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Effects of vehicle traffic and trampling on the macrobenthic community of Amazonian macrotidal sandy beaches

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Abstract

We report for the first time the effects of vehicle traffic and beachgoer trampling on macrobenthic communities of Amazonian sandy beaches. Sampling was performed during four consecutive months with different beach use intensity in 2017 (before, during vacation, and two months after the vacation period) on three contrasting beaches with regard to disturbance (Urban: Atalaia; Intermediate: Farol-Velho; and Protected: Corvinas) in the intertidal zone along two equidistant transects at seven equidistant sampling stations from the high-tide water mark to the swash zone. At each sampling station, four biological and sediment samples were randomly collected. Also, in each station, the sediment compaction was determined using a manual penetrometer. Physical sediment variables remained constant over time in all beaches, whereas differences were found in sediment compaction over the months. Macrobenthic community differences in density and richness among months were observed at Atalaia and Farol-Velho beaches. In contrast, Corvinas beach remained constant throughout the study period. Furthermore, the vulnerability of the polychaetes *Thoracophellia papillata*, *Scolelepis squamata* and *Paraonis* sp. indicates that they might be potential indicators of recreational activity impact.

Introduction

The natural characteristics of sandy beaches attract large numbers of people, subjecting them to increasing anthropogenic exploitation and disturbance (Hardiman & Burgin, 2010; Afghan *et al.*, 2020). Tourism is considered a significant form of human impact on sandy beaches worldwide (Davenport & Davenport, 2006; Thompson & Schlacher, 2008; Schlacher *et al.*, 2008*a*, 2008*b*, 2008*c*) and involves a wide range of activities (McLachlan & Defeo, 2017*a*). This intensive beach use has been recognized to negatively affect the natural physical characteristics of the beaches through compaction, rutting and disturbance to the sand matrix, (Anders & Leatherman, 1987; Priskin, 2003) which cause changes in beach morphology and granulometric characteristics.

These changes are particularly troublesome for the benthic community, which is controlled primarily by the physical environment, with ecosystem functioning, zonation and community structure being mainly linked to beach morphological state (see McLachlan & Defeo, 2017*a*). Thus, changes in physical features can alter species distribution patterns, which can result in a significant loss of biodiversity (Defeo *et al.*, 2009). Several studies have shown that sand compactness in sandy beaches can be affected by the intensity of several recreative activities, including the traffic of a high number of vehicles (van der Merwe & van der Merwe, 1991; Schlacher & Thompson, 2007) and human trampling (Schlacher & Thompson, 2012; Reyes-Martínez *et al.*, 2015; Machado *et al.*, 2017). Thus, sites with high compaction, reflecting firmer substrates, may be unfavourable to a wide range of benthic organisms (Santos *et al.*, 2021*a*), affecting the communities directly (e.g. by removing individuals) and/or indirectly (e.g. by affecting biological interactions) (Brosnan & Crumrine, 1994; Brown & Taylor, 1999).

Macrobenthic communities on sandy beaches are represented by most invertebrate phyla and play a major role in sandy beach ecosystem functioning (McLachlan & Defeo, 2017*a*), as they are involved in nutrient regeneration (Cisneros *et al.*, 2011) and are trophic links between marine and terrestrial systems (Dugan, 1999; Lercari *et al.*, 2010). They are also a pivotal economic asset (Maguire *et al.*, 2011) in many traditional communities, where artisanal fisheries have important socioeconomic relevance (McLachlan & Defeo, 2017*a*). Moreover, some taxa are considered good bioindicators of beach ecological condition due to their intrinsic relationship with the sediment, including taxonomic diversity, abundance and range of physiological tolerance to stress (Veloso *et al.*, 2008). Also, as most of the species generally occupy the sand matrix of the intertidal zone, they are subject to different types of mechanical impacts, such as trampling (Machado *et al.*, 2017; Costa *et al.*, 2018) and vehicle traffic (Schlacher & Thompson, 2007, 2008; Schlacher *et al.*, 2007, 2008*a*, 2008*b*).

The effects of recreational activities on faunal communities have been evaluated in different coastal environments worldwide (Rodgers & Cox, 2003; Rossi *et al*., 2007; Ferreira & Rosso, 2009; Mendez *et al*., 2017). On sandy beaches, this issue has been tackled from different perspectives (Reyes-Martinez *et al*., 2015). In general, most studies assessed the effect of these activities at the population level of some taxa of supralittoral macrofauna, such as Talitridae (Weslawski *et al*., 2000; Ugolini *et al*., 2008; Veloso *et al*., 2008, 2009; Bessa *et al*., 2017), Ocypodidae (Barros, 2001; Neves & Bemvenuti, 2006; Lucrezi *et al*., 2009; Schlacher *et al*., 2016; Costa *et al*., 2018, 2020*a*) and Cirolanidae (Veloso *et al*., 2011). However, the effects of these activities were also assessed at the community level (Schlacher & Thompson, 2012; Reyes-Martinez *et al*., 2015; Machado *et al*., 2017; Wu *et al*., 2018; Bom & Colling, 2020), and the results of the available studies showed a general negative effect of recreational activities on abundance, diversity and composition of the macrobenthic community.

The sandy beaches of the Brazilian Amazon coast are distributed along a 3900 km coastline (Klein & Short, 2016) and have considerable potential for the tourism industry (Pereira *et al*., 2016*a*, 2016*b*). Recreational activities observed on Amazonian beaches can be classified as pulse disturbances (Santos *et al*., 2021*a*) as they are strongly concentrated in short periods. In fact, some of these beaches are overcrowded during vacation periods and extended holidays (Sousa-Felix *et al*., 2017), and subject to an increasing exploration (Szlafstein, 2012), resulting in a range of anthropogenic hazards (e.g. bacteriological contamination from sewage outfalls, litter pollution) (Sousa-Felix *et al*., 2017; Pereira *et al*., 2018). Another emerging environmental problem on many Amazonian beaches is the presence of multiple motor vehicles (Pereira *et al*., 2018; Santos *et al*., 2021*a*). In fact, during vacation periods, multiple vehicles are driven onto some of the touristic beaches and serious problems have been recorded, including accidents and traffic jams (Silva *et al*., 2011; Pereira *et al*., 2018). In addition, especially during vacation periods, vehicles parking on the intertidal zone, are often trapped by the rapid rise of the tide (Silva *et al*., 2011; Pereira *et al*., 2018).

The Amazon region has been undergoing rapid economic and urban growth in recent decades (Becker, 2005), and despite its singular environmental characteristics and high economic and ecological importance, anthropogenic impacts on the benthic fauna have been poorly studied (Paula *et al*., 2007; Morais *et al*., 2020; Pinto *et al*., 2020; Ribeiro-Brasil *et al*., 2021), and studies that evaluate the effect of recreational activities on Amazonian sandy beaches are even more scarce (Santos *et al*., 2021*a*). In this context, the present study evaluated, for the first time, the impact of recreational activities on macrobenthic fauna structure and composition of three Amazonian sandy beaches with different levels of recreational activity intensity (high, intermediate and low), before, during and after a period with high tourist occupancy (July – scholar vacation). The following hypothesis was tested: high intensity of recreational activities (human trampling and vehicle traffic) causes changes in macrobenthic community structure and composition, reducing species richness and density, particularly during the vacation period in the beaches with high tourist occupancy where sediment compaction is higher.

