and less clayey compared to the more clayey subsoil, which is more solid in structure. In terms of color, as the depth increases, it becomes darker towards brown (**Figure 2B**). It was noted that the color ranges from 10 YR 4/4 (0–10 cm depth), 7.5 YR 3/4 (11–20 cm depth), and 7.5 YR 3/4 (21–30 cm depth), respectively.

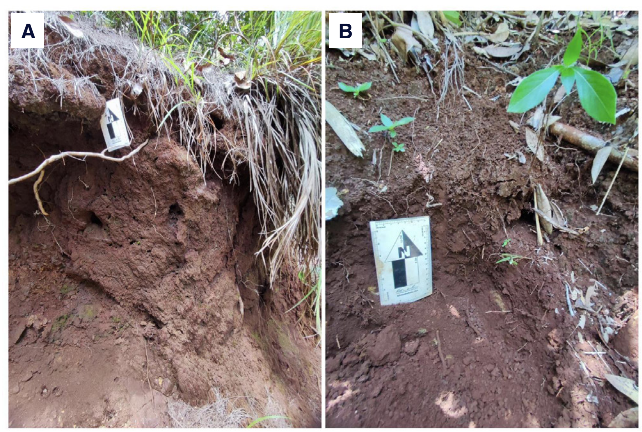

Figure 2. (A) Soil profile of Brgy. Rio Tuba, Bataraza; (B) Soil profile of Brgy. Sta. Lourdes, Puerto Princesa City.

Organic matter and organic carbon content

The SOC concentration in the two ultramafic formations varies between the topsoil (0–20 cm depth) and subsoil (21–50 cm), with levels ranging from 4–7% and 3–5%, respectively. In RTB topsoil, the %SOC ranged from 4.60 to 7.18%, while in PPC topsoil, it ranged from 4.44 to 6.40%. On the other hand, the subsoil %SOC is relatively lower, with RTB having only 3.57 to 4.50%, while PPC generated a higher range between 3.73 to 5.45%. Comparing the two sites, PPC's SOC mean values were relatively higher than RTB (**Table 1**). Similar to the trend in the SOC, it was noted that topsoil SOM of PPC was relatively lower than RTB, with values ranging from 7.91 to 12.35% compared to PPC at 7.63 to 10.43% only. On the other hand, the subsoil values are between 6.13 to 7.74% in RTB, while 6.42 to 9.38% in PPC. This trend is consistent with the report of Liebig *et al*. (2005) and Nabayi *et al*. (2019), indicating that the concentration of SOC is higher in the upper layer of 0–5 cm.

The %SOM and its relationship to the %SOC show a highly positive linear relationship (**Figure 3**). Organic matter acts as a binding agent of carbon in iron and aluminum oxides, increasing enzyme synthesis (Yu *et al*., 2019); thus, its concentration is directly linked to the organic carbon content of the soil. Moreover, it is also important for soil stability, enhancing water and nutrient retention, and in return, making it an essential indicator of quality and functioning (Asabere *et al*., 2018).

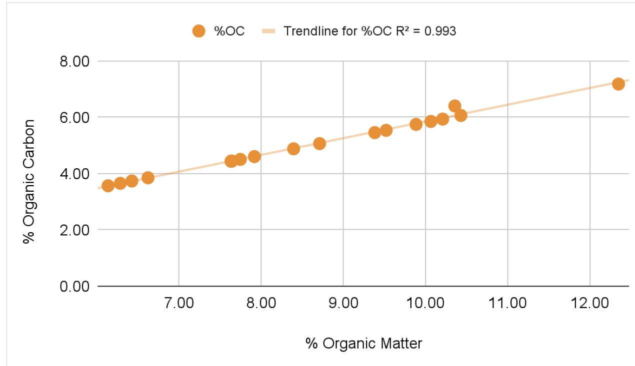

Figure 3. Relationship of %OM and %OC in selected ultramafic formations of Palawan Island. Relatively high linear proportionate %OM derived from %OC.

Physicochemical properties of the soil

Important physicochemical properties, including particle density, bulk density, soil porosity, and pH, were determined in the two types of ultramafic forests (**Table 2**). For PD topsoil, the mean value for RTB was 2.61 g cm^{-3}, while a relatively lower value of 2.52 g cm^{-3} was noticed in PPC. In the subsoil, RTB porosity values ranged from 2.15 to 3.09 with a mean value of 0.52 g cm^{-3}, while PPC subsoil samples ranged

Table 1. Soil organic carbon (SOC) and organic matter (OM) content of the two ultramafic sites covered in the study.

Soil layer	Sample code	%OC	Mean %OC	%OM	Mean %OM
Topsoil	RTB-Plot 1	5.06	5.49 (SD: 1.03)	8.71	9.45 (SD: 1.78)
	RTB-Plot 2	7.18		12.35	
	RTB-Plot 3	5.75		9.88	
	RTB-Plot 4	4.60		7.91	
	RTB-Plot 5	4.88		8.39	
	PPC-Plot 1	4.44	5.67 (SD: 0.76)	7.63	9.63 (SD: 1.17)
	PPC-Plot 2	5.93		10.21	
	PPC-Plot 3	6.40		10.35	
	PPC-Plot 4	5.53		9.52	
	PPC-Plot 5	6.06		10.43	
Subsoil	RTB-Plot 1	4.50	4.12 (SD: 0.47)	7.74	7.09 (SD: 0.81)
	RTB-Plot 2	4.44		7.64	
	RTB-Plot 3	4.44		7.63	
	RTB-Plot 4	3.65		6.28	
	RTB-Plot 5	3.57		6.13	
	PPC-Plot 1	3.73	4.72 (SD: 0.84)	6.42	8.12 (SD: 1.45)
	PPC-Plot 2	3.85		6.62	
	PPC-Plot 4	5.45		9.38	
	PPC-Plot 5	3.73		6.42	

from 1.90 to 2.91 with a mean value of 2.30 g cm^{-3}. Based on these findings, the general PD is higher in the topsoil than in the subsoil, with RTB having a higher overall mean value than PPC.

