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Anthropogenic debris pollution in peri-urban mangroves of South China: Spatial, seasonal, and environmental drivers in Hong Kong

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ABSTRACT

Excessive mismanaged debris along tropical coasts pose a threat to vulnerable mangrove ecosystems. Here, we examined the spatial, seasonal and environmental drivers of anthropogenic debris abundance and its potential ecological impact in peri-urban mangroves across Hong Kong. Seasonal surveys were conducted in both landward and seaward zones, with identification, along belt transects, of macrodebris (>5 mm) based on material type and use. Our results indicate spatial variability in debris abundance and distribution, with plastic being the predominant material type identified. Both plastic and non-plastic domestic items covered the most surface area. Debris aggregation was highest at the landward zones, consistent with the literature. In the dry season, more debris accumulated and covered greater surface area in both seaward and landward zones. These results confirm that land-derived debris from mismanaged waste, rather than debris coming from the Pearl River, is the primary source of anthropogenic debris pollution threatening Hong Kong's mangroves.

1. Introduction

The advent of large-scale plastic production in the 1950s revolutionised the way humans live and has become the dominant material of the modern economy (Geyer et al., 2017; MacArthur, 2017). However, plastics are currently labelled as an environmental scourge as 79% of plastics and plastic items end up in landfills or the natural environment (Geyer et al., 2017; Napper et al., 2020). Plastic debris has been found in all ecosystems from mountain peaks to deep ocean basins and is so ubiquitous that it characterizes the “Anthropocene” era (Napper et al., 2020; Song et al., 2021; Zalasiewicz et al., 2016).

Coastal habitats are particularly vulnerable to the accumulation of anthropogenic debris due to their proximity to rivers that deliver waste from land-based sources coupled with their exposure to marine-borne plastics (Harris et al., 2021; Lebreton et al., 2017; Luo et al., 2021). A significant proportion of the research characterizing anthropogenic debris pollution in coastal ecosystems have been conducted on sandy shores, whereas other coastal habitats, such as coastal wetlands, are underrepresented (Andriolo et al., 2020; Browne et al., 2015; Gómez et al., 2020; Thiel et al., 2013). Coastal wetlands are known to act as natural filters and traps for persistent organic and inorganic pollutants (Li et al., 2007; Ouyang and Guo, 2016). Additionally, the positive rate of sedimentation and shore accretion in coastal wetlands make them ideal sinks for anthropogenic debris, which include macro- and microplastics (Li et al., 2018; Luo et al., 2022; Ouyang et al., 2022). Coastal wetlands sequester 10 times more plastics than sandy shores and preliminary studies suggest that their sediments contain 528 times more plastic than the water column (Lo et al., 2018; Ouyang et al., 2022). Among coastal wetland habitats, mangrove forests represent the largest sink for plastics and are reported to sequester an order of magnitude higher abundance of plastics than seagrass meadows (Ouyang et al., 2022).

Mangroves are known to be one of most important coastal wetland habitats due to their high productivity and contribution to ecosystem services which include storm protection and carbon storage (Friess et al., 2020). These ecosystems fill such an important role but remain seriously threatened by hydrological alteration, clearing due to land reclamation, conversion to aquaculture ponds and anthropogenic debris pollution

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(Friess et al., 2019). The structural complexity of their aboveground root systems allow for the dissipation and absorption of wave energy, change the boundary layer dynamics but also represent efficient traps for floating debris that reaches the system (Luo et al., 2022; Martin et al., 2019; Vorsatz et al., 2021). Previous research on debris pollution within mangroves has mainly focused on microplastics, while limited studies have looked at the abundance and occurrence of macroplastics within this environment (Luo et al., 2021, 2022; Martin et al., 2019; Riascos et al., 2019). Only a handful of the available research, moreover, designed and carried out systematic surveys of macrodebris across years or seasons at a regional level. These studies confirm the role that mangroves play in trapping macrodebris but reiterate that the drivers and accumulation trends need further research.

The Greater Bay Area, comprising of Guangdong-Hong Kong-Macao, situated at the mouth of the Pearl River, has a population of over 66.7 million (Hui et al., 2020). Mismanaged waste arising from these populous cities may be washed into waterways, before being drained into the mangrove habitats in the South China Sea (Cheung et al., 2016). The greater Bay Area harbors 10,889.78 ha of mangroves of which 539.03 is found in Hong Kong (Zhang et al., 2021). To date, only one study has assessed and quantified the extent of anthropogenic marine debris pollution in Hong Kong mangroves (Luo et al., 2022). These authors confirmed that the landward zones of the mangroves in Hong Kong trap debris much more readily than seaward zones, but also noted that illegal dumping may be a serious issue that may impact the functioning of the ecosystem. Hong Kong experiences distinct wet and dry seasons and the variability in environmental conditions between seasons has been observed to influence the abundance of plastics in other coastal habitats (Cheung et al., 2016). Yet, no information exists on the spatio-seasonal trends in anthropogenic debris pollution for Hong Kong's mangroves. Such analyses are important to appraise the influence of weather conditions and of the Pearl River flow in delivering waste to these highly productive and threatened ecosystems.

Here, we examined the spatio-seasonal occurrence, abundance and potentential ecological impact of anthropogenic debris at mangroves across Hong Kong. The information provided in this study will be critical to define the sources and the types of debris most abundantly found, identify the debris items that have the biggest potential ecological impact, due to smothering of the surface sediment, and to plan and organise efficient cleaning efforts in these threatened habitats. Due to its population density, geographical location and peri-urban mangrove context the pollution trends in Hong Kong may be ideal to evaluate how mangroves may be impacted in the future given the ongoing developmental encroachment on coastal areas in Southeast Asia and the rest of the world.

2. Materials and methods

2.1. Study area and environmental conditions

Hong Kong is located off the southern Chinese coast and is near to the upper limits of global mangrove distribution (Giri et al., 2011; Zhang et al., 2021). There are eight true mangrove species that occur in Hong Kong of which *Kandelia obovata* dominates in terms of density and area. Generally, mangrove patches on the western coast of Hong Kong, under the influence of the Pearl River Estuary, can be characterized as tall growing (e.g., 3–5 m), while patches on the east coast under the influence of the oceanic Indo-Pacific waters can be considered dwarfed, growing up to 1.5 m tall on average (Morton, 2016).

2.2. Sampling methodology

Eight mangrove forests were selected based on their geographical distribution, faunal and floral representativeness, and previous analyses of macro-debris pollution (Luo et al., 2022). Ha Pak Nai, Tung Chung and Shui Hau represent the western mangroves of Hong Kong, while Ting Kok, Sai Keng, Pak Tam Chung, Ho Chung and Tai Tam represent the eastern mangroves (Fig. 1). All these sites are dominated by *Kandelia obovata* which develop buttress roots that are less structurally complex than the stilt roots of *Rhizophora* spp. or the pneumatophores of *Avicennia* spp. that occur more frequently in the forests of Southeast Asia (Tomlinson, 2016; Vorsatz et al., 2021). Sampling was carried out at the seaward zone (delineated as the mangrove belt fringing the sea) and landward zone (marked by the presence of the more terrestrial species of true mangroves; *Excoecaria agallocha*, *Lumnitzera racemosa*, *Acanthus ilicifolius*) in both the wet (June to September) and dry seasons (December–March) of 2021 and 2022 (Table A1). Two belt transects spanning 2 × 25 m each were placed in each zone by at least two experienced team members during spring low tides. The macrodebris (>5 mm) encountered on both the sediment and canopy of trees within each transect was identified according to possible material type (Table 1) and use (Table 2) which were condensed into 10 and 5 broad categories, respectively. After the debris were identified within a transect, a photograph was taken of each item using an Olympus Tough TG-5 camera to measure its potential ecological impact, which is the area of the debris item that touches and smothers the sediment (Fig. 2A), or the extent of the debris item stuck on the canopy that has the potential to smother sediment (Fig. 2B).

