Quantifying and Mapping the Ecosystem Carbon Stock of Mangrove Forests in the Philippines using machine learning and new-generation remote sensing data

Castillo Jose Alan A.[1*] and Castillo Judith F.[2]

[1]Scientist I, Ecosystems Research and Development Bureau, Los Banos, Philippines
[2]University Researcher, Forestry Development Center, University of the Philippines, Los Banos, Philippines
*jaacastillo@erdb.denr.gov.ph (Corresponding Author)

Abstract: *Mangrove forests are an important carbon (C) sink in the tropics. Ecosystem Carbon stocks from biomass and soil are important parameters to quantify and map in the mangrove area. However, very few reports are available at the country level, including the Philippines. This study was conducted in selected coastal areas of the Philippines to: 1) quantify and evaluate the Ecosystem Carbon Stocks of mangrove forest; and 2) map and determine the spatial distribution of the Ecosystem Carbon Stocks of mangrove forest. Intensive field assessments, combined with laboratory analysis, remote sensing and geospatial techniques were implemented to achieve the above objectives. We used field data, global mangrove soil C map and data from Sentinel-2 imagery in Google Earth Engine cloud platform to estimate the Ecosystem C Stock using machine learning algorithm. Results of this study revealed that the mean Ecosystem C stocks of mangrove forests based on field plots was 494.12 MgC ha-1 while those predicted from remotely sensed data covering the whole country was 538.5 MgC/ha. The potential contribution of our Philippine mangroves to global Climate Change mitigation could translate to about 550 M tCO2 eq. The province of Palawan had the highest C stock. This study has shown the relatively enormous amount of Carbon stocked and stored in biomass and soil of mangroves in the country and suggests the need to protect them. Future studies should endeavor to explore the use of other datasets (e.g. GEDI-based Canopy Height Map) in predicting and mapping the spatial distribution of the Ecosystem C stock of mangroves in the country.*

Keywords: Mangrove, Ecosystem Carbon Stock Mapping, Google Earth Engine, Philippines

Introduction

Mangroves provide timber and other construction materials, fuelwood, storm protection, fishery products, sediment regulation and many other ecosystems services to coastal residents (Alongi 2002). Equally important is their function as carbon sinks, reducing CO_2 concentrations in the atmosphere mitigating global warming. Specifically, mangrove ecosystems account for 14% of the total carbon sequestration of the world ocean (Alongi 2012). Over the last few years, mangroves are increasingly recognised as among the most carbon (C) dense tropical forests.

Despite their invaluable contribution to coastal protection, productivity, and carbon sequestration, mangroves have declined in global area by 30-50% in the last 50 years (Murdiyarso et al. 2013). For instance, in the Philippines, where 40 out of the 73 species in the world thrive (Fernando & Pancho 1980), mangroves have been cleared on a large-scale from a recorded historical cover of 500,000 hectares in 1918 (Brown & Fischer

1920) to only 120,000 hectares in 1994 (FAO 2007) with around 37% of the mangrove loss attributed to fish/shrimp pond conversion (Primavera 2000). In recent years, however, the establishment of mangrove plantations has become a very prolific strategy for mangrove rehabilitation with government, civil society organizations, and private institutions putting in sizeable contributions to increase the national mangrove cover.

With the recognised huge potential of mangroves for C storage and sequestration, and the carbon consequence of land use conversion in the mangrove ecosystem, it is important, therefore, to monitor the mangroves with the latest tools available that have country-wide coverage and are updated regularly, to evaluate the country-wide C stocks and the potential C losses owing from mangrove conversion to other land uses. However, very few reports are available at the country level, including the Philippines. This study was conducted in selected coastal areas of the Philippines to: 1) quantify and evaluate the Ecosystem Carbon Stocks of mangrove forest; and 2) map and determine the spatial distribution of the Ecosystem Carbon Stocks of mangrove forest.

Literature Review

Whole-ecosystem C stock assessments in mangroves, which include aboveground C pool, belowground biomass C pool and soil C pool, are continuously growing in the literature; however, very few were done on a country-level scale, and none has been reported so far in the Philippines. Alongi (2014) reviewed a number of published studies and showed a consolidated mean global whole-ecosystem C stock of mangrove of 956 MgC ha^{-1}, 2 to 4 times higher than terrestrial forests such as rainforests (241 MgC ha^{-1}) and peat swamps (408 MgC ha^{-1}). About 75% of total C stock in mangroves is stored in the soil compared to rainforests (44%) and peat swamp (70%). The values of whole ecosystem C stock range from 1023 tC ha^{-1} for few Indo-Pacific sites, 937 tC ha^{-1} for mainland Southeast Asia, and 381 to 987 MgC ha^{-1} in Caribbean Mexico (Murdiyarso *et al.* 2013) with the C stored in soils accounting for 49 - 98% of the total mangrove C stocks (Donato *et al.* 2011; Adame *et al.* 2013).

