Title: Plastic pollution on the world's coral reefs

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Coral reefs are losing the capacity to sustain their biological functions[1]. In addition to other well-known stressors, such as climatic change and overfishing[1], plastic pollution is an emerging threat to coral reefs, spreading throughout reef food webs[2], and increasing disease transmission and structural damage to reef organisms[3]. Although recognized as a global concern[4], the distribution and quantity of plastics trapped in the world's coral reefs remains uncertain[3]. Here we survey 84 shallow and deep coral ecosystems at 25 locations across the Pacific, Atlantic and Indian Ocean basins for anthropogenic macro-debris (pollution by human-generated objects larger than 5 cm, including plastics), performing 1231 transects. Our results show anthropogenic debris in 77 out of the 84 reefs surveyed, including in some of the Earth's most remote and near pristine reefs, such as in uninhabited central Pacific atolls. Macroplastics represent 88% of the anthropogenic debris, and, like other debris types, peak in deeper reefs (mesophotic zones at 30 – 150 m depth), with fishing activities as the main source of plastics in most areas. These findings contrast with the global pattern observed in other nearshore marine ecosystems, where macroplastic densities decrease with depth and are dominated by consumer items[5]. As the world moves towards a global treaty to tackle plastic pollution[8], understanding its distribution and drivers provides key information to help design strategies needed to address this ubiquitous threat.

The interactions between well-known global and local stressors for coral reefs are increasing[9], and as we have crossed the planetary boundary for pollutants[10], plastic pollution is emerging as a threat to many ecosystems, including coral reefs[3]. Plastic accumulation on coral reefs is estimated to be no less than 11 billion items on shallow Asia-Pacific reefs alone, and is predicted to increase by 40% before 2025[3]. These numbers suggest that large quantities of plastics may be trapped in the world's coral reefs, likely acting as a global chronic stressor in already and increasingly damaged systems. On the other hand, plastic pollution is highly influenced by local and regional drivers[12], and without a dataset that comprises sites with different geographic, anthropogenic and environmental conditions, we cannot build the knowledge needed to make informed decisions or track trends over time as mitigation interventions are implemented. Additionally, shallow reefs represent only a part of global coral ecosystems, and plastic accumulation in the vast area covered by mesophotic reefs (30 – 150 m depth) is still largely unknown. Although these deeper reefs are ecologically distinct from their shallow counterparts[13] and with some possibly presenting lower recovery capacity, due to the slower growth of reef-building organisms in low-light conditions[14], they are rarely included in conservation discussions and actions[13,15].

We surveyed reefs around the world for macroplastics (i.e., items larger than 5 centimetres) and other anthropogenic debris across photic (<30 m) and mesophotic depths (30 – 150 m) (Fig. 1). Our study sites included 84 shallow and deep coral reefs from 25 locations across the Pacific, Atlantic, and Indian Ocean basins (Fig. 2), covering approximately 68,000 m² of coral reef area. To provide foundational information to support the design of strategies needed to tackle plastic pollution, we investigated key predictors of anthropogenic debris in coral reef systems. Predictors included potential environmental, anthropogenic, and geographic drivers: 1) depth, 2) reef complexity, 3) nearby population density (100 km and 10 km radii), 4) mismanaged plastic waste mass, 5) distance to local markets (main cities and provincial capitals), 6) distance to the nearest marine managed area.

Abundance and distribution

We found 258 anthropogenic debris in the 1231 transects performed. Macroplastics represented 88% of the anthropogenic debris, and were present in nearly all surveyed locations, including very remote and relatively pristine coral reefs. The one exception was the Seychelles Outer Islands (Fig. 2a), where no debris was documented within our surveys, but was seen off transects and is recorded across the islands[16]. At the lowest densities, between 581 and 1,515 anthropogenic debris items per km^2 were observed in locations such as Marshall Islands, the offshore Coral Sea reefs of Australia, and Micronesia. Much higher densities of between 8,529 and 84,495 items per km^2 were found on the reefs of the Philippines, Comoros, and offshore Brazil (Fig. 2a; Extended Data Table 1). The highest density, in the Comoros, if extrapolated, would be spatially equivalent to approximately 520 pieces of anthropogenic debris in one football field (Extended Data Fig. 1). These values cover a wide range and a global estimate will improve as more efforts are consolidated.

Coral reefs seem to be more contaminated by plastic pollution than other marine ecosystems evaluated until now. However, global assessments of plastic pollution in marine ecosystems are rare, and the few were conducted in pelagic ocean waters [17,18]. Therefore, to contextualize our results, we used regional assessments and literature reviews available for other marine ecosystems. The density of debris found here is within the range of regional-scale surveys of Indo-Pacific coral reefs[3], and higher than estimates of macro-plastic in oceanic waters[7,18,19] and the seabed[7,20]. However, plastic densities on shoreline systems – i.e. the transition between marine and terrestrial realms – are orders of magnitude higher than those found on coral reefs[6,7].

Macroplastics and other anthropogenic debris were more abundant on deep reefs than on shallow ones (Fig. 2a, Extended Data Fig. 2 and Extended Data Table 2), with a peak between 50 and 100 m depth (Fig. 3). No significant differences in debris composition or size were found among depth zones (Extended Data Fig. 3 and Extended Data Table 2). However, there were some differences among peak abundance patterns of plastic and non-plastic debris (e.g. metal cans, glass bottles, tissues) along the depth gradient (Fig. 3). On average, plastics represented 85% of the anthropogenic debris among locations (range: 50-100%), and most items (average 73%) were related to fishing (e.g. lines, longlines, ghost gillnets, and discarded traps) (Fig. 2b). All fishing or boating derived debris were composed of plastic materials (e.g., nylon, polyester, polypropylene). Comoros was the only location where most items were classified as consumer debris, which could be explained by the proximity of informal dumping sites along the shoreline, increasing the chances of land-based plastics dispersing into the reef. Locations with the highest amounts of anthropogenic debris relative to human population included both more densely populated areas in the Comoros and Philippines, and almost-unpopulated remote offshore reefs in Brazil and Australia (Fig. 2b).

The higher densities of plastic debris found in deep reefs and the high prevalence of items related to fisheries is in contrast to the global pattern of anthropogenic debris distribution in other marine ecosystems, where macro-plastic densities decrease with depth and are dominated by consumer items[5]. The peak of debris abundance at mesophotic depths may result from a combination of natural and anthropogenic processes. For instance, shallow reefs are exposed to stronger wave energy, which could cause plastic debris to resuspend and be transported to coastlines and the open ocean, or to tumble down the reef slope and accumulate in deeper reef areas. As mesophotic reefs represent the lower depth limits of highly complex tropical marine habitats[13], they may be the last trap for debris before their fragmentation or accumulation on the deep-sea floor[20]. Additionally, shallow reefs may have a larger number of hidden plastics trapped in the reef matrix, due to the higher growth rate of their reef-building organisms. Lastly, lower plastic densities in shallow reef waters may also reflect removal efforts by local reef stewards.

