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Soil carbon stock assessment of the mangrove forest in Socorro, Surigao del Norte, Philippines

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Abstract

In mangrove forests, soils were considered as the largest carbon pool. The result of the study conducted in Barangay San Roque, Socorro, Surigao del Norte showed that the mean soil carbon stock of the top 100cm soil layer of the estimated 50-hectare mangrove forest is 489.3C Mg ha^{-1}. This was attributed by the forest's stand age, species composition, and the absence of direct anthropogenic activities that can influence the primary production. Increases in soil carbon stock were observed as depth increases. However, analysis showed no statistical significance between bulk density and organic carbon concentration at different depths, as well as between soil carbon stock at the different forest parts. Nonetheless, the mean soil carbon stock of the mangrove forest in the study is higher than those in the terrestrial forest. With these, the mangrove stands in Socorro, Surigao del Norte can be considered an important carbon reserve in the province and should be protected from degradation and land-use conversion to manage the potential carbon emission from this pool.

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Introduction

Mangrove forests provides various services such as source of fuel and medicine (Alongi, 2002), fishery products (Sukardjo, 1994), shoreline protection (Ajonina *et al.*, 2014), supports coastal nutrient cycling in the coastal zone (Alongi *et al.*, 2000), and carbon sink and source in the plant body and in the soils below (Kathiresan, Gomathi, Anburaj & Saravanakumar, 2014). In fact, mangroves are considered one of the most carbon-rich ecosystems in the world (He *et al.*, 2018; Donato *et al.*, 2011), despite occupying only 0.5% of the global coastal area (Tinh *et al.*, 2020; He *et al.*, 2018). Several studies suggest that the carbon stored in mangrove forest is higher than those in the terrestrial forest (Donato *et al.*, 2011). Coastal wetlands, in comparison to agricultural lands, can hold up to 40% higher organic carbon (Nahlik & Fennessy, 2016) due to its waterlogged soils that lacked oxygen which in turn greatly reduces decomposition (Ontl & Schulte, 2012) leading to the accumulation of organic matter. As a result, wetlands became good storage of organic carbon (Nahlik & Fennessy, 2016).

Studies on the capacity of the tropical forests to hold aboveground carbon had been widely published. However, estimates of carbon stored belowground, such as the tree roots and soils of terrestrial and mangrove forests were limited (Komiyama *et al.*, 2005; Ajonina *et al.*, 2014). Information has narrowed even more when it comes to the ability of mangroves to sequester carbon (Ajonina *et al.*, 2014). Available data suggests that mangrove ecosystems store the majority of its carbon stock in the soil, accounting to 10-15% of the mean annual global coastal soil carbon storage (He *et al.*, 2018; Collins *et al.*, 2017; Duarte *et al.*, 2013), yet a large percentage of mangrove forests soil carbon storage remains understudied. The naturally grown, primary mangrove forest in Socorro, Surigao Del Norte, Philippines was never studied based on key informant accounts, hence there is no data available on the amount of the carbon sequestered in its soil. There is a need to assess the carbon content of the forest soil to provide baseline information for national-level natural accounting purposes and as scientific basis for decision making in protecting and conserving the mangrove forests in the area as part of the climate change management plan of the island municipality. In a wider perspective, measurement of carbon stored in mangrove forest provides data on the estimates of carbon emission that may result from mangrove loss associated with coastal development and land-use conversion (Donato *et al.*, 2011).

Considering the fact that the largest pool of carbon is found in the soil of mangrove ecosystems (Kauffman & Donato, 2012) and it is a potential mitigation mechanism of climate change, the present study aimed to; (a) assess the carbon in the soil of the mangrove forest in Socorro, Surigao Del Norte; (b) measure the soil bulk at different soil depths; (c) measure the amount of carbon stock in different soil depths and; (d) compare the carbon stock of the strategic areas of the forest. The information gathered from this study provides additional data about the amount of carbon that can be sequestered by an undisturbed and naturally grown mangrove forest soil. This may also inform the public about the important role of the mangrove ecosystem in climate change management.

