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Plastic debris increases circadian temperature extremes in beach sediments

Jennifer L. Lavers[a,*], Jack Rivers-Auty[b], Alexander L. Bond[c]

[a] Institute for Marine and Antarctic Studies, University of Tasmania, Battery Point, TAS 7004, Australia
[b] Tasmanian School of Medicine, University of Tasmania, Hobart, TAS 7000, Australia
[c] Bird Group, Department of Life Sciences, The Natural History Museum, Tring, Hertfordshire HP23 6AP, United Kingdom

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ABSTRACT

Plastic pollution is the focus of substantial scientific and public interest, leading many to believe the issue is well documented and managed, with effective mitigation in place. However, many aspects are poorly understood, including fundamental questions relating to the scope and severity of impacts (e.g., demographic consequences at the population level). Plastics accumulate in significant quantities on beaches globally, yet the consequences for these terrestrial environments are largely unknown. Using real world, in situ measurements of circadian thermal fluctuations of beach sediment on Henderson Island and Cocos (Keeling) Islands, we demonstrate that plastics increase circadian temperature extremes. Particular plastic levels were associated with increases in daily maximum temperatures of 2.45 °C and decreases of daily minimum by − 1.50 °C at 5 cm depth below the accumulated plastic. Mass of surface plastic was high on both islands (Henderson: 571 ± 197 g/m^2; Cocos: 3164 ± 1989 g/m^2), but did not affect thermal conductivity, specific heat capacity, thermal diffusivity, or moisture content of beach sediments. Therefore, we suggest plastic effects sediment temperatures by altering thermal inputs and outputs (e.g., infrared radiation absorption). The resulting circadian temperature fluctuations have potentially significant implications for terrestrial ectotherms, many of which have narrow thermal tolerance limits and are functionally important in beach habitats.

1. Introduction

The last few decades have seen a surge in public interest and media coverage of the problems of climate change and plastic pollution. While our understanding of the threat of climate change as a broad ecological problem is built on a large foundation of research, our understanding of the effects of plastic pollution remains relatively narrow. Research into pollution of the environment with plastics has largely focused on documenting the presence or distribution of plastics in certain species and particular locations (Gall and Thompson, 2015; Lavers and Bond, 2017). There is an urgent need to understand the effects of plastic pollution through the broader environmental lens.

There have been several calls to address some of the grand challenges in plastics research, including our lack of understanding of the broad implications of plastics at the population-level (Rochman et al., 2016; Vegter et al., 2014). However, progress has been slow, in part because these are difficult questions. Plastic pollution is also a rapidly evolving research field, and as our understanding of this complex issue grows, new and ever-more difficult or important questions arise (Provencher et al., 2020). Limitations in our understanding of plastic pollution have also contributed to recent debate regarding the importance of plastics as an environmental issue (Avery-Gomm et al., 2019; Cunningham et al., 2020; Stafford and Jones, 2019). For example, while plastic pollution has already exceeded the irreversibility and global ubiquity thresholds, two of the essential criteria of a planetary boundary threat (safe operating limits for humanity), Villarrubia-Gómez et al. (2018) identify the Earth system consequences of plastic pollution as ‘uncertain’ and a recent assessment of global risks including natural disasters and climate change mitigation did not rank pollution of any kind in the top five (WEF, 2019). Plastic pollution has been labeled a ‘convenient distraction’ (Stafford and Jones, 2019) with risks sometimes overstated by the media (Völker et al., 2019). While some of this active discussion has been rebutted (Avery-Gomm et al., 2019), it has also contributed to an inflated sense of progress in our scientific understanding of plastics (Vegter et al., 2014). Unlike other globally pervasive pollutants, such as mercury, we lack effective, broad-scale mitigation and policy tools (Borrelle et al., 2017; Kessler, 2013), and our understanding of plastics’ harmful effects lags significantly behind that for other environmental contaminants (Kidd et al., 2012; Selin, 2009).