Coral reefs provide food for hundreds of millions of people worldwide[21–23], which may explain the dominance of plastics originating from fisheries. With shallower ecosystems not providing catch yields required to sustain livelihoods[24], fishers are adapting their techniques to exploit deeper (mesophotic) coral reef systems[25]. Thus, the large amount of fishing debris on deep reefs may also reflect this transition in fishing effort along the depth gradient.

Predictors of plastic debris

Our model identified four key predictors of anthropogenic debris densities in coral reef systems: 1. greater depth, 2. greater human population within 10 km, 3. proximity to markets, and 4. proximity to Marine Protected Areas (Fig. 4a, Extended Data Fig. 2a). However, within debris categories (fishing plastics, consumer plastics and non-plastic debris), depth was the only predictor consistent across all categories, (Fig.4 b-d, Extended Data Fig. 2 b - d), highlighting the importance of incorporating reefs beyond 30m in the conservation discussions regarding plastic pollution.

Coastal population size is a known driver of marine plastic pollution[12]. Therefore, we expected to find more consumer-derived debris on reefs near large population centres. Our results confirmed this expectation (Fig. 4c, Extended Data Fig. 2c). For instance, the offshore Coral Sea reefs of Australia sampled here have one order of magnitude less macroplastic debris than coastal Australian reefs[3]. However, surprisingly, we found that the estimated amount of mismanaged waste released by nearby populations did not adequately predict the distribution of any type of anthropogenic debris on coral reefs (Fig. 4). One caveat is that data on the amount of mismanaged waste used to develop the metric here is collated at a national scale[12], which may not encapsulate local variability in the plastic waste management in areas close to reefs[26], or with varying distance to municipal centres. Additionally, the coral reefs evaluated were frequently distant from large rivers, which are presumed primary conduits of terrestrially mismanaged plastics to marine ecosystems[27], thus decreasing the potential influence of mismanaged waste outputs in our analyses.

Fishing places multiple pressures on coral reefs. Overfishing is widely recognised as the main driver of marine biodiversity loss[28] and is known to influence ecosystem processes in reef systems[29]. Our results also suggest that fishing practices play a central role in threats stemming from macroplastic pollution. Fishing-related debris on coral reefs increases with decreased distance to the nearest market, a proxy for fishing intensity[21]. The independence of fishing-related plastics from both local population sizes and estimated levels of waste mismanagement is possibly due to the increasing potential for fishing vessels to travel further[30] and the capability of even small populations to affect ecosystems through intensive fishing effort[21].

The abundance of fishing-related debris was also positively related to habitat complexity (Fig. 4b, Extended Data Fig. 2b). Entanglement is more likely to occur in more complex habitats. In addition, habitat complexity is a known positive driver of fish density and biomass[31], therefore leading to increased fishing pressure and thus higher probability of fishing gear entanglement. Such entanglements can cause both physical damage via abrasion and increased risk of disease occurrence in reef building corals[3], further stressing coral reef ecosystems.

The decline of coral reefs worldwide has urged conservation action, and Marine Protected Areas are a widely implemented strategy to protect biodiversity, by restricting fisheries and tourism activities[32]. There is an increasing body of evidence supporting the effectiveness of Marine Protected Areas in recovering overfished resources and securing food[33]. However, our data indicate that the amount of plastic debris arising from fishing gear increases with proximity to Marine Protected Areas (Fig. 4b, Extended Data Fig. 2b). This probably results from the fact that most Marine Protected Areas allow sustainable fishing within or near their borders. Since these areas are frequently more productive, either historically or through direct management outcomes and spillover processes[34], fishers often congregate in close proximity to managed areas – the "fishing the line" phenomenon[35]. This is especially evident for commercially valuable food fishes as they become increasingly scarce on many of the world's coral reefs[36]. Our data show that the entanglement and littering potential of different fishing gears must be incorporated in the management plans of protected coral reefs in order to reduce their ecosystem impacts. Some management options could include creating more restrictive buffer zones around marine protected areas, projects that ensure fishing gear is not dumped at sea, establishing port reception centres, encouraging community stewardship for debris recovery, and employing alternative methods for tracking lost fishing gear, such as tagging. Nevertheless, the recovery of entangled material from deeper reef zones is still challenging, and management plans should also link with waste management and trash prevention policies on land to address the dispersion of non-fishing related debris into coral reef environments.

Plastics in fisheries

The rapid decline of coral reefs is caused by an interaction of multiple anthropogenic drivers. As plastic pollution is a ubiquitous threat, understanding the reach of its additive and synergistic impacts on coral reefs can help evaluating the capacity of reef ecosystems to survive[37]. The assumption that mesophotic coral ecosystems are ubiquitously less susceptible to human impacts and therefore may provide a global refuge for threatened shallow-water organisms does not appear to be valid[13]. Thus, our findings provide an additional line of evidence indicating that the incorporation of deep coral reefs in management and conservation strategies is essential to their survival through the Anthropocene. Additionally, since the deeper portions of coral reefs are generally under-surveyed and spatially extensive, the current overall accumulation of plastic debris on the world's coral reefs is likely largely underestimated. Finally, the high contribution of fishery-related items to plastic pollution on coral reefs, riverine[38], and open-ocean[19] ecosystems will require additional strategies that are not fully contemplated in the safe circularity principles widely used as a keystone to tackle plastic pollution[8]. Unlike single-use plastic, for which we have several potential manufacturing alternatives, the low cost and high effectiveness of nylon fishing gear, combined with the resource dependence of coastal communities worldwide, means that replacing plastics in fisheries will be a great challenge. To address the impacts of plastic pollution in coral reefs, material innovation towards biodegradable polymers will be required and international agreements to combat plastic pollution should include fishing gear in their frameworks.

References

1. Hughes, T. P. *et al.* Coral reefs in the Anthropocene. *Nature* **546**, 82–90 (2017).

2. Santos, R. G., Machovsky-Capuska, G. E. & Andrades, R. Plastic ingestion as an evolutionary trap: Toward a holistic understanding. *Science* **373**, 56–60 (2021).

3. Lamb, J. B. *et al.* Plastic waste associated with disease on coral reefs. *Science* **359**, 460–462 (2018).

4. MacLeod, M., Arp, H. P. H., Tekman, M. B. & Annika, J. The global threat from plastic pollution. *Science* **373**, 61–65 (2021).

5. Morales-Caselles, C. *et al.* An inshore–offshore sorting system revealed from global classification of ocean litter. *Nat. Sustain.* **4**, 484–493 (2021).

6. Serra-Gonçalves, C., Lavers, J. L. & Bond, A. L. Global Review of Beach Debris Monitoring and Future Recommendations. *Environ. Sci. Technol.* **53**, 12158–12167 (2019).

7. Galgani, F., Hanke, G. & Maes, T. Global Distribution, Composition and Abundance of Marine Litter. in *Marine Anthropogenic Litter* (eds. Bergmann, M., Gutow, L. & Klages, M.) 29–36 (2015). doi:10.1007/978-3-319-16510-3

8. Simon, N. *et al.* A binding global agreement to address the life cycle of plastics. *Science* **373**, 43–47 (2021).

9. Morrison, T. H. *et al.* Advancing Coral Reef Governance into the Anthropocene. *One Earth* **2**, 64–74 (2020).

10. Persson, L. *et al.* Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. *Environ. Sci. Technol.* **56**, 1510–1521 (2022).

