

RESEARCH ARTICLE

Predictive modelling reveals Australian continental risk hotspots for marine debris interactions with key threatened species

Caitlin E. Smith¹  | Ben L. Gilby²  | Jason van de Merwe³  | Jodi Jones⁴  | Heidi Tait⁴  | Kathy A. Townsend¹ 

¹School of Science, Technology and Engineering, University of the Sunshine Coast, Hervey Bay, Queensland, Australia

²School of Science, Technology and Engineering, University of the Sunshine Coast, Petrie, Queensland, Australia

³Australian Rivers Institute, Griffith University, Southport, Queensland, Australia

⁴Tangaroa Blue Foundation, Australian Marine Debris Initiative Database, Dunsborough, Western Australia, Australia

Correspondence

Caitlin E. Smith, School of Science, Technology and Engineering, University of the Sunshine Coast, Hervey Bay, Qld. 4655, Australia.
Email: caitlin.smith@research.usc.edu.au

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Abstract

Anthropogenic debris is a global threat that impacts threatened species through various lethal and sub-lethal consequences, as well as overall ecosystem health. This study used a database of over 24,000 beach surveys of marine debris collated by the Australian Marine Debris Initiative from 2012 to 2021, with two key objectives: (1) identify variables that most influence the occurrence of debris hotspots on a continental scale and (2) use these findings to identify likely hotspots of interaction between threatened species and marine debris. The number of particles found in each beach survey was modelled alongside fifteen biological, social, and physical spatial variables including land use, physical oceanography, population, rainfall, distance to waste facilities, ports, and mangroves to identify the significant drivers of debris deposition. The model of best fit for predicting debris particle abundance was calculated using a generalized additive model. Overall, debris was more abundant at sites near catchments with high annual rainfall (mm), intensive land use (km²), and that were nearer to ports (km) and mangroves (km). These results support previous studies which state that mangroves are a significant sink for marine debris, and that large ports and urbanized catchments are significant sources for marine debris. We illustrate the applicability of these models by quantifying significant overlap between debris hotspots and the distributions for four internationally listed threatened species that exhibit debris interactions; green turtle (26,868 km²), dugong (16,164 km²), Australian sea lion (2903 km²) and Flesh-footed Shearwater (2413 km²). This equates to less than 1% (Flesh-footed Shearwater, Australian sea lion), over 2% (green sea turtle) and over 5% (dugong) of their habitat being identified as areas of high risk for marine debris interactions. The results of this study hold practical value, informing decision-making processes, managing debris pollution at continental scales, as well as identifying gaps in species monitoring.

KEYWORDS

citizen science, conservation, debris surveys, plastic, policy change, pollution

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1 | INTRODUCTION

The diversification and expansion of human development and industrialization along coastlines has profoundly transformed the natural environment, leading to an unprecedented surge in the production of anthropogenic waste that is being discarded into ecosystems (Brandon et al., 2019; Chen et al., 2021; Neumann et al., 2015). Marine debris is defined as any item that has been made or used by humans and discarded into the sea, beach or coast, brought indirectly into the ocean by the action of rivers, sewage outflows, storm-water and winds, or accidentally lost (Rangel-Buitrago et al., 2019). Marine debris is ubiquitous and is found even on the most remote shorelines (Jones et al., 2021) and in the deepest parts of the ocean (Chiba et al., 2018). The accumulation and deposition of debris can be attributed to a range of contributing social and physical factors, which exhibit high variability depending on the location and surrounding conditions (Slavin et al., 2012). These can include variables such as improper waste management systems, coastal and marine activities, coastal development, ocean currents and tides, tourism and recreational activities, and illegal disposal practices (Pawar et al., 2016). Debris found along the coastline detracts from the aesthetic quality of beaches, and can therefore have negative effects on regional economies, marine ecosystem functioning (Balance et al., 2000), and valuable marine ecosystem services (e.g., fishing and aquaculture; and marine and coastal tourism) that contribute significantly to the global economy (Cisneros-Montemayor et al., 2013; Dyck & Sumaila, 2010; Sangha et al., 2019). Therefore, maintaining clean and healthy coastal and marine ecosystems is of international interest.

Approximately 700 marine species have been recorded to interact with marine debris, with the majority of these species occurring in key areas of biodiversity (Hardesty et al., 2015). Marine debris pollution in these areas leads to habitat degradation, poor ecosystem health, and the spread of harmful pathogens and chemicals (Gall & Thompson, 2015; Moy et al., 2018). While the physiological impacts of debris ingestion in coastal vertebrates remain largely unexplored, the consequences can be directly observed through lowered body condition and increased mortality, or more discreet mechanisms such as reduced organ function (Puskic et al., 2020). Debris ingestion poses both lethal and sub-lethal effects, including septicaemia, gastrointestinal perforations and blockages, and organ failure (Baulch & Perry, 2014). Debris particles, due to their longevity, can act as vectors of land-based pathogens, toxic chemicals and invasive species that are harmful to both human and animal health (Bhagwat et al., 2021; Keswani et al., 2016). In addition, the impacts of entanglement as a result of discarded fishing gear, shark nets and fisheries bycatch are highly visible and have been extensively investigated globally (Duncan et al., 2017; Madden Hof et al., 2023).

