Environ Monit Assess (2025) 197:1077
https://doi.org/10.1007/s10661-025-14511-7

RESEARCH

Assessing DNA damage in sentinel crabs as indicators of tourist impact in the Fernando de Noronha Archipelago, a Marine Protected Area and World Natural Heritage Site in Brazil

Mônica Lúcia Adam · Anderson Rodrigues Balbino de Lima · Marcelo Antônio Amaro Pinheiro · Harry Boos · Rodrigo Augusto Torres

Received: 5 May 2025 / Accepted: 14 August 2025

Abstract This study investigates the genotoxic effects of tourism on two sentinel crab species (*Johngarthia lagostoma* and *Grapsus grapsus*) in the Fernando de Noronha Archipelago, Brazil, a Marine Protected Area and World Natural Heritage Site—sampling (October 2020–June 2022) covered periods of varying tourist influx due to COVID-19 restrictions. Genomic damage was assessed using micronucleus (macrolesions) and comet assays (microlesions) in hemolymph samples from crabs at two sites: Dolphin Trail (low visitation) and Porto de Santo Antônio Beach (high visitation). DNA damage increased with tourist numbers. In *J. lagostoma*, macrolesions rose from 3.2 MN/1000 cells (October 2020, 3261 tourists) to 8.8 MN/1000 cells (February 2022, 10,918 tourists), while microlesions increased from a damage index (DI) of 119.1 to 231.5. *Grapsus grapsus* was a more susceptible species, with macrolesions rising from 5.4 to 10.2 MN/1000 cells and microlesions from 184.7 to 303.1 DI (October 2020–October 2021, 12,085 tourists). Regression analysis revealed a strong correlation between tourist numbers and DNA damage, particularly in *J. lagostoma* ($R^2 = 0.99$;

M. L. Adam (✉) · R. A. Torres
Laboratório de Genômica Ambiental (LAGEA), Universidade Tecnológica Federal Do Paraná (UTFPR), João Miguel Caram, Campus LondrinaZip Code86036-370,, Londrina, PR 3131, Brazil
e-mail: monicaadam@utfpr.edu.br

R. A. Torres
e-mail: rodrigotorres@utfpr.edu.br

M. L. Adam · A. R. B. de Lima · M. A. A. Pinheiro · H. Boos · R. A. Torres
Laboratório de Genômica Ambiental (LAGEA)/Grupo de Pesquisa Em Biologia de Crustáceos (CRUSTA), Lages, Brazil
e-mail: anderson.balbino@ufrpe.bre-mail: marcelo.pinheiro@unesp.bre-mail: harry.boos-junior@icmbio.gov.bre-mail: rodrigotorres@utfpr.edu.br

A. R. B. de Lima
Departamento de Morfologia E Fisiologia Animal (DMFA), Universidade Federal Rural de Pernambuco (UFRPE), Dom Manuel de Medeiros, S/N, Zip Code, Recife, PE 52171-900, Brazil
e-mail: anderson.balbino@ufrpe.br

M. A. A. Pinheiro
Instituto de Biociências (IB)Departamento de Ciências Biológicas E AmbientaisLaboratório de Biologia da Conservação de Crustáceos E Ambientes Costeiros (LBC), Universidade Estadual Paulista (UNESP), Campus Do Litoral Paulista (CLP), Praça Infante Dom Henrique, S/N, Zip codeSão Vicente, São Paulo 11330-900, Brazil
e-mail: marcelo.pinheiro@unesp.br

H. Boos
Centro Nacional de Pesquisa E Conservação da Biodiversidade Marinha Do Sudeste E Sul (CEPSUL), Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio), Carlos Ely Castro, 195, Zip Code, Itajaí, SC 88301-445, Brazil
e-mail: harry.boos-junior@icmbio.gov.br

Published online: 02 September 2025

$p < 0.001$). *G. grapsus* experienced more significant genomic damage due to its exposure at Porto de Santo Antônio Beach, a major tourist site, while *J. lagostoma* presented lower damage in the less disturbed Dolphin Trail. On average, *G. grapsus* had a 1.5-fold higher microlesion index (240.1 DI) than *J. lagostoma* (159.0 DI), highlighting interspecific differences. These findings highlight island ecosystems' vulnerability and the urgent need for conservation strategies to mitigate tourism-induced genomic damages in biota.

Keywords DNA lesions · Tourism impact · *Johngarthia lagostoma* · *Grapsus grapsus*

Introduction

The effectiveness of Marine Protected Areas (MPAs) in preserving biodiversity remains a highly debated topic. Within these areas, conflicts of interest have led to varying approaches to land use, occupation, and access to natural resources (Jeronymo et al., 2021). As a result, the core objective of MPAs—conserving ecosystems, ecological processes, and species—has been increasingly challenged by human expansion and resource exploitation. Consequently, anthropogenic pressure is the primary reason for implementing effective management plans to mitigate negative human impacts and preserve ecological integrity (Geldmann et al., 2019; Jeronymo et al., 2021; Witt et al., 2023).

Given the significant advancements in environmental science and technology, it is no longer justifiable to establish ecological management protocols that lack a foundation in scientific evidence. Scientific knowledge provides essential tools for MPA planning and management, enhancing the effectiveness of conservation efforts. However, this knowledge remains underutilized and insufficiently integrated into management plans for MPA (Mills et al., 2020).

A primary concern regarding Fernando de Noronha is that oceanic island ecosystems are highly vulnerable to environmental disturbances, requiring stronger protective measures (Delgado & Riera, 2020; Delgado et al., 2017; Fernandes & Pinho, 2017; Pereira et al., 2024). Due to their high biological value (Delgado et al., 2017; Kueffer & Kinney, 2017) and limited ability to recover from ecological impacts (Delgado & Riera, 2020), these islands demand specific conservation strategies. Tourism-related activities further exacerbate their vulnerability, as their natural beauty and habitat diversity attract many visitors (Ma et al., 2020). These impacts can be long-lasting and, in some cases, irreversible, threatening the stability of island ecosystems (Nogué et al., 2021).

Fernando de Noronha is recognized for its ecological significance. It is classified as a World Natural Heritage Site by UNESCO (Pereira et al., 2024) and a priority MPA for conserving endemic species and marine communities in the South Atlantic (Araújo et al., 2023). This archipelago is in the Atlantic Ocean (03°51′ S–32°25′ W), northeast of Brazil, covering 26 km^2 and comprising 21 volcanic islands (Araújo et al., 2023; Pereira et al., 2024). Two MPA define the archipelago: the Fernando de Noronha Marine National Park (PARNAMAR–3°45′ S to 3°56′ S/32°20′ W), which accounts for 70% of its total area, and the Environmental Protection Area (APA) of Fernando de Noronha-Rocas-São Pedro and São Paulo (3°45′ S to 3°57′ S/32°19′ W to 32°41′ W), occupying the remaining 30% (Araújo et al., 2023; Pereira et al., 2024). The resident population of approximately 3500 people lives within the APA on the main island. However, tourism, the archipelago's primary economic activity, significantly increases the transient population, with over 123,000 visitors recorded in 2023 (Globo, 2024).

