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Exposure of coastal environments to river-sourced plastic pollution

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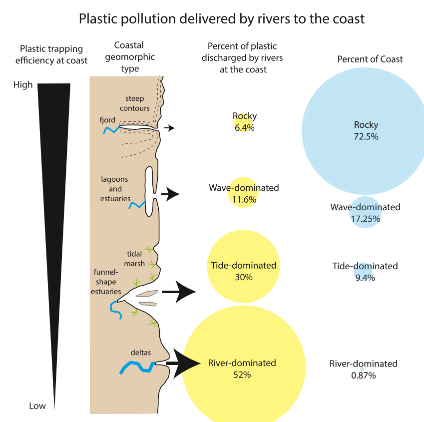
HIGHLIGHTS

- The exposure of coastal environments to river-borne plastic pollution is assessed.
- Deltas comprise 0.87% of the global coast and receive 52% of plastic pollution.
- Rocky coasts comprise 72.5% of the coast and receive 6.4% of plastic pollution.
- 54% of mangroves are within 20 km of >1 t/yr plastic pollution point source.
- Different coastal environments have different plastic trapping efficiency.

GRAPHICAL ABSTRACT



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ABSTRACT

Marine litter is a global problem which poses an increasing threat to ecosystem services, human health, safety and sustainable livelihoods. In order to better plan plastic pollution monitoring and clean-up activities, and to develop policies and programmes to deter and mitigate plastic pollution, information is urgently needed on the different types of coastal ecosystem that are impacted by land-sourced plastic inputs, especially those located in proximity to river mouths where plastic waste is discharged into the ocean. We overlayed the most current existing information on the input of plastic to the sea from land-based sources with maps of coastal environments and ecosystems. We found an inverse relationship exists between coastal geomorphic type, plastic trapping efficiency and the mass of plastic received. River-dominated coasts comprise only 0.87% of the global coast and yet they receive 52% of plastic pollution delivered by fluvial systems. Tide-dominated coasts receive 29.9% of river-borne plastic pollution and this is also where mangrove and salt marsh habitats are most common. Wave-dominated coasts receive 11.6% of river-borne plastic pollution and this is where seagrass habitat is most common. Finally, rocky shores comprise 72.5% of the global coast, containing fjords and coral reefs, while only receiving 6.4% of river-borne plastic pollution. Mangroves are the most proximal to river-borne plastic pollution point sources of the four habitat types studied here; 54.0% of mangrove habitat is within 20 km of a river that discharges more than 1 t/yr of plastic pollution into the ocean. For seagrass, salt marsh and coral reefs the figures are 24.1%, 22.7% and 16.5%, respectively. The findings allow us to better understand the environmental fate of plastic pollution, to advance numerical models and to guide managers and decision-makers on the most appropriate responses and actions needed to monitor and reduce plastic pollution.

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1. Introduction

1.1. Plastic pollution of the oceans

Plastic pollution in the oceans has attained levels that have captured the attention of the global community (UNEP and GRID-Arendal, 2016; Borrelle et al., 2017; Napper and Thompson, 2019). Plastic has been found in all parts of the marine ecosystem (Geyer et al., 2017) from seafood to the most remote environments on Earth including the bottom of the deepest ocean trenches (Fischer et al., 2015; Peng et al., 2018; Kane and Clare, 2019). Most plastic waste that enters the coastal marine environment is sourced from the land (Lebreton et al., 2017). Some is dispersed out to sea but the majority is trapped at the coast (Barnes et al., 2009; Ritchie and Roser, 2020; Harris, 2020).

Humans currently produce approximately 360 million metric tonnes (Mt) of plastic per year (PlasticsEurope, 2019) but the fraction that enters the ocean is uncertain. Jambeck et al. (2015) evaluated mismanaged plastic waste within 50 km of the coast and estimated that, in 2010, between 4.8 and 12.7 Mt entered the ocean. Lebreton and Andrady (2019) used different input data and estimated that 5.1 (3.1–8.2) Mt entered the ocean in 2010. However, the authors also noted that the discharge of plastic waste into the ocean is poorly known and depends on many factors including topography, land use, climate, vegetation and the type of plastic waste (see also Borrelle et al., 2017, and Schmidt et al., 2017).

Lebreton et al. (2017) analysed mismanaged plastic waste in global watersheds calibrated with observations of plastic waste occurrence in samples of river water and estimated that between 1.15 and 2.41 Mt./year is delivered to the coast by the world's rivers. Lebreton et al. (2017) note that their estimate is conservative because it excludes large plastic objects (objects >0.5 m in size) as well as particles smaller than ~0.3 mm and includes only those buoyant particles trapped in a mesh ~0.3 mm in size. Nevertheless, this estimate has an advantage for spatial analysis because river mouths equate spatially to known point sources of input to the ocean. The high volumes of plastic discharged at river mouths (point sources) suggests that these should be the most polluted coastal environments in terms of plastic, but the true exposure of different coastal environments to plastic pollution in terms of their proximity to river-mouth point sources, is unknown. Coastal habitats are also exposed to a varying amount of non-river-point-source plastic pollution including wind-blown plastic, plastic from direct littering of beaches and plastic from fishing, shipping and other sea-based activities. These other (non-river) sources are not considered further in the present study.

1.2. Coastal ecosystems and their relative exposure to plastic pollution

Planning of plastic pollution monitoring and clean-up activities, together with the development of policies and programmes to deter and mitigate plastic pollution, depend upon information on the different types of coastal ecosystems that are impacted by land-sourced plastic inputs, especially those located in proximity to river mouths where plastic waste is discharged into the ocean. It is evident that different coastal environments (estuaries, lagoons, deltas, etc.), habitats and ecosystems (mangroves, seagrasses and coral reefs, for example) will have different levels of exposure to the input of plastic pollution, but such differences are currently unknown. It follows that the response of governments and responsible authorities will need to be tailored to suit the requirements imposed by different kinds of environments.

The geomorphology of coastal environments is determined to a first approximation by a combination of factors that include the input of sediment (e.g. from rivers, coastal erosion, and biological production) and the wave and tidal energy regime which acts to disperse and transport the sediment along the coast (Boyd et al., 1992; Nyberg and Howell, 2016). Coasts that are sediment starved are often rocky and may be prone to erosion, whereas the discharge of sediment from major rivers may build a prograding delta that causes the coastline to locally bulge seawards. Large swell waves generate significant alongshore sediment transport that produces coast-parallel sedimentary features such as spits, barriers, sand bars and barrier islands. In contrast, large tidal ranges (>4 m) and strong tidal currents generally produce coast-normal sedimentary features, including elongate tidal sand banks, wide-mouthed estuaries, funnel-shaped (in plan view) deltaic distributary channels, and broad intertidal flats (Fig. 1).

The physical processes that govern the dispersal of plastic pollution in the marine environment are complex and will vary depending upon the composition, shape and density of the plastic particles together with the prevailing wind, wave and current energy regime (e.g. Hardesty et al., 2017; Koelmans et al., 2017; Atwood et al., 2019; van Wijnen et al., 2019). The energy regime is important to understand the fate of plastic pollution because of its relevance to the dispersal of plastic particles suspended in the water column as well as the fragmentation of particles stranded on beaches and transported as bedload along the seafloor (Enders et al., 2019). Models for the global mass inventory of plastics in the oceans are currently hindered by lack of information on fragmentation and dispersal (Koelmans et al., 2017). The extent of mechanical particle fragmentation and subsequent dispersal is expected to be greater in high-energy environments, in which waves and tidal currents cause large plastic particles to fracture during bedload transport while simultaneously maintaining smaller fragments in suspension in the water column, making them available for transport along-shore or offshore by local wind-driven or other unidirectional ocean currents. In contrast, particles in low-energy environments are more likely to settle to the seabed close to the point source and become sequestered in seabed sediments (Enders et al., 2019; Harris, 2020).

There is clear evidence that plastic particles are widely dispersed along coastlines and offshore into shelf and deep sea environments, some remaining suspended in the water column for years to decades (Pabortsava and Lampitt, 2020). Biological fouling is anticipated to gradually remove floating plastic particles from the water column (Lobelle and Cunliffe, 2011). Microplastic particles are also consumed by zooplankton and expelled as faecal pellets (Cole et al., 2013) or exported to the seabed through flocculation and sinking as aggregates (Andrady, 2015; Long et al., 2015; Bergmann et al., 2017; Michels et al., 2018).

The role of sunlight in the degradation and embrittlement of plastic particles has been documented for samples collected on beaches (e.g. Barnes et al., 2009) as well as samples of plastic floating on the ocean surface (e.g. Cózar et al., 2014). The weakened particles are subsequently prone to mechanical fragmentation. This is particularly likely along high-energy beaches, rocky shorelines and other areas where active bedload transport of sand and gravel occurs. It is to be expected that the mechanical fragmentation of plastic particles is analogous to the creation of detrital calcareous silt from natural carbonate particles (shells) that are broken down by physical (and biological) erosion processes (Harris, 1994; Smith and Nelson, 2003; Trower et al., 2019). Thus the creation of plastic fragments together with their export to distal depositional environments (either offshore to deep water environments, or along-shore to lower energy coastal environments that are efficient sediment traps) are both more likely to occur along high-energy coasts, compared to shorelines exposed to lower wave and tide energy.

