Post-disturbance carbon stocks and rates of sequestration: Implications on "blue carbon" estimates in Philippine mangroves

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Mangrove forest is one of the "blue carbon" ecosystems recognized for its high sequestration and long-term storage of carbon. While reports on blue carbon in mangroves are increasing, studies on the post-disturbance carbon stocks and rates of sequestration are still lacking in the Philippines. In this study, we assessed the stocks and rates of carbon sequestration in mangroves that were disturbed by typhoon and converted to aquaculture ponds. Carbon stocks were measured from the biomass and sediment compartments from typhoon-impacted sites (composed of natural and planted stands) and from mangrove-colonized abandoned fishponds. Using a stock-change approach, the rates of carbon sequestration were estimated at intra-annual and post-disturbance levels. Results showed wide variation in total carbon stocks and ranged from 168.96 to 355.70 Mg/ha (of which the biomass comprised 8.20 ± 4.18 % and the sediment with 92.84 ± 3.56 %). These values are 40-60 % lower than some SE Asian mangroves. Across sites, the post-disturbance rates of carbon sequestration (mean: 17.17 ± 0.57 Mg C/ha/yr) are similar with some studies and are within range from stands that are similarly recovering from disturbance. Our results indicate that disturbances contribute to changes in stocks and rates of carbon sequestration. Mangroves that colonized fishponds, although with relatively slower rates, have more stable carbon recovery. A more pro-active approach on the rehabilitation of abandoned fishponds (rather than leaving it to natural colonization process) is suggested to enhance carbon sequestration in Philippine mangroves.

INTRODUCTION

The high production (Alongi 2012) and accumulation of organic detritus in the sediments (Woodroffe et al. 2016) makes mangroves an important ecosystem in developing climate change adaptation and mitigation (CCAM) strategy (Soares 2009; Feller et al. 2010). Mangroves contribute in reducing atmospheric CO_2 (through photosynthesis and eventually biomass accumulation) and in compensating the impacts of rising sea-level (through increasing the surface elevation capital; Cahoon et al. 2003). Mangroves are considered as "blue carbon" ecosystem (Howard et al. 2014) because of its capacity to sequester and store high amount of carbon (Donato et al. 2011). Its high vegetation structural complexity facilitates the trapping, accumulation and stabilization of organic carbon (Krauss et al. 2003). The anoxic sediment condition limits respiration and enhances long-term burial and storage of carbon (Chen et al. 2017).

The capacity of mangroves to sequester and store carbon depends on several bio-physical and geomorphological factors (Adame et al. 2015). For instance, mature mangroves have high
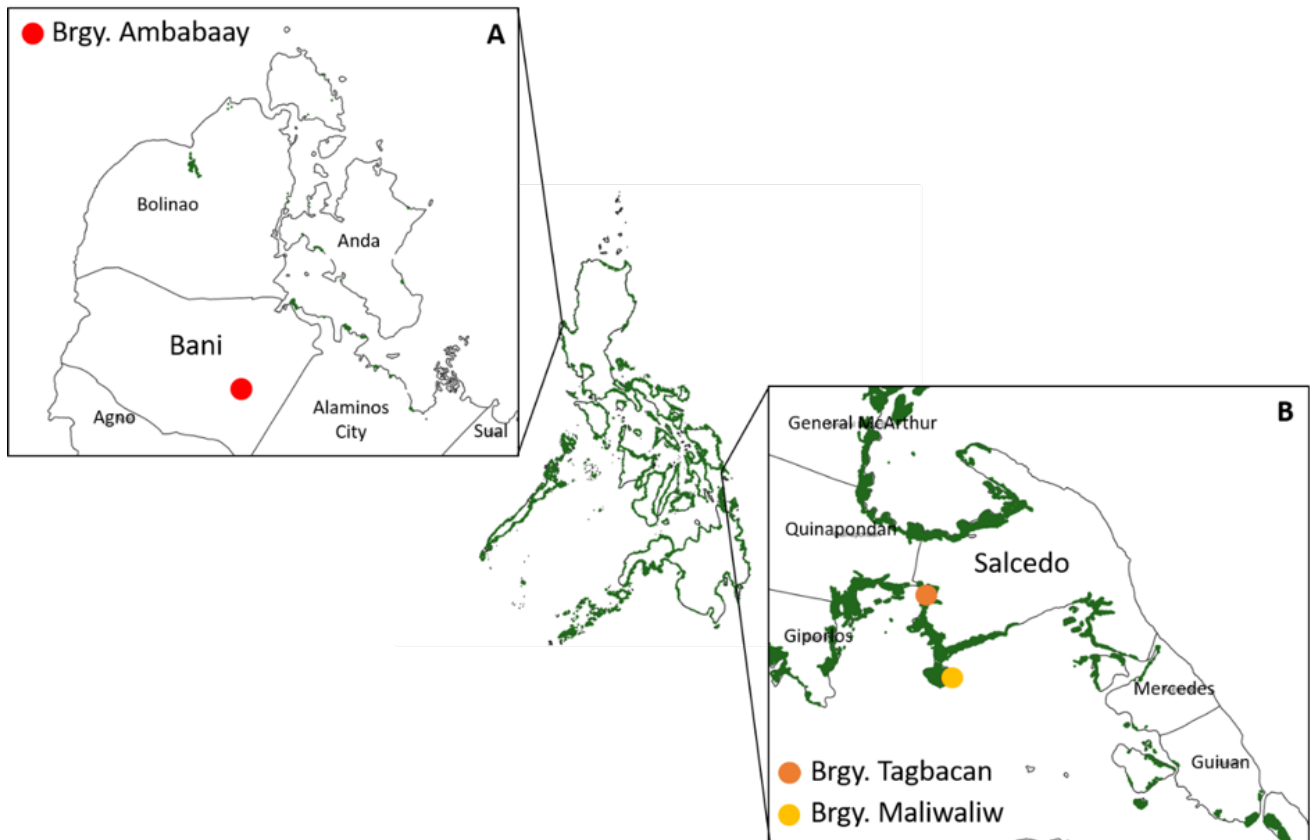
Figure 1: Location of the study sites in mangrove-colonized fishpond in Ambabaay, Bani, Pangasinan (A) and typhoon-disturbed stands in Salcedo, Eastern Samar (B). Green polygons are mangrove forests adapted and modified from Long and Giri (2011).

