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# Managing technology-critical elements from electronic waste in Small Developing Island States: a burden or an opportunity?

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Small Island Developing States (SIDS) face profound challenges from pollution, exacerbated by inadequate infrastructure and resource limitations. This paper examines the longstanding pollution issues plaguing SIDS, highlighting their vulnerability to environmental degradation due to underdeveloped waste management systems and unique oceanographic conditions. The case study of Eleuthera Island in The Bahamas illustrates these challenges vividly, showcasing the island's struggle with e-waste management. This example reinforces the urgency of integrated strategies to enhance environmental resilience and sustainable development in SIDS. Emerging concerns include the proliferation of technology-critical elements (TCEs) in e-waste, driven by rapid urbanization and tourism growth. Despite their crucial role in technological advancement, TCEs pose significant recycling and management difficulties, particularly in the context of limited waste infrastructure. The paper also highlights the imperative for comprehensive regulatory frameworks and sustainable practices to mitigate pollution impacts and safeguard ocean and human health, particularly by shedding light on legislative gaps and opportunities for enhancing pollution control measures in The Bahamas.

KEYWORDS

**environmental resilience, waste management, sustainable development, urbanization, tourism**

# 1 Pollution in Small Island Developing States: long-standing problems, inadequate current solutions

Small Island Developing States (SIDS) face severe pollution challenges that are increasingly acknowledged yet remain inadequately addressed. Despite global recognition of their vulnerability, tangible action is often lacking, exacerbating environmental degradation. Many SIDS, for example, suffer from underdeveloped waste management systems, struggling with inadequate infrastructure and limited resources to combat pollution effectively (UN Environment, 2019). The absence of efficient waste management means that, without external financial aid or specialized programs, SIDS are unable to process recyclables independently. This is due to the fact that SIDS often have limited financial resources and low economic diversification, mostly tourism and fisheries (OECD, 2024), making it challenging to invest in necessary infrastructure, technology, and services, added to the high costs associated with waste management, including collection, transportation, recycling, and disposal. Additionally, efficient waste management systems require advanced technology and specialized knowledge, so external funding allows SIDS to hire experts, train local staff, and acquire modern equipment, also aiding in diversifying SIDS economies by developing recycling industries and creating green jobs (UN, 2013). Thus, most SIDS are ill-equipped to prevent environmental contamination or implement recycling initiatives. SIDS are further burdened by pollution due to their unique oceanographic conditions, which often result in significant marine litter being deposited along their shorelines (Lachmann et al., 2017). Ocean currents and tides frequently carry debris from distant regions, inundating these islands with plastic waste and other solid pollutants that local waste management systems are ill-prepared to handle. Additionally, currents also transport harmful chemicals and toxins, exacerbating environmental contamination and posing severe risks to marine life and human health (Fleming et al., 2006; Engler, 2012). The situation is particularly dire for SIDS situated along hurricane pathways, as storms can exacerbate pollutant influxes, bringing a mix of toxic chemicals and debris from both the ocean and the mainland (Hay, 2013; Hernández-Delgado, 2023). This convergence of solid waste and hazardous substances adds a complex layer to the already pressing issue of pollution.

In addition to dealing with pollution from both local sources and marine debris/chemicals carried by ocean currents, some SIDS face the added burden of receiving waste from other nations through formal agreements. These agreements, often driven by the need for economic assistance, involve SIDS accepting waste shipments in exchange for financial compensation (Morrison and Munro, 1999; Ghina, 2003). While this provides a much-needed revenue stream for these islands, it also exacerbates their existing waste management challenges. The influx of foreign waste, which can include hazardous materials (Mohammadi et al., 2021), strains the limited infrastructure and resources available for waste processing and disposal.

# 2 SIDS and the emerging pollution paradigm: confronting contemporary pollution sources

Despite economic challenges, SIDS are experiencing rapid urbanization and a surge in tourism. This growth leads to an increased presence of technology-critical elements (TCEs) in waste, especially from electronic waste (e-waste) driven by the adoption of modern technologies (Hay, 2013; Gheuens et al., 2019; Mohammadi et al., 2021). These compounds include materials or minerals essential for advanced technologies and high-tech industries, playing a crucial role in technological innovation and economic stability (Ku et al., 2018). As consumer behavior is influenced by social factors, modern technology acts as a catalyst in amplifying consumption trends (Shove, 2004), and environmental impacts are more pronounced when innovations gain public attention (Blut and Wang, 2020). Although TCEs are vital for technological progress, they are challenging to manage and recycle, especially within the limited waste management infrastructure of SIDS. Consequently, the inability to properly dispose of or recycle e-waste exacerbates environmental contamination, adding to the significant pollution issues already faced by these vulnerable islands.

