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# Improving soil carbon estimates of Philippine mangroves using localized organic matter to organic carbon equations

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## Abstract

**Background** Southeast Asian (SEA) mangroves are globally recognized as blue carbon hotspots. Methodologies that measure mangrove soil carbon stock (SCS) are either accurate but costly (i.e., elemental analyzers), or economical but less accurate (i.e., loss-on-ignition [LOI]). Most SEA countries estimate SCS by measuring soil organic matter (OM) through the LOI method then converting it into organic carbon (OC) using a conventional conversion equation ($\%C_{org} = 0.415 * \%\ LOI + 2.89$, $R^2 = 0.59$, $n = 78$) developed from Palau mangroves. The local site conditions in Palau does not reflect the wide range of environmental settings and disturbances in the Philippines. Consequently, the conventional conversion equation possibly compounds the inaccuracies of converting OM to OC causing over- or under-estimated SCS. Here, we generated a localized OM-OC conversion equation and tested its accuracy in computing SCS against the conventional equation. The localized equation was generated by plotting % OC (from elemental analyzer) against the % OM (from LOI). The study was conducted in different mangrove stands (natural, restored, and mangrove-recolonized fishponds) in Oriental Mindoro and Sorsogon, Philippines from the West and North Philippine Sea biogeographic regions, respectively. The OM:OC ratios were also statistically tested based on (a) stand types, (b) among natural stands, and (c) across different ages of the restored and recolonized stands. Increasing the accuracy of OM-OC conversion equations will improve SCS estimates that will yield reasonable C emission reduction targets for the country's commitments on Nationally Determined Contributions (NDC) under the Paris Agreement.

**Results** The localized conversion equation is $\%OC = 0.36 * \%\ LOI + 2.40$ ($R^2 = 0.67$; $n = 458$). The SOM:OC ratios showed significant differences based on stand types ($x^2 = 19.24$; $P = 6.63 \times 10^{-05}$), among natural stands ($F = 23.22$; $p = 1.17 \times 10^{-08}$), and among ages of restored ($F = 5.14$; $P = 0.03$) and recolonized stands ($F = 3.4$; $P = 0.02$). SCS estimates using the localized (5%) and stand-specific equations (7%) were similar with the values derived from an elemental analyzer. In contrast, the conventional equation overestimates SCS by 20%.

**Conclusions** The calculated SCS improves as the conversion equation becomes more reflective of localized site conditions. Both localized and stand-specific conversion equations yielded more accurate SCS compared to the conventional equation. While our study explored only two out of the six marine biogeographic regions in the Philippines, we proved that having a localized conversion equation leads to improved SCS measurements. Using our proposed

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equations will make more realistic SCS targets (and therefore GHG reductions) in designing mangrove restoration programs to achieve the country's NDC commitments.

**Keywords** Philippine mangroves, Carbon stock estimation, Soil organic carbon, Organic matter to organic carbon allometry, Loss-on-ignition, Conservation, Restoration

## Background

Blue carbon ecosystems (BCEs) are vegetated coastal ecosystems (e.g., mangroves, seagrasses, and tidal marshes) that sequester disproportionately large amounts of organic carbon (OC) per area [1]. Their anoxic and waterlogged soils capture and sequester OC by slowing down decay rates [2]. Mangrove forests are one of the important BCEs that rose into prominence for their unique role in the global climate crisis by sequestering atmospheric carbon while providing many ecosystem services [3]. The role of mangroves in climate change adaptation and mitigation (CCAM) through conservation and restoration programs has been emphasized in many countries' Nationally Determined Contributions (NDCs) under the Paris Agreement [4]. However, when mangroves are disturbed, their stored carbon are released as greenhouse gases (GHG) back into the atmosphere [5].

Mangroves contain the largest carbon stock (CS) per unit area when compared to any other ecosystems in the tropical ocean (6.17 Pg $C_{org}$; 17% of the total tropical marine CS, [6]). However, wide variability in CS estimates exists due to local macroscale ecosystem differences (e.g., forest age, geomorphology, among others, [7]). Mangrove soil organic carbon (SOC) locks in 49–98% of the total ecosystem carbon stock (TECS), but is the least studied carbon pool [8, 9] particularly in tropical developing countries. Elemental analyzers that yield direct OC measurements are costly, making them impractical to many tropical developing countries. OC concentration is often estimated semi-quantitatively by converting organic matter (OM) derived from the more economical and more accessible loss-on-ignition (LOI) method using a conversion equation. The usual conversion equation applied in most sediment carbon stock (SCS) estimates in the Philippines is derived from Palau mangroves, $\%C_{org} = 0.415 * \%LOI + 2.89$ ([9]; referred from hereon as the conventional equation). Inherent inaccuracies are expected when determining OC through the LOI method [10]. Site-specific differences, especially on local climate and geomorphology, compound these inherent inaccuracies [6] leading to less accurate SCS measurements [1, 6]. Ultimately, the accuracy of the conversion equation relies heavily on the degree of similarity between the study site and the reference site where the conventional equation was derived [11].

The Southeast Asian (SEA) region is a "blue carbon hotspot" hosting the largest and most diverse mangroves in the world. Among the SEA countries, the Philippines has the third largest mangrove CS (102–576 MgC $ha^{-1}$ [12]) and the fourth largest mangrove extent (284,798 ha [13]). Philippine mangroves exist in a variety of stand conditions (natural, colonized, and restored) based on vegetation structure and the developmental stage with different climatic and geomorphological conditions [14]. These mangroves are also frequently affected by natural and anthropogenic disturbances such as typhoons and conversion to aquaculture ponds [15, 16]. Applying a general OM-OC equation for the Philippines may be prone to misuse as it may discard site-specific mangrove conditions (based on stand types, occurrences/types of disturbances, etc.). These country-specific conditions are less prominent in Palau mangroves hence may not necessarily be accounted for by the conventional OM-OC conversion equation [9, 17].

