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Impact of mangrove forest structure and landscape on macroplastics capture

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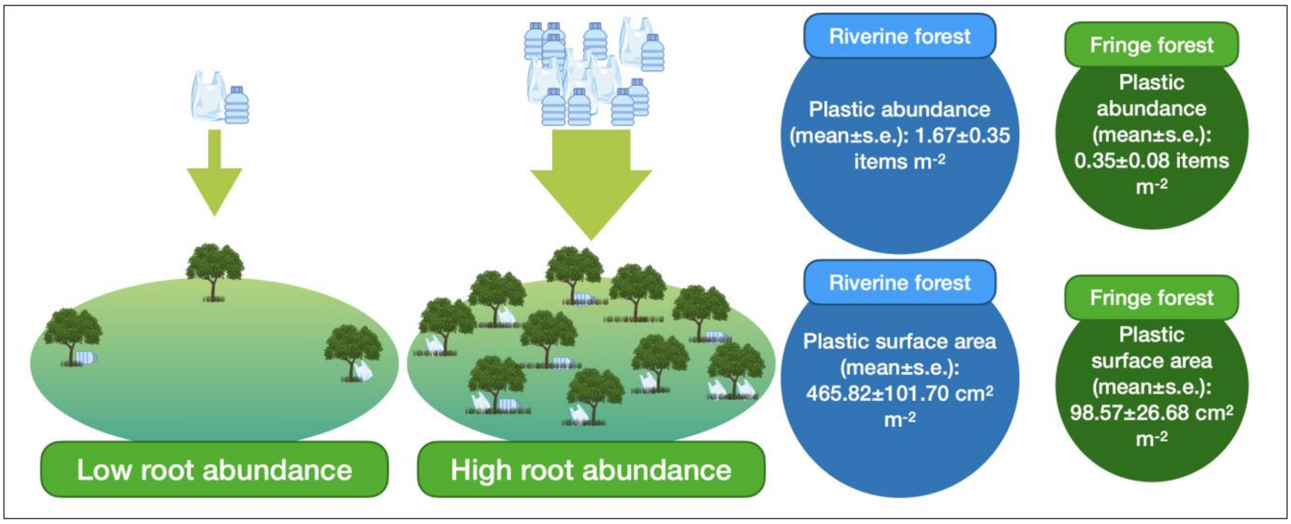
Highlights:

- Mangrove plastic debris rise with proximity to river mouth
- Landward zones have higher quantities of plastics than seaward zones
- Plastic capture is explained by above-ground root abundance
- Tree biomass does not boost plastic capture
- Plastic pollution is linked to mangrove geomorphological type

Graphical abstract:



Abstract:

Complex networks of above-ground roots and trunks make mangrove forests trap plastic litter. We tested how macroplastics relate to tree biomass, root abundance, mangrove geomorphology and river mouth proximity, surveying landward and seaward margins of seven forests in the Philippines, a global hotspot for marine plastic pollution. Macroplastics were abundant (mean±s.e.: 1.1±0.22 items m^{-2}; range: 0.05±0.05 to 3.79±1.91), greatest at the landward zone (mean±s.e.: 1.60±0.41 m^{-2}) and dominated by land-derived items (sachets, bags). Plastic abundance and weight increased with proximity to river mouths, with root abundance predicting plastic litter surface area (i.e., the cumulative sum of all the surface areas of each plastic element per plot). The study confirms rivers are a major pathway for marine plastic pollution, with mangrove roots are the biological attribute that regulate litter retention. The results suggest land-based waste management that prevent plastics entering rivers will reduce marine plastic pollution in Southeast Asia.

Keywords: Mangrove zones, Plastic litter, Root abundance, Riverine forest, Plastic pollution source, Proximity to river mouth

1. Introduction

The global load of plastic litter entering the environment is increasing, with marine inputs estimated at 14.5 million tonnes annually (Wayman & Niemann, 2021). Coastal communities are major generators of marine plastics, accounting for an 8 million tonne input per year (Jambeck et al., 2015), while riverine inputs amount to 1.7 million tonne plastic y^{-1} (Meijer et al., 2021) and fishing gear contributes 0.6 million tonnes y^{-1} (Boucher and Friot, 2017). Southeast Asia has the highest global levels of marine plastic pollution (Omeyer et al., 2022), accounting for 30% of marine plastics in the world's ocean (Jambeck et al., 2015). With an input of 0.28–0.75 million tonnes y^{-1} plastic into the sea, the Philippines ranks third in the world, after China (1.32–3.53 million tonnes y^{-1}) and Indonesia (0.48–1.29 million tonnes y^{-1}) (Jambeck et al., 2015). River mouths are considered the major source of plastic pollution along the coastline (Harris et al., 2021) and the Philippines have the greatest riverine plastic input into the ocean in the world (0.35 million tonnes y^{-1}) (Meijer et al., 2021).

Plastic exposure can have negative impacts on marine biota through suffocation, entanglement, ingestion and multiple biological processes are impacted by plastic exposure (Dar et al., 2022; Mason et al., 2022). Buoyant plastic items facilitate the dispersion of invasive marine species, thereby threatening other ecosystems, marine biodiversity and the food web (García-Gómez et al., 2021). Long exposure of plastics in seawater allows chemical pollutants to accumulate on the plastic surface, which further threaten marine biota (Zhang et al., 2020).

Mangrove forests cover about 132,000 km^2 along tropical and subtropical shores worldwide, of which 68,000 km^2 (34-42% of the world's total) are located in Asia (Hamilton and Casey, 2016). Mangroves are located along the intertidal fringe, where they offer numerous ecosystem services such as protection from tropical storms and tsunamis, and providing breeding and rearing habitats for 75% of tropical commercial fish species (Donato et al., 2011; Lee et al., 2014; Mukherjee et al., 2014). Logic has it that, because mangrove forest structure -i.e., the spatial organization of the forest (Kimins, 1997)- have abundant above-ground prop roots, pneumatophores and tree trunks that form an effective barrier, which attenuates waves and traps objects transported by tidal currents, they should also be a principal cause for the capture of floating plastic items (Horstman et al., 2014; Norris et al., 2017; Martin et al., 2019). Indeed, dense mangroves retain a higher fraction of plastic items than open forests (Ivar do Sul et al., 2014; Martin et al., 2019). In addition, the geomorphology -i.e., the topographical and bathymetric features- of the forest (Lugo and Snedaker 1974) may also play an important role in plastic distribution. Riverine mangroves that include a watercourse within them are believed to exhibit higher plastic pollution than forests without rivers, such as fringe forests bordering the open coast.