Materials and methods

Study Area

The study was carried out in Barangay San Roque, Socorro, Surigao del Norte (Fig. 1) at the coordinates of 9.6250, 125.9206 (9°38' N, 125°55' E). The municipality of Socorro is a fourth-class municipality with a total land area of 12,445 hectares, including the whole island of Bucas Grande, and is under the Siargao Island Protected Landscape and Seascape declared on October 10, 1996. Based on the interview from the representative of the Municipal Environment and Natural Resource Office, the large, naturally grown, and primary mangrove forest of the area is located in Barangay San Roque. It is a *Rhizophora* (*R. apiculata* and *R. mucronata*) dominated mangrove forest of relatively the same stand age, enclosed in an open lagoon that is constantly inundated by marine tide. Unfortunately, data of the actual size of the forest is not available; hence the estimate of approximately 50 hectares was based on the anecdotal information from the elders and local people in the area. The mangrove forest is approximately a 5-10 minutes boat ride to the nearest community. At the time of data gathering, there were no observed anthropogenic activities inside the forest. It was not utilized for any commercial or ecotourism purposes. The community near the forest reported that they were not allowed to gather fuelwood inside the forest. Fishing was also done around the entrance of the lagoon.

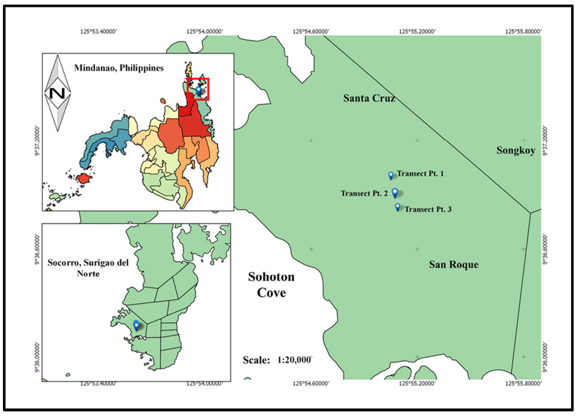

Fig. 1. Map showing the Province of Surigao del Norte (top left), the Municipality of Socorro (bottom left), and Barangay San Roque (right) with the sampling points.

Field Sampling Design

A non-destructive quadrat method was used in this study. The mangrove forest which is situated in a lagoon was divided into three (3) points; the inner part of the forest, middle, and seaward or near the mouth of the lagoon. A passageway was used as a reference point in laying the transect lines. In each point, one (1) transect line was laid perpendicular to the passageway. In each transect line, three (3) 10m x 10 m plots were established with a distance of 20 meters between each plot. Three variables were considered in the measurement of the soil carbon stock; (a) soil depth (b) soil bulk density and (c) organic carbon content.

Soil Collection for Carbon Content

An improvised soil core sampler with 5.08cm diameter and 100cm height was used to collect the top 100-cm layer of the mangrove forest soil. It was partitioned at depths of 0-15cm, 15-30cm, 30-50cm and 50-100cm (Kauffman *et al.*, 2011; Donato *et al.*, 2011). Subsamples representing each depth were collected. This was done by collecting the 5cm midpoint of each depth; 5-10 midpoint for 0-15cm depth range, 20-25cm for the 15-30cm depth, 37.5-42.5 for the 30-50cm depth, and 77.5-82.5 for the 50-100cm depth, respectively. Kauffman and Donato (2012) stated that subsamples representing a given depth are already sufficient for mangroves than collecting the whole range because carbon content changes much more slowly with depth. Hence, subsamples collected from each depth were used for the analysis of soil carbon content.

The collected soil samples were then placed in numbered soil containers with the transect number, plot number, soil depth, and date and were sent to the Soil and Plant Laboratory in Central Mindanao University, Bukidnon, for carbon analysis using Walkley-Black Method.

