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Litter traps: A comparison of four marine habitats as sinks for anthropogenic marine macro-litter in Singapore

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ABSTRACT

The potential for marine litter being trapped in biodiverse marine habitats such as mangrove forests, seagrass meadows and coral reefs is poorly understood. This study presents the first comprehensive investigation on the status of macro-litter across four marine habitats in Singapore during the two monsoonal seasons. Overall, litter density did not vary considerably between the southwest and the northeast monsoon. The litter density in terms of count was generally lower in seagrass meadows and coral reefs compared to mangroves and beaches. Plastic was the major type of litter found across most habitat types. Notably, many fishing-related items were found on coral reefs, while drinking straws were abundant at the mangrove strandlines during the southwest monsoon. Foam fragments and cigarette butts were common at the beach strandlines. These results suggest that mangroves among other habitats examined here should be prioritised for clean-up efforts in order to restore these critical coastal habitats.

1. Introduction

Of the numerous environmental concerns today, marine litter is one of the top priorities on the global agenda since the awareness of its magnitude and impacts has increased tremendously in the last decade (MacLeod et al., 2021; Haarr et al., 2022). Broadly, marine litter is defined as any manufactured or processed item that is discarded or abandoned in the coastal and marine environments (Cheshire et al., 2009). The slow degradation rate of most marine litter, particularly plastics, compounded by the continual increase in the amount being disposed of, result in a range of environmental, economic, health, and socio-cultural impacts (Bergmann et al., 2015; Beaumont et al., 2019; MacLeod et al., 2021). The sources of marine litter can broadly be classified as either land- or sea-based (Bergmann et al., 2015). Specifically, the marine litter originating from land-based sources include: (1) deliberate waste disposal into rivers, coastal waters, or on coastlines, and (2) indirect waste leakage to the sea from rivers, sewage, or urban run-off because of wind or storm-related events (Rech et al., 2014; Bergmann et al., 2015; Chuturkova and Simeonova, 2021). On the other hand, sea-based sources of marine litter may come from shipping activities, sea-based dumping, and abandoned, lost or otherwise discarded fishing gear (ALDFG) that may be deliberately discarded or due to indirect leakages (Macfadyen et al., 2009; Bergmann et al., 2015).

Globally, marine litter has significantly increased over the recent decades and has been reported across all marine environments from beaches to deep-sea floors (Bergmann et al., 2015; United Nations Environment Programme, 2021). In particular, beaches have been the most well studied due to the accessibility for sampling and monitoring (Schernewski et al., 2018; Hanke et al., 2019; Okuku et al., 2020) and garnering the help of citizen scientists in data collection (Hidalgo-Ruz and Thiel, 2015; Bergmann et al., 2017; Kawabe et al., 2022). Surprisingly, less attention has been given to the charismatic and biodiverse marine habitats such as mangrove forests, seagrass meadows and coral reefs (de Carvalho-Souza et al., 2018; Martin et al., 2019; Bonanno and Orlando-Bonaca, 2020). These marine habitats provide key ecosystem services, such as breeding and nursery grounds, carbon sequestration,

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coastal protection, recreation and tourism (Barbier, 2017), but many of which are being negatively impacted by marine litter pollution (Beaumont et al., 2019). Therefore, there is an urgent need to assess the risks of litter pollution in these marine habitats and their potential as sinks for marine litter so that timely interventions may be developed to protect these critical habitats.

Recently, there is a growing body of research assessing the trapping capacity of marine litter in various aquatic environments (Cozzolino et al., 2020; Luo et al., 2022; Navarrete-Fernández et al., 2022). Studies so far have found that vegetated habitats, especially with high surface complexity, can act as efficient sinks for macro- and microplastics (Cozzolino et al., 2020; de Smit et al., 2021). For example, mangrove trees have complex aerial root systems that potentially trap and retain litter that is transported by currents, making them an effective sink for marine litter (Martin et al., 2019; Luo et al., 2022). Seagrass canopies are known to play an important role in promoting particle trapping by reducing water flow (Hendriks et al., 2008). Several studies have found that seagrass canopies and their surrounding sediment efficiently trapped and accumulated microplastics (e.g., Huang et al., 2020; de los Santos et al., 2021) and macro-litter (Sanchez-Vidal et al., 2021; Navarrete-Fernández et al., 2022). While much less is known for coral reefs, the structural complexity of reef-building corals likely promotes the build-up of marine litter on coral reefs, particularly the ALDFG (Chiappone et al., 2005; Valderrama Ballesteros et al., 2018). In addition, marine litter abundance and distribution in each habitat type may vary depending on the zonation that is driven by tidal range and water depth (Pham et al., 2014; Lee et al., 2017; Veerasingam et al., 2020).

Marine litter is a significant source of pollution in many countries (Bergmann et al., 2015; United Nations Environment Programme, 2021). Published information regarding marine litter in Singapore, however, has been far and few (Lyons et al., 2020; Gajanur and Jaafar, 2022). In contrast, the local status of marine litter has predominantly been documented through data collection heavily driven by citizen science programmes such as International Coastal Cleanup Singapore (ICCS) and Dive Against Debris®. In this study, we present the first comprehensive investigation and comparison on the abundance and distribution of marine macro-litter across four marine habitats in Singapore. Specifically, surveys were conducted in sandy beaches, mangrove forests, seagrass beds and coral reefs in Singapore. We also compared how the abundance and composition of marine macro-litter varied temporally between the northeast (NE) and southwest (SW) monsoons. Lastly, we examined the relationships between proxies of habitat complexity (i.e., mangrove root density, seagrass cover and coral cover) and the amount of marine macro-litter, as well as assessed the potential of these marine habitats as litter traps. This is the first study that assessed the extent of marine litter pollution in Singapore across marine habitats in a systematic and standardised manner. Findings from this study provide an important baseline information on the abundance and potential sources of anthropogenic litter in Singapore's marine environment.

2. Materials and methods

2.1. Study locations

The entire coastline of Singapore is exposed to the coastal water of the Johor Strait in the north and Singapore Strait in the south, where a wide variety of natural and artificial coastal environments are situated.

