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The science we need for the beaches we want: frontiers of the flourishing Brazilian ecological sandy beach research

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1 Introduction

Sandy beaches are the most ubiquitous coastal ecosystem and provide essential benefits for people. However, they remain the least studied coastal environment (Lercari, 2023). To maintain the sandy beaches' role in promoting societal welfare, researchers have highlighted critical scientific gaps, governance and regulatory issues that prevent us from developing appropriate management and conservation strategies. For instance, Amaral et al. (2016) prioritized six research areas to assess the influence of environmental changes on Brazilian sandy beaches, while Fanini et al. (2020) highlighted 21 knowledge gaps that preclude beach conservation worldwide.

Brazilian researchers have stood out in the scientific production on beaches in the last decade (Lercari, 2023). Nevertheless, this scientific knowledge is not enough if there are no changes in governance, regulations and culture of stakeholders and society. Herein, we combined the priority research areas and knowledge gaps identified by Amaral et al. (2016) and Fanini et al. (2020) into four major research topics (Table 1). Then, we presented ecological research performed on Brazilian sandy beaches over the last decade to assess the advances (or lack of) in each of these topics. Finally, we highlighted ongoing research and promising topics in sandy beach research in Brazil.

2 Ecological research on Brazilian sandy beaches

2.1 Topic 1. Knowledge of biodiversity, ecological links, and genetic connectivity

Brazilian sandy beaches are distributed along 9000 km of coastline and encompass all beach types, from wide tide-dominated flats in the North to microtidal wave-dominated beaches in the Southeast and South (Klein and Short, 2016). During the past decade, most studies were performed in Southeast and South Brazil. However, we found a recent increase in studies in North Brazil, with investigations showing that the local sandy beach fauna is strongly influenced by riverine discharge, rainfall, morphodynamics, and human activities (Santos and Aviz, 2018; Baia and Venekey, 2019; Santos and Aviz, 2020; Baia et al., 2021; Santos et al., 2021a; Santos et al., 2021b; Santos et al., 2022; Cardoso et al., 2023; Checon et al., 2023a). Information on population attributes of typical beach species, such as *Ocypode quadrata* (Souza et al., 2021) and *Clibanarius symmetricus* (Danin et al., 2020), has just been made available for the Amazon coast.

Studies were also spatially restricted to supratidal and intertidal zones, with only a few studies sampling the subtidal or the whole across-shore gradient (e.g., Corte et al., 2019; Corte et al., 2020; Corte et al., 2022). Investigations mainly focused on macrobenthos, despite recent contributions to fish (Shah Esmaeili et al., 2022) and bird ecology (da Rosa Leal et al., 2013; Linhares et al., 2021; Rangel et al., 2022). There is incipient information on microorganisms and few studies assessed the ecology of meiofauna (reviewed in Maria et al., 2016). The number of investigations on primary producers was also higher in Southeast and South Brazil. Conversely, Brazil was probably the country with the highest number of studies on the secondary production of beach species (Petracco et al., 2013).

Few studies simultaneously investigated multiple biological components and their connectivity (e.g., Lacerda et al., 2014; Corte et al., 2017a). Costa et al. (2017) modeled a sandy beach food web including detritus, phytoplankton, macroinvertebrates, fish, and seabirds, while Pinotti et al. (2014) reviewed macrobenthic trophic relationships along subtropical sandy shores. Data using molecular markers that provide information regarding genetic connectivity and cryptic diversity remain scarce. Hurtado et al. (2016) detected high levels of cryptic diversity for the isopod *Excirolana braziliensis*, warning about potential biases in latitudinal gradient studies. Similarly, Seixas et al. (2021) found new species within the *Diopatra cuprea* complex, while Silva et al. (2017) found new species within the *Capitella capitata* complex. Hernáez et al. (2022) described the ghost shrimp *Callichirus corruptus*. Furthermore, Mattos et al. (2019) showed how contrasting dispersal potentials can affect crustacean genetic structure and connectivity along the entire Brazilian coast.

2.2 Topic 2. Standardized methods, long-term data, and findable, accessible, interoperable and reusable principles

Despite efforts to produce monitoring protocols (e.g., ReBentos and MBON Pole-to-Pole), long-term ecological studies on Brazilian sandy beaches remain scarce. In one of the few examples, Costa et al. (2022b) compiled data from 2013–2021 and showed that the abundance of the ghost crab *Ocypode quadrata* increased during beach closures due to the COVID-19 pandemic. The only current long-term (> 20 years) ecological investigation is being performed at Cassino Beach, South Brazil (Odebrecht et al., 2017). FAIR principles are still hardly applied to sandy beach research in Brazil, and most raw data remain restricted even after the publication of scientific papers.