Like other island ecosystems, Fernando de Noronha has faced governance failures, particularly in tourism control (Fioravanso & Nicolodi, 2021; Pereira et al., 2024). Globally, tourism is recognized as a major driver of environmental degradation in these settings (Bennett & Dearden, 2014; Carvalho et al., 2016; Rees et al., 2015). In Fernando de Noronha, environmental challenges resemble those of urban areas, exacerbated by weak institutional integration and non-compliance with environmental regulations, contributing to socio-environmental conflicts. The current situation could lead to social, ecological, and economic collapse (Bennett & Dearden, 2014; Pereira et al., 2024).

Unusually, tourism's influence on the archipelago was temporarily interrupted when Fernando de Noronha was closed to visitors on March 21, 2020, due to the COVID-19 pandemic. Within days, the floating population of around 7100 people per month dropped to approximately 3500, matching the resident population

(CNN, 2021). The island remained closed until September 1, 2020, when access was granted only to individuals who had recovered from SARS-CoV-19 (Globo, 2020; Correio Brasiliense, 2020). About 2 weeks later, entry was permitted to vaccinated individuals who tested negative, following strict health protocols (Folha de Pernambuco, 2020). These restrictions provided a unique opportunity to study the effects of tourism on the archipelago. The temporary decline in visitors allowed researchers to monitor the gradual return of tourism and assess its ecological impact. Strengthening the link between science and society, this study aimed to evaluate the effects of tourism in Fernando de Noronha by analyzing genomic damage in two sentinel crab species: *Grapsus grapsus* (Linnaeus, 1758), a crab inhabiting intertidal rocky shores, and *Johngarthia lagostoma* (H. Milne Edwards, 1837), a terrestrial crab distributed only in terrestrial environments.

Measuring genomic damage in sentinel species, such as DNA macrolesions through the micronucleus assay (MN‰) and microlesions using the comet assay (CO), offers a direct and sensitive assessment of exposure to genotoxic environmental stressors (Picinini-Zambelli et al., 2025). These biomarkers have been widely applied in ecotoxicological studies across various coastal ecosystems (Truchet et al., 2025), including mangroves and estuaries (Lima et al., 2019; Silva et al., 2024), as well as in Marine Protected Areas (Pinheiro et al., 2013). Their use enables the early detection of sublethal effects on biota, often preceding visible signs of ecological degradation. This approach strengthens ecological monitoring, supports the identification of pollution sources, and informs conservation and management strategies (Adam et al., 2023). Therefore, genotoxic biomarkers in sentinel species represent a robust tool for assessing the environmental quality of sensitive or impacted habitats.

The aim of this study was to assess the environmental effects of intensified tourist activity in Fernando de Noronha by applying genomic damage quantification techniques, using two crab species as sentinel organisms.

Material and methods

After the admission of non-infected and/or vaccinated individuals to the island was permitted, researchers were able to initiate sampling campaigns on *Grapsus grapsus* and *Johngarthia lagostoma*. The first sampling occurred in October 2020, followed by subsequent campaigns in July 2021, October 2021, February 2022, and June 2022.

Study area

Two collection sites were established on the main island of the archipelago (Fig. 1): Dolphin Trail (DT) and Porto de Santo Antônio Beach (PSAB). These sites represent distinct environments: DT, a terrestrial area within the Marine National Park, where *Johngarthia lagostoma* was collected; and PSAB, a rocky coastal area within the Environmental Protection Area (APA), where *Grapsus grapsus* was sampled.

Sentinel species

Johngarthia lagostoma is a terrestrial crab species belonging to the family Gecarcinidae, one of the most adapted to terrestrial life (Marin & Tiunov, 2023; João et al., 2023) and has an omnivorous diet (Entringer-Jr & Srbek-Araujo, 2023; Teschima et al., 2016). It is endemic to only four oceanic islands in the Atlantic Ocean. From the juvenile phase, this species is found exclusively in terrestrial environments (e.g., from beaches to mountains, generally associated with grassy and arboreal forests), among the main areas of tourism impacts.

Conversely, *Grapsus grapsus* is a semi-terrestrial crab from the family Grapsidae, inhabiting intertidal rocky coastal environments on tropical and subtropical oceanic islands in the Atlantic and Pacific Oceans, where both terrestrial and marine factors influence its behavior. This species is also omnivorous, feeding on a wide range of food items, from algal matrices on rocks to newborn seabirds and turtles (Teschima et al., 2016), representing the aquatic matrix, which is also impacted by human activities. The contrasting feeding habits and lifestyles of these species translate into distinct associations with biotic and abiotic matrices (Pinheiro et al., 2021), making them valuable sentinel species for monitoring environmental quality (Adam et al., 2023).

All specimens collected in Fernando de Noronha were adult males, with carapace widths exceeding the species-specific maturity sizes (*G. grapsus*: 51.4 mm, Freire et al., 2011; *J. lagostoma*: 58.0 mm, João