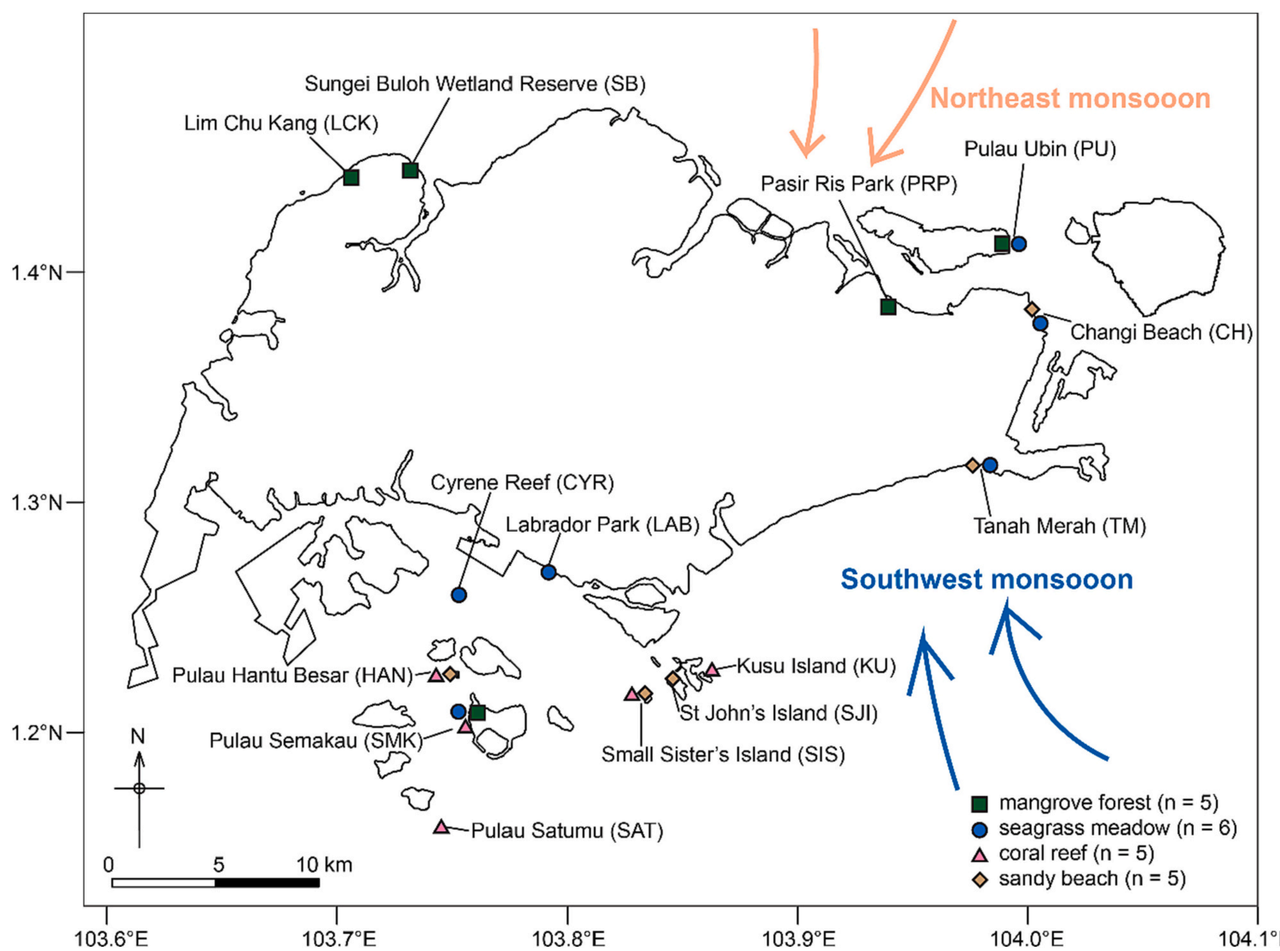

Fig. 1. Map of study sites in Singapore. The colour-coded arrows represent the wind directions during the respective monsoons.

In this study, we surveyed five mangrove forests, six seagrass meadows, five coral reefs and five sandy beaches across the island (Fig. 1). The study sites on mainland Singapore, specifically Changi Beach (CH), Labrador Park (LAB), Pasir Ris Park (PRP), Sungei Buloh Wetland Reserve (SB), Tanah Merah (TM), are mostly adjacent to the residential areas and part of public park systems, with the exception of Lim Chu Kang (LCK) site that is not accessible to most public as it is a military training area. Pulau Ubin (PU) is a small village located off the north-eastern coast of Singapore; it is 15 min away by boat and has >300,000 visitors annually. The remaining study sites are located among the Southern Islands of Singapore [Cyrene Reef (CYR), Kusu Island (KU), Pulau Hantu Besar (HAN), Pulau Satumu (SAT), Pulau Semakau (SMK), Small Sister's Island (SIS), St John's Island (SJI)], which are less accessible to the public and do not have inhabitants. Tourists may visit St John's Island and Kusu Island by taking a 30-minute public ferry ride, while Pulau Hantu Besar and Small Sister's Island can only be accessed by private charters. Visits to Cyrene Reef, Pulau Satumu and Pulau Semakau, however, will require permission from relevant local authorities.

Singapore's climate is typically characterised by two monsoon cycles: the northeast (NE) monsoon (from December to early March) and the southwest (SW) monsoon (from June to September), and these monsoons are separated by two short inter-monsoon periods. During the NE monsoon, the prevailing wind directions are northerly to north-easterly, while during the SW monsoon, the prevailing wind directions are southeasterly to southerly (Fig. 1). The hydrodynamics in the coastal waters of Singapore are also complex and variable as it is under the influence of major currents driven by trade winds and monsoons (Chen et al., 2005; van Maren and Gerritsen, 2012). Within the Southern Islands, the dominant current flow is eastward from April/May to September/October, and westward during the other months (Neo et al., 2013).