2.3. Data and statistical analysis

Using the photos taken of each individual debris item in the field, the surface area (m^2) of the debris that covers the soil and tree canopies were precisely measured using open-source scientific image software ImageJ (Fig. 2). First, the measurements in the software were standardised and calibrated using a known length from a ruler placed beside the debris item using the “Analyze” and “Set Scale” functions. Subsequently, the “measure” function was used along with the “polygon selection” tool to provide an accurate estimation of the surface area and potential ecological impact of each debris item *in situ* on the sediment and in the canopy (Fig. 2A & B).

The debris items quantified in this study are expressed as mean number of items m^{-2} and mean surface area covered m^{-2}. Data were checked for normality and homogeneity using Shapiro-Wilk's and Levene's test, respectively. This was applied to determine whether linear or generalized mixed models were used for each test. To assess if human population density had an influence on the number and distribution of anthropogenic debris, data for district level population density (km^{-2}) were extracted from the Census and Statistics department of the Hong Kong government (Census and Statistics Department HKSAR, 2021). Generalized additive models (GAMs) were then used to determine if population density (km^{-2}) had a significant impact on 1) the number of debris items observed m^{-2} using cubic splines and a negative binomial distribution and 2) the surface area covered by debris items m^{-2} using cubic regression splines and gamma distribution with a log link function in the package *mgcv* (Wood, 2011). Generalized linear mixed models using a negative binomial and gamma distribution with a log link function and specifying sample ID as a random factor were used for all subsequent models where number of items and surface area covered were response variables, respectively. We tested for differences in the number of debris items and the surface area covered m^{-2} among sites and between zones (landward vs seaward), seasons (wet vs dry) and positions (sediment vs canopy). We tested if the type and original use of debris differed in abundance and surface area covered by site and zone. To determine if a significant relationship exists between the number of debris items and the surface area covered m^{-2}, we conducted a linear regression of each individual plastic type. Negative binomial GAMs were used to determine the extent to which local environmental factors were contributing to the number of items and surface area covered by those items m^{-2}. We used the local weather conditions inclusive of the three days prior to and on the day of sampling (wind speed, wind direction and rainfall) as explanatory variables, unique sample ID as a random

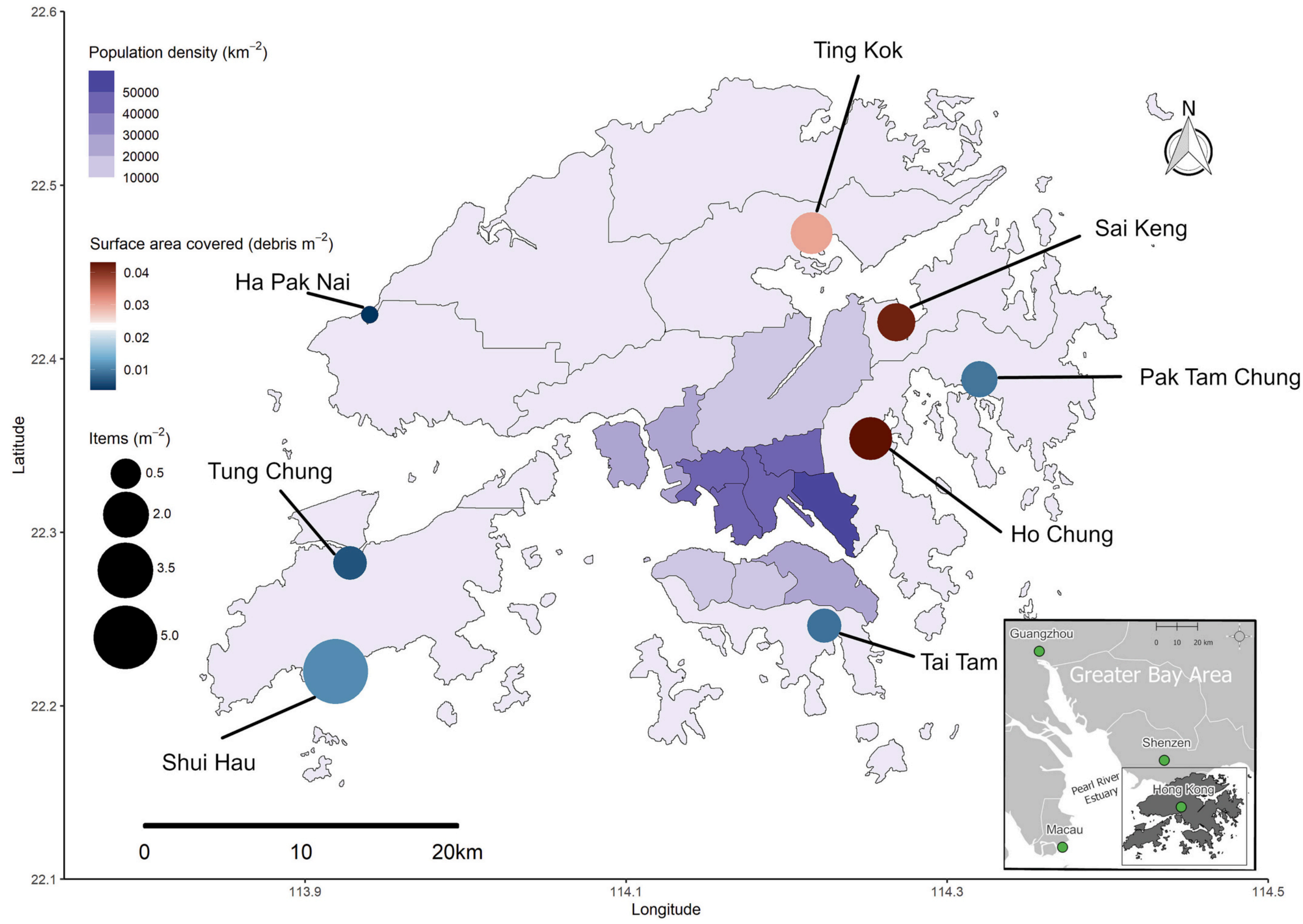

Fig. 1. Map of the Greater Bay Area (inset; adapted from (Luo et al., 2022) and Hong Kong indicating district level population density and the potential ecological impact of mean anthropogenic pollution at selected mangrove sites expressed as items m^{-2} and surface area covered by debris m^{-2}.

Table 1
Material type categories used in the study with some examples.

Material type	Example
Ceramic	Ceramic crockery, jars, vases
Paper	Newspaper, copy paper, cardboard
Fabric	Clothing, footwear
Foamed plastic	Food polystyrene, polystyrene, polyurethane, flip flops
Glass	Broken glass, glass bottle, glass fragments
Hard plastic	Bottle cap, fibre glass, plastic drink bottle
Metal	Metal sheet, metal can
Processed wood	Bamboo, oars, machined wood
Rubber	Footwear, tyres
Soft plastic	Plastic bags, soft plastic packaging

Table 2
Categories used to classify the possible original use of the debris.

Use	Example
Domestic	Plastic bag, footwear, ceramic crockery
Fishing	Fishing rope, buoy, fibre glass
Food	Juice box, metal cans, food polystyrene, cutlery
Industrial	Processed wood, metal sheet, fibre cement
Unknown	Polystyrene, soft and hard plastic fragments

variable and area sampled as an offset. We used a one-term deletion backwards selection process informed by the Akaike Information Criterion to identify the most parsimonious GAM. Local rainfall and wind conditions were recorded at automatic weather stations across Hong Kong (Table A1) and extracted from the Hong Kong Observatory website (https://www.hko.gov.hk/en/cis/climat.htm). All statistical analyses were conducted in R V4.1 (R Core Team, 2021).

