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Baseline

Plastic pollution transcends marine protected area boundaries in the eastern tropical and south-eastern Pacific

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ABSTRACT

The Eastern Tropical and South-Eastern Pacific region is of global biodiversity importance. At COP26, the governments of Costa Rica, Panama, Colombia, and Ecuador committed to the expansion of existing MPAs to create a new Mega MPA, safeguarding the Eastern Tropical Pacific Marine Corridor. It offers a profound step forward in conservation efforts but is not specifically designed to protect against the more diffuse anthropogenic threats, such as plastic pollution. We combine published data with our own unpublished records to assess the abundance and distribution of plastic pollution in the region. Macro- and microplastic concentrations varied markedly and were not significantly different when comparing areas inside and outside existing MPA boundaries. These findings highlight the diffuse and complex nature of plastic pollution and its ubiquitous presence across MPA boundaries. Understanding the sources and drivers of plastic pollution in the region is key to developing effective solutions.

1. Introduction

The leakage of poorly managed plastic waste into the environment has increased exponentially, with the latest global estimates suggesting 19 to 23 million metric tons reach the oceans each year (Borrelle et al., 2020), resulting in dramatic increases of floating microplastics over the

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past two decades (Eriksen et al., 2023). Plastic pollution is predicted to triple by 2030 without significant mitigation and societal changes in plastic production, consumption, and disposal (Borrelle et al., 2020), leading to significant ecological, economic, and social costs (Beaumont et al., 2019).

The Eastern Tropical and South-Eastern (ET/SE) Pacific region is of global biodiversity importance, hosting high levels of abundance, species richness and endemism, whilst supporting globally important fisheries (Chavez et al., 2008; Thiel et al., 2007). Several conservation initiatives exist in the region, such as the Eastern Tropical Pacific Marine Conservation Corridor (CMAR), a non-binding agreement formally established in 2004 that aims to promote the sustainable use of marine resources and safeguard the ecological connectivity between existing MPAs including Galapagos (Ecuador), Cocos (Costa Rica), Malpelo (Colombia), Gorgona (Colombia) and Coiba (Panama) (Enright et al., 2021; United Nations, 2022) (Fig. 1). At the 2021 United Nations Climate Change Conference (COP26), the governments of these countries signed a commitment to expand the protection within the CMAR area and strengthen cooperation between members to establish a biological corridor (WWF, 2021). When this Mega MPA is considered alongside existing and designated MPAs in the region, particularly including the Easter Island ecoregion in Chile (van Gennip et al., 2019) and islands along the coast of Peru (Laínez del Pozo and Jones, 2021), it has the potential to make a significant contribution towards global commitments to protect 30 % of the oceans by 2030 (O'Leary et al., 2019). As part of this new commitment to form the Mega MPA, Regional Working Groups focus on key thematic areas that have been identified as priorities for the conservation of the biodiversity of the region, these include tourism, MPAs, science, fisheries, and communications (Enright et al., 2021). Whilst the issue of plastic pollution is not a key aim, it does link into all of the priorities and as such, would be a valuable focus theme to consider.

Designation of large MPAs offers a profound step forward in conservation efforts but are not designed to offer protection against the harmful impacts of plastic waste (Luna-Jorquera et al., 2019), a problem that is relatively understudied in the region. We hypothesised that both the ET/SE Pacific region and its regional MPAs would be exposed to large quantities of plastic litter due to their proximity to subtropical gyres, singular current systems, industrial fishing activity, and land-based sources from urban areas, tourism, and poor waste management (De Veer et al., 2023; Luna-Jorquera et al., 2019; Ryan et al., 2019) (Fig. 1a). To investigate this, we compiled published data on abundance of both macro- and microplastics (years 2000–2023, 26 publications, 365 beach sites, detailed in **SI**) with our own extensive unpublished data (3 studies, 65 beach sites, detailed in **SI**), to assess the concentrations of plastic pollution on coastlines in the ET/SE Pacific.

2. Methods

2.1. Literature search

We analysed existing literature up to April 2023 on plastic debris (evidence of macro- (>5 mm) and microplastics (1–5 mm) in coastal countries of the CSE Pacific region). Published literature was found for nine countries (Mexico, Guatemala, El Salvador, Costa Rica, Panama, Colombia, Ecuador, Peru, and Chile), but there were no published records for Nicaragua or Honduras. We searched for studies available on Web of Science and Google Scholar using the following keywords related to plastic pollution: "plastic", "macroplastic", "microplastic", "marine litter", "marine debris", "anthropogenic litter" and "anthropogenic debris". Where multiple papers reported abundance data for the exact same locations, only the most recent paper was considered to avoid pseudo-replication. Reports of plastic impacts on, or interactions with, marine organisms were not included in this study. Water borne plastics and those present in seabed sediments were also not included due to variations in collection method and lack of literature for comparison. The collected data included quantitative data on both macro- and microplastics from the intertidal zone, strand line, and the supratidal zone. Surveyed plastic densities were reported in items m^{-2} for both macroplastics and microplastics.