The list of TCEs undergoes periodic revisions directly influenced by economic vulnerabilities of countries or economic unions and military and geopolitical considerations, as well as potential supply chain disruptions (IRENA, 2023). The current listing includes rare earth elements, palladium, platinum, titanium and rubidium, among others. Most of these have been shown to display the ability to biomagnify and bioaccumulate in marine trophic webs, causing sublethal effects in both vertebrates and invertebrates, further exacerbating ecological and human health concerns (Campbell et al., 2005; Espejo et al., 2018; Santos et al., 2023).

The surge in marine pollution attributed to TCEs underscores a growing environmental concern, paralleling the exponential increase in the disposal of manufactured products (Bu-Olayan and Thomas, 2020). Moreover, recognizing that a significant portion of emerging green technologies (e.g., solar panels and electric cars) heavily depends on TCEs, heightens the concern, as these sources of pollution remain poorly investigated and regulated. E-waste is among the fastest-growing types of solid waste globally, with its volume expected to rise significantly in the future (Mohammadi et al., 2021). Simultaneously, increased interest in commercially exploiting TCEs has introduced additional challenges, ranging from regulatory and technical issues to environmental concerns. This includes an intensified focus on deep-sea mining activities (Deberdt and James, 2024), marked by the global issuance of exploration contracts before comprehensive scientific data on potential associated risks becomes available (EASAC, 2023).

The increasing attention towards TCEs and the corresponding surge in deep-sea mining agreements have prompted notable apprehensions, primarily due to the lack of understanding regarding TCEs accumulation and magnification patterns within marine food webs. The potential consequences of these activities extend beyond ecological considerations, raising substantial concerns about human health risks (Hauser-Davis, 2023), especially in SIDS (Petterson and Tawake, 2019), due to uncertainties regarding their impacts on seafood safety and the potential transmission of contaminants up the food chain (Bu-Olayan and Thomas, 2020).

## 3 Challenges and strategies in waste management across Bahamian islands

Waste management in The Bahamas faces significant challenges due to the archipelagic nature of the country, which complicates waste collection and disposal logistics. The lack of a centralized waste management system exacerbates these issues, leading to inconsistent waste handling practices across the islands. Efforts to improve waste management have focused on enhancing recycling programs, increasing public awareness, and developing sustainable waste treatment technologies. For instance, pilot programs for composting organic waste and initiatives to reduce single-use plastics have shown promise. However, the success of these programs depends heavily on government policies, community participation, and adequate funding. To date, literature on the challenges and efforts to improve waste management in the archipelago is scarce, with data available only for some islands and specific scenarios.

Deal (2002) investigated the solid waste management challenges on Green Turtle Cay (GTC), a three-mile-long island in The Bahamas, heavily reliant on tourism. The primary method of waste disposal on the island was open dump burning, which had negative environmental, community, and economic impacts. The research aimed to assess the state of solid waste management (SWM) on GTC and explored ways for government, the private sector, NGOs, and community members to collectively improve the SWM system. Using content analysis of grey literature, surveys of GTC residents, and semi-structured interviews, the study found several significant issues: there were no regulations on integrated SWM, only waste collection and disposal through landfilling or burning; 95% of survey participants expressed concerns about the health impacts of burning waste; the top three types of waste produced from the tourism sector were plastics, organics, and glass; and two tourism businesses reported a waste generation increase of over 260% between low and peak seasons. The study provided recommendations for GTC to address the waste management crisis by implementing an Integrated Solid Waste Management System (ISWMS). Key recommendations included establishing an ISWM committee with government, NGOs, and private sector involvement; developing island-specific regulations to govern the ISWM plan; creating a financial business plan to sustain the ISWMS; compiling a local and regional ISWM resource and waste diversion guide; launching a local educational campaign; developing a phased strategic plan to remediate the dumpsite and construct a formal waste management facility; and advocating for Central Government to create national ISWM regulations.