11. Reichert, J. *et al.* Reef-building corals act as long-term sink for microplastic. *Glob. Chang. Biol.* **28**, 33–45 (2022).

12. Jambeck, J. R. *et al.* Plastic waste inputs from land into the ocean. *Science* **347**, 768–770 (2015).

13. Rocha, L. A. *et al.* Mesophotic coral ecosystems are threatened and ecologically distinct from shallow water reefs. *Science* **361**, 281–284 (2018).

14. Kahng, S. E. *et al.* Light, Temperature, Photosynthesis, Heterotrophy, and the Lower Depth Limits of Mesophotic Coral Ecosystems. in *Mesophotic Coral Ecosystems, Coral Reefs of the World 12* 801–828 (2019). doi:10.1007/978-3-319-92735-0_42

15. Stefanoudis, P. V. *et al.* Stakeholder-derived recommendations and actions to support deep-reef conservation in the Western Indian Ocean. *Conserv. Lett.* 1–11 (2022). doi:10.1111/conl.12924

16. Burt, A. J. *et al.* The costs of removing the unsanctioned import of marine plastic litter to small island states. *Sci. Rep.* **10**, 1–10 (2020).

17. Cózar, A. *et al.* Plastic debris in the open ocean. *Proc. Natl. Acad. Sci. U. S. A.* **111**, 10239–10244 (2014).

18. Eriksen, M. *et al.* Plastic Pollution in the World's Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea. *PLoS One* **9**, 1–15 (2014).

19. Lebreton, L. *et al.* Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. *Sci. Rep.* **8**, 1–15 (2018).

20. Woodall, L. C., Robinson, L. F., Rogers, A. D., Narayanaswamy, B. E. & Paterson, G. L. J. Deep-sea litter: A comparison of seamounts, banks and a ridge in the Atlantic and Indian Oceans reveals both environmental and anthropogenic factors impact accumulation and composition. *Front. Mar. Sci.* **2**, 1–10 (2015).

21. Cinner, J. E., Graham, N. A. J., Huchery, C. & Macneil, M. A. Global Effects of Local Human Population Density and Distance to Markets on the Condition of Coral Reef Fisheries. *Conserv. Biol.* **27**, 453–458 (2013).

22. Hawkins, J. P. & Roberts, C. M. Effects of Artisanal Fishing on Caribbean Coral Reefs. *Conserv. Biol.* **18**, 215–226 (2004).

23. Sing Wong, A., Vrontos, S. & Taylor, M. L. An assessment of people living by coral reefs over space and time. *Glob. Chang. Biol.* 7139–7153 (2022). doi:10.1111/gcb.16391

24. Jackson, J. B. C. *et al.* Historical overfishing and the recent collapse of coastal ecosystems. *Science* **293**, 629–637 (2001).

25. Olavo, G., Costa, P. A. S., Martins, A. S. & Ferreira, B. P. Shelf-edge reefs as priority areas for conservation of reef fish diversity in the tropical Atlantic. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **21**, 199–209 (2011).

26. Royle, J. *et al.* Plastic Drawdown: A rapid assessment tool for developing national responses to plastic pollution when data availability is limited, as demonstrated in the Maldives. *Glob. Environ. Chang.* **72**, 102442 (2022).

27. Lebreton, L. C. M. *et al.* River plastic emissions to the world's oceans. *Nat.*

Commun. **8**, 1–10 (2017).

28. Roberts, C. M. Effects of Fishing on the Ecosystem Structure of Coral Reefs. *Conserv. Biol.* **9**, 988–995 (1995).

29. Allgeier, J. E., Valdivia, A., Cox, C. & Layman, C. A. Fishing down nutrients on coral reefs. *Nat. Commun.* **7**, (2016).

30. Kroodsma, D. A. *et al.* Tracking the global footprint of Fisheries. *Science* **359**, 904–908 (2018).

31. Graham, N. A. J. & Nash, K. L. The importance of structural complexity in coral reef ecosystems. *Coral Reefs* **32**, 315–326 (2013).

32. Pinheiro, H. T. *et al.* Hope and doubt for the world's marine ecosystems. *Perspect. Ecol. Conserv.* **17**, 19–25 (2019).

33. Harrison, H. B., Bode, M., Williamson, D. H., Berumen, M. L. & Jones, G. P. A connectivity portfolio effect stabilizes marine reserve performance. *Proc. Natl. Acad. Sci. U. S. A.* **117**, 25595–25600 (2020).

34. Francini-Filho, R. B. & Moura, R. L. Evidence for spillover of reef fishes from a no-take marine reserve : An evaluation using the before-after control-impact (BACI) approach. *Fish. Res.* **93**, 346–356 (2008).

35. Kellner, J. B., Tetreault, I. T., Gaines, S. D. & Nisbet, R. M. Fishing the line near marine reserves in single and multispecies fisheries. *Ecol. Appl.* **17**, 1039–1054 (2007).

36. Cruz-Trinidad, A., Aliño, P. M., Geronimo, R. C. & Cabral, R. B. Linking Food Security with Coral Reefs and Fisheries in the Coral Triangle. *Coast. Manag.* **42**, 160–182 (2014).

37. Ford, H. V. *et al.* The fundamental links between climate change and marine plastic pollution. *Sci. Total Environ.* **806**, 150392 (2022).

38. Nelms, S. E. *et al.* Riverine plastic pollution from fisheries: Insights from the Ganges River system. *Sci. Total Environ.* **756**, 143305 (2021).

Figure Legends

Fig. 1. Anthropogenic debris is abundant on coral reefs of the world. (A) Sea urchin, *Asthenosoma varium*, entangled with fishing line while camouflaging itself with a plastic bag at 130 m depth in the Philippines. (B) Anchor line at 100 m depth in Palau. (C) Scuba tank and regulator at 105 m depth in Tahiti. (D) Fishing line wrapped around coral at 45 m depth in Fernando de Noronha, Brazil. (E) Diaper at 40 m depth in the Philippines. (F) Fishing lines at 85 m depth in St. Paul's Archipelago, Brazil.

Fig. 2. Distribution of anthropogenic debris on coral reefs of the world. (**a**) Abundance of anthropogenic debris per km^2 in shallow and mesophotic reefs around the world. (**b**) Composition and abundance of macroplastic and non-plastic debris relative to the magnitude of human population around study locations (within a 10 km radius). Pie chart size is proportional to relative debris abundance in each chart. In order to clearly show the relative distribution (a) and composition (b) of debris, pie charts in boxes are shown at a non-uniform magnification, meant solely to make composition information visible. Note: no debris were recorded in transects from the offshore Seychelles sites.

Fig. 3. Relationship between anthropogenic debris and depth. (a) All debris, (b) Fishing plastic debris, (c) Consumer plastic debris, and (d) Non-plastic debris. Bold white lines show relative debris estimates along the depth gradient. Blue lines show variation in these estimates across 500 draws from the model posterior. Black vertical bars at the bottom of each plot represent samples. Smoothed estimates are scaled and provide a relative estimate of debris at each depth.