We then combined the published data with non-published data from multiple sources, including the international research network Pacific Plastics: Science to Solutions (PPSS) (see **Tables S1 & S2** for more information). The methods of each study (published and unpublished) included in this dataset were assessed to ensure similarity in data collection. By only including macroplastic and larger microplastics (1–5 mm in size), we removed the risk of contamination from smaller microplastics, particularly microfibres, during sample collection, transportation, and sample processing.

2.2. Statistical and mapping analyses

All data were analysed using Microsoft Excel (Microsoft Corporation, 2018) and the statistical software R (R Core Team, 2021). Generalised Linear Mixed Effects models were used to explore the influence of the sampling site location on both macro and microplastic abundances within and outside of MPAs, and also between countries in the region. Two variables relating to location were therefore included as fixed effects in the model, '*Country*' and '*InOut*' (whether a sampling site was inside or outside an MPA). Year was also included as a fixed effect to explore the presence of any fluctuations in abundance through time. '*LocationID*'- was included as a random effect to take any pseudo-replication from repeated sampling of specific sites into account. Model selection was based on Akaike's Information Criterion (AIC) and *p*-value, where the model with lowest AIC score was deemed the most reliable. The null hypothesis was rejected if $p \leq 0.05$ (**Tables S3–S6**).

To visualise spatial patterns in plastic abundance, the mean abundance at each location (items m^{-2}) was mapped in the spatial analysis software: QGIS (QGIS.org, 2021. QGIS Geographic Information System. QGIS Association). Geographical location of sampling sites was provided as longitude and latitude (WGS1984). Land and coastline data were sourced from Natural Earth (https://www.naturalearthdata.com/).

3. Results and discussion

We synthesized plastic pollution data from 430 locations in nine countries, of which 90 were located within MPAs in eight countries. Plastic concentrations varied markedly across the region (Fig. 1c & d); macroplastic abundance ranged from 0 to 19.4 items m^{-2} ($n = 342$ sites; 81 in MPAs). Microplastic concentrations ranged from 0 to 806.4 MP m^{-2} ($n = 88$ sites; 9 in MPAs) (Fig. 1c). Macroplastic and microplastic levels did not vary significantly by country or year (**Tables S5 & S6**, Generalised Linear Mixed Effects model (GLMM, 'lme4' package for R,(R Core Team, 2021) $p > 0.05$, see **Supp. Mat.** for models and associated AIC scores).

Whether or not a sampling site was located within or outside an MPA had no significant effect on macro or microplastic levels (Fig. 1b, mean number of macroplastic items within MPAs = 1.1 items m^{-2} and outside MPAs = 0.7 items m^{-2}; mean number of microplastics within MPAs = 179.7 items m^{-2} and outside MPAs = 72.7 items m^{-2}). Despite limited literature from the region, there was a mean abundance of 1.0 items m^{-2} (range: 0.0–7.8 items m^{-2}, $n = 14$) and 137.0 MP m^{-2} (range: 4.0–314.0 MP m^{-2}, $n = 15$), for macro- and microplastics, respectively, in sites that will be within the future Mega MPA. This is compared with 0.7 items m^{-2} (range: 0.0–10.5 items m^{-2}) and 57.6 MP m^{-2} (range: 0.0–545.8 MP m^{-2}) for macro- and microplastics, respectively, in areas outside the Mega MPA. Inclusion of these records as future MPA sites had no significant effect on both macro- or microplastic levels inside or outside an MPA (**Fig. S1**). The plastic abundance in this region demonstrates the likelihood of marine wildlife interacting with plastic debris, with uptake of microplastics into the marine food web already reported within the Galapagos marine reserve (Jones et al., 2021), and several species have