1.3. Aims of the present study

In this study, we overlay the most current existing information on the input of plastic to the sea from rivers with maps of coastal environments and ecosystems in order to address the following questions: 1) what kinds of coastal environment and ecosystem are most exposed to river-sourced plastic pollution; and 2) is plastic pollution entering the coast via rivers into mostly high-energy dispersive, or low-energy retentive environments? Our aim is to provide a broad (global) spatial reference frame to better understand some of the key variables that control

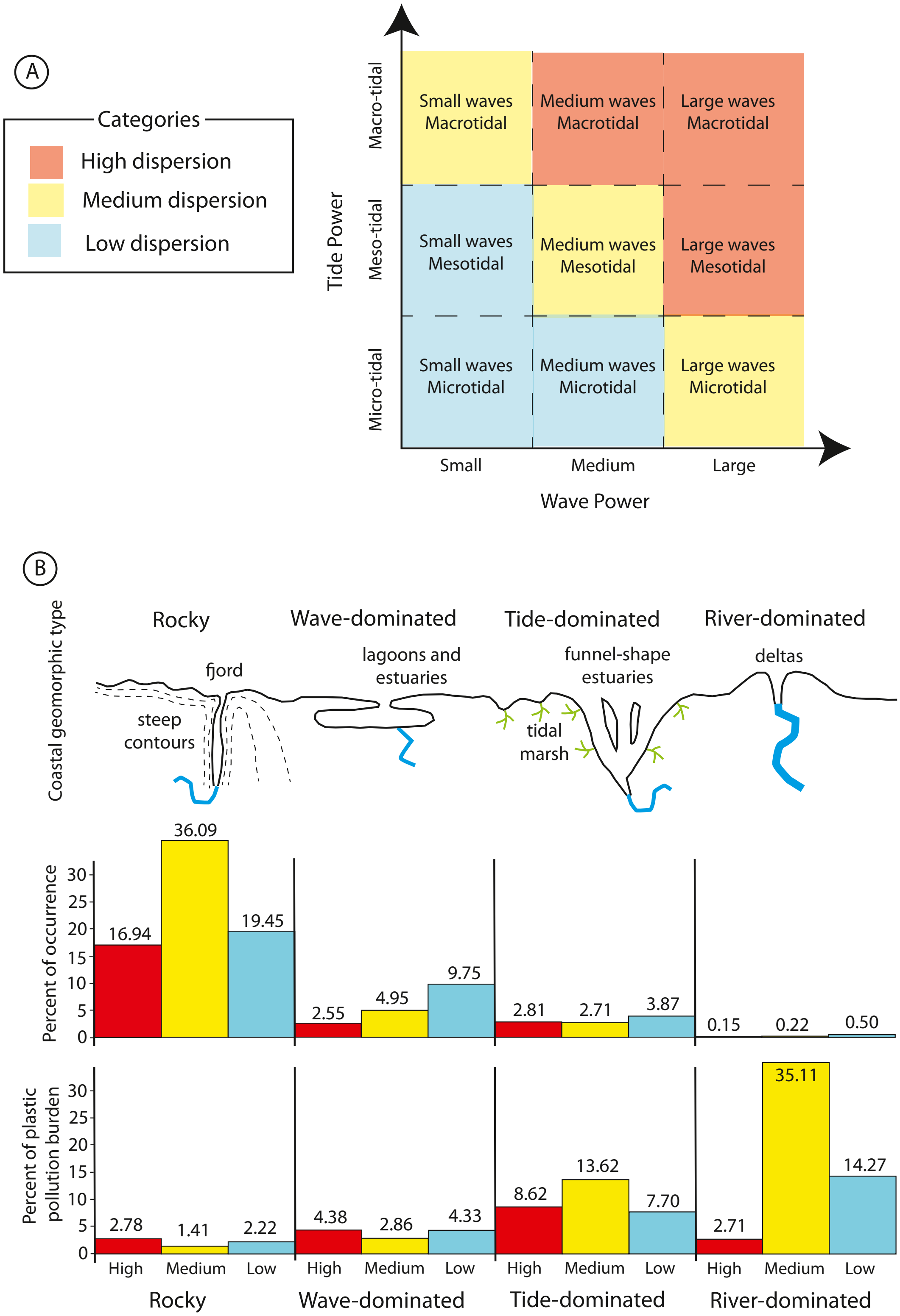

Fig. 1. (A) Diagram illustrating how dispersive energy categories are defined in the present study. Tide power is based on the conventional definition of micro-tidal, meso-tidal and macro-tidal environments based on mean spring tidal range (<2 m, 2–4 m and >4 m, respectively). Wave power uses the annual mean significant wave height (H_{sig}) for data compiled by Nyberg and Howell (2016), where small waves are taken as the lower 25% (<0.42 m), medium wave power refers to the mid-range 25–75% size class (0.42 to 1.13 m) and large wave power refers to the upper 25% (>1.13 m) of significant wave heights. (B) Summary of statistics of natural occurrence of coastal geomorphic types and the percent of plastic pollution burden experienced by different coastal environments. The coastline types are based on the classification scheme of Nyberg and Howell (2016), which are: River-dominated (i.e. their types F and FW); Wave-dominated estuaries, deltas and coasts (types W, WF, and WT); and 4) Tide-dominated estuaries, deltas and coasts (types T, TF and TW). Fjords and deltas have been added for clarity. The coloured bars show the percent of plastic pollution received by the indicated coastal type, divided into three wave/tide dispersive energy categories: high-, medium- and low-energy shown by red, yellow and blue, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the fate of plastic pollution upon entering the marine environment. Such an understanding is needed in order to advance numerical models designed to predict the dispersal of plastic pollution in the environment and to guide managers and decision-makers on the most appropriate responses and actions needed to measure and monitor river-sourced plastic pollution as required under global agreements and (inter)national drivers such as Sustainable Development Goal SDG-14, aimed at alleviating plastic pollution.

2. Methods

Coastal environments were simplified from the global analysis of Nyberg and Howell (2016) as follows: rocky (non-depositional) coasts are defined mainly by steep gradient cliffs, fjords and coastlines undergoing uplift. Depositional coasts include wave-, tide-, and river-dominated systems as defined by Nyberg and Howell (2016), who also specified an equation to distinguish funnel-shaped, tidal systems. Depositional coasts are grouped into three categories (as defined by Nyberg and Howell, 2016) as follows: River-dominated deltas and coasts; Wave-dominated estuaries, deltas and coasts; and Tide-dominated estuaries, deltas and coasts. Thus the four final coastal geomorphic categories used in this study are: 1) rocky coast; 2) river-dominated coasts; 3) wave-dominated coasts; and 4) tide-dominated coasts (Fig. 1A and B).

Additionally, we also used the wave and tide energy data from the study of Nyberg and Howell (2016) to generate a tripartite classification of dispersion for each of the four coastal environment categories. Wave energy represents global averaged mean significant wave height (Hsig) based on Tolman (2002) and tidal energy represents the diurnal and semi-diurnal tidal energy based on the global tidal model of Carrere et al. (2012). Fig. 1A shows the tide and wave values used to generate low, medium and high energy categories. These categories were used in this study to examine the combined wave and tide energy available to disperse floating or neutrally buoyant plastic pollution along and offshore from the coast (referred to here as dispersion categories). The models provide for the characterisation of the global coast into broad categories; local models are needed to yield detailed particle tracking information at a specific location.

The global coastline classification of Nyberg and Howell (2016) is a polyline shapefile that is split every 5 km, resulting in over 246,000 individual features. The attribute table of this shapefile was prepared to include the coastal environment and the dispersion category associated with each 5 km stretch of coastline. This data enabled us to estimate the global proportion of each coastal environment for each of the 3 dispersion categories.

River mouth locations and their yearly plastic output estimates were taken from Lebreton et al. (2017). The annual mass river discharge of plastic estimated by Lebreton et al. (2017) are constrained to the size range of 500 to 0.3 mm and are annual averages (seasonal differences are averaged out). The latest (6th) version of the point shapefile was used for this study, which includes 40,760 river input locations and river catchments from the HydroSHEDS (2020) database covering 80.4 million km^2. The Lebreton et al. (2017) estimate does not include 36.3 million km^2 of land that has no drainage to the ocean (e.g. deserts and land-locked lakes) nor does it include Antarctica or land located north of 60°, comprising an additional 32.2 million km^2 (the total land area of Earth is 148.9 million km^2). Using a join by location tool in QGIS (QGIS, 2020), the coastal classification data from the global coastline polyline was joined to the nearest river point. Because the coastline polyline does not cover the Caspian Sea, and a few small islands, river points data from Lebreton et al. (2017) that exist for these locations were not joined. This resulted in the omission of 561 river points from this study. The results from this join enabled us to estimate the portion of the four coastal environments (rocky, tide-dominated, wave-dominated, and river dominated) for each dispersion category (low, medium and high) that are closest to river mouth points and potentially exposed to plastics.

The second part of our methods concerns assessing the exposure of mangroves, coral reefs, seagrass and saltmarsh to rivers estimated to emit over 1 t of plastics per year (i.e. maximum estimates of Lebreton et al., 2017). This analysis was conducted in GIS software. A global polygon shapefile of the extent of each habitat was downloaded from the UNEP-WCMC Ocean Data Viewer interface. Each feature was clipped to the study area within ± 60 degrees latitude as plastic rivers data is not available from Lebreton et al. (2017) beyond those latitudes. Additionally, only features within 50 km of the coastline file from Nyberg and Howell (2016) are considered in this study. Thus, the area of salt marsh in the UNEP-WCMC database covers a total area of 54,550 km^2 but only 46,121 km^2 (84.6%) was included in this study. For mangroves the UNEP-WCMC database area is 136,855 km^2 of which 136,036 km^2 (99.4%) is included; for coral reefs the UNEP-WCMC database area is 149,179 km^2 of which 84,888 km^2 (56.9%) is included; and for seagrass the UNEP-WCMC area is 322,619 km^2 of which 296,291 km^2 (91.8%) is included in this study.

