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Entrapment in plastic debris endangers hermit crabs

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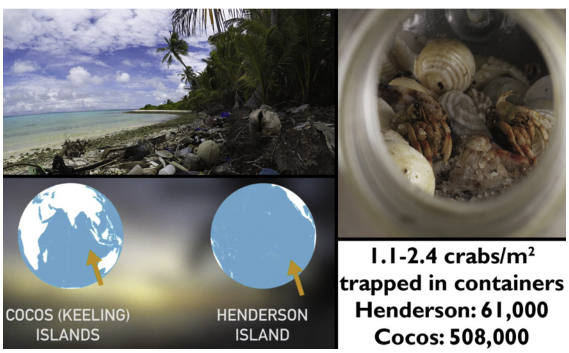
GRAPHICAL ABSTRACT



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ABSTRACT

Significant quantities of plastic debris pollute nearly all the world's ecosystems, where it persists for decades and poses a considerable threat to flora and fauna. Much of the focus has been on the marine environment, with little information on the hazard posed by debris accumulating on beaches and adjacent vegetated areas. Here we investigate the potential for beach debris to disrupt terrestrial species and ecosystems on two remote islands. The significant quantities of debris on the beaches, and throughout the coastal vegetation, create a significant barrier which strawberry hermit crabs (*Coenobita perlatus*) encounter during their daily activities. Around 61,000 (2.447 crabs/m^2) and 508,000 crabs (1.117 crabs/m^2) are estimated to become entrapped in debris and die each year on Henderson Island and the Cocos (Keeling) Islands, respectively. Globally, there is an urgent need to establish a clear link between debris interactions and population persistence, as loss of biodiversity contributes to ecosystem degradation. Our findings show accumulating debris on these islands has the potential to seriously impact hermit crab populations. This is important for countless other islands worldwide where crabs and debris overlap, as crabs play a crucial role in the maintenance of tropical ecosystems.

1. Introduction

Plastics are designed to be light-weight, convenient, and durable; several characteristics that make them suitable packaging alternatives compared to other materials such as wood, glass or metal, but also makes them problematic in marine and terrestrial environments (Hopewell et al., 2009). Low manufacturing costs have contributed to huge demand for new plastic materials, with global production increasing by 6–8 % per annum (UNEP, 2014; Plastics Europe, 2018). Globally, < 10 % of the 348 million tonnes of plastic produced annually

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is ever recycled (Plastics Europe, 2018; Geyer et al., 2017), with approximately 40 % of plastic waste comprised of single-use packaging (PACIA, 2013). The significant increase in disposal rates in the last half century (Geyer et al., 2017), combined with inadequate or ineffective waste management, has led to huge quantities of plastic polluting ecosystems worldwide (Galgani et al., 2015).

Once in the ocean, plastic items can either sink or float, becoming dispersed over long distances via tides and currents (Thiel et al., 2013). Significant quantities of plastic are now recorded in all aquatic ecosystems, accounting for > 95 % of debris items observed at-sea, on beaches, and along river banks (Eriksen et al., 2014; Eerkes-Medrano et al., 2015; Hanvey et al., 2017). These synthetic materials persist for decades in the environment, posing a considerable threat to aquatic flora and fauna (Gall and Thompson, 2015). Mortality of wildlife from plastic debris can occur directly (e.g., entanglement) or indirectly through exposure to plastic-associated toxins, which may contribute to reduced body condition or survival in some species (Lavers et al., 2014; Browne et al., 2013; Martínez-Gómez et al., 2017; McCauley and Bjorndal, 1999).

While evidence of harmful effects on individual organisms is increasing (Gall and Thompson, 2015), there is currently little knowledge or agreement regarding whether plastic debris poses an ecologically relevant threat, affecting wildlife at the population level and contributing to an overall decline in species' abundance (Rochman et al., 2016). Establishing a clear link between debris interactions and population persistence is crucial, as loss of biodiversity contributes to the degradation of ecosystems and the valuable services they provide (Worm et al., 2006; Estes et al., 2011).