Soil Bulk Density Determination

Separate soil samples were collected for the determination of soil bulk density. This was done by collecting the top 100cm soil of the forest with partitioned depths of 0-15cm, 15-30cm, 30-50cm and 50-100cm, respectively. The 5-cm midpoint of each depth were collected as samples for the determination of bulk density; 5 -10cm for 0-15cm depth, 20 - 25cm for 15-30cm depth, 37.5 - 42.5 for 30 - 50cm depth, and 77.5 - 82.5 for 50-100cm depth. Samples were oven-dried for a total of 281 hours at a constant temperature of 60 degrees Celsius. The dry mass was weighed for the calculation of bulk density. Bulk density was calculated using the formula adapted from Kauffman and Donato (2012):

Soil Bulk Density (g/cm^3)= oven-dried sample mass(g)/ volume of soil corer (m^3)

Where; Volume of soil corer= $\pi r^2 h$

The volume of the soil core sampler was computed. With a radius of 2.54cm and a height of 100cm, the volume (V) of the soil core sampler is 2026.83 cm^3.

Organic Carbon Content

A formula adapted from Donato *et al.* (2011) was used to determine the soil organic carbon per hectare, as follows;

Soil carbon (Mg ha-1) = bulk density (g/cm^3) * soil depth interval (cm) *%C

The equation for total soil carbon stock for the whole sampling area was calculated using:

Total soil carbon stock of the area (Mg) = Total soil carbon (Mg ha-1) × Area (ha) of the whole forest.

Data Analysis

The carbon measured in the three different sampling points of the forest; inner, middle, and seaward parts, was analyzed using Analysis of Variance (ANOVA). Pearson's correlation analysis was used to analyze the relationship between organic carbon and bulk density. Simple descriptive statistics were also employed to compare the carbon stock in different soil depths.

Results and discussions

Soil Bulk Density

Fig. 2 shows the average soil bulk density (SBD) at different soil depths. An increasing value of generally 0.00493 gcm^{-3} to 0.00748 gcm^{-3} as the depth increased, were observed.

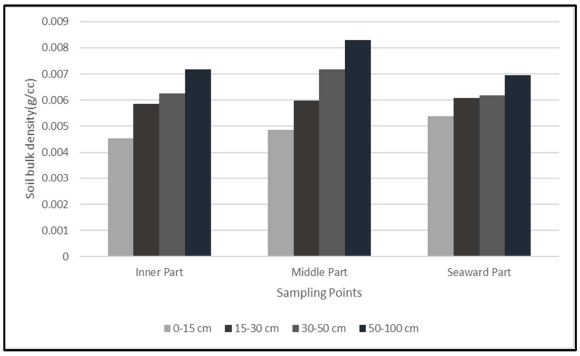

Fig. 2. Average soil bulk density (gcm^{-3}) with increasing soil depths.

This similar pattern was observed by Tinh *et al.* (2020) in the study of the intact and restored mangrove forests of Northern Vietnam, the study on mangrove plantations of Guangdong Province, China (He *et al.*, 2018), and in the mixed mangrove types in the Indo-Pacific region (Donato *et al.*, 2011).

The mean SBD for the entire 1m soil column in the *Kandelia obovata* and *Sonneratia apetala* mangrove forests of Guangdong ranges from 0.45 ± 0.03 and 0.89 ± 0.04 gcm^{-3}, respectively (He *et al.*, 2018). While the SBD of estuarine mangroves and oceanic mangroves in the Indo-Pacific region ranges from ~0.35 to 0.55 gcm^{-3}, showing not much difference in terms of forest settings but did increase with soil depth (Donato *et al.*, 2011).