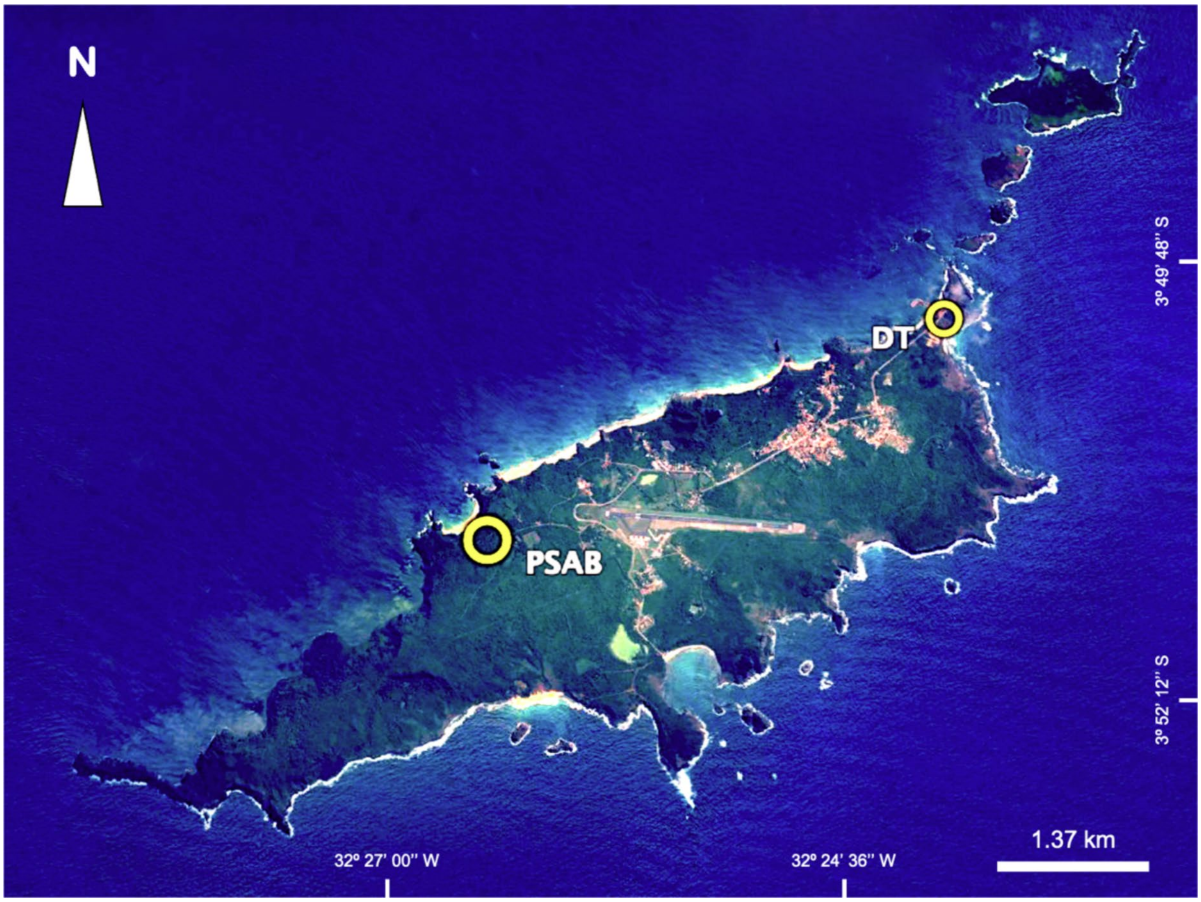

Fig. 1 Map of Fernando de Noronha Island, a Brazilian oceanic archipelago in the South Atlantic Ocean. Sampling locations are indicated on the map: DT (Dolphin Trail; 3°50′10.00″S, 32°23′60.00″W) and PSAB (Porto de Santo Antônio Beach; 3°51′26.00″S, 32°26′30.00″W). A north arrow and scale bar are included for spatial reference. Image source: Google Earth™, CNES/Airbus, Maxar Technologies, Copernicus. Image date: July 23, 2023. Coordinates in WGS84 format

et al., 2022). As recommended by Pinheiro et al. (2012) and Duarte et al. (2016), this ensured sex and maturity standardization, minimizing biomarker bias and enhancing size homogeneity for more reliable comparisons. Size uniformity also favors consistent responses to chronic contaminant exposure, reducing confounding effects. The carapace width was measured using a plastic reference template, and only mature individuals were selected.

Sampling of biological material from sentinel species

A total of ten animals of each species were collected during each expedition, from which 0.5 mL of hemolymph was extracted using syringes containing 0.1 mL of hemolymph anticoagulant. A drop of this mixture was placed on a microscope slide to prepare a smear. Two slides per animal were made for the subsequent analysis of genomic macrolesions using the Micronucleus Assay. The remaining cellular solution was stored in Eppendorf tubes, protected from light, for transport to the processing site and preparation for the analysis of micro lesions using the comet assay.

The microlesion analysis could not be performed on the animals collected in June 2022 due to field sampling issues. After the biological material was collected, all animals were released at their original capture sites. The environmental agency authorized the sampling procedure (License SISBIO/ICMBio #75,834).

Table 1 Statistical summary of the genome macrolesions (MN, micronucleus assay as MN cells/1000) and genome microlesions (CO, comet assay as damage index) for two crab species (*Johngarthia lagostoma* and *Grapsus grapsus*) at Fernando de Noronha Archipelago from samples obtained between October 2020 to June 2022, in function of the number of tourists (NT). *n*, number of samples; *Min*, minimum; *Max*, maximum; *x*, mean; *s*, standard deviation

Month/year	MN (MN cells/1000)				CO (damage index)				NT*
	n	Min	Max	$x \pm s$	*n*	Min	Max	$x \pm s$	
Johngarthia lagostoma									
Oct 2020	10	2	6	3.2 ± 1.4	10	104	144	119.1 ± 12.5	3261
Jul 2021	10	4	13	8.5 ± 3.0	10	109	152	126.5 ± 13.8	10,367
Oct 2021	10	7	12	9.4 ± 1.9	10	122	198	159.0 ± 21.2	12,085
Feb 2022	10	5	13	8.8 ± 2.7	10	216	252	231.5 ± 9.5	10,918
Jun 2022	8	3	19	7.6 ± 5.1	-	-	-	-	10,535
Total	**48**	**2**	**19**	**7.5 ± 3.6**	**40**	**104**	**252**	**159.0 ± 47.2**	
Grapsus grapsus									
Oct 2020	10	3	8	5.4 ± 1.8	10	157	201	184.7 ± 12.4	3261
Jul 2021	8	3	11	7.3 ± 2.4	10	209	242	228.4 ± 10.6	10,367
Oct 2021	10	8	14	10.2 ± 2.2	10	214	289	244.0 ± 23.5	12,085
Feb 2022	10	7	10	8.0 ± 1.2	10	278	335	303.1 ± 16.4	10,918
Jun 2022	10	5	11	7.5 ± 1.8	-	-	-	-	10,535
Total	**48**	**3**	**14**	**7.7 ± 2.4**	**40**	**157**	**335**	**240.1 ± 45.8**	

Genotoxicity tests

Both laboratory procedures for genome damage used in this study followed the protocols described by Adam et al. (2023). The results for DNA microlesions (comet assay) were expressed as DNA damage levels, quantified by tail length, percentage of tail DNA, and tail moment, during electrophoresis. In contrast, the macrolesions (micronucleus assay) results were expressed as the number of micronucleated cells per 1000. As previously mentioned, the number of tourists visiting the island during the sampling months was obtained from data provided by the Fernando de Noronha State District Administration.