While much of the focus of plastic impacts has understandably been on the marine ecosystem, increasing quantities of debris accumulating on beaches and adjacent vegetated areas has the potential to disrupt terrestrial species and ecosystems (Carson et al., 2011; de Souza Machado et al., 2018; Triessnig et al., 2012). In tropical ecosystems, crabs (Malacostraca: Decapoda) play a crucial role in forest growth and development through aeration of soils and creation of carbon-rich soil microhabitats (Lindquist et al., 2009), therefore reductions in crab abundance may impact plant recruitment.

In order to understand the potential impact accumulating plastic may have on coastal crab populations, we recorded the number and frequency of strawberry hermit crabs (*Coenobita perlatus*) entrapped in beach debris on individual beaches within the Cocos (Keeling) Islands (hereafter Cocos) and on Henderson Island, Pitcairn group, two remote areas where significant quantities of debris accumulate (Lavers et al., 2019; Lavers and Bond, 2017). We then estimate entrapment rates across both islands to provide an estimate of population-level impact of plastic beach debris on crab populations.

2. Methodology

2.1. Study sites

Cocos (12°05′S, 96°53′E) comprises two small, mid-oceanic atolls (total land area 14 km^2) located approximately 2760 km north-west of Perth, Western Australia (Fig. 1). The southern atoll consists of a horseshoe chain of 26 islands around a shallow, central lagoon. The northern atoll (North Keeling, administered as Pulu Keeling National Park) is a relatively pristine, uninhabited island. Most of the human population (around 600 people) reside on Home and West Islands. A range of marine resources are fished for food and tourism, including crabs and other crustaceans which are consumed or used for bait (Morgan, 1992; Caton et al., 1998). Henderson Island (24°20′S, 128°19′W, total land area 43 km^2; Fig. 1) is a raised coral atoll and UNESCO World Heritage Site. It is extremely remote, uninhabited, and located on the western boundary of the South Pacific Gyre, a known plastic-accumulation zone (Eriksen et al., 2013). Both Henderson and Cocos are very polluted, with ~38 million (239 items/m^2) and 414 million debris items (713 items/m^2) deposited on beaches and throughout the beach-back vegetation, respectively (Figs. 2 and 3; Lavers et al., 2019; Lavers and Bond, 2017).

2.2. Recording debris in the beach-back

We recorded visible macro-debris located on the surface within randomly-placed quadrats. In the beach-back, significant quantities of debris accumulate amongst the vegetation (Lavers et al., 2019), creating an obvious hazard for crabs (Fig. 2a, c). On Cocos, four quadrats were established on Direction Island and four on West Island from 20 to 29 March 2017, one on Pulu Blan Madar, and two on Home Island, from 1 to 2 September 2019, and 20 quadrats along the East Beach of Henderson Island during 12 to 16 June 2019. The boundary of each quadrat was located along the top edge of the beach and extended into the vegetation towards the centre of the island. On Cocos, the dimensions of each quadrat were 5 × 3 m (2017) or 6 × 4 m (2019), and on Henderson 6 × 6 m, reflecting differences in accessibility at each site. The size was reduced slightly for some quadrats (2/8 on Cocos in 2017 and 2/20 on Henderson) to enable navigation through thick forest and to protect sensitive habitats.

2.3. Entrapment of crabs

The location of the beach-back quadrats and timing of surveys overlapped periods when a range of crab size classes were present on both islands and encompassed a diversity of habitats (e.g., areas dominated by *Heliotropium foertherianum* or *Pemphis acidula*). However, the density of crabs within these habitats was not recorded and no attempt was made to survey across seasons due to the remote nature of each site and limited access.

Within each quadrat, all intact plastic containers (e.g., drink, commercial, and industrial bottles) were recorded. Containers were then assessed for whether they posed a potential entrapment hazard to crabs based on meeting both of these criteria: 1) the lid was missing or the container was damaged such that it allowed crabs access to the inside of the container, and 2) the container was positioned with the opening facing an upward angle, such that a crab would have difficulty exiting and would therefore become entrapped. We then counted the number of crabs (dead or alive) that had become entrapped in each container.