In this study, we generated localized OM-OC site-specific conversion equations representative of the different mangrove stand types (e.g., natural, colonized, restored, and no vegetation) in the Philippines. The soil OM:OC ratios and the slopes of the conversion equations for the (a) natural stands and the (b) restored and recolonized stands based on chronosequence of ages were compared to infer the influence of mangrove age (cf. [18]). The accuracy of the generated equations was then compared to the conventional equation.

## Methods

### Site description

The study was conducted in two areas in the Philippines: Prieto Diaz in the province of Sorsogon (13.0179300°, 124.1867900°), and the municipalities of Bongabong (12.6991487°, 121.5307829°), Mansalay (12.4338929°, 121.4114457°), and Roxas (12.6046100°, 121.5443800°) in the province of Oriental Mindoro (Fig. 1). The municipality of Prieto Diaz is located on the easternmost point of the Bicol Peninsula on the southern portion of Luzon Island and belongs to the North Philippine Sea biogeographic region. The sites in Oriental Mindoro are on the southeastern portion of Mindoro Island and belong to the West Philippine Sea biogeographic region. Prieto Diaz has a tropical rainforest climate while Oriental

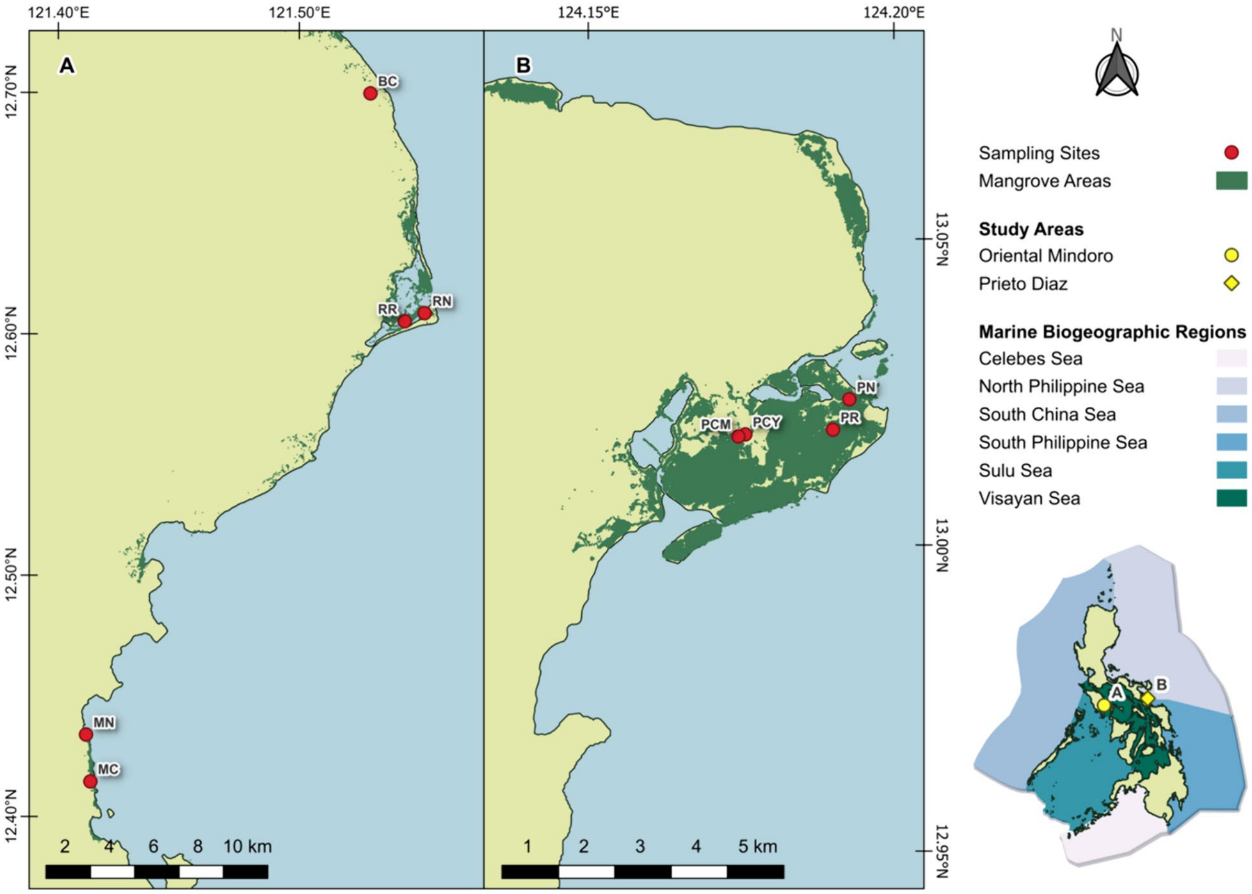

**Fig. 1** Location of sampling sites and mangroves within the study areas (**A** Oriental Mindoro: Bongabong Recolonized, BC; Roxas Restored, RR; Roxas Natural, RN; Mansalay Natural, MN; Mansalay Recolonized, MC; and **B** Prieto Diaz: Natural, PN; Restored, PR; Young recolonized, PCY; Mature recolonized, PCM). Inset map shows the location of study areas within the Philippine marine biogeographic regions

Mindoro has a tropical monsoon climate based on the Koppen Classification (Table 1 [19]). Both sites are categorized as open coast (based on typology, cf. [20]). Natural stands are mangroves that are not planted nor recolonized. Restored mangroves are "planted" stands while recolonized mangroves are mangroves that undergo succession post-fishpond abandonment. The estimated ages of the stands were based on local

