Assessment of the Relationship of Ecosystem Health to the Carbon Sequestration Capacity and Vulnerability to Sea Level Rise in Philippine Mangroves

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I. Introduction

Since 1930s, several mangrove rehabilitation programs were implemented in the country (Primavera & Esteban 2008). These planting programs obtained funding from national government agencies (NGAs), and international and local non-government organizations (NGOs). However, despite various rehabilitation efforts, most of these programs were ineffective. The ineffectiveness can be attributed to improper planning and implementation particularly in terms of site, species and substrate selection (Primavera & Esteban 2008). Most mangrove plantations are located in mudflats and seagrass meadows. These sites are constrained by high fluctuations of salinity and inundation and are sub-optimal for mangrove growth. There are also limited monitoring reports, thus, it is not clear if these planting programs are successful or not.

Obviously, the growth and survival of mangroves planted in coastal fringes are low (Salmo III et al. 2013). There are other areas that have better potential for rehabilitation. Abandoned fishponds, for example, are former mangrove areas that are located above the mean intertidal level. It is less constrained by salinity and tidal inundation, and therefore have better chance of mangrove growth and survival. However, there are limited planting programs in abandoned fishponds due to various socio-political constraints (e.g. ownership, access, etc.). Moreover, there are limited studies in the Philippines that accounts for the contribution of rehabilitated mangroves (in abandoned fishponds and those recovering from disturbance such as typhoon) in the adaptation and vulnerability against climate change.

Depending on its "ecosystem health", mangroves will be able to adapt to the impacts of climate change (Ward et al. 2016). Here, we adapted the definition of ecosystem health as "*comprehensive, multiscale, dynamic, hierarchical measure of system resilience, organization, and vigor*" (cf. Costanza & Mageau 1999). Similar with other plants, mangroves absorb CO_2 through photosynthesis and deposit and accumulate it as carbon (as plant biomass) into its vegetative parts. The anoxic sediments and vegetation structural complexity in mangroves trap and bury carbon for a long time (Marchio et al. 2016). The accumulation of detritus in the forest floor contributes in increasing its surface elevation and is important in compensating the effects of rising sea level. These processes on carbon sequestration and detritus accumulation make mangroves an important ecosystem in developing adaptation and mitigation strategy against climate change.

In this study, we compared carbon stocks and rate of surface elevation change in different stand types: as natural, planted and naturally colonized mangroves (in abandoned fishponds) in selected sites in the Philippines. The natural and planted stands in Salcedo, Samar were severely impacted by Super Typhoon Yolanda in November 2013 while the colonized mangrove stand is one of the many abandoned, underutilized and underdeveloped (AUU) fishponds in Bani, Pangasinan. The study aims to assess and compare the contribution of different mangrove stand types in carbon sequestration and in stabilizing the surface elevation capital.

II. Materials and methods

Site description

The study was conducted from December 2016 to January 2018 in Salcedo, Eastern Samar and Bani, Pangasinan (**Fig. 1**). Monitoring plots were randomly set in three different mangrove stand types, as natural (Barangay Maliwaliw and Tagbacan, Salcedo, Eastern Samar), planted (Barangay Maliwaliw, Salcedo, Eastern Samar), and colonized fishpond (Barangay Ambabaay, Bani, Pangasinan). Field sampling was conducted two to three times per site at 4-7-month interval.