In a study in Indonesia, it was observed that higher bulk densities were recorded in the estuarine mangrove soils than marine mangrove soils (Weiss *et al.*, 2016). The average SBD of Socorro mangrove forest was lower compared with other studies. Conversely, this mangrove forest can be categorized as a marine/ oceanic mangrove because it is situated in marine-edge, on one of the coasts of the Bucas Grande island, and is dominated by *Rhizophora* species; some of the geomorphic characteristic of an oceanic mangroves (Donato *et al.*, 2011). Despite this, the SBD of this forest is relatively lower than that of the oceanic mangroves in the study of Donato *et al.* (2011). Some of the plausible factors can be due to the difference in species diversity and structure of the forest. Mangrove species vary in their root development and soil organic matter enrichment which eventually affect the porousness and compactness of the substrate (Tinh *et al.*, 2020; He *et al.*, 2018; Ha *et al.*, 2018; Grellier *et al.*, 2017), as root types (coarse and fine roots) influence the particle aggregation and soil cohesion (He *et al.*, 2018; Grellier *et al.*, 2017). As depth increases, the compactness of soil also increases (Alavaisha & Mangora, 2016), which makes the subsurface layers less permeable for roots than surface layers. Stoner (1991) stated that bulk density greater than 1.7 g cc^{-1} causes difficulty for roots to penetrate in the soil. The average soil bulk density of this study was less than 1.7 gcc^{-1}. This implies that the root of the mangroves in the sampling area can penetrate the top 100cm of the soil, thus increasing the carbon pool in the deeper part of the forest.

Tinh *et al.* (2020) and Gnanamoorthy *et al.* (2019) also observed that the soil in natural grown, intact, mangrove forest has lesser bulk density compared with restored mangrove forest. Permeability in mangrove forest is slightly higher. Higher bulk density decreases the volume of macropores, which reduces gaseous exchange. The natural mangrove area containing less bulk density leads to more gas exchange processes (Gnanamoorthy *et al.*, 2019). This confirms the low bulk density observed in the study.

Soil Carbon at Different Depths

The soil carbon (Mg ha^{-1}) at different depths varies. It was observed that carbon stock constantly increases as depth increases. A mean of 5.495 Mg ha^{-1} was obtained from the 50-100cm interval. Followed by the 30-50cm interval with a mean of 1.970 Mg ha^{-1}, 1.238 Mg ha^{-1} for 15-30cm, and 1.086 Mg ha^{-1} for 0-15cm interval, respectively (Table 1).

Table 1. Soil Carbon (Mg ha^{-1}) Measurements at Different Depths.

Soil Depth	Mean	Median	Minimum	Maximum
0-15cm	1.086	1.018	0.791	1.381
15-30cm	1.238	1.220	1.018	1.427
30-50cm	1.970	1.840	1.621	2.416
50-100cm	5.495	5.457	3.564	6.715

The soil carbon results of this study coincide with the result of Jones *et al.* (2014) in the mangrove forest of Northern Madagascar which showed an increasing soil carbon with depth, and is characterized by close canopy stands. Similarly, the sampling areas of this present study are also characterized by close canopy *Rhizophora* stands. This may imply that canopy can also affect the amount of carbon as depth increases. When the forest canopy is removed, it causes an increase in soil temperature which eventually increases the activity of decomposers causing the depletion of carbon levels in the soil thus releasing carbon back into the atmosphere (Ontl and Schulte, 2012).

The increase of soil carbon as depth increases might also be due to the low bulk densities observed. Accordingly, the soil bulk density is one factor that limits root penetration to varied depth. Once bulk density exceeds 1.7 g cc^{-1}, root growth becomes restricted due to physical resistance (Stoner, 1991). The average bulk density observed in the 50-100cm interval is far lesser than 1.7g cc^{-1}, which makes the forest soil more permeable by the root within the top 100cm layer. Alongi *et al.* (2004) stated that 75-95 percent of the tree carbon is vested on dead roots and that with increasing stand age soil and dead root carbon increases. Anecdotal accounts claim that Socorro mangrove forest is more than 50 years old, hence the assumption that a massive number of dead roots were deposited deeper in the soil contributing to the high soil carbon observed in the deeper layers (50-100cm). Despite this, Pearson's correlation analysis showed no statistical significance (p-value 0.09571) between bulk density and organic carbon despite the fact that both soil carbon and bulk density increased with depth.

