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Seasonal Monitoring of Circadian Temperatures in Beach Sediments Affected by Plastic Pollution in Northeast Scotland by a not-for-Profit Coastal Partnership

Lauren E. Smith[1]✉ | David. R. Green[2]

1. East Grampian Coastal Partnership, Aberdeenshire Council, Woodhill House, Westburn Road, Aberdeen, AB16 5GB. Scotland, United Kingdom.
2. Aberdeen Institute for Coastal Science and Management (AICSM), Department of Geography and Environment, School of Geosciences, University of Aberdeen, AB24 3UF. Scotland, United Kingdom.

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ABSTRACT

Plastic pollution is an environmental hazard. Data collected by researchers and community science organisations predominantly focuses on the presence, volume and distribution of plastics in specific species and locations. However, little attention has been paid to the effects of plastic debris on the physical properties of the environment in which it exists. In this study, we recorded in-situ, seasonal, circadian temperature fluctuations of beach sediments affected by plastic pollution at three different locations within Northeast Scotland. Results suggest that specific quantities (medium >260 - ≤2400g/m2 and high>2400g/m2 loading) of plastics increase circadian temperature extremes at a 5cm sediment depth throughout the seasons, with a daily maximum average increase of 1.5°C (medium plastic loading) 1.7 °C (high plastic loading) and a daily minimum decrease average of 1.1°C (medium plastic loading) and 1.3°C (high plastic loading) respectively. These temperature fluctuations may pose significant challenges for terrestrial ectotherms occupying these habitats with narrow thermal safety margins.

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INTRODUCTION

The presence of plastics in the marine environment has been documented for more than fifty years (Napper & Thompson, 2020; Carpenter, 2022 and Rangel-Buitrago et al., 2023). Mass production, particularly of single-use plastics, combined with poor waste management have resulted in plastics being major components of waste. Substantial quantities are now accumulating in the environment (Napper & Thompson, 2020), and plastic waste is now regarded as a key geological indicator of the Anthropocene (Jacquin et al., 2024). Consequently, there has been a considerable increase in scientific research, media coverage and public interest in the negative impacts of plastics. However, the majority of research into the pollution of the environment with plastics has focused on documenting the presence or spatial distribution of plastics in certain species and particular locations (Gall & Thompson, 2015, Lavers & Bond, 2017) and few studies have examined the effects of plastic pollution in a broader ecological context with only a handful investigating the consequences of plastic debris on the physical properties of the environment they are found in. A recent study by Lavers et al. (2021) was the

*Corresponding Author Email: *lauren.smith@egcp.org.uk*

first to show how plastic pollution increases circadian temperature extremes of beach sediments on remote offshore Islands in the Southern Hemisphere. As far as we are aware, no similar studies have yet been undertaken in the Northern Hemisphere.

Temperature is one of the main abiotic factors influencing living things. Fluctuating temperatures affect many aspects of species life history, including metabolism, growth, maturation of reproductive organs, reproduction and moulting (Upadhyay, 2020). While many species can tolerate a moderate increase in temperature, a recent assessment of > 530 aquatic and terrestrial species predicted that around 40% will experience local extinctions when maximum temperatures increase by more than 0.5°C (Roman-Palacios & Weins, 2020). For ectothermic species that occupy intertidal habitats, including macrofauna such as gastropods and crustaceans, which rely on external heat sources to regulate their body temperature, changes in environmental temperature are particularly significant. Alterations in behavioural thermoregulation, such as increased time spent in burrows have been observed in crustaceans exposed to a surface temperature increase of just 1°C. Increased time in burrows allowed thermoregulation to take place. However, this then resulted in a fitness trade-off impacting reproduction (Hews et al., 2021). A decrease in temperature also affects ectotherms, with amphipods known to exhibit changes in burrowing behaviour and physiological responses (an increase in the production of hemocyanin concentrations, associated with an increase in stress) (Lynn et al., 2023). Localised range shifts of species due to a warming environment have already been documented (Mieszkowska et al., 2020). On a broader scale, there are also potential impacts from invasive species associated with changing coastal temperatures. Studies have shown that the shore crab *Carcinus maenus* (an important ectothermic marine species which occupies the high water level down to the sublittoral) found around the Scottish coastline could be out-competed by the invasive brush-clawed shore crab *Hemigrapsus takanoi* if it extends its range (*H. takanoi* was first recorded in the UK in 2015 (Wood et al., 2015)), which has a higher thermal performance and plasticity than the native species which is already inhabiting areas close to its upper thermal limits across parts of its range (Theurich et al., 2022, Rato et al., 2024). Although most of the faunal research on sandy beaches has concentrated on macrofauna (>1mm), meiofauna (1mm to 38µm) studies have shown that the abundance, biodiversity, community composition and functional diversity were affected by fluctuating temperature (Vafeiadou, 2018). Thus, localised temperature changes, because of accumulated plastic debris, in conjunction with the longer-term effects of climate change, could have critical implications for biodiversity and environmentally important coastal regions in Northeast Scotland and globally, where wildlife and plastics frequently overlap.