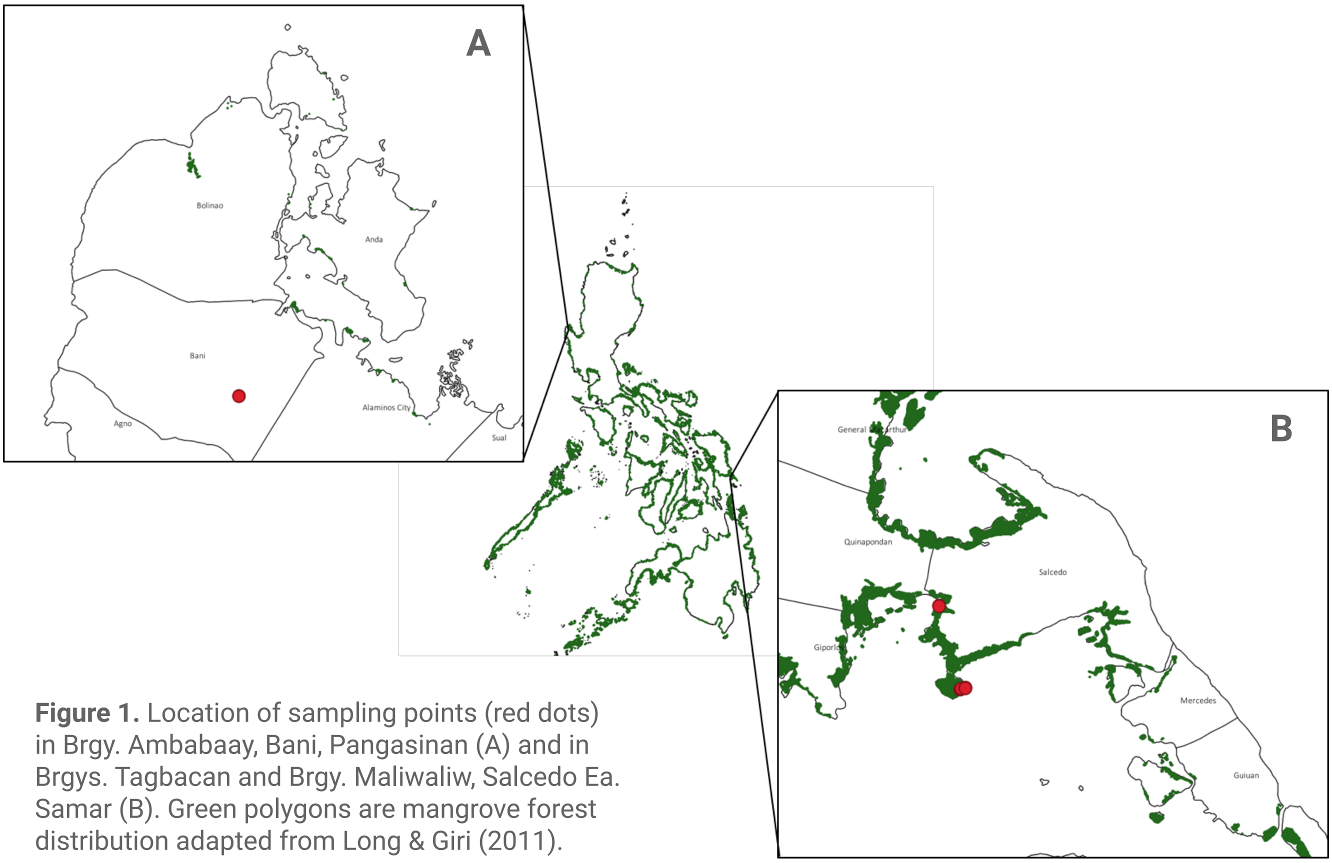

Figure 1. Location of sampling points (red dots) in Brgy. Ambabaay, Bani, Pangasinan (A) and in Brgys. Tagbacan and Brgy. Maliwaliw, Salcedo Ea. Samar (B). Green polygons are mangrove forest distribution adapted from Long & Giri (2011).

Barangays Maliwaliw and Tagbacan were severely affected by the onslaught of Super Typhoon Yolanda (Haiyan) in November 2013. Several mature trees were snapped and died. Maliwaliw is an island barangay, with natural and planted mangrove stands (ca. 0.23 km and 0.08 km from the shoreline, respectively). Tagbacan is a coastal barangay (ca. 0.31 km from the shoreline), receiving freshwater and sediments from a small creek.