On the other hand, while most studies show increasing soil carbon stock as with soil depth, the study on the two 12-year old *Sonneratia apetala* and *Kandelia obovata* mangrove plantations in China revealed opposite results. The mean soil organic carbon concentration of the two forests significantly decreased with depth from 0-100cm (He *et al.*, 2018). In Vietnam, the soil carbon density of the mangroves in the four provinces recorded an increase in depths 0 to 30cm, but declines were observed from 30-100cm (Tinh *et al.*, 2020). Different factors can be attributed to these soil carbon stock differences. It can be the age of the forest (Tinh *et al.*, 2020; Alavaisha & Mangora, 2016), the species structure and composition (Arianto *et al.*, 2015; Jones *et al.*, 2014; Alongi *et al.*, 2000), species root system (Tinh *et al.*, 2020; He *et al.*, 2018), the geomorphological setting of the forest (Tinh *et al.*, 2020; Donato *et al.*, 2011; Alongi *et al.*, 2000), as well as the erosion dynamics of organic matter associated with tidal flushing (Chen *et al.* 2017; Donato *et al.*, 2011), fluctuating sea levels, and episodic disturbances (Donato *et al.*, 2011).

Further, the soil carbon of different sampling points was of similar levels (Fig. 3). This is consistent with the result of Kauffman, Heider, Cole, Dwire and Donato (2011) on the Yap site of their study in the Micronesian mangrove forest. This result may be associated with the species dominating the three (3) sampling points of the forest with relatively similar stand age.

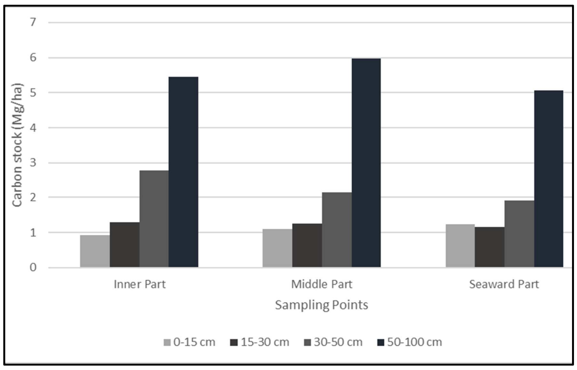

Fig. 3. Mean Soil Carbon Stock (Mg ha^{-1}) per sampling point.

Conversely, the biogeochemistry of mangrove forest sediments differs not only because of the forest physical setting but also on the capacity of the different species to alter the sediment conditions. A clear difference of the soil characteristics between *Rhizophora stylosa* and *Avicennia marina* forests were reported by Alongi *et al* (2000). Similarly, in the study at Awat-Awat Mangrove Forest in Malaysia, the soil carbon content ranges from 1.73% to 6.24% and varies depending on the plant species dominance of the sampled sites. The highest soil carbon content was recorded from the soil of an area dominated by *Rhizophora mucronata* while the lowest was under the dominance of *Sonneratia alba*. Thus, species dominance influences the soil carbon content of a mangrove forest (Arianto *et al.*, 2015).

Differences in carbon stocks between sites and zones may also be due to forest age (Alavaisha & Mangora, 2016). Relationship between forest age to their carbon stock is affirmed in the study of Lunstrum and Chen (2014) where increases in soil carbon concentration were observed in Futian National Nature Reserve forest in China. With these factors, it will explain why the soil carbon stock of the different parts of Socorro mangrove forest did not differ because of the uniformity of species present, which is dominated by *Rhizophora* species, and their relatively similar stand age. Hence, using Analysis of Variance, results show that there is no significant relationship between soil carbon and the different parts of the forest (p-value 0.966; significant at $p<0.05$).

Thus, the hypotheses of this study that the soil carbon stock may differ between different points of the forest can be rejected. The data shows no significant trend and this can be attributed to the fact that the forest is dominated by *Rhizophora* species. which received the same degree of exposure to wave action, inundation and flooding, as well as the draining cycles which influences the biogeochemistry of the forest sediment (Alongi *et al.*, 2000).