Each global habitat polygon was intersected and dissolved in a 5 by 5 km grid, and the area of each habitat in each grid cell was calculated. Data on coastal environments and wave/tide energy dispersion categories were then joined to each habitat cell based on proximity. The resulting joined data enabled us to estimate the percentage of habitat for each coastal environment and energy dispersion category.

Using the buffer tools, a 20 km buffer was generated around river mouths where the total annual plastic output estimates exceeded 1 t ($n = 5498$) based on Lebreton et al.'s (2017) maximum estimate. Both figures, the value of 1 t/year and the 20 km radius, are arbitrary, defined in the absence of thresholds of plastic pollution above which any specific amount of damage is caused to ecosystems within any specific impact radius; these concepts require further refinement in a more detailed risk analysis that will hopefully follow this preliminary study.

Each habitat cell intersecting with the buffer was classified as a habitat area potentially exposed to plastics. Cells that did not intersect with the buffer were classified as not-exposed to plastics from rivers. This spatial classification enabled us to estimate the percentage and location of each habitat cell that is exposed to plastics from rivers. The selection of a 20 km radius is used only as a broad indicator of proximity to a point source and it is acknowledged that in many locations the true dispersal radius of plastic input from a river mouth point source will be far greater than 20 km. On the other hand, in some locations and for some plastic particles of high density, the dispersal radius could be much less than 20 km.

3. Results

3.1. Occurrence of coastal geomorphic types and plastic input

Fig. 2 shows that most of the plastic (52%) exported to the ocean by rivers arrives at river-dominated coasts. However, a significant portion (48%) of river-sourced plastic waste arrives along all the other types of coastal environment. No type of coastal environment, including rocky coasts and fjords, is immune from river-sourced plastic pollution. It is also important to note that river-dominated coasts comprise only 0.87% of the global coast and yet they receive 52% of plastic pollution delivered by fluvial systems. This spatial bias in pollution input explains to at least some extent the extremely high concentrations of plastic pollution observed in certain coastal environments (Galgani et al., 2015).

After river deltas, the largest recipient of plastic pollution is tide-dominated systems (Fig. 1B) which comprise 9.4% of the coastline included in this study and which receive around one third of plastic pollution (29.9%). Tide-dominated environments have the highest proportion of high-energy dispersive waves and currents, indicating their capability for exporting a significant amount of plastic pollution offshore. Wave-dominated coasts comprise 17.3% of the coastline and receive 11.6% of plastic pollution discharged by rivers. Finally, rocky coasts comprise 72.5% of the coastline but they receive only 6.4% of plastic discharged by rivers.

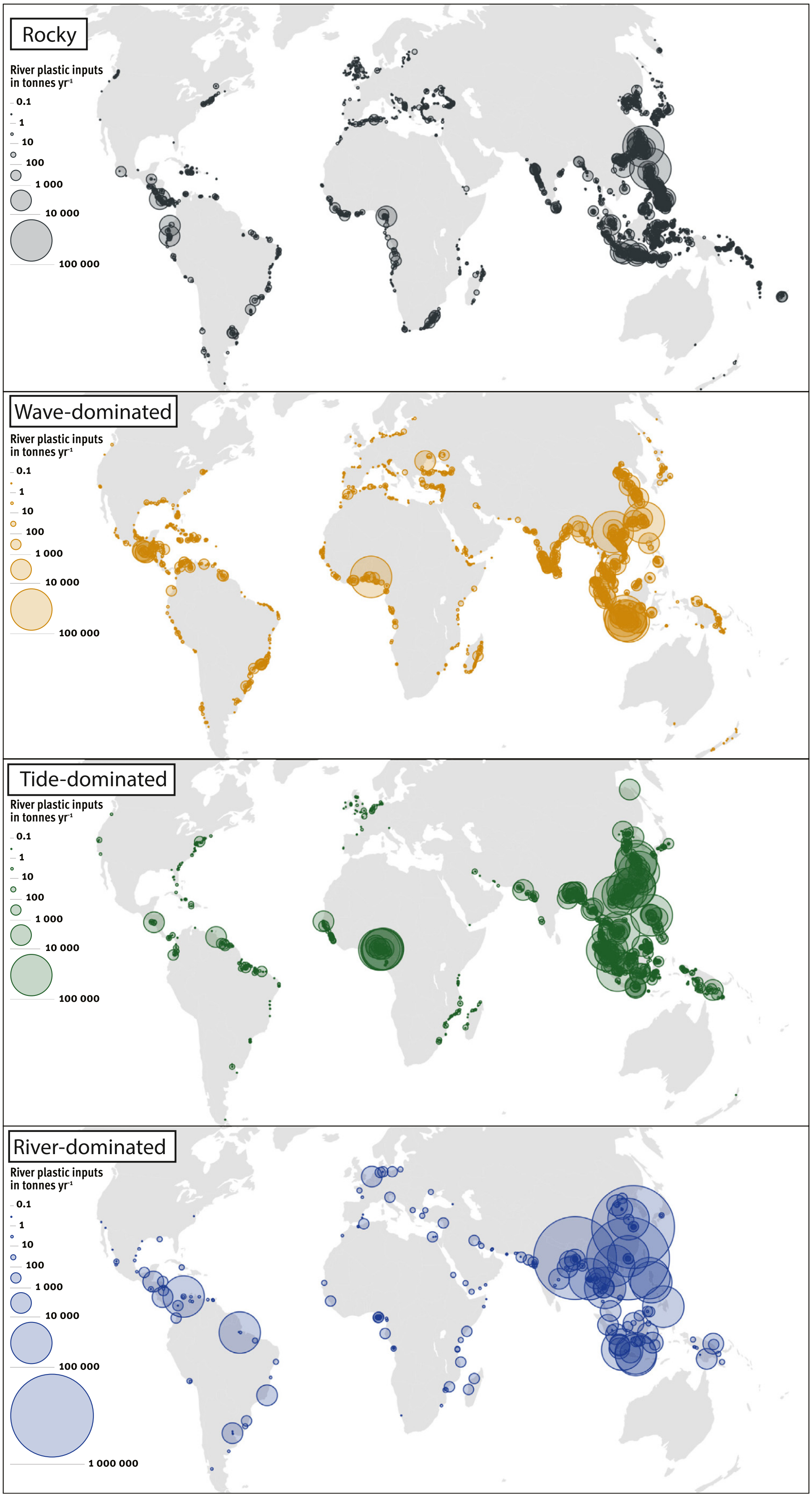

Fig. 2. Maps showing the mass of plastic delivered to the coast by rivers in terms of coastal environment.

Thus, there is an inverse relationship between the percent of coastline and amount of plastic discharged by rivers. River-dominated coasts occupy the smallest percent of coastline length but receive the greatest amount of plastic pollution, followed by tide-dominated, then wave-dominated and finally rocky coasts that occupy the greatest percent of coastline length but receive the smallest amount of plastic pollution (Fig. 1B).

In terms of wave/tide energy, 18.5% of plastic pollution enters high-energy dispersive environments whereas nearly one-third of plastic pollution (28.6%) enters low-energy environments (Fig. 1B) where it is more likely to be trapped at the coast. Moderate wave/tide energy is dominant in river deltaic systems that also receive the greatest burden of plastic pollution (Fig. 1B).

3.2. Spatial patterns of plastic input to different coastal geomorphic types

Rocky coastal geomorphology associated with high inputs of plastic pollution occurs along parts of most coastal regions (Fig. 2A). High concentrations of plastic delivered to rocky coasts occur in Indonesia, the Philippines, China, western India and central America. Rocky coasts are less common in other locations like the southeast coast of the US, Gulf of Mexico and the south-eastern Mediterranean.

Tide-dominated coastal geomorphology associated with high inputs of plastic pollution (Fig. 2B) is prominent in the Yellow Sea, the coasts of China, Thailand, Vietnam, Indonesia, as well as the coast of Nigeria in west Africa, the coasts of Brazil and Venezuela in northern South America and in the Gulf of Fonseca on the Pacific coast of Central America. The macrotidal coast of western Europe receives relatively modest amounts of plastic pollution (Fig. 2B).

Wave-dominated coastal geomorphology associated with inputs of plastic pollution (Fig. 2C) exhibits a broad spatial pattern, with high inputs occurring in southeast Asia, west Africa, the Mediterranean and Black Seas, Central America and parts of South America. The south coast of the island of Java in Indonesia stands out as a hot-spot for plastic input to a wave-dominated shoreline.

Finally, the spatial pattern of plastic pollution input along river-dominated coasts (Fig. 2D) illustrates that southeast Asia is the region of the world that receives the most plastic (Lebreton et al., 2017, estimated that 86% of plastic pollution was delivered by Asian rivers). The high sediment load of these rivers creates prograding deltas whose sediment loads are trapped in prograding subaqueous deltas and adjacent coastal depocentres (Wright, 1989; Caldwell et al., 2019). Outside of the southeast Asian region, Central America and parts of South America also exhibit comparatively high rates of plastic input to coastal and deltaic environments.