**Table 1** Biophysical profile of the study sites

| Site | Site code | Dominant species | Age, yr |
|---|---|---|---|
| Prieto Diaz, Natural | PN | Diverse | Unknown |
| Prieto Diaz, Restored | PR | *Rhizophora* sp. | 30 |
| Prieto Diaz, Recolonized (Young) | PCY | *Rhizophora* sp. | 8 |
| Prieto Diaz, Recolonized (Mature) | PCM | *Avicennia* sp. | 17 |
| Mansalay, Natural | MN | *Avicennia marina, Rhizophora* sp., *Sonneratia alba* | Unknown (ca. 100) |
| Roxas, Natural | RN | *Rhizophora* sp. | 90 |
| Roxas, Restored | RR | *Rhizophora* sp. | 10 |
| Bongabong, Recolonized | BC | *Avicennia marina* | 35 |
| Mansalay, Recolonized | MC | *Avicennia marina,*<br>*Ceriops decandra* | 10 |

accounts/records complemented with local maps. We also added a site without mangroves (referred to as "no vegetation") to depict clear-cut vegetation and represent disturbed mangroves.

### Field sampling

Sampling was conducted in nine sites across different mangrove stand types and stand ages (Table 1). The "no vegetation" samples were collected adjacent to the colonized mangroves in Mansalay. Within each site, core samples were collected across a zonation gradient, if applicable. Sediment cores of up to one meter depth were collected using a 6.5 cm diameter open-faced auger. The core samples were cut every two cm for the upper 0–20 cm surface, and every four cm for the 20–100 cm depths. Each subsample was individually placed in air-tight polyethylene bags. All soil samples from Sorsogon were collected in February 2022 while samples from Bongabong, Mansalay, and Roxas were collected in July 2022.

### Laboratory analysis

In the laboratory, each sub-sample was air-dried then weighed. The samples were then placed in a drying oven at 60 °C until constant mass was attained. Bulk density was calculated using the formula below:

$$Bulk\ Density\ (g/cm^3) = \frac{weight\ of\ subsample\ (g)}{volume\ of\ subsample\ (cm^3)}$$

The OM content was determined through the LOI method (cf. [9]). Dried samples were pulverized with an agate mortar and pestle. Stones, twigs, roots, and other large materials were removed during pulverization (cf [11]). The ground samples were then oven-dried at 60 °C for 24 h. Five grams per subsample were weighed, then placed in a muffle furnace at 550 °C. We standardized combustion for four hours. The change in mass after combustion represented the OM concentration.

$$\%OM = \frac{initial\ mass\ (g) - final\ mass(g)}{initial\ mass(g)} \times 100$$

A separate set of samples was sent to Jakarta, Indonesia for the analysis of OC content using an elemental analyzer (LECO CHN 628 Series: CHN Analyzer, LECO Corp., St. Joseph, MI). In total, 458 soil samples from different sites, stand types, and zonation were analyzed separately for OM and OC concentrations.

### Data analyses

Using simple linear regression, an allometric equation was derived to determine the relationships between the OM and OC concentrations across sites and stand types (referred from hereon as general equation). Allometric equations were also derived for each stand type and age (referred from hereon as stand-specific and age-specific equation, respectively). The SCS of each sampling site was calculated using the generated general OM-OC equation and then compared with the OC derived from the elemental analyzer and the conventional equation derived from Palau mangroves [9].

The OM derived from the LOI method and the OC from the elemental analyzer were used to create OM:OC ratios. The OM:OC ratios were compared across stand types, among natural stands, and among ages for the recolonized and restored stands. The OM:OC ratios were first filtered for outliers (categorized as values greater than or equal to 1.0, following [10]). Shapiro–Wilk normality test and Levene's homogeneity test were then applied to the filtered data then analyzed using one-way ANOVA (followed by Tukey's Highly Significant Difference for post-hoc comparisons). Non-normal data was analyzed using the Kruskal Wallis Test then post-hoc Dunn test. Data uncertainties were expressed in a 95% confidence interval (CI). All data analyses and visualizations were performed using R version 4.0.3 and RStudio version 1.4.1103.

## Results

### Organic carbon strongly correlated with organic matter content

The OM% (derived from the LOI) was significantly correlated with the OC% (derived from the elemental analyzer), $\%C_{org} = 0.36 * \%\ LOI + 2.40$ ($R^2 = 0.67$, $x^2 = 3$; $P = 0.28$; Fig. 2). There were no significant differences in regression slopes across stand types. However, the strength of relationship varied with stand types (Restored, $R^2 = 0.59$; Recolonized, $R^2 = 0.69$; Natural, $R^2 = 0.60$; Fig. 3; Table 2a). The natural stands had the steepest slope (0.39), closely followed by the recolonized stands (0.38). Both the natural and recolonized stands have 23% steeper slopes than that of the restored stands (0.30; Fig. 3).

### Variability of OM:OC ratios within and between stand types

The OM:OC ratios of the restored stands (2.25 ± 0.05) were 11% and 26% significantly lower than the natural (2.53 ± 0.09) and recolonized (3.03 ± 0.14) stands, respectively (Table 2b). Variabilities within groups were also observed. The natural mangroves in Mansalay (1.93 ± 0.06) had 29–31% lower ratio than Prieto Diaz (2.81 ± 0.22) and Roxas (2.74 ± 0.09). In the restored stands, the 10-yr-old plantations (2.12 ± 0.06) had 11% lower ratio than the 30-yr-old plantations (2.38 ± 0.08). In the recolonized stands, the ratios varied with stand ages although pairwise comparisons didn't yield significant differences