Total Soil Carbon

The mean soil carbon stock of the estimated 50-hectare mangrove forest in the present study is 489.3C Mg ha^{-1}. Compared with the other mangrove forest in Mindanao, this forest has higher carbon stock. In the study of Lomoljo *et al.* (unpublished) on the carbon stock of the mangrove forests along Macajalar Bay, Mindanao, Laguindingan mangrove forest has 95.76C Mg ha^{-1}, El Salvador mangrove forest with 117.32C Mg ha^{-1}, Alubijid mangrove forest with 147.81C Mg ha^{-1}, respectively. Although the latter has the same dominant species (*Rhizophora* spp) with Socorro Forest, the difference may be attributed to the forest stand age and the exposure to anthropogenic disturbances such as the threats of deforestation and land clearing, and destructive effects of tourism activities. Of the three forests, only the El Salvador and Alubijid forests are considered natural, primary mangrove forests (Lomoljo *et al*, unpublished). Thus, forest age plays a big role in the soil carbon stock, as soil carbon increases with forest age (Alongi, 2012). Nonetheless, highest soil carbon can be found in undisturbed and natural forest (Ajonina *et al.*, 2014).

Moreover, the soil carbon stock of Socorro mangrove forest is also higher than the natural mangrove forest in Palawan with 173.8C Mg ha^{-1} (Abino *et al.*, 2014), in Yap, and in Palau with 411C Mg ha^{-1} and 414C Mg ha^{-1}, respectively (Kauffman *et al.*, 2011). These forests were dominated by *Sonneratia alba,* *Rhizophora apiculata, and Bruguiera gymnorrhiza*, respectively. However, this soil carbon stock estimate is lower than the undisturbed and natural mangrove forest of Central Africa (Ajonina *et al.,* 2014).

Aside from the natural variation factors mentioned above contributing to the carbon stock estimates difference, other causes may also be due to the difference in sampling techniques used (Kauffman *et al.,* 2011). The Walkley-Black method used to analyze carbon content is known to have an incomplete oxidation of organic carbon. According to Walkley and Black (1934) as cited by Schumacher (2002), Walkley-Black method has been shown to lead to incomplete combustion of organic carbon.

The range of organic carbon recovered using Walkley-Black method was only 60-86%. The data gathered might not be exact due also to the insufficiency of the method used, hence only an estimate.

It was also observed that the canopy of each mangrove overlapped with each other; one factor that leads to high soil carbon observed. In the study of Jones *et al.* (2014) in northern Madagascar, soil carbon was observed to be higher in the closed canopy compared to open canopy mangroves. Forest canopy when removed causes the warming of soil and increases activity of decomposers.

This implies that any anthropogenic activities in the sampling area which cause the forest to have an open canopy, might reduce the carbon deposited in the soil. Also, the carbon stock in an undisturbed forest is higher compared to disturbed or exploited forest.

This was supported by the results of Ajonina *et al.* (2014). Forest reforestation/ afforestation might have positive benefits for wetlands (Howe *et al.*, 2009), however in order to maintain maximum carbon values it is important for mangrove forest to remain in completely undisturbed conditions (Ajonina *et al.,* 2014); as mangrove forest, when left undisturbed, might become a carbon sink for up to a century (Alongi, 2012).

Conclusion

The 50-hectare natural and undisturbed mangrove forest of Barangay San Roque, Socorro, Surigao del Norte was estimated to have sequestered 4403.7C Mg ha^{-1} with a mean of 499.3C Mg ha^{-1}. Bulk density increased with soil depth and with the results obtained it was also concluded that there is no difficulty in the root penetration in the top 100cm of the soil. This soil C stock can be considered relevant in helping address the global warming and climate change problem by maintaining this available C pool and preventing it from possible destruction. Protection and sustainable management of mangrove forest must be one of the core considerations of any coastal developmental activities, to retain the maximum possible carbon values and prevent further releases of these carbon into the atmosphere, aggravating the climate change problem.