Exposure to high level of plastic pollution has negative effects on mangrove health, and trapped plastics can suffocate mangrove seedlings and accelerate the colonization of disease-forming microbes (Suyadi and Manullang, 2020). Surprisingly, the importance of mangrove roots to macroplastics trapping has only been examined by a handful of studies and information on how root abundance affects plastic retention is particularly scarce (Ivar do Sul et al., 2014; Martin et al., 2019). Items trapped by pneumatophores and prop roots are unlikely to be washed off again (Martin et al., 2019). Ivar do Sul et al. (2014) tracked plastics released in mangroves and found plastic bottles were less commonly retained than plastic bags, because bottles floated away on the tide while bags were entangled by roots (Ivar do Sul et al., 2014).

We examined how forest structures (root abundance, tree density and biomass), proximity to river mouths and mangrove geomorphological type (fringe vs. riverine forests, *Sensu* Lugo and Snedaker 1974) affect the amount of plastic material trapped by mangroves. The study was done in the Philippines, which has one of the greatest challenges with marine plastic pollution in the world (Meijer et al., 2021). The following specific hypotheses were tested: (H1) forest structure is a key cause for spatial variation in mangrove macroplastics; (H2) plastic debris increases with proximity to river mouths and (H3) will be higher in riverine than in fringing geomorphological settings.

2. Materials and methods

2.1. Study site

The study was done in seven mangroves sites of Cebu Island, the Philippines (Fig.1). The Philippines has between 35 and 40 mangrove species (Primavera et al., 2004), but Cebu Island mangroves are dominated by *Avicennia marina*, *Rhizophora* spp., and *Sonneratia alba* trees (Seidenschwarz, 1988), and many areas are the product of past *Rhizophora stylosa* mono-species mud-flat replanting (Seidenschwarz, 1988). Mangroves are found along the coastline of almost all of the island, from relatively uninhabited to densely populated areas. Differences in plastic pollution were expected between the east and west coasts, as the east has higher population density (Paler et al., 2022), while several mangrove sites on the west coast have lower population density and/or sites are protected (Lucas & Kirit, 2009).

The survey design we used reflected the survey conducted by Paler et al., (2022). Plastic abundance and forest structure were quantified on six plots of 100 m^2 per mangrove site: three plots at the seaward zone of the forest (SW) and three at the landward zone (LW). The two zones (LW and SW) were separated by >50 m of dense vegetation and plots were a minimum of 15 m apart, also separated by dense vegetation in between. Given these characteristics, the 2 zones were surveyed to understand differences in plastic composition and the dense vegetation between the plots made it difficult for plastic items to pass from one zone to the other. Seaward plots were positioned 5-10 m from the seaward limits of the forest, avoiding areas that did not dry out during neap low tides (Fig. 2). The position per plot was GPS recorded (Table S1). This design generated 42 observation plots, covering a total area of 4200 m^2. The survey was conducted at the beginning of the wet season in June 2022 when the monthly average rainfall is 179 mm (Climate Data Org, 2023).

2.2. Sampling plastic

Macroplastics debris (>2.5 cm) were collected from tree branches, roots and the forest floor in every plot. No items were found in two LW plots of the Badian site. Plastic debris were washed clean of sediments, unfolded, if necessary, dried outdoor and weighed. The length (longest dimension) and width (perpendicular to the length) were measured per item, and the surface area calculated. In order to have a common measure to compare plots in the statistical analysis, we summed up the surface areas of each plastic element per plot in order to obtain a total plot surface area covered by macroplastics. The geographical origin of manufacture per item was determined using labels, if present. Three geographical origins were recognized: the Philippines, foreign or origin unknown. Items were grouped into plastic types (bags, bottles, etc.) using the UNEP/IOC classification scheme (Cheshire et al., 2009), a universal method that facilitates between-study comparisons (e.g., Williams et al., 2016; Campbell et al., 2017).