carbon stocks (CS) but low rate of sequestration. In contrast, young and developing mangroves have low CS but have higher rate of sequestration (Duke 2001; Adame et al. 2018). Intact and contiguous mangroves located near rivers have higher CS as compared to sparse mangroves near coastal fringes (Donato et al. 2011; Dung et al. 2016; Nam et al. 2016). When disturbed, for example by typhoon, the vegetation biomass (and hence carbon from vegetation pools) and sediment carbon are greatly reduced (Salmo et al. 2014; Villamayor et al. 2016; Grellier et al. 2017). Similarly, mangroves that are disturbed through conversion to aquaculture ponds also experience huge carbon losses because of the excavation of carbon-rich sediments (Duncan et al. 2016). Typhoons and conversion to aquaculture ponds are the two most common types of disturbance that affected Philippine mangroves for a long time (Samson and Rollon 2008; Salmo et al. 2014). As mangroves recover from disturbance, the CS is expected to increase over time although the rate and period of recovery will vary with the "ecosystem health" of the mangroves (Alongi 2012). Mangrove restoration programs, if done properly (i.e. with good growth and survival), will contribute in recovering CS (Salmo and Juanico 2015). Similarly, mangroves that naturally colonize an abandoned aquaculture pond, also contribute in recovering CS (Duncan et al. 2016).

While "Blue Carbon Program" has been initiated in the Philippines, empirical measurements of carbon stocks and rates of sequestration in mangroves as affected by, and recovering from, disturbance are still lacking. This information is needed in the assessment of total carbon stocks (TCS) in Philippine mangroves. It will also help estimate the contribution of mangroves in attaining the commitment of the government to Paris Agreement to reduce GHG emission. Thus, in this study, we evaluated the carbon stocks and rates of sequestration in mangroves that were disturbed by typhoon and aquaculture ponds. The study was conducted in Salcedo, Samar and Bani,

Pangasinan. The former was damaged by Super Typhoon Haiyan in November 2013 while the latter was an abandoned fishpond that was naturally colonized by mangroves. Our study specifically aimed to assess the differences in rates of carbon sequestration in mangroves affected by different forms of disturbance. Our study contributes in improving estimates of TCS and suggest strategies that will help improve in understanding the blue carbon ecosystem service in Philippine mangroves.

MATERIALS AND METHODS
Site and Disturbance Information
The sampling sites were composed of mangroves that experienced disturbances: typhoon (Samar) and conversion to aquaculture fishponds (Pangasinan). The typhoon-damaged sites are located in Salcedo, Eastern Samar, while the aquaculture-converted sites are located in Bani, Pangasinan (Figure 1). The sites in Salcedo involved two villages (Maliwaliw and Tagbacan). Maliwaliw is an island barangay, with natural and planted mangrove stands (ca. 0.23 km and 0.08 km from the coast, respectively). Tagbacan is a coastal barangay (ca. 0.31 km from the coast), receiving freshwater and sediments from a small creek. The estimated mangrove areas for the sampling sites in Ambabaay, Tagbacan and Maliwaliw are 2 has, 15 has and 10 has, respectively. The natural stands are multi-species and have more mature and larger trees as compared to the mono-specific plantations (Table 1).

In November 2013, Super Typhoon Haiyan (local name "Yolanda") made its first landfall in Guiuan, Eastern Samar. It was categorized as Typhoon 5 (Saffir-Simpson hurricane wind scale, SSHWS) and is acknowledged as the strongest typhoon recorded in modern meteorological monitoring history (Long et al. 2016). It has maximum sustained winds of over 251 km/ha

Table 1: Summary of vegetation and sediment conditions across sites.