The Reduced Emission from Deforestation and Degradation (REDD+) program highlighted that the key to mitigate climate change is to keep forests intact. This is also a relatively cost-effective strategy compared with others (Donato *et al.*, 2011). Hence, robust estimates and monitoring of carbon storage of various forest types and pools is highly recommended. As an important carbon reserve, mangroves carbon storage capacity must be explored further by estimating the carbon stock and sequestration rate of different pools (such as roots, leaf litters, and others) and different species to broaden the available scientific information significant in crafting forest management. Local and regional assessments of the mangrove carbon storage are still limited, thus needed, to update global estimates.

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References

Abino AC, Lee YJ, Castillo JAA. 2014. Species diversity, biomass, and carbon stock assessments of a natural mangrove forest in Palawan, Philippines. Pakistan Journal of Botany **46(6),** 1955-1962.

Ajonina GN, Kairo J, Grimsditch G, Sembres T, Chuyong G, Diyouke E. 2014. Assessment of Mangrove Carbon Stocks in Cameroon, Gabon, the Republic of Congo (RoC) and the Democratic Republic of Congo (DRC) Including their Potential for Reducing Emissions from Deforestation and Forest Degradation (REDD). Estuaries of the World the Land/Ocean Interactions in the Coastal Zone of West and Central Africa 178-179. DOI: 10.1007/978-3-319-06388-1_15

Alavaisha, Mangoramm E. 2016. Carbon Stocks in the Small Estuarine Mangroves of Geza and Mtimbwani, Tanga, Tanzania. International Journal of Forestry Research, 2016, 1-11.

Alongi DM, Tirendi F, Clough BF. 2000. Below-ground decomposition of organic matter in forests of the mangroves *Rhizophora stylosa* and *Avicennia marina* along the arid coast of Western Australia. Aquatic Botany **68,** 97-122.

Alongi DM, Wattayakorn G, Tirendi F, Dixon P. 2004. Nutrient capital in different aged forests of the mangrove Rhizophora apiculata. Botanica Marina **47(2).** DOI: 10.1515/bot.2004.011

Alongi DM. 2002. Present state and future of the world's mangrove forests. Environmental Conservation **29(03),** DOI: 10.1017/s0376892902000023

Alongi DM. 2012. Carbon sequestration in mangrove forests. Carbon Management **3(3),** 313-322.

Arianto CI, Gandaseca S, Rosli N, Pazi AMM, Ahmed OH, Hamid HA, Abdul Majid NM. 2015. Soil Carbon Storage in dominant species of Mangrove Forest of Sarawak, Malaysia. International Journal of Physical Sciences. Vol **10(6),** 201-214. DOI: 10.5897/IJPS2014.4183

Chen G, Azkab MH, Chumura GL, Chen S, Sastrosuwondo P, Ma Z, Dharmawan IWE, Yin X, Chen B. 2017. Mangroves as a major source of soil carbon storage in adjacent seagrass meadows. Scientific Reports **7,** 42406. DOI: 10.1038/srep42406

Collins DS, Avdis A, Allison PA, Johnson HD, Hill J, Piggott MD, Hassan MHA, Damit AR. 2017. Tidal dynamics and mangrove carbon sequestration during the oligo-Miocene in the South China Sea. Nat Commun **8,** 15698.

Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M, Kanninen M. 2011. Mangroves among the most carbon-rich forests in the tropics. Nature Geoscience **4(5),** 293-297. DOI: 10. 1038/ngeo1123

Duartecm, Losada IJ, Hendriks IE, Mazarrasa I, Marbà N. 2013. The role of coastal plant communities for climate change mitigation and adaptation. Nat Clim Chang **3,** 961-968.

Gnanamoorthy P, Selvam V, Ramasubramanian R, Ramasubramanian S, Pramit D, Karipot A. 2019. Soil Organic Carbon Stock in Natural and Restored Mangrove Forests in Pichavaram South-East Coast of India , Volume **48(05),** 801-808.

Grellier S, Janeau JL, Hoai ND, Kim CNT, Phuong QLT, Thu TPT. 2017. Changes in soil characteristics and C dynamics after mangrove clearing (Vietnam). Sci Total Environ **593,** 654-663.