Fig. 4. The influence of environmental and anthropogenic factors on the abundance of anthropogenic debris on coral reefs. Estimates of predictor effects on anthropogenic debris for: (a) all debris, (b) fishing plastic debris, (c) consumer plastic debris, and (d) non-plastic debris. Lines of each density plot show the 95% credibility

intervals and the shaded areas show the 80% intervals. Blue density plots indicate negative relationships between predictor variables and debris density, whereas tan density plots indicate positive relationships. Darker colours indicate relationships supported with > 95% credibility and lighter colours with > 80% credibility (shaded area of each density plot). Grey density plots indicate predictors with relationships that have < 80% credibility. Categorical effects are relative to estimates from samples in the shallow depth zone, and with low complexity.

Methods

Anthropogenic debris data

Anthropogenic debris were assessed by divers using underwater visual censuses (UVCs), a diver-operated stereo-video system (DOV), and recorded by a stereo-video system mounted on manned submersibles and remotely operated vehicles (ROVs) in 25 locations from 14 countries, including coastal and offshore (distant from mainland and major inhabited islands) reefs (Extended Data Table 1). These methodologies are comparable in their estimates of benthic communities[39–42] and have been used together by several researchers to characterize shallow and deep habitats[43–46]. Among the locations, an average of 55.9% of the surveyed area covered mesophotic reefs, while 44.02% covered shallow reefs (Extended Data Table 3).

Underwater visual censuses were performed in 14 locations from 10 countries (Extended Data Table 1). In the underwater visual censuses, researchers counted each item of debris observed one meter to each side of transects of 20 m length. A total of 800 transects were conducted and 176 debris items counted in a total area of 32,000 m^2 sampled (Extended Data Table 1), with transects conducted at depths from 2 m to 147 m. Mesophotic depths that were accessed using closed-circuit rebreathers (Hollis Prism2) used gas mixes containing up to 85% helium for the deeper dives. All sites were visited by our team or research partners prior to sampling, and transect areas were selected to cover the diversity of coral reefs habitats of each area.

Video-based transect surveys by divers with a DOV, manned submersibles and ROVs were used in 11 locations from four countries (Extended Data Table 1), with a total of 431 transects performed between 5 and 151 m depth, and 82 debris items counted in a total area of 35,507 m^2. In Bermuda, reefs between 15-94 m were surveyed by technical divers equipped with closed-circuit rebreathers, and using a DOV consisting of two cameras (GoPro Hero 4 Camera) and lights pointed at an angle of 3° and spaced 80 cm apart. Transects followed a 50 m measuring tape, about 1.5 m off the bottom, and were approximately 6 min long. The in-view measuring tape was used to scale images in ImageJ and estimate the total sampling area. Deeper reef locations (100-151 m) were explored by manned submersibles (Triton 1000–2 class submersibles) equipped with a downward-pointing camera (GoPro Hero 4 Camera) with lasers and lights. Two parallel lasers spaced at 25 cm were used to scale images in ImageJ and estimate the total sampling area. Transects were approximately 20 min long and covered an estimated distance of 100 m.

In the Seychelles, reefs at 10–12 m were surveyed by SCUBA divers using a DOV consisting of two cameras (Paralenz Dive Camera+). Survey transects were approximately 100 m long and parallel to shore and 0.5m off the bottom. Reefs at 27–138 m were explored by manned submersibles (Triton 1000–2 class submersibles) equipped with stereo-video systems (cameras: Paralenz Dive Camera+) and lights. Submersible transects were 250 m long and ~1.5 m off the bottom. Occasionally, ROVs (SeaBotix and) were used to survey some reefs at 9–26 m Aldabra (ROV SeaBotix) and at 20–24 m in Astove (ROV Ocean Modules V8 M500) following the same survey protocol as for the SCUBA diver-operated transects. Total sampling area was estimated through the stereo-video footage, which allowed for quadrats of known dimensions to be added on each annotated image in TransectMeasure (SeaGis Pty Australia).

In Comoros, reefs between 6–19 m were surveyed by DOVs. Belt transects were 20 m long and ran parallel to the reef edge, and an in-view measuring tape was used to scale images in CPCe and estimate total sampling area. At mesophotic depths (37–122 m) 20-minute transect surveys were conducted with an ROV (SAAB, SeaEye Falcon) equipped with a high-definition camera (Sub Sea Imaging 1Cam) mounted obliquely, lights and lasers, flying 0.5-1.0m from the seabed and a constant speed was maintained where possible. Two parallel lasers spaced at 6cm were used to scale images in CPCe and estimate total sampling area.

In Australia, reefs between 6–98 m were surveyed by ROV (BlueROV2, Blue Robotics). Transects were approximately 30 m long, measured by a timed-swim at a constant speed of 0.2 m s^{-1} and were conducted parallel to the reef edge. The ROV was equipped with an onboard high definition (1080p, 30fps) wide-angle low-light camera and a stereo-video system comprised of two calibrated cameras (Paralenz DC+). Total sampling area was estimated by measuring 2.5m either side of the central field of view using the specialist software EventMeasure (SeaGis Pty Australia).

All transects performed aimed to sample the variety of reef habitats existent in each location. To avoid bias due to differences in transects length, data were modelled as a rate (of debris occurrence) per area surveyed - see modelling methods. Average of total sampling areas was over 5,000 m^2 per country, and the density of anthropogenic debris per country is not correlated to the total sampled area (R^2=0.055), evidence that transect length did not directly affect the rate of occurrence. In addition, autosimilarity curves for trash abundance data indicated that sample size was sufficient for most sites (except Palau) (Extended Data Fig. 4), irrespective of the sampling method used. The curves were calculated by iteratively estimating average similarity values (zero-adjusted Bray–Curtis coefficient; cf. Clarke et al.[47]) between randomly selected samples. Sufficient sample size were attained when resemblance reaches an asymptote (cf. Schneck and Melo[48]).

To compare the density of anthropogenic debris between sites, data were partitioned into three categories (fishing plastic debris, consumer plastic debris, and non-plastic debris) and three depth zones according to their recorded depth: shallow zone = 2 – 30 m depth; upper mesophotic = 31 – 60 m depth; lower mesophotic = 61 – 149 m depth. Depth zones were chosen based on widely established categorization of shallow reefs and mesophotic coral ecosystems[49]. The database is available at https://doi.org/10.5281/zenodo.7679509.

Environmental and anthropogenic factors

At the local-scale, we recorded the sample depth (distance from surface in meters, measured by the diving computer or pressure sensor on submersibles and ROVs) and the benthic complexity for each transect, categorizing the latter in three categories: 1 = high (substrata composed of big boulders and holes larger than 1 m of size and depth, respectively, or predominantly covered by branching corals, providing shelter for a great variety of fish and benthic organisms), 2 = medium (substrata with a predominance of gorgonians, wire corals, encrusting corals, or small boulders and holes smaller than 1 m of size and depth, respectively, providing limited shelter for fish and other organisms), and 3 = low (few and small benthic organisms, predominance of epilithic algae, absence of boulders and holes, with little shelter for fish and other organisms)[50]. Additionally, we estimated the coastal population present within 100 km and 10 km radius from our sites using the 2019 Global Human Settlement dataset (available at https://ghsl.jrc.ec.europa.eu/ghs_pop2019.php). Small island populations were updated via local knowledge sources (see database) and all locations with zero population were given a nominal population of one. Coral reef area was estimated within a standard radius of 600 km around each location[51] – data defined using the Coral Reef Millennium Census project (available at http://data.unep-wcmc.org). Percent of mismanaged waste was compiled from Jambeck et al.[12], distance to nearest market was compiled following Cinner et al.[21], and borders of marine protected areas were compiled from the mpatlas.org directory and confirmed using local management websites.