For BD subsoil, PPC generated a higher mean density of 1.11 g cm^{-3}, while RTB had a mean value of 0.98 g cm^{-3}. The BD of the topsoil was similar in both sites, generating a value of 0.82 g cm^{-3}. However, PPC had a higher mean density of 0.95 g cm^{-3} between the two sites than RTB, which had only 0.90 g cm^{-3}. The difference, however, was found to be insignificant.

The topsoil porosity was higher in RTB, with a mean value of 68.22%, while PPC was slightly lower at 67.62%. Therefore, RTB inside an active mining site exhibited better drainage due to a higher porosity value of 60.65%. On the other hand, the subsoil of PPC was lower at 58.19% compared with RTB, which has a porosity value of 64.43%.

Soil pH

Most ultramafic soils are expected to have a pH that leans toward basic or alkaline. Surprisingly, topsoil pH values generated from the current study, exhibited slightly acidic to neutral. In particular, the soil pH of the two sites varied from 6 to 6.8 for RTB samples, while in PPC, values changed from pH of 6 to 6.3. The mean value per area yielded 6.36 for RTB and 6.14 for PPC, whereas the overall mean for the topsoil yielded a pH of 6.25 (**Table 3**).

Soil texture

The soil texture of the ultramafic forests in Palawan generally falls under the sandy loam classification (**Table 4 and Supplementary Table 1**). The RTB soils are dominated by sandy loam (7) soil textural class, followed by sandy clay loam (2) and loamy sand (1). The PPC soils are dominated by sandy clay loam (3) and sandy loam (3), followed by sandy clay (2) and clay (1). Concerning the amount of organic matter and organic carbon in soil samples, results showed a need to investigate the two sites further to assess the influence of soil textural class on the retention of organic matter and carbon in the soil samples. A higher percentage of clay and a lower percentage of sand particles in PPC samples may likely result in a higher mean value of %OM.

Table 2. Summary of physical properties of the topsoil and subsoil layers of the ultramafic formations in Palawan: density (g cm^{-3}), bulk density (g cm^{-3}), and soil porosity (%).

Soil layer	Sample Code	PD	Mean PD	BD	Mean BD	Soil Porosity	Mean Soil porosity
Topsoil	RTB-Plot 1	2.20	2.61 (SD: 0.51)	0.86	0.824 (SD: 0.22)	60.80	68.22 (SD: 7.35)
	RTB-Plot 2	2.59		0.61		76.40	
	RTB-Plot 3	2.25		0.59		73.97	
	RTB-Plot 4	2.54		1.00		60.48	
	RTB-Plot 5	3.46		1.06		69.45	
	PPC-Plot 1	3.09	2.52 (SD: 0.35)	1.09	0.823 (SD: 0.18)	64.67	67.62 (SD: 2.46)
	PPC-Plot 2	2.30		0.68		70.45	
	PPC-Plot 3	2.13		0.64		69.66	
	PPC-Plot 4	2.73		0.89		67.54	
	PPC-Plot 5	2.36		0.81		65.78	
Subsoil	RTB-Plot 1	2.15	2.52 (SD: 0.35)	0.70	0.98 (SD: 0.19)	67.39	60.65 (SD: 8.70)
	RTB-Plot 2	3.09		0.94		69.64	
	RTB-Plot 3	2.51		0.95		62.19	
	RTB-Plot 4	2.36		1.21		48.49	
	RTB-Plot 5	2.47		1.10		55.51	
	PPC-Plot 1	2.91	2.30 (SD: 0.50)	1.22	1.11 (SD: 0.50)	58.09	58.19 (SD: 12.39)
	PPC-Plot 2	1.90		1.77		41.35	
	PPC-Plot 4	2.50		0.73		70.62	
	PPC-Plot 5	1.90		0.71		62.71	

Table 3. Summary of mean topsoil pH including standard deviation (SD).

Sample code	pH	Mean pH per area	Overall mean
RTB-Plot 1	6.7	6.36 (SD: 0.36)	6.25 (SD: 0.28)
RTB-Plot 2	6		
RTB-Plot 3	6.2		
RTB-Plot 4	6.8		
RTB-Plot 5	6.1		
PPC-Plot 1	6.2	6.14 (SD: 0.13)	
PPC-Plot 2	6		
PPC-Plot 3	6		
PPC-Plot 4	6.2		
PPC-Plot 5	6.3		

Table 4. Summary of soil textural values representing the % clay, silt, and clay in the two ultramafic forests in the study (mean %OM and OC were also represented).

