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Comparative Assessment of Natural, Colonized and Planted Mangroves Disturbed by Lahar Deposition in Sasmuan, Pampanga, Philippines

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ABSTRACT

The lahar deposition from the eruption of Mt. Pinatubo in 1991 altered the mangrove mudflat in Sasmuan, Pampanga. Here, we assessed and compared the vegetation and sediment characteristics of mangroves composed of pre-eruption natural stands, post-eruption colonized stands (ca. 20 yr-old), and post-eruption planted stands (ca. 7 yr-old). Our results revealed that coarse sediments dominated more relative to the fine fractions, which may be related to the massive lahar deposition in the mudflat areas. In natural stands, the organic matter (OM) decreased at 80 to 100 cm depth that coincided with high coarse content but increased from 80 cm to surface implying post-disturbance OM accumulation. Both the colonized and planted stands have similar low OM at the bottom than the natural stands. Similar patterns were observed with bulk density (BD). The natural and colonized stands have comparable vegetation and sediment characteristics implying that mangroves subjected to post-disturbance colonization process may have similar attributes with a pre-disturbance stand in ca. 20 yrs. Although the deposition of lahar materials altered the growth of pre-eruption mangrove stands, the aeration and accretion provided by coarse fractions (on a usually asphyxiated and inundated sediment) may have facilitated mangrove colonization that led to the development of the colonized stands. To our knowledge, our study was the first to report the impacts of lahar in Philippine mangroves.

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KEYWORDS

Mt. Pinatubo eruption; lahar deposition; post-disturbance recovery; mangrove stands; colonization

INTRODUCTION

The eruption of Mt. Pinatubo on June 15, 1991, deposited 5-7 km^3 of pumiceous pyroclastic flow (Pierson et al. 1992) into various river channels in central Luzon (Sasaki et al. 2003). Lahar and other sediment materials were transported downstream via the Pasig-Potrero river (Rodolfo et al. 1996) in the municipalities of Bacolor, San Fernando, Guagua, Sasmuan, Minalin, Santa Rita, Porac, and Angeles in the province of Pampanga (Hayes et al. 2002; Torres et al. 2004). The Pasig - Potrero River received ca. 0.3 - 0.5 km^3 of pyroclastic deposits (Pierson et al. 1992). Twenty percent of the total sediment that was transported in the Pasig - Potrero River alluvial fan remained mobile > 24 km (Hayes et al. 2002). Lahar remobilization and deposition was reported until 1995 (Torres et al. 2004). Lahar could have been transported from the Pasig-Potrero River, passed through the Guagua-Pasak River, and eventually deposited in the mudflat of Sasmuan (Sasaki et al. 2003).

Lahar deposition is usually perceived as a disturbance that cause negative impacts on the environment (Rodolfo et al. 1996). Sediment materials deposited after volcanic eruptions have the capacity to cause physico-chemical changes in the sediment quality and mortality to vegetation (Umbal and Rodolfo 1996). For example, the high sand and low nutrient contents of lahars (Sasaki et al. 2003) may constrain mangrove growth. Similar with other disturbances, when the effects of lahar subside, the impacted ecosystems are expected to gradually recover, although the rates and patterns of recovery may depend on various interacting factors (García-Romero et al. 2015).

Most mangroves in the Philippines are found in coastal fringes and deltas (Long and Giri 2011), making them direct lahar deposition sites. The effects of volcanic eruptions (including lahar deposition) in mangroves are rarely studied. Volcanic eruptions are unplanned disturbances that preclude optimal experimental design. Fortunately, however, the presence of natural mangrove stands in Sasmuan that survived the lahar deposition provide "proxy" information on mangrove conditions before the eruption. Then, massive lahar materials were deposited in former bare mudflats which eventually were colonized by mangroves. Some mudflats were also planted with *Rhizophora* genus (but primarily *Rhizophora mucronata* and *R. stylosa)* by the locals. The presence of pre-eruption stands and post-eruption stands (as naturally colonized and planted) provided a rare opportunity to assess and compare mangroves before vs after the lahar deposition. Here, we assessed and compared the sediment and vegetation characteristics between pre- and post-eruption mangrove stands and inferred on post-disturbance mangrove development.

MATERIALS AND METHODS

Site Description

The study was conducted in Sasmuan Bangkung Malapad Critical Habitat and Ecotourism Area (SBMCHEA) situated at Barangay Batang II, Municipality of Sasmuan, Pampanga. It is an islet within the bounding coordinates of 14.7684^0 and 14.7952^0 in the north, and between 120.6164^0 and 120.6168^0 in the east. The islet is a former barren mudflat located in the mouth of the Guagua - Pasak River leading to Manila Bay (Figure 1). The locals reported that mangroves colonized and eventually developed as a forest (ca. 20 yr-old; see also mangrove distribution depicted from Supplemental Figure). The mangrove species recorded in SBMCHEA were *Avicennia marina, A. officinalis*, *Rhizophora mucronata*, *R. stylosa*, *Sonneratia alba*, and *S. caseolaris*.

Experimental Design and Sampling

The study was designed to assess and compare the sediment and vegetation characteristics of pre-eruption natural stands and post-eruption colonized (ca. 20 yrs.) and planted (ca. 7 yrs.) stands. The criteria in selecting the sampling sites were based on the location and availability of the natural, colonized and planted mangrove stands. Representative sampling plots (of 5-m radii) were established in each site (n = 3 for each planted and colonized stands; n = 4 in natural stands). Sampling were conducted in September 2018 and January 2019. The pore water quality variables (e.g., conductivity, temperature, redox, pH, salinity, and total dissolved solids; Table 1) were measured using portable instruments (TPS WP 81 and Atago Hand-held Refractometer).

Vegetation Assessment

The mangrove vegetation was characterized from each plot following English et al. (1997). All individual plants within the plot were tagged and identified at species level. Trees were categorized as individuals with tree diameter > 5 cm. All trees in each plot were measured of tree diameter (ca. 1.3 m from the ground), total height, and crown diameter. The living above-ground and below-ground biomasses were calculated from the diameter of each measured tree using species-specific allometric equations (Komiyama et al. 2008). The tree density and biomass (as sum of above- and below-ground biomasses) were computed per plot and reported as n individuals/ha and Mg/ha, respectively. Litter production was measured from each plot using a 1 m x 1 m litter trap set two meters above ground for 30 days per sampling. The litter samples were collected and composited per litter trap. The samples were placed in zip lock bags and transported to the laboratory for analysis.

Laboratory Analyses

In the laboratory, the litter samples were air dried for ca. 24 hrs. The weight was measured from each replicate litter trap and was reported as Mg/ha/yr. For sediment samples, each sub-sample was separated and placed into pre-weighed containers on a top loading balance. For grain size analysis (GSA), the samples were analyzed for grain size composition using 2 mm, 1 mm, 0.5 mm, 125 µm, and 63 µm sieves. The collected particles were weighed per sieve and were used in the calculation of the percent composition of different grain sizes per depth. The organic matter (OM) content was analyzed using the Loss on Ignition (LOI) method (cf. Howard et al. 2014). Each sub-sample was air dried (ca. two weeks) and heated at 450 ^{0}C for four to eight hours in the muffle furnace. Each sub-sample was applied with 1 M HCl to remove inorganic carbon. The OM content (in %) was determined by dividing the difference of the weight of the samples after ignition from pre-digestion weight with the

Table 1: Summary of mean (± standard error) pore water quality variables among stands (n = 3 for colonized and planted stands; n = 4 in the natural stands) pooled from two sampling periods.

Stand	Conductivity (µmhos/mS)	Temperature (^{0}C)	Redox (mV)	pH	Salinity (ppt)	Total Dissolved Solids (ppm)
Natural	66.5 ± 26.2	26.7 ± 0.4	-131.1 ± 277.0	6.6 ± 0.1	15.4 ± 2.7	290.8 ± 89.6
Colonized	13.4 ± 8.2	25.0 ± 0.1	39.9 ± 4.6	7.0 ± 0.2	20.3 ± 0.1	193.3 ± 132.0
Planted	11.3 ± 7.5	24.5 ± 0.4	- 29.1 ± 68.7	8.4 ± 1.7	26.8 ± 3.2	56.0 ± 39.6