Modelling

All statistical modelling was coded in R, version 4.0.4 (R core team).

In order to test for effects of depth and anthropogenic, environmental, and geographic drivers of debris densities, we utilized a Bayesian generalized linear mixed modelling process using zero-inflated negative binomial distributions with a log link, in the package 'brms' [52]. For each of the three debris subcategories, and total debris, we modelled relationships to seven scaled predictors: 1) depth, 2) reef complexity on a three-point scale, 3) the density of nearby populations for the given coral reef area around sites - both calculated at 100 km, 4) the mass of mismanaged plastic waste as calculated using country scale per-population metrics[12] multiplied by the population within 100 km of sites, 5) the distance of sites from local markets, 6) the distance of sites from the nearest managed marine area, and 7) local population density within 10 km of sites. The local population density (predictor 7) was calculated using 10 km radii, not 100 km – to reduce evidently high correlations between this metric and metrics for predictors 3 and 4, which used population densities from 100 km radii as coefficients. Site scale variation was incorporated into models, using sites nested within locations as a grouping variable. Variation among per-observation sample areas was incorporated/standardized using the log of sampling area for each observation (m^2) as an offset. Each model used a normal prior distribution for population-level effects - with a mean of zero and standard deviation of one point five and was run for 10,000 iterations in each of four chains and a 2,000 iteration warmup.

Because a) depth is a non-linear covariate to many oceanographic processes and b) three ecologically distinct depth zones are commonly delineated within coral reef ecology - Shallow reefs (0-30m), Upper Mesophotic reefs (30-60m), and lower mesophotic reefs (60-130m), depth can legitimately be considered a continuous or categorical variable within our study, *a-priori*. For the model predicting non-linear relationships to observation depth (on a continuous scale), we used Bayesian spline smooths, for (scaled) depth, using a standard cauchy prior (mean = 0, standard deviation = 2) for spline variance. We used leave-one-out cross validation (package 'loo') to compare model performance of full covariate models with depth considered either as a continuous or categorical predictor. Depth was a significant predictor in all models, both as a categorical and non-linear continuous predictor. Cross validation did not distinguish a difference between models with the two depth conditions (Extended Data Table 3), except for a potential small difference for consumer derived plastics that showed a small preference for depth as a continuous predictor. Because of our *a-priori* interest in both depth conditions, we extracted smoothed non-linear relationships between debris density and observation depths, after conditioning on other predictors, and plotted these using 500 conditional smooth draws, extracted from the full covariate model. Posterior distributions for predictor estimates were plotted at 80% and 95% credibility intervals, using the mcmc_areas function from the package 'bayesplot' [53]. Posterior estimates for models with depth as a categorical predictor are presented in the main text. Those for models with depth as a continuous predictor are in the supplemental material (Extended Data Figure 2).

For all models we confirmed the suitability of the commonly used general priors by plotting the range of plausible debris-density predictions under prior-only models. Model suitability was assessed for all models using a range of Bayesian diagnostic tests (LOO Pareto k: >95% <0.5, <5% 0.5–0.7; Rhat: all = 1; Neff ratio: all > 0.9; Non-divergent trace plots; acf = low autocorrelation; density plots = unimodal, posterior predictive checks matched data closely). Effect probabilities were calculated using one-sided tests that compare if posterior effects were greater than zero, using the hypothesis function 'hypothesis' from the package 'brms'. Posterior distributions of model R^2 were calculated using 'bayes_R2', also from 'brms'.

To test for differences in debris composition (type and size) among depth zones and levels of reef complexity we first filtered the data to contain only sites with at least one debris observation. We then removed two outliers - a site in the Coral Sea and a site in Cape Verde that each had only one large piece of non-plastic debris, which precluded observation of other site-level differences in composition. We analysed this filtered dataset in the package 'vegan' [54]. We first created a distance matrix using Bray-Curtis dissimilarities via the function vegdist. We then tested for composition differences among depth zones and levels of reef complexity by comparing within-group distance to centroids, to across-group distances to centroids using the adonis function. We then compared among group similarities in composition using the anosim function. We plotted nMDS ordinations of debris compositions in bivariate space with minimum convex hulls using metaMDS and correlation vectors calculated with envfit and 999 permutations.

Data availability

Data is available at DOI: 10.5281/zenodo.7679509

Code availability

Code is available at DOI: 10.5281/zenodo.7679509

Methods References

39. Lam, K. *et al.* A comparison of video and point intercept transect methods for monitoring subtropical coral communities. *J. Exp. Mar. Bio. Ecol.* **333**, 115–128 (2006).

40. Lirman, D. *et al.* Development and application of a video-mosaic survey technology to document the status of coral reef communities. *Environ. Monit. Assess.* **125**, 59–73 (2007).

41. Boavida, J., Assis, J., Reed, J., Serrão, E. A. & Gonçalves, J. M. S. Comparison of small remotely operated vehicles and diver-operated video of circalittoral benthos. *Hydrobiologia* **766**, 247–260 (2016).

42. Bull, A. S. *et al.* Comparison of Methods (ROV vs Diver) Used to Estimate Invertebrate Assemblages and Densities on an Offshore California Oil Platform. *Cont. Shelf Res.* https://doi.org/10.1016/j.csr.2022.104856. (2022). doi:10.1016/j.csr.2022.104856

43. Rabalais, N. N., Harper, D. E. & Turner, R. E. Responses of nekton and demersal and benthic fauna to decreasing oxygen concentrations. 115–128

(2011). doi:10.1029/ce058p0115

44. Leichter, J. J., Stokes, M. D. & Genovese, S. J. Deep water macroalgal communities adjacent to the Florida Keys reef tract. *Mar. Ecol. Prog. Ser.* **356**, 123–138 (2008).

45. Friedman, A., Pizarro, O., Williams, S. B. & Johnson-Roberson, M. Multi-Scale Measures of Rugosity, Slope and Aspect from Benthic Stereo Image Reconstructions. *PLoS One* **7**, (2012).

46. Appeldoorn, R. *et al.* Mesophotic coral ecosystems under anthropogenic stress: a case study at Ponce, Puerto Rico. *Coral Reefs* **35**, 63–75 (2016).

47. Clarke, K. R., Somerfield, P. J., Airoldi, L. & Warwick, R. M. Exploring interactions by second-stage community analyses. *J. Exp. Mar. Bio. Ecol.* **338**, 179–192 (2006).

48. Schneck, F. & Melo, A. S. Reliable sample sizes for estimating similarity among macroinvertebrate assemblages in tropical streams. *Ann. Limnol.* **46**, 93–100 (2010).