2.4. Statistical methods

We used a Gamma Hurdle Model (Zuur et al., 2009) to estimate crab entrapment rates as the data were zero-inflated (190 of 218 containers on Cocos, 65 of 77 containers in the Henderson beach back and 25 of 33 on East Beach). This was modelled as a two-step process: first, the probability of a non-zero event (i.e., entrapment) was estimated, and then of those non-zero events, the value (i.e., entrapment intensity) was estimated. Multiplying these two values together produces an overall entrapment rate for all quadrats.

Entrapment probability, the first step of the model, was estimated using a binomial generalized linear model with logit-link function. The entrapment intensity, the second step, was estimated using a gamma generalized linear model with log-link function.

We used the density of bottles available to entrap crabs across the eight quadrats on Cocos, 20 quadrats in the beach-back vegetation of Henderson, and four transects along Henderson's East Beach (totalling 1139 m) to extrapolate the total number across the archipelago by resampling the values, with replacement, 10,000 times and scaling this to the area of beach-back vegetation (defined as the length of the vegetation line and extending 10 m inland; Table 1). Beach length and beach-back dimensions were obtained using Google Earth Pro (version 7.3.2) and satellite imagery from 2016 to 2018 for beaches that were ocean-facing. Beaches that faced into the lagoon on Cocos (e.g., away from prevailing currents, sheltered by other islands) or small unnamed

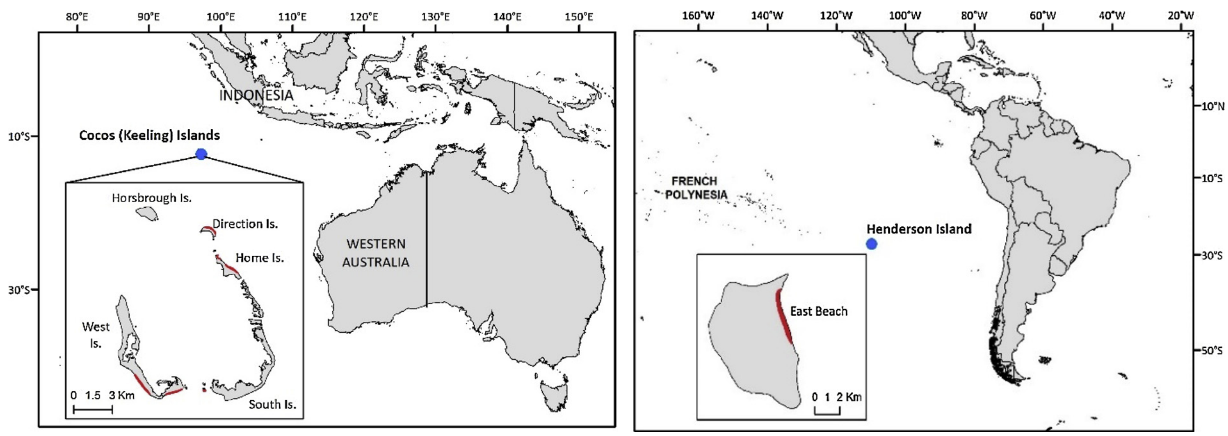

Fig. 1. Map of the study sites (blue circles): Cocos (Keeling) Islands (left; North Keeling not shown on inset map) and Henderson Island (right) with sampling regions shown in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. (A) accumulated plastic debris creates an obstacle for crabs on the beaches of the Cocos (Keeling) Islands. (B) a hermit crab inside a green bucket along the high tide of South Island. (C) accumulated plastic debris in the beach-back vegetation on West Island. (D) crabs that became trapped and died inside a plastic drink bottle that washed up on Cocos.

and potentially ephemeral sand bars were excluded as they do not likely accumulate significant quantities of plastic debris.