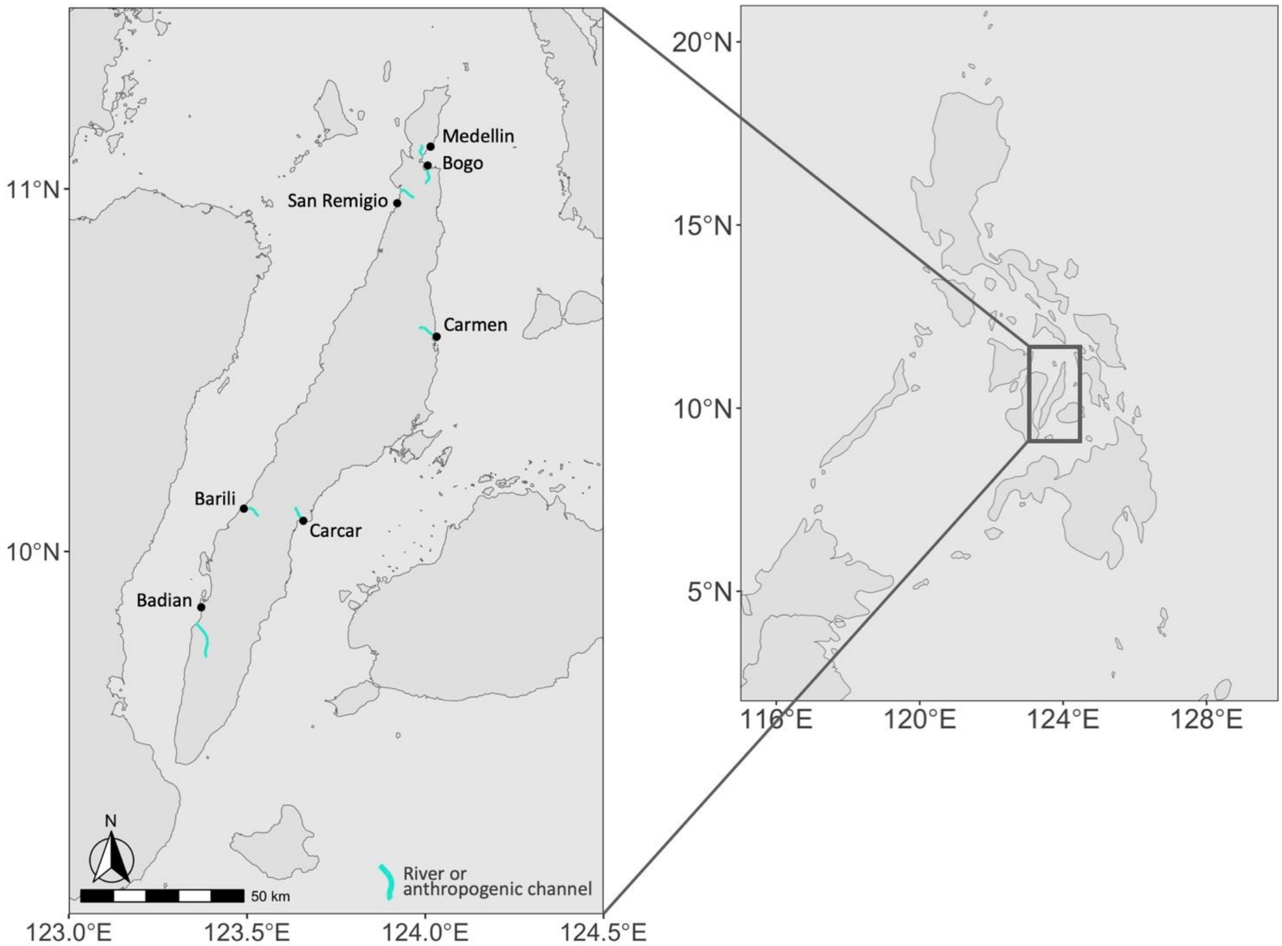


Fig. 1 Geographical location of Cebu Island, the Philippines. Black dots represent the seven mangrove sites of the survey. Rivers and anthropogenic channels (not in scale) are showed in blue.

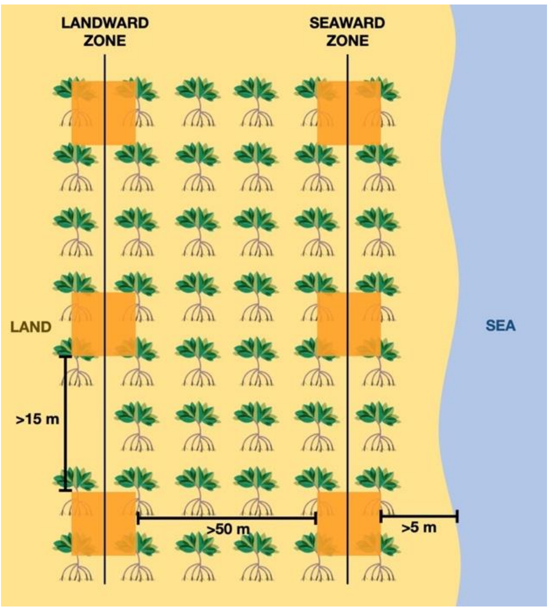


Fig. 2 Spatial disposition of the plots in the landward and seaward zone used in the survey of Cebu Island. Distances between landward and seaward zones are not to scale and were much greater than illustrated.

2.3. Explanatory variables

Detailed methodologies for calculating the below explanatory variables can be found in the Supplementary Material. All of the mangrove species that dominated our plots have an aerial root system. Root abundance (m^{-2}) was assessed in every plot. Moreover, tree biomass (kg m^{-2}), forest degradation status (m^2 of ground covered by dead branches), percentage canopy cover, seedling abundance (m^{-2}) and tree abundance (m^{-2}) were also assessed on a plot scale.
Per plot, the distance (m) between the mouth of the nearest river, or anthropogenic channel, and the geometric centre of the plot was determined using Google Maps (data of 2022). Forest geomorphological types were determined on a forest scale using satellite images in Google Maps (data of 2022). Sites were classified into two geomorphological types (only types present in survey), according to Lugo and Snedaker (1974): fringe forest or riverine forest.

2.4. Statistical analysis

Separate analyses were done for plastic litter abundance, plastic surface area and weight, unless otherwise specified. A permutational ANOVA (PERMANOVA) using the R package 'vegan' (Oksanen et al., 2007) was used to understand if plastic litter categories differed between zones (LW vs SW), with distance to proximity to urban agglomerations, or between the more populated east coast and the less populated west coast. After testing for assumption, three-way ANOVAs, with the R package 'base' (R Core Team, 2021), were performed to test for effects of coasts, geomorphological types and zones. With the R package 'nlme' (Pinheiro et al., 2007) a linear mixed model (LMM), using sites as a random effect, was used to understand which of the predictor variables explained most variation in plastic response variables, following Zuur et al., (2009). Multicollinearity between some of the seven predictor variables (assessed statistically and graphically) meant only 3 variables were used in the LMM: tree biomass, root abundance and proximity to river mouth. All analytical variables were continuous and numerical. Data were log10+1 transformed to address skewness and conform with model assumptions (Changyong et al., 2014). The statistical analyses were performed using R statistical software version 2022.02.03. Tests were considered significant if the p-value was <0.05. Values are presented as means and standard errors.

3. Results

3.1. Density and geographical distribution of plastic debris and litter types

In total 4645 plastic items were collected, collectively representing a total weight of 39.46 kg and a surface area cover of 129.54 m^2. Plastic litter abundance averaged 1.1±0.22 items m^{-2}, ranging from 0.05±0.05 items m^{-2} in Badian (LW) to 3.79±1.91 items m^{-2} in Barili (LW) (Table S3). Ninety-nine percent of labelled items were manufactured in the Philippines. Plastic types (Cheshire et al., 2009) differed significantly between the east and west coasts (PERMANOVA: $F_{1,41}=3.190$, $p<0.01$) and between the LW and SW zones (PERMANOVA: $F_{1,41}=3.144$, $p<0.01$). A key contributor to similarity between LW and east coast plots was the plastic category PL24 (sachets), while PL07 (plastic bags) (Cheshire et al., 2009) contributed to the similarity of SW and west coast plots (Fig. 3).

3.2. Effects of geomorphological type, coasts and zones

Geomorphologically, three sites were located on the open coast and were classified as fringe mangroves (Badian, Medellin and San Remigio) and four sites included a watercourse within them, so they were classified as riverine mangroves (Barili, Bogo, Carcar and Carmen) (Fig. S2).

Riverine forests had higher plastic abundance (mean±s.e.: 1.67±0.35 items m^{-2}), plastic surface area (465.82±101.70 cm^2 m^{-2}) and plastic weight (13.76±2.55 g m^{-2}) than fringe forest (0.35±0.08 items m^{-2}, 98.57±26.68 cm^2 m^{-2} and 3.57±1.67 g m^{-2}). There were two-way interactions between geomorphological type and zone for plastic abundance (ANOVA: $F_{7,34}$= 7.880, p<0.01) and plastic surface area ($F_{7,34}$= 12.944, p<0.01): riverine forests had greater plastic abundance and surface area in the landward mangrove. The amount (Fig. 4a), plastic surface area (Fig. 4b) and weight (Fig. 4c) did not differ between the east and west coasts of Cebu Island. Riverine forests had greater plastic abundance (ANOVA: $F_{7,34}$= 29.647, p<0.01) (Fig. 4d), surface area (ANOVA: $F_{7,34}$= 25.824, p<0.01) (Fig. 4e), and weight (ANOVA: $F_{7,34}$= 26.034, p<0.01) (Fig. 4f), than fringe forest. The landward zone showed greater plastic abundance (ANOVA: $F_{7,34}$= 10.711, p<0.01) in comparison with the seaward plots of Cebu Island (Fig. 4g).