2.2. Survey methodology

Surveys were generally conducted by laying three 30 m length × 4 m width belt transects parallel to the coastlines at the following areas: (1) the seaward fringes of mangroves (at mid-tide level, 0.7–1.0 m above chart datum), (2) the strandlines of mangroves (2.5–3.0 m above chart datum), (3) mid-tide areas of beaches (0.7–1.0 m above chart datum), (4) the strandlines of beaches (2.5–3.0 m above chart datum), (5) seagrass meadows at low-tide zones (0.1–0.3 m above chart datum), and (6) reef crest of coral reefs (2–3 m below chart datum). The mangrove forests were dominated by *Avicennia* spp. (*A. alba*, *A. marina*, *A. officinalis*, and *A. rumphiana*; Turner and Yong, 1999). The strandlines of beaches are marked by the high tide lines, before the backshore vegetation. Due to environmental constraints of the mangrove forests, three shorter belt transects (20 m length × 4 m width) were laid at the strandline and mid-tide level, respectively at LCK, while only the mid-tide areas were assessed at the PRP. The macro-litter surveys were carried out by at least two observers per belt transect, where observers would walk along the transect to pick up all visible litter items on the surface. Surveys were conducted once during the wetter SW monsoon (July–September 2021) and once during the drier period of the NE monsoon (January–March 2022).

The consolidated litter items within each belt transect were sorted into one of the eight main categories (i.e., 'plastic', 'fishing gear', 'metal', 'rubber', 'glass', 'wood', 'cloth', 'other') and 51 specific categories (see Supplementary Table 1 for the full list of litter categories documented). The category classification for macro-litter was adopted following the National Oceanic and Atmospheric Administration (NOAA) Marine Debris Shoreline Survey Field Guide (Opfer et al., 2012), with modifications to include additional categories to increase the resolution of the composition of macro-litter found at local survey sites. The combined mass of each litter type was also estimated using handheld digital scales (precision to 0.005 kg). For items that were below the detection limit of the scale, we assumed the mass was 0.0025 kg. Litter density was expressed in terms of count (items m^{-2}) and mass (g m^{-2}).

To understand how habitat complexities might influence the amount of macro-litter loading, we quantified the density of mangrove roots, seagrass cover and coral cover, respectively for each habitat type (Fig. S1). Along the three 30-m transects at the mangrove forests and seagrass meadows, a 25 × 25 cm^2 quadrat was placed every 5 m ($n = 6$ quadrats per transect). Mangrove aerial root density was estimated by counting the number of pneumatophores (i.e., aerial roots; predominantly from *Avicennia* spp.) within the quadrat. Seagrass cover was determined by estimating the total percentage of substrata within each quadrat that was covered by seagrass and this was estimated using the seagrass percent cover photo standards provided by Seagrass-Watch (McKenzie et al., 2003). The main seagrass species found at our study sites were *Halophila ovalis*, *Halodule universis*, *Cymodocea rotundata* and *Thalassia hemprichii*. Coral cover was estimated via the Point Intercept Transect (PIT) method by recording the substratum type directly below the transect tape at every 50 cm. The substratum types recorded were scleractinian corals (genus-level), macroalgae, epilithic algal matrix, other biotic organisms (e.g., anemones, soft corals, sponges, zoanthids) and abiotic substratum (e.g., sand, rock). Coral cover is generally positively correlated with habitat complexity because corals are responsible for much of the structure on coral reefs (Graham and Nash, 2013). Stress-tolerant and generalist species (e.g., *Montipora*, *Platygyra*) were the dominant coral taxa on Singapore's coral reefs.

2.3. Statistical analysis

All analyses were performed in R v.4.2.1 (R Core Team, 2022). To compare how the densities of macro-litter based on count and mass varied across habitat types between monsoons, we performed generalised linear mixed-effect models using the *glmmTMB* package (Brooks et al., 2017). Count data were fitted following Poisson distribution while mass data were fitted following Tweedie distribution, with transect area included as an offset term in both models to standardise response variables as densities. "Habitat type", "Season", and their interaction were fitted as fixed factors in both models. To account for repeated measurements and spatial auto-correlation of some sites with multiple habitat types, we considered "Monsoon" and "Habitat type" nested within "Site" as random effects, with optimal random structure chosen based on Akaike's Information Criterion (AIC). Full model specifications were included in Supplementary Table 2. When a significant factor was identified, *post-hoc* analysis was performed using the estimated marginal means (*emmeans* package; Lenth, 2022) and adjusted *p*-values following False Discovery Rate methods. Assumptions on normally distributed residuals and homogeneity of variance of GLMM models were validated using the *DHARMa* package (Hartig, 2022).

The relationships between proxies of habitat complexities (i.e., mangrove aerial root density, seagrass cover and coral cover) and the densities of macro-litter based on count and mass were visualised by applying the LOESS smoothed conditional mean with a span of 0.8.

3. Results

3.1. Density of macro-litter across habitat types and monsoons

The count density of macro-litter was significantly different across habitat types, but not between monsoons (Fig. 2, Table S2). Seagrass meadows and coral reefs had lower count densities (0.06 ± 0.02 and 0.04 ± 0.01 items m^{-2}, respectively; mean ± SE) compared to mangroves (mangrove strandline: 2.58 ± 0.76 items m^{-2}, mangrove mid-tide: 0.37 ± 0.07 items m^{-2}) and beach strandline (1.03 ± 0.29 items m^{-2}; Figs. 2 and S2). There were no differences in the macro-litter count density between beach mid-tide and mangrove mid-tide, seagrass meadows, and coral reefs (Fig. S2). Mangrove mid-tide and beach mid-