49. Loya, Y., Eyal, G., Treibitz, T., Lesser, M. P. & Appeldoorn, R. Theme section on mesophotic coral ecosystems: advances in knowledge and future perspectives. *Coral Reefs* **35**, 1–9 (2016).

50. Pinheiro, H. T., Martins, A. S. & Joyeux, J.-C. The importance of small-scale environment factors to community structure patterns of tropical rocky reef fish. *J. Mar. Biol. Assoc. United Kingdom* **93**, 1175–1185 (2013).

51. Parravicini, V. *et al.* Global patterns and predictors of tropical reef fish species richness. *Ecography* **36**, 1254–1262 (2013).

52. Bürkner, P.-C. Advanced Bayesian Multilevel Modeling with the R Package brms. *R J.* **10**, 395–411 (2018).

53. Gabry, J., Simpson, D., Vehtari, A., Betancourt, M. & Gelman, A. Visualization in Bayesian workflow. *J. R. Stat. Soc. A* **182**, 389–402 (2019).

54. Oksanen, A. J. *et al.* Package ' vegan '. 298 (2020).

55. R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Supplementary Information is available in the online version of the paper.

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Author contributions

HTP, RGS, CM, LAR designed the study; HTP, CM, RGS, AB, BC, GG, PM, TAP, BS, PVS, JBT, LCW, LAR collected the data; CM, HTP led the investigation; CM, LAR worked on the visualization; HTP, RGS led the original draft; All authors discussed the results, reviewed, edited and commented on the manuscript.

Author Information

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Competing interests

Authors declare that they have no competing interests.

Extended Data Table 1 – Summary information on the methods, effort and results for quantifying anthropogenic debris in each studied coral reef location. Transects were sampled by divers using diver-operated stereo-video system (DOV) and underwater visual censuses (UVC), and also using remotely operated vehicles (ROV) and manned submersibles (SUB).

Extended Data Table 2. Probability of effects (influence unequal to zero) of each analysed variable on the density of anthropogenic debris on coral reefs. Hyp. = Hypothesis; Est. = Estimate; 'CI': 90%-CI for one-sided and 95%-CI for two-sided hypotheses; CI.L = lower credibility limit; CI.U = upper credibility limit; Evid. Ratio = Evidence ratio; Post. Prob. = Posterior probability; '*': For one-sided hypotheses, the posterior probability exceeds 95%; #': For one-sided hypotheses, the posterior probability exceeds 90%; Inv: Posterior probability supports the inverse of the listed hypothesis.

Extended Data Table 3. Leave-one-out cross validation comparison of model fits for models using depth as a continuous or categorical predictor, calculated as the difference (and standard error) in expected log pointwise predictive density

(ELPD). elpd_diff = difference in expected log pointwise predictive density; se_diff = standard error in eldp_diff.

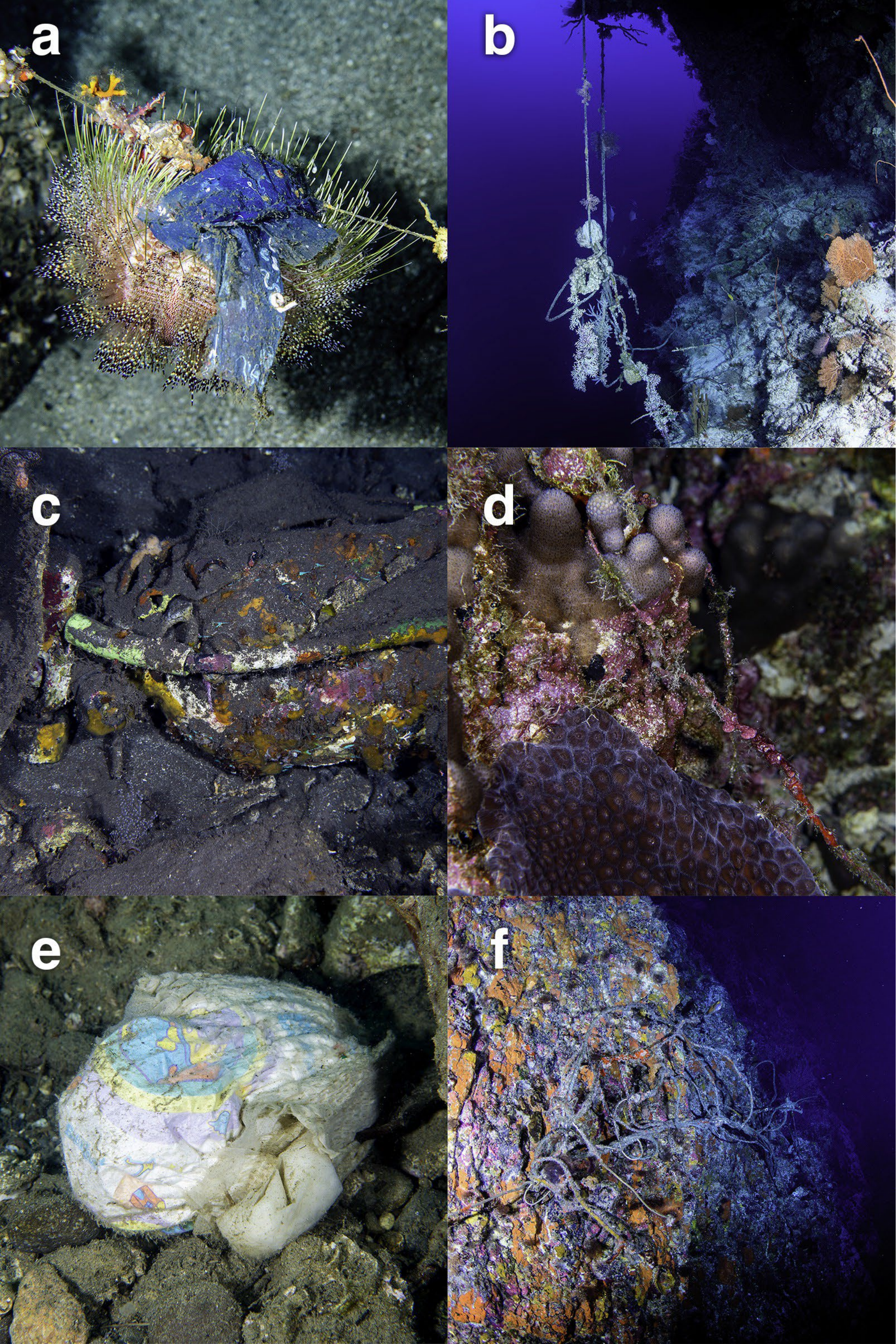
Extended Data Figure 1. Mean (above) and maximum (below) densities of plastics on the world's coral reefs - as relative to a football field. Each white dot represents a piece of plastic.

Extended Data Figure 2. The influence of environmental and anthropogenic factors on the abundance of anthropogenic debris on coral reefs. These models differ from those in Figure 4 in the main text as they consider non-linear depth effects, rather than the effects of depth considered in the three common categorical depth zones. Estimates of predictor effects on anthropogenic debris for: (a) all debris, (b) fishing plastic debris, (c) consumer plastic debris, and (d) non-plastic debris. Lines of each density plot show the 95% credibility intervals and the shaded areas show the 80% intervals. Blue density plots indicate negative relationships between predictor variables and debris density, whereas tan density plots indicate positive relationships. Darker colours indicate relationships supported with > 95% credibility and lighter colours with > 80% credibility (shaded area of each density plot). Grey density plots indicate predictors with relationships that have < 80% credibility. Categorical effects are relative to estimates from samples in the shallow depth zone, and with low complexity.