Sullivan-Sealey and Cushion (2009) examined the environmental management efforts, resources, and costs associated with the long-term management of the Baker's Bay Golf and Ocean Club (BBC) on Great Guana Cay, Abacos, The Bahamas. As a coastal tourism development, BBC incorporated an Environmental Management Program (EMP) and specific environmental goals into its Environmental Impact Assessment (EIA). Waste management impacts in the area included land clear-cutting for disposal, pollution from trash burning, and water quality issues from leaching sewage pits. To address these challenges, the BBC EMP implemented a solid waste management program with advanced composting and recycling. The total estimated cost for these infrastructures and mitigation projects was approximately US$10,345,000, excluding ongoing waste management costs during construction and operation. Despite the high cost, these measures were deemed essential to safeguard against environmental impacts, including chemical leaching affecting ground and nearshore water quality due to debris containing chemically treated wood and corroding metals. The mitigation projects were crucial to meet the project's environmental goals and ensure sustainable resort development.

Sealey and Smith (2014) conducted a multi-year study focusing on Great Exuma in The Bahamas, documenting solid waste generation since 2010, with a year of benchmarking followed by limited food waste recycling at the Sandals Emerald Bay (SEB) resort. The research highlighted that the rapid increase in solid waste due to a large destination resort had led to pest problems and frequent fires from unburied waste. In 2013, SEB contributed approximately 36% of the island's total solid waste, generating about 1,752 tons out of 4,841 tons, excluding vegetation waste. Benchmarking revealed that 48.5% of the waste from SEB was compostable organic waste, although the composition varied over time. Exuma Waste Management (EWM) and Recycle Exuma (RE), both private Bahamian businesses, collaborated with SEB from 2012 to 2013 on a pilot recycling project to meet Earth Check green resort certification requirements. The study outlined the costs, resources, and barriers to implementing effective solid waste management for the tourism industry on small islands, emphasizing the need for tailored strategies to manage waste sustainably in such unique environments.

The study by del Campo et al. (2023) investigated the systemic risks and cascading effects associated with resource-use patterns in The Bahamas, highlighting how these factors inhibited the delivery of socioeconomic services. The researchers emphasized the importance of identifying and reshaping resource-use patterns to transition towards a sustainable, resilient, and resource-secure system. Using The Bahamas as a case study, the paper presented the first mass-balance account of socio-metabolic flows, revealing significant socio-metabolic risks. The study found that annual direct material input was 9.4 tons per capita per year, with 60% being imports. A large portion of waste (1.4 tons per capita per year) remained unrecovered due to inadequate recycling. The authors advocated for a holistic resource management strategy and nature-based solutions that addressed the trade-offs and synergies between different resource-use patterns to mitigate these risks.

## 4 Eleuthera island: a case study

Eleuthera, a narrow island in The Bahamas stretching approximately 110 miles in length and just over a mile in width at its narrowest point, with a population of around 11,000 residents scattered across various settlements, faces significant waste management challenges, and the island's waste management infrastructure is under considerable strain. Research on pollution in Eleuthera has, however, primarily focused only on marine plastic debris, leaving other significant pollution issues, such as e-waste, largely unexamined. In this sense, studies such as those by Ambrose et al. (2019) and Ambrose and Walker (2023) provide a comprehensive analysis of the spatial distribution and drivers of marine debris on the island's beaches. The 2019 study identified the sources and abundance of marine debris on 16 beaches across three coastal exposures: the Atlantic Ocean, Great Bahama Bank, and Exuma Sound, revealing that about 93% of all debris items were plastic, with plastic fragments being the most prevalent. Significant spatial differences in plastic debris abundance were also noted, with Atlantic Ocean beaches containing the highest amounts, likely due to currents associated with the North Atlantic subtropical gyre. Ambrose and Walker (2023) further highlight the increasing prevalence of microplastics and mesoplastics in area, assessing the spatial and seasonal abundance of microplastics (1–5 mm) and mesoplastics (5–25 mm) across the same 16 beaches, and verifying a predominance of microplastics, constituting 74% of the total, emphasizing the urgent need for their inclusion in global treaties aimed at ending plastic pollution.