Parameter	Study Site							
	Tagbacan (natural)		Maliwaliw (natural)		Maliwaliw (planted)		Ambabaay (mangrove-colonized fishpond)	
	Time 1	Time 2	Time 1	Time 2	Time 1	Time 2	Time 1	Time 2
Vegetation								
Dominant Species	*Bruguiera gymnorrhiza; Xylocarpus granatum*		*Sonneratia alba; B. gymnorrhiza*		*Rhizophora apiculata; R. stylosa*		*Aegiceras corniculatum; Avicennia* sp.	
Tree density (n/ha)	2674 ± 903	467 ± 225	467 ± 185	212 ± 85	1019 ± 100	340 ± 42	382 ± 127	467 ± 225
Sapling density (n/ha)	4244 ± 1244	1231 ± 405	212 ± 85	1316 ± 278	552 ± 331	552 ± 331	637 ± 147	849 ± 153
Seedling density (n/ha)	2886 ± 695	4626 ± 852	849 ± 297	1443 ± 467	509 ± 337	1401 ± 724	764 ± 265	382 ± 247
Tree diameter (cm)	2.43 ± 0.27	2.49 ± 0.35	3.61 ± 0.97	4.94 ± 2.01	1.35 ± 0.09	3.15 ± 1.05	3.60 ± 0.47	4.20 ± 0.37
Canopy cover (%)	40 ± 0.00	66.67 ± 3.33	33.33 ± 3.33	45 ± 2.89	10 ± 2.00	10 ± 3.00	43.33 ± 3.33	66.67 ± 3.33
Porewater Quality								
Salinity (psu)	6.93 ± 1.44	12.00 ± 1.25	2.81 ± 0.68	6.40 ± 1.31	6.05 ± 2.88	11.57 ± 0.79	7.40 ± 2.68	7.40 ± 2.68
Temperature (°C)	29.33 ± 0.57	26.00 ± 0.06	31.36 ± 0.79	25.63 ± 0.38	30.74 ± 1.14	26.07 ± 0.43	28.1 ± 0.31	28.1 ± 0.31
Redox potential (mV)	152.22 ± 31.57	73.37 ± 5.52	111.66 ± 1.41	157.88 ± 23.17	72.02 ± 41.14	150.06 ± 45.19	238.49 ± 130.25	238.49 ± 130.250
Total Dissolved Solids (ppK)	7.90 ± 3.05	12.21 ± 1.04	4.81 ± 3.49	6.92 ± 0.74	7.05 ± 3.75	12.50 ± 0.43	8.30 ± 2.75	8.30 ± 2.75
Conductivity (mS)	245.40 ± 126.92	216.62 ± 126.92	49.92 ± 45.74	11.36 ± 1.93	85.48 ± 17.95	17.65 ± 0.59	22.45 ± 5.62	22.45 ± 5.62
Sediment								
Type	Muddy		Muddy; Coralline		Sandy; Coralline		Muddy	
Organic Carbon (%)	3.17 ± 0.04	3.73 ± 0.01	3.04 ± 0.02	3.73 ± 0.11	2.94 ± 0.004	3.10 ± 0.02	3.29 ± 0.08	3.48 ± 0.02

and wind gusts > 275 km/h (Long et al. 2016). The study sites in Eastern Samar are directly along the typhoon path (ca. 20 km). The typhoon resulted to severe tree damages (defoliated, snapped and uprooted) and mortalities in mangroves.

The mangrove-colonized fishpond in Ambabaay is one of the many abandoned, underutilized and undeveloped (AUU) fishponds in the municipality. It is located along the national road of Bani (ca. 8.5 km from the shoreline and ~0.0025 km away from a river). The local communities and government officials reported that the fishpond was abandoned for ca. 10 years and since then was gradually colonized by mangroves. The site is dominated by *Aegiceras corniculatum* with some *Avicennia* spp. (Table 1).

Experimental Design and Sampling
The study was designed to account and compare the TCS and rates of carbon sequestration of different mangrove stands (as natural, planted and colonized). Field sampling were conducted twice (at 6- to 10-mo interval) from each site from December 2016 to January 2018. All sampling activities were conducted during low tide period.

In each site, three representative 5-m radii vegetation plots were set. In each plot, the trees, saplings and seedlings were tagged using plastic wires. The trees were identified at species level using Primavera et al. (2004) and measured of tree diameter and total height. Sediment porewater quality (pH, temperature, oxidation-reduction potential (ORP), total dissolved solids (TDS), conductivity and salinity) were measured from the center of the plot using a portable water quality instrument (TPS-WP81 Australia).

Two 20-cm sediment samples were collected from each plot using a fabricated 6.5-cm diameter PVC transparent pipes. The sediment samples, subdivided at 5-cm interval, were used for the analyses of organic carbon (OC) content. This approach allowed us to assess the patterns of changes in SC stocks with depth and also to compute for intra-annual change of SC stocks.

Two 100-cm sediment samples were collected (once each) from Tagbacan and Ambabaay using a fabricated open-faced 6.5-cm PVC transparent pipes. The sediment samples were brought to the laboratory and analyzed for OC content. In the laboratory, the 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 down-core variation of OC per depth. Each sub-sample was air dried, oven-dried (for about 24 hours to remove moisture content), and then ignited at 450 °C for 4 hours (using Thermolyne™ Benchtop 1100 °C muffle furnace). This approach was used to infer patterns and rate of OC accumulation (or reduction) relative to depths and also to compute for the rate of change in SC stocks post-disturbance. There were no 100-cm samples collected from Maliwaliw because the substrates were too soft and were difficult to retrieve. Instead, the SC values from the 20-cm samples from each site were added to the values derived from 20-100 cm depth (from 100-cm samples) collected from Tagbacan to infer the total SC of the natural and planted stands of Maliwaliw. Both Maliwaliw and Tagbacan sites have relatively similar bio-physical conditions and were both affected by typhoon.

Data Analyses
Using species-specific allometric equations (Komiyama et al. 2008), the measured tree diameter for each tree was used to calculate the above- and below-ground biomasses (AGB & BGB, respectively). The AGB and BGB values were then converted to above-ground carbon (AGC) and below-ground carbon (BGC) stocks based on the assumption that ca. 50 % of the biomass is made up of carbon (Kauffman et al. 2011). The AGC and GBC were summed and reported as C stocks from the biomass compartments.

The SC stocks were determined through Loss on Ignition method (cf. Howard et al. 2014). The dry bulk density (DBD) 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 depth by multiplying the % OC, bulk density and the depth of the sample (for both 20-cm and 100-cm samples). The total SC stock was calculated as the sum of the SC stock for the entire 100-cm sample (Tagbacan and Ambabaay). The TCS was computed by summing the AGC, BGC and SC per plot and reported as Mg C/ha.