3. Results

3.1. Spatio-seasonal variability of anthropogenic debris

A total of 9561 debris items were identified and measured to cover a cumulative surface area of 123.65 m^2 throughout the 2-year study period across all sites considered. At the site level, Shui Hau, which is situated on southern Lantau island, had the most items m^{-2} (5.2 ± 1.81; average ± SE), followed by Ho Chung (1.61 ± 0.33) and Ting Kok (1.46 ± 0.54; Fig. 1). Comparatively, debris at Ho Chung (0.04 ± 0.01) had the largest potential ecological impact measured as surface area covered m^{-2}, followed by Sai Keng (0.04 ± 0.01) and Ting Kok (0.03 ± 0.01; Fig. 1). District level population density was not a significant driver of the number of debris items recorded m^{-2} (GAM; $R^2 = 0.23$, $p = 0.069$) or

Fig. 2. Example of using ImageJ to measure the surface area of the A) sediment and B) canopy covered by debris as a proxy for ecological impact.

surface area covered by debris m^{-2} (GAM; $R^2 = 0.08$, $p = 0.417$).

There were significant differences in the surface area covered by debris m^{-2} among sites (GLM; χ^2 (7) = 120.779, $p < 0.001$), between seasons ($\chi^2_{(1)} = 19.121$, $p < 0.001$), positions (sediment vs canopy) (χ^2 $_{(1)}$ = 20.744, $p < 0.001$) and the interaction among site and zone (landward vs seaward) (χ^2 $_{(7)}$ = 14.425, $p < 0.001$). There were significant differences in the number of items m^{-2} recorded among sites (GLM; $\chi^2_{(7)} = 217.048$, $p < 0.001$), between zones ($\chi^2_{(1)} = 60.551$, $p < 0.001$), seasons ($\chi^2_{(1)} = 7.378$, $p = 0.006$), positions ($\chi^2_{(1)} = 115.991$, $p < 0.001$) and the interaction between site and zone ($\chi^2_{(7)} = 63.319$, $p < 0.001$) and site and season ($\chi^2_{(7)} = 16.601$, $p = 0.02$). The landward side of the mangroves surveyed had a higher proportion of items m^{-2} than those at the seaward side (Fig. 3A) indicated by the significant interaction term of site × zone (GLM; χ^2 $_{(7)}$ = 27.334, p < 0.001). The same trend was observed when using proportion of surface area covered, with Ha Pak Nai being the exception, showing more surface area covered in the seaward zone when compared to the landward zone (GLM; χ^2 $_{(7)}$ = 28.641, p < 0.001).

In the landward zone, more surface area was covered by debris in the wet season at Ha Pak Nai, Shui Hau, Tai Tam, while the opposite was true for the remaining sites (Fig. 3A). At the seaward zone only Shui Hau and Sai Keng had more surface area covered on average in the wet season as compared to the dry season (Fig. 3A). Debris also covered more surface area on the sediment than in the canopy at all sites except at the seaward zone at Shui Hau (Fig. A1A). Only Shui Hau and Ho Chung had more items surveyed at the landward zone in the wet season, whereas, counts in the seaward zone remained low, with the majority of items surveyed in the dry season (Fig. 3B). Again, the abundance of items was greater on the sediment than trapped in the canopy of trees in mangroves across Hong Kong (Fig. A1B).

Table 3
Generalized linear models evaluating the abundance and surface area covered m^{-2} as a function of the material type of the anthropogenic debris recorded, site, zone (landward vs seaward) and their interactions at the mangrove forests of Hong Kong. χ^2, Chi-square value; df, Degrees of freedom; p, significance value. All significant results ($p < 0.05$) are indicated in bold.

Variable	χ^2	Items m^{-2}		Surface area covered m^{-2}		
		df	p	χ^2	df	p
Site	**344.71**	**7**	**<0.001**	**128.524**	**7**	**<0.001**
Use	**176.67**	**4**	**<0.001**	**102.634**	**4**	**<0.001**
Zone	**91.12**	**1**	**<0.001**	**4.153**	**1**	**0.042**
Site × use	**130.08**	**28**	**<0.001**	**73.038**	**28**	**<0.001**
Site × zone	**29.32**	**7**	**<0.001**	**38.304**	**7**	**<0.001**
Use × zone	**24.23**	**4**	**<0.001**	2.369	4	0.668
Site × use × zone	31.41	27	0.254	28.897	27	0.365

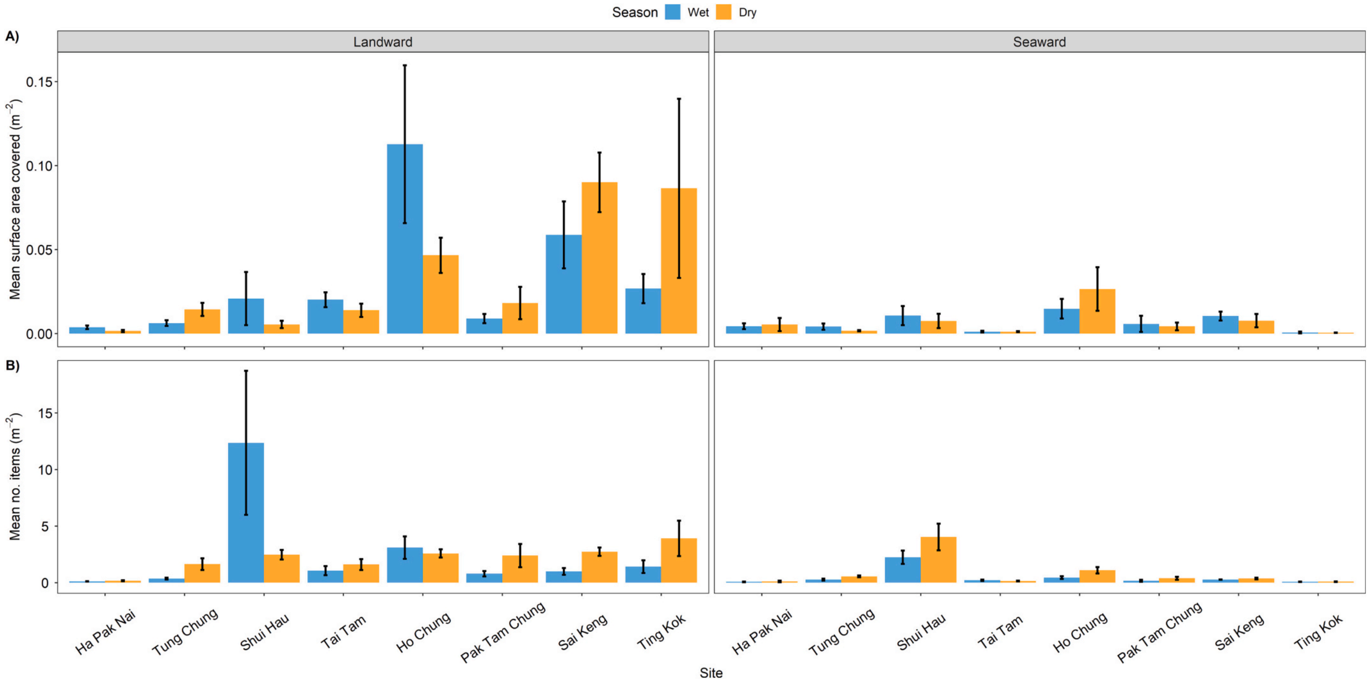

Fig. 3. The seasonal distribution of debris by A) number of items m^{-2} and B) proportion of surface area covered comparing the landward and seaward zone of mangrove sites across Hong Kong, SAR.

Table 4
Generalized linear models evaluating the abundance and surface area covered m^{-2} as a function of possible original use of the anthropogenic debris recorded, site, zone (landward vs seaward) and their interactions at the mangrove forests of Hong Kong. χ^2, Chi-square value; df, Degrees of freedom; p, significance value. All significant results ($p < 0.05$) are indicated in bold.