Researchers continue to explore the variables that drive debris hotspots, the sub-lethal impacts of ingestion and entanglement, and identify areas in need of rehabilitation (Duncan et al., 2017; Slavin et al., 2012; Woods et al., 2019). Studies on anthropogenic debris has dramatically increased since the late 1990s, with the majority of publications focussing on abundance and composition of beach

debris (Ansari & Farzadkia, 2022). Species inhabiting populated coastal ecosystems, which face numerous anthropogenic impacts, are particularly vulnerable (Nielsen et al., 2021). Quantifying the impact of these anthropogenic variables is key to effectively manage and conserve threatened species. For example, identifying areas where there is a high risk of interaction between debris and marine organisms is essential in highlighting regions in need of increased rehabilitation and updated legislation in regard to waste management (Jepsen & de Bruyn, 2019).

Accumulation patterns of marine and coastal debris have been mapped using both high and low tech methodologies, including drone imagery and citizen science programs (Gacutan et al., 2022; Lambert et al., 2020; Moy et al., 2018). Moy et al. (2018) used high resolution imagery to map coastal debris in the Hawaiian Islands, which highlighted hotspots on windward shorelines. With over 25,000km of coastlines to survey, Australia has relied upon citizen scientist programs to highlighting hotspots of debris accumulation (Gacutan et al., 2022). While data from citizen science projects are often treated with caution, one study found that there was no difference between the quality of data obtained by citizen scientists and trained survey teams, emphasising the importance of citizen science datasets to fill important knowledge gaps (Gacutan et al., 2022).

Sources of marine debris include both land- and ocean-based sources. Land-based sources of marine debris include storm water discharge, littering, landfill and industrial activities (Pawar et al., 2016). Some studies have suggested that localities often have a higher density of debris due to physical ocean variables such as current direction and velocity (Barnes et al., 2010; Maximenko et al., 2012). The debris found on beaches has been linked to that in the surrounding marine environments (e.g., land use types), however it is often severely underestimated due to infrequent sampling (Smith & Markic, 2013). Key attributes of coastal landscapes, such as the presence of mangroves, have also been shown to impact the amount and type of debris found in the surrounding area (Ivar Do Sul et al., 2014).

Increased knowledge regarding the distribution and drivers of marine debris hotspots can inform policy and decision makers (Hardesty et al., 2015). There are hundreds of species that have been identified as being at-risk of debris impacts within Australia in the Marine Debris Threat Abatement Plan (Commonwealth of Australia, 2018). Most of the species highlighted in the abatement plan, including several marine mammals, reptiles, birds and fish, inhabit shallow coastal zones, have site philopatry, and dietary preferences that make them susceptible to debris.

Despite the overwhelmingly damning evidence of the effects of marine debris, there are still many knowledge gaps regarding the drivers of debris deposition, and how data on the distribution of marine debris can be effectively used for conservation management and policy change (Luo et al., 2021; Vince & Stoett, 2018). This study used over 24,000 beach surveys from the Australian Marine Debris Initiative Database (Australian Marine Debris Initiative, 2023) as a proxy for debris pressure to the surrounding coastal environment to accomplish two key objectives: (1) identify

environmental and spatial variables that most influence the occurrence of debris hotspots and (2) use these data as a research tool to identify locations where there is risk of interaction between debris and at risk species identified in Australia's Marine Debris Threat Abatement Plan (Commonwealth of Australia, 2018). Therefore, this study presents a novel quantitative assessment of the impact of debris on threatened species based on statistical spatial patterns. Achieving these two objectives results in an increased understanding of the drivers of debris deposition and contributes data towards the management and legislative change required for the conservation of threatened marine species.

2 | METHODS

2.1 | Coastal debris surveys

This study collated 24,445 coastal debris surveys from the Australian Marine Debris Initiative Database (AMDID), collected from their citizen science app. Some surveys were carried out by Tangaroa Blue Foundation's ReefClean project in more remote locations where citizen science surveys are not common. There are sparse data collection in the Gulf of Carpentaria (GoC), Cape York, and Kimberley regions, as they are remote areas with low population centers, and high safety risks (e.g., high saltwater crocodile densities). Survey data were collected from 01/01/2012 to 31/12/2021 and filtered for data quality assurance. Data that had a value of '0' in important fields such as the number of people in the survey, duration (hours) etc. were removed, as were surveys in which GPS locations were positioned in the open ocean or inland. This reduced the final database for analysis from 28,000 to 24,445 surveys. Every item that was classified as anthropogenic in the AMDID Data Collection App (inc. treated wood products) regardless of size was included in the total number of items. Survey clustering and spatial autocorrelation was investigated to avoid sampling bias using hotspot analysis and Global Moran's I test (Figure S1). This flagged several locations as potential areas of survey bias, including the areas surrounding Sydney, Melbourne and the Sunshine Coast. This was considered when interpreting the outputs of analyses.