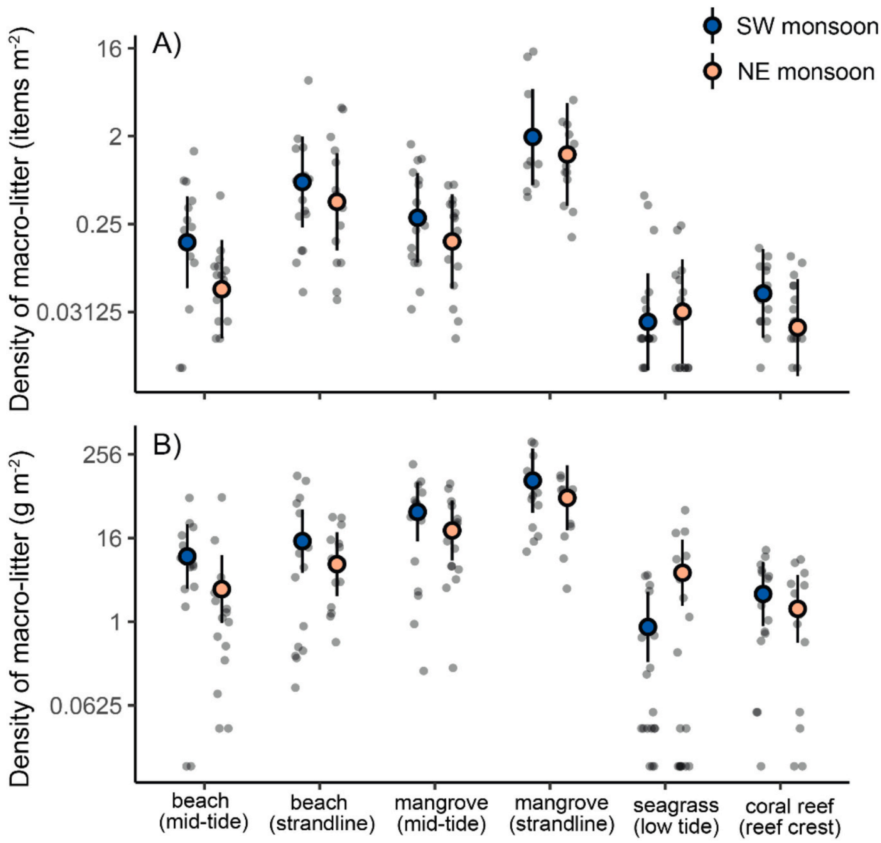

Fig. 2. The estimated marginal means and 95 % confidence intervals of the density of macro-litter (in logarithmic scale) in terms of count (A) and mass (B) across habitat types and monsoons. Smaller gray points represent raw data.

tide had 83–87 % lower macro-litter count density than their respective strandlines (Fig. S2).

In contrast, there was a significant interaction effect between habitat type and monsoon on the mass density of macro-litter (Figs. 2 and S3, Table S2). During the SW monsoon, both the strandline and mid-tide zones in mangrove forests (120.92 ± 39.53 and 47.94 ± 12.99 g m^{-2}, respectively; mean ± SE) had higher mass density of macro-litter compared to seagrass meadows and coral reefs (0.95 ± 0.39 and 3.33 ± 0.89 g m^{-2}, respectively). On the other hand, during the NE monsoon, higher mass densities of macro-litter were found in both mangrove areas (mangrove strandline: 55.51 ± 11.99 g m^{-2}, mangrove mid-tide: 27.49 ± 7.73 g m^{-2}) compared to coral reefs (2.32 ± 0.66 g m^{-2}), but only mangrove strandlines had higher macro-litter mass density than seagrass meadows (5.75 ± 2.51 g m^{-2}). Significant differences between SW and NE monsoons were only observed for the seagrass meadows (Fig. S3).

3.2. Composition of macro-litter

Across all habitat types, plastic was the major type of macro-litter found in terms of count density, where 72.1 to 93.7 % of count density was made up of plastics, except on coral reefs during both monsoons and on seagrass meadows and beach mid-tide zones during the NE monsoon (Fig. 3). Notably, fishing-related items, such as fishing lines, lures and sinkers, were commonly found on coral reefs (an average contribution of 32.9–52 % to overall count density). In contrast, in terms of mass density, plastics usually made up <50 % across the habitat types and monsoons. The exception was the strandlines in the mangrove forests, where plastics contributed 80.1 % to the overall mass densities during the SW monsoon and 68.6 % during the NE monsoon (Fig. 3).

Within the category of plastic litter, a wide range of items was found, ranging from household-related items such as plastic bottles, drinking straws, food packaging and plastic bags to cigarette butts (Fig. 4). "Other plastic items" mainly consisted of clear or foamed food containers, disposable cutleries, high density polyethylene (HDPE) containers, gunny sacks, ropes and lighters. A very high number of plastic drinking straws (mean of 2.27 items m^{-2}) was found at the strandline areas in the mangroves during the SW monsoon, while foam fragments and cigarette butts were the most abundant at the strandline areas on beaches during both monsoons.

3.3. Relationships between habitat complexity on macro-litter density

For mangrove forests, the transects consisting of higher mangrove aerial root density generally had higher count and mass densities of macro-litter (Fig. 5). For seagrass meadows, the count density of macro-litter also increased with seagrass cover, but not for mass densities (Fig. 5). No strong linear relationships were found between coral cover and macro-litter densities (Fig. 5).

4. Discussion

4.1. Effects of habitat types on macro-litter density

Across the habitat types, our findings revealed that mangroves were the most efficient at capturing and trapping marine macro-litter, which coincides with the results of previous studies (Martin et al., 2019; Luo et al., 2022). Broadly, substantially higher densities of macro-litter by count and mass were found in the strandline and mid-tide areas of mangroves compared to seagrass meadows and coral reefs between the monsoons. There was an exception during the NE monsoon, whereby no significant difference was found in the mass density of macro-litter between the mangrove mid-tide areas and seagrass meadows. The average macro-litter abundance in Singapore's mangroves was 1.35 ± 0.37