Variable	χ^2	Items m^{-2}		Surface area covered m^{-2}		
		df	p	χ^2	df	p
Site	**372.35**	**7**	**<0.001**	**147**	**7**	**<0.001**
Material type	**235.96**	**9**	**<0.001**	**151.7**	**9**	**<0.001**
Zone	**114.31**	**1**	**<0.001**	**0.783**	**1**	**0.376**
Site × material type	**268.97**	**59**	**<0.001**	**93.75**	**59**	**0.003**
Site × zone	**34.13**	**7**	**<0.001**	**41.03**	**7**	**<0.001**
Material type × zone	**34.45**	**9**	**<0.001**	**8.539**	**9**	**0.481**
Site × material type × zone	55.73	45	0.131	57.19	45	0.105

3.2. *Differential potential ecological impact among anthropogenic debris material types*

There were significant differences in the surface area covered among material types, sites and the interaction between material type and sites (Table 3). The same was true when debris items were categorized by possible original use (Table 4). Overall, plastic items accounted for ~60% of the surface area covered. Plastic items ranged from making up ~48% of items that covered the surface area at Ha Pak Nai to ~79% at Tung Chung (Fig. 4A). At the landward zone materials such as processed wood, fabrics, paper and glass dominated the surface area covered at the majority of sites surveyed (Fig. 4B). Processed wood made up the largest proportion as a single material category covering the landward surface area at Tung Chung, Shui Hau, Ho Chung, Pak Tam Chung and Sai Keng (Fig. 4B). Soft plastic debris, however, dominated the landward sediment surface area at Ha Pak Nai and Tai Tam. At the seaward zone, the material type that dominated the proportion of surface area covered varied (Fig. 4C). Metal dominated at Ha Pak Nai and Shui Hau, while plastics had the largest potential ecological impact at the remainder of sites (Fig. 4C).

There were significant differences in the number of debris items m^{-2} among material types, possible original use, sites and their interactions (Tables 3 & 4). Plastics constituted 76% of all items surveyed. The abundance of plastic items m^{-2} ranged from ~32% at Pak Tam Chung to ~94% at Shui Hau (Fig. 4D). Hard and foamed plastics were the most numerous material type m^{-2} at the landward zone of majority of sites indicating the uncoupling of dominant material types between the surface area covered and abundance of debris items (Fig. 4B & E). Soft and

Fig. 4. The anthropogenic debris by material type surveyed in the mangroves across Hong Kong expressed as the A) mean proportion of surface area covered overall, B) mean proportion in number of items m^{-2} overall, C) mean proportion of surface area covered at the landward zone, D) landward mean proportion in number of items m^{-2} at the landward zone, E) mean proportion of surface area covered at the seaward zone and F) mean proportion in number of items m^{-2} at the seaward zone.

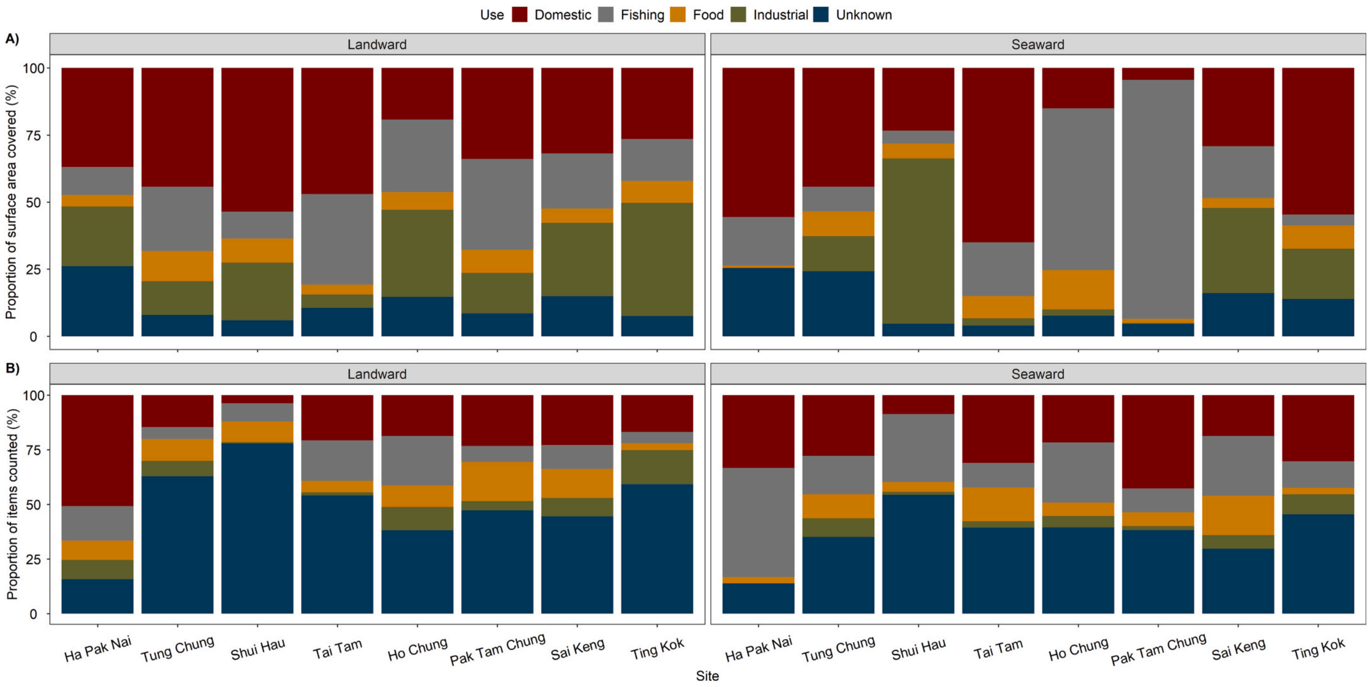

Fig. 5. The composition of debris by possible original use in landward and seaward zones of mangroves surveyed across Hong Kong expressed as A) proportion of surface area covered and B) proportion of number of items m^{-2}.

hard plastic dominated in item abundance m^{-2} at the seaward zone at most sites (Fig. 4F). The uncoupling between surface area covered and abundance of debris items is also evident at the seaward zone. At Pak Tam Chung, non-plastic materials made up >60% of number of items counted, however, foamed plastics dominated the surface area covered (Figs. 4C & F). Another notable example of this trend was observed at Shui Hau, Ha Pak Nai, Tai Tam and Sai Keng albeit with different materials. Ho Chung and Ting Kok were the only two sites that were dominated by hard plastic material as a single category in both surface area covered and number of items m^{-2}.

3.3. Comparison of the abundance and potential ecological impact among anthropogenic debris items' usage

Discarded items deemed for domestic use accounted for ~28% of the surface area covered by debris, followed by unknown (~26%) and industrial (~20%) use. Debris originating from domestic use as a single category covered the largest proportion of surface area at Ha Pak Nai,