The East Grampian Coastal Partnership (EGCP) is a not-for-profit company representing individuals and organisations who have an interest in maintaining and improving the sustainability and wellbeing of the Grampian coast between Fraserburgh and St Cyrus. A central focus of EGCP is the Turning the Plastic Tide (TTPT) beach litter project which began in 2018 to raise awareness of, and take action to combat, the harmful impacts of marine litter. This study, therefore, provided a unique opportunity for an environmental organisation to further the science of our existing beach litter project whilst contributing to the existing body of research.

MATERIALS & METHODS

The aim was to investigate the seasonal effects of plastic pollution on beach sediment temperature using dataloggers during winter, spring, summer, and autumn seasons in three separate locations.

Twelve 1m^2 quadrats were positioned within 5m of the mean high-water mark along the Aberdeenshire coastline at Whinnyfold, Craigewan and Cairnbulg (Figure 1). Whinnyfold is part of a stretch of coastline that is designated a Site of Special Scientific Interest (SSSI) due to the nationally important colonies of cliff-nesting seabirds. Craigewan and Cairnbulg are part of an expansive dune system, and this important assemblage supports a variety of species, some of which are of high conservation concern (Dargie, 2001). The ecology of these sites is typical for the Northeast of Scotland and is representative of other regions around the Scottish coastline. These locations were specifically chosen as they had surface litter levels, consisting predominantly of plastic in relatively undisturbed areas with low footfall. Thus, the risk of the quadrats being disturbed, or the litter being removed was minimal. The distribution of the surface litter on these beaches varied at different points due to factors such as prevailing currents and wind direction, thus allowing quadrats to be sited in specific sandy beach areas with no visible debris, and low, medium and high plastic debris.

Quadrat one acted as a control with no visible surface debris, whilst the others were situated in areas of low, medium, and high marine plastic density (Figures 2 and 3). In the centre of each quadrat, dataloggers (ibutton Thermochron DS1922L (-40 to +85°C)) were placed inside waterproof capsules (DS9107) (Figure 4) and fixed to stakes in the sediment at 5cm and 30cm depths to record the temperature every 30 minutes (using the methodology described in Lavers et al., 2021) for 10 days.

All surface debris was removed on the final day of sampling using a 1mm sieve (as per Lavers et al., 2021). All the debris was then sorted (Figure 5) into OSPAR categories (consisting of 112 predefined litter items), counted, measured, and weighed (Ohaus SJX1502N/E Scout Gold). The data was downloaded from the loggers and analysed for each quadrat in relation to the mass of surface plastics. This was then repeated at these same locations across the four seasons. Winter deployments commenced on February 3rd 2023, Spring on June 2nd 2023, Summer on September 6th 2023, and Autumn on November 2nd 2023.

Data was analysed using XLSTAT. The data from the 5cm and 30cm depths were analysed

Fig. 1. The three study sites in Northeast Scotland, showing where the quadrats were located: 1. Whinnyfold (57°23'21.6"N 1°51'48.0"W), 2. Craigewan (57°31'14.6"N 1°48'02.7"W) and 3. Cairnbulg (57°40'38.9"N 1°57'00.5"W).


Fig. 2. LHS an example of a control quadrat. **Fig. 3.** RHS an example of a quadrat with high litter loading.