3.3. Spatial patterns of wave/tide energy regimes

The spatial pattern of plastic pollution input in relation to combined wave/tide energy is illustrated in the first instance by comparing high-energy (Fig. 3A) versus low energy (Fig. 3C) coasts. Hot-spots of high wave/tide energy with significant plastic input (Fig. 3A) occur on the east coast of China, the Gulf of Thailand, south coast of the island of Java in Indonesia, Nigeria and the Pacific coast of Central America. This is in contrast to the hot-spots of low-energy with significant plastic input (Fig. 3B) which occur extensively in Indonesia, the Philippines, some parts of China, the Black Sea and Brazil. Notable hot-spots of moderate wave/tide energy with significant plastic input (Fig. 3B) occur on the east coast of China and at the mouth of the Ganges-Brahmaputra River in the Bay of Bengal.

3.4. Occurrence and spatial patterns of plastic input to mangrove habitats

The natural distribution of mangrove habitat occurs chiefly along tide-dominated coasts (Fig. 4A). Mangrove habitat is most common in low wave/tide environments in the three main coastal categories (tide-, wave-dominated and rocky coasts) which overall accounts for 40.3% of mangrove occurrence. In contrast, 27.3% of mangrove habitat occurs in high wave/tide energy environments (Fig. 4A).

Overall, 54.0% of mangrove habitat is within 20 km of a river that discharges more than 1 t/yr of plastic pollution into the ocean. Mangroves located on tide-dominated coasts are exposed to the majority of this pollution (Fig. 4A). Of mangroves that occur on low wave/tide energy coasts, 21.6% are within 20 km of a river that discharges over 1 t/yr of plastic pollution compared with 15.5% of mangroves that occur on high wave/tide energy coasts (Fig. 4A).

Our analysis shows that, spatially, mangrove habitat that is located within 20 km of a river that discharges over 1 t/yr of plastic pollution is concentrated in southeast Asia and along the coasts of India and west Africa (Fig. 4B). Mangroves occurring in Australia, the Gulf of California and the northern Caribbean Sea are located further than within 20 km of a river that discharges over 1 t/yr of plastic pollution.

3.5. Occurrence and spatial patterns of plastic input to seagrass habitat

The natural distribution of seagrass habitat (Fig. 5A) occurs chiefly along wave-dominated coasts. Seagrass habitat is most common in low wave/tide environments in the three main coastal categories (tide-, wave-dominated and rocky coasts) which overall accounts for 59.9% of seagrass occurrence whereas 11.5% of seagrass habitat occurs in high wave/tide energy environments (Fig. 5A).

Overall, 24.1% of seagrass habitat is within 20 km of a river that discharges more than 1 t/yr of plastic pollution into the ocean. Seagrass located on rocky coasts are exposed to the majority of this pollution (Fig. 5A). Of seagrass occurring on low wave/tide energy coasts, 11.2% are within 20 km of a river that discharges over 1 t/yr of plastic pollution compared with 4.30% of seagrass that occurs on high wave/tide energy coasts (Fig. 5A).

Our analysis shows that, spatially, seagrass habitat that is located within 20 km of a river that discharges over 1 t/yr of plastic pollution is concentrated in southeast Asia, along the coast of west Africa and with patches in the Caribbean Sea (Fig. 5B). Seagrasses occurring in Australia, North Africa, Europe and the Mediterranean Sea are mostly located further than within 20 km of a river that discharges over 1 t/yr of plastic pollution (Fig. 5B).

3.6. Occurrence and spatial patterns of plastic input to coral reefs

The natural distribution of coral reef habitat occurs chiefly along rocky coasts; there are virtually no coral reefs present on river-dominated coasts (Fig. 6A). Coral reef habitat is most common in low wave/tide environments in the three main coastal categories (tide-, wave-dominated and rocky coasts) which overall accounts for 53.3% of coral reef occurrence whereas 15.0% of coral reef habitat occurs in high wave/tide energy environments (Fig. 6A).

Overall, 16.5% of coral reef habitat is within 20 km of a river that discharges more than 1 t/yr of plastic pollution into the ocean. Coral reefs located on rocky coasts are exposed to the majority of this pollution (Fig. 6A). Of coral reefs occurring on low wave/tide energy coasts, 9.2% are within 20 km of a river that discharges over 1 t/yr of plastic pollution whereas 2.7% of coral reefs on high wave/tide energy coasts are within 20 km of a river that discharges over 1 t/yr of plastic pollution (Fig. 6A).

Our analysis shows that, spatially, coral reef habitat that is located within 20 km of a river that discharges over 1 t/yr of plastic pollution is concentrated in the so-called "coral triangle" of Indonesia, the Philippines and southeast Asia, along the coasts of India, west Africa, the east coast of South America and in the Caribbean Sea (Fig. 6B). Coral reefs occurring in Australia and the Red Sea are mostly located further away than 20 km of a river that discharges over 1 t/yr of plastic pollution (i.e. there are few if any rivers that discharge more than 1 t/yr of plastic pollution in these regions; Fig. 6B).

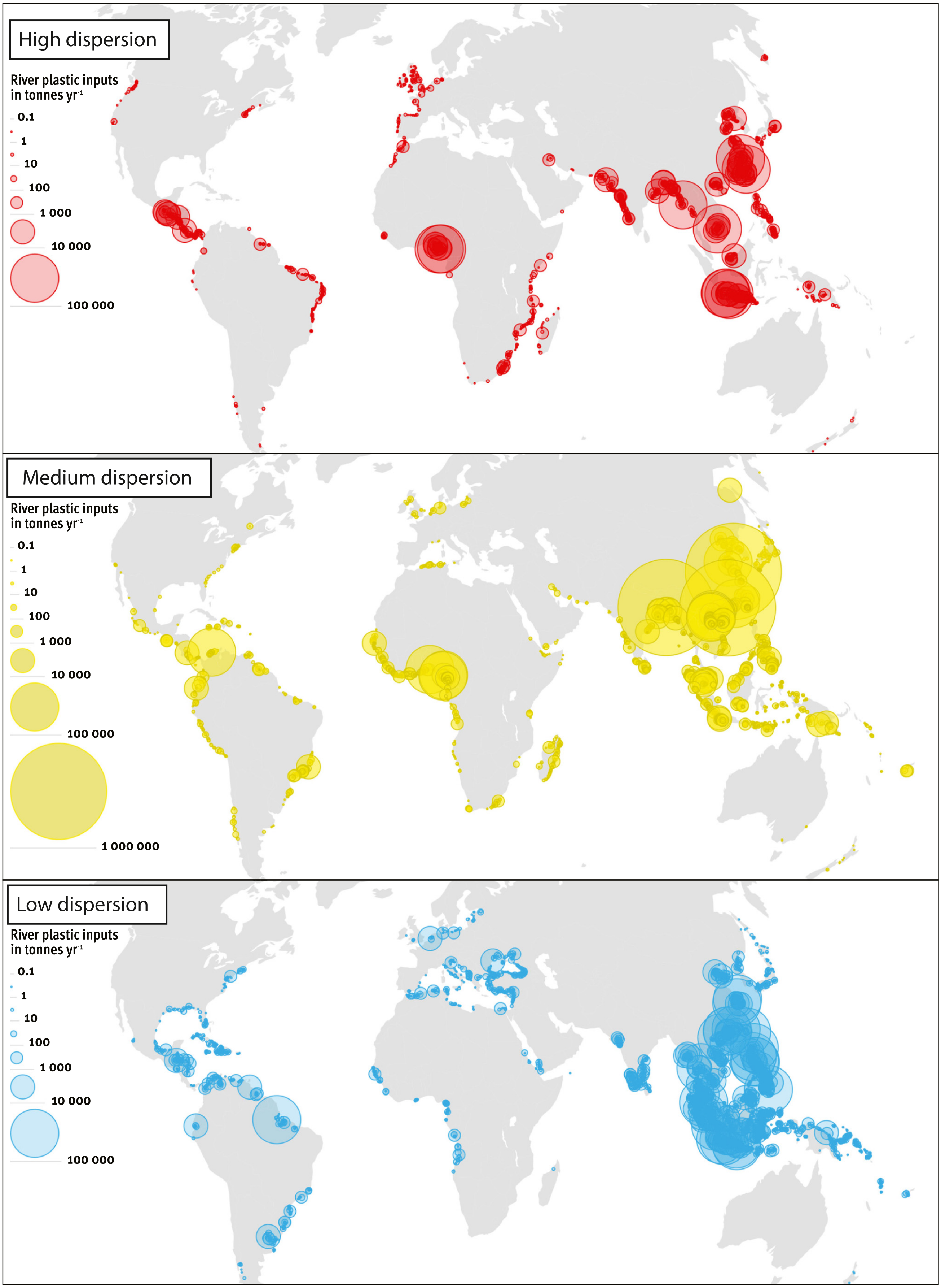

Fig. 3. Maps showing the mass of plastic delivered to the coast by rivers in terms of wave/tide energy available for dispersion of the pollution.