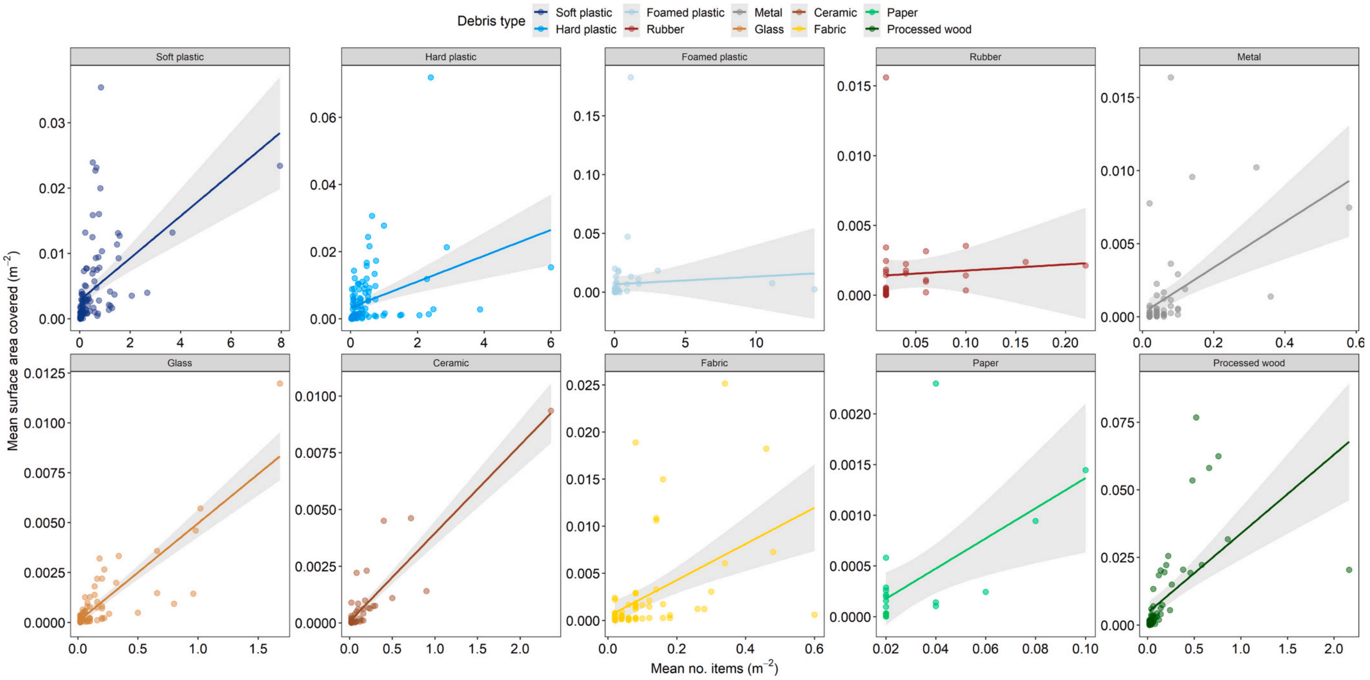

Fig. 6. Scatterplot and regression lines of mean surface area covered m^{-2} as a function of mean abundance of items m^{-2} for the 10 anthropogenic debris material types categorized in this study.

Sai Keng, Tai Tam and Tung Chung (Fig. 5A). The landward side of sites surveyed on the west coast (Ha Pak Nai, Shui Hau, Tai Tam and Tung Chung) had most debris covering the surface area originating from domestic use, while at sites on the east coast, items originating from fishing and industrial use dominated the surface area covered (Fig. 5A). At the seaward zone, debris deriving from domestic origins were the dominant category at Ha Pak Nai, Tai Tam and Ting Kok, while industrial related items dominated at Shui Hau. Comparatively, fishing related items dominated the proportion of debris covering the sediment surface at Ho Chung and Pak Tam Chung (Fig. 5A). Debris items that were too fragmented and classified as unknown use accounted for ~57% of items surveyed. Debris deriving from unknown uses were the greatest by count at the landward zones at all sites except Ha Pak Nai, which was dominated by items of domestic use (Fig. 5B). Items related to fishing were the most numerous category at the seaward zone at Ha Pak Nai, whereas, items of unknown use were the most abundant category at all other sites considered (Fig. 5B).

3.4. *Relationship among metrics of assessing anthropogenic debris*

When data are pooled, there is no overall relationship between surface area covered and number of debris items m^{-2} (LM; F$_{(1,626)}$ = 0.892, p = 0.345), however surface area covered m^{-2} has a significant relationship with material type (LM; F$_{(9,626)}$ = 2.644, p = 0.005) and the interaction between material type and items m^{-2} (LM; F$_{(9,626)}$ = 7.268, p < 0.001). This indicates that a linear relationship between the surface area covered and the number of items recorded is dependent on the material type of the debris item surveyed. The debris items categorized as rubber and foamed plastics were the only two groups that showed a non-significant relationship between the number of items and surface area covered (Table A2; Fig. 6). All other material types showed a positive relationship between the two metrics (Fig. 6).

3.5. *Environmental conditions influencing anthropogenic debris abundance and potential ecological impacts*

The local weather conditions explained ~45% of the variability in the number of debris items m^{-2} (Table 5). An increase in wind speed two days before sampling drives an increase in the number of debris items surveyed in the mangrove, however, when the wind speed increases one and three days before sampling, there is a decrease in the number of items surveyed (Fig. 7A, C and E). Only rainfall occurring on the day before sampling leads to a significant effect on the number of debris items encountered m^{-2} (Fig. 7B and D). We also determined that wind blowing in a northerly direction increases the probability of debris items being surveyed at the mangrove (Fig. 7F), while north-easterlies significantly reduce the probability of depositing debris within mangroves (Fig. 7F). The local weather conditions only explained ~31% of variability of the surface area covered by debris (Table 5). Only wind speed could significantly predict the probability of surface area covered by debris which revealed a similar trend to that of the number of debris items. An increase in wind speed one and three days before sampling resulted in less surface area covered by debris and if the wind speed increases two days before sampling, debris are expected to cover more surface area at the mangrove (Fig. 8A, C, E). Total rainfall one and two days before sampling were weak predictors of surface area covered by debris (Fig. 8B, D). Wind direction influenced the probability of the surface area covered by debris (Fig. 8F). When the wind blew in a south-westerly direction, surface area coverage was likelier to be higher; and when the wind blew in a north-easterly direction, surface area coverage was likelier to be lower than when the wind blew in an easterly direction (Fig. 8F).

4. Discussion

Here, for the first time we present the spatio-seasonal abundance and potential ecological impact (surface area covered) of anthropogenic debris pollution in mangroves by using precise image analysis. The abundance and the surface area covered m^{-2} by debris items are spatially driven at the regional (among sites) and local scale (between zones within sites). Plastic makes up most items and surface area covered by debris present at mangrove sites across Hong Kong. At the territory level, sites on the east coast of Hong Kong harbored more debris that covered more surface area than sites on the west, indicating that sites on the east coast are more likely to be ecologically impacted. At the site level, debris were concentrated at the landward zones of the

Table 5

Generalized additive mixed model of local weather parameters predicting the abundance and surface area covered by anthropogenic debris m^{-2} sampled in Hong Kong mangroves.

	Items m^{-2}	Surface area covered m^{-2}
Family	Negative binomial	Gamma
n	128	128
Deviance explained	45.2%	30.7%

Coefficients	Estimate	z	p	Estimate	t	p
Intercept	**0.538**	**2.516**	**0.011**	**−3.961**	**−14.357**	**<0.001**
Wind direction (N)	**2.131**	**4.539**	**<0.001**	0.009	0.014	0.988
Wind direction (NE)	**−1.526**	**−4.731**	**<0.001**	**−1.028**	**−2.476**	**0.014**
Wind direction (NW)	−0.385	−0.734	0.462	−0.312	0.46	0.646
Wind direction (S)	−0.737	−1.38	0.167	0.114	0.193	0.847
Wind direction (SE)	**−0.978**	**−2.183**	**0.029**	−0.47	−0.834	0.406
Wind direction (SW)	0.338	0.71	0.477	**1.126**	**1.993**	**0.048**

Smooth terms	EDF	χ2	p	EDF	F	p
s(Wind speed 1 dB)	**2.772**	**10.949**	**0.014**	**4.091**	**2.863**	**0.037**
s(Rainfall 1 dB)	**1.964**	**12.721**	**0.001**	1.858	2.602	0.08
s(Wind speed 2 dB)	**1**	**18.069**	**<0.001**	**2.158**	**4.966**	**0.005**
s(Rainfall 2 dB)	2	4.6	0.074	2.051	3.754	0.081
s(Wind speed 3 dB)	**2.081**	**12.606**	**0.004**	**3.52**	**3.252**	**0.01**
s(Sample_ID)	1.775	2.67	0.298	**0.965**	**34.964**	**<0.001**