The estimated mean number of bottles on each beach was then used to predict the total entrapment using the probability and intensity values (with 95 % confidence intervals) from the two models. Parameter estimates are provided as the mean and SD, and the estimated number of entrapped crabs is presented as the mean and 95 % confidence interval. All analyses were conducted in R 3.6.1 (R Core Team, 2019).

3. Results

On Cocos we recorded 218 bottles that could potentially entrap crabs across eight quadrats. Of these, 190 (87 %) contained no crabs, and the probability of entrapment was 0.128 ± 0.020 (95 % CI: 0.088-0.177). Of bottles that contained crabs, the mean entrapment intensity was 7.857 ± 1.213 crabs/bottle (95 % CI: 5.479–11.837). The overall entrapment rate was therefore 1.009 ± 0.024 crabs/bottle.

The density of plastic bottles in beach back ranged from 0.13 to 3.67 bottles/m^2. Across the 454,720 m^2 of ocean-facing beach back habitat, we estimated there were 562,352 bottles that could potentially entrap crabs, producing an estimate of 507,938 crabs (95 % CI: 363,387–796,037) entrapped in bottles across the archipelago.

In the beach-back vegetation on Henderson Island, we recorded 77 bottles across 20 quadrats covering 690 m^2, of which 65 (84 %) contained no crabs, and the probability of entrapment was 0.156 ± 0.035 (95 % CI: 0.248). There were 106.25 ± 29.95 (95 % CI: 47.55–318.27) individuals in those containers with crabs, resulting in an overall entrapment rate of 16.55 ± 1.06 crabs/bottle.

On East Beach, crabs were found in 8 of 33 bottles (24 %) across 12,762 m^2 of the beach. The probability of entrapment was 0.242 ± 0.063 (95 % CI: 0.119-0.404), and the entrapment intensity was 60.00 ± 16.06 (95 % CI: 28.52–161.17). This resulted in an overall entrapment rate of 14.55 ± 1.01 crabs/bottle.

The density of bottles ranged from 0.083 to 1.103 bottles/m^2 in the beach-back, and was 0.035 bottles/m^2 on East Beach of Henderson Island, resulting in a potential 2046 bottles in 7600 m^2 of beach-back vegetation and 865 bottles on 24,908 m^2 of East Beach where crabs could become entrapped. Combining the entrapment values, we estimate 33,922 crabs (95 % CI: 6700-127,530) entrapped on the beach-back, and 28,003 crabs (95 % CI: 8420-94,979) on the beach, for a total

Fig. 3. (A) a strawberry hermit crab navigates through natural and anthropogenic debris on East Beach, Henderson Island. (B) accumulated debris on East Beach, Henderson Island. (C) 526 hermit crabs trapped inside a single container on Henderson Island in June 2019. (D) some of the 526 hermit crab shells from the container shown in panel (C).

of 60,961 (95 % CI: 23,450-165,180) entrapped crabs on Henderson Island.

4. Discussion

Overall hermit crab entrapment rates were extremely high on both Henderson and Cocos, with nearly 61,000 (2.447 crabs/m^2) and 508,000 crabs (1.117 crabs/m^2) becoming entrapped, respectively. Though overall mortality on Henderson is lower, the beach area is much smaller than that on Cocos, and both the rate and severity of entrapment and mortality is much higher. These estimates are liberal, as the rate of degradation of crab carcasses is unknown, therefore some shells may have been present in the bottles for more than 12 months. Furthermore, our analysis does not account for temporal patterns, such as localised abundance during the breeding season, which could influence entrapment rates, and must be considered as point estimates rather than a temporal rate (e.g., annual mortality). Such rates should be a research priority on sites that are heavily polluted and can be visited regularly.