Concerning waste disposal, this is largely managed through open sky dumping sites (Figure 1), leading to an increasing accumulation of waste, including e-waste, for which there is no effective contingency plan, posing serious environmental risks (Sealey and Smith, 2014), due to the release of toxic substances from decomposing material, including electronic materials, mainly electronic devices, such as smartphones and mobile devices, computers and laptops, televisions and monitors, household appliances and batteries as the most common e-waste items, contaminating soil, groundwater, and oceans. These sites are used not only by the municipal government for household waste but also by companies investing in the island, including those involved in tourism and development. Furthermore, recent developments in Eleuthera, including increased urbanization, tourism expansion, and technological advancements are likely to exacerbate the island's e-waste issue. The construction of new resorts has led to a surge in tourism, bringing an influx of modern electronic devices and appliances used by visitors and staff. This rise in tourism is

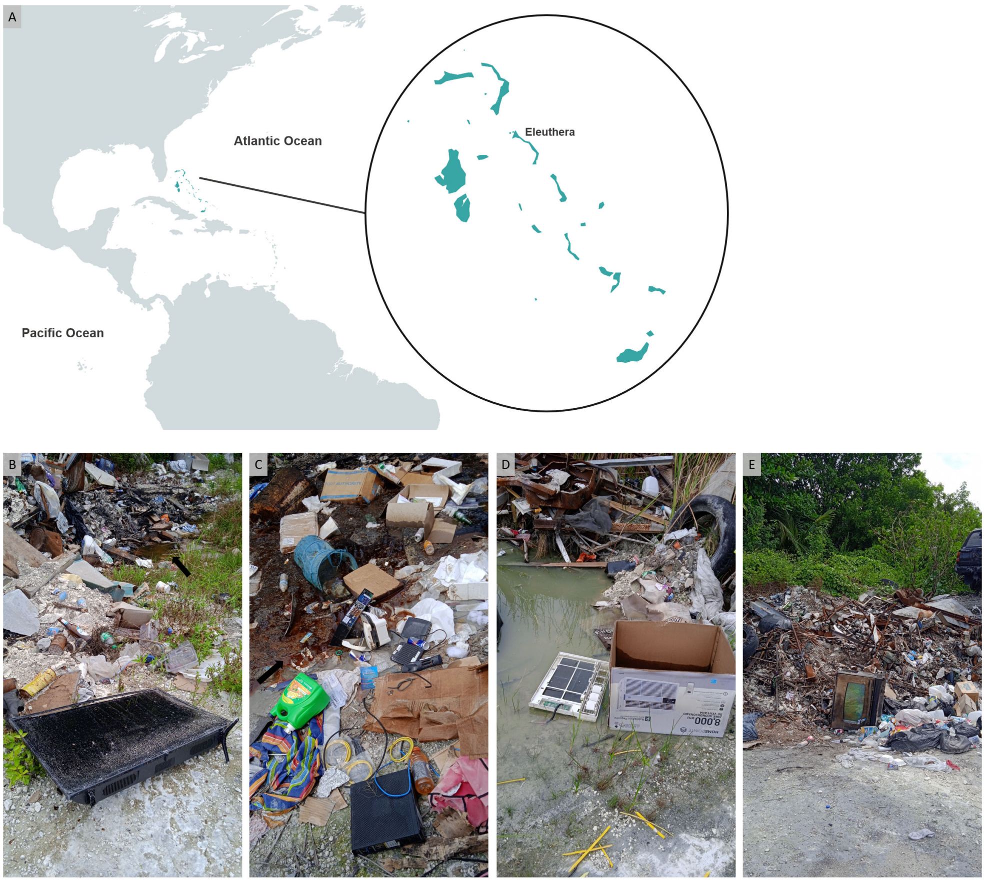


FIGURE 1
Dumping sites in the Deep Creek and Waterford settlements, located in the southern region of Eleuthera Island, The Bahamas **(A)**, showing: **(B)** A broken TV. **(C)** Various electronic devices (including telephones, remote controls, and cable TV routers/modems). **(D)** Pieces of broken air conditioning units. **(E)** An electric oven. Black arrows indicating leachate.