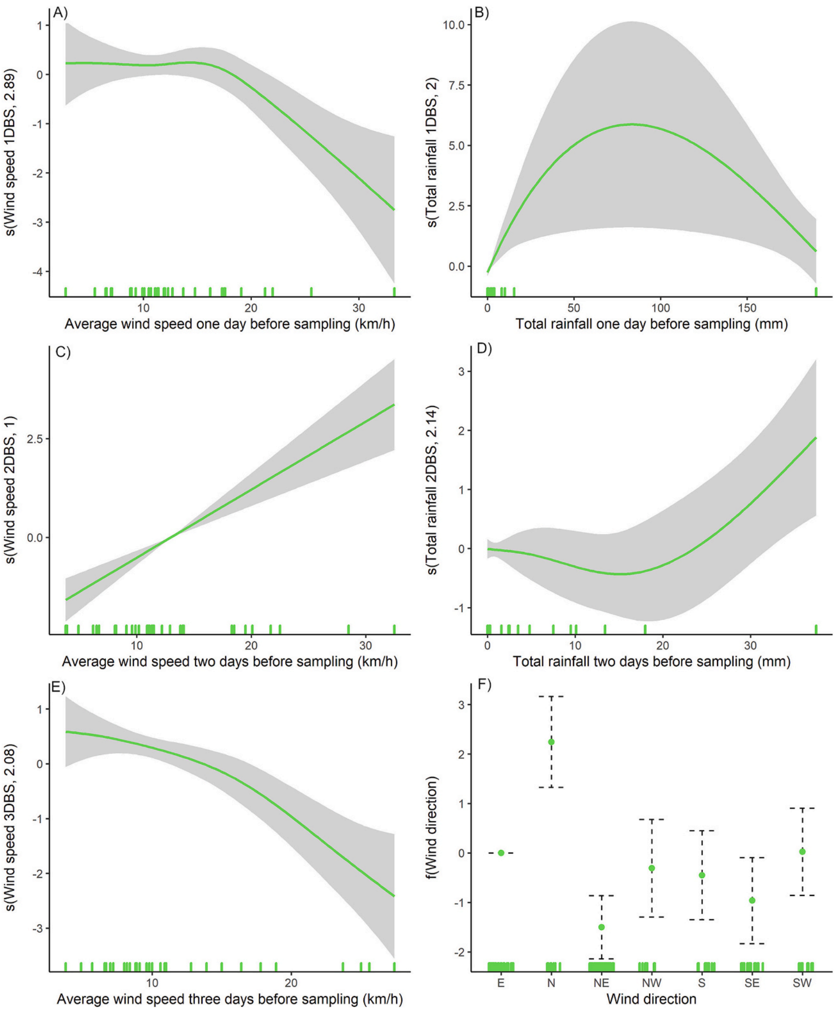

Fig. 7. Generalized additive mixed model of environmental parameters predicting the abundance of anthropogenic debris m^{-2} sampled in Hong Kong mangroves according to A) average wind speed and B) total rainfall one day before sampling, C) average wind speed and D) total rainfall two days before sampling, E) average wind speed three days before sampling and F) wind direction as predictor variables.

mangroves and were in contact with the sediment more frequently than stuck in the canopy of trees. Seasonally, debris items were more numerous and covered more surface area during the dry season at both zones of the mangrove forests. Local weather conditions such as wind speed and direction play an influential role in transporting debris items to and from mangrove areas along the coast of Hong Kong. The data collected in the different seasons and in different weather conditions strongly suggest that Hong Kong mangroves are more prone to be affected by debris coming from terrestrial sources, although the east coast was still impacted by marine-borne activities.

4.1. Population density as a driver of anthropogenic debris pollution

Hong Kong is characterized as a highly urbanized area which accommodates over seven million residents within the territory (Hua et al., 2021). The population density is estimated to be 6777 people/km^2 on average, ranking it one of the most densely populated in the world (Gou et al., 2018; Hua et al., 2021). Despite such high density, it proved to be a weak predictor of the level of anthropogenic debris pollution recorded in the territory's mangroves. Indeed, human population density and level of urbanisation has generally shown to be a weak predictor of debris and plastic leakage into the environment (Schuyler et al., 2021). Other factors such as socio-economic status along with waste removal infrastructure has been shown to be the most influential factors associated with lower mismanaged waste and debris density (Schuyler et al., 2022). In this study, the debris abundance m^{-2} within mangroves in Hong Kong was much lower than that of its South- and Southeast-Asian neighbors (Luo et al., 2021). The disparity in wealth and solid waste infrastructure may explain these differences among countries (Ferronato and Torretta, 2019; Marshall and Farahbakhsh, 2013).

4.2. Spatio-seasonal comparison of anthropogenic debris

At the territory level, sites on the east coast harbored debris that covered more surface area, in line with the only previous study in Hong Kong (Luo et al., 2022). Sites on the west coast, however, contained a higher abundance of debris items m^{-2}. Mangroves on the east coast of Hong Kong are more ecologically impacted by debris pollution resulting in a larger proportion of sediment being unavailable for propagule establishment and epi- and infauna foraging and burrowing behaviors (Agusto et al., 2021). Debris partially covering the forest floor has been shown to stress mangrove trees by suffocating root systems, resulting in an immediate local response in root growth and roots completely smothered by debris, results in the ultimate death of the individual tree (Pranchai et al., 2019; van Bijsterveldt et al., 2021). Landward areas contained higher densities of items and covered larger surface areas than the seaward zones at the mangroves surveyed here, reaffirming that mangroves act as traps for debris originating from both marine and land-based sources (Luo et al., 2022; Martin et al., 2019). The sediment and trunks of the trees harbored more debris than the canopy, this is

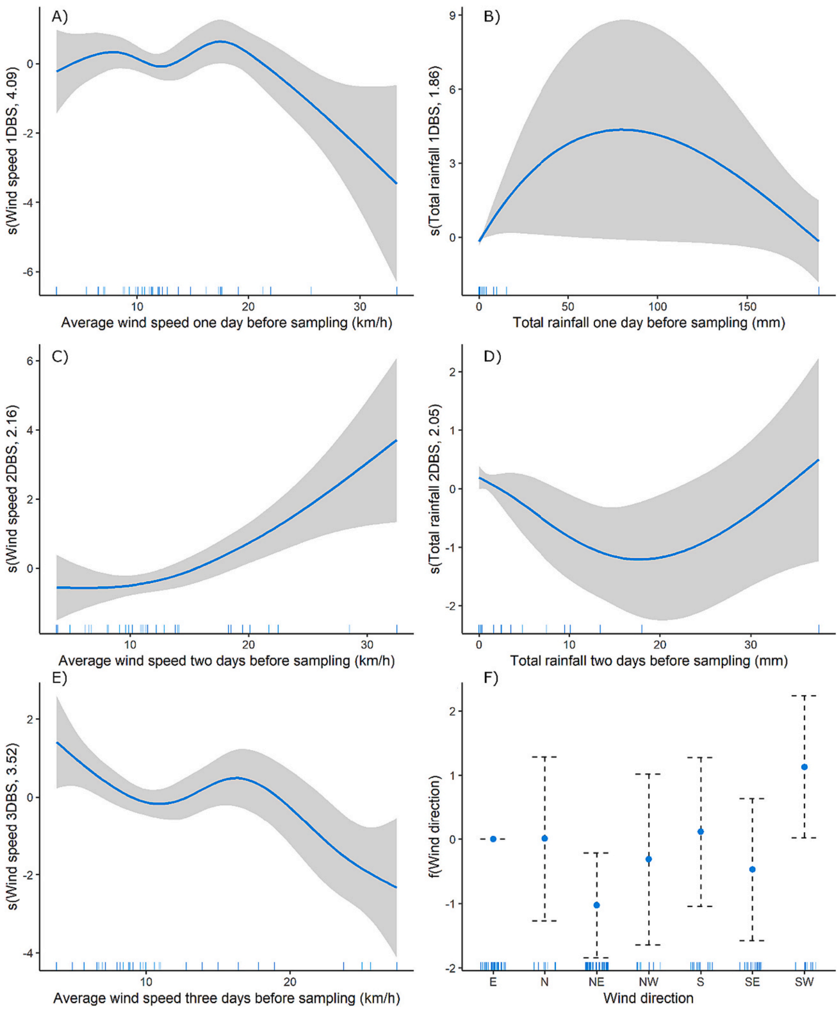

Fig. 8. Generalized additive mixed model of environmental parameters predicting the surface area covered by anthropogenic debris m^{-2} sampled in Hong Kong mangroves according to A) average wind speed and B) total rainfall one day before sampling, C) average wind speed and D) total rainfall two days before sampling, E) average wind speed three days before sampling and F) wind direction as predictor variables.

unsurprising because plastic items trapped in the canopy will eventually be broken down by environmental and mechanical factors to reach and finally be buried in the sediment (Martin et al., 2020). It is therefore plausible to consider the canopy a temporary sink for macroplastics before they eventually reach the sediment.