The consequences of plastic debris on the physical properties of

* Corresponding author.
E-mail address: Jennifer.Lavers@utas.edu.au (J.L. Lavers).

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terrestrial and marine environments are also poorly documented. Only a handful of studies have investigated this issue, indicating accumulated debris can alter the permeability and microbial assemblage of beach sediments (Carson et al., 2011; Lin et al., 2020; Seeley et al., 2020). Increasing debris inputs into the ocean (Jambeck et al., 2015) will therefore have important implications for ecological processes (e.g., nutrient cycling) as beaches represent a major sink for marine debris (Olivelli et al., 2020). The consequences will likely include changes in the abundance or behavior of vulnerable species, many of whom have temperature-dependent sex determination (Valenzuela, 2004). Accumulating plastics on beaches may directly impact species through ingestion of debris (Horn et al., 2019; Xu et al., 2020) and indirectly through subsequent contamination, as sediments artificially contaminated with plastic-associated chemicals (e.g., plasticizers) can leach into soil-dwelling organisms (Hu et al., 2005; Neuhauser et al., 1986). However, our knowledge of these complex, beach ecosystems is largely based on lab-based simulations (Carson et al., 2011; Lin et al., 2020; Seeley et al., 2020), which often have limited application to real world scenarios (Rochman, 2016).

Offshore islands provide a useful setting in which to generate essential data on plastic impacts on sediments. Islands are often home to unique or vulnerable species and include areas where debris can accumulate. Being distant from metropolitan centers, remote islands also provide an opportunity to collect plastics data that is free from human interference (e.g., no debris removal via beach clean-ups). Two remote islands, Henderson Island in the South Pacific and the Cocos (Keeling) Islands in the Indian Ocean, have recently been the focus of debris research due to having ~ 38 million and 414 million debris items deposited on their beaches, respectively (Lavers and Bond, 2017; Lavers et al., 2019). Here we use real world data to provide the first data showcasing how plastic pollution increases circadian temperature extremes of beach sediments, with moderate plastic pollution increasing the daily temperature maximum by 2.45 °C and decreasing the daily minimum temperature by 1.50 °C of the sediment below. This could have critical implication for biodiverse and environmentally important coastal regions where wildlife and plastics frequently overlap.

2. Materials and methods

2.1. Study sites

The Cocos (Keeling) Islands (hereafter Cocos; 12°05'S, 96°53'E)