The rates of change in carbon stocks (in both biomass and sediments) were computed using stock-change approach (Kauffman et al. 2011). The differences in biomass, SC and TCS between two sampling periods (as between December 2016 and January 2018 for Samar sites, and between June and November 2017 for Pangasinan sites) were used to calculate the intra-annual rate of change. The post-disturbance rate of change was calculated using the TCS divided by the number of years post-disturbance. From the sediment compartment, the carbon stocks from 0 to 45-cm depth were assumed as the carbon that were accumulated post-disturbance as inferred from down-core OC variation (cf. Marchand 2017; Salmo et al. 2019).

Principal Component Analysis (PCA) plot was made to visualize the relative differences between and among sites. All vegetation and sediment parameters (from Table 1) including the carbon stocks and sequestration rates were used. The PCA was implemented in R statistical software (R Core Team, 2017).

We acknowledge the limitations of our experimental and sampling designs particularly on the estimation of rates of change in carbon stocks. The limited number of temporal data points and the inference we used (limited at 45-cm depth) to estimate both the intra-annual and post-disturbance rates may not necessarily directly linked *sensu stricto* to the effects of disturbance. Our interpretations of datasets were therefore limited on a relatively shorter term post-disturbance period.

RESULTS AND DISCUSSION

Our results indicate, overall, that mangroves that were both disturbed by typhoon and converted to fishponds have low CS but have different rates of carbon sequestration. These values also varied with compartments (Figure 2A) where lower CS from the biomass compartment was manifested more in mangrove-colonized fishponds (Bani). In contrast, lower CS from the sediment compartment was manifested more in the typhoon-disturbed sites (Samar). The typhoon-disturbed mangroves have at least 40 % lower C stocks than the mangrove-colonized fishpond. Both the intra-annual and post-disturbance rates are within range with the rates reported in SE Asian and Asia Pacific mangroves.

The Principal Component Analysis (PCA) plot showed clear patterns of similarities and dissimilarities between and among sites based on vegetation, porewater and sediment parameters (PC1 = 28.4 %, PC2 = 22.4 %; Supplemental Figure 1). The parameters OC content (ρ = -0.42), canopy cover (ρ = -0.39) and redox (ρ = -0.36) characterized PC1, while proximity to freshwater (ρ = -0.50), seedling density (ρ = -0.42) and sapling density (ρ = -0.40) characterized PC2. The natural stands in Tagbacan, the plantation stands and the mangrove-colonized fishponds in Bani have more similarities based on tree diameter, species richness, redox and distance from shoreline. The natural stands in Maliwaliw were more correlated with high seedling density, high sapling density and distance from freshwater source. The plantation stands were more characterized by high temperature and low rate of carbon sequestration.
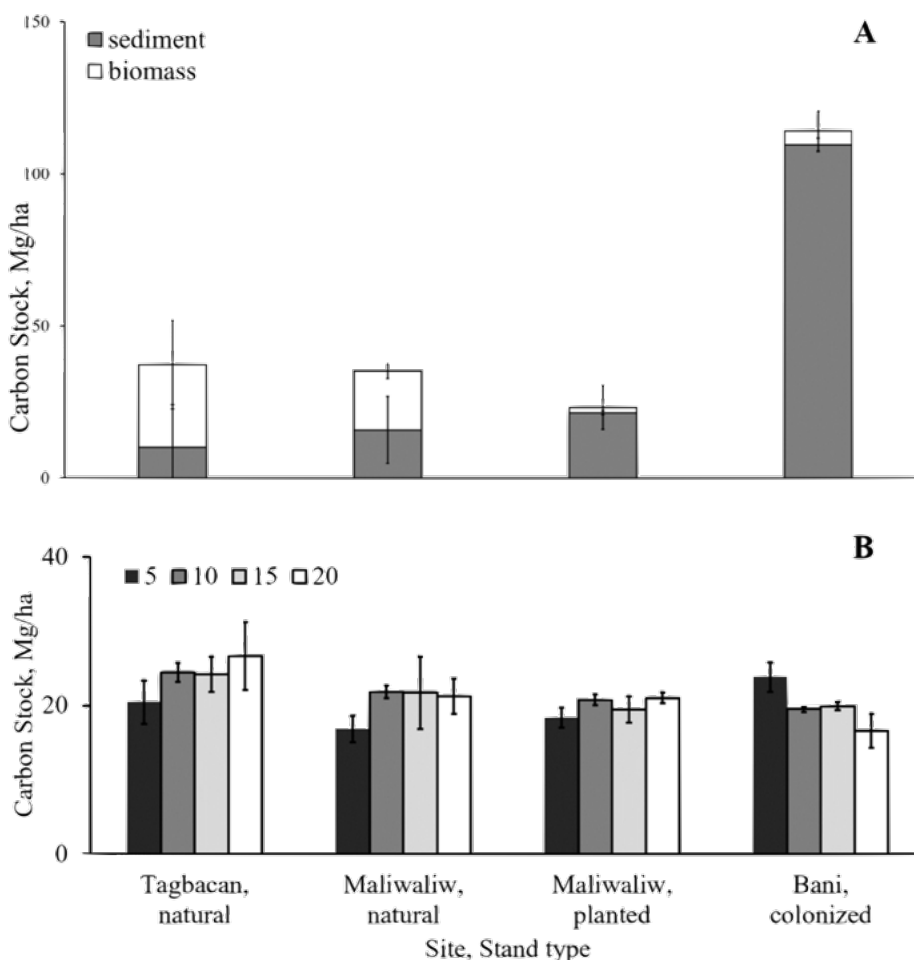

Figure 2: Differences in biomass and sediment carbon stocks (CS) across stands (A), and in sediment from surface to 20-cm depth (B). **There were lower CS in the vegetation compartment in the planted and mangrove-colonized fishponds than the natural stands indicating less developed vegetation.** The down-core variation of CS showed higher carbon accumulation at the surface in the mangrove-colonized fishponds. In contrast, the typhoon-disturbed stands have lower CS indicating less carbon accumulation at the upper surface.