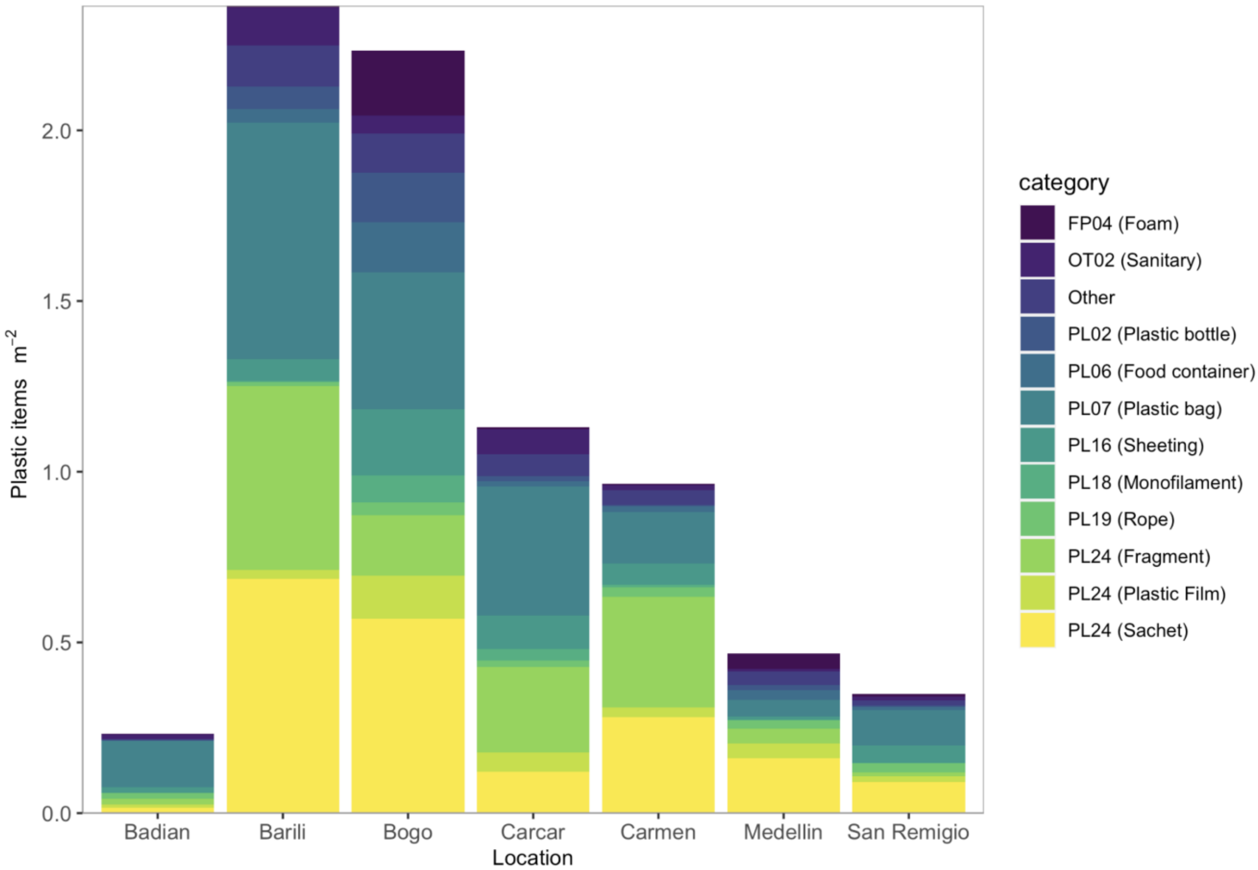


Fig.3 Plastic items observed in Cebu Island mangroves, divided per category and site. Together, 1157 sachets (PL24) and 1145 plastic bags (PL07) represented 50% of all items recorded.