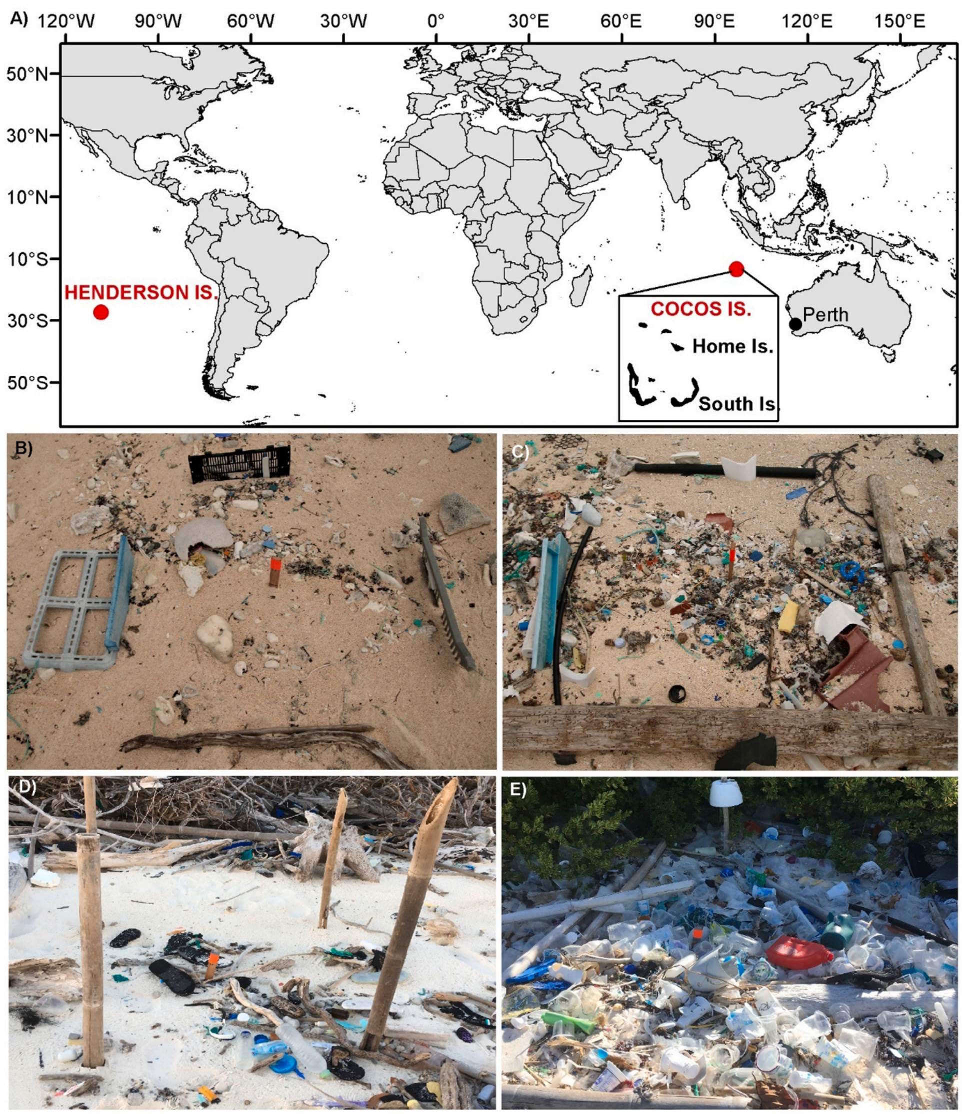

Fig. 1. Examples of low (panels B, D) and high density debris quadrats (panels C, E) on Henderson Island (middle row) and Cocos (Keeling) Islands (bottom row). Each wooden stake (with orange tape along the top edge) has two Thermochron iButtons attached (not visible) which are buried below the sediment at 5 and 30 cm depth. The iButtons recorded temperature every 30 min.

comprise two small, mid-oceanic atolls (total land area 14 km^2) located 2750 km northwest of Perth, Western Australia (Fig. 1). The southern atoll consists of a horse-shoe chain of 26 islands around a shallow, central lagoon. The human population (~ 600 people) resides on Home and West Islands. Henderson Island (24°20′S, 128°19′W, total land area 43 km^2) is a raised coral atoll and UNESCO World Heritage Site in the Pitcairn Islands, 5200 km northeast of New Zealand (Fig. 1). 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). On Henderson Island, five 1 m^2 quadrats were established along East Beach from 10 to 20 June 2019. On Cocos, two 1 m^2 quadrats were established on South Island and three on Home Island from 31 August to 10 October 2019 (Fig. 1). The center of each quadrat was located along the extreme high water mark, typically within 5–6 m of the mean high water line. It was not possible to establish a control quadrat (zero debris) as debris was ubiquitous on the surface of all beaches surveyed on Henderson Island and Cocos. We used 1 m^2 quadrats as this is a standard measure and it ensured the data collected was manageable given the remote location and limited access.

2.2. Sediment properties on Henderson Island

On Henderson Island, we recorded thermal conductivity (W/m × K), specific heat capacity (J/K), and thermal diffusivity (mm^2/S) using a Decagon KD2 Pro Thermal Properties Analyzer (Meter Environment, Pullman, Washington, USA) and percent moisture using a HH2 Moisture Meter (Delta-T Devices, Cambridge, UK). Daily measurements were recorded between 1300 and 1500 (UTC-8) from 10 to 20 June 2019 at 5 cm depth following a clockwise grid located 50 cm from the center of each quadrat.