Study site	Mean % Clay	Mean % Silt	Mean % Sand	Mean %OM	Mean %OC
Bataraza	13.02	19.84	67.13	8.27	5.20
Puerto Princesa City	25.50	16.70	57.79	8.96	5.25

In contrast, RTB samples have a lower percentage of clay and a higher percentage of sand, which may have a direct link to their porosity and density. A similar study by Yu *et al*. (2019) noted that the stabilization of SOC was significantly affected by the soil's clay fraction, which may have occurred through absorptive protection or micro-aggregate formation with SOC. Since most of the PPC samples' textural classes are sandy clay loam (3) and sandy clay (2), the amount of organic matter and carbon it can store varies. This is primarily because clay particles provide physical protection and stabilization for organic matter against decomposition and provide more surface area for the adsorption of organic molecules (Wiesmeier *et al*., 2019). Eventually, the greater specific surface area can act as a binding agent to organic matter, leading to a more efficient and higher adsorption capacity. In return, it can retain more moisture and nutrients in the soil than sandy soils, which drain water and nutrients faster due to large particles and lower surface area. In addition, soil particles and organic matter may combine to form aggregates, minimizing microbial degradation (Yu *et al*., 2019).

Consequently, soil texture affected the organic carbon content, with higher amounts observed in the topsoil (0–20 cm depth) compared to the subsoil (21–50 cm depth) (**Table 1**). These findings were supported by the data gathered from the RTB site, with a value of 90.51 tons ha^{-1} for the topsoil and 80.84 tons ha^{-1} in the subsoil layer. PPC subsoil yielded higher amounts of OM with a value of 104.77 tons ha^{-1}, while 93.34 tons ha^{-1} in topsoil generating a discrepancy value of 11.43 tons ha^{-1}. This can be attributed to the difference in soil textural class in these areas, wherein PPC has a considerable percentage of silt and clay particles that can hold more significant amounts of organic matter and organic carbon. Compared to its topsoil, a lower percentage of clay particles is attributed to a lower capacity to hold organic matter and carbon. The same trend was observed in RTB soils as its soil textural class is mainly sandy loam; thus, lower amounts of organic matter and carbon can be stored in the soil due to the low percentage of clay particles. Overall, the total organic carbon per area was higher in Puerto Princesa City, with 99.05 tons ha^{-1} on both topsoil and subsoil, while Bataraza generated lower values at 85.68 tons ha^{-1} (**Table 4**).

Influence of soil physicochemical properties

The PD and the percentage of OC showed an inversely proportional relationship with each other; that is, as PD increases, the %OC content in the soil decreases (**Figure 4**). It has been noted in previous work that the density of soil minerals is significantly higher than organic matter on a per-unit volume basis; thus, soils exhibiting higher OM levels, and consequently, higher OC, have lower particle density in comparison to soils possessing similar textures (Creswell & Hamilton, 2002; Nabayi *et al*., 2021).

It is also significant how it shows an upward trend as soil depth increases, owing to the corresponding decrease in organic matter. It also varies on the specific soil mineral composition and the quantity of organic matter present. It is commonly assumed that the particle density of mineral soils is 2.65 Mg m^{-3} (g cm^{-3}); however, in cases where there is a significant presence of heavy minerals such as magnetite, the particle density of the soil may exceed 2.65 Mg m^{-3} (g cm^{-3}) (Nabayi *et al*., 2021). Among the study sites, PPC samples have a notable presence of magnetite minerals.

Similar to the trend of PD, BD, and %OC show an inversely proportional relationship wherein as