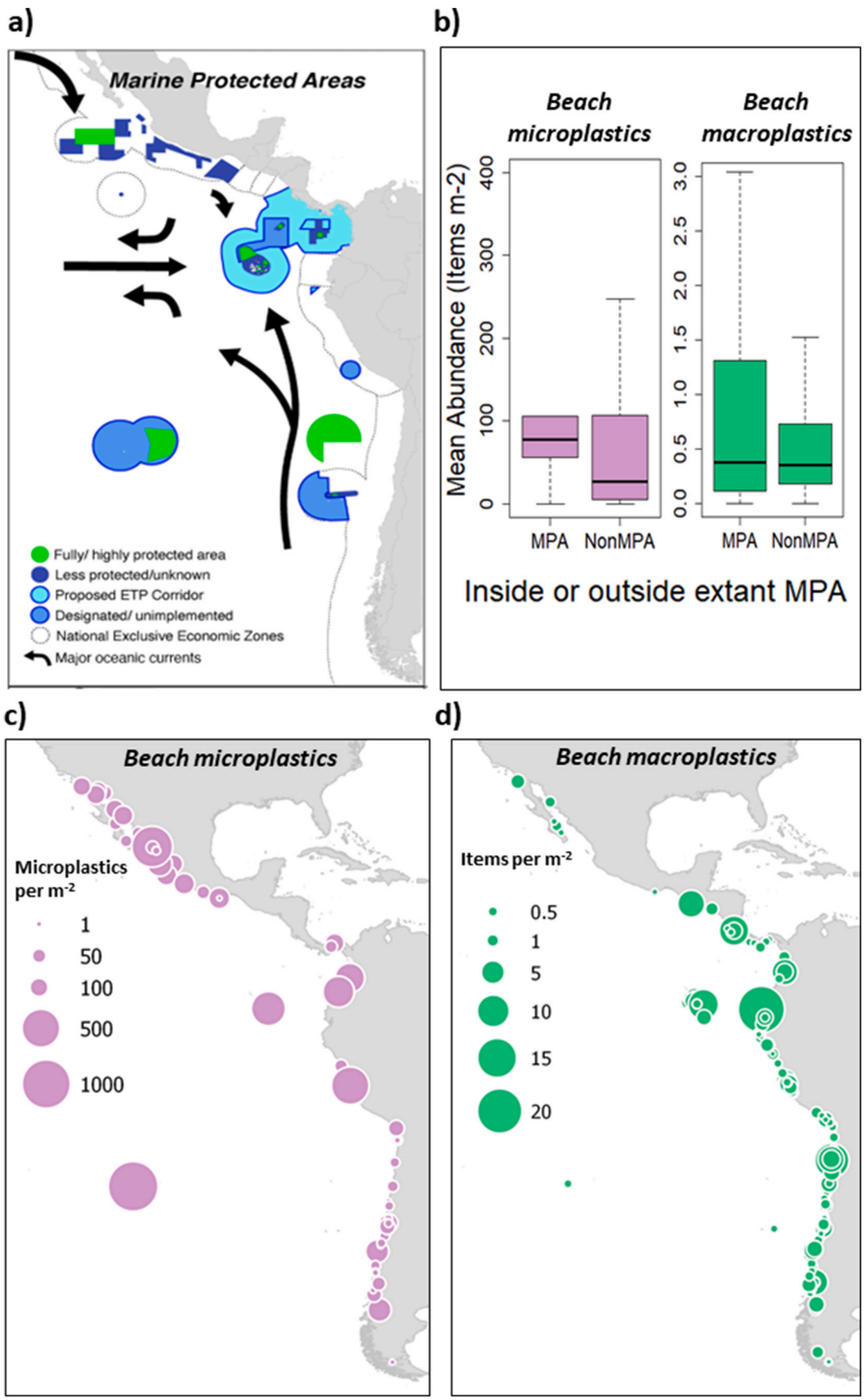

Fig. 1. **a)** Locations of existing and designated marine protected areas (MPAs) in the eastern tropical and south-eastern Pacific, including the proposed Mega MPA within the Eastern Tropical Pacific (ETP) marine corridor (CMAR); **b)** Mean abundance of beach micro- and macroplastics within or outside extant MPAs; **c)** Microplastic abundance (microplastics m^{-2}) and **d)** Macroplastic abundance (items m^{-2}) on beaches in the region.

been identified as high risk of ingestion or entanglement (Muñoz-Pérez et al., 2023).