Statistical analyses

Statistical analyses were performed in R Core Team (2021) using the methods described by Sokal and Rohlf (2003). Empirical data on quantitative variables of DNA damage (microlesions, assessed by the comet assay; and macrolesions, evaluated by the micronucleus assay) were first subjected to a normality test (Shapiro–Wilk, SK) and a variance homogeneity test (Levene, L). If normality and homoscedasticity were confirmed, means were compared using ANOVA followed by Tukey's HSD post hoc test. If these assumptions were not met, means were compared using the Kruskal–Wallis test, followed by Nemenyi's post hoc test (Pohlert, 2014; Zar, 1999). Thus, data for each variable for *J. lagostoma* and *G. grapsus* were compared between sampling months based on their statistical assumptions, with a 5% significance level.

Results

The DNA macrolesion (MN) variable for both species met the assumptions of normality (Shapiro–Wilk test: $SW \geq 0.952$, $P \geq 0.553$) and homogeneity of variances (Levene's test: $L \geq 0.309$, $P \geq 0.667$). Accordingly, each dataset was analyzed by ANOVA, followed by Tukey's HSD post hoc test when appropriate. The monthly averages of DNA macrolesions (MN) for both species followed the same variation trend, with this biomarker being associated with the impact caused by tourism activity (Table 1, Fig. 2). The lowest MN averages recorded for both species occurred in October 2020 (*J. lagostoma*, 3.2 MN/1000; *G. grapsus*, 5.4 *MN*/1000), linked to a lower tourism impact in this same month (3261 tourists). These averages significantly contrasted with those of this parameter in subsequent months, from July 2021 to June 2022 (*J. lagostoma*, 7.6 to 9.4 million per 1000; $F = 7.17$, $P < 0.001$; and *G. grapsus*, 7.3 to 10.2 million per 1000; $F = 6.26$; $P < 0.001$), when the tourism impact exceeded 10,000 tourists.

The DNA microlesion (CO) variable showed homogenous variances between species (Levene's test:

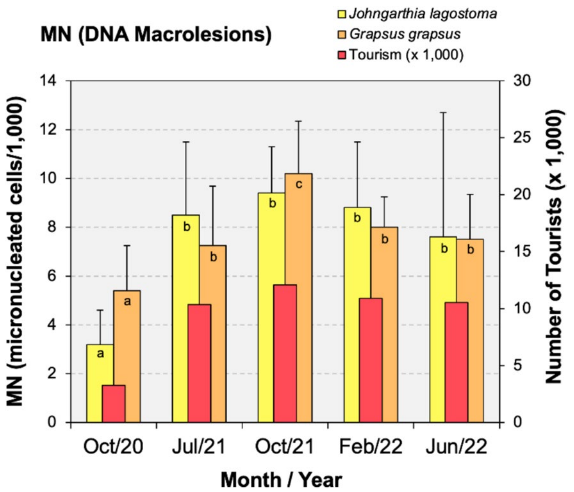

Fig. 2 Genome-damaging by macrolesion data (MN, micronucleus assay) registered for two crab species (*Johngarthia lagostoma* and *Grapsus grapsus*) at Fernando de Noronha Archipelago from samples obtained between October 2020 and June 2022; bars, biomarker mean; vertical line, the standard deviation of the means. Means of the same species associated with different letters have statistically significant differences ($P<0.05$) by ANOVA followed by Tukey HSD post hoc test

$L=0.030$, $P=0.864$), but normality was only confirmed for *G. grapsus* (Shapiro–Wilk: SW = 0.958, $P=0.160$; *J. lagostoma*: SW = 0.857, $P=0.00013$). Thus, comparisons were made using the Kruskal–Wallis test with Nemenyi's post hoc.

This analysis revealed a gradual increase in the averages of microlesions over the 18-month study period (Table 1, Fig. 3), with the damage index rising by 1.6 to 1.9 times for *G. grapsus* and *J. lagostoma*, respectively, when comparing the averages from October 2020 (the first month of analysis) to February 2022 (the final month of analysis).

A gradual and significant increase in microlesions (CO) was detected over the months in both species (*G. grapsus*: KW = 33.04, $P<0.0001$; and *J. lagostoma*: KW = 30.49, $P<0.0001$), with a more pronounced pattern in *G. grapsus*, as indicated by its higher values (184.7–303.1) compared to *J. lagostoma* (119.1–231.5). Nonetheless, both species showed similar relative variation (45.8% and 47.2%, respectively).

It is also important to note that the two crab species responded differently to anthropogenic impact (number of tourists). In *G. grapsus*, a significant contrast in the damage index averages emerged starting in the second month of analysis (July 2021), coinciding with a 3.2-fold increase in monthly tourist numbers compared to the initial analysis in October 2020. In contrast, *J. lagostoma* was only observed starting from the third month of analysis (October 2021), when the tourism impact had risen 3.7-fold compared to the initial analysis (October 2020).

The genotoxic impact (MN) showed a positive correlation with tourism intensity (NT) for both species ($r \geq 0.850$), although this association was only significant for *J. lagostoma* ($r=0.995$; $P<0.0001$) (Fig. 4A). Nevertheless, the fit of the points using a simple linear function was significant when these two species were evaluated separately in terms of the relationship between *MN vs. NT—J. lagostoma* ($MN = 0.0007 \cdot NT + 0.904$; $R^2 = 0.990$) and *G. grapsus* ($MN = 0.0004 \cdot NT + 3.73$; $R^2 = 0.726$)—or grouped ($MN = 0.0006 \cdot NT + 2.32$; $R^2 = 0.848$) (Fig. 4B), enabling the conversion between these variables in each case.

Regarding the total genome damaging (MNs) analyses conducted for the two species, the mean frequency of micronucleated cells (*J. lagostoma*, 7.5 ± 3.6 MN‰; *G. grapsus*, 7.7 ± 2.4 MN‰) did not differ significantly ($F=0.16$; $P=0.688$). Overall, the MN‰ results for both species in Fernando

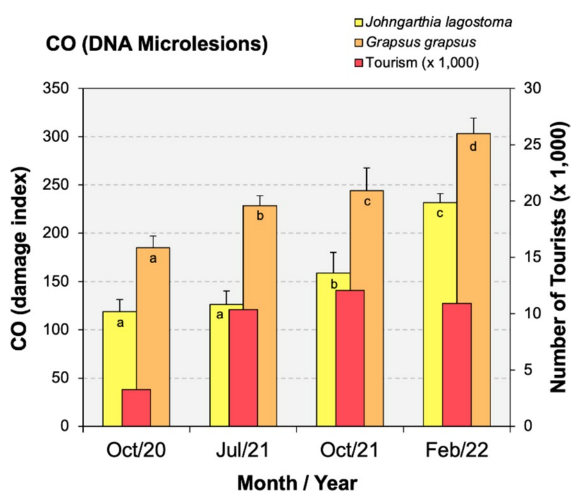

Fig. 3 Genome-damaging by microlesion data (CO, comet assay) registered for two crab species (*Johngarthia lagostoma* and *Grapsus grapsus*) at Fernando de Noronha Archipelago from samples obtained between October 2020 and February 2022; bars, biomarker mean; vertical line, the standard deviation of the means. Means of the same species associated with different letters have statistically significant differences ($P<0.05$), by Kruskal–Wallis, followed by Nemenyi's post hoc test