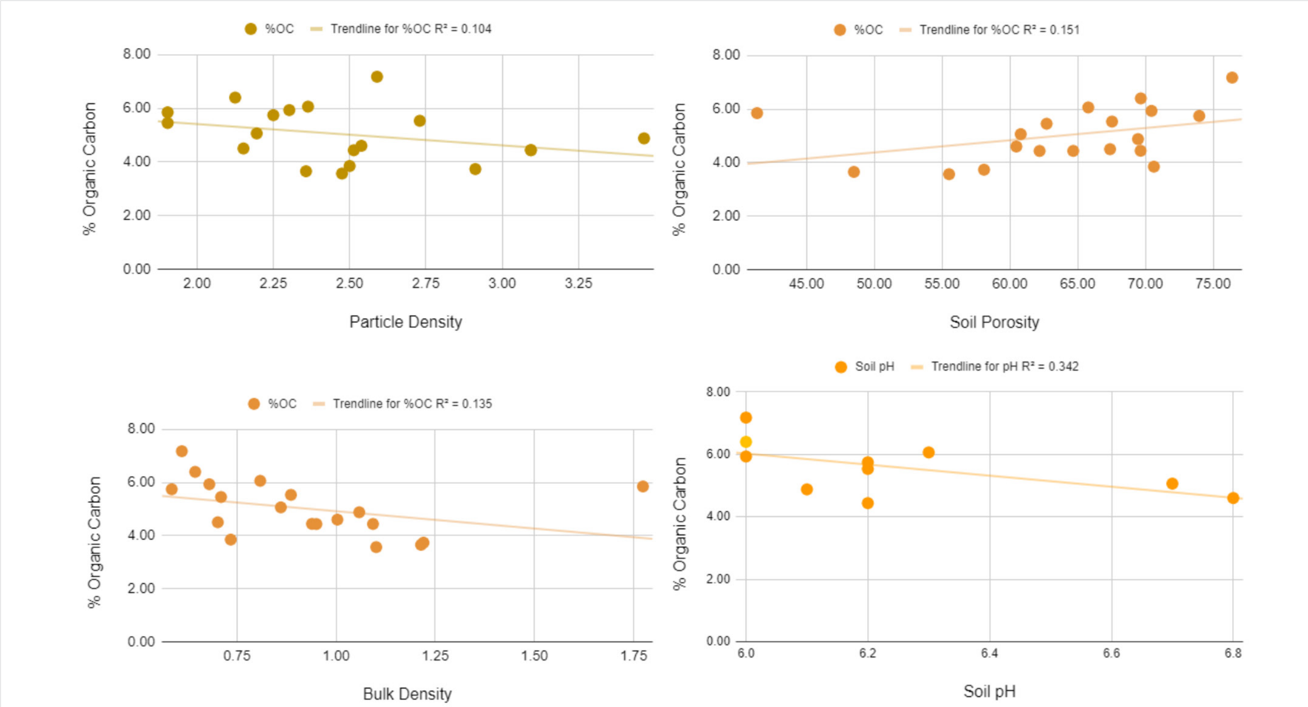

Figure 4. Relationship of %OC to particle and bulk densities, porosity, and soil pH of the ultramafic sites in selected ultramafic formations of Palawan Island.

BD increases, OC decreases (**Figure 4**). The same results were found in the study of Sakin (2012), wherein SOC and BD resulted in a negative correlation and statistically significant at $p<0.001$. It is also notable how the BD increases at deeper soil layers, particularly in RTB subsoils, which have a mean bulk density value of 0.98 g cm^{-3}, while the topsoil only had 0.824 g cm^{-3}. Moreover, the PPC subsoil's mean bulk density is 1.11 g cm^{-3}, while the topsoil's is 0.823 g cm^{-3}. It is, therefore, clear that there is a positive correlation between depth and BD and other attributes that create variation (*e.g.*, the porosity of the soil and the relative proportion and specific gravity of solid organic and inorganic particles), similar to the study of Hossain *et al*. (2015) and Nabayi *et al*. (2021).

Soil porosity and percentage carbon relationship depicted a positive linear trend (**Figure 3**). As soil porosity increases, the %OC also increases. In the study of Fukumasu *et al*. (2022), the correlation between SOC and porosity within the diameter range of 0.2–5 µm was significant. However, in most other pore size classes, porosities correlated more strongly with clay and sand than SOC contents. One possible interpretation of the findings is that the development of pores within the size range of 0.2–5 µm could be influenced by the micro-aggregation of particles in the silt/clay size range, with the physicochemical protection of SOC serving as a binding agent (Fukumasu *et al*., 2022). In this case, the soil porosity decreases with soil depth, wherein topsoil mean values are 68.22% and 67.62% in RTB and PPC, respectively.

In contrast, the subsoil mean values are 60.65% and 58.19%, respectively. On average, the primary impact of soil depth indicates that the greatest porosity was observed in the topsoil and is statistically significant ($p<0.01$) compared to the porosity of the subsoil, findings similar to Nabayi *et al*., 2021. The increased total porosity observed in the upper depth may be attributed to the higher OM content of the surface layer, which is markedly distinct from that of the lower depth (Nabayi *et al*., 2021). Moreover, an increase in the OM content of soil leads to a reduction in soil density, thereby increasing soil pore spaces (Nabayi *et al*., 2017).

Soil pH has a negative correlation to SOC amount (**Figure 4**). This is similar to the findings of Kuśmierz (2023), wherein they observed that soils with a pH below 5.5 exhibited lower levels of SOC content while soils with a pH ranging from 6.5 to

7.2 demonstrated escalated levels of SOC content. Additionally, soils with a pH above 7.2 displayed the highest levels of organic carbon accumulation. The observed outcomes can be attributed to the impact of pH on the quantity and quality of humus substances in the soil and their potential for stabilization (Lemanowicz *et al*., 2023).

Soil texture ranked as the most influential parameter that affects the concentration of OC in the soil samples as it had a p-value of 1.46^{-13}, which is lesser than the alpha value of less than or equal to 0.5 of Kruskal-Wallis, indicating a high significance (**Supplementary Table 2**). On the other hand, among the parametric variables, soil pH ranked second with a moderate positive significance (p-value = –0.59), followed by soil porosity with a positive significance (p-value = 0.39), bulk density with a negative significance (p-value = –0.37) and lastly, particle density with moderate negative significance value (p-value = –0.32) (Minitab Statistical Software, 2002) (**Supplementary Table 3**).

Comparison to other soil lithology

To compare the ultramafic soils in Palawan with other lithologies, supplementary soil samples obtained from Cavinti, Laguna, were subjected in the same laboratory and analytical procedures. In contrast to the ultramafic soils found in Palawan, the soils in Cavinti are composed of limestone. The reason for comparing was the similarity in having high pH values. However, this similarity was attributed to different mineral content, as the presence of alkaline minerals in ultramafic soils leads to its high pH, whereas the calcium carbonate content causes high pH levels in limestone soils. **Supplementary Table 4** shows the result of the SOC measurement in soil type of limestone parent rock materials. A comparison of the three sites revealed that PPC exhibited the highest overall SOC with a value of 99.05 tons ha^{-1}, followed by Bataraza with 85.68 tons ha^{-1} and Cavinti, Laguna with 41.95 tons ha^{-1} (**Table 5**). The statistical analysis involved the application of the Wilcoxon Signed Rank Test to test for significant differences in %OC of the three sites; given that the samples did not follow a normal distribution, the Wilcoxon Signed Rank Test was used for verifying the significant difference of the %OC values ($\alpha = 0.05$), which implies that a value less or equal to 0.05 means a significant difference among median values (LaMorte, 2017). The obtained p-value = 0.03125 indicates significant findings implying the presence of a notable difference in the mean percentage of OC and overall SOC content of two types of lithologies comes from the underlying inherent properties.