2.2 | Spatial analysis

Using ArcGIS 10.8, the geometry of different land use types within 672 coastal catchments (McPherson et al., 2011) were calculated. The *Land use of Australia* (ABARES, 2022) raster layer was polygonised to calculate the geometry (km²) of the land use categories and clipped to each coastal catchment using QGIS3.28.2. These land use types (including codes) were:

- Irrigated farming, encompassing irrigated pastures, irrigated cropping, and irrigated horticulture (400, 420–454).

- Dry farming, inclusive of grazing native vegetation, production native forests, grazing modified pastures, plantation forests, dryland cropping, dryland horticulture and land in transition (200–365, 410–414, 460–465).
- Intensive use, including urban and rural residential, commercial, utilities, services, transport and communication (500–575).
- Minimal use land, including nature conservation land and managed resource protection (100–134).
- Mining and waste land, such as mined land, waste treatment facilities and landfill (580–595).
- Water bodies, such as lakes, rivers, waterways, and creeks (600–663).

Using the "NNjoin" plugin in QGIS 3.28.2, all the survey data points ($n=24,445$) were attributed the area of the nearest coastal catchment's land use categories, mean rainfall per catchment (mm per annum), and total population. Variables including the distance (in km) to the nearest mangrove, waste management facility, wastewater facility, port and airport was also calculated for each survey as these were hypothesised to affect the level of debris in the surrounding area (Table S1).

Physical ocean variables collected from Australia's Integrated Marine Observing System (IMOS) were added to the debris survey dataset based on GPS location and date time stamps. Using the *remora* (Rapid Extraction of Marine Observations for Roving Animals) package (Jaime et al., 2021) in the R statistical framework (version 4.2.0; R Core Team (2023)), ocean current velocity and direction data at the shallowest sensor depth were downloaded from the IMOS database and added to the survey dataset based on the closest available mooring sensor. Mooring sensors are widespread; therefore, a buffer of 100km was used to allow data to be allocated to the nearest beach survey.

2.3 | Statistical analysis

Correlations between the number of debris particles in each survey and the hypothesized driving variables were quantified using generalized additive models (GAMs) in the *mgcv* package (Wood, 2011) of R. In total, 15 physical, biological, and social variables were calculated and attributed to the 24,445 beach survey data entries (Table 1). We tested for multicollinearity between the variables using a pairwise Pearson's correlation test. Any two variables that had a correlation coefficient either >0.6 or <-0.6 were considered collinear, resulting in one of the variables being removed based on the strength of the underlying hypothesis. Following this, the 11 variables were included in the final GAM; distance (km) to ports, waste management facilities, airports, mangroves; area (km²) of intensive use, irrigated farming, mining land, water bodies; total rainfall (mm); current direction (north, south, east, and west) and current velocity (ms⁻¹) (Table 1). Model overfitting was minimized by limiting GAM relationships to three knots or fewer (i.e., $k=3$) and by calculating GAMs with all possible combinations of four variables or fewer using

Variable name	Variable obtained	Used in GAM	Best fit model	F-statistic	p value
Distance to mangrove (km)	X	X	X	689.6	<.01
Distance to airport (km)	X	X	-	-	-
Distance to port (km)	X	X	X	473.6	<.01
Distance to waste management facility (km)	X	X	-	-	-
Distance to wastewater facility (km)	X	-	-	-	-
Total annual rainfall (mm)	X	X	X	1184.0	<.01
Total human population	X	-	-	-	-
Intensive land use (km ²)	X	X	X	986.6	<.01
Water surface area (km ²)	X	X	-	-	-
Minimal use land (km ²)	X	-	-	-	-
Mining and waste land (km ²)	X	X	-	-	-
Dry farming (km ²)	X	-	-	-	-
Irrigated farming (km ²)	X	X	-	-	-
Mean current velocity (ms ⁻¹)	X	X	-	-	-
Current direction (north, south, east, west)	X	X	-	-	-
Year (random)	X	X	X	4288	<.01

TABLE 1 Variables used in spatial and generalized additive model (GAM) quantifying effects of the presence of marine debris in beach surveys, as well as the corresponding *F*-statistic and *p*-values from the GAM.

the *MuMIn* package (Barton, 2023; Gilby et al., 2023). The best fit model was the resulting model with the lowest Akaike's Information Criterion (AIC) value. The level of effort undertaken during each site was accounted for in the GAM using an offset variable of the duration of the survey (the time taken to complete the survey multiplied by the number of participants), which is indicative of effort. Survey year was also added to the GAM as a random variable to account for repeat surveys at some sites. Only the fixed variables in the resulting best-fit GAM were plotted.

2.4 | Hotspot analysis

Data were visualized using the hotspot analysis in ArcGIS, using inverse-distance and Euclidean distance to spatially pool the total number of debris particles per survey. The ArcGIS hotspot analysis calculated a *Gi** statistic per data point, and subsequent *p*-values and *z*-scores indicated spatial clustering (Getis & Ord, 1992). A statistically significant hotspot was indicative of high total debris particles, with neighbors of similarly high values clustered together. Data points with a *Gi** statistic greater than 2 were classified as significant hotspot, with a 95% confidence interval or higher, or *p*-value <.05.