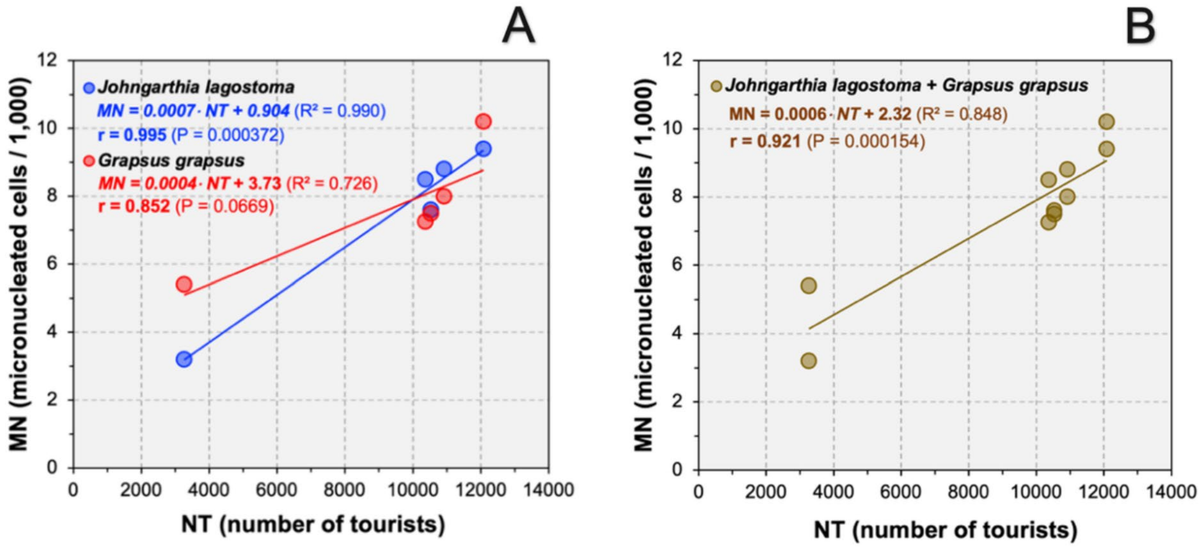

Fig. 4 Regression analysis and correlation to the relationship *MN* (micronucleated cells/1000) *vs. NT* (number of tourists) registered at Fernando de Noronha Archipelago (Brazil) for *Johngarthia lagostoma* and *Grapsus grapsus*, in 5 months comprising from October 2020 to June 2022 for each species separately (**A**) and grouped (**B**)

de Noronha were much higher than those observed on Trindade Island (*J. lagostoma*, 1.3 ± 1.2 MN‰; $F = 28.18$, $P < 0.0001$; *G. grapsus*, 4.6 ± 4.2 MN‰; $F = 10.21$, $P = 0.0023$), showing 5.8 and 1.7 times increases, respectively.

On the other hand, there was a significant contrast between the two species regarding genome microlesions (comet assay), with the mean value for *G. grapsus* (240.1 ± 45.8 DI) being 1.5 times higher than that of *J. lagostoma* (159.0 ± 47.2 DI) (Kruskal–Wallis: KW = 32.35; $P < 0.0001$).

Discussion

The fragility of an environment is often only revealed over time. In this context, quantifying genome damage in sentinel species can uncover the impact of potential environmental stressors, even when they may not initially appear harmful. This is evident in the case of tourism in Fernando de Noronha. The results of this study demonstrated a growing effect of genome damage in sentinel species (*Grapsus grapsus* and *Johngarthia lagostoma*) as tourism intensified on the island following the lifting of visitation restrictions imposed during the COVID-19 pandemic.

Both sentinel species responded negatively to the increase in tourists on the island, exhibiting high levels of genome damage, as indicated by the presence of micronucleated cells and microlesion indices. Comparatively, *J. lagostoma* exhibited lower impacts than *G. grapsus*, generally showing lower genotoxic effects as measured by both biomarkers: micronucleus (MN) and comet (CO) assays. This may reflect the terrestrial habits of *J. lagostoma*, suggesting that tourism impacts insular terrestrial habitats as well, although to a lesser extent than aquatic environments.

The Dolphin Trail, where *J. lagostoma* was sampled, is located within the Marine National Park and is primarily used for dolphin-watching, as dolphins use the bay for feeding and reproduction. This land-based tourist attraction contrasts with the island's main draw—its beaches and the opportunity to observe dolphins from boats during tourist excursions. As a result, visitation to the trail is comparatively lower than to the island's main beaches. However, despite the lower human footprint in the trail area, we still detected associated genome disturbance effects. This difference may have contributed to the lower expression of genome damage in *J. lagostoma* compared to *G. grapsus*, as specimens of *G. grapsus* were collected on the rocky coast from one of the most visited beaches on the island, Porto de Santo Antônio Beach.

Porto de Santo Antônio Beach, part of the Environmental Protection Area (APA), serves as a port and receives numerous boats for tourist excursions, sport fishing, diving, and island supply operations, resulting in a high number of daily visitors. The disparity in genome damage between the two species likely reflects the different characteristics of their sampling sites. This conclusion is further supported by the rising microlesion indices in *G. grapsus* starting from the second sampling (July 2021), when tourism increased 3.7 times compared to October 2020. In contrast, in *J. lagostoma* (a more terrestrial species), microlesion indices (comet assay) only increased in October 2021, 3 months later. These findings suggest that tourism may have a faster and more pronounced impact on environments with a higher influence on the water.

Importantly, this hypothesis can serve as foundational evidence to support the development of new and updated regulations addressing the frequency and intensity of human activities in aquatic insular environments. Specifically, this includes controlling the number of tourists and regulating the frequency and number of boats operating in Marine Protected Areas (MPAs).

It is also worth noting that no entrance fee is charged for accessing Porto de Santo Antônio Beach, making it one of the few freely accessible beaches on the island. In contrast, a fee is required to visit the beaches and attractions within the Marine National Park, where the Dolphin Trail is located. The easy access to Porto de Santo Antônio Beach likely contributes to its higher visitation rates, including by island residents, leading to a more significant impact, as demonstrated by the higher frequency of genome damage in *G. grapsus*.