There is a paucity of reports on mapping the Ecosystem C Stock of mangroves. While the studies are growing on mangrove C stock mapping, available reports dealt separately on mapping the biomass and mapping the soil C stock. The literature is growing on the use of

Sentinel imagery for mapping the spatial distribution of mangrove biophysical variables such as cover/extent and biomass. Castillo et al. (2017) and Baloloy et al. (2020) were the first to use this free imagery for mangroves in the country. Baloloy et al. (2020) used Sentinel imagery data to map the country-level mangrove cover in 2019 while Castillo et al. (2017) utilised the imagery for mangrove biomass mapping in southern Honda Bay, Palawan, and developed several models for mangrove biomass prediction and mapping.

For Soil Carbon Stock, there is also a paucity of reports on country-level mapping in mangroves although global mangrove soil C stock maps have been produced (Jardine & Siikamäki, 2014; Sanderman et al. 2018). Mapping the soil C stock will increase our understanding of the spatial distribution and variability of soil C stocks in the coastal zone and can help improve our estimates of soil C stocks in the country.

Methodology

The study sites included both the forested and deforested mangrove areas in selected coastal areas of the Philippines, covering as many kinds and quality of mangroves in the country as possible (natural stand, plantation, intact, secondary, degraded and converted mangroves) to capture the variability in C stocks, both in the biomass and soil C pools. To have a good estimate of ecosystems C stock and emissions for the whole county, mangrove areas in Luzon, Visayas and Mindanao, covering the northern, central, southern, western and eastern seaboards of the country, were selected for the study.

Of the total 10 mangrove sites that were studied, five were dominated by *Rhizophora* species while two were dominated by *Sonneratia caseolaris*, two sites also for *Avicennia marina* and one site for *Bruguiera cylindrica*. The sites with *Rhizophoras* were either natural stands that were subjected to enhancement planting in the past or planted mangroves as in the case of Bantayan Island. The rest of the sites (n = 5) are natural mangrove stands, albeit only Pagbilao (Quezon province) and Bulakan (Bulacan province) mangroves can be considered as intact. The mean DBH of trees is 10.9 cm while the average height is 6.1 m and the stem density per plot of 7m radius is 22 individuals, suggestive of the secondary forest condition of the studied mangrove stands. Most of the sites have mean heights of at least 5m.

The protocol developed by Kauffman and Donato (2012) for the measurement, monitoring and reporting of ecosystem carbon stocks in mangrove forests was adopted. In each mangrove site, a line transect about 120m long and marked every 25m was established perpendicular to the coast/water to cover the natural environmental gradient in a mangrove ecosystem. The 25m marking was used as the centre of each circular plot (radius is 7m) where measurements and sampling of plants and soil were be done. A total of six plots, at the most, were established per transect to sample the biomass, downed woody debris and soil organic carbon. The C stock values of the aboveground biomass, belowground biomass, downed woody debris biomass and soil organic carbon was added together to determine the Ecosystem C stock value. The value was converted to their CO_2-equivalent based on the protocol of IPCC to monitor the C stock changes (Pendleton *et al.* 2012).

The method used by Castillo et al. (2017) to map the biomass of mangroves in southern Honda Bay, Palawan was used. Among the models studied, the one based on the Inverted Red Edge Chlorophyll Index (IRECI), in tandem with elevation data, was used in mapping the mangrove biomass for this study. The cloud-free 2018-2020 image collection from Sentinel 2 was first processed using the .median() command and converted to IRECI. Then the IRECI map was used in tandem with elevation data from STRM Digital Elevation Model (30 m) to derive the AGB map. Prior to raster operations, the IRECI and SRTM maps were first subsetted using the 2019 Philippine mangrove cover produced by Baloloy et al. (2020).