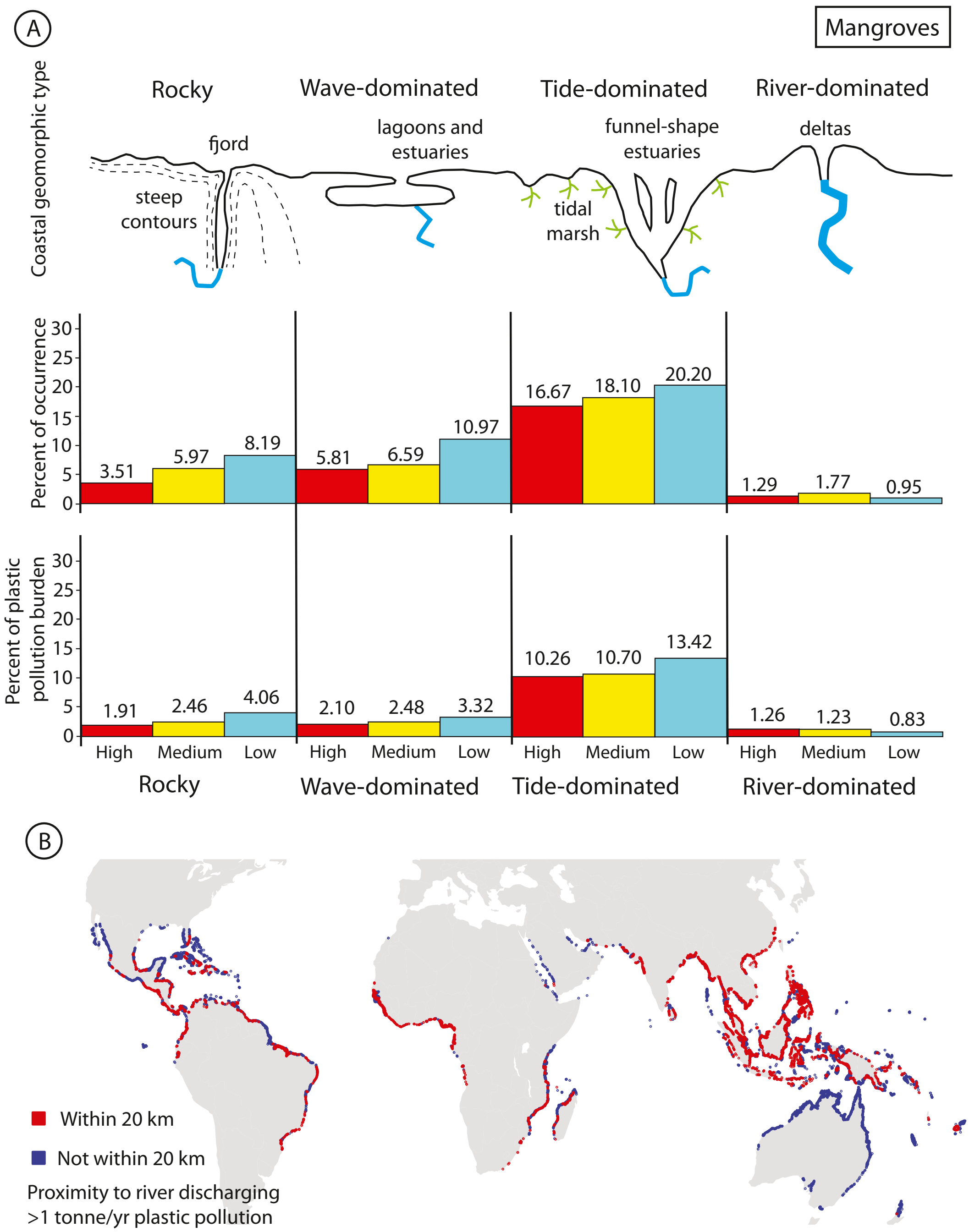

Fig. 4. (A) Summary of statistics of natural occurrence of mangrove habitat according to coastal geomorphic types and the percent of habitat that occurs within 20 km of a river that discharges more than 1 t/yr of plastic pollution. The natural distribution of mangrove habitat occurs chiefly along tide-dominated coasts (55.0%) followed by wave-dominated coasts (23.4%), rocky coasts (17.7%) and lastly by river-dominated coasts (4.0%). Mangroves located on tide-dominated coasts are the most exposed to plastic pollution (34.4% of mangrove habitat) followed by rocky coasts (8.4%), wave-dominated coasts (7.9%) and lastly river-dominated coasts (3.3%). (B) Map showing mangrove habitat located within 20 km of a river that discharges more than 1 t/yr of plastic pollution (red) versus mangrove habitat located greater than 20 km away from a river that discharges more than 1 t/yr of plastic pollution (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.7. Occurrence and spatial patterns of plastic input to salt marsh

The natural distribution of salt marsh habitat (Fig. 7A) occurs chiefly along tide-dominated coasts. Salt marsh habitat is most common in low wave/tide environments in the three main coastal categories (tide-, wave-dominated and rocky coasts) which overall accounts for 51.0% of salt marsh occurrence whereas 16.5% of salt marsh habitat occurs in high wave/tide energy environments (Fig. 7A). Salt marsh on rocky coasts is more common in high wave/tide-energy environments; this is the only habitat that exhibits such a preference as all other habitat types considered in this study (mangrove, coral reefs and seagrass) are most common in low wave/tide energy environments for all four coastline types.

Overall, 22.7% of salt marsh habitat is within 20 km of a river that discharges more than 1 t/yr of plastic pollution into the ocean. Salt marsh located on tide-dominated coasts is exposed to the majority of this pollution (Fig. 7A). Of salt marsh occurring on low wave/tide energy coasts, 12.5% are within 20 km of a river that discharges over 1 t/yr of plastic

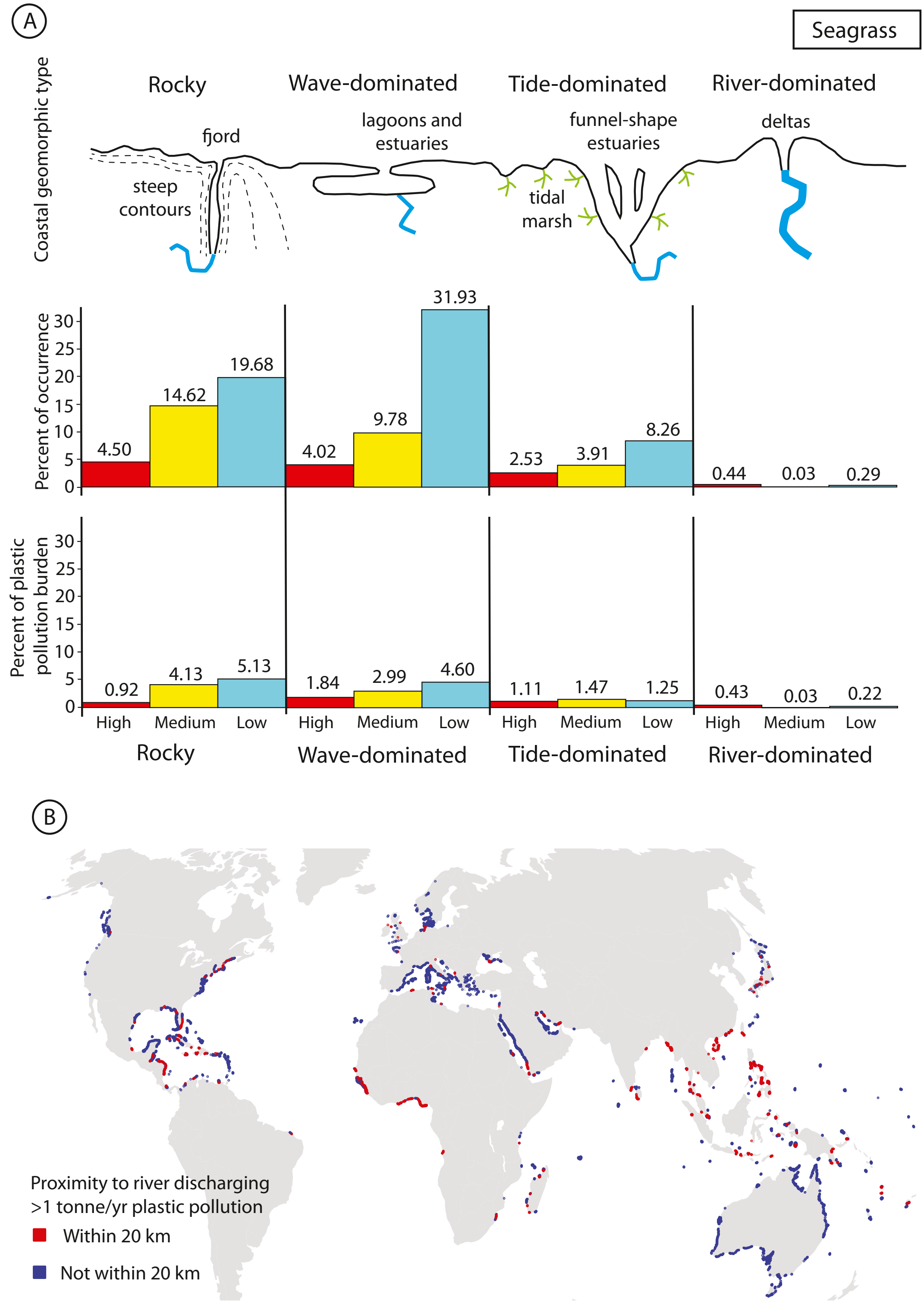

Fig. 5. (A) Summary of statistics of natural occurrence of seagrass habitat according to coastal geomorphic types and the percent of habitat that occurs within 20 km of a river that discharges more than 1 t/yr of plastic pollution. The natural distribution of seagrass habitat occurs chiefly along wave-dominated coasts (45.7%) followed by rocky coasts (38.8%), tide-dominated coasts (14.7%) and lastly by river-dominated coasts (0.76%). Seagrass located on rocky coasts are exposed to the majority of plastic pollution (10.2% of seagrass habitat) followed by wave-dominated coasts (9.4%), tide-dominated coasts (3.83%) and lastly river-dominated coasts (0.68%). (B) Map showing seagrass habitat located within 20 km of a river that discharges more than 1 t/yr of plastic pollution (red) versus mangrove habitat located greater than 20 km away from a river that discharges more than 1 t/yr of plastic pollution (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

pollution whereas 4.0% of salt marsh on high wave/tide energy coasts are within 20 km of a river that discharges over 1 t/yr of plastic pollution (Fig. 7A).