The influence of human activity on the environment of Fernando de Noronha was also highlighted by Araújo et al. (2023). Similar to the genotoxic impacts observed in crabs in this study, Araújo et al. (2023) reported high genotoxic effects in shark species, *Negaprion brevirostris* (Poey, 1868) and *Galeocerdo cuvier* (Péron & Lesueur, 1822), sampled in Fernando de Noronha, using two genomic damage biomarkers (micronuclei and nuclear morphological alterations). The researchers attributed this high impact to surfactants in the water, which were linked to the large influx of tourists on the island. Surfactants, commonly found in cleaning products, cosmetics, and pesticides, are closely associated with human activities and are released into the island's environment due to inadequate waste treatment and sanitation systems (Araújo et al., 2023).

In a separate study, Araújo et al. (2024) also found various metals in the blood of the same shark species, which exhibited high levels of genome damage in their erythrocytes. This research similarly linked these effects to anthropogenic activities and the island's inadequate waste management and environmental policies.

Fernando de Noronha faces challenges like those of many Environmental Protection Areas in Brazil and globally, particularly regarding management (Belsoy et al., 2012; Fioravanso & Nicolodi, 2021; Sezerel & Karagoz, 2023; Witt et al., 2023). In this context, the absence of a strategic sustainability plan for the island's activities has become a significant concern. Currently, Fernando de Noronha lacks a Local Tourism Plan. However, the findings of Araújo et al. (2023), Araújo et al. (2024), and this study provide strong scientific evidence to support the urgent development of such a plan. These studies encompass vertebrate and invertebrate species inhabiting terrestrial and aquatic environments under different ecological conditions, allowing for a comprehensive and integrative approach.

The existing policy falls under the Integrated Sustainable Tourism Development Plan for the Costa dos Arrecifes region, developed in 2012 (Pereira et al., 2024). This plan's outdated nature, combined with insufficient enforcement, has hindered the archipelago's sustainable development. Some non-governmental organizations have attempted to create educational and awareness programs promoting sustainable tourism in Fernando de Noronha. However, these efforts have not addressed the island's broader ecological challenges (Pereira et al., 2024).

A 2007 study established Fernando de Noronha's carrying capacity, estimating the island's global capacity at 6000 people. At that time, the Environmental Vulnerability Index (EVI) had already classified the island as a "highly vulnerable environment." Despite these estimates, and with a resident population of approximately 3300 people in 2024 (IBGE, 2024), the floating population of tourists significantly contributes to the ecosystem's degradation, as evidenced by the genome damage observed in sentinel species.

The maximum carrying capacity determined by the island's administration permits a daily flow of 675 visitors. However, in contrast to the regulations designed to ensure sustainability, tourism growth has resulted in a daily flow of 812 tourists. In 2021, the island received 114,106 tourists (Pereira et al., 2024). Recent data comparing the first six months of 2023 (50,235 tourists) with the same period in 2024 show a 13.36% increase, reaching 56,948 tourists in 2024 (ICMBio, 2024).

This scenario raises concerns about the proportionality of ecological and biological disturbances, including those at the genomic level, which are not immediately visible to the naked eye but are demonstrated in this study.

The apparent failure to regulate the island's visitor population has compromised its environmental health, biodiversity, and overall ecosystem, deviating from the conservation goals of its protected areas. Therefore, the results highlight the urgent need to establish continuous monitoring programs and implement an effective tourism management plan in Fernando de Noronha to mitigate the environmental impacts on its two Marine Protected Areas.

Conclusions

Our analysis identified a strong correlation between tourist activity and DNA damage, particularly in *J. lagostoma*. *Grapsus grapsus* exhibited significantly greater genomic damage, especially at Porto de Santo Antônio Beach (a major tourist hotspot), whereas *J. lagostoma* showed lower levels of damage along the less disturbed Dolphin Trail. On average, the microlesion index in *G. grapsus* was 1.5 times higher than in *J. lagostoma*, underscoring clear interspecific differences. These findings highlight the vulnerability of island ecosystems and underscore the urgent need for effective conservation strategies to mitigate the genomic impacts of tourism on local biota.

The use of sentinel species and specific genetic, physiological, and enzymatic biomarkers offers a promising approach for identifying contaminants and assessing environmental quality on oceanic islands. In the case of *J. lagostoma*, a species threatened with extinction in Brazil, effective monitoring depends on validating these biomarkers by integrating their responses, testing interactions with known pollutants (e.g., metals and microplastics), and prioritizing non-lethal methods. This strategy enables the early detection of environmental changes and supports timely actions by environmental agencies.

Acknowledgements The authors thank the Integrated Management Team of the Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio) in Fernando de Noronha and the anonymous reviewers for their valuable contributions.

Author Contributions All authors (M.L.A., A.R.B.L., M.A.A.P., H.B., and R.A.T.) contributed to the writing of the main manuscript, preparation of figures, and critical revision of the content. M.L.A., M.A.A.P., and R.A.T. were responsible for the conceptualization of the study and conducted the formal analysis. H.B. coordinated the project and was in charge of its administration.

Funding Funds supporting this study were provided by Instituto Chico Mendes de Conservação da Biodiversidade—ICMBio [Project "Toxicidade genética de *Johngarthia lagostoma* e *Grapsus grapsus*, como sentinelas da qualidade Ambiental em ambientes insulares brasileiros: o caso do turismo em Fernando de Noronha (PE-Brasil)]. MAAP is also financial support provided by the Research Productivity Fellowship (CNPq Proc. no. 305957/2019–8).

Data Availability No datasets were generated or analysed during the current study.

The authors declare no competing interests.

Declarations

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Competing interests The authors declare no competing interests.

References

Adam, M. L., Torres, R. A., Boos, H., & Pinheiro, M. A. (2023). Espécies sentinelas: Monitoramento Ambiental com base em biomarcadores de efeito cito- e genotóxico. *Revista CEPSUL - Biodiversidade e Conservação Marinha,12*, Article e2023002. https://doi.org/10.37002/revistacepsul.vol12.2333e20230002

Araújo, C., Carneiro, P., Fidelis, L., Nascimento, B., Antunes, M., Viana, D., Oliveira, P., Torres, R., Hazin, F., & Adam, M. (2023). Comparative genomic damage among three shark species with different habits: Sublethal impacts of human origin in a protected island environment in the South Atlantic. *Marine Pollution*

Bulletin, 191, Article 114924. https://doi.org/10.1016/j.marpolbul.2023.114924

Araújo, C. B. B., Mendonça, S. A., Viana, D., Martins, M. F., Costa, P. G., Bianchini, A., Oliveira, P. G. V., Torres, R. A., Hazin, F. I., & Adam, M. L. (2024). Effects of blood metal(loid) concentrations on genomic damages in sharks. *Environmental Pollution, 359*, Article 124569. https://doi.org/10.1016/j.envpol.2024.124569

Belsoy, J., Korir, J., & Yego, J. (2012). Environmental impacts of tourism in protected areas. *Journal of Environment and Earth Science, 2*, 64–73.