2.3 Topic 3. Ecological impacts related to climate change and anthropic activities

Brazilian beaches have been jeopardized by oil spills (Marques et al., 2017; Sills et al., 2020; da Rosa, 2022), sewage discharges (Roth et al., 2016), marine litter (Neves et al., 2022), overfishing (Bender et al., 2014), chemical contamination (Cabrini et al., 2017; Cabrini et al., 2018; Ragagnin and Turra, 2022), trampling and vehicles traffic (Bom and Colling, 2020; Santos et al., 2021b; Bom and Colling, 2022; Santos et al., 2022) and coastal urbanization (Rêgo et al., 2018; Corte et al., 2022; Laurino et al., 2022; Shah Esmaeili et al., 2022). Furthermore, researchers have shown that urbanization may increase parasitism in invertebrates and fishes

TABLE 1 Priority research areas highlighted by Amaral et al. (2016) and Fanini et al. (2020) combined into the four broad topics, and considerations on the advances (or lack of) in each of these areas during the previous decade.

Priority research areas	Considerations
1) Knowledge of the environmental characteristics and biodiversity of Brazilian sandy beaches, including ecological links between habitats and biodiversity groups.	
Amaral et al., 2016	
Holistic studies on sandy beaches.	Reduced number of studies investigated multiple beach habitats or biological groups.
Studies on the secondary production of key species to understand processes of energy transfer in the ecosystem of sandy beaches.	Insufficient information on energy transfer in beach ecosystems.
Fanini et al., 2020	
Knowledge about links and connectivity between the components of the littoral active zone (LAZ).	Few studies assessed different zones of the LAZ.
The identification of key physical and ecological processes and their boundary areas, to manage the littoral active zone as a sedimentary unit.	Few studies assessed different zones of the LAZ.
Studies of the ecohydrological links between the physical characteristics of the substratum, their dynamics, and the fauna of sandy beaches.	Limited information on the ecological links in sandy beach ecosystems.
An increase in data emanating (and a better collation of those data) from case studies from less-represented areas, beach morphotypes, and issues.	Larger number of studies performed in the Northern region, but the number remains low.
The production and delivery of autochthonous and allochthonous organic material related to different beach types, hydro physical conditions, and adjoining habitats.	No study on this topic.
2) Standardized methods, long-term data, and FAIR principles.	
Amaral et al., 2016	
Temporal replication of sampling to allow the compilation of long-term data series.	Reduced number of long-term studies.
Standardization of the methodologies used and the systematic application of monitoring protocols for large spatial and temporal scales.	Monitoring protocols were developed but not applied in large-scale studies.
Fanini et al., 2020	
The short and long-term storage of carbon and its utilization and turnover.	No study done on this topic.
The development of long-term data sets and their collation/curation following internationally agreed standards (e.g. FAIR).	Most data remain inaccessible.
The identification of standards, both for gathering and using data, and for the quality of beaches.	Monitoring protocols were developed but not frequently applied in ecological investigations.
3) Ecological impacts related to climate change and anthropic activities	
Amaral et al., 2016	
Field and laboratory experiments to understand differences resulting from anthropogenic impacts and climate change.	The number of experimental studies increased in comparison with previous decades; however, it is still low.
Fanini et al., 2020	
The resistance and resilience of beaches to short (pulse) and long (press) term perturbations, including the physical system, residency and facultative behavior (i.e. spending only a stage of their life on beaches) of the biota.	Studies, including experiments, assessed how perturbations affect beach ecosystems, but less attention was paid to the resilience of beach ecosystems and biodiversity.
An increase in data resulting from case-studies related to different human use, including urban beaches.	Considerable number of studies assessed how human use affects beach ecosystems.
The quantities of sediment lost and gained through human activities, including mechanical maintenance, tourism frequency, extent and duration and soft and hard measures to counteract erosion.	Few studies have been conducted on this topic. An overall method has yet to be established.
The resistance and resilience of beaches to global changes, including temperature fluctuation, temperature rise and sea level rise.	Studies mainly focused on storm effects.
The assessment of short and long-term impacts of harmful micro- and macroalgal blooms.	No study assessed the impact of harmful algal blooms on Brazilian sandy beaches.