The abandoned fishpond in Barangay Ambabaay is located along the national highway of Bani (ca. 8.5 km from the shoreline and ~0.0025 km away from a small creek). According to the locals, the fishpond was abandoned for > 10 years and was naturally colonized by mangroves. The site is dominated by *Aegiceras corniculatum* with some *Avicennia* spp. (**Table 1**).

Assessment of Carbon Stocks

Biomass Component

Three representative 5 m radii mangrove vegetation plots were randomly established for each site. The plots were approximately 10-20 m apart from each other. In each plot, trees were tagged using plastic wires and measured of total height, canopy height, canopy diameter, and stem diameter. The number and heights of seedlings and saplings were also measured.

Sediment Component

Twenty-centimeter sediment samples were collected twice from each plot for two sampling periods. The samples were collected using a fabricated 6.5-cm diameter PVC transparent corer. These samples were used for the analysis of sediment carbon (SC) stocks. Each sample was subdivided at 5-cm interval. This approach allowed us to calculate the rate of change in SC stocks over depth.

One-meter sediment samples were collected from Tagbacan and Bani using a 1-m fabricated corer (with 6.5 cm diameter). [No samples were collected from Maliwaliw as the site has coarse sediment which constrained the collection at 1-m depth]. The sediment samples were subdivided at different depths (one cm interval for the 0-10 cm layer, two cm interval for the 10-20 cm layer and five cm interval for 20-100 cm layer) to trace the variation of organic matter (OM) per depth. This approach was used to infer patterns of OM accumulation or loss relative to depths. Physico-chemical variables were measured thrice per plot using a portable water quality monitoring instrument (TPS-WP81 Australia).

Laboratory Analysis

In the laboratory, the sediment samples were air dried prior to OM analysis. The OC was derived from the OM content of each sub-sample which was analyzed using loss on ignition (LOI) method (cf. Howard et al., 2014). The subsamples were oven-dried at 60 °C for 24 hours (to remove the moisture content) and were then ignited at 450 °C for 4 hours (using Thermolyne™ Benchtop 1100 °C muffle furnace). The bulk density (BD) was computed using the dry mass of the sample over its volume. The obtained % LOI per sample was converted to % OC following Kauffman et al. (2011). The SC was computed per sampling depth in Mg C/ha (**eq. 1**),

eq. 1

$$SC = \%\ OC * \text{bulk density} * \text{depth of sample}$$

Table 1. Summary of vegetation and sediment conditions across sites. The depth indicates the extent of the steel rod fixed and used as reference point (from each study site) for the measurement of the rate of surface elevation change.

Parameter	Site/Mangrove Type			
	Tagbacan (natural)	Maliwaliw (natural)	Maliwaliw (planted)	Bani (colonized fishpond)
Coordinates	125.56 °N, 11.14 °E	125.58 °N, 11.09 °E	125.58 °N, 11.09 °E	119.88 °N, 16.18 °E
Depth, m	7.5	9.9	3.8	9.5
Sediment type	Muddy (coralline)	Muddy (coralline)	Sandy (coralline)	Muddy
Dominant Species	*Bruguiera gymnorrhiza*; *Xylocarpus granatum*	*Sonneratia alba*; *B. gymnorrhiza*	*Rhizophora apiculata*; *R. stylosa*	*Aegiceras corniculatum*

Carbon Stock Computations

The measured tree diameter for each tree was used to calculate for the above- and below-ground biomasses (AGB & BGB) using species-specific allometric equations (Komiyama et al., 2008). The AGB and BGB values were then converted to above-ground carbon (AGC) and below-ground carbon (BGC) stocks based on the assumption that 50 % of the biomass is made up of carbon (Kauffman et al., 2011). The AGC and BGC were combined to represent carbon stocks from the biomass compartment. We assumed that the total SC of the natural and planted stands of Maliwaliw are similar with that of Tagbacan. The assumption was based on the following conditions: both sites are located in Samar, with coralline substrate and were affected by typhoon. The total carbon stock was computed by summing the biomass and SC stocks per plot and reported as Mg C/ha.