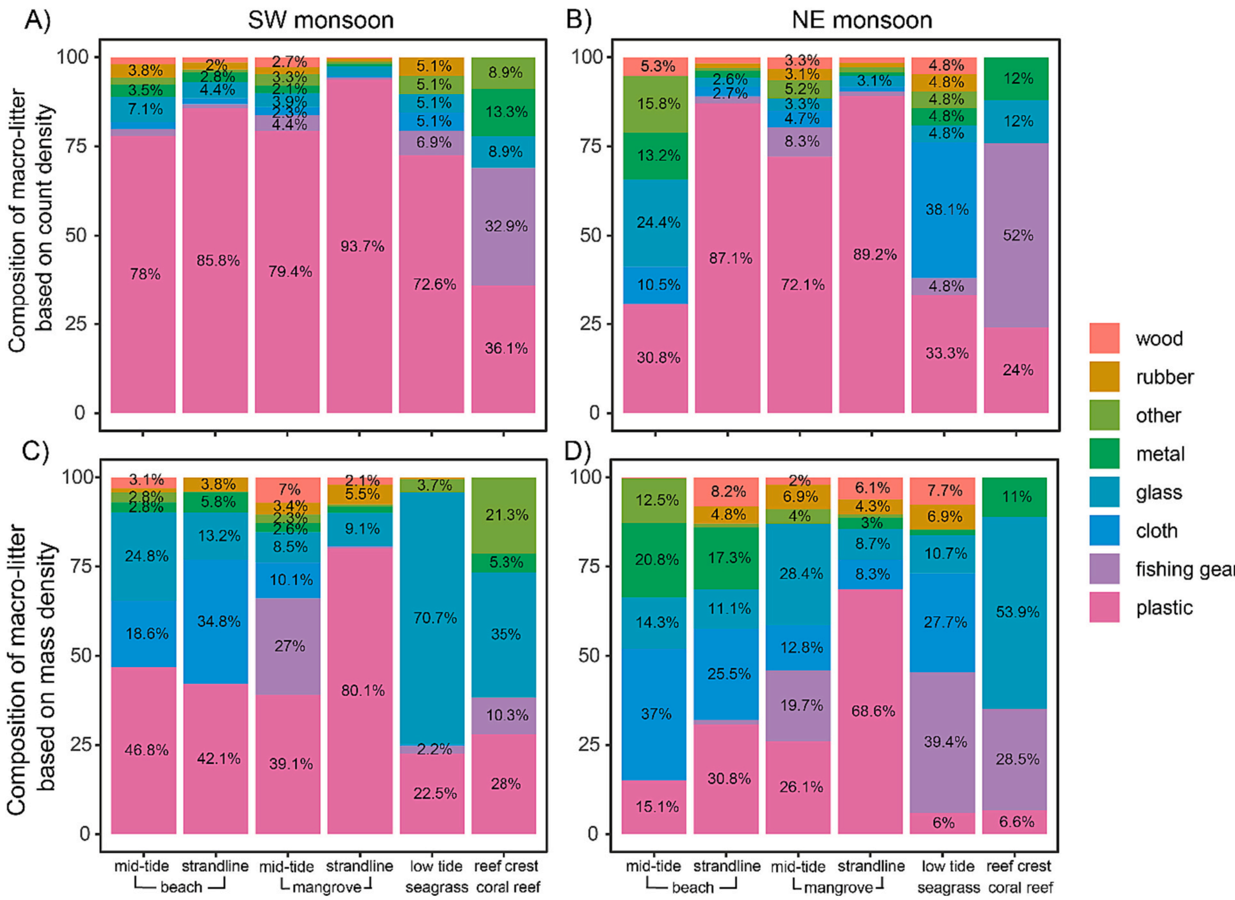

Fig. 3. Average composition of macro-litter based on count (A and B) and mass densities (C and D) across habitat types and monsoons. Values <2 % were not annotated.

items m^{-2}, ranging from 0.26 items m^{-2} in Semakau to 3.90 items m^{-2} in Lim Chu Kang. These values were within the same order of magnitude as those reported for mangroves of the Red Sea and Arabian Gulf dominated by *Avicennia marina* (0.66–1.21 items m^{-2}; Martin et al., 2019) and for Hong Kong mangroves dominated by *Kandelia obovata* (1.45 items m^{-2}; Luo et al., 2022). In contrast, the average abundances of marine macro-litter in Singapore's seagrass meadows and coral reefs were lower by >20-fold (0.06 ± 0.02 and 0.04 ± 0.01 items m^{-2}, respectively). Interestingly, the macro-litter abundance was found to be much higher along the strandline areas compared to the seaward zones. Mangrove trees usually grow along the coastline, forming a protective barrier between the land and sea zones, thus preventing the leakage or redispersion of trapped litter into the marine environment (Ivar do Sul et al., 2014; Luo et al., 2022). Therefore, the high densities of macro-litter in the mangrove forests were likely due to the retention of land-based anthropogenic litter and the trapping of litter items from sea-based sources that were washed ashore by tidal and wave action.

The beach strandlines were found to capture higher number of macro-litter relative to the beach mid-tide areas, seagrass meadows and coral reefs. The litter densities by count on the strandlines of beach sites that were offshore and remote (Pulau Hantu Besar and Small Sister's Island) were substantially lower (average of 0.36 and 0.38 items m^{-2}, respectively) compared to beach sites on the mainland of Singapore (Changi Beach and Tanah Merah: 1.30 and 1.51 items m^{-2}, respectively). This difference was likely due to the proximity of urban areas to mainland sites (Leite et al., 2014; Nelms et al., 2017), which implies a greater contribution of land-based litter to the overall count densities. It was also possible that macro-litter on offshore beach sites had higher ratio of sea- to land-based sources, but a further study is needed to confirm this. Notably, a higher litter density was observed at the beach site of St John's Island (average of 1.57 items m^{-2}), which is a semi-enclosed bay. Considering the typical hydrodynamics of partially or fully enclosed water bodies such as poor water exchange, marine litter found within bays or lagoons rarely disperse from the areas, resulting in the accumulation and stranding of litter (Rodríguez-Díaz et al., 2020; Garcés-Ordóñez et al., 2022).