(Continued)

TABLE 1 Continued

Priority research areas	Considerations
The overlap (interference) of emergent phenomena such as beach litter, macro and microplastics with beach dynamics at micro, meso, and macro scales.	A significant number of investigations examined the concentration and impact of marine litter on sandy beach ecosystems.
4) Sandy beach as socio-ecological systems and management strategies based on the ecosystem	
Amaral et al., 2016	
Improved interactions between scientists and decision makers.	There was an increase in interaction between scientists and decision makers. However, this interaction is limited to a few researchers.
Fanini et al., 2020	
Quantifying the ecosystem services and societal goods and benefits provided by beaches across different geographical areas, including the rate of economic dependency on beach-related resources, and the dynamics driven by seasonality.	Limited number of studies on this topic.
The need to assess pollution on beaches in terms of human health and safety risks.	Studies on pollution need to be performed on a larger number of beaches and with higher frequency.
The detection and rigorous assessment of social-ecological regime shifts and collapses, including the identification of early warning tipping points to support governance.	Limited number of studies on this topic.
The identification of ecological and socio-economic indicators to undertake comprehensive and long-term impact assessments. Such broadening of the focus would necessarily include climate change-related stressors, market forces and governance regimes.	Brazilian researchers advanced in the use of biodiversity as tools for environmental monitoring and assessment, including both species and assemblage-level.
The use of indicators to assess the performance of management interventions.	Brazilian researchers advanced in the use of biodiversity as tools for environmental monitoring and assessment, including both species and assemblage-level.
The development of ecosystem-based solutions to readdress management failures, together with the establishment of networks combining Marine Protected Areas and community-based exploitation areas to facilitate spill-over effects and balance bio-socio-economic factors.	Limited number of investigations on this topic. Studies were spatially restricted.
The carrying capacity of beach units for human activities (e.g. tourism) having a direct, quantifiable effect. This would allow a set of choices to be made adequately balancing recreation and conservation needs. There is also the need to determine the assimilative capacity of beaches in n which they can accept human activities without adverse effects.	Very low number of studies investigated the carrying capacity of Brazilian beaches.

(Corte, 2015; Shah Esmaeili et al., 2021a). Investigation of plastic pollution has advanced significantly (Costa et al., 2022b; Mengatto and Nagai, 2022), and studies suggested that assessments should consider the physical variables that regulate beach dynamics such as wave action and tidal cycles (Balthazar-Silva et al., 2020; Tsukada et al., 2021).

Investigations on the effects of climate change focused mainly on high-intensity storms (Machado et al., 2016; Turra et al., 2016; Corte et al., 2017b; Corte et al., 2018; Oliveira and Yokoyama, 2021). Experiments to assess anthropogenic and climate change impacts are still scarce (but see Laurino et al., 2020; Izar et al., 2022; Laurino et al., 2022, Laurino et al., 2023; Laurino and Turra, 2021). Nevertheless, Brazilian researchers advanced in the use of biodiversity as tools for environmental monitoring and assessment (Pombo and Turra, 2013; Cardoso et al., 2016; Gorman et al., 2017; Pombo and Turra, 2017; Checon et al., 2018a; Checon et al., 2018b; Costa and Zalmon, 2019; Costa et al., 2020b; Barboza et al., 2021; Costa and Zalmon, 2021; Costa et al., 2022a; Checon et al., 2023b; Checon et al., 2023c).

2.4 Topic 4. Sandy beach as socio-ecological systems and management strategies based on the ecosystem

While sandy beaches ecosystems provide regulating, cultural, supporting, and provisioning services (Harris and Defeo, 2022), studies in Brazil were mostly focused on cultural services such as tourism activities (Checon et al., 2022b). Accordingly, Brazilian sandy beach management remains overwhelmingly focused on social-economic aspects such as engineering interventions to mitigate erosion (e.g., armoring and nourishment), cleaning, and tourism support (e.g., Simões et al., 2022, Borges et al., 2023). To improve management practices, Xavier et al. (2020) and Corrêa et al. (2021) highlighted the need for a more holistic understanding of the beach environment, including the diversity and interactions of ecological and social components. Moreover, Araújo et al. (2021) adapted the conceptual model DPSWIR (Driving Force-Pressure-State-Impact-Well-being-Response) to assess the effects of coastal ecosystem services loss on human well-being.