2.5 | Using debris hotspots to inform threatened species research

Using the Marine Debris Threat Abatement Plan (2018), 64 species listed on the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) were highlighted as at risk for interacting with debris. We selected four species from this list: the green turtle (*Chelonia mydas*), the dugong (*Dugong dugon*), the Australian sea lion (*Neophoca cinerea*), and the Flesh-footed Shearwater (*Ardenna carneipes*). These species offer ideal case studies for this analysis as they differ in their

distribution ranges, biological constraints, habitat usage, and taxonomy. Species distributions were taken from the Species of National Environmental Significance Database (SNESD). Distribution extents were created in the SNESD using environmental data and modeling software and are indicative of species distribution (Australian Government Department of Climate Change, 2023). Species distributions have a resolution of ca. 10km and are separated into two categories: "species/species habitat likely to occur" and "species/species habitat may occur." For this analysis, only the "species/species habitat likely to occur" distributions were used for optimal confidence. The hotspot analysis shapefile generated was buffered by 10km, to be in line with the species distribution resolution and therefore represented a conservative estimate of risk overlap and was overlaid with the species distribution layers. Areas that overlapped were deemed to be locations where species' exposure to debris were a risk.

3 | RESULTS

3.1 | Predictive hotspot variables

The abundance of marine debris at sites were best explained by the combined effects of distance to mangroves (km; $F=7.669$, $p<.01$), distance to ports (km; $F=6.505$, $p<.01$), area of intensive land use (km², $F=72.174$, $p<.01$) and total rainfall (mm; $F=35.030$, $p<.01$) (Table 1; $R^2=.11$). Deposited marine debris particles on beaches were lower with increasing distance from mangroves, with high particle counts (2500) attributed to areas within 0–1km of port areas (Figure 1). This trend was replicated with distance to ports, with approximately 2500 debris particles associated with areas within 0–10km of a major port. The amount of intensive land use (km²) predicts a more complicated relationship. Hotspots of debris occur in both remote and intensive use/populated areas. In our predictive