Our analysis shows that spatially salt marsh habitat that is located within 20 km of a river that discharges over 1 t/yr of plastic pollution is concentrated along the coast of eastern China and in a few locations in western Europe and on the west and east coasts of the US (Fig. 7B). Salt marsh occurring in other areas of the world is mostly (but with some local exceptions) located further than 20 km from a river that discharges over 1 t/yr of plastic pollution (Fig. 7B).

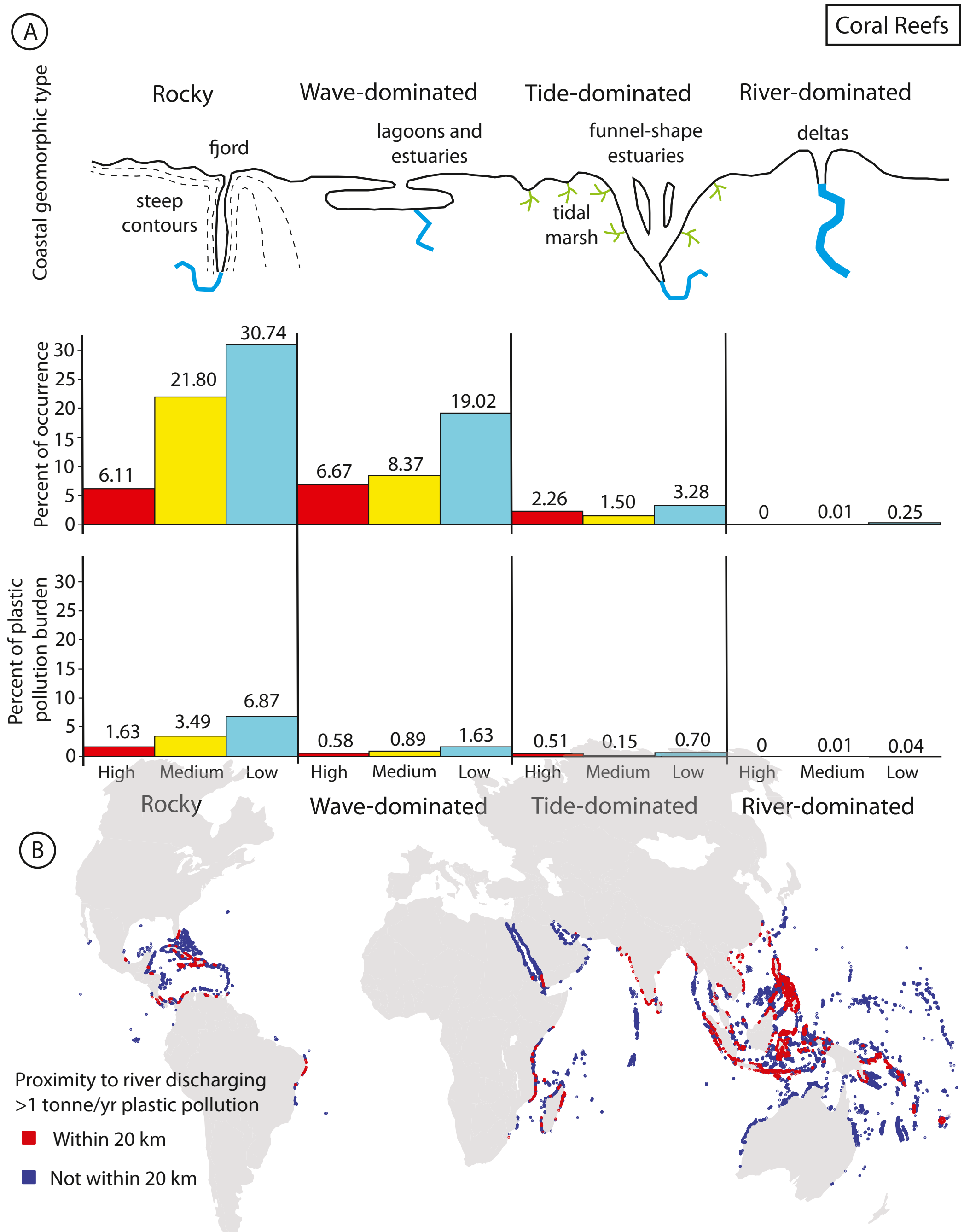

Fig. 6. (A) Summary of statistics of natural occurrence of coral reef habitat according to coastal geomorphic types and the percent of habitat that occurs within 20 km of a river that discharges more than 1 t/yr of plastic pollution. The natural distribution of coral reef habitat occurs chiefly along rocky coasts (58.7%) followed by wave-dominated coasts (34.06%) tide-dominated coasts (7.0%) and river-dominated coasts (0.26%). Coral reefs located on rocky coasts are exposed to the majority of plastic pollution (12.0% of coral reef habitat) followed by wave-dominated coasts (3.1%), tide-dominated coasts (1.4%) and lastly river-dominated coasts (0.05%). (B) Map showing coral reef habitat located within 20 km of a river that discharges more than 1 t/yr of plastic pollution (red) versus coral reef habitat located greater than 20 km away from a river that discharges more than 1 t/yr of plastic pollution (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

4.1. Spatial patterns of river-sourced plastic pollution in coastal environments

The results of the present assessment into the relative exposure of coastal environments to the input of river-borne plastic pollution have illustrated differences that exist between different environments/ecosystems. Fundamentally, the largest river systems discharge their loads of sediment (including plastic pollution) into coastal deltas; our analysis demonstrates that the majority of plastic pollution (52%) arrives at coastlines that are geomorphically classified as the “river-dominated” type, comprising only 0.87% of the global coastline. The coastal geomorphology in these areas is generally characterized by prograding deltas whose geomorphic character reflects the dominance of fluvial input (Nyberg and Howell, 2016) with moderate wave or tidal current reworking or redistribution of material (Fig. 1B).

Sedimentation within deltaic systems is focused onto the prograding, front slope of a delta, in a sedimentary unit known as a clinoform. Here, the energy conditions are such that much of the fine sediment falls out of