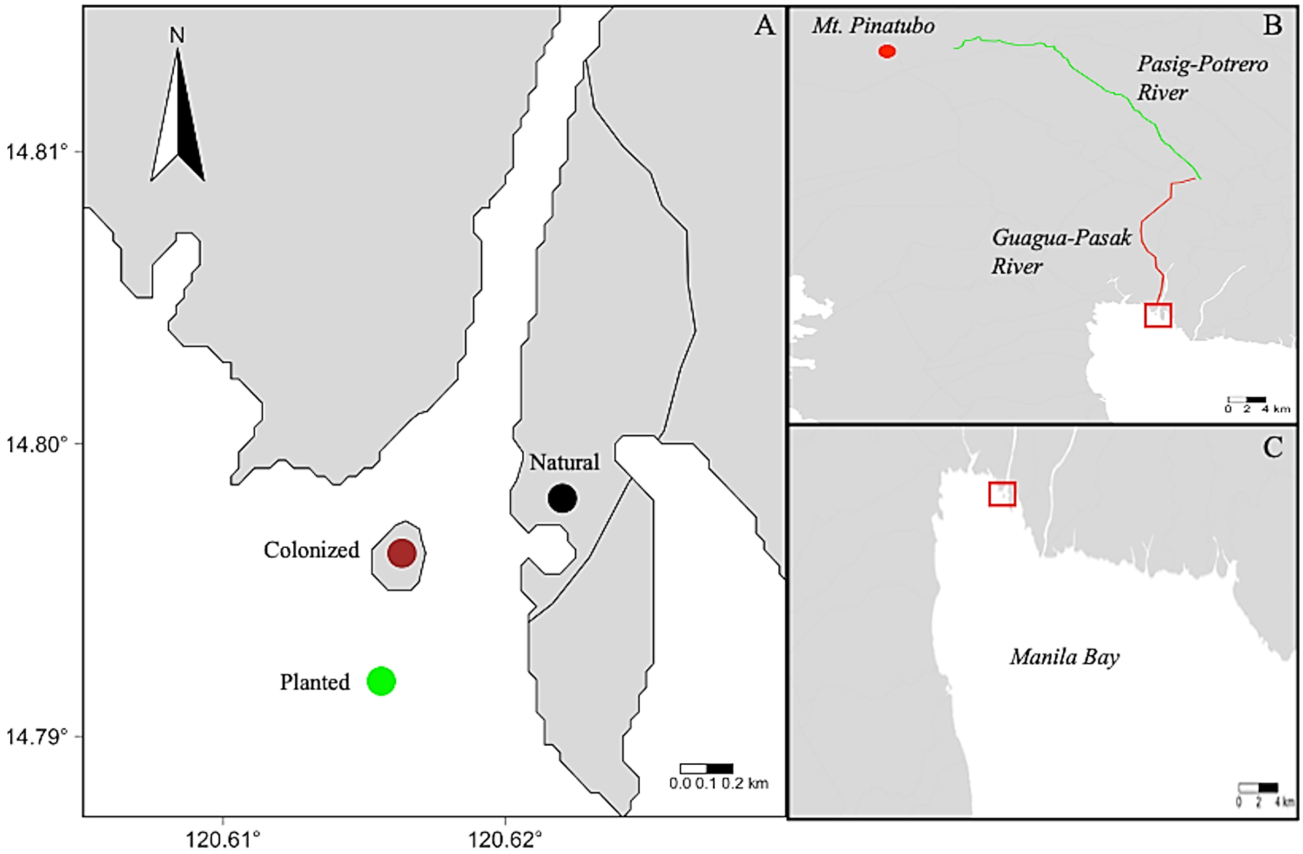

Figure 1: Location of the study site showing the distribution of sampling points relative to the location of Mt. Pinatubo (B) and Manila Bay (C).

pre-digestion weight. The bulk density (BD) was computed as weight of oven-dried samples divided by the total volume for each sub-sample prior to oven-drying.

Sediment Assessment

A one-meter sediment sample (diameter = 7 cm) was collected from each plot using a fabricated steel corer. The samples were subdivided every 5 cm to infer differences in sediment grain size over depths. A separate one-meter sediment sample was collected from each plot for the analyses of OM content and BD (cf. Howard et al. 2014). The samples were subdivided every 1 cm for 0 - 10 cm, 2 cm for 10 - 30 cm, and 5 cm for 30 - 100 cm to infer downcore variations of OM and BD. The sediment samples were stored in ziplock bags and brought to the laboratory for analysis.

Data Analyses

As parametric tests were not possible (due to high data variability), we used the nonparametric aligned ranks transformation Analysis of Variance (ARMA; see Mansouri et al. 2004) to analyze and compare the sediment and vegetation variables between stands (pooled from the two sampling periods). The grain size, OM and BD were pooled at 0-10 cm, 10-20 cm, 20-40 cm, 40-70 cm and 70-100 cm depths to infer deposition and changes at different depths. Post hoc comparisons were made using Tukey's test to determine pairwise differences (with Bonferroni corrections; $P < 0.05$) between stands. The ARMA test was implemented using the ARtool and emmeans packages (Kay et al. 2021 and Lenth et al. 2021, respectively). The relationship of sediment and vegetation characteristics were analyzed across stands and per stand using Pearson correlation. All statistical tests were implemented in R Statistical Software (R Core Team 2021).

RESULTS AND DISCUSSION

Dominant Coarse Fractions with Low OM and Bulk Density

Mangrove sediments across all vegetation stands were dominated by 0.50 mm (66.15 ± 9.92 %) and 1.00 mm (19.47 ± 8.70 %) grain sizes followed by 125 µm (8.01 ± 7.03 %) and 2 mm (4.57 ± 4.68 %; Table 2). The < 63 µm fraction was minimal (at 1.88 ± 2.15 %). The downcore distributions of the different sediment sizes did not vary significantly across vegetation stands as indicated by no lithological discontinuities of the sediment material from the surface down to 100 cm. The 2 mm size was uniformly distributed throughout the 100 cm depth and did not vary with stands in all depth gradients ($P > 0.05$; Table 2; Figure 2A). The 1 mm size varied with stands at > 20 cm depths, but was comparable at 0-20 cm depths (Figure 2B). The 0.50 mm and 125 µm sizes (Figures 2C and 2D, respectively) significantly varied with stands and depths. The 63 µm size significantly varied with stands at > 40 cm depths but was comparable at 0-40 cm depths (Figure 2E; Table 2).

The OM content was comparable between the natural (8.62 ± 0.20 %) and colonized (7.72 ± 0.28 %) stands, but were both higher than the planted stands (4.92 ± 0.17 %; Table 2; Figure 3A). In all stands, lowest OM content was found at the bottom then slightly increased at 40-70 cm. For the natural and colonized stands, OM content peaked at 20-40 cm, slightly decreased at 10-20 cm, then became relatively stable at 0-10 cm. The planted stands had much lower variation at 0-50 cm (Figure 3A). At 70-100 cm and 40-70 cm depths, the natural stands (6–9 %) had higher OM content than the colonized (3 – 4 %) and planted stands (4 – 5 %). At the upper layers however, the colonized stands had comparable OM content with the natural stands, and were 40-50 % higher than the planted stands (Table 2).

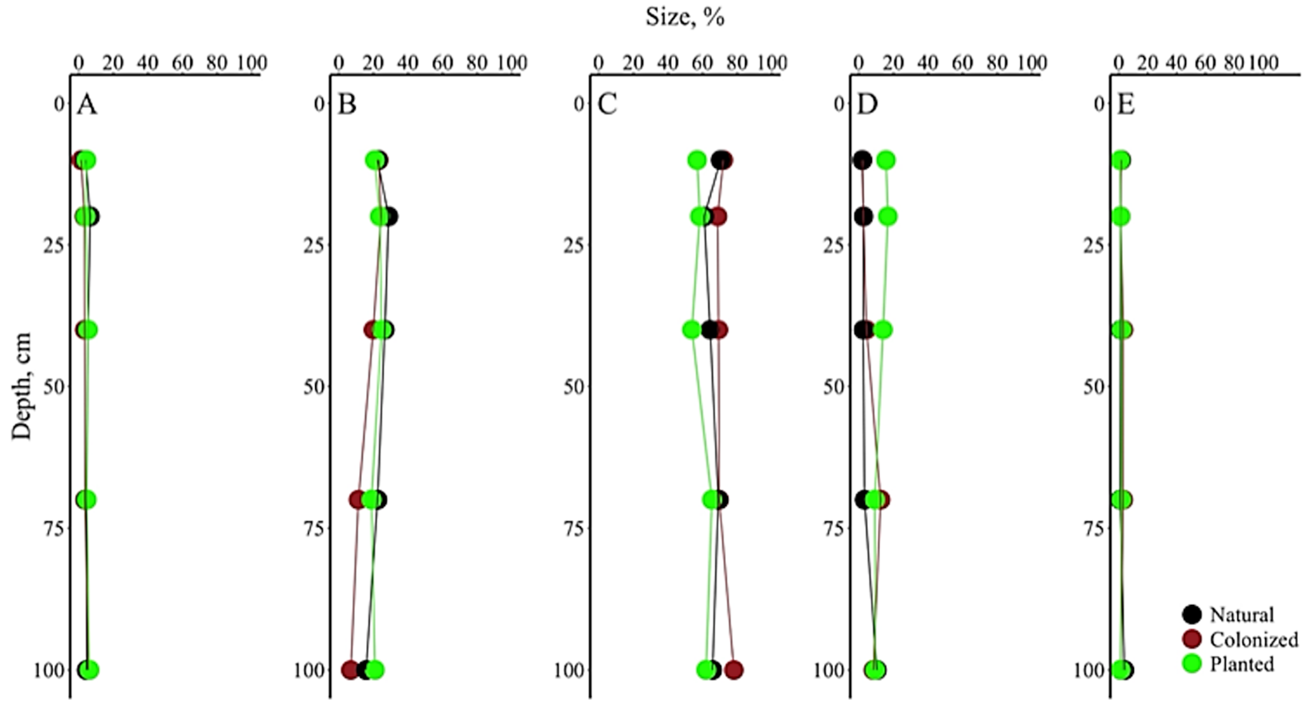

Figure 2: Down-core variation of different grain sizes 2.00 mm (A), 1.00 mm (B), 0.50 mm (C), 125 µm (D), and 63 µm (E) per stand and across stands.