Rate of Surface Elevation Change

The rate of surface elevation change was measured using a rod Surface Elevation Table (rSET). Two rSETs were installed per site near the mangrove vegetation plots. The rSETs were approximately 15 m apart from each other. The rSET is made up of a non-moving benchmark (which is the installed receiver) and steel rods driven into the soil until resistance. For each monitoring period, the rSET arm was attached where nine pins are inserted into the arm. The pins reached the ground and were measured from north, east, south and west directions. The measured height of each pin represents the mean surface elevation for that sampling period. The succeeding measurements represents the differences in either gain or loss of surface elevation (reported as cm/yr).

Data Analyses

The carbon stocks (as biomass and sediment components) and rates of surface elevation change were measured and compared among mangrove stands (natural, planted and colonized) and between sampling periods.

III. Results

Carbon stocks

The carbon stocks from the biomass ranged from 1.75 to 27.22 Mg/ha (mean: 13.22 ± 6.06; **Fig. 2**). It was highest in Tagbacan natural stands (27.22 ± 14.06 Mg/ha) and lowest in the planted stands of Maliwaliw (1.75 ± 0.67 Mg/ha). The SC at 20-cm depth ranged from 10.03 to 109.56 Mg/ha (mean: 39.19 ± 23.57 Mg/ha; **Fig. 2**). The recolonized fishpond has the highest SC at 109.56 ± 6.54 Mg/ha. It was followed by the planted stands of Maliwaliw at 21.42 ± 7.16 Mg/ha. The natural stands in Tagbacan has the lowest SC at 10.03 ± 14.59 Mg/ha.

The recolonized fishpond in Bani (114.11 ± 8.77 Mg C/ha) has the highest total carbon stocks followed by the natural stands in Tagbacan (37.25 ± 28.65 Mg C/ha) then the natural stands in Maliwaliw (35.09 ± 13.38 Mg C/ha). The least carbon stock was found in the planted stands in Maliwaliw (23.17 ± 7.83 Mg C/ha; **Table 2**).

In the natural stands, the % OC was relatively increasing with depth (from surface to 50-cm depth; **Fig. 3**). At 55-cm depth, the % OC dropped by almost 1.05 % per cm. The highest recorded % OC was at 60-cm depth (5.37 %). In the colonized stands, the % OC was relatively uniform with depth (mean: 3.34 ± 0.02 %). The highest OC was observed at 100-cm depth (3.75 %).

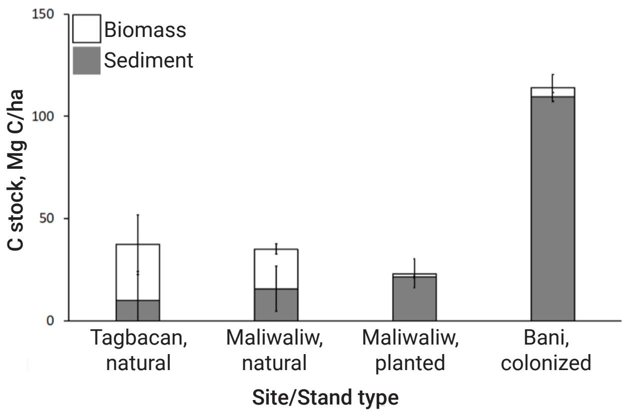

Figure 2. Differences in biomass and sediment carbon stocks (at 20-cm depth; Mg/ha) across stands.

Table 2. Summary of total carbon stocks (Mg/ha) across mangrove stand types (up to 20-cm depth).