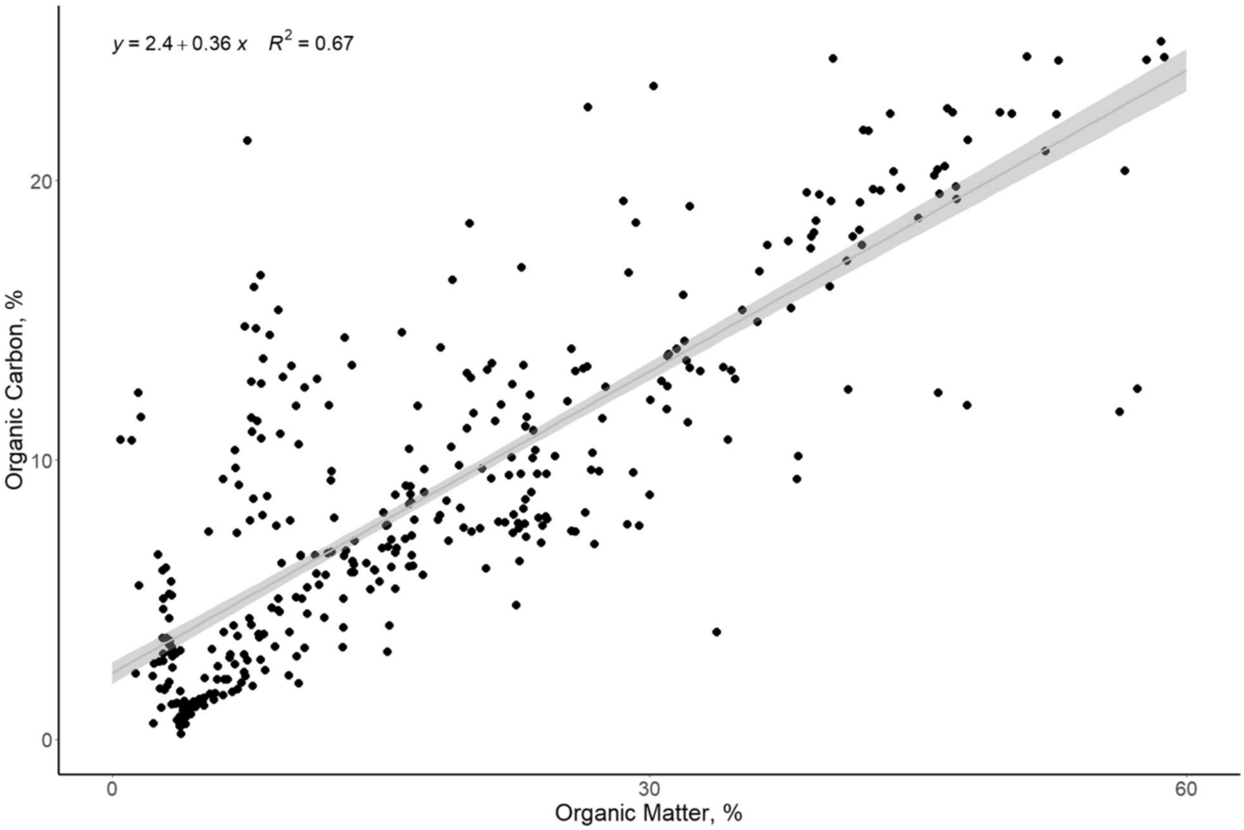

**Fig. 2** Scatter plot of organic matter (OM) and organic carbon (OC) contents used to derive the general OM-OC conversion equation for Philippine mangroves. The OM was calculated using the loss-on-ignition (LOI) method, while OC was calculated using the conversion equation, $\%C_{org} = 0.415 * \% LOI + 2.89$ [9]

between ages (8-yrs = 2.25 ± 0.07; 10-yrs = 2.77 ± 0.19, 17-yrs = 2.23 ± 0.08, 35-yrs = 3.85 ± 0.30).

### Locally-derived equation has higher accuracy than the conventional equation

The mean SCS estimated using %OC from the elemental analyzer was 585.61 ± 72.16 Mg/ha (Fig. 4A). Our general equation was 5% higher across stands (616.04 ± 64.09 Mg/ha; Fig. 4A) and 7% higher with stand-specific calculations (625.56 ± 61.79 Mg/ha; Fig. 4B) than the values derived from the elemental analyzer (Fig. 4C). In contrast, the conventional equation overestimates SCS by 20% (718.69 ± 71.85 Mg/ha; Fig. 4C). Our derived general and stand-specific equations yielded higher SCS for the natural stands ($\%C_{org} = 0.39 * \% \text{LOI} + 0.94$ [$R^2 = 0.60$, $x^2 = 2$; $P = 0.37$; Fig. 3A]), but lower SCS for both the restored ($\%C_{org} = 0.38 * \% \text{LOI} + 2.3$ [$R^2 = 0.69$, $x^2 = 1$; $P = 0.32$; Fig. 3B; Fig. 5]) and recolonized stands ($\%C_{org} = 0.30 * \% \text{LOI} + 3.6$ [$R^2 = 0.59$, $x^2 = 3$; $P = 0.32$; Fig. 3C; Fig. 5]).

## Discussion

Our study generated general and stand-specific OM-OC conversion equations for Philippine mangroves. The equations we developed for Philippine mangroves, specifically for open coast typology [20], are within the range of the slopes (0.35 vs 0.23–0.50) and correlation strengths ($R^2 = 0.67$ vs. 0.25–0.79) reported in SE Asia and Micronesia (Table 3). The regression slopes in the stand-specific and age-specific equations, although not statistically significant between and within groups, proved that localized equations will be more appropriate to calculate SCS compared to the conventional equation [9]. To our knowledge, these equations were the first account that established OM-OC relationship that was used in the measurements of SCS in Philippine mangroves.