Table 2: Comparison of biomass, sediment and total carbon stocks (Mg/ha) across mangrove stand types. The typhoon-disturbed mangroves have ca. 50 % less carbon stocks than the mangrove-colonized fishponds.

Site	Stand Type	Biomass	Sediment	Total Carbon Stock
Tagbacan	Natural	27.22 ± 14.06	155.02± 0.83	182.24 ± 14.89
Maliwaliw	Natural	19.36 ± 11.01	149.60 ± 0.84	168.96 ± 11.85
Maliwaliw	Planted	1.75 ± 0.67	177.81 ± 0.71	179.56 ± 1.38
Ambabaay	Colonized fishpond	4.55 ± 2.23	351.15 ± 1.28	355.70 ± 3.51

Biomass and Sediment Carbon Stocks Varied with Stands and Compartments

The carbon stocks from the biomass compartment ranged from 3.75 to 26.61 Mg/ha (mean: 14.37 ± 5.57; Figure 2A). It was highest in the typhoon-disturbed natural stands (25.61 ± 10.34 Mg/ha) and lowest in the planted stands (3.75 ± 0.85 Mg/ha) in Maliwaliw. Across sites and depths, the total SC at 20-cm depth ranged from 10.03 to 33.51 Mg/ha (mean: 20.18 ± 5.02 Mg/ha; Figure 2A) and 16.83 to 26.67 Mg/ha (mean: 21.05 ± 1.92 Mg/ha; Figure 2B), respectively. Oftentimes, the upper surface depths have higher SC then gradually decreased with depth as there are higher and more recent carbon accumulation at the surface (see for example Walcker et al. 2011; Salmo et al. 2019). In typhoon-disturbed mangroves however, higher SC was observed in the 15-20 cm depths than the surface. In contrast, the highest SC in the mangrove-colonized fishpond was observed in the upper 0-5 cm then gradually decreased with depth.

From the 100-cm samples, both the typhoon-damaged natural stands and mangrove-colonized fishpond had comparable OC contents (mean: 3.46 ± 0.05 %; Figure 3). However, the down-core OC varied with stands and depths. In the typhoon-disturbed stands, the OC increased with depth from the surface (3.14 %) up to 45-cm depth (4.64 %), decreased at 50-cm (3.60 %), increased at 55-cm (4.64 %), then gradually decreased until the bottom. In contrast, the mangrove-colonized fishpond had relatively more homogenous OC distribution with depth. The highest OC was recorded at the 100-cm depth (3.75 %). The total SC stocks derived from the 100-cm samples for the natural stands in Tagbacan and mangrove-colonized fishpond were 155.02 and 351.15 Mg C/ha, respectively. Using the values from Tagbacan, the estimated TCS for the natural stands and planted stands in Maliwaliw were 149.60 and 177.81 Mg C/ha, respectively (Table 2).

The mangrove-colonized fishpond (355.70 ± 3.51Mg C/ha) had the highest TCS followed by the natural stands in Tagbacan (182.24 ± 14.89 Mg C/ha), the planted stands in Maliwaliw (179.56 ± 1.38 Mg C/ha), then the natural stands in Maliwaliw (168.96 ± 11.85 Mg C/ha; Table 2). The typhoon-impacted stands in Samar had 50 % lower TCS than the mangrove-colonized fishponds. In all sites, the biomass compartment only comprised < 12 % of the TCS while the sediment compartment comprised 88 – 98 %. However, the biomass in mangrove-colonized fishponds had < 300 % CS than the typhoon-disturbed stands.

Role of Disturbance on Changes in Carbon Stocks

In this study, the mean TCS across sites (221.62 ± 44.79 Mg C/ha) is at least 40 – 60 % lower than some sites in SE Asia and the Asia Pacific (Table 3). It is however comparable in mangroves in the Philippines that similarly experienced typhoon disturbance (Garcia 2017) and conversion to fishponds (Duncan et al. 2016). The sediment compartment usually has larger fraction (by at least 60 %) than the biomass compartment (see for example Donato et al. 2011; Kauffman et al. 2011). In Bani and Samar however, the sediment compartment comprised > 85 % of the TCS. The biomass compartment has minimal contribution indicating that its vegetation is either less developed, still under early development stage, or is still recovering poorly from disturbance.
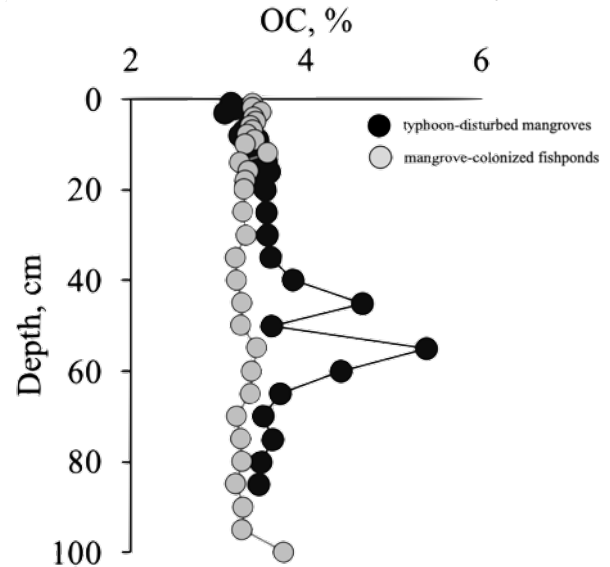

Figure 3: Differences in down-core variation in organic carbon (OC) between typhoon-disturbed mangrove stands and mangrove-colonized fishponds. The former showed wider fluctuation with depths while the latter has more homogenous pattern indicating more stable carbon accumulation.