Site	Stand Type	Biomass	Sediment	Total Carbon Stock
Tagbacan	Natural	27.22 ± 14.06	10.03 ± 14.59	37.25 ± 28.65
Maliwaliw	Natural	19.36 ± 11.01	15.74 ± 2.38	35.09 ± 13.38
Maliwaliw	Planted	1.75 ± 0.67	21.42 ± 7.16	23.17 ± 7.83
Ambabaay	Recolonized fishpond	4.55 ± 2.23	109.56 ± 6.54	114.11 ± 8.77

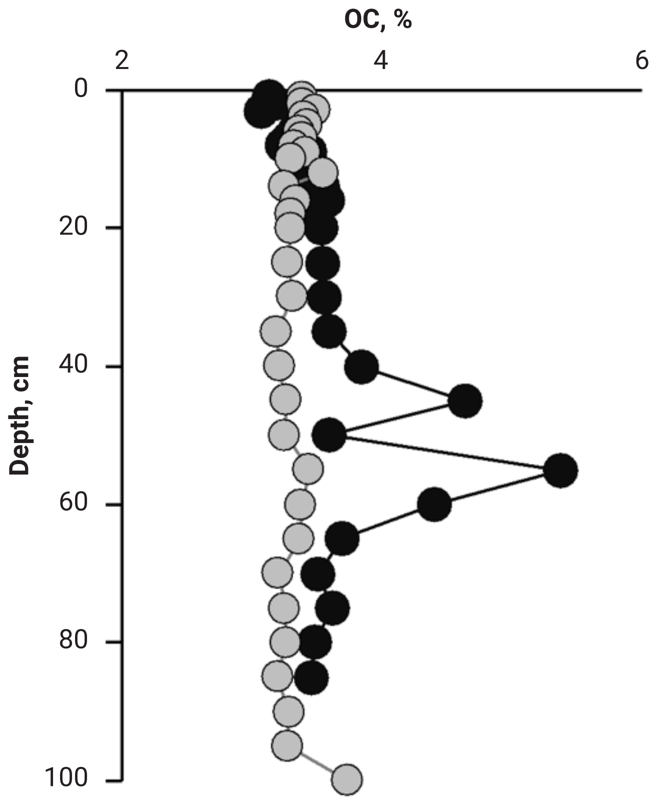

Figure 3. Differences in % OC with depth between Ambabaay (gray) and Tagbacan (black).

Surface Elevation Change

Both natural and planted mangrove stands of Tagbacan and Maliwaliw have negative rates of surface elevation change (subsiding; **Fig. 4**). The lowest rate was recorded in the planted stands (-0.32 ± 0.04 cm/yr). The only site with positive rate (accreting) was the recolonized fishpond (0.37 ± 0.06 cm/yr).

IV. Discussion

This study accounted the differences in the carbon stocks and rate of surface elevation change in different mangrove stands. The mangrove stands also serve as proxy indicator for ecosystem health status referred to as natural, planted and colonized mangroves. The differences in carbon stocks and rates of elevation change can be attributed to several localized factors, but mainly because of ecosystem health status and also probably with the effects of disturbances, such as typhoons.

Low carbon stocks

The low CS in the natural and planted stands in Salcedo, Samar can be attributed to the damages in mangroves caused by Super Typhoon Yolanda in 2013. The mangroves in Samar (and practically the entire eastern and central Visayas) were severely damaged by the typhoon but more particularly those within the 20 to 30 km radius of the typhoon path (Long et al. 2016). Several trees were defoliated, snapped and uprooted resulting to lower biomass, and hence lower CS.

The natural stands in Maliwaliw and Tagbacan have relatively higher biomass as compared to the planted stands. The higher CS in the natural stands can be attributed to the presence of more mature trees that survived the typhoon. There were also several saplings and seedlings that may have contributed to post-typhoon recovery in the natural stands. In contrast, the planted stands barely recovered and have very few seedling recruits. Similar observations on reduced mangrove biomass (by at least 70 %) were also reported in typhoon-damaged monospecific mangrove plantations in Lingayen Gulf (Salmo III et al. 2014).

Despite having more structurally complex stands, the natural stands of Maliwaliw and Tagbacan have low sediment CS. Supposedly, if the stands are structurally complex, it may result to high SC because of the presence of mangroves that are effective in sediment binding and retention (Krauss et al. 2013). However, aside from structural complexity, the accumulation and binding of sediments could be influenced by other factors such as hydrogeomorphic setting (Howard et al. 2014; Marchio et al. 2016) and productivity (Alongi 2012).