2.3. iButton deployment

Thermochron iButtons (model DS1921G-F5; Thermochron, Baulkham Hills, New South Wales, Australia) were programmed to record temperature every 30 min and two were attached to each of five custom wooden stakes using cable ties. Each stake was then inserted into the beach sediment at the center of the quadrats so that the iButtons were buried at a depth of 5 and 30 cm on both Henderson and Cocos (Fig. 1).

2.4. Recording debris

We recorded visible debris located on the beach surface only within the quadrats on the final day of sampling at each location. All debris items located on the surface of the quadrats were removed using a 1 mm sieve. Due to time and logistical constraints, debris items buried below the surface were not recorded. Items were counted, weighed to the nearest 1 g using a spring balance, and sorted into standard categories following Provencher et al. (2017).

2.5. Statistical methods

Data was analyzed using R 3.6.1 (R Core Team, 2020). To account for the autocorrelative nature of circadian data, general additive mixed models (GAMM) were employed to investigate the relationship between temperature and plastic. Day and quadrant ID were treated as random factors. Data from the two depths (5 and 30 cm) were analyzed separately to allow for different temperature, plastic and time relationships in the GAMM analysis. Generalized cross-validation was used to set the number of knots (k = 8 for splines; Wood, 2017). Temperature was adjusted for island location using mixed linear modeling (MLM) using the lmr4 package (Bates et al., 2015) with day and quadrant ID treated as random factors, prior to GAMM analysis. Data are shown as ΔTemperature (°C) defined as the difference in temperature from predicted based on depth and island location alone. Thus, ΔTemperature is the modeled adjusted temperature difference induced by the plastic-debris and time-of-day variables. Models were fit using a restricted maximum likelihood methods. The full statistical analyzes of the GAMM models and associate plots are provided in the Supplementary material. The relationship between sediment physical properties (thermal conductivity, specific heat capacity, thermal diffusivity, and percent moisture) and plastic mass on Henderson was analyzed using MLM with sampling day and quadrat ID as random factors to account for repeated measurements (Bates et al., 2015).

3. Results

Summaries of physical properties data and plastic abundance are presented in Table 1. The mass and density of surface plastic debris were 571 ± 197 g/m^2 (range: 329–871 g/m^2) and 1436 ± 685 items/m^2 (range: 814–2393 items/m^2) on Henderson and 3164 ± 1989 g/m^2 (range: 660–5500 g/m^2) and 2108 ± 2720 items/m^2 (range: 57–6248 items/m^2) on Cocos (Table 1).

After adjusting for island as a nuisance variable, the GAMM model of the data from 5 cm sediment depth revealed that plastic mass did not have a significant main effect on temperature ($F = 0.061$, edf = 1, $p = 0.805$) but did have a very significant effect on the relationship between time and temperature ($F = 47.76$, edf = 21.8, $p < 0.001$). This indicates that plastic mass did not increase or decrease the average temperate of the sediment, rather significantly influenced the circadian (naturally occurring 24-hour) fluctuations in temperature. Moderate amounts of plastics increased the maximum temperatures and decreased the minimum temperatures of the sediments substantially at 5 cm depth during the 24 h cycle (Fig. 2A, C & E). With greater mass of plastics, this effect abates potentially due to shading and insulating effects (Fig. 2A, C & E). At 30 cm sediment depth, the effects of plastic mass on the mean temperature or the circadian temperature cycle were not significant ($F = 0.696$, edf = 1, $p = 0.404$; $F = 0.004$, edf = 1, $p = 0.949$, respectively; Fig. 2B, D & F).