Carbon stocks and sequestration rates in mangroves are affected by several biological and geomorphological factors (Alongi 2014; Kusumaningtyas et al. 2019). The mangrove-colonized abandoned fishponds (located in higher intertidal zone that is ca. 8.5 km from the shoreline) have at least 80 – 100 % higher TCS than the typhoon-disturbed sites (located in coastal fringes and are below mean intertidal level). The high TCS in Bani (despite less developed vegetation) can be influenced by its location. It is situated in the mid to upper intertidal zone that is less likely to be influenced by hydroperiod and wave action. This condition helped in effectively accumulating and stabilizing autochthonous carbon. In contrast, the sites in Samar are more exposed to waves and tidal actions and are therefore less likely to stabilize and store carbon.

Typhoons are known to influence the community structure and dynamics of mangroves (Roth 1992). Strong catastrophic typhoons are known to result to the uprooting of trees, breaking of branches, defoliation, and massive mortality that will eventually lead to peat collapse and therefore severe reductions in TCS (Cahoon et al. 2003; Salmo et al. 2014; Ward et al. 2016). The occurrence of Super Typhoon Haiyan resulted to massive tree mortalities in eastern and central Philippines especially those along its typhoon path (e.g., Samar sites; Primavera et al. 2016).

Consistent with some reports (see for example Villamayor et al. 2016), most trees that died were tall. However, similar with other catastrophic typhoons, the damages are not spatially homogenous and could have been affected by gradients of wind speed as well as localized site gradients (see for example Busby et al. 2008).

Table 3: Total carbon stocks (Mg/ha) from other mangrove sites in the Philippines and in comparison with other SE Asian and Asia-Pacific countries.

Location/Region	Stand Type	Total Carbon Stock	Source
Philippines			
Bani, Pangasinan	Natural	750 ± 21	Garcia 2017
Bantayan Island, Cebu	Natural	615 ± 82	Garcia 2017
	Planted	167 ± 8	Garcia 2017
Nabitasan, Iloilo	Abandoned fishpond	212	Duncan et al. 2016
Dumangas, Iloilo	Abandoned fishpond	710.13	Duncan et al. 2016
San Juan, Batangas	Natural	115*	Gevaña and Pampolina 2009
SE Asia/Asia-Pacific			
Indonesia	Natural	1,083 ± 378	Murdiyarso et al. 2015
Indonesia	Fishpond/Restored	338 ± 72	Cameron et al. 2018
Malaysia	Natural/Plantation	1,267	Alongi 2012
Malaysia	Plantation	896 ± 114	Adame et al. 2018
Micronesia	Natural	890 ± 192	Kauffman et al. 2011
Palau	Natural	720 ± 309	Murdiyarso et al. 2015
Thailand	Natural/Plantation	662 ±127	Alongi 2012
Vietnam	Restored	911 ± 32	Dung et al. 2016
Vietnam	Disturbed	574	Dung et al. 2016
Vietnam	Planted	899 ± 111	Nam et al. 2016
Vietnam	Natural/Regenerated	844 ± 58	Nam et al. 2016
Indo-Pacific	Natural	1023	Donato et al. 2011

* limited to the upper 10 cm depth

Hence, mangroves in Samar, despite the proximal distance (between Maliwaliw and Tagbacan) may have different extent of typhoon damages, and therefore different reductions in TCS.

The carbon stocks in typhoon-damaged sites in Samar varied with stands where the natural stands had 20-40 % higher carbon stocks than the planted stands. The natural stands are dominated by *Sonneratia alba* and have more species (hence with higher structural complexity). Most trees that survived the typhoon are mainly *S. alba.* This species is known to coppice, re-sprout and can produce and disperse seeds (Walters 2005). In contrast, the plantations are monospecific composed of species from the genus *Rhizophora* which have limited regrowth potential (Roth 1992; Snedaker et al. 1992). Similar findings on massive tree mortalities on monospecific *Rhizophora* plantations and slow recovery were reported in Lingayen Gulf (Salmo et al. 2014) and in Bantayan Island, Cebu (Villamayor et al. 2016).

Role of Disturbance on Intra-Annual and Post-Disturbance Carbon Sequestration Rates
The rates of intra-annual total carbon sequestration varied widely with stands and with compartments (2.14 ± 1.16 Mg C/ha/yr). It was highest in the mangrove-colonized fishponds (5.02 ± 2.34 Mg C/ha/yr) and lowest in the typhoon-disturbed natural stands in Maliwaliw (-0.29 ± 0.16 Mg C/ha/yr). The rates for both biomass and sediment compartments were higher in the mangrove-colonized fishponds (3.79 ± 1.73 Mg C/ha/yr and 1.49 Mg C/ha/yr, respectively) than the typhoon-disturbed stands (1.49 ± 0.44 Mg C/ha/yr and 1.13 ± 0.97 Mg C/ha/yr, respectively).