The seagrass meadows of Singapore had very low densities of macro-litter relative to the other sampled habitats, ranging from 0.001 items m^{-2} in Cyrene Reef to 0.24 items m^{-2} in Tanah Merah, suggesting that these habitats are likely not efficient traps or sinks for macro-litter in Singapore. Although previous studies have confirmed the presence of macro-litter in seagrass meadows, the efficiency of these habitats as sinks has been inconclusive. For instance, Cozzolino et al. (2020) found that seagrass habitats in southern Portugal dominated by *Zostera noltei* (mean canopy height of 37.8 cm) and *Cymodocea nodosa* (mean canopy height of 24.6 cm) did not significantly trap more macro-litter than their neighbouring non-vegetated areas. On the other hand, for the subtidal seagrass meadows in Southern Spain colonised by *Posidonia oceanica* (canopy heights ranged between 15 and 122 cm), Navarrete-Fernández et al. (2022) found that the edges of the meadows had the highest macro-litter abundance compared to the areas outside and inside of the meadows. Despite the contrasts, these habitats can reduce or dampen water velocities within the canopy based on hydrodynamic studies of water flow through seagrass beds (Fonseca and Cahalan, 1992; Lacy and Wyllie-Echeverria, 2011). Therefore, we can expect that these hydrodynamic changes over seagrass beds influence the capture rates of macro-litter within the meadows, whereby taller seagrass canopies are more likely to retain and trap macro-litter compared to shorter seagrass canopies (Navarrete-Fernández et al., 2022). Notably, our study found significantly higher count density of macro-litter at transects with higher

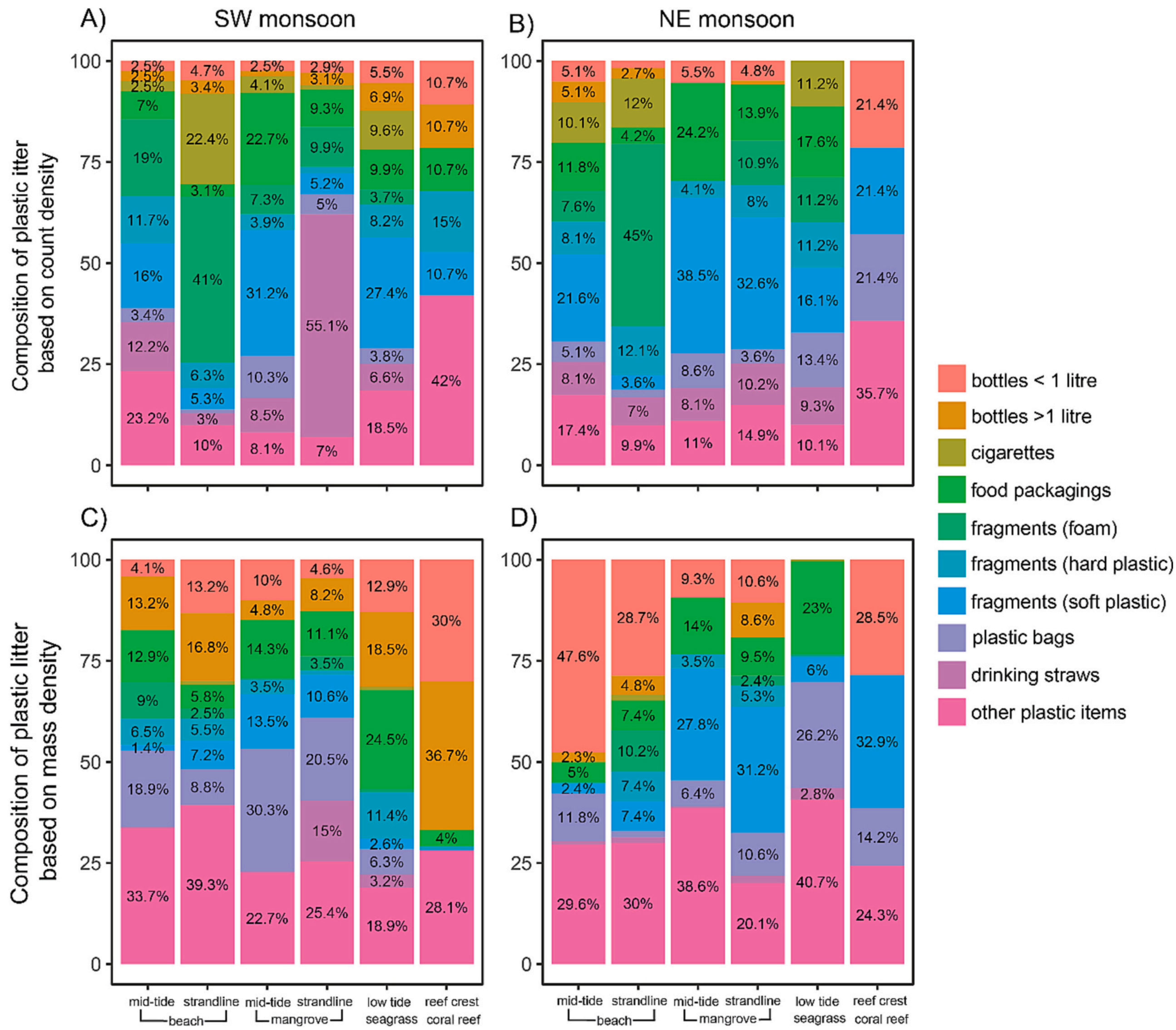

Fig. 4. Average composition of plastic litter based on count (A and B) and mass densities (C and D) across habitat types and monsoons. Values <2 % were not annotated.

seagrass cover, even though these sampled meadows were mostly composed of *Halophila ovalis* and *Halodule uninervis* that had low canopy heights (<10 cm; Yaakub et al., 2013). It was likely that increasing seagrass density resulted in greater flow reductions inside the canopy (Peterson et al., 2004), where the resultant of increased drag and reduced wave energy (Fonseca and Cahalan, 1992; Bradley and Houser, 2009) helped promote the trapping of marine litter. Overall, the potential for seagrass meadows to serve as marine plastic sinks is yet to be decided, considering that emerging studies reveal contrasting patterns in their ability to trap macro- and microplastics (Cozzolino et al., 2020).