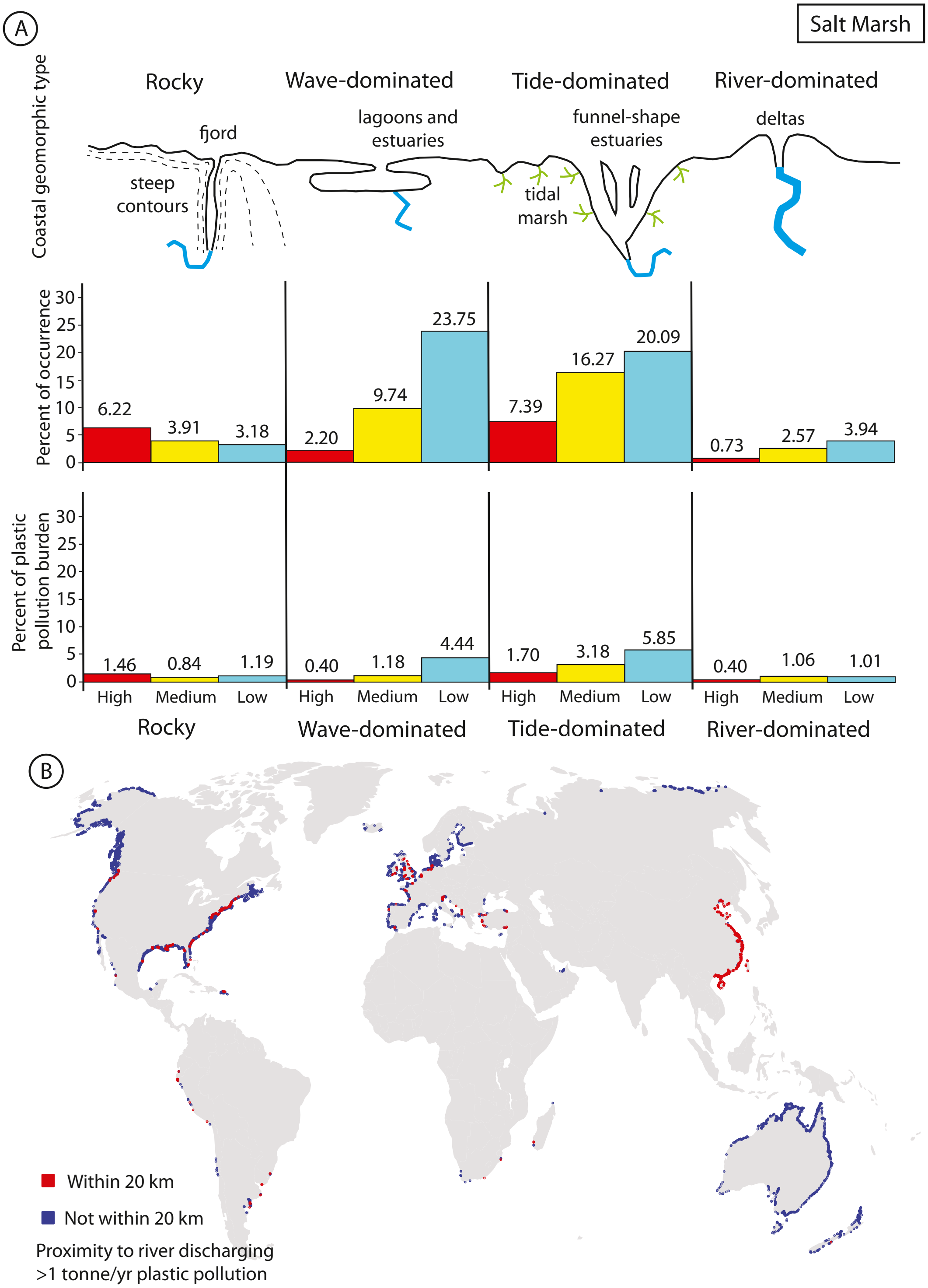

Fig. 7. (A) Summary of statistics of natural occurrence of salt marsh habitat according to coastal geomorphic types and the percent of habitat that occurs within 20 km of a river that discharges more than 1 t/yr of plastic pollution. The natural distribution of salt marsh habitat occurs chiefly along tide-dominated coasts (43.8%) followed by wave-dominated coasts (35.7%) rocky coasts (13.3%) and river-dominated coasts (7.2%). Salt marsh located on tide-dominated coasts are exposed to the majority of plastic pollution (10.7% of salt marsh habitat) followed by wave-dominated coasts (6.0%), rocky coasts (3.5%) and lastly river-dominated coasts (2.5%). (B) Map showing salt marsh habitat located within 20 km of a river that discharges more than 1 t/yr of plastic pollution (red) versus coral reef habitat located greater than 20 km away from a river that discharges more than 1 t/yr of plastic pollution (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

suspension and is deposited, often with vertical accretion rates measured in cm/yr (Wright, 1989; Patruno and Helland-Hansen, 2018). Over time, deposition of sediment on the clinoform causes the delta to advance seawards onto the continental shelf. In the case of plastic particles, it is mainly those having a density greater than seawater (about 40% of plastic produced according to Andrady (2011) which includes Polyamide (Nylon), Cellulose acetate, Polyvinyl chloride (PVC), Polyesther, Polyethylene terephthalate (PET) and Rayon) that will be deposited on the clinoform. The concentration of plastic particles in the clinoform is diluted by the mass of sediment that is also accumulating in this environment. Hence the concentration of plastic pollution may appear less than occurs in other areas that experience lower rates of net sediment accumulation (i.e. ≪1 cm/yr) such as occurs in most shelf and deep sea environments.

Particles less dense than seawater (i.e. Polypropylene (PP), Polyethylene (PE) and Polystyrene) will float on the surface or become incorporated into the buoyant river plume, to be carried seaward and/or be advected along the coast by the prevailing wind and current regime. Van Emmerik et al. (2020) found that floating macro-plastic particles are stored in river channels that discharge into Manilla Bay, Philippines, during low-flow periods with offshore export occurring mainly during periods of increased river flow. In their study of the Po River delta in Italy, for example, Atwood et al. (2019) estimate that 80% of microplastic particles are exported offshore in the buoyant river plume. Once exported offshore, such floating and suspended particles can be washed ashore onto beaches along the coast but also have the potential to travel a long distance (Maes et al., 2018).

A different picture emerges when we focus attention on the four categories of habitat types (i.e. mangroves, seagrass, salt marsh, coral reefs) that are associated with the input of river-borne plastic pollution. In the first place, these habitats are not spatially associated with river-dominated coasts simply because of the small spatial area (0.87% of coasts) where river-dominated coasts occur (Figs. 4–7). Instead, we find that these habitats are distributed among tide-dominated, wave-dominated and rocky coasts, which collectively receive 48% of river-borne plastic pollution (Fig. 1B). It is also important to note that since the plastic pollution of interest in this study is delivered by rivers, it is the estuarine marine environment, rather than the open coast, that is directly impacted.

Tide-dominated coasts receive 30.0% of river-borne plastic pollution (Fig. 1B) and this is also where mangrove and salt marsh habitats are most common (Figs. 4A and 7A). Rivers discharge their loads into funnel-shaped estuaries along such coasts, in which intertidal flats along the estuary margins are the main depositional sites for fine sediments (Harris, 1988) as well as plastic particles (e.g. Costa et al., 2011; Claessens et al., 2011; Blumenröder et al., 2017; Wu et al., 2020). Tidal currents keep the less dense particles in suspension and tidal residual circulation will tend to transport them landwards along the estuary margins and out to sea along the axis of the mid-channel (Harris and Collins, 1991).

Our results indicate that 22.7% of salt marsh habitat is located within 20 km of a river that discharges more than 1 t/yr of plastic pollution into the ocean. Viehman et al. (2011) studied marine debris accumulation in North Carolina salt marsh and found positive correlations between debris abundance and wave exposure, vegetation type and proximity to human population. The vegetation acts to filter out and retain debris and several studies have noted the elevated concentration of plastic particles in vegetated versus non-vegetated tide flats (e.g. Wu et al., 2020). For salt marsh habitats of southeast China, Yao et al. (2019) reported this habitat is an efficient trap for floating macroplastic debris that is gradually transformed into microplastic particles that are subsequently buried in accreting salt marsh deposits or become available for export back into the ocean.

Our results indicate that 54.03% of mangrove habitat is within 20 km of a river that discharges more than 1 t/yr of plastic pollution into the ocean. Thus mangroves are estimated to have the greatest exposure to river-sourced plastic pollution of the four habitat types studied here. A number of studies have been published on the impact of plastic pollution on mangrove habitat, examples being papers by Cordeiro and Costa (2010), Costa et al. (2011), Smith (2012), Nor and Obbard (2014), Martin et al. (2020) and Luo et al. (2021). These studies document how mangrove roots and branches act as a sieve that retains large plastic objects, in amounts that exceed beaches where mangroves are absent. Large macroplastic objects disintegrate in a manner similar to the salt marshes described above, producing microplastics. In their recent review of the subject, Deng et al. (2021) document how microplastic debris becomes incorporated into mangrove sediments and biota.

It is interesting to note that salt marsh and mangrove habitats are most common along tide-dominated coasts (Figs. 4 and 7). Thus there is competition between the high efficiency of these habitats in trapping sediment and plastic particles and the capacity for tide-dominated systems to export materials to offshore environments (Li et al., 2018). In general, fjords and wave-dominated lagoons and estuaries are highly efficient natural sediment traps, whereas tide-dominated estuaries are less efficient (Harris and Heap, 2003); existing data indicates that, in general, microplastic particles are found in high concentrations in estuarine sediment deposits (Harris, 2020).

Wave-dominated coasts receive 11.6% of river-borne plastic pollution (Fig. 1B) and this is where seagrass habitat is most common (Fig. 5A). Rivers discharge their loads into wave-dominated estuaries along such coasts, in which a central muddy basin, located in the shelter of a sandy barrier, is the main depositional site for fine sediments (Roy et al., 2001) and presumably for the more dense plastic particles. Very low wave and tidal energy conditions in the back-barrier region make these environments highly efficient sediment traps, particularly among the root systems of shallow seagrass communities.

Our results indicate that 24.1% of seagrass habitat is within 20 km of a river that discharges more than 1 t/yr of plastic pollution into the ocean. Microplastic particles have been reported in macrofauna living in and feeding on seagrass macrophytodetritus (Remy et al., 2015) and work has been done on sampling and measuring microplastics found on the surfaces of seagrasses (Seng et al., 2020).

Finally, rocky shores receive 6.4% of river-borne plastic pollution and this type of coastline is favored by 58.7% of coral reefs (Fig. 6A). Rocky coasts account for 72.5% of coastal types studied here (Fig. 1B) and include glacial fjords as well as bays and estuaries.

Our results indicate that 16.5% of coral reef habitat is within 20 km of a river that discharges more than 1 t/yr of plastic pollution into the ocean. Lamb et al. (2018) reported widespread mesoplastic entanglement of coral reefs, especially among the more "spikey" coral species, which increased by 20-fold the likelihood of disease. Reichert et al. (2018) documented a decline in coral health with an increase in microplastic abundance in the environment.

An important factor is the amount of wave/tide energy available to disperse plastic pollution along the coast. River dominated coasts experience mainly moderate wave/tide energy regimes (Fig. 1B). But the occurrence of all four of the habitat types studied here (mangroves, seagrass, salt marsh, coral reefs) in most cases correspond with low wave/tide energy environments (Figs. 4A, 5A, 6A and 7A). In other words, the environmental attribute of low wave/tide energy that apparently renders the environment most suitable for these four habitat types also implies relatively low dispersal and hence greater retention of plastic waste within them.

Thus the 52% plastic that is discharged by rivers onto river-dominated coasts arrives in environments having relatively moderate wave/tide energy available to disperse plastic pollution. A portion of this pollution is sequestered in the prograding clinoform on the delta front, but much (especially low-density plastic) is exported offshore as floating and suspended particles in the buoyant plume of river water. In contrast, 48% of plastic waste is discharged into mainly low-energy, tide-dominated and wave-dominated estuaries where it is more likely to be retained along the coast. Indeed, the plastic pollution trapping efficiency of different coastal geomorphic types appears to increase from deltas to tide-dominated estuaries, wave-dominated estuaries and lagoons and finally to rocky coasts with fjords, which have been shown to contain the highest concentrations of plastic particles of any environment (Harris, 2020). In other words, the apparent plastic particle trapping efficiency is inversely proportional to the input of plastic pollution as well as the overall coastline length: river-dominated coasts have the smallest percent of coastline length, lowest plastic trapping efficiency, have moderate wave/tide energy and greatest amount of plastic pollution received, followed by tide-dominated, then wave-dominated and finally rocky coasts that have the greatest percent of coastline length and the smallest amount of plastic pollution received (Fig. 1B) but which include fjords that have the highest plastic trapping efficiency.