Materials and methods

Study area

The selected beaches are located in the Atlantic coastal sector of north Brazil, one of the most densely populated areas of the Amazonian region (Sousa *et al*., 2011) with a total of 433,302 inhabitants (IBGE, 2020). The coastline is highly irregular and indented (Souza-Filho *et al*., 2005), being formed by several tide-dominated estuarine and oceanic sandy beaches (Pereira *et al*., 2016*a*), and includes the oceanic beaches most visited by tourists in the region (Pereira *et al*., 2021). This coast has semidiurnal macrotides (4–6 m) with moderated wave energy (Hs <2 m during high tides) and strong tidal currents (up to 2 m s^{-1}) (Pereira *et al*., 2013). Local climate is equatorial humid with annual mean temperature of 26–27°C and rainfall up to 3000 mm (Martorano *et al*., 1993; INMET, 2009; Pereira *et al*., 2013). The trade winds blow from the north-east in the dry and south-east in the rainy season, respectively (Klein & Short, 2016; Pereira *et al*., 2016*a*).

This study was conducted in Salinópolis city on the northern Brazilian coast (0°36′49″S 47°21′22″W) (Figure 1). Salinópolis has ~40,000 residents and its economy is based on fishing and tourism, receiving >280,000 beachgoers during July vacation (IBGE, 2020). Sampling was performed on three beaches with a variable anthropogenic pressure gradient. The Atalaia beach (considered as the Urban area) has a high level of urban development (e.g. restaurants and hotels) and high human occupancy during the summer season. The backshore is partially occupied by construction and tourism infrastructure, which have destroyed the vegetation cover and dune system (Santos *et al*., 2021*a*). In contrast, Corvinas beach (considered as the Protected area) is a pristine sector with a low level of disturbance and a well-preserved dune system and mangrove vegetation in the backshore area (Silva *et al*., 2010). This beach can only be reached on foot (Martinelli Filho & Monteiro, 2019).

The Farol-Velho beach is an intermediate sector located in the transitional area between Atalaia and Corvinas. Farol-Velho is partially urbanized with a lower level of tourism occupancy and the backshore includes construction and low tourism infrastructure (Santos *et al*., 2021*a*). Vehicles are only allowed on Atalaia and Farol-Velho beaches; however, the highest influx occurs on Atalaia beach. The beaches have similar sedimentological and morphodynamic characteristics: dissipative exposed state, gentle slope, spilling waves, and sediment comprised mainly of fine to very-fine sand (Ranieri & El-Robrini, 2015, 2016). The main hydrodynamic features are macrotides, strong coastal currents (up to 1.5 m s^{-1}) and wave energy modulated by wave attenuation on sand banks during low tide (Monteiro *et al*., 2009; Pereira *et al*., 2009; Klein & Short, 2016).

Sampling procedures

To evaluate the effects of tourism-related activities on macrofauna, four sampling campaigns were conducted on each beach (Atalaia, Farol-Velho and Corvinas) during spring tides: June 2017 – Before Vacation; July 2017 – Vacation; August 2017 – After 1 (one month after vacation); and September 2017 – After 2 (two months after vacation). Macrofauna was sampled in the intertidal zone of each beach along two across-shore transects (100 m distant from each other). Seven equidistant sampling levels (SL) were established 50 m apart from each other at each transect, from the high tide mark to the swash zone. Four samples were collected at each sampling station with a cylindrical corer (10 cm diameter and 20 cm height). After collection, samples were sieved through a 0.3 mm mesh screen and preserved in 70% ethanol stained with rose bengal. Simultaneously, sediment samples were collected from each sampling station for granulometric and organic matter content analyses using the same corer used for biological samples. Sediment compaction was determined at each station using a manual penetrometer (data in centimetres penetrated using 20 kgf cm^{-2}) with a modification of a method described by McLachlan & Defeo (2017*a*, 2017*b*).

Levels of surface disturbance were estimated using the number of vehicles and beachgoers observed on each beach. For this purpose, four campaigns were conducted (one per month on each

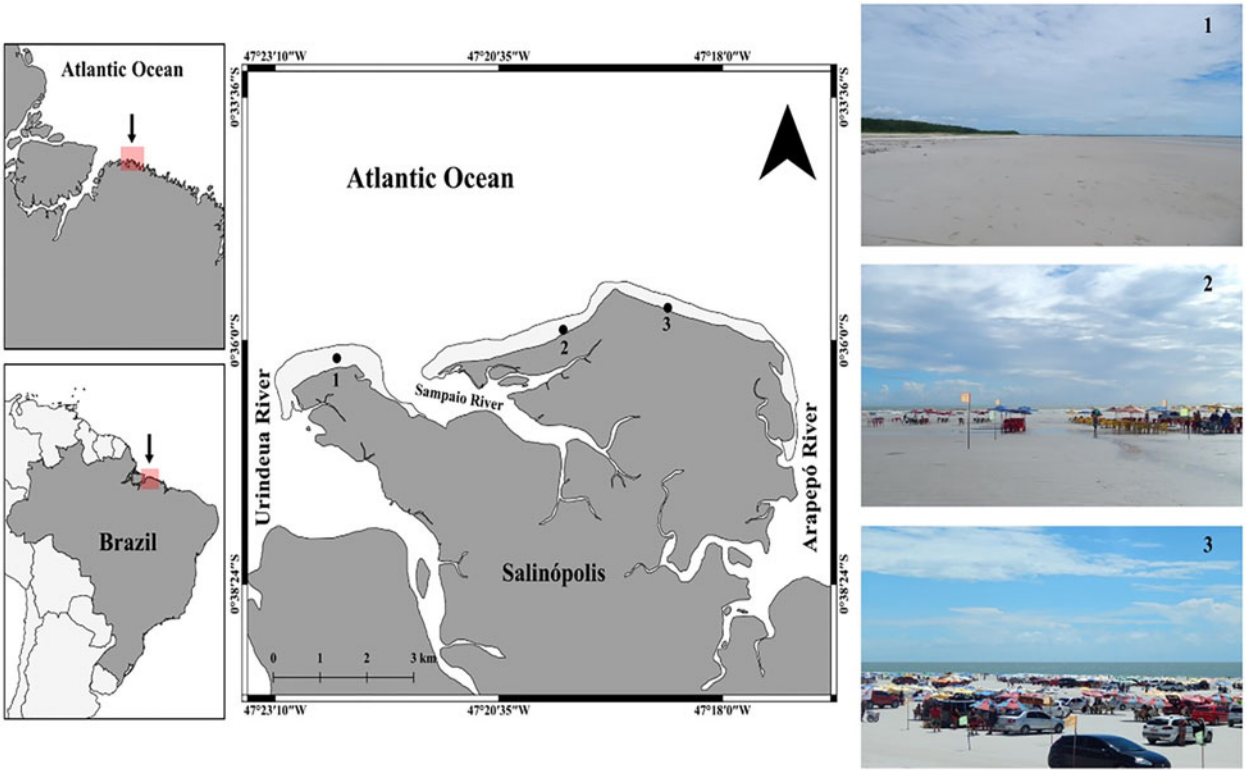

Fig. 1. Map showing the location of Salinópolis and the three sandy beaches studied (1: Corvinas – Protected area; 2: Farol-Velho – Intermediate area; 3: Atalaia – Urban area).

beach) along with biological sampling procedures. In each campaign, vehicles and beachgoers were counted in an area between two across-shore transects (100 m × 350 m) along the intertidal zone for 10 min every 30 min within a 4 h period (a total of 8 counts/beach/sampling campaign).