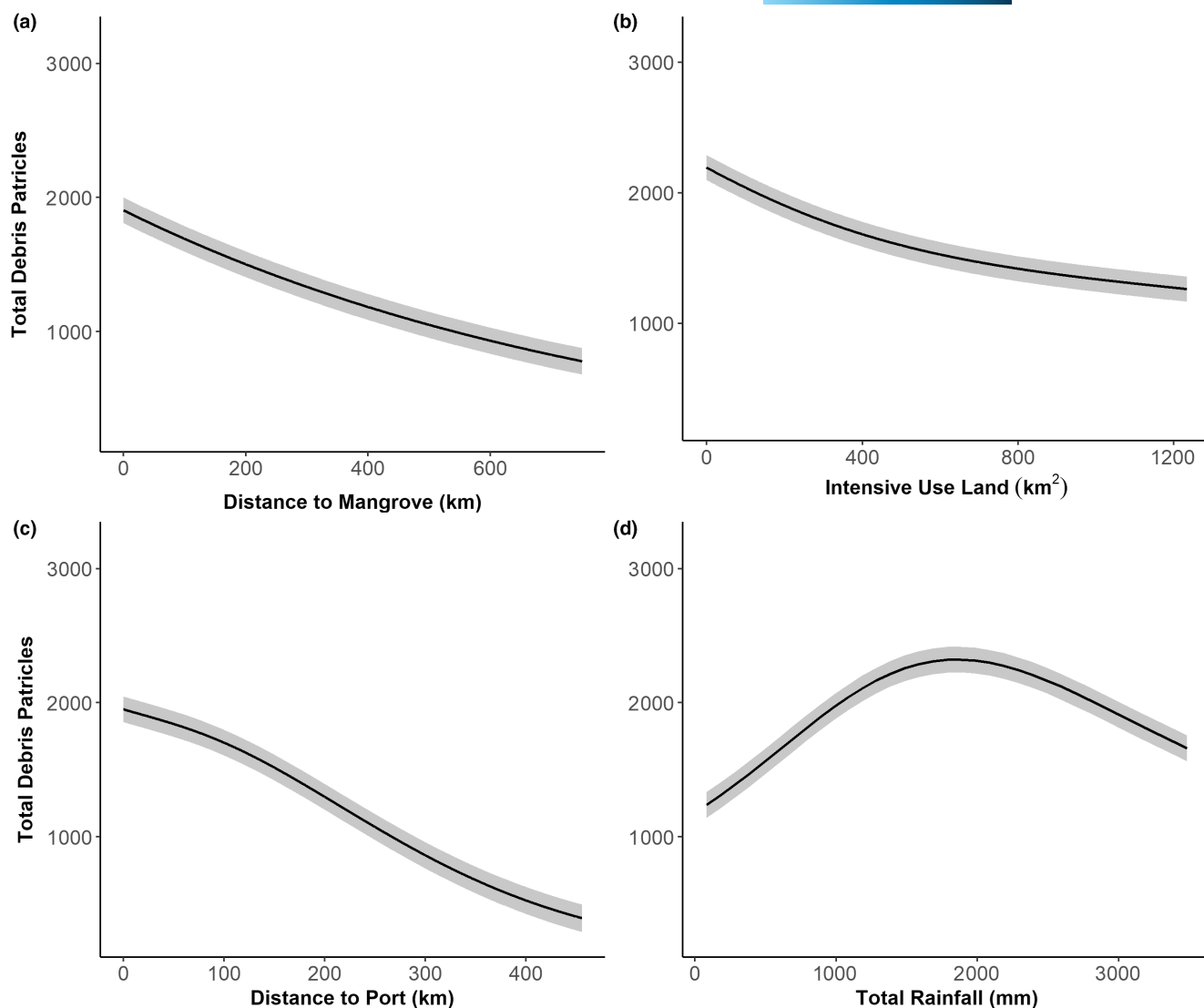


FIGURE 1 Generalized additive model (GAM) output of the best-fit model illustrating relationships between environmental variables and marine debris particle abundance across Australia. Grey bands indicate 95% confidence intervals.

model, lower extents of intensive land use (0–400 km²/catchment) are attributed to high numbers of debris particles (2100–2900) found on beaches. However, high levels of intensive land use (400–1200 km²) also yield high numbers of debris particles (1800–2100), suggesting that high debris loads are found in both remote and populated areas. The abundance of marine debris particles increases on shorelines with increasing rainfall in the catchment, to a maximum of 3000 items at ca. 1600 mm of rain, before declining at catchments with the highest amount of rainfall. The random variable of ‘year’ had a significant effect on overall patterns with the total number of debris particles increasing over time (Figure S2).

3.2 | Coastal debris hotspots

Hotspots were defined as areas that had a Gi* statistic of 2 or higher and had a confidence interval >95% (Figure 2). A large proportion of Australia's coastline experiences clustering of debris particles on

its shorelines. The entire east coast of Australia from southern New South Wales, up to the Torres Strait, experiences constant exposure of debris. The number of beach surveys increased every year since 2012 and are missing in the more rural parts of the country, such as the Kimberly region in Western Australia, the western side of Cape York and in the Gulf of Carpentaria. Some surveys have been carried out in these regions, but there were insufficient replicates to identify hotspots (Figure S1).

3.3 | Threatened species interactions with debris

Several areas of potential risk between debris particles and the four threatened species included in this study have been highlighted (Figure 3). Due to green turtle's extensive distribution across temperate and tropical Australia, this species had the largest area of potential interaction with debris hotspots with a total of 26,868 km² of ocean, equating to 2.2% of their total known distribution within

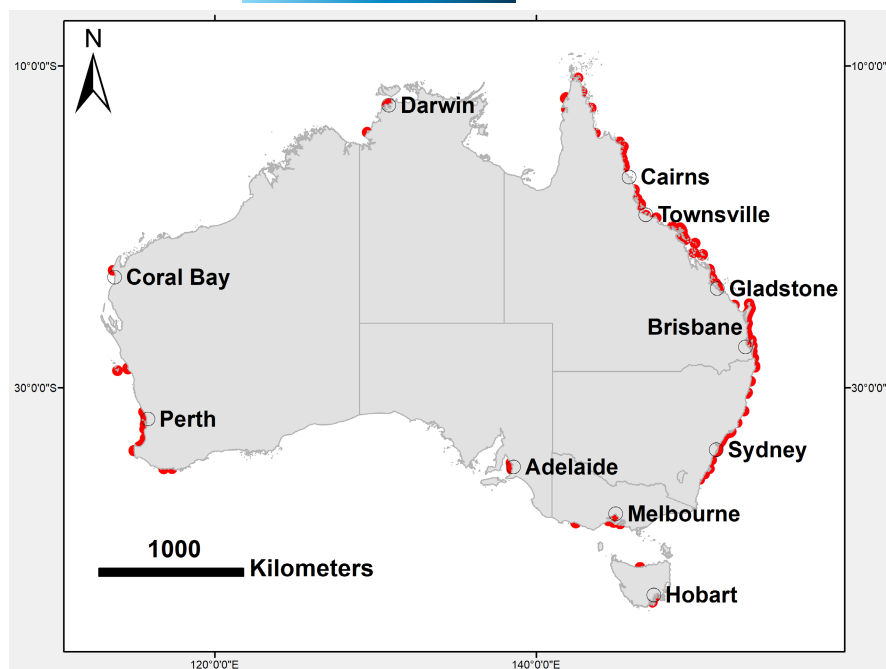


FIGURE 2 Coastal debris hotspots along the Australian coastline pooled from 2012 to 2021 and standardized for sampling effort. All hotspots have a confidence interval >95%.

Australian waters. Green turtle interaction with marine debris was consistently patchy along the eastern coast of Australia (Figure 3). In Western Australia, estimated green turtle interactions with debris were confined to Coral Bay, the Abrolhos Islands, and the Perth region. Dugongs, like green turtles, have a large distribution in the northern regions of Australia (Figure 3). The areas of concern for dugongs encompassed 16,164 km² (5.2%) of their known distribution.