### The need for a localized OM-OC equation

Blue carbon studies in Philippine mangroves have increasingly become popular since 2009 [21]. With the need to utilize blue carbon as a nature-based solution (NbS) and as an integral part of CCAM strategy, the topic

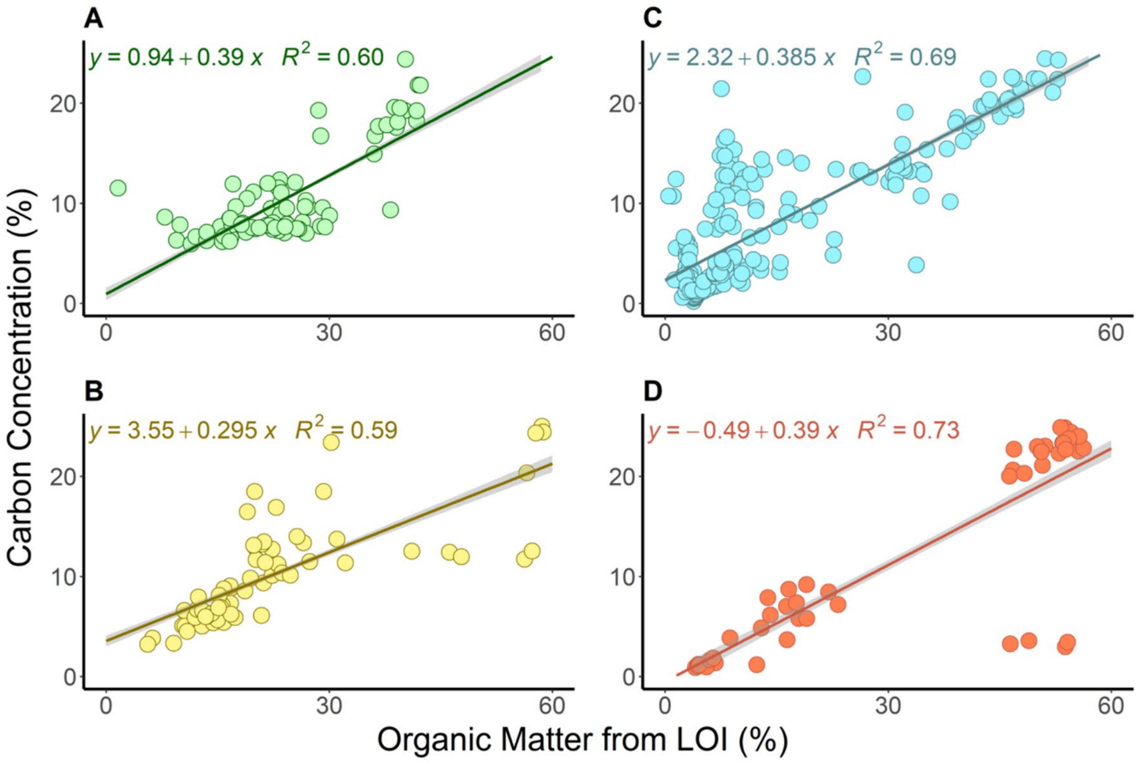

**Fig. 3** Stand-specific OM-OC conversion equations derived for natural stands (**A**), restored stands (**B**), recolonized stands (**C**), and no vegetation (**D**)

**Table 2** Summary of slopes, intercepts and $R^2$ values of the OM-OC conversion equations (A) and the results of the analysis of variance (ANOVA) tests on the OM:OC ratios (mean ± CI) according to stand-specific and site-specific parameters (B)

| **Parameters** | **A. OM-OC Conversion Equation** | | | | **B. OM:OC Ratio Analysis** | | |
|---|---|---|---|---|---|---|---|
| **Stand-Specific** | **Site-Specific** | **Slope (m)** | **Intercept (b)** | **Relationship strength ($R^2$)** | **Ratio** | **F ratio** | **P** |
| All Stands | Excluding NV | 0.36 | 0 | 0.67 | | 19.244 | $6.63 \times 10^{-5}$ |
| | Including NV | 0.35 | 2.20 | 0.67 | | | |
| Natural | **All Sites** | **0.39** | **0.94** | **0.60** | $\mathbf{2.53 \pm 0.09}^{a}$ | **23.22** | **1.17 x $10^{-8}$** |
| | Mansalay | 0.41 | 3.00 | 0.88 | $1.93 \pm 0.06^{a}$ | | |
| | Prieto Diaz | − 0.0064 | 7.80 | 0.00085 | $2.81 \pm 0.22^{b}$ | | |
| | Roxas | 0.041 | 8.10 | 0.0082 | $2.74 \pm 0.09^{b}$ | | |
| Restored | **All Ages** | **0.30** | **3.60** | **0.59** | $\mathbf{2.25 \pm 0.05}^{b}$ | **5.14** | **0.03** |
| | 10-yrs | 0.43 | 0.92 | 0.59 | $2.12 \pm 0.06^{a}$ | | |
| | 30-yrs | 0.12 | 12.00 | 0.15 | $2.38 \pm 0.08^{b}$ | | |
| Recolonized | **All Ages** | **0.38** | **2.30** | **0.69** | $\mathbf{3.03 \pm 0.14}^{a}$ | **3.35** | **0.02** |
| | 8-yrs | 0.18 | 8.90 | 0.41 | $2.25 \pm 0.07^{a}$ | | |
| | 10-yrs | 0.08 | 6.60 | 0.02 | $2.77 \pm 0.19^{a}$ | | |
| | 17-yrs | 0.20 | 12.00 | 0.42 | $2.23 \pm 0.08^{a}$ | | |
| | 35-yrs | 0.085 | 1.90 | 0.0 | $3.85 \pm 0.30^{a}$ | | |

Different letters in the OM:OC ratios indicate significant differences between sites across stands, among sites in the natural stands, and among ages in the restored and recolonized stands ($P < 0.05$). NV = no vegetation