Fig. 4. LHS the ibutton thermochron datalogger and the waterproof capsule. **Fig. 5.** RHS an example of how surface litter from a quadrat was sorted and laid out prior to weighing.

separately using General Additive Mixed Models (GAMM) to account for the autocorrelative nature of circadian data and relationships between temperature and plastics investigated, with the date and quadrat being treated as random variables.

RESULTS & DISCUSSION

Litter surface loading was categorized as the control (0g/m^2), low (0 - ≤260g/m^2), medium (>260 - ≤2400g/m2) and high (>2400g/m2). GAMM analysis suggests that despite plastic loading not having a significant effect on the temperature at a 5cm depth ($F = 0.074$, edf = 1, $p = 0.714$), it did have a significant effect on the relationship between time and temperature ($F = 45.58$, edf = 19.7 p = <0.013). This shows that moderate and high surface litter loading significantly increased the maximum temperatures by 1.5°C and 1.7°C respectively and decreased the minimum temperatures by 1.1°C and 1.3°C respectively at a depth of 5cm during a 24-hour cycle (Figure 6). At a depth of 30cm no significant effect was observed between plastic loading and temperature or the circadian temperature cycle ($F = 0.594$, edf = 1, p= 0.812; $F = 0.063$, edf = 1, $p = 0.698$).

Global plastic production doubles approximately every decade. Estimates of how much of this can potentially end up in our oceans vary from 12.7 Mt/year (Geyer et al., 2017) to 90 Mt/year by 2030 if we include all aquatic ecosystems (Borelle et al., 2020). Plastic pollution is recognised as a threat to the sustainability of our planet and ourselves, and there are many actions

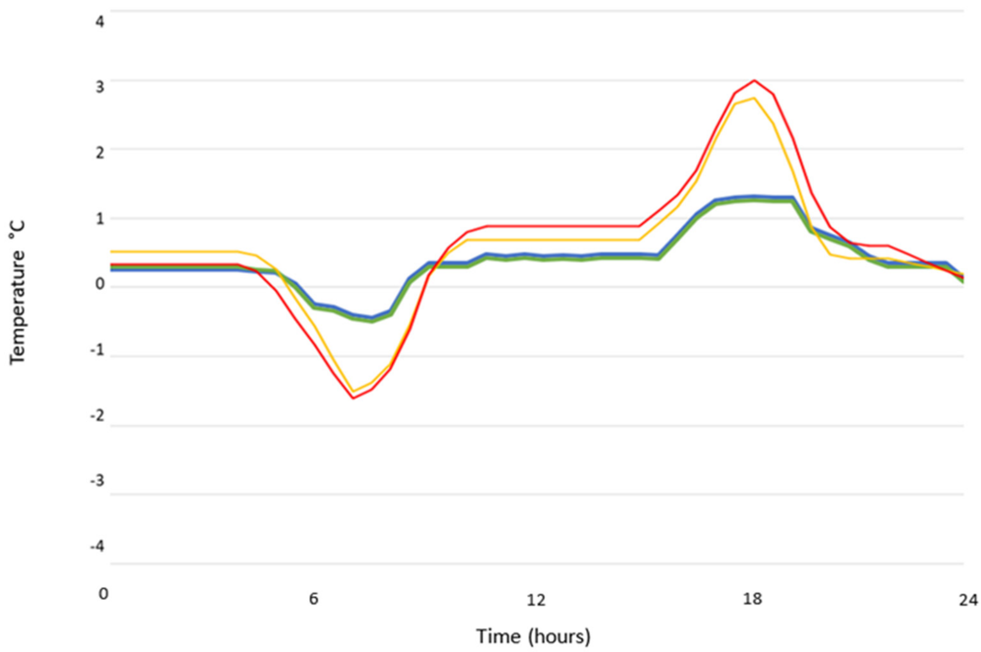

Fig. 6. The presence of plastic in medium (yellow) and high (red) densities significantly affected the maximum and minimum temperatures of the 24-hour temperature cycle (circadian rhythm) at a depth of 5cm in comparison to the control (green) and low (blue) plastic density quadrats.

already being implemented to reduce the volume of plastic waste polluting the environment. These include, grassroots action groups campaigning for greater awareness and transparency about plastic waste (e.g. Surfers Against Sewage, and the Marine Conservation Society) beach clean initiatives, government-implemented bans on products (single-use plastic bags, cotton buds etc.), innovative industrial approaches for the recycling of plastic waste (pyrolysis, depolymerisation and solvent dissolution), as well as the creation of alternative products to replace the use of plastics (e.g. sugar cane wrapping, and seaweed packaging).