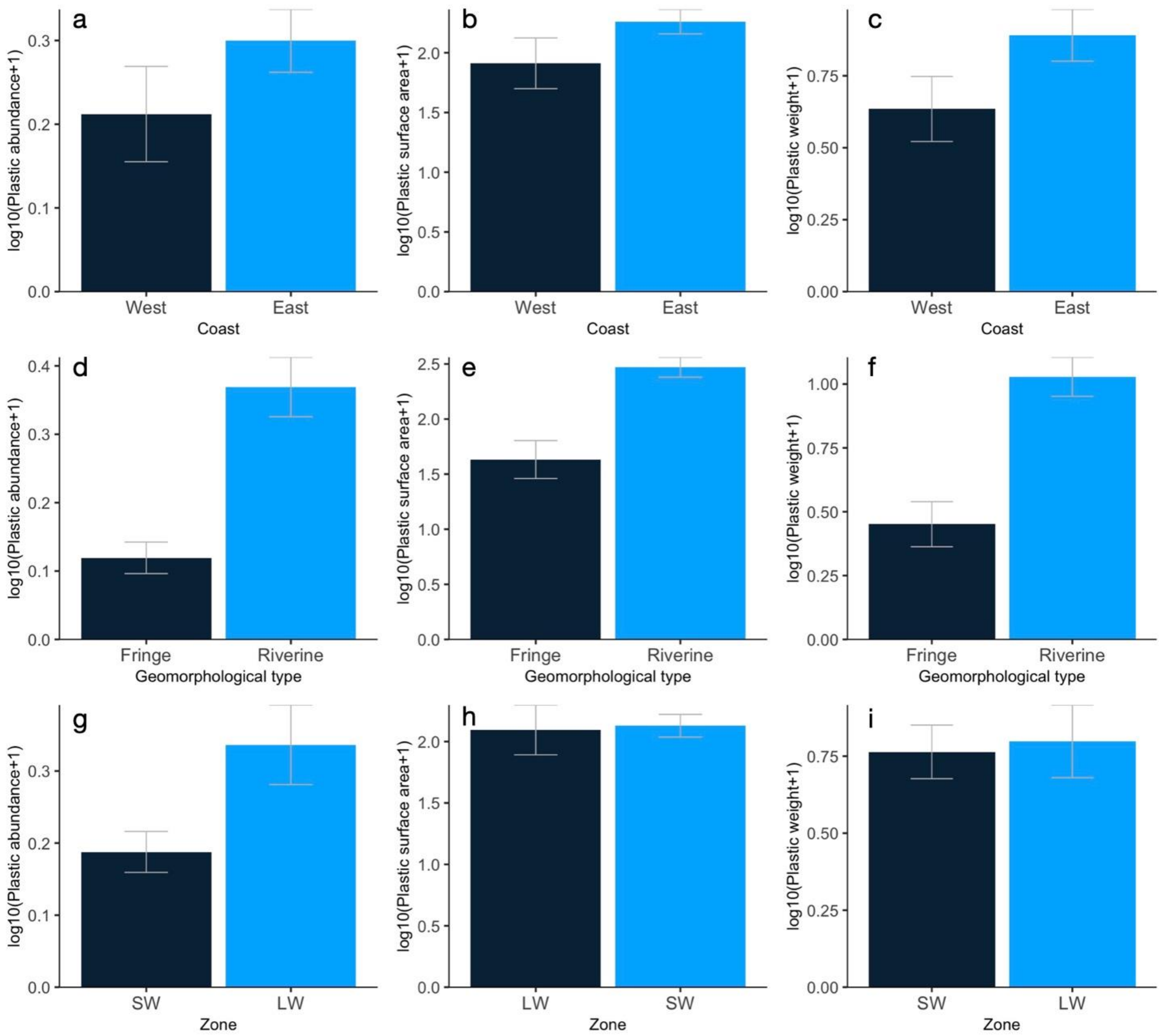


Fig. 4 Effects of coasts, geomorphological type and zones (LW: landward. SW: seaward) on the mean±s.e. abundance (items m^{-2}), surface area (cm^{2} m^{-2}) and weight (g m^{-2}) of plastic litter in Cebu mangroves.

3.3. Correlation of plastic debris with tree biomass, root abundance and proximity to river mouths

Forest above-ground root abundance varied substantially among the plots and from 3 m^{-2} in Badian (LW) to 766 m^{-2} in Carmen (SW). After model selection, the linear mixed model (LMM) showed that proximity to river mouths significantly predicted plastic litter abundance ($t_{1,34}$=-3.15, $p<0.05$) (Fig. 5a), and plastic weight ($t_{1,34}$=-2.42, $p<0.05$) (Fig. 5c). Using the LMM to predict plastic surface area we found root abundance as a significant predictor ($t_{1,34}$=4.87, $p<0.001$) (Fig. 5b). Tree biomass was not significantly related to any plastic metric.

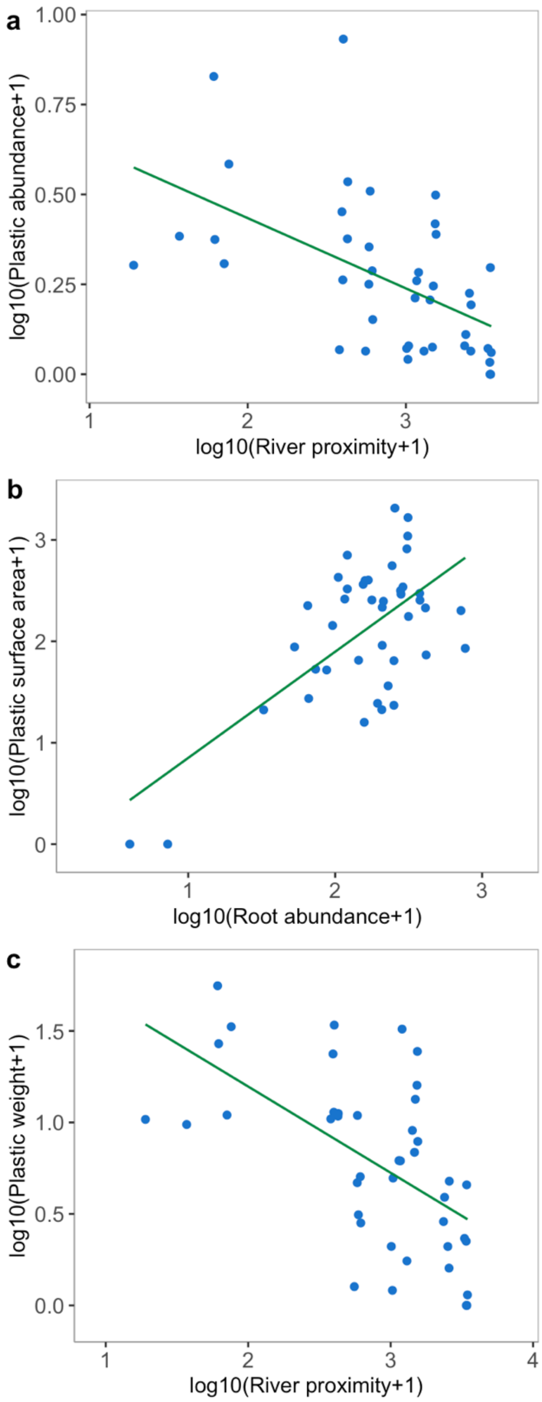


Fig. 5 Effects of proximity to river mouths and root abundance on plastics abundance, surface area and weight.

4. Discussion

This study confirms that mangroves are significant traps for plastic litter and that the quantity, weight and surface area cover of macroplastics are influenced by landscape setting. Proximity to rivers was the dominant cause for increases in plastics abundance and weight while root abundance the main cause for increases in surface area covered. Landscape context consistently explained variation in plastic pollution, with proximity to rivers stimulating plastic abundance and weight and mangroves in a riverine environment containing more plastic than those fringing the open coastline. Plastic was dominated by local and land-sourced litter types, such as sachets and plastic bags. The composition of litter varied between the landward and seaward zones of forests, and between the less populated west coast and the more populated east coast of Cebu Island, where the survey took place. The results imply that the amount of plastic arriving in mangrove sites will be principally controlled by local plastic management and landscape context, while it is the biological structure that traps plastic litter and prevents it from spreading to other coastal and marine settings.

4.1. Proximity of mangroves to river mouths

Our study corroborates the notion that marine plastic pollution is principally attributable to land-based activities (Li et al., 2016) through direct discharge from coastal populations (Jambeck et al., 2015) and mediated by riverine transport (Meijer et al., 2021). We show proximity to river mouth to be an influential driver of plastic litter in forests, with the pattern attributable to multiple factors. Rivers collect plastic throughout its basin, which may pass through cities and towns and large amounts of plastic are likely to be introduced in the river through this route (Meijer et al., 2021). Plastic input in rivers is accentuated by stormwater runoff during the rainy season (Meijer et al., 2021). Rainfall during May-October in the study region can reach a monthly average of 227.2 mm (Galarpe and Parilla, 2012). Rainwater runoff transports plastic litter to the nearest watercourse or, in case of coastal communities, directly into the marine environment. Although riverine-dominated coasts represent <1% of the coastline, they receive 52% of the global plastic waste and, as 55% of mangroves flourish in riverine areas, they are invariably exposed to river-borne plastic pollution (Harris et al., 2021). It is therefore not surprising that the riverine sites studied here accounted for the highest plastic concentrations. Yet, few studies have examined the effect of river proximity to mangrove plastic littering (Harris et al., 2021), as was done here.