Table 5. Summary of mean %OC and overall OM content in two lithologies.

Sample code	Mean %OC	Overall SOC (tons ha^{-1})
Bataraza, Palawan	4.81	85.68
Puerto Princesa City, Palawan	5.25	99.05
Cavinti, Laguna	3	41.95

Comparison to other studies

Additional analysis was conducted to understand further the difference in the amount of OM and OC per area that can be stored in different soil types and management practices. **Supplementary Table 5** summarizes values of overall mean stored CO_2 from different related studies representing different soil types wherein the Zamboanga Peninsula Adtuon Series has the highest amount of SOC with a total of 429.90 tons ha^{-1}, followed by the Zamboanga Peninsula Faraon Series 271.17 tons ha^{-1}, Puerto Princesa with 99.05 tons ha^{-1}, General Nakar with 93.39 tons ha^{-1}, Bataraza with 85.68 tons ha^{-1}, Tanay with 58.67 tons ha^{-1}, Cavinti with 41.95 tons ha^{-1}, and urban soil in Guangzhou City, China with 27.15 tons ha^{-1}, respectively (Lasco *et al*., 2007; Dela Cruz, 2010, cited by Ilao *et al*., 2010; Salang, 2010; Yuan *et al*., 2022). **Figure 5** shows the difference in total organic carbon in eight places under the influence of various factors, including soil maturity, physicochemical properties, and mineralogy, which can influence the capacity of SOM to store carbon. The Zamboanga Peninsula Adtuon and Faraon Series are agroforestry lands that are being managed with the use of different traditional tillage and cropping systems that can promote the conservation of existing carbon stock and also increase its amount by promoting bonding between organic carbon compound and clay minerals of the soil series (BSWM, 2004 cited by Ilao *et al*., 2010). Additionally, having soil that is high in pH directly benefits the soil by accumulating more organic matter and, in return, accumulating more organic carbon (Kuśmierz, 2023). On the other hand, General Nakar and Tanay soils are from a secondary forest stand (Lasco *et al*., 2007, cited by Ilao *et al*., 2010) with low aboveground biomass caused by low vegetation

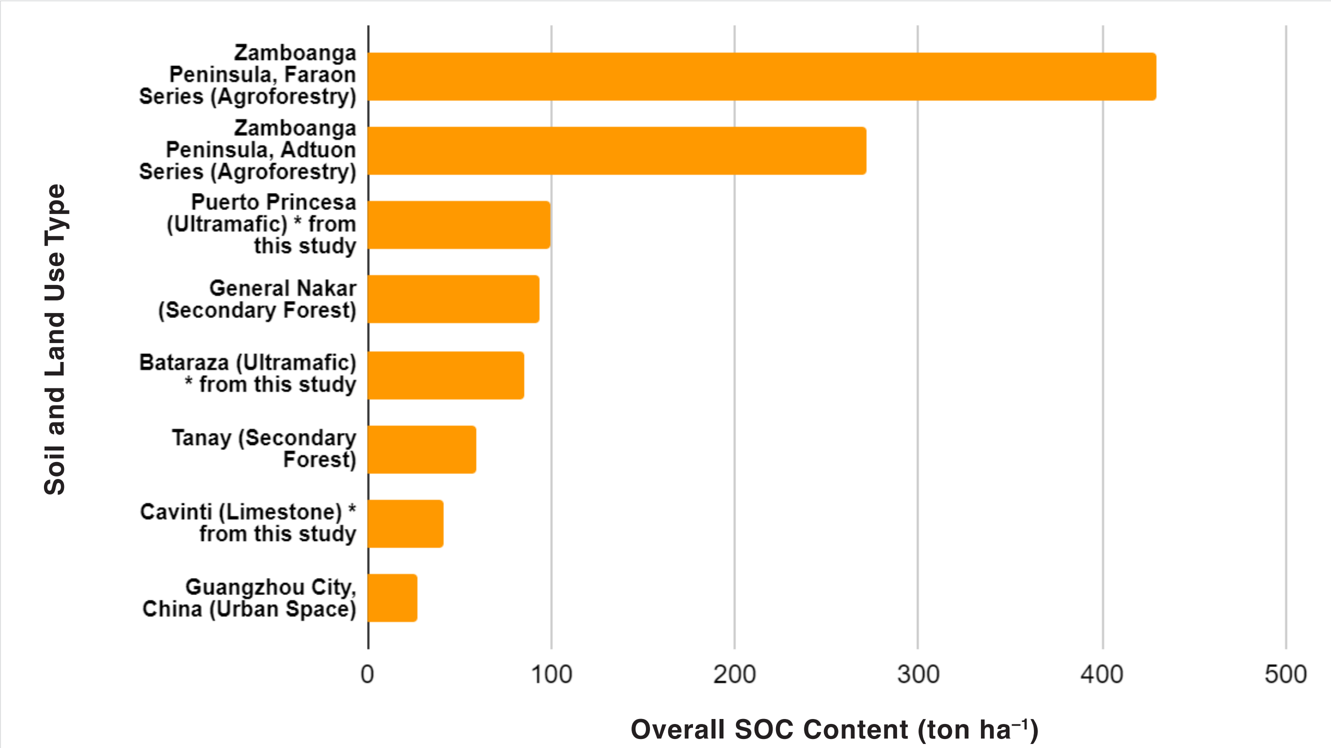

Figure 5. Compared values of stored CO_2 from different related studies and research representing different soil and land use types (Lasco *et al.*, 2007, cited by Ilao *et al.*, 2010; Dela Cruz, 2010; Salang, 2010; Yuan *et al.*, 2022).