Laboratory procedures

Biological samples were examined under a stereoscopic microscope, and organisms were counted and identified to the lowest taxonomic level possible. Granulometric analysis was conducted by sieving the coarse sediments and pipetting the fine sediments, as proposed by Suguio (1973). Textural parameters (mean grain size, sorting, percentage of sand and gravel) were calculated using the equations of Folk & Ward (1957). Grain sizes were determined by sieving the sediment in an automatic shaker and classifying the grains according to the Wentworth scale (Buchanan, 1984). Dried samples were combusted at 550°C for 4 h to determine organic content (O.M.) (Dean, 1974).

Statistical analysis

The potential impact of recreational activities on the composition and structure of the macrofaunal community was evaluated using a modified Before/During/After/Control/Impact (BDACI) method comparing the beach that was heavily impacted by recreation with the less impacted beaches before, during and after the impact. For each biological sample, the richness (total of taxa) and density (ind. m^{-2}) were analysed using a three-way nested ANOVA (months: 'Before', 'Vacation', 'After 1' and 'After 2'; Beaches: Atalaia, Farol-Velho and Corvinas; and Sampling levels: A–G nested in beaches) after checking normality using the Kolmogorov–Smirnov and homogeneity of variance Levene's tests. When necessary, data were fourth root transformed. When ANOVA results were significant, the Tukey's test was used for pairwise comparisons.

A non-metric multidimensional scaling ordination (nMDS) of 'beach × month' interaction was performed (based on Bray–Curtis similarity) to visualize differences in macrofauna structure. The

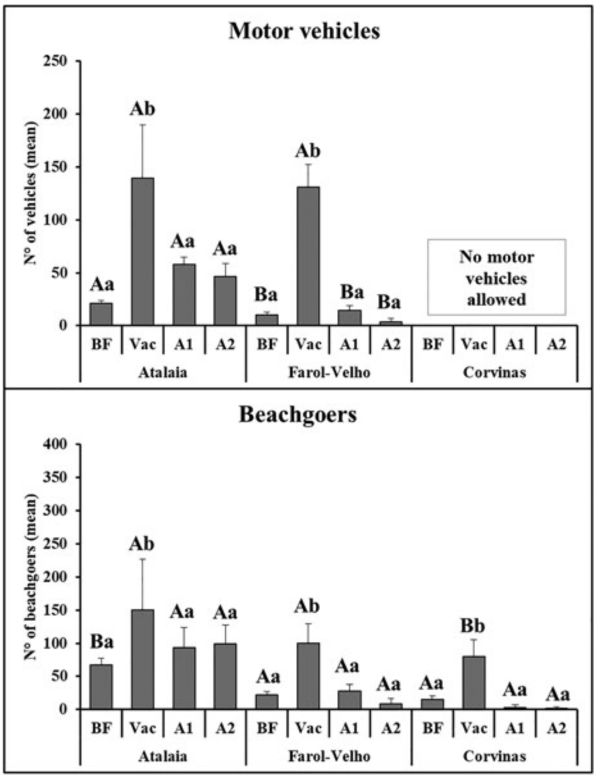

Fig. 2. Number of vehicles (A) and beachgoers (B) counted (mean ± SE) in each area in the different study periods (BF, Before vacation; Vac, during Vacation; A1, After vacation 1; and A2, After vacation 2). Different letters indicate significant differences ($P < 0.05$); uppercase letters (A≠B) indicate differences between beaches among months and lowercase letters (a ≠ b) indicate differences between months on each beach.

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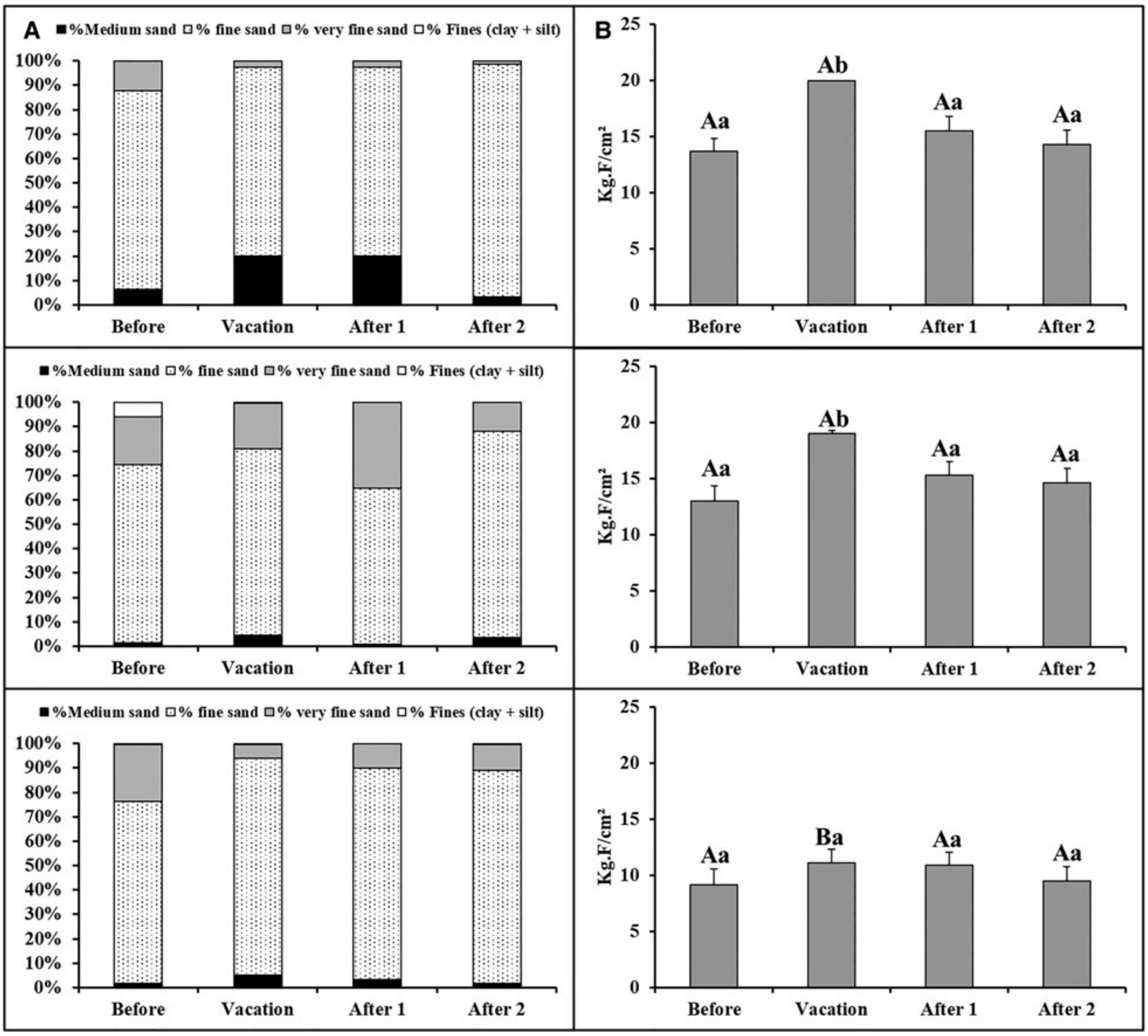