Efforts have been also made to propose an Ecosystem-Based Management (EBM) approach for Brazilian sandy beaches (e.g. Bombana et al., 2022), but empirical and theoretical research on sandy beach management is still incipient (Xavier et al., 2020; Corrêa et al., 2021). Most studies aim to understand the anthropogenic drivers associated with social and ecological deterioration rather than assess the performance of management interventions (Xavier et al., 2020). Corrêa et al. (2020) identified two barriers to EBM implementation at the local level: overcoming current undesirable governance structures and fitting governance to multilevel ecosystem dynamics.

Nature-based solutions (NbS) assume that natural processes can solve management failures and have been proposed to mitigate the degradation and vulnerability of coastal environments to erosion (Slinger et al., 2021). Manes et al. (2023) estimated that nature-based shoreline protection can reduce the risks of climate-induced hazards to the Brazilian coastline by 2.5 times. Costa et al. (2020a) suggested the addition of natural obstructions in the supralittoral and reforestation to prevent ghost crabs and turtle hatchlings from being killed by vehicles on the sand.

3 Future directions

Sandy beach ecological studies performed in Brazil increased over the past decade; however, these advances do not ensure the preservation of our beaches. While ecological knowledge is crucial to preserve our beaches, it alone is insufficient since successful management is largely contingent upon changes in the environment, governance, and new technologies.

Management and governance have a key role in maintaining sustainable ecosystem services and their benefits (Harris and Defeo, 2022), and it is essential to use scientific knowledge to subsidize the decision-making process by developing evidence-based management strategies to reduce the harmful consequences of anthropic activities and mitigate climate change effects.

Collaborative and multidisciplinary networks are crucial for ensuring that the knowledge produced leads to effective changes in governance and cultural aspects towards beach ecosystems conservation. EBM should be fostered, integrating both social and natural systems in a transdisciplinary way, considering the temporal and spatial scales of processes, the benefits from beaches to people, and attempting to build socioecological models that support decision-making (Gonçalves et al., 2020; Corrêa et al., 2021; Xavier et al., 2022).

Incorporating ecological principles into engineering can improve management practices and foster the development of mechanisms to address complex challenges threatening beach conservation, such as the synergic effects of coastal urbanization and climate change. Emerging technologies such as eDNA, Remote Sensing (RS), and unmanned aerial vehicles for imaging are promising tools for evaluating sandy beach biodiversity and ecological processes, which can reduce the costs and effort associated with biodiversity assessment and monitoring (Barboza et al., 2021; Shah Esmaeili et al., 2021a; Checon et al., 2022a).

Long-term data are necessary to comprehend how climate change is affecting sandy beach ecosystems and may compromise their goods and services, as well as to understand the population dynamics of exploited species, changes in species distribution, storage and turnover of organic carbon, and impacts of human activities and harmful algal blooms (Fanini et al., 2020). Expanding knowledge about larval dispersion, settlement, and resilience to environmental changes is also needed to understand the dynamics of beach biodiversity. We have limited information on the diversity and ecological role of microorganisms (viruses, bacteria, fungi, parasites) and meiofaunal species, and beaches from North and Northeast Brazil remain largely understudied. Similarly, sublittoral communities and the backshore remain overlooked. Stable isotope analysis may help elucidate the connection between sandy beaches and adjacent habitats. Studies on the whole Littoral Active Zone are essential to identifying key physical and ecological processes and their boundary areas (Fanini et al., 2020). It is also urgent to conduct studies on the effects of heat waves on beach species and assemblages.

We strongly recommend that data collation/curation follow the FAIR principles that lead to legislation focused on advances in EBM. For example, data should be published in open-access databases (e.g., GBIF and OBIS) and made available using a CC-BY license.

Importantly, the effort for knowledge production should consider societal demands, and assist managers in providing assertive and applicable responses to such a complex system in a changing environment. In addition, an effort should be made to congregate the science we are doing and to implement the science we need for the beaches we want (e.g., ABC, 2021), promoting a better dialogue with the Sustainable Development Goals of the United Nations 2030 Agenda for Sustainable Development (UNGA, 2015) and the outcomes and challenges of the United Nations Decade of Ocean Science for Sustainable Development (IOC/UNESCO, 2020; Claudet et al., 2020).

Author contributions

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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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