Plastic pollution in the marine ecosystem is dispersed through complex physical processes, where the shape and weight of items interact with the effects of wind and wave-energy regimes (i.e., tide-dominated coasts, wave dominated coast etc.) (van Wijnen et al., 2019; Harris et al., 2021). Cebu Island mangroves are a tidally dominated and thought to receive 30% of their plastic pollution discharged through rivers (Harris et al, 2021). When plastic is dispersed in the sea as a river output, tides can help disperse plastics into mangrove forests close to the river mouth (Ivar do Sul et al., 2014). The tidal range in Cebu Island was 2.6 m during the survey period. It is likely that meso-tidal ranges, such as those in Cebu, facilitate the transport of plastics all the way up to the landward zone. Tides are thought as a strong cause for plastic input into mangroves (Ivar do Sul et al., 2014).

4.2. Tree biomass and root abundance

The literature suggests plastic pollution is boosted by mangrove tree density (Ivar do Sur et al., 2014; Martin et al., 2019). We found plastic litter statistically unrelated to tree density or biomass. Differences between studies could be caused by variable ranges in forest structural variables, such as tree density, or be caused by differences in population density and/or differences in geomorphological type. We incorporated seven sites and two zones, and, thereby, substantial variation in context. We found a positive correlations between one forest variable (root abundance) and plastic surface area covered, although it had no impact on the numbers and weights of plastic items found.

4.3. Plastic distribution and type

Paler et al., (2022) showed mangrove plastic pollution on Cebu Island was greater than at sites in the Middle East (Martin et al., 2019) and the Caribbean (García-Gómez et al., 2021), but lower than in Hong Kong (Luo et al., 2022). Studies from Southeast Asia record similar abundances, areas and weights of plastics to those encountered here (Manullang and Corry, 2020. Paler et al., 2022. Paulus et al., 2020). Population-density can change the distribution of plastic in between forests: forest near rural areas showed lower pollution than forest close to peri-urban and urban areas (Jambeck et al., 2015), as densely populated areas produce more plastic waste that will end up in the mangrove forest (Suyadi and Manullang, 2020; Luo et al., 2022; Paler et al., 2022). Here, the landward sides of forests, which is closer to human dwellings, had more plastic pollution than the seaward side, in agreement with the majority of mangrove studies (Suyadi and Manullang, 2020; Luo et al., 2022; Paler et al., 2022), and the plastic items were largely locally generated. Local Philippine brands are unlikely to be sold outside the Philippines. However, it is a difficult task to determine provenance with certainty, as items may be produced in one country, but then labelled and sold in other nation (Paler et al., 2022).

5. Conclusion

This study represents one of the first assessments of how forest structure and landscape context affect the distribution of plastic waste. It shows it is proximity of forests to river mouths that drive the plastic pollution in mangroves, causing plastic items to be trapped by aerial roots. The study confirmed that proximity to rivers and human settlements (i.e., landward zone of forests) combine to elevate plastic materials within forests (Harris et al., 2021; Martin et al., 2019). The findings affirm the importance of mangrove forests as a filter of macroplastics litter on the coast that prevents or delays further dispersal of pollutants into the marine environment (e.g., Martin et al., 2019; Luo et al., 2022).

The study elucidates the role of mangrove forest structure on macroplastics capture and contributes understanding towards dealing with the global plastic crisis. Our observations that the majority of plastics were locally produced, land derived and not marine-originating suggests that a principal route to diminishing the pollution of mangroves would be to improve the land-based management systems for handling plastics waste. Identifying mechanisms for preventing litter from entering rivers, in combination with regular clean-ups of forests, would improve coastal conservation and safeguard the many ecosystem services provided by the mangrove habitat.

CRediT authorship contribution statement

Paolo Cappa: Conceptualization; Methodology; Software; Validation; Formal analysis; Investigation; Resources; Data curation; Writing-Original Draft; Visualization. Mark E. M. Walton: Conceptualization; Validation; Investigation; Resources; Writing-Review & Editing; Supervision. Maria Kristina O. Paler: Conceptualization; Validation; Writing-Review

& Editing. **Evelyn B. Taboada:** Conceptualization; Validation; Writing-Review & Editing. **Jan G. Hiddink:** Conceptualization; Validation; Formal analysis; Resources; Writing-Review & Editing; Visualization; Project administration. **Martin W. Skov:** Conceptualization; Validation; Formal analysis; Investigation; Resources; Writing-Review & Editing; Supervision; Project administration and Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

Supplementary data on this article can be found online at:

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Supplementary material

Table S1 Coordinates of the mangrove survey plots in the Degrees Decimal minutes (DDM) format

Site	Plot	Zone	Coordinates (taken in the centre of the plot)	
Badian	1	LW	N 09°50.3468’	E 123°22.4445’
Badian	2	LW	N 09°50.3627’	E 123°22.4368’
Badian	3	LW	N 09°50.7776’	E 123°21.6309’
Badian	1	SW	N 09°50.3619’	E 123°22.3726’
Badian	2	SW	N 09°50.3608’	E 123°22.3801’
Badian	3	SW	N 09°50.4043’	E 123°22.3961’
Barili	1	LW	N 10°06.9808’	E 123°29.4656’
Barili	2	LW	N 10°06.9713’	E 123°29.4865’
Barili	3	LW	N 10°06.9996’	E 123°29.5346’
Barili	1	SW	N 10°07.0089’	E 123°29.4537’
Barili	2	SW	N 10°07.0066’	E 123°29.4599’
Barili	1	SW	N 10°07.0061’	E 123°29.5034’
Bogo	1	LW	N 11˚03.5600’	E 123˚59.5680’
Bogo	2	LW	N 11˚03.5460’	E 123˚59.5730’
Bogo	3	LW	N 11˚03.5370’	E 123˚59.5770’
Bogo	1	SW	N 11˚03.5420’	E 123˚59.6060’
Bogo	2	SW	N 11˚03.5320’	E 123˚59.6140’
Bogo	3	SW	N 11°03.5200’	E 123° 59.6312'
Carcar	2	LW	N 10°05.0005’	E 123°39.7083’
Carcar	3	LW	N 10°04.9899’	E 123°39.6895’
Carcar	1	LW	N 10°04.9994’	E 123°39.6672’
Carcar	2	SW	N 10°04.9574’	E 123°39.7019’
Carcar	3	SW	N 10°04.9505’	E 123°39.6673’
Carcar	1	LW	N 10°04.9631’	E 123°39.6868’
Carmen	1	LW	N 10˚34.8610’	E 124˚01.9860’
Carmen	2	LW	N 10˚34.8560’	E 124˚01.9740’
Carmen	3	LW	N 10˚34.8460’	E 124˚01.9610’