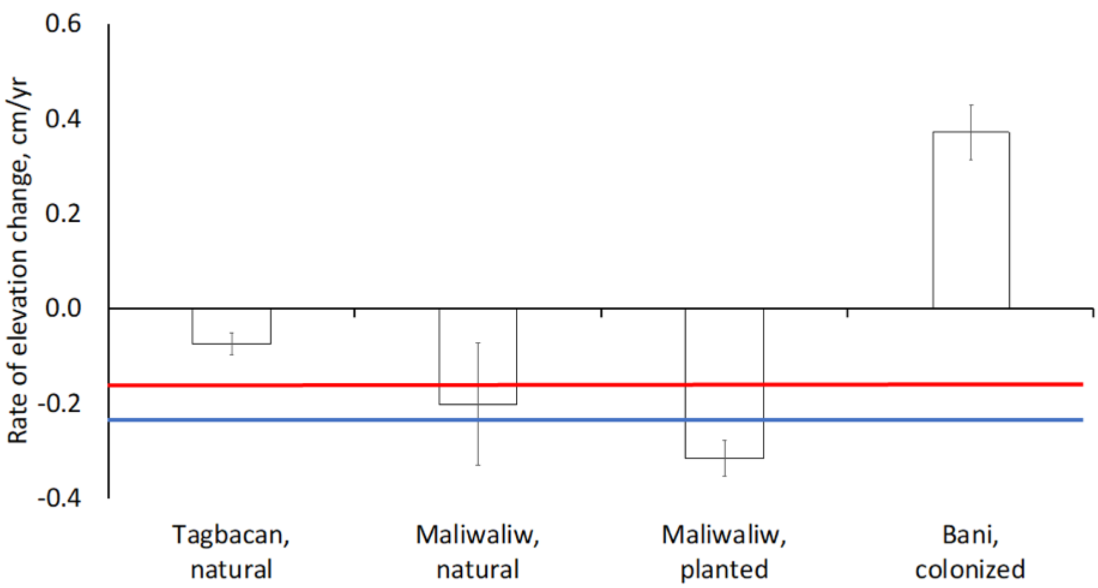

Figure 4. Differences in rates of surface elevation change (cm/yr) across study sites (red line - projected increase in SLR; blue line – mean values from other study sites in the country (from USAID-PEER Project; unpublished data)

In contrast, despite its location and lower structural complexity, the planted stands in Maliwaliw have relatively higher SC stocks as compared to the natural stands. The plantation is located in a seagrass bed with sandy substrate. Windusari et al. (2014) reported that sandy substrates generally have lower organic carbon content, as compared to a muddy substrate (e.g., natural stands of Maliwaliw and Tagbacan). However, this was not found in this study and it is possible that sediments were deposited from other adjacent mangroves and seagrass areas.

The total SC stocks from the 1-m sample (derived from Tagbacan and Bani) are 155.02 and 351.15 Mg C/ha, respectively (**Fig. 3**). Using these values, the estimated total CS for 1-m sediment depth for the Tagbacan natural stands, Maliwaliw natural stands, Maliwaliw planted stands, and Bani colonized stands are 155.02, 149.60, 177.81 and 351.15 Mg C/ha, respectively. The total CS in this study (natural and planted stands) are almost two to four times lower as compared to other sites in the Philippines and in other SE Asian countries. The total CS of the recolonized fishponds is almost half of the total CS in one of the abandoned fishponds in Iloilo (Duncan et al. 2016; **Table 3**).

Fluctuations on sediment carbon gains and losses over depth

The general pattern of the OC with depth differ for each stand (**Fig. 3**). These fluctuations possibly represent the gains and losses of OC over time and may reflect the rate of accumulation (or loss) of OC at different periods (Eid & Shaltout 2015).