The highest macroplastic abundances found within MPAs were reported within the Machalilla National Park, off the coast of mainland Ecuador (19.4 items m^{-2}), followed by the Galapagos MPA (8.3 items m^{-2}) and Uramba Bahia Malaga National Park, mainland Colombia (5.8 items m^{-2}). Some of the highest microplastic abundances found within MPAs were reported from remote islands in the SE Pacific: Rapa Nui MPA, Chile (806.4 MP m^{-2}) and Galapagos MPA, Ecuador (381.0 MP m^{-2}). This may be consistent with the fragmentation of larger plastic items that have been in the marine environment for a long time, via UV degradation, wave action and physical abrasion. The sources of marine plastic found in the ET/SE Pacific area are predominantly fisheries and aquaculture (Astudillo et al., 2009; Figueroa-Pico et al., 2016; Luna-Jorquera et al., 2019), and land-based sources transported by rivers (Rech et al., 2014) captured by the South Pacific Subtropical Gyre and distributed to the open ocean by currents which concentrate the plastic pollution (Martinez et al., 2009; Van Sebille et al., 2019). One of the most important currents in the SE Pacific is the Humboldt Current, which flows northwards from South Chile to Northern Peru, before flowing westwards in the direction of the equator (Thiel et al., 2003). It transports nutrients, biota, and marine debris northwards (Van Sebille et al., 2019), likely contributing to the higher plastic abundances found in the downstream direction of the current, such as mainland Ecuador, Galapagos, and Colombia. In addition to transportation via currents, beach characteristics such as beach morphology and coastal topography will influence plastic deposition in certain locations. Inclusion of this information in future studies could aid in the identification of debris hotspots. Hence, whilst recent policy changes to create the Mega MPA and increased protection of migratory species in connectivity corridors are to be applauded, our data suggest the ubiquitous and mobile nature of plastic pollution will continue to increase in the region's marine environment. An exception may be that of fisheries waste, which may be reduced at some locations depending on level of protection and restrictions on fishing activities. Of the published literature used in this study that categorized macroplastics by potential source ($n = 9$), 45 % ($n = 4$) recorded fisheries related debris as one of the major plastic debris contributors. However, this is likely to be an underestimate, as it has been shown in other regions that many plastic bottles, usually categorized as a land-based source, are originating from marine vessels (Ryan et al., 2019).

To protect the unique biodiversity within the MPAs of the ET/SE Pacific from the harmful effects of marine plastic pollution, it is necessary to identify the key sources and drivers. Modelled estimates and coastal clean-up initiatives suggest mainland Ecuador, Peru and Chile may be the main plastic pollution sources in the region (van Duinen et al., 2022). However, there remain key data gaps for Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, Panama, and Colombia (Fig. 1c & d). Reducing plastic leakage into the environment requires a pan-regional, multidisciplinary approach across environmental, economic, and social disciplines, applying locally relevant circular economy thinking to identify and test evidence-based solutions and systemic interventions that help to reduce the input of plastic waste (De Veer et al., 2023; van Duinen et al., 2022). For such a sustainable plastics economy to become mainstream in any region, numerous technical, economic, social, and environmental barriers must be overcome or removed, perhaps to be accelerated by the adoption of a legally binding regional treaty which could in turn contribute to a Global Plastics Treaty.

CRediT authorship contribution statement

Zara L.R. Botterell: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Francisca Ribeiro:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Daniela Alarcón-Ruales:** Writing – review & editing, Investigation. **Eliana Alfaro:** Writing – review & editing. **Joanna Alfaro-Shigueto:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Nicola Allan:** Writing – review & editing. **Nicole Becerra:** Writing – review & editing. **Laura Braunholtz:** Writing – review & editing. **Susana Cardenas-Diaz:** Writing – review & editing. **Diamela de Veer:** Writing – review & editing, Formal analysis, Data curation. **Gabriela Escobar-Sanchez:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Maria Virginia Gabela-Flores:** Writing – review & editing, Investigation. **Brendan J. Godley:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition. **Inty Grønneberg:** Writing – review & editing. **Jessica A. Howard:** Writing – review & editing. **Daniela Honorato-Zimmer:** Writing – review & editing, Formal analysis, Data curation. **Jen S. Jones:** Writing – review & editing, Investigation, Funding acquisition, Formal analysis, Data curation. **Ceri Lewis:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Jeffrey C. Mangel:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Maximilian Martin:** Writing – review & editing. **Juan Pablo Muñoz Pérez:** Writing – review & editing, Investigation. **Sarah E. Nelms:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation. **Clara Ortiz-Alvarez:** Writing – review & editing. **Adam Porter:** Writing – review & editing. **Martin Thiel:** Writing – review & editing, Funding acquisition, Formal analysis, Data curation. **Tamara S. Galloway:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

Our dataset is fully available within the Supplementary Information.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.116271.

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