paralleled by a notable increase in the number of vacation homes and rental properties equipped with contemporary electronics to meet tourist expectations. Additionally, the development of local infrastructure, including schools, health centers, and commercial establishments, often involves integrating new technologies, resulting in higher turnover rates of electronic equipment. For instance, recent investments in renewable energy projects, while beneficial for sustainability, also contribute to the disposal of outdated electronic components. Moreover, the rising trend of land acquisition for property development by visitors, coupled with the island's growing appeal as a vacation spot, has strained the water, electricity, and internet infrastructure, leading to frequent service outages that can last for days. Despite the increasing interest and urbanization, there has been no investment in upgrading these essential services. Consequently, residents and developers are turning to personal solutions such as solar panels, advanced water collection systems, and satellite internet. This shift towards self-sufficiency is likely to generate more e-waste and increase the burden on waste disposal systems in the coming years, without adequate plans or legal obligations for proper e-waste removal. This pressing problem, however, also reveals a crucial opportunity to implement a circular economy (Mohammadi et al., 2021). By adopting recycling and reusing strategies, e-waste can be transformed into valuable resources, reducing the need for raw material extraction and mitigating environmental damage. To transition effectively to a circular economy, it is essential to establish public policies that promote such practices. Governments should provide tax incentives to companies and initiatives that support the recycling and reuse of electronic components. This approach not only addresses the adverse effects of electronic waste but also fosters a sustainable economic cycle that benefits both the environment and society.

Various initiatives have been launched to address these issues on Eleuthera, focusing on sustainability, community involvement, and innovative solutions. Key strategies include increasing public awareness about the environmental and health impacts of poor waste management through educational programs and media campaigns, building and maintaining facilities for recycling, composting of organic waste, and proper waste disposal to ensure effective waste management, enforcing regulations that promote waste reduction, recycling, and the responsible disposal of hazardous materials, and encouraging community participation in waste management initiatives to foster a sense of responsibility and ownership among residents.

The Bahamas Plastic Movement (BPM), for example, is a youth-led initiative founded by Kristal Ambrose (Ambrose et al., 2019). This movement aims to reduce plastic pollution through education, activism, and community clean-up efforts, encompassing beach clean-ups, educational workshops in schools, and community outreach programs to raise awareness about the impact of plastic pollution and promote sustainable practices. This initiative has been instrumental in advocating for the reduction of single-use plastics, leading to policy changes and a cultural shift towards more sustainable practices on Eleuthera and other Bahamian islands. In another example, the Cape Eleuthera Institute (CEI) at Island School, an educational and research institution focused on sustainable development and conservation, has implemented several waste management initiatives, including composting programs for processing all of its organic waste (e.g., food scraps, green waste, paper/cardboard), recycling projects, and the promotion of sustainable living practices within the community (Figure 2) (Thomas, 2017). The One Eleuthera Foundation (OEF), a non-profit organization committed to sustainable development and community empowerment in Eleuthera, has introduced several


FIGURE 2
Waste management initiatives at Island School. **(A)** Middle school students from Deep Creek Settlement (DCMS) engaged in a waste management and recycling class. **(B, C)** Community Day: a biannual event where all Island School members participate in campus improvement activities, including waste management. **(D)** Early Learning Center (ELC) students involved in a beach cleanup. **(E)** DCMS students contributing to a beach cleanup effort. **(F)** Spring 2023 Island School semester students in a research class on plastic pollution, led by Dr. Imogen Napper, Marine Scientist and National Geographic Explorer.

initiatives to enhance waste management infrastructure. These initiatives include funding and constructing recycling centers that accept aluminum, plastics, and e-waste, processing glass bottles into cullet, and promoting waste separation at the source. The OEF works closely with local communities to raise awareness and encourage participation in waste reduction and recycling efforts (Roy, 2017).

Although these initiatives are promising and have yielded excellent results for managing waste in SIDS, there remains a significant gap in addressing e-waste. Currently, there are no comprehensive plans or initiatives to tackle the challenges posed by this emerging pollution category. This lack of foresight necessitates urgent discussions and planning to manage the potential hazards associated with TCEs and other harmful components in e-waste. Without proactive measures, this could evolve into an escalating problem, exacerbating environmental and health risks. Moreover, only 20% of nations collect data on e-waste, highlighting the urgent need for mapping/monitoring initiatives (Mohammadi et al., 2021). To address this, potential solutions include forming a community-driven committee to oversee new construction projects, ensuring they incorporate e-waste management practices from the outset. Additionally, engaging tourism entrepreneurs and foreign homeowners in these discussions can promote responsible waste practices in their developments. Implementing domestic legislation to prevent e-waste from being dumped in existing burning sites is crucial, alongside promoting awareness campaigns and establishing dedicated e-waste recycling programs that involve the local community in sustainable practices.