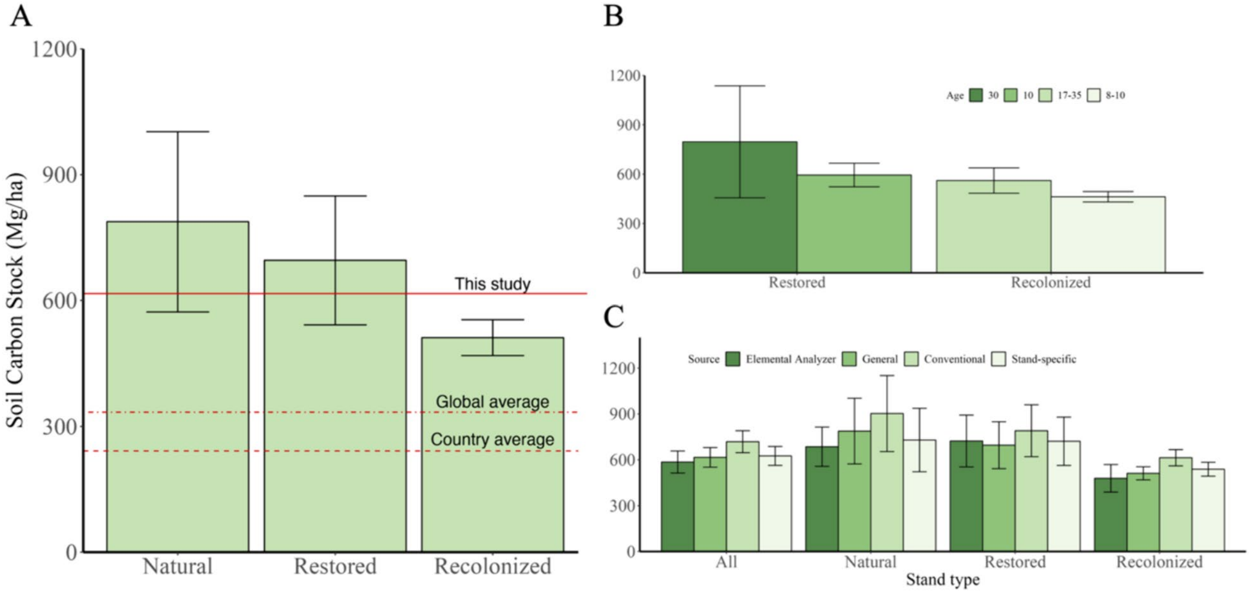

**Fig. 4** (Mean ± CI) SCS across stand types using the stand-specific equation (**A**), across ages in the restored and recolonized stands using the age-specific equations (**B**), and pooled comparison with an elemental analyzer relative to the general, stand-specific and the conventional equations (**C**; [9])

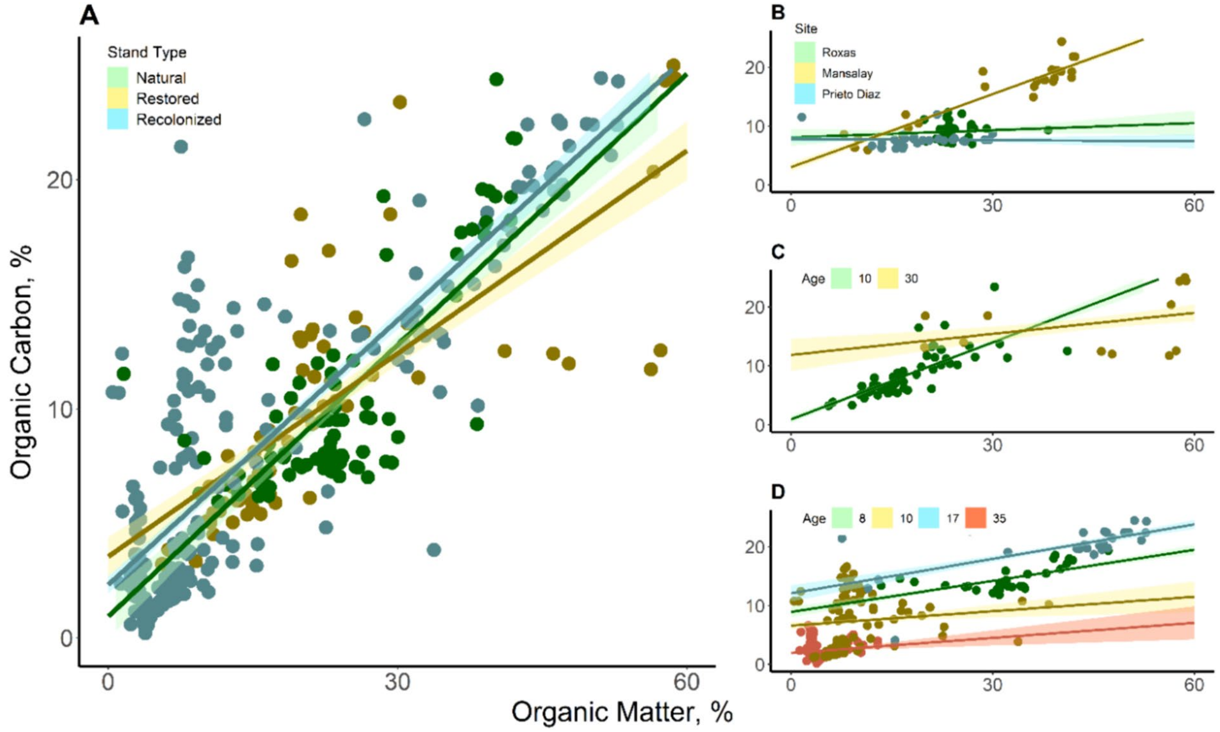

**Fig. 5** Stand-specific scatter plots of the OM to OC ratios per stand type (**A**), among natural stands (**B**), across ages of the restored stands (**C**), and across ages of the recolonized stands (**D**)