Bennett, N. J., & Dearden, F. (2014). Why local people do not support conservation: Community perceptions of marine protected area livelihood impacts, governance and management in Thailand. *Marine Policy, 44*, 107–116. https://doi.org/10.1016/j.marpol.2013.08.017

Correio Brasiliense. (2020). Fernando de Noronha reabre apenas para turistas que já tiveram covid-19. Mariana Fernandes. Retrieved October 3, 2024, from https://www.correiobraziliense.com.br/brasil/2020/08/4871605-fernando-de-noronha-reabre-para-turistas-que-ja-tiveram-covid-19.html

Carvalho, R. G. A., Decol, F. G., Fruet, L., & Lanzer, R. M. (2016). Um estudo sobre as atividades turísticas em seis ilhas brasileiras. *Revista Brasileira de Pesquisa em Turismo,10*, 173–188. https://doi.org/10.7784/rbtur.v10i1.879

CNN, Brasil. (2021). Isolada contra o novo coronavírus, ilha de Noronha volta no tempo. Retrieved October 3, 2024, from https://www.cnnbrasil.com.br/viagemegastronomia/noticias/isolada-contra-o-novo-coronavirus-ilha-de-noronha-volta-no-tempo/

Delgado, J. D., & Riera, R. (2020). Anthropogenic disturbances and conservation of coastal environments in an oceanic archipelago. *Journal of Integrated Coastal Zone Management,20*(4), 249–264. https://doi.org/10.5894/rgci-n267

Delgado, J. D., Riera, R., Rodríguez, R. A., González-Moreno, P., & Fernández-Palacios, J. M. (2017). A reappraisal of the role of humans in the biotic disturbance of islands. *Environmental Conservation, 44*(4), 371–380. https://doi.org/10.1017/S0376892917000236

Duarte, L. F. A., Souza, C. A., Nobre, C. R., Pereira, C. D. S., & Pinheiro, M. A. A. (2016). Multi-level biological responses in *Ucides cordatus* (Linnaeus, 1763) (Brachyura, Ucididae) as indicators of conservation status in mangrove areas from the Western Atlantic. *Ecotoxicology and Environmental Safety, 133*, 176–187. https://doi.org/10.1016/j.ecoenv.2016.07.018

Entringer-Jr, H., & Srbek-Araujo, A. C. (2023). Habitat use, non-breeding groupings and chromatic pattern in *Johngarthia lagostoma* (H. Milne Edwards, 1837) (Decapoda, Gecarcinidae) in Trindade Island, South Atlantic Ocean. *Neotropical Biology and Conservation, 18*, 83–95. https://doi.org/10.3897/neotropical.18.e101409

Fernandes, R., & Pinho, P. (2017). The distinctive nature of spatial development on small islands. *Progress In Planning,112*, 1–18. https://doi.org/10.1016/j.progress.2015.08.001

Fioravanso, A. G., & Nicolodi, J. L. (2021). Governança ambiental em áreas marinhas protegidas: O contexto do Arquipélago de Fernando de Noronha, Brasil. *Desenvolvimento e Meio Ambiente, 58*, 755–785. https://doi.org/10.5380/dma.v58i0.74152

Folha de Pernambuco. (2020). Noronha abre também para pessoas não infectadas pela Covid-19. Retrieved October 3, 2024, from https://www.folhape.com.br/economia/noronha-abre-visitacao-para-pessoas-que-ainda-nao-foram-infectadas/155829/

Freire, A. S., Pinheiro, M. A. A., Karam-Silva, H., & Teschima, M. M. (2011). Biology of *Grapsus grapsus* (Linnaeus, 1758) (Brachyura, Grapsidae) in the Saint Peter and Saint Paul Archipelago, Equatorial Atlantic Ocean. *Helgoland Marine Research,65*, 263–273. https://doi.org/10.1007/s10152-010-0220-5

Geldmann, J., Manica, A., Burgess, N. D., Coad, L., & Balmford, A. (2019). A global-level assessment of the effectiveness of protected areas at resisting anthropogenic pressures. *Proceedings of the National Academy of Sciences of the United States of America,116*(46), 23209–23215. https://doi.org/10.1073/pnas.1908221116

Globo, G1-PE. (2020). Fernando de Noronha recebe primeiros turistas desde fechamento devido à pandemia. Retrieved October 3, 2024, from https://g1.globo.com/pe/pernambuco/blog/viver-noronha/post/2020/09/05/fernando-de-noronha-recebe-primeiros-vistantes-apos-reabertura-para-turistas.ghtml

Globo, G1-PE. (2024). Fernando de Noronha recebeu mais de 123 mil turistas em 2023; São Paulo foi o principal emissor de visitantes. Retrieved October 3, 2024, from https://g1.globo.com/pe/pernambuco/blog/viver-noronha/post/2024/02/03/fernando-de-noronha-recebeu-mais-de-123-mil-turistas-em-2023-sao-paulo-foi-o-principal-emissor-de-visitantes.ghtml

IBGE – Instituto Brasileiro de Geografia e Estatística. (2024). Estimativas da população residente para os municípios brasileiros. Retrieved October 3, 2024, from https://www.ibge.gov.br/cidades-e-estados/pe/fernando-de-noronha.html

ICMBio – Instituto Chico Mendes de Conservação da Biodiversidade. (2024). Dados de visitação do Parque Nacional Marinho de Fernando de Noronha referentes ao primeiro semestre de 2024. Retrieved October 3, 2024, from https://www.parnanoronha.com.br/transparencia

Jeronymo, C. A. L., Silva, E. R., & Fonseca, K. T. (2021). The ideal of environmental protection as protected areas: A literature review. *Ciência e Natura, 43*, Article e84. https://doi.org/10.5902/2179460X63107

João, M. C. A., Duarte, R. C., Freire, A. S., Kriegler, N., & Pinheiro, M. A. A. (2023). Population biology of the endangered land crab *Johngarthia lagostoma* (H. Milne Edwards, 1837) in the Trindade Island, Brazil: Identifying crucial areas for future conservation strategies. *Marine Ecology,45*, Article e12778. https://doi.org/10.1111/maec.12778

João, M. C. A., Duarte, R. C., da Bispo Silva, L. S., Freire, A. S., & Pinheiro, M. A. A. (2022). Sexual maturity of an endemic insular land crab: Priority information toward the conservation of *Johngarthia lagostoma*. *Biological Bulletin,243*, 14–27. https://doi.org/10.1086/720581