Ha TH, Marchand C, Aimé J, Dang HN, Phan NH, Nguyen XT, Nguyen TKC. 2018. Belowground carbon sequestration in a mature planted mangroves (northern Viet Nam). For Ecol Manag **407,** 191-199.

He Z, Peng Y, Guan D, Hu Z, Chen Y, Lee SY. 2018. Appearance can be deceptive: shrubby native mangrove species contributes more to soil carbon sequestration than fast-growing exotic species. Plant Soil. DOI: 10.1007/s11104-018-3821-4

Howe A, Rodríguez J, Saco P. 2009. Surface evolution and carbon sequestration in disturbed and undisturbed wetland soils of the Hunter estuary, southeast Australia. Estuarine, Coastal and Shelf Science **84(1),** 75-83. DOI: 10.1016/j.ecss.2009.06.006

Jones T, Ratsimba H, Ravaoarinorotsihoarana L, Cripps G, Bey A. 2014. Ecological Variability and Carbon Stock Estimates of Mangrove Ecosystems in Northwestern Madagascar. Forests **5(1),** 177-205. DOI: 10.3390/f5010177

Kathiresan K, Gomathi V, Anburaj R, Saravanakumar K. 2014. Impact of mangrove vegetation on seasonal carbon burial and other sediment characteristics in the Vellar Coleroon estuary, India. Journal of Forestry Research **25(4),** 787-794. DOI: 10.1007/s11676-014-0526-2

Kauffman JB, Donato DC. 2012. Protocols for the measurement, monitoring and reporting of structure, biomass, and carbon stocks in mangrove forests. Bogor Barat, Indonesia: CIFOR.

Kauffman JB, Heider C, Cole TG, Dwire KA, Donato DC. 2011. Ecosystem Carbon Stocks of Micronesian Mangrove Forests. Wetlands **31(2),** 343-352.

Komiyama A, Poungparn S, Kato S. 2005. Common allometric equations for estimating the tree weight of mangroves [Abstract]. Journal of Tropical Ecology **21(04),** 471-477.

Lomoljo N, Tampus A, Tatil W, Dagoc FL, Amparado RJ. Unpublished. Carbon Stock Assessment of Mangrove Forests Along Macajalar Bay, Misamis Oriental, Philippines. Master's Thesis. MS Environmental Science Program, Department of Biological Sciences, College of Science and Mathematics, Mindanao State University - Iligan Institute of Technology, Iligan City, Philippines.

Lunstrum A, Chen L. 2014. Soil carbon stocks and accumulation in young mangrove forests. Soil Biology and Biochemistry **75,** 223-232.

Nahlik AM, Fennessy MS. 2016. Carbon storage in US wetlands. Nature Communications **7,** 13835. DOI: 10.1038/ncomms13835

Ontl TA, Schulte LA. 2012. Soil Carbon Storage. Nature Education Knowledge **3(10),** 35.

Schumacher BA. 2002. Methods for the determination of total organic carbon (TOC) in soils and sediments. Cincinnati, OH: U.S. Environmental Protection Agency, Office of Research and Development, Ecological Risk Assessment Support Center.

Stoner ER. 1991. Physical constraints to root growth in savanna oxisols. Raleigh, NC: North Carolina State University.

Sukardjo S. 1994. Soils in the Mangrove Forests of the Apar Nature Reserve, Tanah Grogot, East Kalimantan, Indonesia. Southeast Asian Studies **32(3),** 385-398.

Tinh PH, Hanh NTH, Thanh VV, Tuan MS, Quang PV, Sharma S, MacKenzie RA. 2020. A Comparison of Soil Carbon Stocks of Intact and Restored Mangrove Forests in Northern Vietnam. Forests **11,** 660. DOI: 10.3390/f11060660

Walkley A, Black IA. 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.

Weiss C, Weiss J, Boy J, Iskandar I, Mikutta R, Guggenberger G. 2016. Soil organic carbon stocks in estuarine and marine mangrove ecosystems are driven by nutrient colimitation of P and N. Ecology and Evolution **6(14),** 5043-5056.