Carmen	1	SW	N 10˚34.8600’	E 124˚01.9980’
Carmen	2	SW	N 10˚34.8530’	E 124˚01.9950’
Carmen	3	SW	N 10˚34.8370’	E 124˚01.9790’
Medellin	1	LW	N 11˚06.7343’	E 124˚00.2768’
Medellin	2	LW	N 11˚06.7224’	E 124˚00.2581’
Medellin	3	LW	N 11˚06.6965’	E 124˚00.2679’
Medellin	1	SW	N 11°06.6383'	E 124°00.3317’
Medellin	2	SW	N 11°06.6367'	E 124°00.3167’
Medellin	3	SW	N 11°06.6200’	E 124°00.3067’
San Remigio	1	LW	N 10˚58.0170’	E 123˚55.3930’
San Remigio	2	LW	N 10˚58.0270’	E 123˚55.4000’
San Remigio	3	LW	N 10˚58.0370’	E 123˚55.4070’
San Remigio	1	SW	N 10˚58.0470’	E 123˚55.3660’
San Remigio	2	SW	N 10˚58.0520’	E 123˚55.3830’
San Remigio	3	SW	N 10˚58.0650’	E 123˚55.3960’

5.0. Variables calculation

The following approaches were used to calculate the forest structure and other explanatory variables. For clarity, only those not found to be correlated are explained.

Root abundance were quantified in three representative quadrats (1 m^2) per plot according to the following. All pneumatophores (A. marina and S. alba) were counted. Since it is difficult to find a method in the literature, prop root abundance were quantified as the times that the prop roots penetrate the soil in the quadrats (Fig. S1). Given that just one tree of Bruguiera cylindrica was found in all the survey (Badian LW), B. cylindrica root abundance was excluded by the statistical analysis. Root abundance per plot was then defined as the sum abundance of pneumatophores and prop roots.

Every tree per plot was observed for speciation (Primavera et al., 2004) and trunk circumference at breast height (DBH) (1.37 m) (Kauffman & Donato, 2012). Tree biomass was then derived from the DBH observations according to Kauffman and Donato (2012), using species-specific allometric equations derived for geographically nearest sites within South East Asia, Asia and Oceania (Table S2).

Site proximity to river mouths might, therefore, partly explain the variation in plastic abundance between sites. Consequently, per forest, the distance (m) between the mouth of the nearest river or anthropogenic channel and the geometric centre of the forest was determined using Google Maps.

The geomorphological type of the forest alters the wave and tide action in mangroves to potentially influence plastic distribution within the forest. The geomorphological type per site was determined using satellite images in Google Maps. Sites were classified into two geomorphological types according to Lugo and Snedaker (1974): fringe and riverine forest.

Table S2 Allometric equations and wood mass used to calculate mangrove biomass in the survey sites across Cebu Island.

Mangrove species	Allometric equations	Data origin	Wood mass (ρ) when required	References
Sonneratia alba	$B= 0.3841DBH^{2.101}*\rho$	Micronesia	0,78	Modified from Cole et al., 1999; ICRAF 2011
Rhizophora spp.	$B = 0.0695DBH^{2.644}*\rho$	Micronesia	1,05	Modified from Cole et al., 1999; ICRAF 2011
Ceriops spp.	$B= 0,20792DBH^{2.407}$	Vietnam	-	Binh & Nam, 2014
Excoecaria agallocha	$B= 1.0996DBH^{2}$	Bangladesh	-	Hossain et al., 2015
Bruguiera spp.	$B = 0.289DBH^{2.327}$	Sri Lanka	-	Perera et al., 2011
Nypa fruticans	$LogB=0.85*LogDBH^{2}L+1.54$	Thailand	-	Modified from Matsui et al., 2014
Avicennia marina	$B = 0.1848DBH^{2.3524}$	Indonesia	-	Dharmawan & Siregar, 2008
Avicennia alba	$B = 0.128DBH^{2.417}$	Vietnam	-	Binh & Nam, 2014

B = biomass (kg), DBH = diameter at breast height (cm), ρ = wood density (g cm^{-3}), L = frond length (Modified from Kauffman & Donato, 2012).

Fig. S1 Proop root abundance in the red quadrat were quantified as the times that the prop root penetrates the ground (red circles)

Table S3 Dataset used in this study showing plastic litter abundance, surface area and weight with the variable of root abundance, proximity to river mouth and tree biomass from each plot.