In contrast with the wide variation on intra-annual rate, the post-disturbance rate of carbon sequestration was more similar across stands (17.18 ± 0.57 Mg C/ha/yr). Similarly, the sequestration in the sediment compartment was fairly similar across stands (15.82 ± 0.17 Mg C/ha/yr). However, there were wide variations in the biomass compartment where the mangrove-colonized fishpond (0.59 ± 0.30 Mg C/ha/yr) have ca. 140 % lower rate than the typhoon-disturbed stands (1.61 ± 0.40 Mg C/ha/yr). Both intra-annual and post-disturbance rates are within the range of rates reported from mangroves that are undergoing development (for example mangroves that colonized saltmarsh in Australia; 27.5 Mg C/ha/yr; Kelleway et al. 2016), or mangroves that are approaching forest maturity (5 - 9 Mg C/ha/yr in Brazil; Perez et al. 2018). The post-disturbance carbon sequestration rates are also similar in mangroves that are recovering from deforestation (9.5 Mg C/ha/yr in Malaysia; Adame et al. 2018), or in mangroves that similarly colonized an abandoned fishponds (and also of almost similar age; 18 Mg C/ha/yr; Sidik et al. 2019) or in mangroves that were uplifted by an earthquake event (10.2 Mg C/ha/yr in Calapan City, Mindoro, Philippines; Salmo et al. 2019; Table 4). These high rates however are perceived to be reduced and will become more stable as the mangrove stands approached maturity.

The occurrence, duration and frequency of disturbance results to changes in vegetation and sediment conditions in mangroves (Ball 1980; Roth 1992; Baldwin et al. 2001). Like other terrestrial ecosystems, mangroves that experience disturbance are expected to recover, although the amount and rate of recovery relative to pre-disturbance values will depend on several factors (e.g., stand age and development, species composition, and impact of disturbance; Duke 2001). Both typhoon and conversion to aquaculture ponds are known to result to drastic changes in vegetation and sediment carbon stocks.

The carbon stocks that were lost from the typhoon-damaged biomass compartment may just be transferred and deposited in the sediment compartment similar to the report in Florida, USA (Kristensen et al. 2008; Smoak et al. 2013) and Micronesia (Call et al. 2019). However, we argue that the strong wave action and storm surge (up to 7 m height) brought by Super Typhoon Yolanda may have led to severe wash-off of carbon-rich surface sediment (Kusumaningtyas et al. 2019). Moreover, the stability of the deposited sediments will also depend on the health of the mangroves that survived the typhoon (Asbridge et al. 2018). Because there were very few trees that survived the typhoon, it is possible that the transferred carbon stocks in the sediments may not be stable since the vegetation has limited capacity to hold the newly transferred sediments.

Table 4: Comparison of rates of carbon sequestration (Mg/ha/yr) from this study with other mangroves in Asia-Pacific countries representing mature/senescent stands and mangroves that recovered from disturbance.

Location/Region	Stand Type	Stage/Disturbance	Rate			Source
			Biomass	Sediment	Total	
Philippines						
Samar	Natural	Typhoon	1.63 ± 0.92	18.44 ± 0.91	22.15 ± 3.73	This study
	Natural	Typhoon	2.30 ± 0.51	17.81 ± 2.17	21.66 ± 3.86	This study
	Planted	Typhoon	0.90 ± 0.28	16.41 ± 0.28	16.41 ± 0.28	This study
	Colonized	Fishpond	0.59 ± 0.30	16.04 ± 0.30	16.04 ± 0.30	This study
Mindoro	Natural	Earthquake/Typhoon	2.10 ± 0.30	8.00 ± 0.40	10.20 ± 0.70	Salmo et al. 2019
Global*	Natural	Mature		1.74 ± 0.23		Alongi 2014
		Mature		1.63 ± 0.40		Breithaupt et al. 2012
		Mature		2.26 ± 0.39		McLeod et al. 2011
		Conserved/Disturbed		5.00 – 9.00		Perez et al. 2018
		Mature		0.44 – 3.50		Wilkinson et al. 2018
Australia	Natural (salt marsh colonized by mangroves)	Mature	9.10 ± 1.90	18.40 ± 6.60	27.50 ± 8.50	Kelleway et al. 2016
China	Planted	Deforestation/Urbanization		1.55		Lunstrum and Chen 2014
French Guiana	Natural	Mature	3.58	3.00 ± 1.80	6.58 ± 1.80	Walcker et al. 2018
Indonesia	Natural	Mature	16.60 ± 1.10	1.50 ± 0.40		Sidik et al. 2019
	Colonized fishpond [+]	Fishpond	16.20 ± 1.70	2.20 ± 0.60		Sidik et al. 2019
	Colonized [+] fishpond/planted	Fishpond	4.90 ± 0.70	8.30	58.00 – 96.00	Cameron et al. 2018
Malaysia	Planted	Deforestation	4.40 ± 0.00	2.9 – 6.1	9.50	Adame et al. 2018

* review paper; [+] stand age ca. 10 yrs

Post-typhoon canopy refoliation, seedling recruitment and growth, and eventually natural revegetation will help recover carbon stocks. The estimated recovery in some typhoon-damaged mangroves range from 10 to 25 years (Salmo et al. 2014). In Samar however, the rates of recovery for both natural and planted stands are very slow (based on vegetation structure) and can be attributed to the extent of damage (as most trees died and those that survived are severely damaged) with very few seedling recruits (seedling density: 1952 ± 562 individuals/ha; Table 1). In fact, the natural mangrove stands in Maliwaliw even had a negative sequestration rate (-0.29 ± 0.16 Mg/ha/yr) because of dead trees and lower SC (and hence reduced carbon stock) at the upper depth (Figure 2B) measured during the second sampling. Although Primavera et al. (2016) reported an initial rapid recovery in most natural stands in Samar and Leyte, it is possible that the negative rate in Maliwaliw is a manifestation of a lag effect that is known to happen even ten years post-typhoon similar to the typhoon-damaged mangroves in Nicaragua and Dominican Republic (Roth 1992; Sherman et al. 2001). Similarly, the slow and negative sequestration rates are also reflected in the fluctuations in both the 20-cm and 100-cm samples (Figures 2B and 3) indicating reduced accumulation and sequestration rates at different times.