At a temperature of 28–29 °C and relative air humidity of 75 % (similar to conditions at both field sites), de Wilde (1973) reported average survival of hermit crabs was 5–9 days when the crabs lacked access to water. Thus, once entrapped in plastic containers, mortality of hermit crabs likely occurs over a very brief period, depending on rainfall. Hermit crabs, including *Coenobita perlatus*, use the odour of dead conspecifics to locate available shells, increasing shell-acquisition behaviour by up to 10 times (Small and Thacker, 1994; Valdes and Laidre, 2019; Gherardi and Tricarico, 2011), which are a limiting resource and both live and freshly dead crabs were occasionally observed together inside plastic containers (Fig. 2b, d). This suggests entrapments occur on a regular basis and conspecific attraction, the very mechanism that evolved to ensure hermit crabs could replace their shells, has resulted in a lethal lure. Accumulation of > 20 crabs in containers suggests a threshold, or dose response, may exist whereby the chemical signals of decaying crabs act additively or multiplicatively with 526 crabs observed in a single container (Fig. 3c, d).

The significant entrapment rate has the potential to negatively impact hermit crab populations. While no population size data exist for any hermit crab species on Henderson or Cocos, and estimates of adult or juvenile survival are not available, existing pressure on these crabs is appreciable on Cocos as small crabs are used as bait in recreational and artisanal fishing and there are localised depletions of crabs around populated areas (Hourston, 2010). Concerns have been raised regarding the current recreational fishery bag limit on Cocos, 9 l per day for mixed, small crabs, and a no-take regulation was considered as part of a Parks Australia review of recreational fishing regulations (Hourston, 2010). Information on longevity of crabs is sparse, but suggests Anomuran crabs are long-lived [5–30 years in the wild; Vogt, 2012; Wolcott, 1988]. Entrapment in debris along beaches (Fig. 2a) and in the beach back vegetation (Fig. 2c) therefore presents an additional, significant threat to crab populations which are already under pressure and likely rely on high survivorship of breeding adults to maintain populations. On Henderson, crab populations are likely under predation pressure from introduced Pacific rats (*Rattus exulans*) (Shiels et al., 2014); which can modify coastal ecosystems greatly (Kurle et al., 2008; Bond et al., 2019).

Significant reductions in crab populations have the potential to harm islands in several ways. On Cocos, tourism is a major source of employment, providing substantial economic and social benefits, and receiving widespread community support (Carlsen, 1999). On the main islands of Cocos, seabirds no longer breed (Armstrong, 1992), therefore charismatic species like hermit crabs may provide an important opportunity for tourists to observe native wildlife. For example, on Christmas Island, the diversity and abundance of crabs is a well-known

Table 1
Estimated surface area (m^2) of the plastic accumulation zone (beach length × 10 m) for ocean-facing beaches of 19 islands in the Cocos (Keeling) Islands (excluding small unnamed islets and ephemeral sand bars) and East Beach, Henderson Island, including the mean number of bottles estimated to be present, and mean number of crabs estimated to be entrapped with 95 % confidence intervals (LCL, UCL).

Island	Accumulation zone (m^2)	Mean number of bottles	Crabs entrapped		
			Mean	LCL	UCL
Cocos (Keeling) Islands					
Direction Island	32,370	40,032	36,158	25,868	56,667
East Cay	1080	1336	1206	863	1891
Home Island	28,560	35,320	31,903	22,824	49,997
Horsborough Island	41,590	51,434	46,457	33,236	72,808
North Keeling	57,370	70,949	64,084	45,847	100,432
Pulu Ampang[a]	10,630	13,146	11,874	8495	18,609
Pulu Capelok	14,240	17,611	15,907	11,380	24,929
Pulu Kambing[b]	0	0	0	0	0
Pulu Kembang	3150	3896	3519	2517	5514
Pulu Labu	2300	2844	2569	1838	4026
Pulu Maria	4110	5083	4591	3284	7195
Pulu Bian	3210	3970	3586	2565	5619
Pulu Blan Madar	3200	3957	3575	2557	5602
Pulu Pandan	15,740	19,466	17,582	12,579	27,555
Pulu Siput	6990	8645	7808	5586	12,237
South Island	99,570	123,138	111,223	79,571	174,308
West Island	130,610	161,525	145,896	104,376	228,647
Total (Cocos)	**454,720**	**562,352**	**507,938**	**363,387**	**796,037**
Henderson Island					
East Beach	24,908	2046	33,922	6700	127,530
Beach-back	7600	865	28,003	8420	97,979
Total (Henderson)	**32,508**	**2911**	**61,925**	**15,120**	**225,509**