Table 2: Summary results of aligned-ranks transformation Analysis of Variance (ARMA) in grain size, organic matter (OM) content and bulk density (BD) across depths and between stands (n = 3 for colonized and planted stands; n = 4 for natural stands). The OM and BD values were pooled from two sampling periods. Different superscript letters indicate differences between stands at P < 0.05 (*), P < 0.01 (**) and P (< 0.001) (***) based on Tukey's test with Bonferroni corrections (α < 0.05; ns = not significant).

Stand	Depth, cm	Grain size, 2.00 mm	1.00 mm	0.50 mm	125 µm	63 µm	OM, %	BD, g/cm^3
Natural	0-10	4.03 ± 1.28	22.38 ± 2.06	71.93 ± 1.84 ^{a}	1.87 ± 0.49 ^{b}	1.45 ± 0.52	9.84 ± 0.41 ^{a}	1.19 ± 0.04 ^{b}
Colonized		1.40 ± 0.38	23.06 ± 2.24	70.28 ± 3.15 ^{a}	2.11 ± 0.81 ^{b}	1.50 ± 0.61	9.20 ± 0.37 ^{a}	1.41 ± 0.06 ^{a}
Planted		4.52 ± 0.95	20.84 ± 4.66	56.85 ± 3.27 ^{b}	15.71 ± 3.87 ^{a}	0.89 ± 0.20	4.91 ± 0.37 ^{b}	1.15 ± 0.08 ^{b}
F		2.81	0.55	6.42	12.94	0.26	40.71	4.07
P		ns	ns	**	***	ns	***	*
Natural	10-20	6.55 ± 2.60	28.72 ± 1.85	60.91 ± 2.86	2.66 ± 0.70 ^{b}	1.15 ± 0.25	8.89 ± 0.56 ^{a}	0.64 ± 0.04
Colonized		3.23 ± 1.28	24.39 ± 3.19	68.59 ± 3.48	2.65 ± 0.52 ^{b}	1.15 ± 0.37	8.84 ± 0.47 ^{a}	0.74 ± 0.01
Planted		3.95 ± 1.08	23.71 ± 5.96	58.39 ± 6.50	16.79 ± 3.21 ^{a}	1.15 ± 0.93	4.96 ± 0.44 ^{b}	0.60 ± 0.06
F		0.32	0.46	1.16	11.42	1.28	18.08	1.35
P		ns	ns	ns	***	ns	***	ns
Natural	20-40	5.35 ± 1.78	26.60 ± 1.79 ^{a}	64.29 ± 2.48 ^{ab}	2.49 ± 0.41 ^{b}	1.27 ± 0.28	9.69 ± 0.43 ^{a}	0.49 ± 0.05
Colonized		3.33 ± 1.79	19.92 ± 1.59 ^{b}	69.15 ± 1.68 ^{a}	4.41 ± 0.92 ^{b}	3.19 ± 0.91	10.98 ± 0.44 ^{a}	0.55 ± 0.05
Planted		5.46 ± 1.75	24.81 ± 1.46 ^{ab}	53.78 ± 3.80 ^{b}	14.02 ± 2.46 ^{a}	1.96 ± 0.64	5.09 ± 0.40 ^{b}	0.41 ± 0.06
F		1.56	5.03	5.71	9.20	0.66	47.06	1.79
P		ns	**	**	***	ns	***	ns
Natural	40-70	4.45 ± 1.08	22.38 ± 1.29 ^{a}	68.99 ± 2.18	3.23 ± 0.70 ^{b}	0.95 ± 0.14 ^{b}	8.53 ± 0.46 ^{a}	0.27 ± 0.05
Colonized		3.58 ± 1.12	11.35 ± 2.47 ^{b}	69.52 ± 2.96	12.58 ± 2.07 ^{a}	2.98 ± 0.60 ^{a}	4.12 ± 0.40 ^{b}	0.30 ± 0.00
Planted		4.69 ± 0.98	18.96 ± 1.78 ^{ab}	65.37 ± 2.23	9.27 ± 2.12 ^{a}	1.74 ± 0.41 ^{ab}	5.14 ± 0.38 ^{b}	0.23 ± 0.03
F		0.84	6.94	1.22	13.67	3.33	30.43	2.61
P		ns	**	ns	***	*	***	ns
Natural	70-100	4.50 ± 3.72	15.73 ± 1.68 ^{a}	65.67 ± 2.21 ^{ab}	10.37 ± 1.70	3.77 ± 0.82 ^{a}	6.50 ± 0.43 ^{a}	0.30 ± 0.01
Colonized		5.42 ± 1.58	6.96 ± 2.36 ^{b}	78.02 ± 2.76 ^{a}	8.40 ± 1.36	1.21 ± 0.42 ^{ab}	3.41 ± 0.46 ^{b}	0.26 ± 0.02
Planted		6.23 ± 1.05	20.88 ± 1.83 ^{a}	62.03 ± 2.09 ^{b}	9.49 ± 2.14	1.18 ± 0.82 ^{b}	4.47 ± 0.28 ^{b}	0.21 ± 0.04
F		0.85	11.52	8.39	0.09	5.34	13.83	2.73
P		ns	***	***	ns	**	***	ns

The down-core variations of BD were similar across stands (Figure 3B). It was homogenous from 50 cm to 100 cm, slightly decreased at 35 cm, then increased towards the surface. There were no significant differences in the BD among vegetation stands at the 10-20 cm, 20-40 cm, 40-70 cm, and 70-100 cm depths (P > 0.05). At the surface, the colonized stands had higher BD (1.41 ± 0.06 g/cm^3) than the natural (1.19 ± 0.04 g/cm^3) and planted stands (1.15 ± 0.06 g/cm^3; Table 2).

The apparent similarity of the 0.50 mm grain size from the 0 to 100 cm depths suggest the continuous deposition of lahar sediments from Mt Pinatubo (Hayes et al. 2002; Torres et al. 2004) and the similarity in the origin and sources of the sediments into the mudflat areas (Sasaki et al. 2003). Mangrove sediments particularly in a mudflat environment are usually characterized by high fine sediment fractions such as silt and clay (see for example in Calapan, Oriental Mindoro [Salmo et al. 2019] and Kalibo, Aklan [Salmo et al. 2013]). However, the mangrove sediments in Sasmuan in all stands were dominated by coarse fractions (> 80 %; Table 2) suggesting lahar materials deposition from Mt. Pinatubo eruption, which is characterized by coarse and sand fractions (Sasaki et al. 2003). The deposition of lahar materials may have reached more than one-meter depth (*pers. obs.*), although different stands had different accumulation patterns. The dominance of coarser size fractions with depths may indicate different amounts and several times of deposition (or suspension, remobilization and redeposition), which likely happened at different post-eruption periods (Torres et al. 2004). The higher fine fractions at the bottom for the natural stands (Figure 2E) suggest pre-eruption nature of sediments which was then probably altered by the massive deposition of coarse sediment fractions that occurred after the eruption. Together, these results suggest that it is likely that the sediment materials in both the colonized and planted stands were relatively more recent as compared to the natural stands.

The dominance of coarse sediment fractions also affected the OM and BD in all vegetation stands (Figures 3A and 3B). At 35-100 cm depths, the sediments have almost homogenous distribution because of coarse sizes having lighter weights than the finer sizes. But, as depth approaches the surface, BD increased indicating accumulation of denser materials. The higher BD in the colonized stands may indicate its relatively better efficiency in the trapping/accumulation of sediments (see for example Joshi and Ghose 2014) as compared with the natural and planted stands.

The OM content in this study was comparable with the natural, colonized, and planted stands in other mangrove areas in the Philippines (Table 3). The higher OM content in the natural and colonized stands (as compared with the planted stands) are probably related to the amount of litter materials produced and the structural complexity of the mangrove vegetation that contributes to the trapping and stabilization of OM (Sasmito et al. 2020). The deposition of new sediments in the natural and colonized stands have buried the OM deep into the sediments