Here, we observed seasonal debris abundance and surface area coverage to be site and zone dependent. At the landward zones of Ho Chung and Shui Hau the density and surface area covered by debris was greater in the wet as compared to the dry season. Tung Chung, Pak Tam Chung, Sai Keng and Ting Kok, however, had greater abundances during the dry rather than the wet season. The seasonal wind speed patterns in Hong Kong and the Greater Bay Area are influenced by the East Asian monsoon (Ren et al., 2022). In the dry winter season, winds are generally stronger and northerly, whereas in the wet summer, winds are weaker and blow south-easterly and may explain the difference in the number of items observed between the two seasons (Ren et al., 2022). The single previous seasonal macrodebris study in Hong Kong reported that the abundance of debris items were typically greater during the wet season at beaches (Cheung et al., 2016). These authors suggest that low-density debris items may have been removed from those exposed systems that are devoid of structural complexity in the days leading up to sampling during the dry season resultant of strong prevailing winds (Browne et al., 2010; Cheung et al., 2016). Coastal habitats on the west coast of Hong Kong are expected to be more heavily impacted during the rainy season due to its position at the mouth of the Pearl River Estuary and the influence that riverine inputs have on the transport of macroplastics into drainage basins (Lechthaler et al., 2020; Zhang et al., 2021). Here, we argue that seasonally selective debris pollution sampling could provide underestimates in both an overall and site-specific context as the mean surface area covered by debris and density of items are variable between seasons and among sites. This is exemplified by the fact that four sites had greater densities in the dry season, two sites' densities were greater in the wet season and the remaining two sites displayed no differences between seasons. Furthermore, spatio-seasonal appraisals of macrodebris patterns can better inform on the optimal time frame for non-governmental organisations and concerned citizen groups to arrange clean-up activities in specific areas (Battisti et al., 2020; Ehl et al., 2017).

4.3. Environmental conditions influencing anthropogenic debris abundance and potential ecological impacts

The impact of local weather conditions explained the variability in the abundance of items better than the surface area covered by debris. Larger and often heavier debris items that cover more surface area such as processed wood and fibre glass remains of abandoned boats are expected to be more difficult to transport in and out of the complex mangrove environment (Luo et al., 2022). Conversely, smaller and lower-density items such as expanded polystyrene and soft plastic films may be more easily displaced via environmental transport processes

(Chan and Not, 2023; Garello et al., 2021). This assertion is corroborated by observing that when wind speeds increased one and three days before sampling, there was a decrease in the number of items recorded in the mangroves, indicating that there was net positive removal of debris. However, when windspeed increases two days before sampling, more debris is expected to be deposited into the mangrove. Wind speed and direction play an influential role in predicting an increase or decrease in the levels of anthropogenic debris pollution in mangroves, riverine and other coastal habitats (Lechthaler et al., 2020). Here, northerly winds are associated with a greater density of debris items recorded in the mangroves than when the wind blows in an easterly and southerly direction which supports the seasonal pattern of pollution observed. This observation suggests that the Pearl River may not be the main driver for delivering debris to the mangroves of Hong Kong, but rather land-based sources from north of Hong Kong may play a bigger role in the source-sink pathway of anthropogenic debris. Rainfall one day before sampling affected the density of debris items encountered in the mangrove. This is in line with previous studies that have observed moderate to heavy rainfall increasing the number of debris encountered due to increases in surface runoff that may move plastics more readily to coastal areas from urban centres (Lo et al., 2020; Ouyang et al., 2022).

4.4. Comparison of the abundance and potential ecological impact among anthropogenic debris material type and possible original use

Overall, plastic covered most of the surface area and dominated the number of items at the sites surveyed. This is in line with studies that showed plastic was the debris type that were retained at the highest rate in Brazilian mangrove forests (Ivar do Sul et al., 2014). However, when debris items are evaluated by zone, debris such as processed wood, fabrics, paper and glass retained at the landward part of the mangroves surveyed covered the largest surface area probably because they are usually heavier and more difficult to move, while plastics were the most numerous materials. Plastic and non-plastic items that were possibly originally used for domestic purposes dominated the surface area covered for sites on the west coast, whereas fishing debris dominated on the east. An uncoupling of the impact of different materials and sources of debris is evident here, which stresses the importance of using different metrics for a holistic view of anthropogenic debris pollution (Luo et al., 2022). The sites dominated by fishing debris on the seaward zones are in areas where aquaculture and fishing industries are still operational. Sites on the east coast are in the Sai Kung peninsula and Ha Pak Nai is located in Lau Fau Shan both which are popular areas for both fishing and maricultural activities and may explain the high number of fishing related debris in these areas (Cheung, 2019; Patchell and Cheng, 2019). Ting Kok, Ho Chung and Sai Keng where the landward areas had a high proportion of industrial debris indicating that illegal dumping is a major contributor of pollution in these areas (Lu, 2019; Luo et al., 2022; Tam and Wong, 2002). These illegal dumping behaviors may be brought about as an attempt to escape paying disposal charges which leads to long lasting environmental consequences given the net positive debris retention of landward zone mangroves coupled with the long decomposition times of synthetic materials (Chu, 2021; Singh and Sharma, 2008; Yin et al., 2020).

5. Conclusions

Here, we argue that having the most precise and appropriate abundance, surface area cover, material type and potential use data available is imperative to stage interventions with an aim to reduce anthropogenic pollution going forward. Those specific data also allow for a quantitative appraisal of not only the occurrence and density of anthropogenic pollution but how this cascades into ecosystem level effects through smothering and faunal ingestion and degradation (So et al., 2022; van Bijsterveldt et al., 2021). Our in-depth, long-running, and season-based sampling strategy allowed us to correlate, for the first time, the trends of macrodebris accumulation in Hong Kong intertidal forests to some critical weather events. Besides site specific differences, the accumulation of debris increased during the dry season and when the winds blow from continental Asia. These results corroborate the hypothesis that the primary source of debris pollution affecting Hong Kong mangroves is the mismanagement of anthropogenic waste produced by urban and industrial areas, although sea-borne waste can have a strong impact at some areas. The observed influence of season and local weather on the pollution trends may better inform the optimal time for clean ups in mangroves across Hong Kong. However, besides clean ups, urban and industrial waste management procedures must be implemented and policies better enforced to stop illegal dumping behaviors. These procedures, along with substantial reductions in plastic waste generation, will be the best way to stop the mismatch between the rate of plastic pollution versus the efforts to reduce it in mangroves and other coastal ecosystems that act as sinks for anthropogenic debris pollution (Borrelle et al., 2020).