Fig. 3. Granulometric composition (%) of the sediments (A) and sediment compaction (B) in each area in the different study periods (Before, Vacation, After 1 and 2). Different letters indicate significant differences ($P < 0.05$); uppercase letters (A ≠ B) indicate differences between beaches among months and lowercase letters (a ≠ b) indicate differences between months on each beach.

contribution of each taxon to the dissimilarity (>50%) found among groups was evaluated using the SIMPER (similarity percentage) routine. Simultaneously, the similarity matrix was analysed using a permutational multivariate analysis of variance (PERMANOVA), using the same configuration as in the ANOVA. When the PERMANOVA detected a significant difference, Tukey's a posteriori test was applied to identify significant pairwise differences. A 5% significance level was considered in all analyses.

The mean number of beachgoers and vehicles obtained on each beach was used to determine the intensity of sediment disturbance caused by recreational activities in each month and the differences between beaches and months were analysed using a two-way analysis of variance (ANOVA). To detect changes in abiotic variables (grain size, sorting, % sand and % fines, % O.M., and sand compaction) a three-way nested ANOVA (months: 'Before', 'Vacation', 'After 1' and 'After 2'; Beaches: Atalaia, Farol-Velho and Corvinas; and Sampling levels: A–G nested in beaches) was performed. When ANOVA results were significant, the Tukey's test was used for pairwise comparisons. Abiotic variables were also analysed using multivariate methods (Clarke & Gorley, 2006). Multiple regression analyses were performed to assess the relationship between human beach use (number of beachgoers and vehicles) and sediment parameters, and the relationship of human beach use and sediment parameters with changes in macrobenthic density and richness.

Results

Environmental parameters and human beach use

In general, the number of vehicles and beachgoers was higher during Vacation in all beaches compared with the other months (beach × month). Both Atalaia and Farol-Velho showed significant differences compared with Corvinas during Vacation ($F_{(1.84)} = 6.38$; $P < 0.05$) with higher numbers of vehicles and beachgoers on both beaches compared with Corvinas; however, differences were not detected between Corvinas and Farol-Velho in the other months. All beaches showed the same monthly pattern, with significant differences found only between Vacation and other months (Figure 2). Data for all environmental parameters are shown in Supplementary Material 1.

Overall, the studied beaches were characterized by well-sorted fine to very-fine sand (Supplementary Material 1) with fine sand representing more than 65% of sediment composition in all

Table 1. ANOVA analysis results highlighting significance differences in the environmental parameters of the study areas

			Compaction		Grain size		Sorting		O.M.	
Factors		df	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Month		3	42.6	**	29.3	0.07	17.7	0.08	4.5	0.06
Beach		2	128.2	**	4.8	0.08	5.3	0.06	9.0	0.4
Sampling Levels (Beach)		18	2.6	**	1.4	0.1	3.8	0.06	7.7	0.1
Month × Beach		6	8.9	**	28.5	0.07	3.9	**	8.9	0.5
Month × Sampling Levels (Beach)		54	1.4	**	0.6	0.9	2.7	**	1.2	
Error		84								
Pair-wise test										
		BF × V	BF × A1		BF × A2		V × A1		V × A2	A1 × A2
Compaction		**	0.08		0.06		**		**	0.1
Sorting		**	0.5		0.3		**		**	0.1
		BF × V	BF × A1		BF × A2		V × A1		V × A2	A1 × A2
Atalaia (Ata)	Compaction	**	0.6		0.6		**		**	0.07
	Sorting	**	0.4		0.2		**		**	0.3
Farol-Velho (FV)	Compaction	**	0.6		0.1		**		**	0.4
	Sorting	0.7	0.1		0.5		0.7		0.3	0.4
Corvinas (Cor)	Compaction	0.2	0.08		0.3		0.2		0.7	0.4
	Sorting	0.2	0.6		0.2		0.4		0.08	0.1
		Ata × FV			Ata × Cor		FV × Cor			
Before (BF)	Compaction	0.07			0.06		0.2			
	Sorting	0.1			0.8		0.1			
Vacation (V)	Compaction	0.3			**		**			
	Sorting	0.5			**		0.4			
After 1 (A1)	Compaction	0.5			0.4		0.3			
	Sorting	0.3			0.7		0.6			
After 2 (A2)	Compaction	0.2			0.7		0.08			
	Sorting	0.1			0.5		0.2			

*$P < 0.05$; ** $P < 0.001$.

beaches (Figure 3A). Sediment characteristics (mean grain size, sorting and O.M.) did not differ among the beaches over the months (Table 1). However, some differences were found in sediment sorting and O.M. between months and beaches, with higher values of sorting found in Atalaia during vacation whereas higher values of O.M. were found in Corvinas beach (Supplementary Material 1). Overall, higher sand compactness was found during vacation (Figure 3B) but it differed significantly only from the values obtained in before vacation (Table 1). Atalaia beach sand was always more compacted than sand in the other beaches (Figure 3B). The multiple regression analysis showed negative correlation between recreational activities (number of beachgoers and vehicles) and sediment characteristics; however, only sediment compaction had significant correlations (Table 2).

Macrobenthic community

A total of 46 taxa were recorded (Table 3). Annelida (mainly Polychaeta) was the most diverse phylum (18 species), followed by Crustacea (16 species) and Mollusca (five species). Relative abundances of the major taxa in each beach in different months are shown in Figure 4. Before vacation, polychaeta and Bivalvia were dominant in all beaches except for Corvinas beach, where Bivalvia had lower abundance. During the vacation month, polychaetes dominated in all beaches, followed by bivalves and crustaceans in the Atalaia and insects in the Farol-Velho beach. After vacation, the abundance of crustaceans and insects increased in the Atalaia and Farol-Velho beaches. Concerning the Corvinas beach, the relative abundances of the major taxa were constant over time.