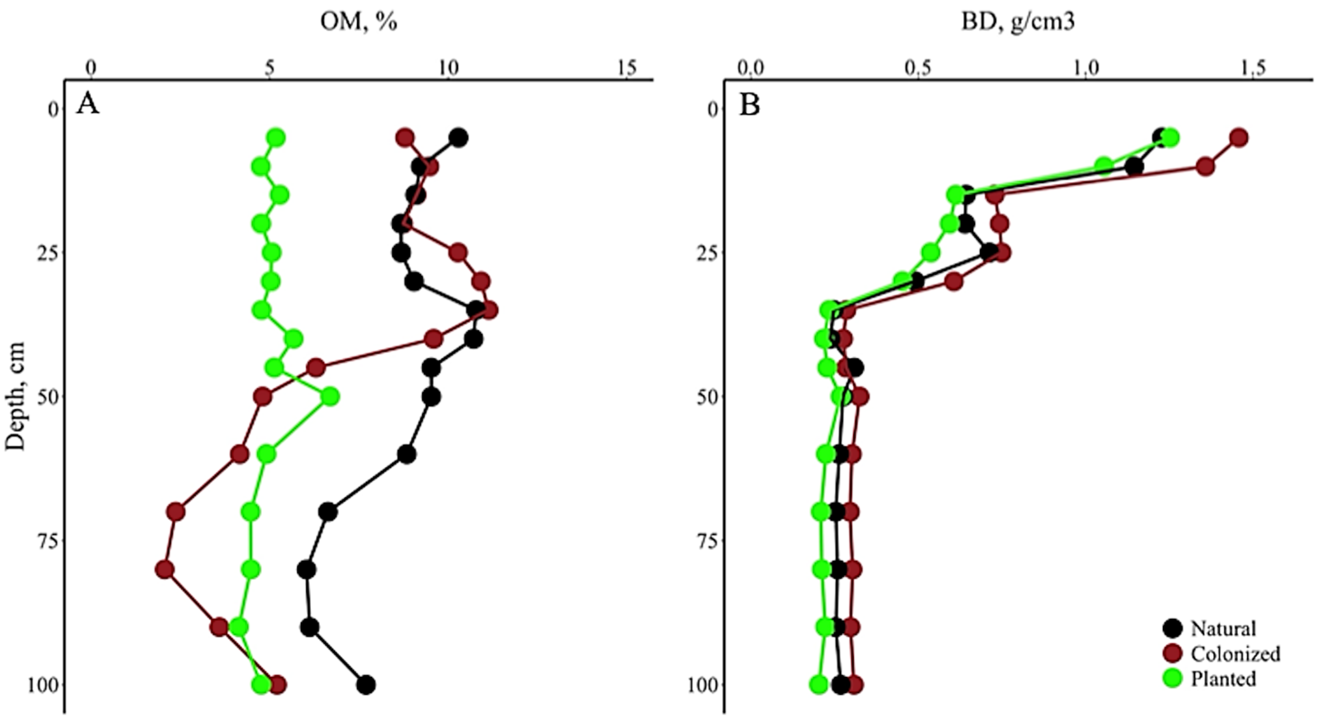

Figure 3: Down-core variation of organic matter (%; A) and bulk density (g/cm^3; B) with depths per stand and across stands.

Table 3: Comparative OM and vegetation attributes among natural, colonized and planted mangrove stands (this study; pooled from two sampling periods) with other mangrove stands in the Philippines (* - stem density).

Site	Stand Type/ Age (yrs)	OM, %	Tree diameter (cm)	Total Height (m)	Tree density (trees/ha)	Biomass (Mg/ha)	Reference
Sasmuan	Natural	8.26	12.02	7.84	1082	92.13	This study
Salcedo, Samar	Natural	6.42	4.94	3.40	1570	27.22	Salmo and Gianan 2019
Salcedo, Samar	Natural	6.42	2.49	3.80	340	19.36	Salmo and Gianan 2019
Puerto Princesa, Palawan	Natural	-	4.33		1620	149.83	Castillo et al. 2018
Palauig, Zambales	Natural	13.67	11.76	11.50	1399	137.98	Salmo et al. 2013
Masinloc, Zambales	Natural	11.73	10.05	10.08	1485	142.79	Salmo et al. 2013
Dumangas, Iloilo	Natural	3.59	18.0	6.67	2151*	241.62	Duncan et al. 2016
Kalibo, Aklan	Natural	2.25	5.76	6.16	6500*	177.88	Duncan et al. 2016
Leganes, Iloilo	Colonized (fishpond)	2.94	3.27	1.99	2380*	15.25	Duncan et al. 2016
Dumangas, Iloilo	Colonized (fishpond)	4.88	3.98	2.89	6951*	37.96	Duncan et al. 2016
Bani, Pangasinan	Colonized (10; fishpond)	5.99	4.20	4.70	743	4.55	Salmo and Gianan 2019
Sasmuan	Colonized (20; lahar)	8.06	13.59	7.36	934	97.01	This study
Calapan, Oriental Mindoro	Colonized (23; earthquake-uplift)	3.78	9.82	5.80	2600	94.77	Salmo et al. 2019
Anda, Pangasinan	Planted (6)	1.02	2.50	2.01	7780	21.12	Salmo et al. 2013
Sasmuan	Planted (7)	5.88	6.84	4.95	1061	17.86	This study
Alaminos, Pangasinan	Planted (8)	1.49	4.00	3.66	6450	22.56	Salmo et al. 2013
Anda, Pangasinan	Planted (10)	2.49	4.50	4.14	2387	38.73	Salmo et al. 2013
Bolinao, Pangasinan	Planted (11)	7.53	5.00	5.32	1886	45.37	Salmo et al. 2013
Kalibo, Aklan	Planted (12)	6.14	6.00	6.41	2122	51.43	Salmo et al. 2013
Kalibo, Aklan	Planted (17)	6.62	8.96	8.00	1886	101.80	Salmo et al. 2013
Bani, Pangasinan	Planted (18)	7.99		10.51	1358	90.59	Salmo et al. (2013b)
Salcedo, Samar	Planted (20)	5.33	3.15	3.30	1400	1.75	Salmo and Gianan 2019
Balanga, Bataan	Planted (20)	6.62	8.74	15	1560	128.86	Castillo and Breva 2012
Pinabacdao, Samar	Planted (27)	16.79					Castillo and Breva 2012

resulting in the long-term preservation of OM in the mangrove sediments (Dicen et al. 2019). The amount of OM at the 100 cm depth in the natural stands indicate the ambient high OM content prior to the lahar deposition. However, the accumulation of coarser sizes and less dense sediments contributed to lower OM at the 70-100 cm depths (Figure 3A) as lahar materials are known to have low OM (Dacanay 1997). When mangroves are disturbed (for example due to typhoons and aquaculture), OM is severely reduced but expected to gradually recover as the effects of disturbance decrease (see for example Salmo et al. 2014). The amount of OM is expected to increase with age of the stands and is an indicator of forest maturity (Marchand et al. 2003, 2004), ecosystem health, and post-disturbance recovery (Salmo et al. 2019). Similar patterns were observed in both the colonized and planted stands and appear to approach the OM content in the natural stands.

Similarities in Vegetation Characteristics

The natural (12.02 ± 1.29 cm) and colonized (13.59 ± 0.43 cm) stands had 40-50 % bigger tree diameter than the planted stands (6.84 ± 0.81 cm; $F = 6.94$; $P < 0.05$; Figure 4A). The natural stands (7.84 ± 0.50 m) had 30 – 40 % taller height than the planted stands (4.95 ± 0.45 m) but was comparable with the colonized stands (7.36 ± 0.74 m; $F = 6.97$; $P < 0.05$; Figure 4B). There was no significant difference between the colonized and planted stands ($P > 0.05$). The natural (92.13 ± 21.86 Mg/ha) and colonized (97.01 ± 9.59 Mg/ha) stands had 80 % higher biomass than the planted stands (17.86 ± 2.03 Mg/ha; $F = 6.32$; $P < 0.05$; Figure 3D). All vegetation stands had similar crown diameter (3.13 ± 0.30 m; $F = 3.83$; Figure 3C), tree density (1025 ± 205 trees/ha; $F = 0.42$; Figure 3E), and litter production (12.58 ± 1.87 Mg/ha/yr; $F = 1.20$; Figure 3F).

The similarities in vegetation structure between the natural and colonized stands demonstrate post-disturbance regeneration which is consistent with the literature (see for example Duke 2001). In fact, most variables (e.g., tree height and tree diameter) were even higher in the colonized stands. The measured tree diameter, tree height, tree density, and biomass in this study are within range of those reports from other natural and colonized mangroves in the Philippines (Table 3). Our findings may imply that vegetation structure and litter production in the colonized stands increase with time post-disturbance and possibly is still developing. It follows a restoration trajectory pattern consistent with the proposition of Duke (2001). Similar vegetation structural development patterns were observed for the planted stands except for tree density (1061 ± 449 trees/ha). The tree density is similar to mature planted mangroves (>15 yrs) but is much higher compared to other mangroves of the same age in the Philippines (Table 3). At high density planting such as the case in Sasmuan (1-1.5 m between seedlings), the planted seedlings are expected to be self-thinning as it matures. The case in Sasmuan at the least imply that it is less developed as compared to the colonized stands. The lower values for tree diameter, height and biomass indicate that its growth is sub-optimal probably due to poor species-substrate matching common in massive mangrove planting projects in the Philippines (Wodehouse and Rayment 2019). In both the natural and colonized stands, the species *A. marina* and *S. alba* dominates. These species are known colonizers that are adaptive to salinity and inundation and therefore are expected to grow and dominate in coastal fringes (Kusmana et al. 2018; Kathiresan et al. 2021). In the planted stands however, the locals planted *R. stylosa*, a common species used in massive restoration programs (Mendoza et al. 2019) but is sensitive with salinity and inundation common in coastal fringes (Asaeda and Barnuevo 2019) and therefore has stunted growth.