Similarly, we found low densities of marine litter on coral reefs in Singapore, ranging from 0.01 items m^{-2} in Pulau Semakau to 0.1 items m^{-2} in Kusu Island. These values were within the range of macroplastic litter density (0.02 to 0.109 items m^{-2}) reported on the coral reefs in the Asia-Pacific region (Lamb et al., 2018). We did not find strong linear relationships between coral cover and densities of macro-litter, suggesting that sites with more complex habitat structures would not necessarily trap higher amounts of litter. As the coral reef sites examined in this study are generally located away from the main island of Singapore, they typically experienced lower impacts from human activities. For example, Pulau Satumu recorded high coral cover (>50 %) as it is located farthest away from mainland Singapore, and therefore the most pristine site with low density of marine litter. It was also possible that areas with intermediate coral cover (30–40 %) trapped the greatest amount of litter items due to the availability of gaps unoccupied by live corals (e.g., dead corals, rubbles, sand), but further studies are needed to validate this. Nevertheless, despite the density of marine litter being lowest on coral reefs compared to other habitat types, marine litter is an emerging threat to coral reefs. Plastic particles have been found to act as vectors for pathogens responsible for coral diseases (Lamb et al., 2018), but more research is needed to thoroughly understand the extent and impact of marine litter on coral reefs.

4.2. Effects of habitat types on macro-litter composition

In the mangroves, plastic was the dominant litter based on count density, representing an average of 85.3 % of the total litter found. The most common types of plastic litter recorded were soft plastic fragments (26.9 %), drinking straws (20.5 %) and food packaging (17.5 %). These results are unsurprising as other studies have similarly found that soft plastics such as fragments and food packaging are most easily retained in the mangrove forests as these items tend to become entangled and

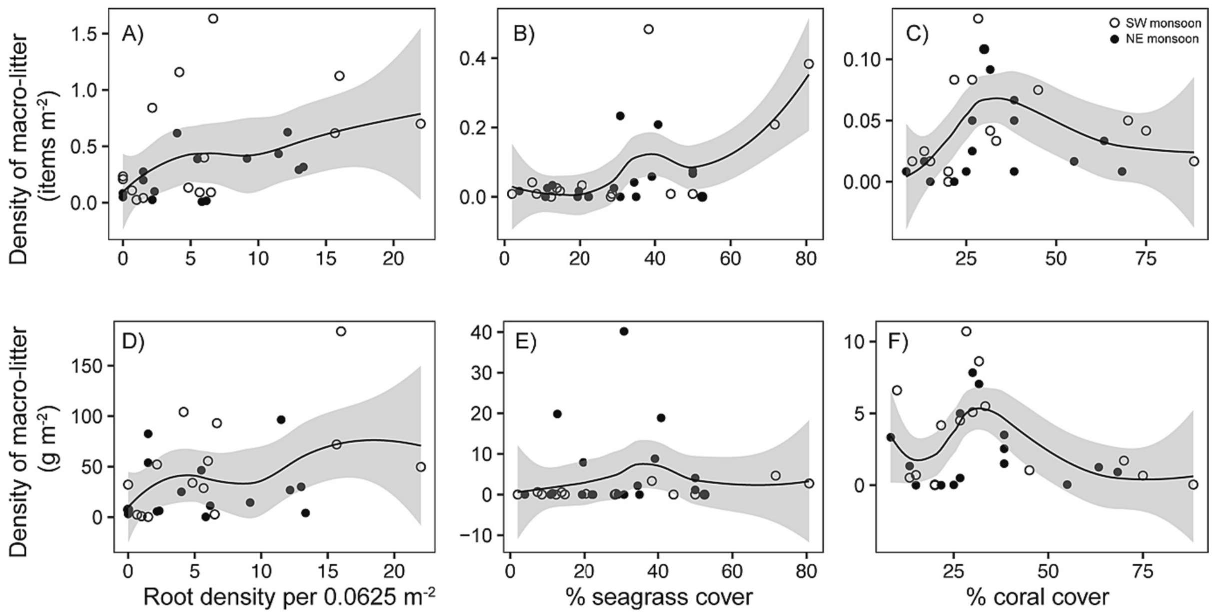

Fig. 5. Relationships between proxies of habitat complexities (i.e., mangrove root density, seagrass cover and coral cover) and densities of macro-litter.

stranded amid the vegetation (Ivar do Sul et al., 2014). We also found evidence to show a significant positive correlation between macro-litter density and pneumatophore density, where mangrove forests with denser vegetation and higher density of pneumatophores (mainly of *Avicennia* spp.) were more vulnerable to marine plastic pollution. A consequence of plastic litter entangling within mangroves is the smothering and suffocating of aerial roots, causing tree mortality over time (van Bijsterveldt et al., 2021). A high abundance of marine macro-litter may also negatively impact epibenthic fauna in mangroves by reducing the availability of foraging area for surface sediment feeders and blocking the holes for burrowing crabs and mudskippers (Luo et al., 2021). We also found a notably high abundance of drinking straws, which was only recorded from the strandlines of the northern mangrove sites (1424 straws at Lim Chu Kang and 137 straws at Sungei Buloh Wetland Reserve) during the SW monsoon. As discussed earlier, this localised trapping of drinking straws on the strandlines of mangroves suggests dumping from land-based activities or indirect leakage of sewage or urban run-off due to storm-related events. Drinking straws were also one of the most common litter types reported by the ICCS, whereby they were the third most abundant litter collected in 2018 and 2019, and as the fifth most abundant litter in 2020.