In the colonized fishpond, there is minimal change in the OC with depth. The complete removal of vegetation and excavation of ca. 1 m substrate (done when mangroves were converted into fishponds) results to massive carbon losses. The slight increase in OC in the upper layer (0 – 15 cm) can be attributed to OM from litters derived from the developing mangroves that slowly colonized the area. However, it is still evident that the recolonized stands have difficulty in recovering CS even after < 10 years of fishpond abandonment.

There is evident instability of carbon with depth in the natural stands. The OC slightly increases over depth, which is contradictory with the observations from *Avicennia marina*-dominated mangrove stands in Egyptian Red Sea Coast (Eid & Shaltout 2015).

Table 3. Total carbon stocks (Mg/ha) from this study (and in comparison with other mangrove sites in the Philippines and SE Asia).

Location	Stand Type	Total Carbon Stock (Mg/Ha)	Source
Tagbacan, Salcedo, Ea. Samar	Natural	182.24 ± 28.65	This study
Maliwaliw, Salcedo, Ea. Samar	Natural	168.96 ± 13.38	This study
Maliwaliw, Salcedo, Ea. Samar	Planted	179.56 ± 7.83	This study
Ambabaay, Bani, Pangasinan	Recolonized fishpond	355.70 ± 8.77	This study
Bani, Pangasinan	Natural	750.07 ± 21.09	Garcia 2017
Kodia, Bantayan Island, Cebu	Natural	615.14 ± 82.18	Garcia 2017
Oboob, Bantayan Island, Cebu	Planted	166.97 ± 8.28	Garcia 2017
Nabitasan, Iloilo	Abandoned fishpond	212.14	Duncan et al. 2016
Dumangas, Iloilo	Abandoned fishpond	710.13	Duncan et al. 2016
Vietnam	Restored	910.70 ± 32.20	Dung et al. 2016
Vietnam	Disturbed	573.50	Dung et al. 2016
Vietnam	Planted	899.00 ± 111.00	Nam et al. 2016
Vietnam	Natural; regenerated	844.00 ± 58.00	Nam et al. 2016
Indo-Pacific region	Natural	1,023.00	Donato et al. 2011

The OC supposedly should be higher in the surface because it is where most carbon inputs occur and then decreases with depth (Lunstrum & Chen 2014; Eid & Shaltout 2015). The storm surge from ST Yolanda may have led to washed-off of C-rich sediment in the upper surface layer.

Subsidence

Aside from vegetation structural damages, the typhoon may have also caused peat collapse or a rapid decrease in surface elevation capital (Cahoon et al. 2003). This is evident in the negative rate of surface elevation change in the typhoon-damaged stands indicating that the mangroves are either subsiding or are less effective in stabilizing its elevation capital.

The maintenance of elevation capital is affected by the location and species composition of mangrove stands. Other factors that contribute in the vulnerability of mangroves against subsidence are the low tree density, low litter production, and prolong inundation period. Allochthonous and autochthonous sediment inputs are important to stabilize the elevation capital, but unfortunately are less evident in all sites. McKee (2011) reported that surface elevation could be high in fringe and basin mangroves. However, this is not the case in this study as the sites in Samar are subjected to more intense wave actions that erode the surface elevation.

In the Maliwaliw natural stands, *S. alba* and *B. gymnorrhiza* are the co-dominant species. *S. alba* has pneumatophores that are supposedly effective in the binding and retention of sediments (Young & Harvey 1996; McKee 2011; Krauss et al. 2013). However, despite having denser pneumatophores, the natural stands have negative rate of surface elevation change implying its vulnerability to subsidence. Tagbacan mangroves has negative rate of elevation change (-0.07 ± 0.02 cm/yr). It is a fringing-type stand, which is more exposed to wave action that limits sediment retention. Similarly, the plantations are mainly monospecific *Rhizophora* stands which has limited capacity in retaining and binding sediments.

The rates of surface elevation change obtained in Samar are lower as compared with the mangrove stands of Bani, Pangasinan; Oboob, Cebu; and in Pohnpei, Micronesia (**Table 4**). These stands have negative rates of elevation change and can be presumed that the mangroves of Samar are highly susceptible to rising sea level. It is possible that these mangroves are still manifesting peat collapse. However, the values generated from the rSET measurements in this study can be considered as preliminary findings. The study needs to be conducted longer (e.g., at least two years) to establish a more consistent rates.