Mean densities significantly varied among treatments (Table 4) with differences mostly between Vacation and the other months (Before Vacation and After 1 and 2) in the Atalaia and Farol-Velho. Overall, higher density values occurred at Corvinas beach in all months. Regarding months, a marked decrease in density occurred in the Atalaia and Farol-Velho beaches during Vacation, when the lowest densities were recorded. In the After-vacation months (1 and 2), density increased in all beaches and the values were similar to those found before vacation (Figure 5A).

Richness also presented significant differences among treatments (Table 4). Overall, a similar macrofaunal composition was found among beaches, although higher richness was found in Corvinas beach in all months and lower richness was found during Vacation in Atalaia beach. Regarding months, a marked decrease in richness occurred in the Atalaia and Farol-Velho

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Table 2. Multiple regression results showing the correlations and levels of significance for each significant predictor environmental variable used for modelling sandy beach community attributes

	Model results											
	R			R^2			$F_{(3.80)}$			*P*		
Organic matter	0.44			0.14			3.90			**		
Mean grain size	0.41			0.13			5.46			**		
Sorting	0.36			0.10			4.09			**		
Compaction	0.78			0.61			66.68			**		
	Dependent variables											
	Mean grain size			Sorting			Compaction			Organic matter		
Independent Variables	β	*t*	*P*	β	*t*	*P*	β	*t*	*P*	β	*t*	*P*
Vehicles	0.30	2.69	**	−0.19	−1.49	0.14	0.33	3.13	**	−0.05	−0.47	0.63
Beachgoers	0.11	0.94	0.35	0.24	1.91	0.07	0.5	4.68	**	−0.14	−1.14	0.25
Mean grain size	–	–	–	0.10	1.05	0.29	−0.05	−0.72	0.47	−0.12	−1.51	0.13
Sorting	0.09	1.12	0.26	–	–	–	0.14	1.5	0.13	0.34	3.18	**
Compaction	−0.10	−0.90	0.36	0.34	1.99	**	–	–	–	0.04	0.35	0.72
Organic matter	−0.11	−1.51	0.13	0.24	2.21	0.3	0.01	0.16	0.87	–	–	–

**$P < 0.05$; β – standardized coefficients.

Table 3. ANOVA analysis and pairwise test regarding the significance of differences in descriptors of macrofaunal community of the study beaches

				Density		Richness	
Factors		df		*F*	*P*	*F*	*P*
Month		3		13.5	**	14.06	**
Beach		2		3.1	0.06	3.04	0.07
Sampling Levels (Beach)		18		7.7	**	7.4	**
Month × Beach		6		50.2	**	43.7	**
Month × Sampling Levels (Beach)		54		1.96	**	1.8	**
Error		671					
Pair-wise test							
		BF × V	BF × A1	BF × A2	V × A1	V × A2	A1 × A2
Density		**	0.4	0.9	**	**	0.1
Richness		**	0.3	0.07	**	**	0.06
		BF × V	BF × A1	BF × A2	V × A1	V × A2	A1 × A2
Atalaia (Ata)	Density	**	0.7	0.2	0.1	**	0.07
	Richness	**	0.7	0.6	**	**	0.7
Farol-Velho (FV)	Density	**	0.5	0.6	**	**	0.4
	Richness	**	0.08	0.09	0.7	**	0.1
Corvinas (Cor)	Density	0.09	0.6	0.6	0.08	0.4	0.7
	Richness	0.4	0.06	0.1	0.2	0.6	0.3
		Ata × FV		Ata × Cor		FV × Cor	
Before (BF)	Density	0.4		0.1		0.08	
	Richness	0.5		0.07		0.1	
Vacation (V)	Density	0.4		**		**	
	Richness	0.8		**		**	
After 1 (A1)	Density	0.1		**		0.1	
	Richness	0.1		**		0.4	
After 2 (A2)	Density	0.8		0.2		0.4	
	Richness	0.9		0.2		0.4	

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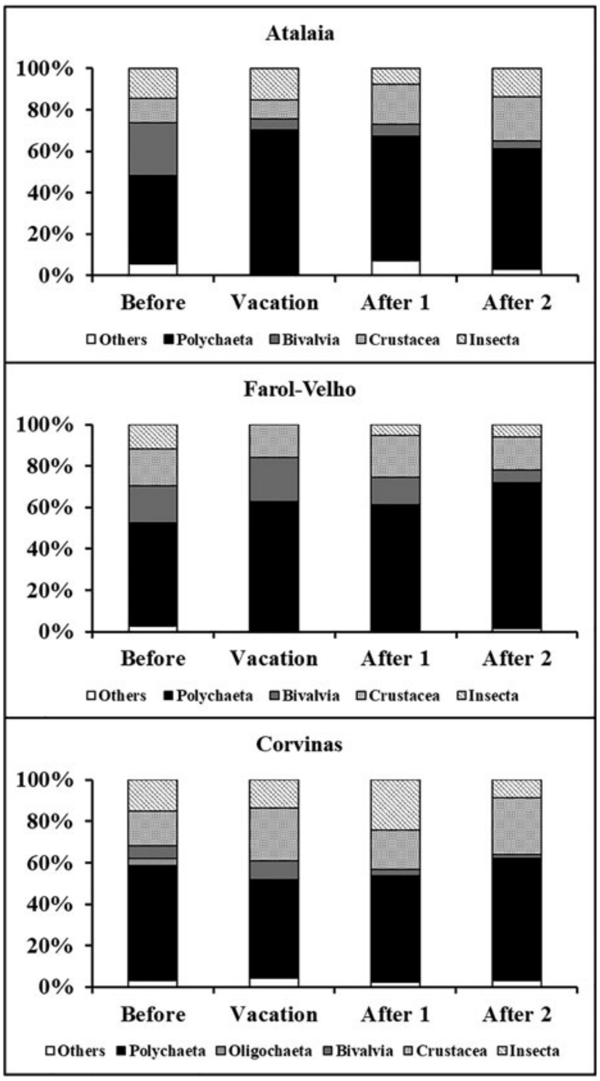

Fig. 4. Relative abundance (%) of macrobenthic community in the study beaches in the different sampling months (Before vacation, Vacation, After vacation 1 and 2).

beaches. In the After-vacation months (1 and 2), richness increased in all beaches and the values were similar to the values found before vacation (Figure 5B).

The PERMANOVA analysis showed significant differences in the macrobenthic community structure among months and beaches (Table 5). The pairwise comparisons indicated that these differences occurred especially between Before Vacation and Vacation in Atalaia and Farol-Velho beaches (Table 5). The nMDS ordination showed that samples grouped according to month. It is possible to identify in nMDS plots that Atalaia and Farol-Velho, and the Corvinas were different over time (Figure 6). In Atalaia and Farol-Velho, it is possible to identify a group of samples from Before Vacation and After 2 months, and a second group of samples from Vacation and After 1 months.

The SIMPER test showed a high level of dissimilarity in the communities among all months in all beaches (Table 6). Overall, most taxa were more abundant in the Before and After vacation. Concerning beaches, higher dissimilarities occurred mostly during vacation in Atalaia and Farol-Velho, due to low abundance of the polychaetes *Thoracophellia papillata*, *Scolelepis squamata* and *Paraonis* sp. The multiple regression analysis showed that macrobenthic density and richness had significant negative correlations with sediment compaction and human beach use (beachgoers and vehicles) (Table 7).