Flesh-footed shearwaters and Australian sea lions had considerably smaller risk areas, relative to the green sea turtles and dugongs. Flesh-footed Shearwater distribution overlapped with 2413 km² (0.9%) of debris hotspots, with several isolated areas highlighted as areas of consequence for this species (Figure 3). The overlap between the Australian sea lion distribution and debris hotspots showed four main areas where interaction has the potential to occur and had 2903 km² (0.8%) of their distribution overlap with debris hotspots (Figure 3).

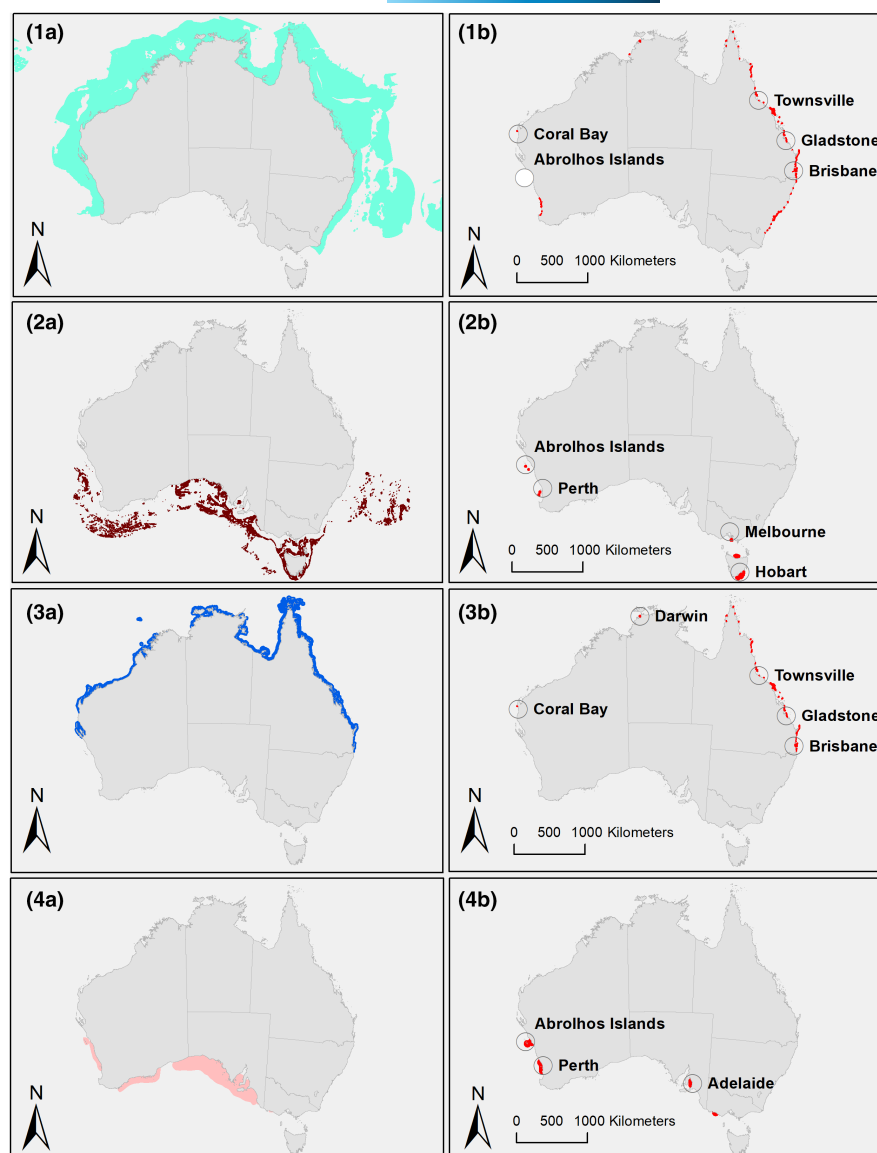
4 | DISCUSSION

An increased understanding of the environmental variables that most affect marine debris deposition is important in achieving optimal management and legislative change (United Nations Environment Programme, 2021). This study aimed to identify key variables that influence the presence of debris hotspots and use these data as a predictive tool for species risk management. Distance to mangroves and ports, area of intensive land use, along with total rainfall were identified as significant predictors of marine debris deposition along Australia's coastlines. Of the four threatened species modelled, dugongs were the most at risk, with 5.2% of their known habitat overlapping with debris hotspots.

This study has corroborated previously identified debris hotspots around the Australian coastline, with two additional years of data collection included in the analysis (Gacutan et al., 2022). Surveyed areas have expanded over the last 10 years, with the number of surveys conducted each year and recorded using the Tangaroa Blue application increasing in line with the growth, usability and popularity of mobile applications (Lemmens et al., 2021).