Extended Data Figure 3. NMDS analysis of the abundance of distinct categories and sizes of anthropogenic debris organized in relation to levels of habitat complexity and depth zones of coral reefs. The composition of plastics here is separated into fifteen classes: five size classes for each of three debris types. 'plastics' = all non-fishing-related plastics, 'fishing' = all fishing related plastics, 'other' = all non-plastic debris. Size 1 = 5–10 cm, Size 2 = 10–25 cm, Size 3 = 25–50 cm, Size 4 = 50–100 cm, and Size 5 = >100 cm.

Extended Data Figure 4. Sampling sufficiency, evaluated considering the three categories (fishing, other, plastics) by using autosimilarity curves based on zero-

adjusted Bray–Curtis coefficient of abundance data. Results indicated that sampling effort was sufficient to stabilize similarity among transects of locations sampled irrespective of the different methods used (except for Palau, sampled with UVCs).


a
b
c
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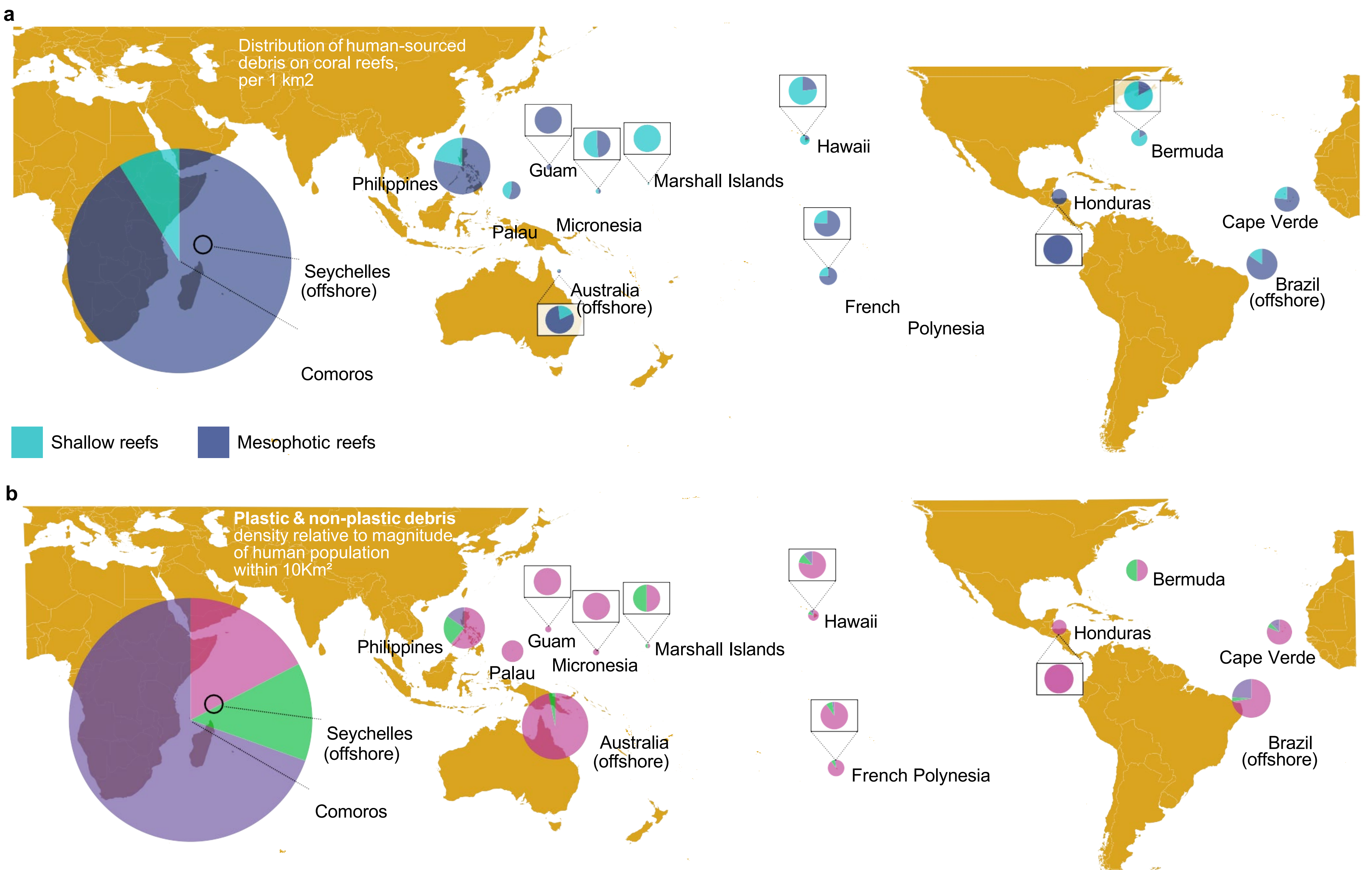
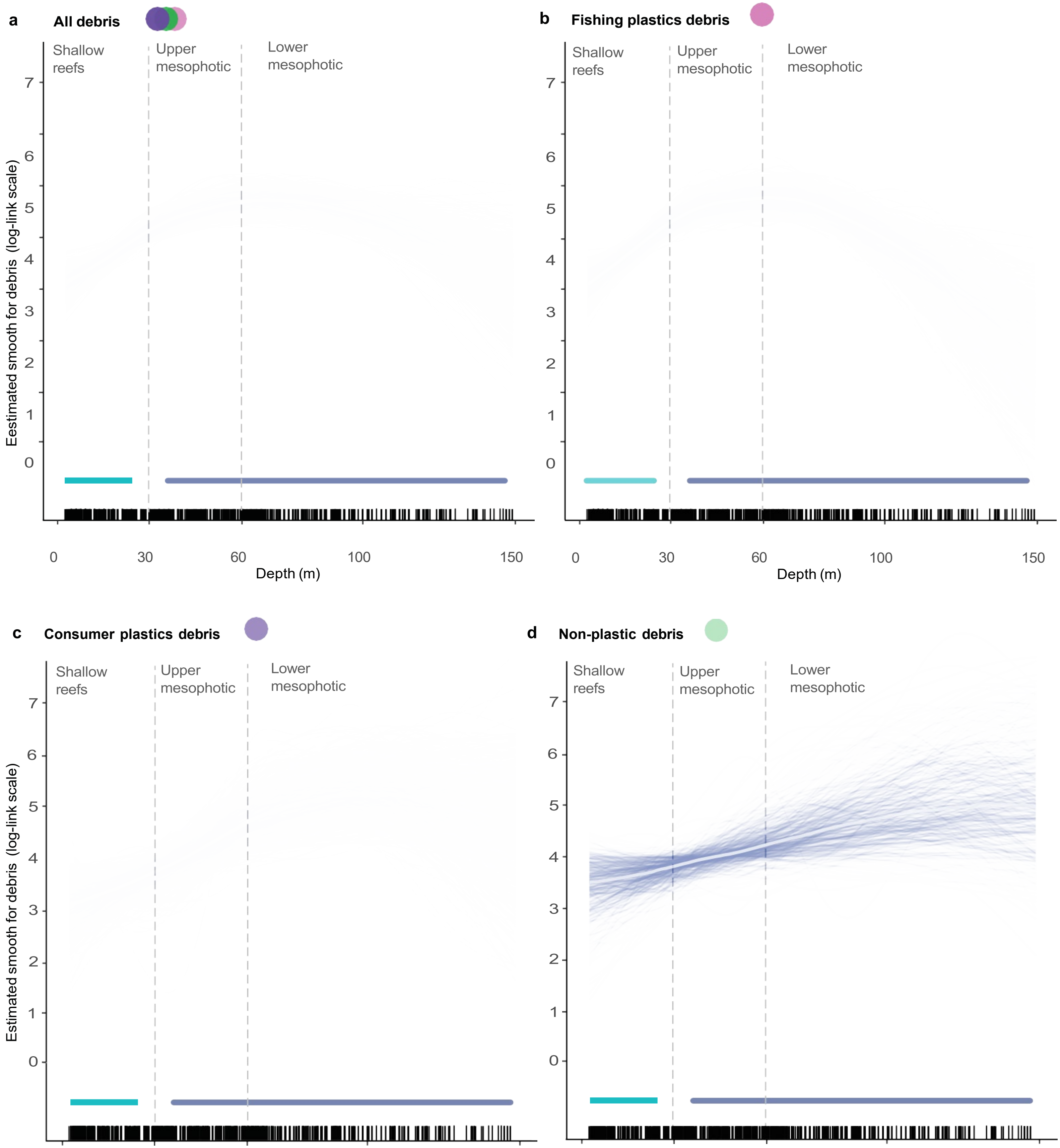
f