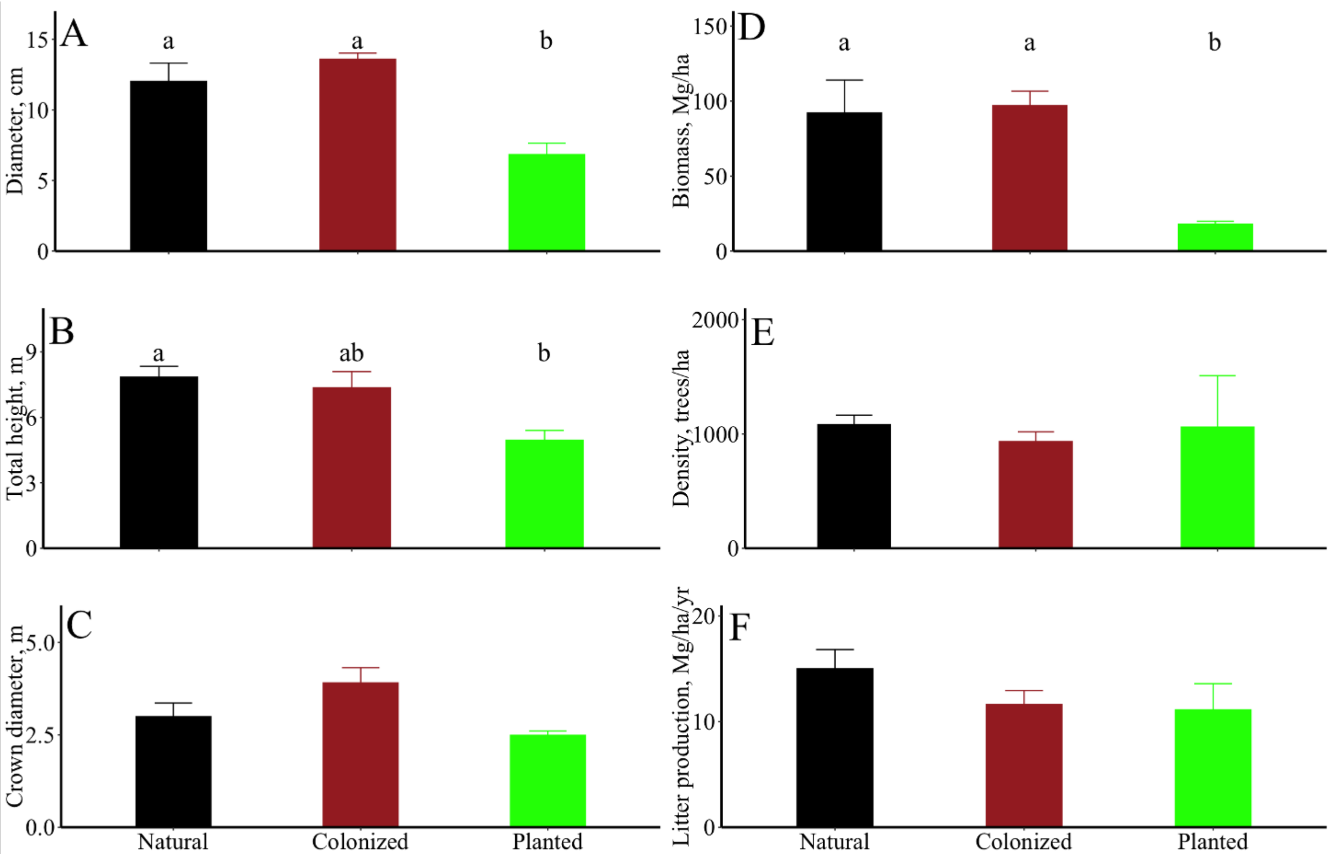

Figure 4: Differences in tree diameter (A), tree height (B), crown diameter (C), biomass (D), tree density (E), and litter production (F) among stands. Different letters between bars indicate significant difference at P < 0.05.

Sediment-Vegetation-Pore water Correlation

Across stands, the vegetation was correlated with the sediment and porewater variables although different vegetation parameters had varying correlation patterns (Table 4A). In the sediment for example, the tree diameter, tree height, and biomass were positively correlated with 125 µm, 63 µm, and OM but were negatively correlated with 0.50 mm. These variables were negatively correlated with salinity, pH, and redox. The sapling density was negatively correlated with OM and TDS but were positively correlated with salinity, pH, and redox. The crown diameter and tree density were correlated to only one to two variables (e.g., 1.00 mm and pH). In the natural stands, the vegetation was correlated with more sediment variables than porewater variables (1-2 variables; Table 4B). Among sediment variables, the 63 µm and OM have more correlations. Both the colonized (Table 4C) and planted (Table 4D) stands have more correlations than the natural stands, although different variables showed contrasting patterns.

The relationships among vegetation, sediment and pore water variables in mangroves are established (see for example Marchand et al. 2004). Such relationships are also used in inferring the state of ecosystem health, in the assessment of effects of disturbance (e.g., typhoons), and in inference of post-disturbance recovery trajectory (Peneva-Reed et al. 2020). For example, the vegetation structure and litter production provide detritus that increases OM content and regulate temperature in the sediments. In return, the sediment helps in providing a suitable environment for mangrove growth and development (Xiong et al. 2018). But it is widely reported that vegetation structure develops earlier than the sediment (Chen et al. 2021). Similar relationships were found in this study. However, different vegetation variables had different correlations with different sediment and porewater variables and in different mangrove stands. Our result implies that despite proximal distances (< 2 km) of the different vegetation stands, the sediment conditions are different although the vegetation structure may look similar.

The colonized stands followed vegetation development consistent with succession concept (Duke 2001) as expected and actually have better vegetation than the natural stands. It is also possible that the natural stands were slow to recover. Seedling recruitment and growth serves as source for post-disturbance regeneration (Duke 2001). There were very few to complete absence of seedling recruits in all stands probably implying that the sediment still has impoverished condition due to coarse sediment fractions and low OM content and BD values.

Summary: Research and Management Implications

Most Philippine mangroves are subjected to different natural (and also anthropogenic [Garcia et al. 2014]) disturbances, e.g., typhoons (Buitre et al. 2019). Depending on the frequency, recurrence and magnitude of these disturbances, mangroves are usually adaptive (Long et al. 2016) although there are also cases wherein mangroves are severely damaged that it failed to recover (Villamayor et al. 2016). The capacity of mangroves to recover depends primarily on its ecosystem health, structural complexity and extent (Rivera-Monroy et al. 2019). Disturbance resulting from volcanic eruption and deposition and accumulation of lahar in mangroves are rarely reported. To our knowledge, our study provides the first account on the effects of lahar deposition on the growth and development of mangroves. We infer that the lahar deposition altered the mangrove vegetation and sediment conditions (and partly porewater quality) in SBMCHEA. The volcanic disturbance through lahar deposition may have contributed to the differences in the vegetation and sediment characteristics although the patterns (e.g., patchiness and fragmentation) and rates of changes varies among natural, colonized and planted stands. Damages are usually reported in the forms of high tree mortalities and stunted growth in the vegetation (Aljahdali et al. 2021), and increased temperature and salinity, and reduced redox in the sediment (Alongi 2008). In most cases, vegetation recovers faster than the sediment (Chen et al. 2021) but its rate of recovery also depends on the sediment condition (Salmo et al. 2014). From Google Earth satellite images (1996, 2006, 2016, 2020; and also from Long et al. [2010], Giri et al. [2011] and Baloloy et al. [2020]) , we infer that the post-eruption natural stands became highly fragmented probably as a result of initial high tree mortalities at 1-yr to 5-yr post-eruption although the mangroves rapidly expanded until 10-yr post-eruption (Supplemental Figure). However, the mangrove cover in the natural stands gradually declined from 2000 to 2019 probably a consequence of lag effect (e.g., delayed mortality). It is likely that the initial high recovery of mangroves was due to the fast mangrove colonization and OM reserves (Osland et al. 2020). The failure to sustain its recovery may be due to its limited resiliency as it is already in its climax stage. It is also possible that the sediment still has an impoverished condition (e.g., compacted sediment) that exert prolonged stress (similar to the reports in Bali, Indonesia disturbed by volcanic eruption; Sidik et al. 2016) and limits seedling recruitment and growth. In fact, lahar materials are still visually evident during our sampling.

Vegetation has the capacity to improve the sediments, and vice versa, but it is possible that lahar may have longer or more persistent effects than other disturbances (e.g., typhoon). When sediments are severely disturbed, the post-disturbance vegetation-sediment development does not necessarily follow similar trajectories and pathways (sensu Lugo 2008). Or alternatively, it will take longer to improve the sediment (based on grain size, OM, BD and porewater values; see Table 2). As the effects of lahar deposition subside (i.e., reduced compaction, increased OM), the environmental conditions (and hence forest recovery) are expected to improve. Although the high sand content from dumped lahar materials lessens the capacity of the mangroves to grow due to lower structural stability, the dominance of coarse sediment may have actually improved aeration on otherwise asphyxiated sediments. Moreover, the sediment deposition may have resulted in the increased surface elevation of the area that eventually compensate for the usually submerged substrate. The improved aeration and the increase in surface elevation may have facilitated the colonization and eventual mangrove forest development in the colonized stands consistent with forest succession phenomenon (see for example Simpson et al. 2019; Chen et al. 2021). Hence, a contrasting pattern was observed in the colonized stands (in contrast with the natural stands) where it slowly but gradually grows and develop over time (from 4.72 to 5.42 hectares from 2000 to 2010). Most vegetation variables (e.g., tree height, tree diameter) were even higher in the colonized stands than the natural stands possibly implying that the "relatively newer" mangrove environment is more favorable for recovery than the previous condition. The planted stands have a different case and may not have similar restoration trajectory observed in the colonized stands. It is less mature and has inferior vegetation and sediment conditions than the natural and colonized stands. For one, the species composition was deliberately a consequence of species preference of mangrove planters (e.g., monospecific *R. stylosa*) rather than choosing species that naturally occurred. Hence, the planted stands had sub-optimal growth with lower vegetation and sediment values. Lower structural complexity and litter production means that the amount of OM returning to the sediment is minimal.