Site	Plot	Coast	Zone	Geomorphological type	Plastic abundance (items m^{-2})	Plastic surface area (cm^2 m^{-2})	Plastic weight (g m^{-2})	Root abundance (root m^{-2})	Proximity to river mouth (m)	Tree biomass (kg m^{-2})
Badian	1	West	LW	Fringe	0.15	20.10	0.14	31.6	3463	0.56
Badian	2	West	LW	Fringe	0	0	0	3	3430	0.60
Badian	3	West	LW	Fringe	0	0	0	6.25	3401	0.53
Badian	1	West	SW	Fringe	0.98	290.45	3.56	279.5	3418	1.17
Badian	2	West	SW	Fringe	0.08	86.97	1.24	51.9	3390	0.43
Badian	3	West	SW	Fringe	0.18	52.07	1.32	72.6	3300	1.27
Barili	1	West	LW	Riverine	1.38	396.46	9.82	158.6	426	0.93
Barili	2	West	LW	Riverine	2.43	555.76	10.19	243	428	1.12
Barili	3	West	LW	Riverine	7.55	2056.99	33.05	253.85	401	1.40
Barili	1	West	SW	Riverine	0.83	342.43	10.37	288	398	0.77
Barili	2	West	SW	Riverine	1.83	1090.18	22.69	310.5	393	0.48
Barili	3	West	SW	Riverine	0.17	26.308	9.46	65	379	1.01
Bogo	1	East	LW	Riverine	2.84	815.56	32.37	306.5	75	1.06
Bogo	2	East	LW	Riverine	5.73	1659.59	54.85	311.85	60	1.20
Bogo	3	East	LW	Riverine	1.37	315.2	25.94	277.62	61	0.88
Bogo	1	East	SW	Riverine	1.01	174.78	9.39	314.19	18	1.13
Bogo	2	East	SW	Riverine	1.42	212.46	8.75	410.53	36	1.30
Bogo	3	East	SW	Riverine	1.03	295.94	9.98	375	70	1.38
Carcar	1	East	LW	Riverine	2.15	706.28	23.45	120	1540	1.07
Carcar	2	East	LW	Riverine	1.62	426.77	14.97	104	1530	0.64
Carcar	3	East	LW	Riverine	1.45	327.29	6.87	120	1550	1.19
Carcar	1	East	SW	Riverine	0.61	363.59	8.04	154.1	1420	1.15
Carcar	2	East	SW	Riverine	0.19	51.16	5.87	86.5	1470	1.21
Carcar	3	East	SW	Riverine	0.76	260.07	12.39	115.2	1490	1.13
Carmen	1	East	LW	Riverine	0.94	253.34	4.05	376.67	611	1.41
Carmen	2	East	LW	Riverine	2.23	246.97	2.13	211.98	593	1.41
Carmen	3	East	LW	Riverine	0.78	254.48	3.68	176.67	582	0.94
Carmen	1	East	SW	Riverine	0.42	84.25	1.82	766.67	616	0.81
Carmen	2	East	SW	Riverine	1.26	199.87	9.92	716.67	584	1.02
Carmen	3	East	SW	Riverine	0.16	64.04	0.27	143.33	555	1.31
Medellin	1	East	LW	Fringe	0.56	14.90	3.77	156.67	2580	0.47
Medellin	2	East	LW	Fringe	0.16	20.19	0.60	206.67	2570	1.20
Medellin	3	East	LW	Fringe	0.68	23.45	1.10	193.33	2520	1.51
Medellin	1	East	SW	Fringe	0.20	142.22	1.87	95	2350	1.28
Medellin	3	East	SW	Fringe	0.92	400.67	31.39	167	1202	1.32
Medellin	2	East	SW	Fringe	0.29	90.23	2.9	208.02	2390	0.96
San Remigio	1	West	LW	Fringe	0.82	224.06	5.17	64.04	1169	1.16
San Remigio	2	West	LW	Fringe	0.63	215.51	5.19	208.12	1142	1.06
San Remigio	3	West	LW	Fringe	0.16	35.38	0.75	228.18	1300	1.36
San Remigio	1	West	SW	Fringe	0.20	63.41	3.96	250	1039	1.55
San Remigio	2	West	SW	Fringe	0.10	22.39	0.21	249.85	1028	1.32
San Remigio	3	West	SW	Fringe	0.18	72.35	1.10	414.88	1010	1.30

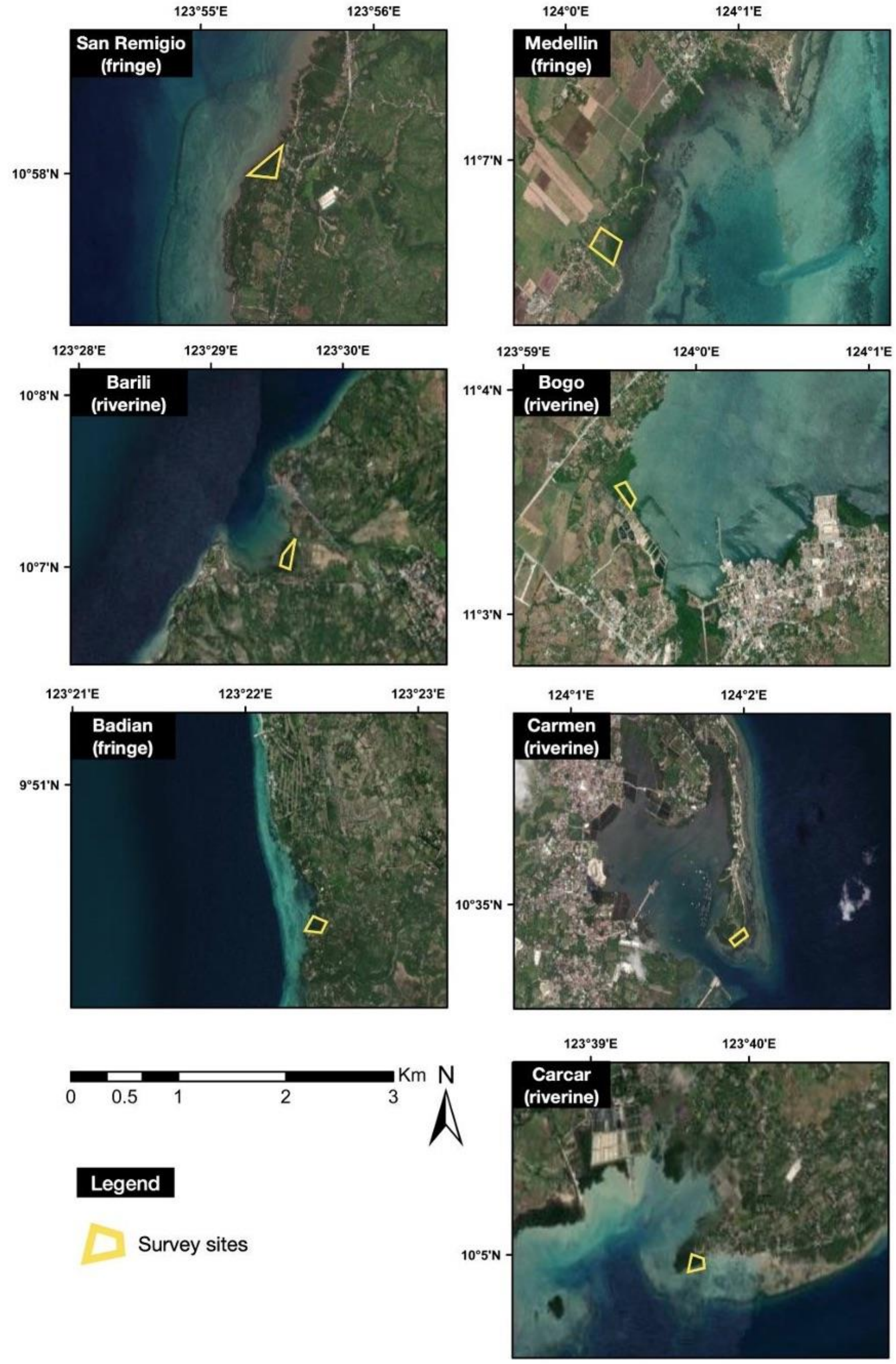

Fig. S2 Satellite images for the surveyed sites across Cebu Island where fringe (Badian, Medellin, San Remigio) and riverine (Bogo, Barili, Carcar, Carmen) forest geomorphological types were identified.