**Table 3** Comparison of OC-OM relationships from SCS studies in Southeast Asia and Micronesia (Adapted/modified from Kauffman and Donato [9])

| Location | n | OM% mean, Range | Slope (m) | Intercept (b) | Relationship strength, ($R^2$) |
|---|---|---|---|---|---|
| Matang, Malaysia [53] | 103 | n/a; 20–55 | 0.37 | − 0.1 | 0.61 |
| Hau Loc, North-Central Vietnam [54] | | 7.3; 2–11 | 0.25 | − 2.7 | 0.72 |
| Chonburi Province, Gulf of Thailand [55] | 29 | 11.1; 6–17 | 0.5 | 0.1 | 0.25 |
| Can Gio Mangrove Forestry Park, Vietnam [56] | 316 | 11.2; 5–20 | 0.35 | − 1.3 | 0.80 |
| Dong Rui, Vietnam [57] | 30 | 7.6; 3–17 | 0.41 | n/a | 0.79 |
| Chek Jawa, Singapore [58] | 40 | 14; 0–30 | 0.24 | 1.2 | 0.46 |
| Mui Ca Mau National Park, Vietnam [59] | 225 | 7.8; 3–20 | 0.23 | 0.2 | 0.56 |
| Republic of Palau and Yap, Micronesia [9] | 78 | n/a; 15–52 | 0.42 | 2.9 | 0.59 |
| Philippines (This study) | 458 | 22.95; 0.45–78 | 0.35 | 2.2 | 0.67 |

**Table 4** SCS estimation methods of mangrove carbon stock studies in the Philippines

| Location | Estimation method | Depth |
|---|---|---|
| Macajalar Bay, Misamis Oriental [29] | Elemental Analyzer | 50 cm |
| Infanta, Quezon [23] | LOI | 100 cm |
| Entire Philippines [14] | LOI | |
| Quezon [60] | unspecified | |
| Zamboanga del Sur [44] | unspecified | |
| Cotabato City [61] | unspecified | 30 cm |
| Bani, Pangasinan and Salcedo, Samar [62] | LOI | |
| Calapan, Oriental Mindoro [24] | LOI | |
| Honda Bay, Palawan [30] | Elemental Analyzer | 100 cm |
| Aklan [26] | Walkley–Black | |
| Banacon Island, Bohol [27] | Walkley–Black | 100 cm |
| Panay Island [52] | LOI | 150 cm |
| Puerto Princesa, Palawan [28] | Walkley–Black | |
| Aklan, Bataan, Palawan, Samar [31] | Elemental Analyzer | 30 cm |
| San Juan, Batangas [63] | unspecified | 10 cm |
| Mindoro, Sorsogon (This study) | LOI<br>Elemental analyzer | 100 cm |

is anticipated to become even more prominent as a priority research agenda in the country [22]. Empirical studies are therefore needed to provide science-based policy support in the conservation and restoration of mangroves.

In the Philippines, empirical blue carbon studies are limited and concentrated in few places (Table 4). Out of the published studies, most are limited to the assessment of aboveground carbon stocks (AGCS, n = 62) as compared to the SCS (n = 38; [14]). This could be due to the labor-intensive nature of sampling, lack of adequate funding, and lack of instrument needed for the direct measurement of OC (i.e., through an elemental analyzer; [10]). In determining soil OC, the most used is the LOI method [23, 24] because of cheaper cost despite being considered as semi-quantitative [25]. Some studies used the Walkley–Black method [26–28]; see also Table 4. Although elemental analyzer is used in some studies (n = 3; [29–31]), it is less used primarily because of the expensive analytical costs.

The calculated OM from LOI method is typically converted into OC for SE Asian mangroves as $\%C_{org} = 0.415 *$ % LOI + 2.89 ($R^2 = 0.59$ [9]) and then used in the calculation of SCS. We acknowledge that some of our samples were below the < 18% OM threshold for the OM to OC conversion [9]. But, this OM to OC conversion equation has been widely used, not just in the Philippines [14], but in most SE Asian countries [32], despite it being derived from limited sampling points and having low correlation coefficient. It has already been criticized (see for example [33]) because of the overestimation of SCS. The overestimation is likely due to the small sample sizes (n = 78) and the differences in biophysical conditions between the site that the equation was developed from (Palau and Yap Islands [9, 17]) and the site it was applied to (for example this study). When compared to the mangroves in Palau and Yap Islands, our mangroves are visited more frequently by stronger catastrophic typhoons. Typhoons have profound effects on the wash out (i.e., decreased SCS) and possible post-typhoon recovery (i.e., increased SCS) especially in the upper sediment strata [34].

Our study supports the assertion that site-specific OM-OC equations (with larger sample sizes) are needed for more accurate calculations of OC [10]. The localized equations will be more sensitive to account the different mangrove vegetation conditions and local geomorphologies. And in the case of the Philippines, a localized equation will be needed to account for the effects of disturbances (e.g., typhoons, conversion of mangroves to aquaculture ponds) and post-disturbance recovery of carbon. Having a locally derived OM-OC conversion equation can enhance the SCS estimation by improving the accuracy of the LOI method and reducing reliance on costlier and less accessible elemental analyzers.

### Limitations, opportunities, and further improvements of localized OM-OC conversion equations

Estimating SCS using the LOI method requires intensive labor in the laboratory to determine the OM. Any inaccuracy in OM determination and the subsequent conversion to OC will also lead to inaccuracy in SCS estimates. The conventional equation [9] overestimate SCS by 20%. In comparison, our proposed equation for the open coast Philippine mangroves ($\%OC = 0.36 * \% LOI + 2.40$ ($R^2 = 0.67$, $n = 458$) is within 5%–7% when compared with the values derived from the elemental analyzer. Despite having a relatively stronger relationship, our proposed equation will still produce uncertainties, as with other conversion equations due to the semi-quantitative nature of the LOI method [10].