While it is unlikely that one model will fit all localities and situations, the development of indicative, nation-wide models such as these can aid in the facilitation and progression of our understanding of debris accumulation in coastal areas (Smith & Markic, 2013). We identified four variables that together best explained the number of debris particles found on beach surveys. Despite a relatively low R^2 value (likely due to very high replication >24,000), the strength of the statistical relationships and underlying ecological explanations builds confidence in the patterns found here. Rainfall has been shown in many other studies to alter the number of debris particles washed from inland sources to the coastal and marine ecosystems (Tasseron et al., 2023). Our model suggested that there is a maximum rainfall amount to which the number of debris particles on beaches decreases. We hypothesize that rainfall in catchments flushes inland debris onto beaches but when large rain events occur, the particles are flushed from coastal ecosystems into the ocean, and therefore are not picked up by beach surveys; a finding that aligns with the broader understanding of coastal pollutant dynamics (Devlin et al., 2012; Devlin & Schaffelke, 2009). The main source of transportation of debris from the land to the coast is through terrestrial waterways (Willis et al., 2017). Rainfall amount has a higher impact on the transport of debris, compared to the frequency of rainfall events (Morishige et al., 2007), further highlighting the importance of stormwater management (Axelsson & van Seville, 2017).

FIGURE 3 Distribution maps of key threatened species (left) and areas of risk of species' interaction with debris particles (right) for (1) green turtles (2.2% of their distribution), (2) Flesh-footed Shearwaters (0.9% of their distribution), (3) dugongs (5.2% of their distribution), and (4) Australian sea lions (0.8% of their distribution). Circled areas indicate large cities and townships.



It has been hypothesized that due to the lack of rubbish receptacle facilities in ports, spillage caused by the loading and unloading of vessels, and the sheer volume of vessels visiting Australian ports, that waste generated may be lost in a large enough quantity to affect the surrounding marine environment (Olson, 1994). Predictive modelling shows that there is a steady decrease in the number of debris particles as surveys moved further away from ports, suggesting that ports may be a significant contributor to debris pollution in Australia. As most cargo ships come from an international origin, these lost or discarded debris particles have the potential to act as vectors for invasive species dispersals (Ibabe et al., 2020). However, this trend could also be explained by the co-occurrence of ports with large rivers and increased human populations. Therefore, future research should investigate ports as a potential source of marine debris.

Mangroves have historically been found to overlap with areas of high debris density (Luo et al., 2021). Numerous studies have shown that mangroves are a sink for both land and water borne debris due to their structural complexity (Ivar do Sul et al., 2014; Luo

et al., 2022; Martin et al., 2019). This is consistent with our results showing that distance from mangroves (km) was a significant predictor of increased debris. Coastal mangroves provide several unique services to both people and nature such as acting as carbon sinks, buffering coastlines against storms, and providing nursery habitats for juvenile fish species (Romañach et al., 2018). This highlights the need for clean ups and increased protection to be prioritized around mangrove systems.

Surprisingly, there were several surveyed areas adjacent to catchments with low levels of intensive land use/human population that recorded high debris loads. Our model showed that there was a decrease in the number of debris particles as the area of intensive land use in the adjacent catchment increased, corroborating the notion that there are other factors (e.g., ocean currents) influencing the debris hotspots in remote areas with low intensive land use/population. Higher debris quantities on remote beaches are often associated with less frequent clean ups (Schmuck et al., 2017). However, Gacutan et al. (2022) found that there were high debris

accumulation rates in the remote locations where local communities were not the source of pollution, concluding that debris deposition was likely driven by ocean currents.

Despite not being a significant predictor of increased debris in this study, ocean currents have been demonstrated to play a large role in the deposition, transportation, and accumulation of debris particles (Mansui et al., 2015; Serra-Gonçalves et al., 2019). There are several reasons why ocean current data was not a significant predictor in determining high debris particle loads in our study. The first is that this dataset has a large number of surveys and encompasses a wide range of localities, that the effects of other major variables simply overwhelmed the effects of ocean variables in this analysis. Beach orientation has also been found to be a significant variable in determining average debris density (Gacutan et al., 2023). We suggest a relationship between ocean current variables and beach orientation could be incorporated into future models by sub-setting the data into smaller eco-regions.

The beach surveys collated by AMDI are an underutilized dataset with large amounts of data that has been made possible with the large community of citizen scientists. As this dataset mostly relies on citizen scientists, there are some regions with low population that are not surveyed to the same extent as others, such as the Kimberly region in Western Australia and the Gulf of Carpentaria; these may indeed be sites where current-drive marine debris deposition dominates patterns. Studies have shown that the Gulf of Carpentaria experiences high net entanglement rates of turtle species due to regional fishing activities (Hardesty et al., 2021; Wilcox et al., 2013). However, sites in the Gulf of Carpentaria were not highlighted as areas of concern in this analysis, as there were very sparse surveys conducted in this region. This gap in data may be a source of bias, pulling data away from other significant drivers of debris deposition. We also recognise that debris sources, sinks, modes of transportation and deposition will vary at the local scale, and therefore the findings presented are broad.

This study has brought to light several locations around Australia's coastline where interaction between threatened species and debris are likely to occur. Other studies have created risk matrices for specific species (Schuyler et al., 2016). However, working with species that have very little empirical evidence on their interaction with debris makes it difficult to quantify risk. Therefore, this mapping of areas of interest gives managers and researchers alike a good starting point in which to conduct surveys or sample the target species to gain a more in depth understanding of debris impacts.