In contrast with the typhoon-damaged mangroves, the mangrove-colonized fishponds have a more stable carbon sequestration rate (inferred from down-core carbon variation in Figures 2B and 3). In fact, the OC at the 95- 100-cm depth was higher than the other depths (Figure 3) indicating that recent carbon accumulation and sequestration are much lower as compared to the time when mangroves were converted to aquaculture ponds.

When aquaculture fishponds are abandoned, "spaces" are provided for mangroves to colonize (dos Reis-Neto et al. 2019)

and eventually recover carbon stocks (Duncan et al. 2016). Similar with most aquaculture ponds in SE Asian countries, mangroves are clear cut and excavated to around 100-cm depth (Primavera et al. 2013). These sediments have the highest carbon stocks. The damaged sediments are highly compacted and may have also released sulfide that limits seedling recruitment and growth (tree density: 424 ± 176 individuals/ha; seedling density: 573 ± 206 individuals/ha; Table 1). Ten years after abandonment, the mangrove-colonized fishponds still have impoverished condition resulting to very slow colonization process. The mangroves in Bani have less developed vegetation and sediment conditions unlike the mangrove-colonized fishponds in Aklan (Duncan et al. 2016) and Indonesia (Cameron et al. 2018; Sidik et al. 2019). Our findings imply that the recovery of carbon stocks in mangrove-colonized fishponds, if left at natural colonization process, may be longer for both the vegetation and sediment compartments.

SUMMARY

Restoration and Implications on Estimates of Blue Carbon in Philippine Mangroves
When healthy, the Philippine mangroves (national average of ca. 624 Mg C/ha; Salmo 2019) can potentially contribute carbon sequestration estimated at 180 Tg (1 Tg = 1,000,000 Mg) that is equivalent to ca. 661 Tg of avoided CO_2 emission. These values definitely will significantly contribute on achieving the commitment of the Philippine government to Paris Agreement of reducing 70 % of GHG emissions by 2030. Hence, aside from the other ecosystem services naturally rendered by mangroves, its conservation will significantly contribute in climate change adaptation and mitigation strategy.

However, Philippine mangroves are subjected to various natural and anthropogenic disturbances. The occurrences of catastrophic typhoons will definitely cause significant reductions in carbon stocks. With an annual average of 20 typhoons, it is possible that typhoon-disturbed mangroves can be subjected to repeated disturbances. That is, while still undergoing recovery, it is highly possible that another catastrophic typhoon will occur resulting to further delay in recovery and therefore further reduction in carbon stocks. Aside from typhoons, Philippine mangroves have long been subjected to anthropogenic disturbances, but primarily land use conversion (or modification) such as aquaculture ponds. In Palawan for example, when healthy mangroves are converted to aquaculture ponds, its carbon stocks are reduced by at least 50 – 90 % (Castillo et al. 2017). Furthermore, even when the fishponds are abandoned, the recovery of carbon stocks from both vegetation and sediment compartments are slow (Castillo et al. 2018). Hence, to better manage "blue carbon ecosystem service", mangrove conservation should be complemented with a more pro-active restoration.

Mangrove restoration, when done properly, will definitely help enhance carbon sequestration in Philippine mangroves (Salmo and Juanico 2015). However, the conventional practice of mangrove planting in coastal fringes produces sub-optimal success with minimal carbon sequestration. In contrast, mangroves that grows in an AUU fishponds (Figures 2A and 3) following natural colonization process can sequester and store higher carbon stocks than those planted in coastal fringes. In Bani, the mangrove vegetation and sediment conditions in mangrove-colonized fishponds are less developed because of slow colonization process and impoverished sediment condition. But, if mangrove planting will complement the natural colonization process, carbon stocks will further increase.

There are approximately 232,000 ha of aquaculture ponds in the Philippines (cf. Castillo et al. 2017), some of which are active and some are considered AUU. Assuming 50 % of these fishponds are AUU (as some are presumed to have an expired lease based from the Philippine Fisheries Code, RA 10654), and assuming mean carbon sequestration of 624 Mg C/ha (Salmo 2019), the country will gain additional carbon stocks of 72.38 Tg equivalent to ca. 265.36 Tg CO_2e of avoided emission. But, these carbon stocks can only be achieved 10 years after mangrove planting.

To our knowledge, we reported the first account of rates of carbon sequestration, including the possible role of disturbance, in Philippine mangroves. While we acknowledge the limited number of sites and the limited post-disturbance time we covered, our study nonetheless provided an impetus in the estimation and/or calibration of sequestration rates and TCS in Philippine mangroves. In order to have a more accurate of TCS, we suggest that more permanent monitoring plots be assessed in other biogeographic regions in the country, of different ecosystem health, and of different disturbance types. By doing so, there will be a better estimate and comparison of carbon stocks in conserved vs. disturbed mangroves, an understanding of how much is being lost when mangroves are disturbed or converted to other uses, and an understanding of how much time will be needed to recover the lost carbon stocks.

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CONFLICTS OF INTEREST

None.

CONTRIBUTION OF INDIVIDUAL AUTHORS

SS conceptualized and designed the study. ELG conducted field sampling, lab analyses and drafted the manuscript. SS revised the manuscript. SS and ELG finalized the manuscript.

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Supplemental Figure 1: Principal Component Analysis (PCA) plot of mean vegetation and sediment parameters (derived from Table 1) showing patterns of similarities and dissimilarities between and among sites. The natural stands in Maliwaliw are clearly isolated from the other sites. The colonized stands are more similar with the natural stands of Tagbacan. Legend: td – tree density; sa – sapling density; se – seedling density; dia – tree diameter; sal – salinity; tmp – temperature; orp – redox potential; tds – total dissolved solids; cnd – conductivity; crate – rate of change of carbon stocks.