4.2. Implications for monitoring and policy response

With the above information in mind and noting that control of plastic pollution is a factor for the conservation and successful management of all types of coastal habitat, our results suggest that mangrove habitat has a potentially greater exposure to plastic pollution than some other (seagrass, salt marsh or coral reef) habitats due to its overall closer proximity to plastic pollution (river mouth) point sources. The results of this study thus allow relevant authorities to address the plastic pollution problem at a local level by developing actions aimed at reducing the levels of litter entering the sea via rivers near sensitive and protected ecosystems and by targeting and removing litter which is already there. Ideally, retentive coastal environments should be chosen for clean-up actions. Wave-dominated estuaries and rocky coasts are most efficient at trapping plastic pollution. The large mass of plastic arriving at river-dominated coasts makes them suitable candidates for beach litter removal activities. Furthermore, the exposure of dispersive versus retentive coastal environments has serious implications for beach litter monitoring. The selection and comparison between beach litter sites should take into account the different coastal types in order to improve harmonization and future assessments across regions.

Bonanno and Orlando-Bonaca (2020) point out a lack of knowledge on impacts of plastic on seagrass habitat. From our findings it is clear that almost a quarter of seagrass habitat, the breeding chambers of the oceans, are exposed to large amounts of plastic pollution, which is one of many cumulative human pressures on this habitat (Griffiths et al., 2020). However, no currently existing anti-plastics regulation aims specifically to protect seagrass ecosystems (Bonanno and Orlando-Bonaca, 2020).

Stafford and Jones (2019) have pointed out that plastic pollution is one of many anthropogenic stressors on the marine environment and that policies must acknowledge the cumulative impact of multiple stressors to effectively manage human environmental impacts. Coral reefs in Australia, for example, appear to have escaped severe impact from plastic pollution but anthropogenic climate change has caused massive coral reef bleaching and death there in recent years (Hughes et al., 2018). Conversely, coral reefs in the southeast Asian region have been impacted by both climate change and plastic pollution (in addition to other stressors).

4.3. Correspondence between sediment yield and plastic loads of rivers

Lebreton et al. (2017) estimate that 86% of plastic pollution enters the ocean from Asian rivers. Interestingly, these Asian river catchments are commonly characterized by steep topography and high rainfall which gives them very high sediment discharge rates. The sediment yield of such mountainous hinterlands (as much as 10,000 t/km^2) is orders of magnitude greater than, for example coastal plain river systems common in Europe and North America (typically 10 to 100 t/km^2; Milliman and Syvitski, 1992). Most sediment (and plastics) in these short, steep and high river discharge systems are likely flushed to the coastline as opposed to trapped in the upstream catchment floodplain. Thus, mismanaged waste is not the only problem facing these countries in their efforts to limit the amount of plastic and other litter entering the ocean, because their natural environments are apparently pre-disposed to much higher rates of transfer of material from their river catchments to the sea. In other words, waste management systems must operate in southeast Asian countries at an even greater efficiency than in countries whose river catchments have less extreme sediment yields.

4.4. Possible re-introduction of plastic back into the environment due to climate change and sea level rise

Plastic pollution that becomes trapped in shallow sediment deposits of lagoons and wave-dominated estuaries may not remain sequestered in such deposits under rising global sea level. This is because as sea level rises coastlines will retreat, including the sandy barriers that protect central muddy basins of estuaries where plastic pollution accumulates (Kumbier et al., 2018). The retreat of sand barriers will eventually erode previously deposited fine-sediments and expose them to the erosive power of ocean swell waves, causing the re-introduction of microplastic pollution into the environment (Fig. 8). It is the case that all fluvial systems that have flood plains which contain recent sediment deposits mixed with plastic pollution will face a similar prospect of submergence and reworking by rising global seal level. This scenario is independent of dominant processes (tides, waves or rivers). The re-introduced microplastics will occur even where future land-sourced pollution has ceased. Other human activities, such as channel dredging for navigation purposes, also have the potential to liberate previously deposited plastic and re-introduce it into the environment (e.g. Costa et al., 2011).

Similarly, plastic pollution that becomes buried in Arctic coastal and continental shelf sediment deposits may not remain sequestered in such environments as sea ice retreats and the Arctic Ocean wave climate grows increasingly energetic. In their modeling study of projected Arctic Ocean wave climate, Casas-Prat and Wang (2020) predict a two- to three-fold increase in mean significant wave height by 2081. The authors anticipate increased rates of coastal erosion and coastal inundation will occur in response to the more energetic wave climate. It is expected that the larger waves will induce erosive seabed stress that could potentially liberate previously buried plastic in shallow continental shelf sediments causing its re-introduction into the Arctic environment.

5. Conclusions

This study has revealed the following:

1) We find an inverse relationship exists between coastal geomorphic type, plastic trapping efficiency and the mass of plastic received. River-dominated coasts comprise only 0.87% of the global coast and yet they receive 52% of plastic pollution delivered by fluvial systems. The combination of higher wave/tide energy with buoyant freshwater plumes means that these environments also have the lowest capacity to trap plastic particles (especially low-density materials). Next in order of increasing length of coastline, increasing trapping efficiency and decreasing amount of plastic pollution received are tide-dominated, wave-dominated and finally rocky coasts; the latter comprise 72.5% of the global coast and contain fjords which are most efficient at trapping plastic pollution and yet they receive only 6.4% of plastic pollution delivered by fluvial systems.
2) Tide-dominated coasts receive 30.0% of river-borne plastic pollution and this is also where mangrove and salt marsh habitats are most common. Wave-dominated coasts receive 11.6% of river-borne plastic pollution and this is where seagrass habitat is most common. Finally, rocky shores receive 6.4% of river-borne plastic pollution and this type of coastline is favored by coral reefs.
3) Mangroves are the most proximal to river-borne plastic pollution point sources of the four habitat types studied here; 54.0% of mangrove habitat is within 20 km of a river that discharges more than 1 t/yr of plastic pollution into the ocean. For seagrass, salt marsh and coral reefs the figures are 24.1%, 22.7% and 16.5%, respectively.

These conclusions are relevant to monitoring and policy responses to coastal plastic pollution, providing a basis for targeted strategies that reflect differences between exposure to river-sourced plastic pollution, coastal dynamics and ecology.

CRediT authorship contribution statement

Peter T. Harris – article conception, drafting text, figure preparation
Levi Westerveld – article conception, drafting text, GIS analysis, figure preparation

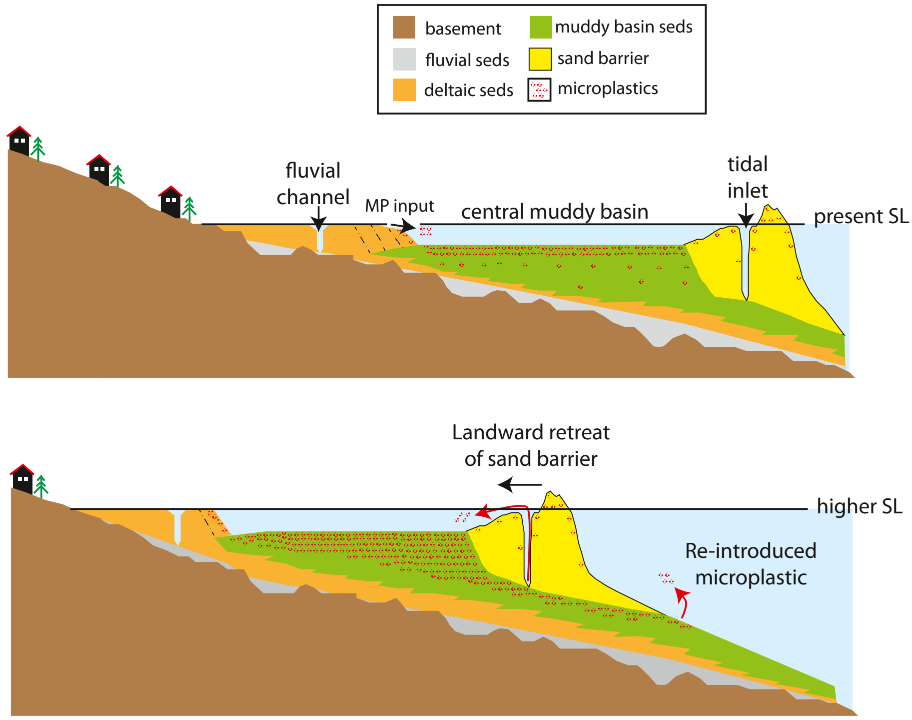

Fig. 8. Conceptual model showing effect of sea level rise on sediments deposited in a wave-dominated estuary (after Nichol et al., 1994). As sea level rises the sand barrier retreats landward and muddy basin sediments are eroded thus re-introducing microplastic particles, first by currents within the tidal inlet and eventually by ocean swell waves once the sand barrier has moved past.

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Thomas Maes – article conception, drafting text
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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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