This study showed that mangroves can be adaptive to disturbance caused by massive lahar deposition. However, the study also showed that the lahar-derived sediments exert prolonged stresses in the older mangrove stands and the newer

Table 4: Summary results of correlation tests as correlation coefficients and significance (at * P < 0.05, ** P < 0.01 and *** P < 0.001) among vegetation, sediment and porewater variables across stands (A), in natural stands (B), colonized stands (C), and planted stands (D).

Stands/Variables	Sediment							Porewater					
	2.00 mm	1.00 mm	0.50 mm	125 µm	63 µm	OM	BD	Conductivity	TDS	Salinity	pH	Temp	Redox
A. Across stands													
Tree diameter	-0.81	-0.16	0.92 ***	-0.72 *	0.76 *	0.92 ***	0.23	0.46	0.60	-0.74 *	-0.83 *	0.65	-0.78 **
Total height	-0.87	0.05	0.80 **	-0.71 *	0.82 ***	0.97 ***	0.35	0.45	0.69	-0.81 **	-0.69	0.82 **	-0.76 *
Crown diameter	-0.54	-0.56	0.87 ***	-0.40	0.43	0.51	0.43	0.29	0.25	-0.47	-0.68	0.16	-0.41
Biomass	-0.79 **	0.00	0.83 ***	-0.77 ***	0.75 *	0.95 ***	0.11	0.44	0.66	-0.77 **	-0.77 **	0.75 *	-0.76 *
Tree density	0.25	0.59	-0.49	0.01	-0.57	-0.36	-0.01	-0.10	-0.08	0.24	0.78 **	0.02	0.55
Sapling density	0.54	0.13	-0.69	0.64	-0.69	-0.80 **	0.04	-0.61	-0.73 *	0.87 ***	0.98 ***	-0.61	0.75 *
Seedling density	0.37	0.17	-0.57	0.54	-0.64	-0.69	0.22	-0.34	-0.53	0.72 *	0.69	-0.50	0.41
Litter production	-0.75 *	0.31	0.48	-0.53	0.74 *	0.84 ***	0.12	0.32	0.49	-0.51	-0.46	0.78 **	-0.89 ***
B. Natural stands													
Tree diameter	0.73 *	-0.19	-0.03	-0.31	0.03	0.47	-0.79 *	-0.19	-0.95 ***	0.94 ***	0.50	-0.42	-0.47
Total height	-0.09	-0.96 ***	-0.76 *	0.91 ***	0.95 ***	0.83 ***	-0.14	-0.84 **	-0.09	0.14	0.69	0.28	-0.38
Crown diameter	0.30	0.87 ***	0.58	-0.84 ***	-0.85 ***	-0.72 *	0.21	0.92 ***	-0.05	0.01	-0.50	-0.50	0.15
Biomass	0.49	-0.59	-0.28	0.10	0.42	0.76 **	-0.86 ***	-0.61	-0.83 ***	0.85 ***	0.59	-0.11	-0.41
Tree density	-0.12	-0.56	-0.78 **	0.89 ***	0.72 *	0.36	0.68	-0.16	0.34	-0.31	0.49	-0.04	-0.43
Sapling density	0.92 ***	-0.25	-0.61	0.16	0.29	0.42	0.22	0.41	-0.65	0.65	0.70	-0.96 ***	-0.92 ***
Seedling density	-0.46	0.95 ***	0.82 **	-0.68	-0.89 ***	-0.99 ***	0.37	0.65	0.63	-0.67	-0.93 ***	0.20	0.74 *
Litter production	0.12	-0.70	-0.27	0.30	0.54	0.77 **	-0.83 ***	-0.87 ***	-0.55	0.57	0.49	0.27	-0.19
C. Colonized stands													
Tree diameter	-0.93 ***	0.97 ***	-0.51	-0.78 *	-0.95 ***	-0.36	-0.67	0.20	0.88 ***	0.48	-0.79 **	0.60	-0.81 ***
Total height	0.92 ***	-0.97 ***	0.49	0.79 **	0.96 ***	0.34	0.66	-0.18	-0.89 ***	-0.50	0.78 **	-0.61	0.80 **
Crown diameter	0.76 **	-0.85 ***	0.21	0.94 ***	0.99 ***	0.04	0.41	0.12	-0.98 ***	-0.74 *	0.56	-0.81 **	0.58
Biomass	-0.90 ***	0.96 ***	-0.45	-0.81 ***	-0.97 ***	-0.30	-0.63	0.14	0.91 ***	0.54	-0.75 **	0.64	-0.77 **
Tree density	0.34	-0.19	0.84 ***	-0.66	-0.34	0.92 ***	0.71 *	-0.97 ***	0.52	0.89 ***	0.58	0.83 ***	0.56
Sapling density	0.99 ***	-0.96 ***	0.87 ***	0.36	0.67	0.78 **	0.95 ***	-0.66	-0.52	0.02	0.99 ***	-0.10	0.99 ***
Seedling density	0.34	-0.19	0.84 ***	-0.66	-0.34	0.92 ***	0.71 *	-0.97 ***	0.52	0.89 ***	0.58	0.83 ***	0.56
Litter production	-0.87 ***	0.78 **	-0.99 ***	0.02	-0.35	-0.96 ***	-0.99 ***	0.89 ***	0.16	-0.39	-0.97 ***	-0.27	-0.96 ***
D. Planted stands													
Tree diameter	-0.31	-0.63	0.74 *	0.96 ***	0.99 ***	0.64	0.30	0.26	-0.34	0.28	-0.71 *	-0.36	-0.95 ***
Total height	-0.88 ***	0.88 ***	0.52	-0.44	-0.07	0.64	0.88 ***	-0.90 ***	-0.86 ***	0.89 ***	0.82 ***	0.98 ***	-0.12
Crown diameter	0.06	-0.87 ***	0.44	0.99 ***	0.88 ***	0.31	-0.07	0.12	0.03	-0.09	-0.92 ***	-0.68*	-0.77 **
Biomass	0.51	0.45	-0.87 ***	-0.89 ***	-0.99 ***	-0.79 **	-0.50	0.46	0.53	-0.48	0.55	0.15	0.99 ***
Tree density	-0.11	0.90 ***	-0.40	-0.99 ***	-0.86 ***	-0.26	0.12	-0.17	-0.08	0.14	0.94 ***	0.71 *	0.74 *
Sapling density	-0.74 *	0.96 ***	0.32	-0.63	-0.29	0.45	0.75 **	-0.78 **	-0.73 *	0.77 **	0.93 ***	0.99 ***	0.09
Seedling density	-0.96 ***	0.27	0.97 ***	0.33	0.66	0.99 ***	0.95 ***	-0.94 ***	-0.96 ***	0.95 ***	0.17	0.56	-0.80 **
Litter production	-0.85 ***	-0.02	0.99 ***	0.56	0.83 ***	0.98 ***	0.85 ***	-0.82 ***	-0.87 ***	0.84 ***	-0.09	0.33	-0.93 ***

environment can be more favorable for colonized vegetation stands. Variables that can serve as "disturbance indicators" and "recovery indicators" are well documented (Salmo et al. 2013) including its assumptions and limitations (e.g., with established trends; Weilhoefer 2011). It typically includes the structure, productivity, seedling/sapling recruits for the vegetation, and OM, and temperature for the sediments (Asbridge et al. 2015; Kodikara et al. 2018). These variables are usually designated based on its sensitivity to changes (Weilhoefer 2011). In the case of lahar disturbance where massive sediment dumping occurred, the down-core variations in grain sizes over depths, and over inter- and intra-annual short- and long-term trends (including fluctuations) may also qualify as indicator of disturbance and recovery. The grain sizes are directly related to OM content and BD. But additionally, its variation over depths or the lack of it, may also indicate probable periods when disturbance happened and post-disturbance recovery may have likely happened.

We acknowledge the limitations of our study particularly on the lack of pre-disturbance information and other factors aside from lahar that could have affected the vegetation and sediment conditions in SBMCHEA. Nonetheless, our study provides at the least a perspective on the possible effects of volcanic eruption and lahar deposition in mangroves, a condition that have direct effects on Philippine mangroves but are rarely reported. The deposited lahar inflicted damages in the mangrove vegetation and sediment (and at different post-disturbance periods), but also possibly facilitated colonization of new mangroves from improved aeration and increased surface elevation. The "disturbed/recovered mangrove forest" provides several opportunities to understand the effects of disturbance as well as restoration trajectory and pathways. Also, the SBMCHEA mangroves perform similar ecosystem services as that of natural forest, e.g., fisheries, biodiversity, etc. and is now an important site for biodiversity conservation, e.g., birds (Mayuga 2021). The site was also recently declared as an international area for wetland conservation under the RAMSAR convention (Orejas 2021; Ramsar Sites Information Service 2021). The site should be conserved, monitored, and protected for the possible effects of threats from coastal development/reclamation programs.

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CONTRIBUTION OF INDIVIDUAL AUTHORS

All authors equally contributed in the design, analyses and writing of the study. MJC, MKC and MPJ drafted the manuscript and did all the laboratory analyses. SS and MPJ did the statistical analyses and mapping. SS and IN revised and finalized the manuscript.