Kueffer, C., & Kinney, K. (2017). What is the importance of islands to environmental conservation? *Environmental Conservation, 44*(4), 311–322. https://doi.org/10.1017/S0376892917000479

Lima, A. R. B., Torres, R. A., Jacobina, U. P., Pinheiro, M. A. A., & Adam, M. L. (2019). Genomic damage in *Mugil curema* (Actinopterygii: Mugilidae) reveals the effects of intense urbanization on estuaries in northeastern Brazil. *Marine Pollution Bulletin,138*, 63–69. https://doi.org/10.1016/j.marpolbul.2018.07.037

Ma, X., de Jong, M., Sun, B., & Bao, X. (2020). Nouveauté or Cliché? Assessment on island ecological vulnerability to tourism: Application to Zhoushan. China. *Ecological Indicators, 113*, 106247. https://doi.org/10.1016/j.ecolind.2020.106247

Marin, I. N., & Tiunov, A. V. (2023). Terrestrial crustaceans (Arthropoda, Crustacea): Taxonomic diversity, terrestrial adaptations, and ecological functions. *ZooKeys,1169*, 95–162. https://doi.org/10.3897/zookeys.1169.97812

Mills, M., Magris, R. A., Fuentes, M. M. P. B., Bonaldo, R., Herbst, D. F., Lima, M. C. S., Kerber, I. K. G., Gerhardinger, L. C., Moura, R. L., Domit, C., Teixeira, J. B., Pinheiro, H. T., Vianna, G., & Freitas, R. R. (2020). Opportunities to close the gap between science and practice for Marine Protected Areas in Brazil. *Perspectives in Ecology and Conservation, 18*(3), 161–168. https://doi.org/10.1016/j.pecon.2020.05.002

Nogué, S., Santos, A. M. C., Birks, H. J. B., Björck, S., Castilla-Beltrán, A., Connor, S., de Boer, E. J., de Nascimento, L., Felde, V. A., Fernández-Palacios, J. M., Froyd, C. A., Haberle, S. G., Hooghiemstra, H., Ljung, K., Norder, S. J., Peñuelas, J., Prebble, M., Stevenson, J., Whittaker, R. J., … Steinbauer, M. J. (2021). The human dimension of biodiversity changes on islands. *Science, 372*, 488–491. https://doi.org/10.1126/science.abd6706

Pereira, A. I. A., Silva, F. J. L., Candido, G. A., & Oliveira, J. E. L. (2024). Analysis of tourism sustainability in the Fernando de Noronha Archipelago, Brazil. *Revista de Gestão Social e Ambiental, 18*, e04622. https://doi.org/10.24857/rgsa.v18n4-005

Picinini-Zambelli, J., Garcia, A. L. H., & Silva, J. (2025). Emerging pollutants in the aquatic environments: A review of genotoxic impacts. *Mutation Research - Reviews in Mutation Research, 795*, Article 108519. https://doi.org/10.1016/j.mrrev.2024.108519

Pinheiro, M. A. A., Duarte, L. F. A., Toledo, T. R., Adam, M. L., & Torres, R. A. (2013). Habitat monitoring and genotoxicity in *Ucides cordatus* (Crustacea: Ucididae), as tools to manage a mangrove reserve in southeastern Brazil. *Environmental Monitoring and Assessment,185*, 8273–8285. https://doi.org/10.1007/s10661-013-3172-9

Pinheiro, M. A. A., Kriegler, N., Souza, C. A., & Duarte, L. F. A. (2021). Feeding habit and lifestyle influence the baseline micronuclei frequency of crab species in pristine mangroves. *Wetlands, 41*, 1–14. https://doi.org/10.1007/s13157-021-01427-4

Pinheiro, M. A. A., Silva, P. P. G., Duarte, L. F. A., Almeida, A. A., & Zanotto, F. P. (2012). Accumulation of six metals in the mangrove crab *Ucides cordatus* (Crustacea: Ucididae) and its food source, the red mangrove *Rhizophora mangle* (Angiosperma: Rhizophoraceae). *Ecotoxicology and Environmental Safety, 81*, 114–121. https://doi.org/10.1016/j.ecoenv.2012.05.004

Pohlert, T. (2014). The Pairwise Multiple Comparison of Mean Ranks Package (PMCMR). R package. https://CRAN.R-project.org/package=PMCMR. Accessed 13 Jan 2024

R Core Team. (2021). R: A language and environment for statistical computing [Software]. R Foundation for Statistical Computing.

Rees, S. E., Mangi, S. C., Hattam, C., Gall, S. C., Rodwell, L. D., Peckett, F. J., & Attrill, M. J. (2015). The socio-economic effects of a marine protected area on the ecosystem service of leisure and recreation. *Marine Policy,62*, 144–152. https://doi.org/10.1016/j.marpol.2015.09.011

Sezerel, H., & Karagoz, D. (2023). The challenges of sustainable tourism development in special environmental protected areas: Local resident perceptions in Datça-Bozburun. *Sustainability,15*, Article 3364. https://doi.org/10.3390/su15043364

Silva, M. R., Faial, K. C. F., Freitas, Á. C., & Fernandes, M. E. B. (2024). Use of the gonadal structures of the mangrove crab *Ucides cordatus* as a biomarker for environmental contamination by metals. *Marine Pollution Bulletin,198*, Article 115862. https://doi.org/10.1016/j.marpolbul.2023.115862

Sokal, R. R., & Rohlf, F. J. (2003). *Biometry: The principles and practice of statistics in biological research* (3rd ed.). Freeman.

Teschima, M. M., Ströher, P. R., Firkowski, C. R., Pie, M. R., & Freire, A. S. (2016). Large-scale connectivity of *Grapsus grapsus* (Decapoda) in the Southwestern Atlantic oceanic islands: Integrating genetic and morphometric data. *Marine Ecology,37*, 1360–1372. https://doi.org/10.1111/maec.12347

Truchet, D. M., Villagran, D. M., & Menone, M. L. (2025). Pollution biomarkers in Latin American and Caribbean marine environments: A review to identify gaps in passive biomonitoring studies. *Journal of Hazardous Materials Advances, 17*, Article 100554. https://doi.org/10.1016/j.hazadv.2024.100554

Witt, P. B. R., Faria, H. H., Oliveira, J., & Oliveira, L. R. (2023). Management effectiveness of nature conservation units in southern Brazil. *Neotropical Biology and Conservation,18*(3), 209–230. https://doi.org/10.3897/neotropical.18.e103019

Zar, J. H. (1999). *Biostatistical Analysis* (4th ed.). Prentice Hall.