a
Distribution of human-sourced debris on coral reefs, per 1 km2
Philippines
Guam
Marshall Islands
Hawaii
Bermuda
Honduras
Cape Verde
Palau
Micronesia
Seychelles (offshore)
Australia (offshore)
French Polynesia
Brazil (offshore)
Comoros
Shallow reefs
Mesophotic reefs
b
Plastic & non-plastic debris density relative to magnitude of human population within 10Km²
Philippines
Guam
Marshall Islands
Hawaii
Bermuda
Honduras
Cape Verde
Palau
Micronesia
Seychelles (offshore)
Australia (offshore)
French Polynesia
Brazil (offshore)
Comoros

Fishing plastics debris

Non-plastic debris

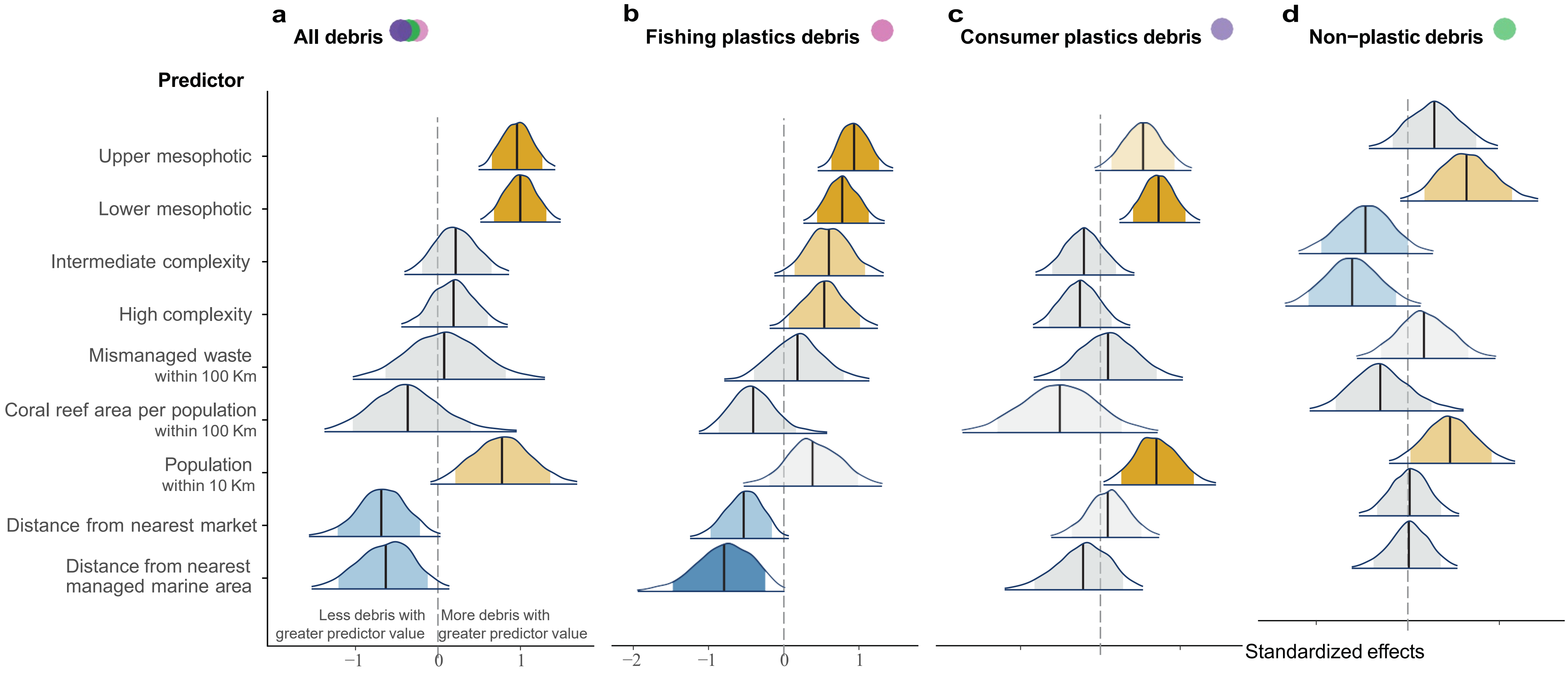
Consumer plastics debris



a
All debris
b
Fishing plastics debris
c
Consumer plastics debris
d
Non-plastic debris
Shallow reefs
Upper mesophotic
Lower mesophotic
Estimated smooth for debris (log-link scale)
Depth (m)
0
30
60
100
150
0
1
2
3
4
5
6
7

0 30 60 100 150
Depth (m)

0 30 60 100 150
Depth (m)



a
All debris
b
Fishing plastics debris
c
Consumer plastics debris
d
Non−plastic debris
Predictor
Upper mesophotic
Lower mesophotic
Intermediate complexity
High complexity
Mismanaged waste
within 100 Km
Coral reef area per population
within 100 Km
Population
within 10 Km
Distance from nearest market
Distance from nearest
managed marine area
Less debris with
greater predictor value
More debris with
greater predictor value
−1
0
1
−2
−1
0
1
Standardized effects

Standardized effects

−2 0 2

Standardized effects

−2 0 2

Standardized effects