REFERENCES

Aljahdali MO, Munawar S, Khan WR. Monitoring mangrove forest degradation and regeneration: Landsat time series analysis of moisture and vegetation indices at Rabigh Lagoon, Red Sea. Forests 2021; 12(1), 52. doi: 10.3390/f12010052.

Alongi DM. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. Estuar Coast Shelf Sci 2008; 76(1): 1–13. doi:10.1016/j.ecss.2007.08.024.

Asaeda T, Barnuevo A. Oxidative stress as an indicator of niche-width preference of mangrove *Rhizophora stylosa*. For Ecol Manage 2019; 432: 73–82. doi:10.1016/j.foreco.2018.09.015

Asbridge E, Lucas R, Accad A, Dowling R. Mangrove response to environmental changes predicted under varying climates: case studies from Australia. Curr For Rep 2015; 1: 178-194. doi: 10.1007/s40725-015-0018-4

Baloloy AB, Blanco AC, Sta. Ana RRC, Nadaoka K. Development and application of a new mangrove vegetation index (MVI) for rapid and accurate mangrove mapping. ISPRS J Photogramm Remote Sens 2020; 166: 95-117. doi: 10.1016/j.isprsjprs.2020.06.001

Buitre MJC, Zhang H, Lin H. The mangrove forests change and impacts from tropical cyclones in the Philippines using time series satellite imagery. Remote Sens 2019; 11(6), 688. doi: 10.3390/rs11060688

Castillo JAA, Apan AA, Maraseni TN, Salmo III SG. Tree biomass quantity, carbon stock and canopy correlates in mangroves forest and land uses that replaced mangroves in Honda Bay, Philippines. Reg Stud Mar Sci 2018; 24: 174-183.

Castillo JAA, Breva LA. Carbon stock assessment of four mangrove reforestation/plantation stands in the Philippines. In: Palis HG, Pasicolan SA, Villamor CI, eds. Proceedings of the 1st ASEAN Congress on Mangrove Research and Development. Department of Environment and Natural Resources – Ecosystems Research and Development Bureau (DENR-ERDB). Manila, Philippines, 2014: 244-254.

Chen S, Chen B, Chen G, Ji J, Yu W, Liao J, Chen G. Higher soil organic carbon sequestration potential at a rehabilitated mangrove comprised of *Aegiceras corniculatum* compared to *Kandelia obovata.* Sci Total Environ 2021; 752: 142279.

Dacanay E. Restoring the productivity of the potential of Mt. Pinatubo-affected soils. In: Ando T, Fujita K, Mae T, Matsumoto H, Mori S, Sekiya J, eds. Plant Nutrition for Sustainable Food Production and Environment. Developments in Plant and Soil Sciences. Dordrecht: Springer, 1997; 78: 557-558.

Dicen GP, Navarrete IA, Rallos RV, Salmo III SG, Garcia MCA. The role of reactive iron in long-term carbon sequestration in mangrove sediments. J Soils Sediments 2019; 19(1), 501-510.

Duke NC. Gap creation and regenerative processes driving diversity and structure of mangrove ecosystems. Wetl Ecol Manag 2001; 9(3), 267-279.

Duncan C, Primavera JH, Pettorelli N, Thompson JR, Loma RJA, Koldewey HJ. Rehabilitating mangrove ecosystem services: A case study on the relative benefits of abandoned pond reversion from Panay Island, Philippines. Mar Pollut Bull 2016; 109(2), 772-782.

English SS, Wilkinson CC, Baker VV (eds.). Survey manual for tropical marine resources. 2nd edition. Townsville, QLD: Australian Institute of Marine Science, 1997.

Garcia KB, Malabrigo PL, Gevaña DT. Philippines' mangrove ecosystem: status, threats and conservation. In: Faridah-

Hanum I, Latiff A, Hakeem KR, Ozturk M, eds. Mangrove Ecosystems of Asia. New York: Springer, 2014: 81-94.

García-Romero A, Alanís-anaya R, Muñoz-Jiménez J. Environmental factors that affect primary plant succession trajectories on lahars (Popocatépetl Volcano, Mexico). J Mt Sci 2015; 12(5): 1254-1266. doi: 10.1007/s11629-014-3237-4

Giri C, Ochieng E, Tieszen LL, Zhu Z, Singh A, Loveland T, Masek J, Duke N. Status and distribution of mangrove forests of the world using earth observation satellite data. Glob Ecol Biogeogr 2011; 20(1): 154-159. doi: 10.1111/j.1466-8238.2010.00584.x

Google Earth V 7.3.3.7786. (31 December 1996, 31 December 2006, 2 February 2016, 30 January 2020). Sasmuan, Pampanga. 14° 47′ 59.69″ N, 120° 37′ 9.75″ E, Eye alt 2.85 km. Landsat/Copernicus and Maxar Technologies 2021. http://www.earth.google.com [12 February 2021].

Hayes S, Montgomery D, Newhall C. Fluvial sediment transport and deposition following the 1991 eruption of Mount Pinatubo. Geomorphology 2002; 45(3-4): 211-224. doi: 10.1016/s0169-555x(01)00155-6

Howard J, Hoyt S, Isensee K, Telszewski M, Pidgeon E. Coastal blue carbon: methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses. Arlington, Virginia: Conservation International, Intergovernmental Oceanographic Commission of UNESCO, & International Union for Conservation of Nature, 2014.

Joshi HG, Ghose M. Community structure, species diversity, and aboveground biomass of the Sundarbans mangrove swamps. Trop Ecol 2014; 55(3): 283-303.

Kathiresan K, Rajendran N, Balakrishnan B, Thiruganasambandam R, Narayanasamy R. Carbon sequestration and storage in planted mangrove stands of *Avicennia marina.* Reg Stud Mar Sci 2021; 43: 101701.

Kay M, Elkin L, Higgins J, Wobbrock J. *ARTool: Aligned Rank Transform for Nonparametric Factorial ANOVAs*. 2021. R package version 0.11.0, https://github.com/mjskay/ARTool. doi: 10.5281/zenodo.594511.

Kodikara KAS, Jayatissa LP, Huxham M, Dahdouh-Guebas F, Koedam N. The effects of salinity on growth and survival of mangrove seedlings changes with age. Acta Bot Brasilica 2018; 32(1): 37-46. doi: 10.1590/0102-33062017abb0100.

Komiyama A, Ong J, Poungparn S. Allometry, biomass, and productivity of mangrove forests: A review. Aquat Bot 2008; 89(2): 128-137. doi: 10.1016/j.aquabot.2007.12.006.

Kusmana C, Hidayat T, Tiryana T, Rusdiana O, Istomo. Allometric models for above- and below-ground biomass of *Sonneratia* spp. Glob Ecol Conserv 2018; 15: e00417.

Lenth, RV (2021). emmeans: Estimated Marginal Means, aka Least-Squares Means. 2021. R package version 1.6.3. https://CRAN.R-project.org/package=emmeans

Long J, Giri C. Mapping the Philippines' mangrove forests using Landsat imagery. Sensors 2011; 11(3): 2972-2981. doi: 10.3390/s110302972

Long J, Giri C, Primavera J, Trivedi M. Damage and recovery assessment of the Philippines' mangroves following Super Typhoon Haiyan. Mar Pollut Bull2016; 109(2): 734–743. doi: 10.1016/j.marpolbul.2016.06.080

Lugo AE. Visible and invisible effects of hurricanes on forest ecosystems: an international review. Austral Ecol 2008; 33(4): 368-398. doi: 10.1111/j.1442-9993.2008.01894.x

Mansouri H, Paige RL, Surles JG. (2004). Aligned rank transform techniques for analysis of variance and multiple comparisons. Commun Stat Theory Methods 2004; 33(9): 2217-2232. doi: 10.1081/STA-200026599

Marchand C, Lallier-Vergès E, Baltzer F. The composition of sedimentary organic matter in relation to the dynamic features of a mangrove-fringed coast in French Guiana. Estuar Coast Shelf Sci 2003; 56(1): 119-130. doi: 10.1016/s0272-7714(02)00134-8

Marchand C, Baltzer F, Lallier-Vergès E., Albéric P. Pore-water chemistry in mangrove sediments: relationship with species composition and developmental stages (French Guiana). Mar Geol 2004; 208(2-4): 361-381. doi: ff10.1016/j.margeo.2004.04.015

Mayuga JL. Sasmuan Pampanga Coastal Wetlands: PHL's 8th wetland of international importance. Retrieved March 24, 2021, from https://businessmirror.com.ph/2021/02/07/sasmuan-pampanga-coastal-wetlands-phls-8th-wetland-of-international-importance/

Mendoza ARR, Patalinghug JMR, Divinagracia JY. The benefit of one cannot replace the other: seagrass and mangrove ecosystems at Santa Fe, Bantayan Island. J Ecol Environ 2019; 43(18). doi: 10.1186/s41610-019-0114-7.