Plastic mass on Henderson Island was not related significantly to thermal conductivity ($t = -0.49$, $p = 0.63$), specific heat capacity ($t = 0.56$, $p = 0.61$), thermal diffusivity ($t = -0.57$, $p = 0.60$), or percent moisture ($t = 0.56$, $p = 0.61$).

4. Discussion

Much of the debris that accumulates in our oceans eventually makes its way onto beaches. This is a global challenge, but especially so for remote islands and regions where it is difficult to remove accumulated debris (Lavers and Bond, 2017; Ryan et al., 2019). Understanding current rates of accumulation and consequences for ecosystems and species is therefore crucial as plastic production and pollution of the marine environment is predicted to increase into the future (Borrelle et al., 2020). On both Henderson and Cocos, significant changes in debris accumulation were noted during subsequent surveys (Nichols et al.,

Table 1
Summary statistics of physical sediment properties and plastic abundance from five 1 × 1 m quadrats each on Henderson Island and the Cocos (Keeling) Islands.

Variables	Mean	SD	Range	N
Thermal conductivity (W/m × K)	0.35	0.03	0.26–0.42	45
Specific heat capacity (J/K)	1.25	0.08	1.06–1.48	45
Thermal diffusivity (mm^2/S)	0.28	0.02	0.24–0.32	45
Moisture (%)	10.78	1.64	6.80–14.40	45
Temperature (°C)	18.3	3.0	7.0–29.0	
Henderson				10,699
Cocos	33.2	3.4	22.0–57.0	20,480
Plastic mass (g/m^2)	571	197	329–871	
Henderson				5
Cocos	3164	1989	660–5500	5
Plastic count (items/m^2)				
Henderson	1436	685	814–2393	5
Cocos	2108	2720	57–6248	5