Discussion

Macrofaunal density and richness showed different patterns among the studied months. The Atalaia and Farol-Velho beaches followed the same temporal pattern. This pattern was characterized by a sharp reduction in density and richness with significant change in community structure before and during the disturbance period (vacation month), followed by an increase of the community descriptors (density and richness) in the After-vacation months. Conversely, on Corvinas beach the macrobenthic communities were very stable, with no significant temporal changes in structure even during the Vacation month. Consequently, we consider that touristic use, in the form of beachgoers and vehicle traffic is the major source of variability that affected macrofaunal community in our study. This observation is supported by the negative correlation between the number of beach users and community structure descriptors in the study areas. In addition, the pattern found here is similar to the results found in studies evaluating the effect of vehicle traffic and human trampling on macrofauna of sandy beaches worldwide (Wolcott & Wolcott, 1984; Veloso *et al.*, 2006; Schlacher & Thompson, 2012; Fanini *et al.*, 2014; Wu *et al.*, 2018; Bom & Colling, 2020; Costa *et al.*, 2020*b*).

With exception for the sediment compaction, the other environmental parameters described here (e.g. sediment size, sorting and O.M.) did not markedly differ among beaches and remained constant over the months. In fact, higher sediment compaction values were found in the Vacation month (July) in all studied beaches, especially at Atalaia and Farol-Velho where most of the beachgoers and vehicles were found. In several Amazon beaches the number of beachgoers increases dramatically during the school vacation month (July) (Pereira *et al.*, 2018), and consequently also increases the number of motor vehicles (e.g. cars, buses, motorcycles, off-road vehicles and trucks) on the beaches.

Considering our results and lack of significant differences at Corvinas beach even during the vacation month, we can attribute faunal differences to the distribution of physical impacts caused by recreational activities. The severity of these impacts was mainly dependent on the compactness of the sand since the lowest faunal densities were found at high compaction values (>20 kgf cm^{-2}): Atalaia and Farol-Velho beaches during Vacation. It is known that recreational activity has a negative effect on several beach organisms, once these activities may increase the sediment compaction (Rossi *et al.*, 2007; Ugolini *et al.*, 2008; Schlacher *et al.*, 2008*a*, 2008*b*, 2008*c*, 2014; McLachlan & Defeo, 2017*a*). Also, invertebrates can be killed through direct crushing by a high presence of vehicle traffic and human trampling (Wolcott & Wolcott, 1984; van der Merwe & van der Merwe, 1991; Schlacher *et al.*, 2008*a*, 2008*b*, 2008*c*; Bom & Colling, 2020). Therefore, the lower density found at Atalaia and Farol-Velho beaches might be linked to sediment compaction in these areas, a consequence of the high number of vehicles and beachgoers present during vacation.

The macrobenthic community composition in the studied beaches was similar and comprised 46 taxa with a dominance of Polychaeta. In fact, the studied beaches were expected to have similar compositions, as they are located close to each other and have similar morphodynamic characteristics and granulometry (Santos *et al.*, 2021*a*). However, only Corvinas beach had all taxa occurring throughout the study period. Beaches with fewer recreational activities in general are more complex, organized, mature and active environments than urbanized beaches (Reyes-Martínez *et al.*, 2014). In our study all macrobenthic taxa were affected by the recreational activities, however, their responses varied according to beach and month and these differences were found mainly in Atalaia and Farol-Velho, where sharp decreases in the richness occurred. In fact, recreational activities

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Table 4. Mean density (ind. m^{-2} ± SE) of the benthic macrofauna at the study area

		Atalaia beach							Farol-Velho beach							Corvinas beach						
Taxa		A	B	C	D	E	F	G	A	B	C	D	E	F	G	A	B	C	D	E	F	G
Nemertea (N)	B					47.46 ± 134.26				15.82 ± 44.75		15.82 ± 44.75	31.64.58.59	15.82 ± 44.75							47.46 ± 134.26	63.29 ± 135.32
	Vac																				63.29 ± 135.32	63.29 ± 95.68
	A1							47.46 ± 94.18													15.82 ± 44.75	63.29 ± 135.32
	A2						15.82 ± 44.75	31.64 ± 89.5						15.82 ± 44.75	47.16 ± 94.18						15.82 ± 44.75	47.46 ± 94.18
Acari (AC)	B	110.75 ± 105.63																				
	Vac																					
	A1	31.64 ± 89.50	15.82 ± 44.75																			
	A2	47.46 ± 94.18																				
Eunicidae (P)	B		15.82 ± 44.75		15.82 ± 44.75	15.82 ± 44.75																
	Vac																					
	A1																					
	A2																					
Capitella capitata (P)	B														47.46 ± 94.18		15.82 ± 44.75			15.82 ± 44.75	63.29 ± 95.68	
	Vac									15.82 ± 44.75												47.46 ± 94.18
	A1													15.82 ± 44.75	15.82 ± 44.75				47.46 ± 134.26			
	A2																					
Armandia sp. (P)	B		31.64 ± 58.59	94.93 ± 175.78							63.29 ± 179.01	31.64 ± 89.50	63.29 ± 95.68					158.22 ± 200.14	94.93 ± 122.20	31.64 ± 89.50		
	Vac																	94.93 ± 147.46				
	A1		15.82 ± 44.75	79.11 ± 115.96					15.82 ± 44.75	15.82 ± 44.75	15.82 ± 44.75	47.46 ± 94.18					15.82 ± 44.75	31.64 ± 89.50				
	A2			15.82 ± 44.75	15.82 ± 44.75					31.64 ± 89.50	15.82 ± 44.75	63.29 ± 179.01						94.93 ± 147.46	47.46 ± 65.51	47.46 ± 94.18		
Thoracophelia papillata (P)	B		15.82 ± 44.75	395.56 ± 385.35	31.64 ± 58.59					158.22 ± 175.78	142.40 ± 196.53	63.29 ± 117.19	15.82 ± 44.75				15.82 ± 44.75	322.27 ± 233.77	142.40 ± 142.53			
	Vac			395.56 ± 347.89	15.82 ± 44.75						110.75 ± 142.53	79.11 ± 94.18						158.22 ± 131.02	189.97 ± 213.96	15.82 ± 44.75		
	A1			158.22 ± 200.14	31.64 ± 58.59	15.82 ± 44.75		63.29 ± 179.01		79.11 ± 115.96	158.22 ± 200.14	110.75 ± 171.67						221.51 ± 221.84	79.11 ± 115.96	15.82 ± 44.75		
	A2																					

(*Continued*)

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Table 4. (*Continued.*)