present in the area; thus, this subsequently affects the amount of organic carbon stored in the area. Soils studied in Guangzhou City is an urban space; it exhibited low OC storage, accounted for anthropogenic disturbances, low OM inputs, and high soil compaction that causes huge alteration in physical, chemical, and biogeochemical properties, increases the bulk density, decreases the soil porosity, reduction of aeration, alteration of oxide conditions and other pedological processes that limit organic matter and organic carbon accumulation (Yuan *et al*., 2022).

This observation demonstrates that land use, land conservation practices, and vegetation cover influence variations in SOC amounts. Other factors correlated with this phenomenon include soil compaction, decomposition rate, availability of cation nutrients, inputs from above and below ground, and overall soil health (Yuan *et al*., 2022). These factors can cause significant changes in the soil's physical, chemical, and biogeochemical properties. Moreover, this research can help prioritize parameter selection for carbon market sites. The study result's hierarchy of variables can help develop a credible verification mechanism to track SOC levels over time and maintain carbon sequestration and storage credibility and transparency in the carbon market. Big industries and rich countries trade carbon, yet many are skeptical due to a lack of transaction transparency and legal grounding. It could also help standardize criteria for determining upcoming carbon marketplaces. Lastly, further understanding how soil conservation influences carbon storage is a viable solution to soil deterioration and climate change issues.

CONCLUSIONS

Comprehending the mechanisms governing soil carbon storage facilitates the estimation of SOC across various land uses, empowering informed decisions in conservation and soil management. This study on the Philippines' ultramafic soils using Bataraza and Puerto Princesa City samples showed that this type has a wide range of potential in storing large amounts of carbon, with the range of SOC content between 4 – 7% in the topsoil and 3 – 5% in the subsoil. Soil samples also have a relatively large capacity to store carbon; Puerto Princesa City had the highest overall SOC content (99.05 tons ha^{-1}) compared to the Bataraza site, which had 85.68 tons ha^{-1}. Moreover, results highlighted that the most influential soil variables are soil texture and clay particles, followed by soil pH, porosity, bulk density, and particle density. Comparing the mean %OC and overall SOC content, this study established the differences between the two lithologies and soils with various land use and conservation techniques. It highlights the importance of ultramafic soil in carbon sequestration efforts and warrants immediate conservation.

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LITERATURE CITED

Angst, G., Messinger, J., Greiner, M., Häusler, W., Hertel, D., Kirfel, K., Kögel-Knabner, I., Leuschner, C., Rethemeyer, J., & Mueller, C. W. (2018). Soil organic carbon stocks in topsoil and subsoil controlled by parent material, carbon input in the rhizosphere, and microbial-derived compounds. *Soil Biology & Biochemistry, 122*, 19–30.

Asabere, S. B., Zeppenfeld, T., Nketia, K. A., & Sauer, D. (2018). Urbanization leads to increases in pH, carbonate, and soil organic matter stocks of arable soils of Kumasi, Ghana (West Africa). *Frontiers in Environmental Science*, *6*. <https://doi.org/10.3389/fenvs.2018.00119>.

Barré, P., Durand, H., Chenu, C., Meunier, P., Montagne, D., Castel, G., Billiou, D., Soucémarianadin, L., & Cécillon, L. (2017). Geological control of soil organic carbon and nitrogen stocks at the landscape scale. *Geoderma*, *285*, 50–56.

BMB [Biodiversity Management Bureau]. (2017). Manual on Biodiversity Assessment and Monitoring System for Terrestrial Ecosystems: How-to Guidelines. *Biodiversity Management Bureau, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH*. Manila, Philippines.

Basile-Doelsch, I., Balesdent, J., & Pellerin, S. (2020). Reviews and Syntheses: The Mechanisms Underlying Carbon Storage in Soil. Retrieved from: <https://doi.org/10.5194/bg-2020-49>.

BSWM. 2004. Land resource evaluation projects in the province of Zamboanga Peninsula. Manila: Department of Agriculture.

Cresswell, H. P., & Hamilton, G. J. (2002). Bulk density and pore space relations. *In* N. J. McKenzie, *et al*. (Eds.), Soil physical measurement and interpretation for land evaluation. Australian Soil and Land Survey Handbook. pp. 35–58. CSIRO.

Cutts, J., Steinthorsdottir, K., Turvey, C. C., Dipple, G. M., Enkin, R. J., & Peacock, S. M. (2021). Deducing mineralogy of serpentinized and carbonated ultramafic rocks using physical properties with implications for carbon sequestration and subduction zone dynamics. *Geochemistry Geophysics Geosystems*, *22*(9). <https://doi.org/10.1029/2021gc009989>.

Dela Cruz, L. 2010. Harnessing the carbon sequestration potentials of forest soils: Strategies for climate change mitigation and adaptation. Guillermo Ponce Professorial Chair Lecture. College, Laguna, UPLB.