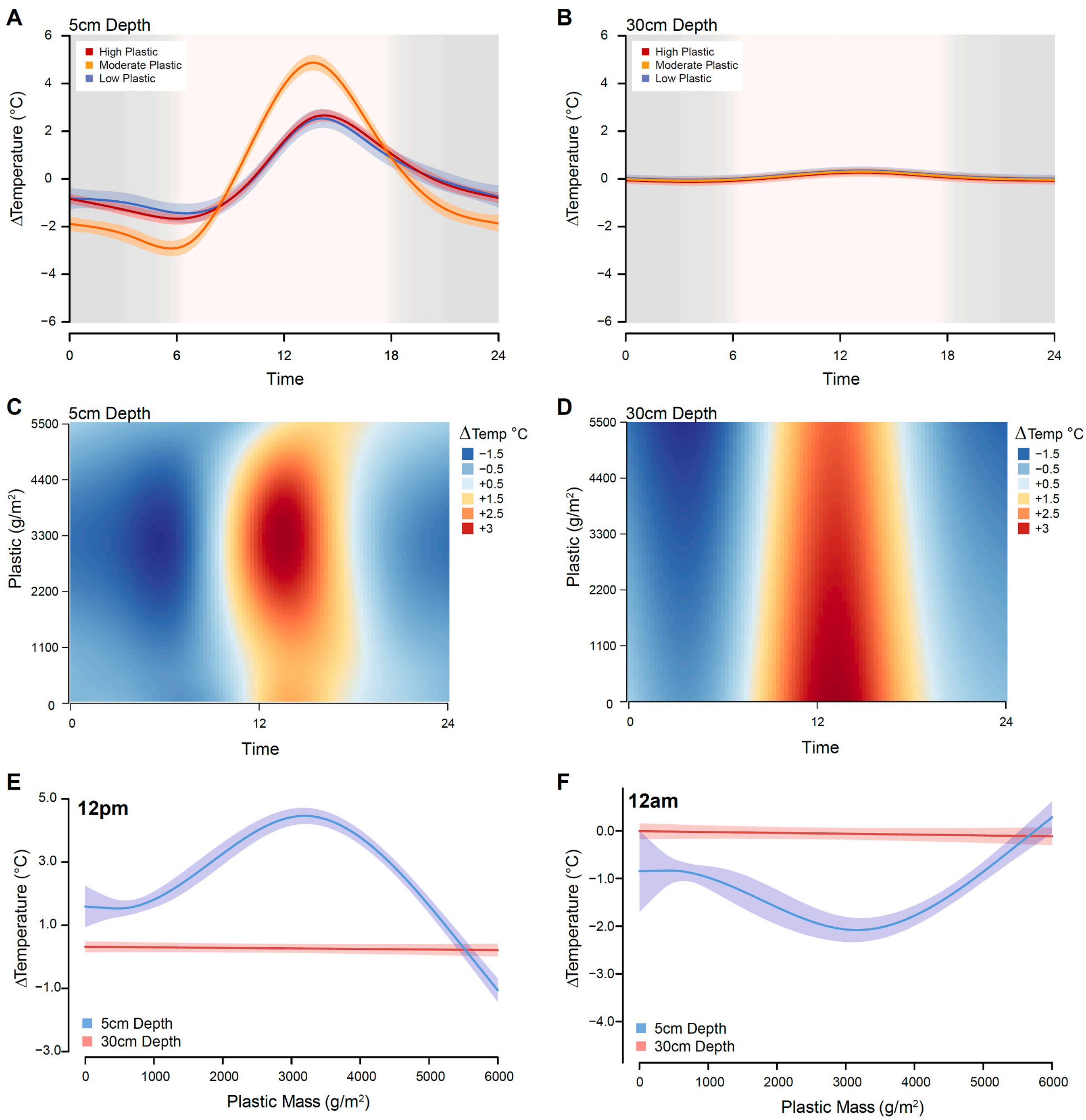

Fig. 2. Moderate plastic debris greatly increased circadian temperature fluctuations of beach sediment at 5 cm depth. (A & B) Adjusted temperature difference (ΔTemperature °C) over the course of a 24 h period. Moderate plastic (2500 g/m^2, orange) increased daily temperature maximums and decreased temperature minimums at 5 cm sediment depth (A) but not at 30 cm depth (B). High plastic (5500 g/m^2, red) and low plastic (350 g/m^2, blue) debris severity did not meaningfully affect the circadian temperature profile at 5 cm or 30 cm sediment depth. (C & D) Heatmaps showing the full relationship between adjusted temperature difference (ΔTemperature °C), time of day and plastic debris severity (g/m^2) at 5 cm (C) and 30 cm (D) beach sediment depth. (E & F) The effects of plastic debris severity (g/m^2) on adjusted temperature difference (ΔTemperature °C) at 12 pm (E) and 12 am. (F) Reported relationships are predicted values with 95% confidence intervals derived from general additive mixed modelling of 10 plots, across two islands, probed for circadian temperature fluctuations over periods of 10–42 days. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

2021). At the North Cove site on Cocos, for example, debris counts and mass had increased substantially over this short timeframe (2017: 55.67 items/m^2, 75.55 g/m^2; 2019: up to 6248 items/m^2, 5500 g/m^2; Table 1) (Lavers et al., 2019). The source of this influx of debris is not known, but the implications for ecosystem integrity, resilience, and value, including sediment properties and even tourism are a significant concern (Hayati et al., 2020).