Taxa		Atalaia beach							Farol-Velho beach							Corvinas beach						
		A	B	C	D	E	F	G	A	B	C	D	E	F	G	A	B	C	D	E	F	G
				316.45 ± 165.73	110.75 ± 142.53	31.64 ± 89.50	63.29 ± 179.01		15.82 ± 44.75		363.72 ± 320.49	300.63 ± 233.77	110.75 ± 125.44	31.64 ± 58.59				205.69 ± 190.62	126.58 ± 179.01	15.82 ± 44.75		
Scolelepis squamata (P)	B			126.58 ± 135.32	63.29 ± 67.66			15.82 ± 44.75		47.46 ± 134.26	47.46 ± 134.26	15.82 ± 44.75	31.64 ± 89.50					47.46 ± 94.18	63.29 ± 135.32	158.22 ± 147.46	94.93 ± 188.36	
	Vac			237.34 ± 196.53						47.46 ± 94.18	15.82 ± 44.75		79.11 ± 115.96	31.64 ± 89.50					110.75 ± 210.85	79.11 ± 150.34		
	A1	15.82 ± 44.75	15.82 ± 44.75	47.46 ± 94.18	47.46 ± 94.18	142.40 ± 157.77	79.11 ± 115.96	300.29 ± 178.21		47.46 ± 94.18	189.87 ± 234.38		47.46 ± 65.51	15.82 ± 44.75	142.40 ± 157.77			47.46 ± 94.18	31.64 ± 58.59	94.93 ± 147.46	205.69 ± 178.21	15.82 ± 44.75
	A2			15.82 ± 44.75	63.29 ± 117.19	94.93 ± 175.78	63.29 ± 135.32	31.64 ± 89.5			15.82 ± 44.75	110.75 ± 157.77	79.11 ± 150.34	142.40 ± 265.84	15.82 ± 44.75			79.11 ± 150.34	126.58 ± 179.01	126.58 ± 191.37	94.93 ± 147.46	63.29 ± 179.01
Dispio remanei (P)	B			31.64 ± 58.59	47.46 ± 94.18				15.82 ± 44.75	31.64 ± 89.50		63.29 ± 95.68	15.82 ± 44.75						15.82 ± 44.75	94.93 ± 147.46	79.11 ± 150.36	
	Vac					31.64 ± 89.50	15.82 ± 44.75											63.29 ± 179.01	47.46 ± 134.26			
	A1						110.75 ± 157.77	15.82 ± 44.75			31.64 ± 89.50	15.82 ± 44.75	94.93 ± 268.52	15.82 ± 44.75				31.64 ± 58.59	31.64 ± 89.50	31.64 ± 58.59		
	A2			31.64 ± 89.50	47.46 ± 134.26	126.58 ± 151.29		15.82 ± 44.75				15.82 ± 44.75	94.93 ± 174.46		15.82 ± 44.75		31.64 ± 58.59	47.46 ± 94.18	63.29 ± 95.68	15.82 ± 44.75		
Paraonis sp. (P)	B			47.46 ± 94.18	47.46 ± 94.18	94.93 ± 147.46		15.82 ± 44.75			31.64 ± 58.59	47.46 ± 65.51	189.87 ± 191.37	63.29 ± 95.68						47.46 ± 65.51	79.11 ± 65.51	142.40 ± 142.53
	Vac					47.46 ± 94.18	79.11 ± 115.96	15.82 ± 44.75				63.29 ± 179.01	47.46 ± 134.26	31.64 ± 89.50						47.46 ± 94.18	94.93 ± 89.50	110.75 ± 184.52
	A1				31.64 ± 58.59	79.11 ± 178.21	189.87 ± 234.38				63.29 ± 179.01	63.29 ± 117.19							31.64 ± 89.50	63.29 ± 135.32	142.40 ± 142.53	110.75 ± 184.52
	A2				31.64 ± 89.50	15.82 ± 44.75	31.64 ± 89.50	490.50 ± 367.1	15.82 ± 44.75			189.87 ± 358.02		552.15 ± 456.08	332.27 ± 164.86				31.64 ± 89.50	110.75 ± 125.44	174.05 ± 150.34	273.34 ± 184.52
Nephtys simoni (P)	B					79.11 ± 94.18	47.46 ± 94.18	94.93 ± 112.20	15.82 ± 44.75		15.82 ± 44.75	47.46 ± 65.51	63.29 ± 135.32	79.11 ± 94.18						158.22 ± 175.78	221.51 ± 211.27	15.82 ± 44.75
	Vac					15.82 ± 44.75	94.93 ± 58.59	47.46 ± 94.18				31.64 ± 58.59	94.93 ± 112.20	79.11 ± 150.34	79.11 ± 150.34				31.64 ± 58.59		47.46 ± 94.18	47.46 ± 65.51
	A1				31.64 ± 89.50	31.64 ± 58.59	63.29 ± 95.68	63.29 ± 117.19				110.75 ± 171.67	31.64 ± 58.59	63.29 ± 95.68	110.75 ± 142.43				15.82 ± 44.75	79.11 ± 150.34		94.93 ± 221.84
	A2					63.29 ± 135.32	189.87 ± 213.96	142.50 ± 105.63			15.82 ± 44.75	31.64 ± 58.59	94.93 ± 175.78	142.40 ± 196.53	63.29 ± 117.19			31.64 ± 58.59	94.93 ± 147.46	205.69 ± 178.21	110.75 ± 184.52	79.11 ± 150.34
Orbiniia sp. (P)	B																			79.11 ± 134.26	79.11 ± 94.18	31.64 ± 89.50
	Vac												31.64 ± 89.50	31.64 ± 58.59	63.29 ± 135.32							174.05 ± 190.62
	A1											47.46 ± 94.18	79.11 ± 150.34	15.82 ± 44.75	15.82 ± 44.75				31.64 ± 58.59	31.64 ± 58.59	31.64 ± 58.59	47.46 ± 94.18
	A2													31.64 ± 89.50	15.82 ± 44.75						31.64 ± 89.50	
Sigambra grubii (P)	B												31.64 ± 89.50							31.64 ± 89.50		

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Table 4. (*Continued.*)