European Union. (2011). *Soil: The Hidden Part of the Climate Cycle*. Publ. Office of the European Union. Retrieved from: <https://doi:10.2779/3066>.

Fukumasu, J., Jarvis, N., Koestel, J., Kätterer, T., & Larsbo, M. (2022). Relations between soil organic carbon content and the pore size distribution for an arable topsoil with large variations in soil properties. *European Journal of Soil Science, 73*(1). <https://doi.org/10.1111/ejss.13212>.

Germaine, J. T. & Germaine, A. V. (2009). *Geotechnical Laboratory Measurements for Engineers*. John Wiley & Sons.

Hossain, M. F., Chen, W., & Zhang, Y. (2015). Bulk density of mineral and organic soils in the Canada's arctic and sub-arctic. *Information Processing in Agriculture, 2*(3–4), 183–90.

Ilao R., Salang, E., & Floresca J. (2010). Soil carbon sequestration and greenhouse gases mitigation in selected ecosystems in the Philippines. Proceedings of International Workshop on Evaluation and Sustainable Management of Soil Carbon Sequestration in Asian Countries. Bogor, Indonesia, Sept. 28-29, 2010. pp. 139–152.

Kelemen, P. B., Benson, S. M., Pilorgé, H., Psarras, P., & Wilcox, J. (2019). An overview of the status and challenges of CO_2 storage in minerals and geological formations. *Frontiers in Climate, 1.* <https://doi.org/10.3389/fclim.2019.00009>.

Kuśmierz, S., Skowrońska, M., Tkaczyk, P., Lipiński, W., & Mielniczuk, J. (2023). Soil organic carbon and mineral nitrogen contents in soils as affected by their pH, texture and fertilization. *Agronomy, 13*(1), 267. <https://doi.org/10.3390/agronomy13010267>.

Labis, F. A. C., Payot, B. D., Valera, G. T. V., Pasco, J. A., Dycoco, J. M. A., Tamura, A., Morishita, T., & Arai, S. (2020). Melt-rock interaction in the subarc mantle: Records from the plagioclase peridotites of the southern Palawan ophiolite, Philippines. *International Geology Review, 63*(9), 1067–1089.

LaMorte, W. (2017). *Nonparametric tests: Wilcoxon Signed Rank Test*. Boston University School Modules. Retrieved from: <https://sphweb.bumc.bu.edu/otlt/mph-modules/bs/bs704_nonparametric/BS704_Nonparametric6.html#:~:text=The%20test%20statistic%20for%20the,W%2D%20would%20be%20similar>.

Lasco, R. D., Pulhin, F. B., & Cruz, R. V. O. (2007). Carbon stocks assessment of forest land uses in the Kaliwa watershed, Philippines. *Journal of Environmental Science and Management 10*(2):40-48.

Lemanowicz, J., Bartkowiak, A., Zielińska, A., Jaskulska, I., Rydlewska, M., Klunek, K., & Polkowska, M. (2023). The effect of enzyme activity on carbon sequestration and the cycle of available macro- (P, K, Mg) and microelements (Zn, Cu) in Phaeozems. *Agriculture, 13*(1), 172. MDPI AG. <http://dx.doi.org/10.3390/agriculture13010172>.

Minitab Statistical Software. (2002). *Interpret the key results for Kruskal-Wallis Test*. Minitab. Retrieved from: <https://support.minitab.com/en-us/minitab/21/help-and-how-to/statistics/nonparametrics/how-to/kruskal-wallis-test/interpret-the-results/key-results/>.

Nabayi, A., Danmowa, N. M., Hayatu, N. G., Girei, A. H., Santuraki, H. A., Haruna, F.D., & Mahmud, A. T. (2019). Influence of organic matter on some selected physical and hydraulic properties of a Sudan Savannah entisols. *In: Understanding Nigerian soils for sustainable food and nutrition, security, and healthy environment*. Proceedings of Soil Science of Nigeria. Held at College of Agronomy Complex (North Core), University of Agriculture, Makurdi on 14-18 July 2019. pp. 719–725

Nabayi, A., Girei, A. H., Hayatu, N. G., Garba, J., & Santuraki, H. A. (2021). Effect of soil organic matter (SOM) content on true particle density and other physical properties of Sudan savannah entisols. *Bulgarian Journal of Soil Science*.

Nabayi, A., Onokebhagbe, V. O., Nkereuwem, M. E., Santuraki, H. A., Haruna, F. D., Hayatu, N. G., &Mahmud, A. T. (2017). Modification of some physical and chemical properties under different tillage systems in Hadejia. *Dutse Journal of Agriculture and Food Security, 5*(1), 167-176

Reeves, R. D., Baker, A. J. M., Becquer, T., Echevarria, G., & Miranda, Z. J. G. (2007). The flora and biogeochemistry of the ultramafic soils of Goias state, Brazil. *Plant and Soil, 293*, 107–119.

Salang, E. D. (2010). Carbon sequestration by Faraon and Adtuyon soils under different cropping and tillage systems in Zamboanga Peninsula.

Sakin, E. (2012). Organic carbon organic matter and bulk density relationships in arid-semi arid soils in Southeast Anatolia region. *African Journal of Biotechnology, 11*(6). <https://doi.org/10.5897/ajb11.2297>.