Beach sediment temperature circadian extremes were influenced by the presence of plastic, particularly at 5 cm depth and at moderate plastic densities (Fig. 2a). The only prior studies of sediment properties and plastics incorporated debris items directly into sediments (i.e., at depth), finding plastics may cause sediments to warm more slowly and reach lower maximum temperatures (Carson et al., 2011; de Souza Machado et al., 2018). These lab-based studies concluded the observed changes in sediment conditions were largely due to increased permeability and reduced bulk density as plastic fragments increased the mean grain size (Carson et al., 2011; de Souza Machado et al., 2018). In our study, plastic mass did not significantly alter the thermal properties of the sediment itself, including thermal conductivity, specific heat capacity, thermal diffusivity, or percent moisture on Henderson Island (Fig. S1) indicating the thermal properties of the sediment below the plastic pollution are not substantially altered under these conditions. This suggests that plastic mass influences the relationship between thermal inputs and outputs, such as infrared radiation absorption and air flow (convection), rather than the thermal properties of the sediment itself. In particular, moderate plastic densities may be increasing the infrared absorption and decreasing heat loss through convection and this results in the increase of 2.45 °C of the daily maximum temperature (Fig. 2A). While larger quantities of plastics ($\geq$ 4400 g/m^2) may cause sediments to warm more slowly during the day (Fig. 2C, E) and cool more slowly at night (Fig. 2C, F) due to the plastics creating an insulating effect. Ultimately, the mechanisms by which plastic alters sediment temperatures is unknown as few data exist and further research is required. The exacerbation of circadian temperature extremes that we observed at low (~ 350 g/m^2) and moderate plastic densities (~ 2500 g/m^2), where accumulated surface plastics dramatically raised the daily maximum temperature of the sediment immediately below (Fig. 2A, E), are likely widespread as similar densities are reported on beaches worldwide (Bouwman et al., 2016; Ribic et al., 2012).

Significant temperature changes due to the presence of surface plastics were not recorded at 30 cm depth (Fig. 2B, D), suggesting the effects of accumulated plastics on thermal inputs and outputs of the sediment surface are negligible in deeper sediments. This corresponds with our results indicating conductivity is unlikely to be the mechanism altering sediment properties, instead, heat transfer from the surface likely occurs via infrared radiation and reduced convection. In addition, recent data from Henderson and Cocos suggest plastics buried at 10 cm depth account for 68–93% of beach debris (Lavers and Bond, 2017; Lavers et al., 2019). An unknown factor is the potential changes in other sediment properties we did not measure, such as permeability and water capacity (Carson et al., 2011; de Souza Machado et al., 2018), where buried debris items could potentially buffer the subsurface environment against increasing temperatures.

Temperature is one of the main abiotic factors influencing living things. While many species can tolerate a moderate increase in temperature, a recent assessment of > 530 aquatic and terrestrial species predicts around 40% will experience local extinctions when maximum temperatures increase by more than 0.5 °C (Román-Palacios and Wiens, 2020). For species that occupy intertidal habitats, range shifts due to a warming environment are already happening (Sagarin et al., 1999). For example, 29 shoreline invertebrates, including barnacles and gastropods, shifted an average of 29 km per decade in response to a warming rate of only 0.2 °C per decade (Pitt et al., 2010). Sea turtles are often the focus of studies investigating the consequences of alteration to beach habitats. For example, loggerhead turtles (*Caretta caretta*) in Florida shifted their nesting northward over a 20-year period, due in part to warming temperatures (Reece et al., 2013). Recent evidence also indicates warming sediments due to climate change are contributing to female-biased turtle populations (Jensen et al., 2018; Tanabe et al., 2020). While removal of large debris items from beaches can increase sea turtle nesting success by 24–38% (Fujisaki and Lamont, 2016), the specific mechanisms influencing egg or hatchling success remain unknown. To our knowledge, no study has investigated the consequences of sediment temperature due to the accumulation of plastic debris on sea turtles. Addressing this question is a priority for turtles, and myriad other coastal species, as feminization of sea turtle hatchlings or breeding failure can occur when temperatures rise by as little as 2 °C (Yntema and Mrosovsky, 1982). It is unclear what impact sediment temperature change due to plastics may have on turtles nesting on Henderson and Cocos (Brooke, 1995; Whiting et al., 2014), as the warming was largely confined to the beach surface (Fig. 2A). However, plastic accumulation is likely to influence the diversity and abundance of crabs and other meiofauna, either through altering the temperature of beaches as described here, or through shading and smothering of sediments (e.g., Fig. 1E; Uneputty and Evans, 1997). Overall, the temperature changes we observed on Cocos and Henderson were significant, with a mean daily maximum temperature increase of 2.45 °C of the beach sediment due to accumulated surface plastics. The consequences of a > 1 °C change in beach sediment temperatures due to widespread accumulation of plastics are unknown, but likely to be significant. Based on future climate scenarios developed by Román-Palacios and Wiens (2020), when temperatures increase by more than 2.8 °C, the number of aquatic and terrestrial species predicted to experience local extinctions will rise to nearly 95%. Of these species, terrestrial ectotherms found close to the Equator (e.g., crabs and other coastal invertebrates) are the most vulnerable as they have relatively narrow thermal safety margins (Deutsch et al., 2008; Trisos et al., 2020).