[a] Cluster of 3 islands.
[b] Located inside the lagoon and sheltered by West Island; no beaches are ocean-facing.

tourist attraction (Misso and West, 2014). Cocos and Henderson Island lack native ground predators, therefore crabs play a critical role in seed dispersal, removing detritus, and provide a range of benefits, such as soil turbation through burrow excavation and collection of leaf litter (Lindquist et al., 2009; Lucrezi and Schlacher, 2014). Entrapment and mortality of large numbers of crabs could therefore affect ecosystem function of coastal areas, which would have consequences for other biota as well as for tourism.

The accumulation of plastic debris alters water movement and heat transfer through beach sediments (Carson et al., 2011). Accumulated debris can also create a physical barrier, reducing the accessibility of beaches for breeding and hatchling sea turtles (Aguilera et al., 2018; Fujisaki and Lamont, 2016). Limited information is available for other species, especially invertebrates, however the presence of beach debris smothers benthic communities resulting in fewer polychaete worms (Uneputty and Evans, 1997) and reduces the number of burrows constructed by crabs (Widmer and Hennemann, 2010). Significant annual losses of crabs could lead to reduced breeding, and consequently lower recruitment. The larval duration and transport distance of most small decapods, including hermit crabs, is relatively short with populations maintained through a combination of allochthonous and autochthonous recruitment (Rodriguez and Jones, 1993). However, with the increasing isolation of an island, it becomes difficult for shallow water species to traverse the open ocean and establish a viable population [i.e., the Island Biogeography Concept; MacArthur and Wilson, 2001], and crab species richness on Cocos and Henderson is markedly lower than other island and mainland populations in the region (Berry and Wells, 2000; Cuthbert et al., 2012; Poupin, 1996). Similarly, Henderson's remoteness would significantly impede successful larval dispersal to the island. Successful recruitment of crabs therefore relies on considerable new individuals being released into the environment. Depleted populations, or those located on smaller, isolated islands therefore have less resilience to acute stressors than mainland ones, since they do not have the diversity of habitats to act as refuge for populations of species under pressure.

5. Conclusions

The increasing urbanization and pollution of much of the world's coasts with plastic debris threatens increasing and irreversible damages to beach ecosystems (Galgani et al., 2015; Nordstrom, 2000). Over the last three decades, plastic drink bottles have shown the fastest growth rate of all debris types reported on some remote islands (Ryan et al., 2019). When such widespread changes are overlaid with the broad distribution of hermit crabs throughout the subtropics and tropics (Poore, 2007), it becomes clear the negative interactions between crabs and debris are set to increase. This is of particular concern in areas of high hermit crab abundance, diversity, and endemism (Reay and Haig, 1990).

The mortality of hermit crabs attributed to beach debris, documented here for the first time, is significant, and likely a key factor contributing to the reported declines in hermit crabs on Cocos. Unfortunately, Cocos and Henderson are not unique, with similarly high concentrations of debris reported on beaches and in coastal vegetation worldwide (Serra-Gonçalves et al., 2019). Other beaches with high debris load and hermit crabs may well experience similar mortality. The global mortality of hermit crabs is undocumented, likely to be substantial, and requires urgent investigation.

Author contributions

All authors collected data, ALB analysed data, JLL wrote the first draft, all authors commented on the manuscript.

Declaration of Competing Interest

JLL: none.

PBS: PBS is an employee of Two Hands Project. Two Hands Project provided support in the form of a salary for PBS, but did not have any other role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

SS: SS is an employee of Two Hands Project. Two Hands Project provided support in the form of a salary for SS, but did not have any other role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

ALB: none.

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