At the sampled beach sites, we observed a considerably higher count density of macro-litter at the strandline areas compared to the mid-tide areas, but this was not observed for mass density. The macro-litter observed on the strandlines of beaches consisted of a high number of small, lightweight foam fragments and cigarette butts, particularly at Tanah Merah (average of 2.55 foam items m^{-2}). We hypothesised that the presence of vegetation at the backshore, such as the sea morning glory (*Ipomoea pes-caprae*), a type of creeper, in our survey sites might have promoted the likelihood of macro-litter being trapped and retained at the strandlines (pers. obs.). Globally, cigarette butts and foams have also been reported as the most ubiquitous plastic litter across numerous beaches (Lacroix et al., 2022; Ocean Conservancy, 2023). In Singapore, cigarette butts have also been consistently found as the most abundant litter between 2017 and 2020 by the ICCS. Even though it was difficult to identify the exact sources of foam fragments in our study as they had been broken up into small pieces, they likely originated from packaging materials, which are frequently used as disposable, single-use plastic containers in Singapore and neighbouring countries.

Soft plastic fragments and food packaging were observed as the most common plastic litter items by count on seagrass meadows. As these items were lightweight, they were more easily transported and deposited in seagrass meadows with low canopies such as those in Singapore (Navarrete-Fernández et al., 2022). During the NE monsoon, a greater number of cloth items were also found, resulting in higher mass density of macro-litter. Macroplastics may break down and degrade into microplastics and adhere on seagrass blades, which could be consumed by herbivores and serve as a pathway for plastics to enter the seagrass food webs (Goss et al., 2018; Seng et al., 2020).

On the coral reefs, the most common litter recorded was derelict fishing gear, or ALDFGs. Specifically, they consisted of monofilament lines, hooks, and sinkers, which are common items used for artisanal and recreational fishing. This result was also consistent with the ALDFGs composition and patterns reported in Gajanur and Jaafar (2022), where the literature review based on citizen science data on ALDFGs between 2000 and 2019 revealed the prevalence of fishing lines, lures, sinkers, hooks, and rods on Singapore's coral reefs. Coincidentally, the sites with higher count density of marine litter (i.e., Kusu Island and Pulau Hantu Besar) were popular and publicly accessible fishing sites. ALDFGs may enter the marine environment through several pathways, for instance, the fishing gear may be lost due to improper fishing methods, worn gear, or inclement weather (Gilman, 2015). Also, fishers may abandon gear that becomes snagged on underwater features or to escape detection when fishing illegally. In other instances, large fishing gear (such as fish aggregating devices) may be abandoned or lost at sea (Sinopoli et al., 2020). Most of the ALDFGs found in the coral reefs were usually entangled with corals, which might cause tissue abrasion and negatively impact coral health over time (Valderrama Ballesteros et al., 2018). Corals that suffer tissue wound might also become more susceptible to pathogen infection (Lamb et al., 2018). Ghost fishing, where ALDFGs continue to fish passively and indiscriminately in an uncontrolled manner, was not observed in this study.

4.3. Effects of monsoons on macro-litter density

Macro-litter density, both in terms of count and mass, did not differ considerably between monsoons across all habitat types, except for seagrass meadows having higher mass density during the NE monsoon compared to the SW monsoon. While a higher mean monthly rainfall was recorded during the SW monsoon (231.6 mm between July and September 2021 versus 146 mm between January and March 2022; Singapore Government public weather database: https://data.gov.sg/d ataset/rainfall-monthly-total), intense rainfall events typically occur throughout the year in Singapore. Monsoon surges bring about heavy rain and strong wind episodes during the NE monsoon while the Sumatra squalls are responsible for thunderstorms and wind gusts during the SW monsoon. Our results contradicted with the distribution patterns observed in a recent study by Jong et al. (2022), who documented higher microplastic abundance in the sediment and water samples collected around Singapore during the SW monsoon compared to the NE monsoon. Similarly, a modelling study by Tong et al. (2021) predicted that the northern coastline of Singapore could be a hotspot for floating plastic litter during the SW monsoon while plastic litter would be concentrated along the eastern coastline of Singapore during the NE monsoon. However, this trend was not observed in this study (Figs. S4 and S5). A possible reason was that the models in Tong et al. (2021) focused on simulating floating litter movement based on hydrodynamics and windage, while the stranding of litter is likely driven by other parameters such as the trapping capacity of habitat types along the coastlines. Nevertheless, the litter density in this study was surveyed only once during each monsoon, which might not be representative of the annual patterns. It is therefore critical to establish sustained monitoring to have a good quality data for interpreting the temporal patterns of litter abundance and composition.

4.4. Managing marine macro-litter in Singapore

In Singapore, the problem of marine litter pollution is ubiquitous across all sampled habitats in this study. Specifically, the mangroves and beaches were found to have higher litter pollution compared to the seagrass meadows and coral reefs. Results from this study provide critical baseline information on the state of marine litter pollution in Singapore, which has been largely reliant on data generated from citizen science programmes such as International Coastal Cleanup Singapore and Dive Against Debris. However, these programmes do not implement standardised sampling efforts and are therefore not suitable for assessing the spatial and temporal changes in litter abundance. Setting up long-term monitoring protocol, such as the ones used in our study, is critical to determine if there are any changes in the state of pollution and to assess the effectiveness of litter management policies. In recent years, Singapore government introduced better waste management policies, including the Resource Sustainability Act in 2019 that implemented the Mandatory Packaging Reporting framework and Extended Producer Responsibility Framework for waste (Ministry of Sustainability and the Environment, 2020) and Singapore's inaugural National Action Strategy on Marine Litter (NASML) (Ministry of Sustainability and the Environment, 2022), which aims to galvanise the nation to combat marine litter across six priority areas including the reduction of land-based and sea-based source litters. Coupled with the goals of NASML, the results from this study can further provide the impetus for monitoring marine litter abundance at the various marine habitats to evaluate the results of litter reduction strategies.

CRediT authorship contribution statement

Jenny Fong: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft. **Samuel Hsien Rong Lee:** Investigation, Writing – review & editing. **Yuchen Sun:** Investigation, Writing – review & editing. **Cheng Ling Lim:** Investigation, Writing – review & editing. **Yean Ai Jolin Tan:** Investigation, Writing – review & editing. **Yi Hong Tan:** Investigation, Writing – review & editing. **Mei Lin Neo:** Conceptualization, Methodology, Writing – review & editing, 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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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