The sources of carbon are generally categorized as autochthonous or allochthonous [35], hence the stability of the accumulated carbon largely depend on the state of ecosystem health and geomorphological conditions of mangroves. In general, the factors that contribute to SCS are biomass, latitude, precipitation, tidal range, soil pH, and soil depth [36]. In the Philippines, out of the available empirical datasets, the factors that contribute to SCS are related to the "ecosystem health" and geomorphological conditions, e.g., temperature, redox, biomass, mangrove area, stand age, and latitude [10]. Our sites are composed of wide ecosystem status and environmental settings, from natural to recolonized, and restored stands of different ages. These stands have also likely undergone periods of disturbance and regeneration (e.g., primarily typhoons). Although our proposed equation is already relatively better than the conventional equation, it can still be improved by applying stand-specific equations (Fig. 3) consistent with the proposition of Breithaupt et al. [10]. Otherwise, SCS will still either be over- or underestimated because it does not integrate yet the chronosequence of changes in carbon linked from the bare vegetation (synonymous to a situation when mangroves are degraded; Fig. 3d) to the vegetation growth and development in the restored (Fig. 3b) and recolonized stands (Fig. 3c; see also the differences in OM-OC ratios across stands; Table 2b). In fact, even for natural mangroves, there were some variabilities in regression slopes (although not statistically significant; Table 2). Furthermore, although our equation encompasses a large variety of site conditions, it only represents two (West Philippine Sea and North Philippine Sea) out of the six marine biogeographic regions in the Philippines [37]. Based on our results, it is likely that a biogeographic region-specific conversion equations will be more realistic.

### Implications for conservation and restoration

The Philippines experienced a massive reduction of about 46% in mangrove cover from about 450,000 ha in 1918 to about 264,818 ha in 2020 [38] caused by various anthropogenic and climate-related factors [39]. Mangrove losses contribute to $CO_2$ emission (globally estimated at 0.09–0.45 Pg $CO_2$/year, [40]). In accordance with the Paris Agreement, the country committed to reduce and avoid its projected GHG emissions to 75% by 2030 in its first NDC submitted to the United Nations Framework Convention on Climate Change (UNFCCC) in 2021 [41]. As successive NDC's call for adaptive climate change mitigation program every five years, preparing for future NDCs is a critical opportunity to revisit the current NDC and consider how to meet the country's commitment in the Paris Agreement.

The Philippines is one of the three countries in Southeast Asia, alongside Indonesia and Malaysia, that incorporates conservation and restoration of blue carbon ecosystems in their NDCs [42]. In Indonesia, optimal mangrove restoration sites have been prioritized nationwide with the aim to contribute to achieving the country's rehabilitation targets and to reduce national GHG emissions [43]. Increased accuracy of CS estimates of Philippine mangroves through the use of our proposed localized conversion equation can help provide insights on the extent of restoration required to achieve the country's NDC by 2030. These sites include mangrove-recolonized abandoned, undeveloped, or underutilized (AUU) fishponds which have exhibited similar levels of CS with natural mangroves, decades after restoration [44]. The rehabilitation of recolonized AUU fishponds has been noted for its potential in contribution to mangrove conservation [45–47]. Our proposed stand-specific equations can provide further empirical evidence on the carbon storage potential of different mangrove stands, particularly of recolonized ponds, further incentivizing their rehabilitation.

The TECS estimation has been used to determine the success of restoration in forest ecosystems [44, 48–51]. However, only a limited number of studies in the Philippines has assessed CS as a restoration indicator [44, 52]. Our proposed equation could make SCS estimation more accurate. Additional studies could provide more evidence on the effectiveness of various rehabilitation and restoration strategies and determine the influence of disturbances on SCS. Strategic mangrove restoration combined with focused conservation using more accurate OM to OC conversion equation will be key in achieving the national commitment on Paris Agreement.

## Conclusions

The proposed localized OM-OC conversion equations were more accurate in estimating SCS of Philippine mangroves than the conventional conversion equation. The proposed equations are also comparable to published equations with other Southeast Asian mangroves in terms of slopes and relationship strengths. The existence of localized OM-OC conversion equations can promote further research on mangrove SCS in the Philippines by increasing the accuracy of the LOI method and reducing reliance on costlier and less accessible elemental analyzers. Increased accuracy in carbon stock estimates can have implications in conservation and restoration by contributing to the identification of optimal and priority restoration sites, particularly the mangrove-recolonized fishponds. Elemental analyzers will still provide the most accurate OC values for SCS estimation. But in the absence of elemental analyzers, using the LOI method with our proposed equations can be the most suitable and accurate alternative in estimating the SCS of Philippine mangroves.

### Abbreviations

| | |
|---|---|
| OC | Organic carbon |
| CS | Carbon stock |
| SOC | Soil organic carbon |
| TECS | Total ecosystem carbon stock |
| OM | Organic matter |
| SCS | Soil carbon stock |

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### Author contributions

SGS: Conceptualization, writing, revision, analysis, supervision, project administration, funding acquisition SBM: Lab analysis, writing, data collection and organization, data/statistical analysis, visualization PBJ: Lab analysis, writing, data collection and organization, data/statistical analysis, visualization MGD: Sampling, writing CFP: Sampling, lab analysis, writing MWM: Lab analysis, writing MB: Writing, funding acquisition FS: Writing RM: Writing, funding acquisition.

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### Data availability

Data will be made available upon request.

## Declarations

### Competing interests

The authors declare no competing interests.

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## Publisher's Note