CRediT authorship contribution statement

Lyle Dennis Vorsatz: Conceptualization, Methodology, Data curation, Writing – original draft, Formal analysis, Project administration. **Mandy Wing Kwan So:** Methodology, Visualization, Writing – review & editing. **Christelle Not:** Funding acquisition, Writing – review & editing, Conceptualization, Methodology. **Stefano Cannicci:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A

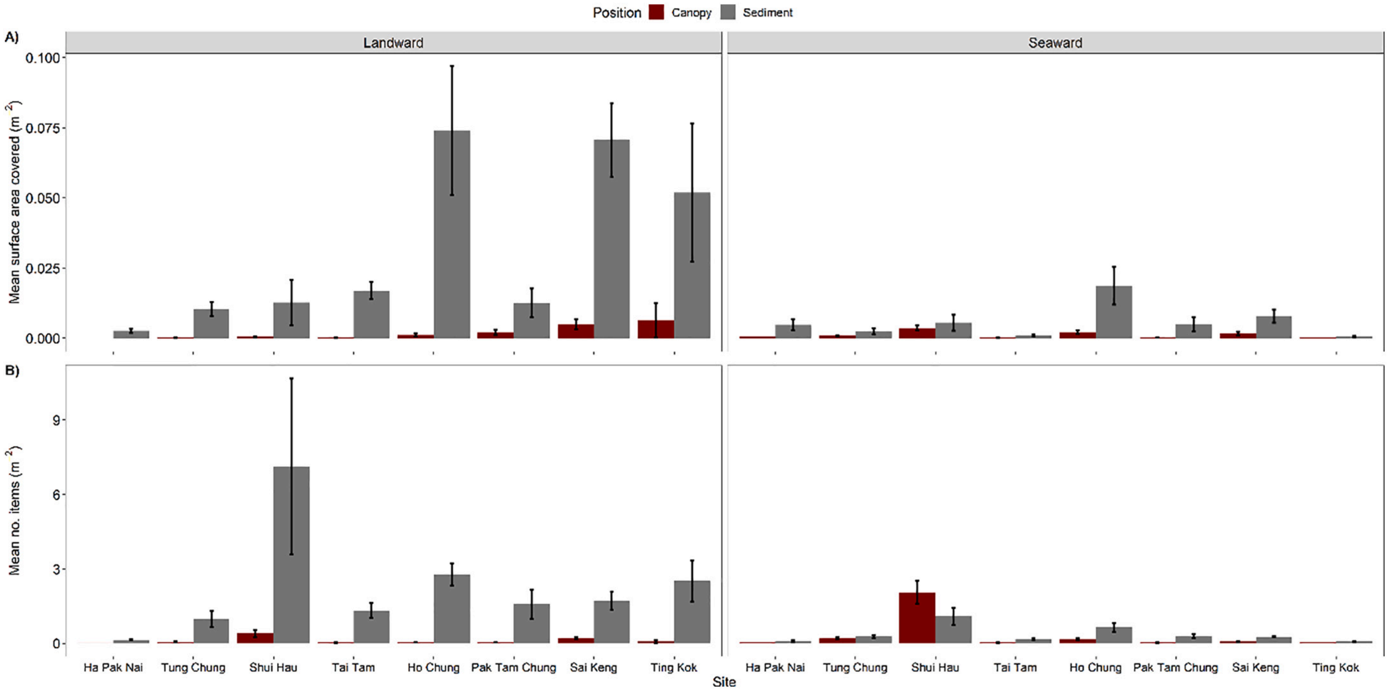

Fig. A1. The positional distribution of debris by A) number of items m^{-2} and B) proportion of surface area covered comparing the landward and seaward zone of mangrove sites across Hong Kong, SAR.

Table A1

Sampling date, location, season and weather station used to extract rainfall, wind direction and speed. HKIA, Hong Kong International Airport; HKO, Hong Kong Observatory.

Date	Site	Season	Weather station
2020-08-29	Pak Tam Chung	Wet	Pak Tam Chung & Sai Keng
2020-08-30	Ha Pak Nai	Wet	Lau Fau Shan
2020-08-31	Ho Chung	Wet	Pak Tam Chung & Sai Keng
2020-09-01	Tung Chung	Wet	HKIA
2020-09-14	Tai Tam	Wet	HKO
2020-09-15	Ting Kok	Wet	Tai Mei Tuk
2020-09-16	Sai Keng	Wet	Pak Tam Chung & Sai Keng
2020-09-28	Ting Kok	Wet	Tai Mei Tuk
2020-09-30	Shui Hau	Wet	HKIA
2021-01-29	Pak Tam Chung	Dry	Pak Tam Chung & Sai Keng
2021-01-30	Sai Keng	Dry	Pak Tam Chung & Sai Keng
2021-01-31	Tai Tam	Dry	HKO
2021-02-01	Ha Pak Nai	Dry	Lau Fau Shan
2021-02-25	Shui Hau	Dry	HKO
2021-02-26	Ting Kok	Dry	Tai Mei Tuk
2021-02-27	Tung Chung	Dry	HKIA
2021-02-28	Ho Chung	Dry	Pak Tam Chung & Sai Keng
2021-03-01	Ho Chung	Dry	Pak Tam Chung & Sai Keng
2021-07-14	Pak Tam Chung	Wet	Pak Tam Chung & Sai Keng
2021-07-17	Sai Keng	Wet	Pak Tam Chung & Sai Keng
2021-08-09	Shui Hau	Wet	HKIA
2021-08-10	Tai Tam	Wet	HKO
2021-09-03	Ting Kok	Wet	Tai Mei Tuk
2021-09-04	Ha Pak Nai	Wet	Lau Fau Shan
2021-09-06	Ho Chung	Wet	Pak Tam Chung & Sai Keng
2021-09-07	Tung Chung	Wet	HKIA
2021-12-06	Ho Chung	Dry	Pak Tam Chung & Sai Keng
2021-12-07	Ting Kok	Dry	Tai Mei Tuk
2021-12-08	Shui Hau	Dry	HKIA
2021-12-09	Pak Tam Chung	Dry	Pak Tam Chung & Sai Keng
2021-12-28	Sai Keng	Dry	Pak Tam Chung & Sai Keng
2021-12-30	Tung Chung	Dry	HKIA
2022-01-10	Ha Pak Nai	Dry	Lau Fau Shan
2022-02-04	Tai Tam	Dry	HKO

Table A2
The linear regressions of surface area covered m^{-2} as a function of the number of items recorded m^{-2} for the 10 material types categorised in this study. SS, sum of squares; DF, degrees of freedom; F, Fisher's statistic; *p*, significance value. All significant results ($p < 0.05$) are indicated in bold.

Response: Surface area covered m^{-2}	SS	F	*p*
Processed wood			
Intercept	0.001	5.6023	0.021
Items m^{-2}	**0.005**	**30.023**	**<0.001**
Foamed plastic			
Intercept	0.002	3.8103	0.056
Items m^{-2}	0.001	0.2103	0.648
Soft plastic			
Intercept	**0.001**	**23.375**	**<0.001**
Items m^{-2}	**0.001**	**31.736**	**<0.001**
Hard Plastic			
Intercept	**0.001**	**14.056**	**<0.001**
Items m^{-2}	**0.001**	**16.524**	**<0.001**
Rubber			
Intercept	0.001	3.826	0.059
Items m^{-2}	0.001	0.162	0.689
Metal			
Intercept	0.001	0.413	0.523
Items m^{-2}	**0.001**	**118.38**	**<0.001**
Glass			
Intercept	0.001	0.071	0.791
Items m^{-2}	**0.001**	**155.68**	**<0.001**
Ceramic			
Intercept	0.001	0.303	0.584
Items m^{-2}	**0.001**	**174.71**	**<0.001**
Fabric			
Intercept	0.001	0.376	0.542
Items m^{-2}	**0.001**	**18.34**	**<0.001**
Paper			
Intercept	0.001	0.402	0.533
Items m^{-2}	**0.001**	**9.306**	**0.006**

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