Orejas T. Sasmuan is haven for birds, mangroves. Philippine Daily Inquirer. Retrieved February 21, 2021, from https://newsinfo.inquirer.net/1392895/sasmuan-is-haven-for-birds-mangroves

Osland MJ, Feher LC, Anderson GH, Vervaeke WC, Krauss KW, Whelan KRT, Balentine KM, Tiling-Range G, Smith TJ, Cahoon DR. A tropical cyclone-induced ecological regime shift: mangrove forest conversion to mudflat in Everglades National Park (Florida, USA). Wetlands 2020; 40: 1445-1458. doi:10.1007/s13157-020-01291-8

Peneva-Reed EI, Krauss KW, Bullock EL, Zhu Z, Woltz VL, Drexler JZ, Conrad JR, Stehman SV. Carbon stock losses and recovery observed for a mangrove ecosystem following a major hurricane in Southwest Florida. Estuar Coast Shelf Sci 2020; 248: 106750.

Pierson TC, Janda RJ, Umbal JV, Daag AS. Immediate and long-term hazards from lahars and excess sedimentation in rivers draining Mt. Pinatubo, Philippines. Water-Resources Investigations Report 1992; 92- 4039.

R Development Core Team R: A language and environment for statistical computing (Version 3.4.1). R Foundation for Statistical Computing, Vienna, Austria. 2021. http://www.R-project.org/.

Ramsar Sites Information Service. Sasmuan Pampanga coastal wetlands. 2021. Retrieved from https://rsis.ramsar.org/ris/2445

Rivera-Monroy VH, Danielson TM, Castañeda-Moya E, Marx BD, Travieso R, Zhao X, Gaiser EE, Farfan LM. Long-term demography and stem productivity of Everglades mangrove forests (Florida, USA): Resistance to hurricane disturbance. For Ecol Manage 2019; 440: 79-91.

Rodolfo KS, Umbal JV, Alonso RA, Remotigue CT, Paladio-Melosantos ML, Salvador JHG, Evangelista D, Miller Y. Two years of lahars on the western flank of Mount Pinatubo: Initiation, flow processes, deposits, and attendant geomorphic and hydraulic changes. In: Newhall CG, Punongbayan RS, eds. Fire and Mud. University of Washington Press, 1996: 989-1013.

Salmo III SG, Gianan EL. Post-disturbance carbon stocks and rates sequestration: Implications on "blue carbon" estimates in Philippine mangroves. Philipp Sci Lett 2019; 12: 122-132.

Salmo III SG, Lovelock CE, Duke NC. Vegetation and soil characteristics as indicators of restoration trajectories in restored mangroves. Hydrobiologia 2013; 720(1): 1-18. doi: 10.1007/s10750-013-1617-3

Salmo III SG, Lovelock CE, Duke NC. Assessment of vegetation and soil conditions in restored mangroves interrupted by severe tropical typhoon 'Chan-hom" in the Philippines. Hydrobiologia 2014; 733(1): 85-102.

Salmo III SG, Malapit V, Garcia MCA, Pagkalinawan HM. Establishing rates of carbon sequestration in mangroves from an earthquake uplift event. Biol Lett 2019; 15(3): 20180799.

Sasaki R, Yoshida M, Ohtsu Y, Miyahira M, Ohta H, Watanabe M, Suzuki S. Soil formation of new lahar materials derived from Mt. Pinatubo. Soil Sci Plant Nutr 2003; 49(4): 575-582. doi: 10.1080/00380768.2003.10410047

Sasmito SD, Kuzyakov Y, Lubis AA, Murdiyarso D, Hutley LB, Bachri S, Friess DA, Martius F, Borchard N. Organic carbon burial and sources in soils of coastal mudflat and mangrove ecosystems. Catena 2020; 187: 104414. doi: 10.1016/j.catena.2019.104414

Sidik F, Neil D, Lovelock CE. Effect of high sedimentation rates on surface sediment dynamics and mangrove growth in the Porong River, Indonesia. Mar Pollut Bull 2016; 107: 355-363.

Simpson LT, Stein CM, Osborne TZ, Feller IC. Mangroves dramatically increase carbon storage after 3 years of encroachment. Hydrobiologia 2019; 834: 13-26.

Torres R, Mouginis-Mark P, Self S, Garbeil H, Kallianpur K, Quiambao R. Monitoring the evolution of the Pasig–Potrero alluvial fan, Pinatubo Volcano, using a decade of remote sensing data. J Volcanol Geotherm Res 2004; 138(3-4): 371-392. doi: 10.1016/j.jvolgeores.2004.08.005.

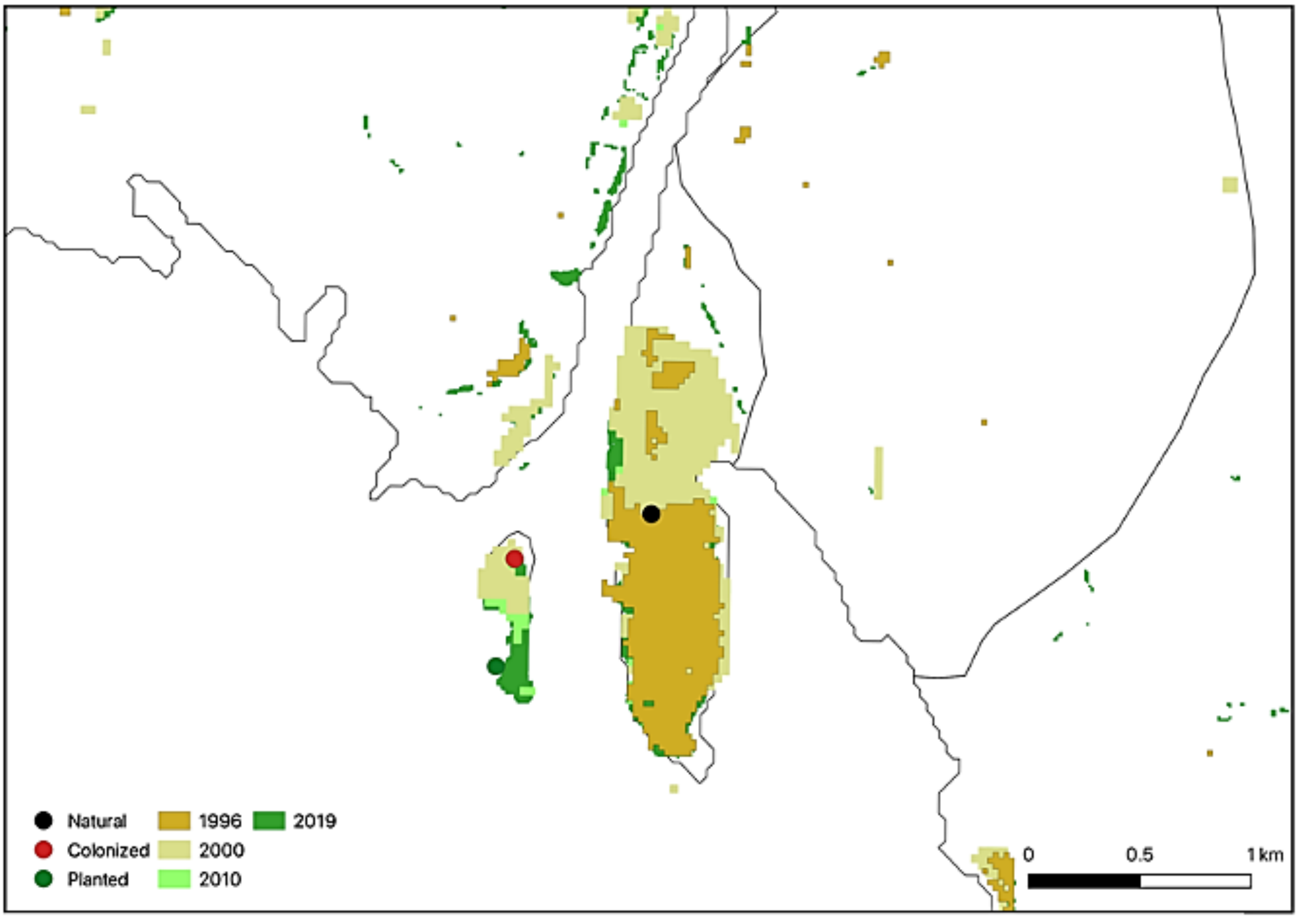
Umbal J, Rodolfo, K. The 1991 lahars of southwestern Mount Pinatubo and evolution of the lahar-dammed Mapanuepe Lake. In: Newhall CG, Punongbayan RS, eds. Fire and Mud. University of Washington Press, 1996: 951-970.

Villamayor BMR, Rollon RN, Samson MS, Albano GMG, Primavera JH. Impact of Haiyan on Philippine mangroves: Implications to the fate of the widespread monospecific Rhizophora plantations against strong typhoons. Ocean Coast Manag 2016; 132: 1–14. doi:10.1016/j.ocecoaman.2016.07.011

Weilhoefer CL. A review of indicators of estuarine tidal wetland condition. Ecol Indic 2011; 11(2): 514–525.

Wodehouse DCJ, Rayment MB. Mangrove area and propagule number planting targets produce sub-optimal rehabilitation and afforestation outcomes. Estuar Coast Shelf Sci 2019; 222: 91-102.

Xiong Y, Liao B, Wang F. Mangrove vegetation enhances soil carbon storage primarily through in situ inputs rather than increasing allochthonous sediments. Mar Pollut Bull 2018; 131: 378-385.



Supplemental Figure. Spatio-temporal distribution of mangroves in the SBMCHEA and its vicinity at pre-eruption and post-eruption periods (images derived from Long et al. (2010), Giri et al. (2011), and Baloloy et al. (2020)).