5. Conclusions

Sandy beaches have largely been overlooked in studies of the ecological, socioeconomic, and environmental impacts of human activities, particularly in relation to climate change (Dugan et al., 2010). For example, of the > 3800 papers included in a recent review of sandy beach science, only 6% considered warming temperatures and so few studies focused on pollution that it was reported as "never a major research thrust" (Nel et al., 2014). Yet, coastal habitats are clearly under increasing pressure. Rather than address pressures in isolation, a concurrent and aligned approach is needed (Avery-Gomm et al., 2019) given the roles of both global heating and plastic contamination of sediments in pushing species out of their thermal envelopes.

So, what might a future with plastics, and climate change, look like for the world's beaches? At present, global plastic production doubles approximately every decade with around 12,000 million metric tons (Mt) estimated to be discarded in landfills or the natural environment by 2050 (Geyer et al., 2017). Much of this (up to 12.7 Mt/yr) makes its way into the ocean (Jambeck et al., 2015), with islands acting as 'sinks' for significant volumes of debris (Lavers and Bond, 2017; Olivelli et al., 2020; Ryan et al., 2019). In light of these inputs, beaches worldwide that currently exemplify the low and moderate debris loads we observed on Henderson and Cocos are likely to transition to high debris over the next few decades. With this change in debris load will be a concurrent shift in sediment temperature (e.g., from low to moderate is ~ 2.4 °C; Fig. 2 A), with temperature-related effects magnified by the median rate of warming on land due to climate change (0.24 °C/decade) (Burrows et al., 2011). Accumulating debris will also contribute to increased rates of entanglement, entrapment and contamination (Lavers et al., 2020), and an overall decline in the suitability of beaches for biodiversity through exposure to chemicals, microbes, and invasive species (Kirstein et al., 2016; Lo Brutto et al., 2021; Rech et al., 2016). While further study into the physical impacts of plastics on ecosystems is undoubtedly needed to understand the severity and scope of these issues, significant shifts in how we produce and manage plastic waste is also urgently required (Borrelle et al., 2020). Between 4% and 8% of fossil fuels extracted are used in the production of plastics (Hopewell et al., 2009), and these extractive industries are heavily subsidized, totaling 6.5% of global gross domestic product, or $5.3 trillion (2015 USD; Coady et al., 2017), meaning the annual subsidy to the initial step of plastic production is ca. $200–400 billion (2015 USD), with further subsidies from downstream production and manufacturing. The reduction of these subsidies would be beneficial to human health (Linou et al., 2018), the global climate (Johnsson et al., 2019), and concurrently reduce the volume of plastics produced (Borrelle et al., 2017), though additional actions, policies, and pressures would be needed (Jewell et al., 2018).

CRediT authorship contribution statement

Jennifer L Lavers: Conceptualization, Investigation, Methodology, Resources, Writing – original draft. **Jack Rivers-Auty:** Formal analysis, Visualization, Writing - Review & Editing. **Alexander L Bond:**

Investigation, Methodology, Formal analysis, Writing – original draft.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2021.126140.

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