## 5 Legal considerations and future steps

Considering the Food and Agriculture Organization Legal Office (FAOLEX) and The Government of The Bahamas databases, about 60 legal documents—encompassing both current and repealed regulations, policies, and legislation—reveal the Bahamian government's significant commitment to mitigating the impacts of human activities on the environment (Supplementary Table 1). These documents primarily focus on organic and plastic pollution, exposing a notable gap in the legal framework regarding other pollution categories (e.g., inorganic/e-waste, light and noise). The existing regulations mainly address specific issues such as Persistent Organic Pollutants (POPs) and sewage management within port and settlement areas, often employing generalized terms such as "waste" without detailed descriptions. Interestingly, legislation targeting plastic pollution appears to be more recent and comprehensive, for example banning single-use plastics and Styrofoam products (Clayton et al., 2021), likely reflecting increased global attention to this issue. This emphasis suggests that while Bahamian public policies are in line with the recognized pollution categories in official reports, they fall short of covering the full spectrum of pollution issues comprehensively.

A recent study on e-waste in the Caribbean examined trends in five island states—Aruba, Barbados, Grenada, Jamaica, and Trinidad and Tobago—over a 60-year period from 1965 to 2025 (Mohammadi et al., 2021). Utilizing a dynamic material flow analysis (MFA) approach, the research estimated flows and stocks of Electrical and Electronic Equipment (EEE) for 206 product types. The findings revealed that these islands produced twice the global average of e-waste per capita per year, with 13 kg per capita compared to the global 6.1 kg in 2016. E-waste generation on these islands was projected to increase substantially, from 27,500 tons in 2010 to 59,000 tons in 2025. Although data is not available for The Bahamas, a similar trend might be expected, with the level and pace of urbanization henceforth likely dictating the amount of e-waste rather than merely the population size or the size of the islands within this archipelago. Analyses of this nature are essential for The Bahamas, as they provide critical insights to refine and enhance the regulatory frameworks governing pollution control. Additionally, they offer vital guidance for legislative development pertaining to sustainable tourism expansion and strategic planning in the real estate sector. Moreover, understanding the potential risks associated with deep-sea mining activities, for which the nation already holds exploration contracts, is also imperative. It is essential not only to develop strategies for handling e-waste but also to prevent environmental disasters during the extraction of these valuable technological elements across the Bahamian EEZ. This proactive approach is necessary to ensure that this emerging form of pollution does not escalate into a crisis that is difficult, if not impossible, to mitigate.

Given these uncertainties and potential risks for SIDS, including Eleuthera, it is imperative to prioritize comprehensive research beyond the immediate environmental impact to also encompass potential human health ramifications through the consumption of marine organisms affected by e-waste and associated TCEs. Moreover, the implementation of robust regulations that go beyond conventional environmental frameworks and explicitly consider the broader implications for societal well-being is essential. This holds particular significance within the context of the One Health concept, which embraces a collaborative, multisectoral, and transdisciplinary approach, recognizing the interconnections between people, animals, plants, and their shared environment. Several Sustainable Development Goals (SDGs) are directly relevant to this aspect, particularly SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and SDG 14 (Life Below Water). SDG 14, which aims to conserve and sustainably use oceans, seas, and marine resources, is especially vital for SIDS reliant on the ocean for their livelihoods, culture, and survival. Furthermore, the United Nations Decade of Ocean Science for Sustainable Development initiative seeks to mobilize the global scientific community, policymakers, business sectors, and civil society to advance ocean science and achieve sustainable management of ocean resources. This initiative provides SIDS with access to cutting-edge research, technological innovation, and international collaboration to address their unique challenges.

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The goal is to safeguard ocean health, not merely as an environmental mission but as a crucial strategy for ensuring human resilience, particularly in response to challenges posed by the Anthropocene.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author/s.

## Ethics statement

Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

## Author contributions

NW: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. DC: Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. RH: Conceptualization, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2024.1459794/full#supplementary-material

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