The Houtman Abrolhos Islands, Western Australia, is a location where debris hotspots consistently overlapped with the distribution of threatened species. Three out of the four included species distributions identified this island group as a location of concern for interaction with debris. However, this location did not possess the characteristics that predict a typical debris hotspot. Therefore, ocean currents are potentially a source of debris in this locality. The Abrolhos Islands are in the path of the Leeuwin current, an eastern boundary current which could be transporting debris from external sources in the Indian Ocean. Hajbane and Pattiaratchi (2017)

found that plastic pollution in the offshore regions of Western Australia were highest where the Leeuwin current was the strongest, and therefore was a significant driver in the transportation of debris. Despite being a marine park with several IUCN zones, there are no known peer-reviewed papers, to the authors knowledge, that have assessed debris impacts within the Houtman Abrolhos Island group.

Green turtles have a large distribution and therefore had the most locations in which interaction with debris could occur across the study site. This is reflected heavily in scientific literature and mainstream media, as marine turtles frequently have visible interactions with debris, witnessed by the public (Donnelly et al., 2020; Schuyler et al., 2016, 2019). Similarly, the Flesh-footed Shearwater has had their interactions with debris well documented over the last several decades. While most of these publications have sampled shearwaters on Lord Howe Island and Tasmania (Bond et al., 2021; Lavers, 2014; Lavers et al., 2014, 2021; Lavers & Bond, 2016), the sites identified in this study, such as the Houtman Abrolhos Islands and Perth, could potentially serve as new sampling locations.

Dugongs have a similar distribution and feeding style to green turtles, but there are no peer-reviewed papers on the interaction between dugongs and debris ingestion within Australia. However, data from the Queensland Stranding Database and Queensland Shark Abatement Programs provide evidence that dugongs are regularly entangled in discarded fishing gear and shark nets (Meager, 2016). Other populations of dugong in Thailand and India, have also been observed to have negative interactions as a result of debris ingestion (Fullerton, 2019). In addition, the Florida manatee, also in the order Sirenia, has been documented to have ingested anthropogenic debris as far back as 1978 (Beck & Barros, 1991).

Very few papers have explored the impacts of debris on Australian sea lions (Byard & Machado, 2019; Hamer et al., 2013). It was reported the sea lion entanglement rate was 1.3% in 2002 (Page et al., 2004). With the rate of plastic production increasing to 359 million Mt in 2018, it is likely that this figure has increased in the last two decades (Okoffo et al., 2021). Apart from these three studies the impact of debris on Australian sea lions is poorly understood, despite being an endangered species (EPBC Act 1999; IUCN Red List), with their limited distribution attributed to strong site fidelity. Despite there being a paucity of literature concerning marine mammal interactions with debris within our study site, similar species have recorded observations of negative interactions such as the New Zealand sea lion and Galapagos sea lion (McMahon et al., 1999; Muñoz-Pérez et al., 2023). The lack of information and peer-reviewed research on marine mammal debris interactions could be attributed to limited samples available for necropsies and difficulty in live sampling. However, this dearth of data limits our understanding of the impact of anthropogenic debris on these populations of threatened marine megafauna. Therefore, through calculating the overlap of debris hotspots and species distributions, this study provides direction for future sampling efforts when assessing the impact of debris on Australian sea lion and dugong populations.

This study has identified several spatial variables that are predictive of high debris abundance on Australia coastlines, as well as areas where debris interaction with threatened species is likely. Methods used in this study can be replicated for other localities and datasets, such as the high-resolution imagery research conducted by Moy et al. (2018). This can add value to hotspot assessments by further explaining the drivers of increased debris deposition, providing key information to managers and policy makers, as well as highlighting significant areas where species monitoring/research should be conducted. These findings add further credence to the notion that addressing issues of marine debris pollution requires a multifaceted approach covering all of waste management practices, education and awareness campaigns, policy interventions, and sustainable coastal development initiatives.

AUTHOR CONTRIBUTIONS

Caitlin E. Smith: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; validation; visualization; writing – original draft; writing – review and editing. **Ben L. Gilby:** Conceptualization; formal analysis; investigation; methodology; supervision; validation; visualization; writing – review and editing. **Jason van de Merwe:** Conceptualization; supervision; writing – review and editing. **Jodi Jones:** Data curation; writing – review and editing. **Heidi Tait:** Data curation. **Kathy A. Townsend:** Conceptualization; funding acquisition; project administration; supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the UniSC Research Data Collection at <https://doi.org/10.25907/00837>. Raw data tables provisioned for the modelling of this paper may be made available for the purpose of peer review of the paper and may not be released by any third party for any other purpose. Data provided should not be used to generate reports or other outputs without a data sharing agreement.

ORCID

Caitlin E. Smith  <https://orcid.org/0000-0002-8321-8042>

Ben L. Gilby  <https://orcid.org/0000-0001-8642-9411>

Jason van de Merwe  <https://orcid.org/0000-0002-0838-5780>

Heidi Tait  <https://orcid.org/0000-0001-8444-2567>

Kathy A. Townsend  <https://orcid.org/0000-0002-2581-2158>

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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