The equation developed by Castillo et al. (2017) of the form below was applied to the clipped images to predict and map the biomass value and distribution in the study site. The model was derived using machine learning algorithm inside the WEKA software. This model has an observed : predicted agreement (r) of 83% and Root Mean Square Error (RMSE) of 28.02 MgC/ha. These remote sensing and GIS operations were all performed in the cloud-computing platform Google Earth Engine (GEE). The model is of the form below (Castillo et al. 2017):

Above-ground Biomass (Mg/ha) = -12.7514 + 36.0378 * IRECI + 8.0015 * elevation (m)
where:

IRECI = (Band 7 - Band 4)/(Band 5 / Band 6) of Sentinel 2 image elevation = SRTM digital elevation model

The belowground : aboveground biomass ratio of tropical trees of 0.37 based on Fittkau and Klinge (1973) as cited by IPCC (2006) was used to derive the below-ground biomass map. The values from the two maps were converted to C value using 47% for AGB and 39% for BGB based on Kauffman and Donato (2012), and were added together to generate the Total Biomass C stock map. The soil C stock map was generated using the global mangrove soil carbon map produced by Sanderman et al. (2018). The global soil C map was also first subsetted using the 2019 mangrove cover layer of Baloloy et al. (2020). The Ecosystems C density map was generated by adding the total biomass map and the soil C map.

Results and Discussion

The mean C stock of all the mangrove forests was 494.12 MgC ha^{-1} (range: 65.29 to 1381.56 MgC ha^{-1}, $p < 0.05$). Of all the 3 major carbon pools, soil organic carbon has the highest proportion of C stock with 72% (range: 50 – 95%), followed by 27% for the biomass C stock (range: 4% - 44%) and only 1% on downed woody debris C stock (range: < 0.01 – 6%). This highlights the role of the soil C stock, which in this study is 72% on average, to the overall total, Ecosystem C stock of the site. The mean Ecosystem C stock value (494 MgC/ha) generated in this study is well within the values reported in the literature. However, it is lower than the value reported for Indonesia (1,082 MgC/ha) reported by Murdiyarso et al. (2015).

With this national average, albeit only from 10 sites, the potential contribution of our Philippine mangroves to global Climate Change mitigation can be highlighted. Given our national total for Philippine mangroves of 303,381 ha from the 2019 Philippine Forestry Statistics (FMB, 2020), this mangrove C stock translates to about 149.8 M tC or 550 M tCO_2 eq. The enormous amount of carbon stocked and locked in the country's mangrove forests, especially in its soil pool, highlights the need to protect it from human disturbance.

The mean Ecosystems C stock predicted from the mapping exercise was computed at 538.5 (SD = 108.6) MgC/ha. The minimum estimate was 36 MgC/ha while the maximum was 828 MgC/ha.. The predicted map has an accuracy of 66.7%. Future studies should endeavour to increase this accuracy. Most of the predicted values belong to C density classes 500-700 MgC/ha (64%) and 300-500 MgC/ha (29%). This is followed by 700-828 MgC/ha class (4.3%) and 100-300 MgC/ha class (2%). The 36-100 class has the least number of values (0.7%). The potential of the country's mangrove forest to mitigate the carbon emissions was estimated using the area (ha) of mangroves published in the 2019 Philippine Forestry Statistics. The total area of mangroves published is 303,381 ha as of 2015 (FMB 2020). Given this area, the total C stock computed is 163.9 M tonnes of Carbon (601.5M tonnes of CO_2eq). The province of Palawan, having the largest area of mangrove in the country, has the highest C stock with 32.9M tC. This is followed Sulu with 16.1M tC and Quezon with 10.1 M tC. This large amount suggests the need to protect the mangrove forests in the country due to the huge carbon that they store.

Conclusion and Recommendation

Mangroves provide enormous ecosystem goods and services to coastal communities, including carbon storage and sequestration. The relatively enormous amount of Carbon stocked and stored in biomass and soil of mangroves in the country suggests the need to protect them from human disturbance in order not to contribute further to the rising GHG emissions to the atmosphere.

The approach used in this study to predict and map the distribution of Ecosystem Carbon stock at the country-level, province-by-province with mangroves, would be a useful tool for up-to-date mangrove C stock estimation and monitoring, especially those in the hard-to-reach coastal zones in the country, particularly those with peace and order problem, and when manpower and financial resources are limited.

In order to address the limitations of this study, add more sites and field plots in order to refine the estimate and explore the use of other datasets (e.g. Global Ecosystem Dynamics Investigation (GEDI) forest height map) in predicting and mapping the spatial distribution of Ecosystem C stocks of mangroves in the country

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