Despite these actions, the accumulation of plastic debris around the coastline is set to continue for years to come affecting coastal ecosystems, by posing threats of entanglement, ingestion, exposure to chemicals and microbes and the introduction of non-native species having "hitch-hiked" on drifting debris (Kirsteain et al., 2016; Lo Brutto et al., 2021; Rech et al.,2016; Lavers et al., 2020; Gundogdu et al., 2024, and Bamigboye et al., 2024) and as we have shown in this study by affecting the temperature of coastal habitats. This is further compounded by the fact that plastic pollution is amplified by a warming climate, as documented in a recent study by Wei et al., 2024, which describes how climate change and plastic pollution are interconnected global challenges; rising temperatures and moisture alter plastic characteristics, contributing to waste by accelerating structural degradation, leading to microplastic generation, and release of hazardous substances. Thus, to effectively tackle the intertwined challenges of plastic pollution and climate change, a multi-dimensional strategy encompassing global policy and regulation, technological advances, improved waste management, public engagement and international collaboration is essential (Wei et al., 2024).

CONCLUSION

Our results showed that moderate and high surface litter loading significantly affected circadian temperature extremes by increasing the maximum temperature by 1.5°C and 1.7°C respectively and decreasing the minimum temperature by 1.1°C and 1.3°C respectively at a depth of 5cm. Plastic, although primarily considered an insulator, due to its low thermal conductivity as a result of it being comprised of long polymer chains, result in a less efficient and slower rate of thermal conductivity when compared to metal. However, heat transfer will still occur due to temperature gradients across the plastic object, with heat moving from the hotter side to the cooler side to obtain an equilibrium. The efficiency of this heat transfer will vary depending on the composition of the plastics. Once heat transfer has occurred, the plastic then acts as an insulator maintaining that higher temperature; the opposite is true for when plastics encounter cooler environmental temperatures. Unlike the findings of Lavers et al., 2021, we did not see the temperature extremes abating at high plastic mass (which Lavers et al. surmised may be due to the shading effects of the debris). However, this is most likely because we encountered lower volumes of plastic compared to the study by Lavers et al., 2021, where their high surface litter category was >4400 g/m^2 compared to our >2400 g/m^2. Lavers et al., 2021, suggest 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 (due to them finding no significant effect of plastic mass on the thermal properties of the sediment itself i.e. thermal conductivity, specific heat capacity, thermal diffusivity, or percent moisture).

For species that occupy intertidal habitats, it is well-documented that increased temperatures affect the assemblages of species within the ecosystem, with increases in the abundance of warm-affinity species, and declines in cold-affinity ones, poleward advances of species at cold range edges, and retreat of species at warm boundaries (Burrows et al., 2020). Despite this, assessment of local habitat conditions is lacking (Amstutz et al., 2021), particularly for sandy beach habitats (Scapini et al., 2019 and Lavers et al., 2021) despite sandy shorelines comprising one of the most extensive intertidal systems worldwide (Short, 1999). However, with recent studies of terrestrial and aquatic ecosystems indicating that maximum temperatures increasing by more than 0.5°C can result in local extinctions (Roman-Palacios and Weins, 2020), then it is reasonable to assume that increased temperatures >0.5°C, as found in our study, are likely to impact species assemblages. This is exacerbated when combined with the vulnerability of intertidal macrofaunal ectotherms (crustaceans, and other invertebrates) to temperature changes due to their narrow thermal safety margins (Edward et al., 2007; Scapini et al., 2019; and Trisos et al., 2020), and particularly key to intertidal meiofauna since the majority (70%) are found concentrated within the first 5cm from the surface (Kotwicki et al., 2005); as this sediment depth seems particularly susceptible to temperature change. Further studies on the impact of plastic debris as a factor affecting sandy beach ecosystems should therefore be investigated to expand upon our initial study, with a more critical look at the species assemblages, both macrofauna and meiofauna, and how they vary with temperature fluctuations. This could be looked at both in the laboratory and in-situ. An in depth look at the waste plastic size and composition and relationships with associated temperatures would also be beneficial.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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