Thomas, G. W. (1996) Soil pH and soil acidity. *In*: Sparks, D. L. (Ed.)., *Methods of Soil Analysis Part 3: Chemical Methods*, SSSA Book Series 5, Soil Science Society of America, Madison, Wisconsin, pp. 475-490.

Trumbore, S. E. (1997). Potential responses of soil organic carbon to global environmental change. *Proceedings of the National Academy of Sciences of the United States of America, 94(*16), 8284–8291.

Walkley, A. & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science, 37*(1), 29–38.

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., Von Lützow, M., Marín-Spiotta, E., Van Wesemael, B., Rabot, E., Ließ, M., García-Franco, N., Wollschläger, U., Vögel, H., & Kögel-Knabner, I. (2019). Soil organic carbon storage as a key function of soils – A review of drivers and indicators at various scales. *Geoderma, 333*, 149–162.

Yu, M., Wang, Y., Jiang, J., Wang, C., Zhou, G., & Yan, J. (2019). Soil organic carbon stabilization in the three subtropical forests: importance of clay and metal oxides. *Journal of Geophysical Research: Biogeosciences, 124*(10), 2976–2990.

Yuan, S., Stuart, A. M., Laborte, A. G., Rattalino Edreira, J. I., Dobermann, A., Kien, L. V., Thúy, L. T., Paothong, K., Traesang, P., Tint, K. M., San, S. S., Villafuerte, M. Q., Quicho, E. D., Pame, A. R., Then, R., Flor, R. J., Thon, N., Agus, F., Agustiani, N., . . . Grassini, P. (2022). Southeast Asia must narrow down the yield gap to continue to be a major rice bowl. *Nature Food, 3*(3), 217-226. <https://doi.org/10.1038/s43016-022-00477-z>.

Supplementary Table 1. Soil textural classification and percentage of the ultramafic forests of Palawan.

Sample code	% Clay	% Silt	% Sand	Soil textural class
RTB Plot 1 S0-20	27.78	20.53	51.69	sandy clay loam
RTB Plot 2 S0-20	6.49	23.62	69.89	sandy loam
RTB Plot 3 S0-20	8.57	27.84	63.60	sandy loam
RTB Plot 4 S0-20	9.62	22.05	68.33	sandy loam
RTB Plot 5 S0-20	9.47	15.79	74.74	sandy loam
RTB Plot 1 S21-50	22.57	24.94	52.49	sandy clay loam
RTB Plot 2 S21-50	7.51	14.64	77.85	loamy sand
RTB Plot 3 S21-50	9.62	17.82	72.57	sandy loam
RTB Plot 4 S21-50	12.88	22.15	64.98	sandy loam
RTB Plot 5 S21-50	15.76	9.08	75.17	sandy loam
PPC P1 S0-20	11.76	17.41	70.83	sandy loam
PPC P2 S0-20	36.63	10.00	53.37	sandy clay
PPC P3 S0-20	21.53	14.60	63.87	sandy clay loam
PPC P4 S0-20	9.39	27.86	62.75	sandy loam
PPC P5 S0-20	22.59	17.12	60.29	sandy clay loam
PPC P1 S21-50	9.74	18.76	71.49	sandy loam
PPC P2 S21-50	51.14	13.05	35.82	clay
PPC P4 S21-50	29.42	23.45	47.13	sandy clay loam
PPC P5 S21-50	37.31	8.08	54.60	sandy clay

Supplementary Table 2. Established ranking among nonparametric factors.

Parameter	p-value	Confidence interval at 95%	Significance to %OC (Rank)
Soil texture	$1.46E^{-13}$	[25, 12.90] = 12.1 (% Clay);	1
		[21.22, 15.50] = 5.70 (% Silt);	2
		[68.05, 57.37] = 10.68 (% Sand)	3

Note: Kruskal-Wallis Test other values for soil texture include chi-squared = 62.825, df = 3.

Supplementary Table 3. Established ranking among parametric factors.

Parameter	p-value	Confidence interval at 95%	Significance to %OC (Rank)
Soil pH	–0.5851862	[6.05, 6.45] = 0.4	2
Soil porosity	0.3886367	[68.12, 59.80] = 8.32	3
Bulk density	–0.3678254	[1.06, 0.80] = 0.26	4
Particle density	–0.3227414	[2.70, 2.30] = 0.4	5

Supplementary Table 4. Summary of %OC and %OM content in Cavinti, Laguna.

Sample code	%OC	Mean %OC	%OM	Mean %OM
Cavinti 1	2.77	3.00	4.77	5.16
Cavinti 2	3.36		5.77	
Cavinti 3	4.85		8.34	
Cavinti 4	2.62		4.50	
Cavinti 5	2.82		4.85	
Cavinti 6	1.60		2.75	

Supplementary Table 5. Summarized overall mean stored CO_2 values from different related studies and research representing different soil types (Lasco *et al*., 2007; Dela Cruz, 2010; Salang, 2010; Yuan *et al*., 2022).

Soil type	Overall SOC content (tons ha^{-1})
Zamboanga Peninsula, Faraon Series (Agroforestry)	429.90
Zamboanga Peninsula, Adtuon Series (Agroforestry)	271.17
Puerto Princesa (Ultramafic)*	99.05
General Nakar (Secondary Forest)	93.39
Bataraza (Ultramafic)*	85.68
Tanay (Secondary Forest)	58.67
Cavinti (Limestone)*	41.95
Guangzhou City, China (Urban Space)	27.15

**from this study*