Potential of abandoned fishponds in carbon sequestration and maintenance of elevation capital

Based from the two-year sampling, the CS in the mangrove-colonized AUU fishponds is relatively higher as compared to the disturbed planted stands. Similar with the fishponds in Aklan (Duncan et al. 2016; **Table 3**), the AUU fishponds in Bani are located in mid to upper intertidal zone and is therefore less likely to be influenced by hydroperiod and wave action. These conditions help facilitate seedling colonization, growth and storage of carbon. The rate of C burial in the sediment is estimated at 0.37 Mg C/ha/yr.

Aside from being a carbon sink, the colonized AUU fishpond is also effective in holding sediment. It is relatively less reached by wave and retain more litter materials. The high CS and accreting sediments imply that prioritizing AUU fishponds for rehabilitation is more effective in restoring mangroves than the conventional planting in coastal fringes. Rehabilitation of these AUU fishponds will not just help in restoring mangroves but also in developing adaptation and mitigation strategies to combat the impacts of climate change.

Table 4. Comparison of rates of surface elevation change (cm/yr) with other published/unpublished data in the Philippines and Micronesia.

Location	Stand Type	Surface Elevation Change Rate (cm/yr)	Source
Tagbacan, Salcedo, Ea. Samar	Natural	-0.07 ± 0.02	This study
Maliwaliw, Salcedo, Ea. Samar	Natural	-0.20 ± 0.13	This study
Maliwaliw, Salcedo, Ea. Samar	Planted	-0.32 ± 0.04	This study
Ambabaay, Bani, Pangasinan	Colonized (Abandoned fishpond)	0.37 ± 0.06	This study
Bani, Pangasinan	Natural	0.70 ± 0.0008	USAID-PEER (unpublished)
Bani, Pangasinan	Planted	-1.25 ± 0.24	USAID-PEER (unpublished)
Kodia, Bantayan Island, Cebu	Natural	0.71 ± 0.33	USAID-PEER (unpublished)
Obo-ob, Bantayan Island, Cebu	Planted	-1.08 ± 0.4	USAID-PEER (unpublished)
Palompon, Leyte	Natural	2.43 ± 0.77	USAID-PEER (unpublished)
Enipoas River, Pohnpei, Micronesia	Natural (fringe)	-0.58	Krauss et al. 2010
Enipoas River, Pohnpei, Micronesia	Natural (riverine)	-0.14	Krauss et al. 2010
Enipoas River, Pohnpei, Micronesia	Natural (interior)	-0.28	Krauss et al. 2010

IV. Summary and Recommendations

The impact of disturbance to mangroves can have lag effects. Thus, it is important to have a longer assessment period to capture the lag period. The findings in this study emphasize the need for long-term monitoring and assessment of permanent plots. The information that can be derived from these monitoring can provide further understanding of how mangroves may adapt with the impacts of climate change.

The carbon stocks and vulnerability of mangroves differ with stand type. The recolonized fishponds have the highest total carbon stocks, followed by natural stands. But the total carbon stocks obtained in this study is two to four times lower as compared to published datasets in the Philippines and in neighboring SE Asian countries. The colonized fishponds in Bani, Pangasinan has higher rate of surface elevation change as compared to the natural and planted stands in Salcedo, Samar. This implies that the mangroves in Samar are more vulnerable to SLR as compared to the colonized AUU fishpond in Pangasinan.

The findings in this study indicate the need to do further long-term research to understand better the differences in carbon stocks and rates of surface elevation change with different ecosystem health status. Continuous monitoring of the rate of surface elevation change for at least two years will help further understand the sediment accretion dynamics. Lastly, this study reiterates the importance of understanding how naturally colonized abandoned fishponds contribute in sequestering carbon and in restoring the mangrove ecosystem services.

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