		Atalaia beach							Farol-Velho beach							Corvinas beach						
Taxa		A	B	C	D	E	F	G	A	B	C	D	E	F	G	A	B	C	D	E	F	G
	Vac											15.82 ± 44.75			79.11 ± 115.96							
	A1													15.82 ± 44.75	15.82 ± 44.75							
	A2													31.64 ± 89.50					15.82 ± 44.75	47.46 ± 134.26	47.46 ± 94.18	
Magelona sp. (P)	B							15.82 ± 44.75														
	Vac																					
	A1																					
	A2																					
Hesionidae (P)	B																					
	Vac																		15.82 ± 44.75			
	A1																					
	A2																					
Laeonereis culveri (P)	B					15.82 ± 44.75		15.82 ± 44.75	31.64 ± 5.59			63.29 ± 179.01	94.93 ± 188.36									
	Vac								126.58 ± 135.32					63.29 ± 117.19	31.64 ± 89.50		47.46 ± 65.51	205.69 ± 302.11	63.29 ± 179.01	15.82 ± 44.75	15.82 ± 44.75	
	A1													15.82 ± 44.75	31.64 ± 89.50		221.51 ± 308.21	363.92 ± 880.73	63.29 ± 179.01	110.75 ± 228.82	205.69 ± 394.16	94.93 ± 268.52
	A2			15.82 ± 44.75								31.64 ± 89.50	15.82 ± 44.75	79.11 ± 150.34			15.82 ± 44.75	47.46 ± 94.18	174.05 ± 178.21	189.67 ± 179.01	205.69 ± 178.21	205.69 ± 213.29
Eteone sp. (P)	B					15.82 ± 44.75	31.64 ± 89.50						47.46 ± 94.18	31.64 ± 89.50								
	Vac														31.64 ± 89.50				31.64 ± 89.50	31.64 ± 58.59		
	A1												31.64 ± 89.50	47.46 ± 134.26					15.82 ± 44.75	31.64 ± 58.59		31.64 ± 58.56
	A2							15.82 ± 44.75				31.64 ± 89.50								79.11 ± 150.34	63.29 ± 179.01	31.64 ± 84.50
Glycera sp. (P)	B					63.29 ± 117.19						15.82 ± 44.75	31.64 ± 89.50						31.64 ± 58.59	31.64 ± 89.50	15.82 ± 44.75	
	Vac			15.82 ± 44.75									47.46 ± 94.18					15.82 ± 44.75	15.82 ± 44.75			
	A1				47.46 ± 94.18						15.82 ± 44.75		31.64 ± 89.50					15.82 ± 44.75	31.64 ± 89.50	15.82 ± 44.75		
	A2			63.29 ± 95.68								47.46 ± 94.18	15.82 ± 44.75					31.64 ± 89.50	110.75 ± 142.53	63.29 ± 135.32		
Goniadides sp. (P)	B					15.82 ± 44.75	31.64 ± 89.50					31.64 ± 89.50	47.46 ± 134.26					47.46 ± 134.26	15.82 ± 44.75	31.64 ± 89.50		15.82 ± 44.75

(*Continued*)

Table 4. (*Continued.*)

		Atalaia beach							Farol-Velho beach							Corvinas beach						
Taxa		A	B	C	D	E	F	G	A	B	C	D	E	F	G	A	B	C	D	E	F	G
	Vac			31.64 ± 89.50									47.46 ± 94.18					31.64 ± 89.50	15.82 ± 44.75			
	A1					31.64 ± 89.50						47.46 ± 94.18	15.82 ± 44.75						63.29 ± 135.32	31.64 ± 89.50		
	A2			31.64 ± 89.50	63.29 ± 135.32							31.64 ± 89.50	15.82 ± 44.75					63.29 ± 179.01	31.64 ± 58.59	31.64 ± 89.50	15.82 ± 44.75	
Diopatra cuprea (P)	B													31.64 ± 58.59						47.46 ± 94.18	15.82 ± 44.75	
	Vac																					
	A1																					
	A2																					
Lumbrinereis sp. (P)	B														31.64 ± 58.59							
	Vac												15.82 ± 44.75									
	A1														15.82 ± 44.75							
	A2																					
Oligochaeta (O)	B																	15.82 ± 44.75	152.22 ± 356.42			
	Vac																					
	A1																					
	A2																					
Donax striatus (B)	B		79.11 ± 134.26	47.46 ± 65.51	31.64 ± 58.59			31.64 ± 58.59	332.27 ± 302.11	63.29 ± 67.66				31.64 ± 89.50					15.82 ± 44.75		63.29 ± 95.68	126.58 ± 135.32
	Vac			15.82 ± 44.75	15.82 ± 44.75	15.82 ± 44.75			15.82 ± 44.75	110.75 ± 105.63		31.64 ± 89.50		15.82 ± 44.75			15.82 ± 44.75		31.64 ± 89.50	63.29 ± 95.68	31.64 ± 58.59	110.65 ± 171.67
	A1			47.46 ± 65.51	31.64 ± 58.59	15.82 ± 44.75	15.82 ± 44.75					15.82 ± 44.75	63.29 ± 95.68	31.64 ± 58.59	31.64 ± 89.50					15.82 ± 44.75	47.46 ± 65.1	63.29 ± 95.68
	A2			47.46 ± 65.51	31.64 ± 58.59	15.82 ± 44.75	47.46 ± 65.51				31.64 ± 89.50	47.46 ± 94.18	63.29 ± 117.19	63.29 ± 95.68					15.82 ± 44.75	31.64 ± 58.59	31.64 ± 58.59	15.82 ± 44.75
Corbula sp. (B)	B																					
	Vac																					
	A1																					
	A2					15.82 ± 44.75																
Petricolaria sp. (B)	B							142.40 ± 125.44						47.46 ± 65.51	253.16 ± 376.72						31.64 ± 89.50	63.29 ± 95.68
	Vac														189.97 ± 213.96							79.11 ± 134.26
	A1																					

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Table 4. (*Continued.*)

		Atalaia beach							Farol-Velho beach							Corvinas beach						
Taxa		A	B	C	D	E	F	G	A	B	C	D	E	F	G	A	B	C	D	E	F	G
								47.46 ± 94.18				47.46 ± 94.18		47.46 ± 94.18	142.40 ± 142.53							31.64 ± 89.50
	A2							15.82 ± 44.75							63.29 ± 95.68							31.64 ± 58.59
Hiatella sp. (B)	B														15.82 ± 44.75							
	Vac																					
	A1											31.64 ± 58.59		15.82 ± 44.75	31.64 ± 89.50							
	A2																					
Olivella minuta (G)	B																					
	Vac																					
	A1					15.82 ± 44.75	15.82 ± 44.75	31.64 ± 89.50														15.82 ± 44.75
	A2																					15.82 ± 44.75
Melita quisqueperforata (E)	B						15.82 ± 44.75	31.64 ± 89.50						15.82 ± 44.75								47.46 ± 94.18
	Vac							15.82 ± 44.75							15.82 ± 44.75							15.82 ± 44.75
	A1							47.46 ± 134.26						15.82 ± 44.75	15.82 ± 44.75							31.64 ± 59.58
	A2							15.82 ± 44.75							15.82 ± 44.75						15.82 ± 44.75	94.93 ± 112.20
Cumacea (CR)	B			15.82 ± 44.75	47.46 ± 94.18									15.82 ± 44.75				47.46 ± 94.18	15.82 ± 44.75			
	Vac								15.82 ± 44.75		15.82 ± 44.75							15.82 ± 44.75				31.64 ± 59.58
	A1	47.46 ± 94.18							31.64 ± 89.50				15.82 ± 44.75					15.82 ± 44.75				
	A2		79.11 ± 150.34								31.64 ± 89.50								15.82 ± 44.75	15.82 ± 44.75	15.82 ± 44.75	
Phoxocephalidae (CR)	B				47.46 ± 94.18	31.64 ± 89.50		15.82 ± 44.75	15.82 ± 44.75						15.82 ± 44.75				15.82 ± 44.75	79.11 ± 150.34	15.82 ± 44.75	
	Vac							31.60 ± 89.50		63.29 ± 95.68	15.82 ± 44.75		31.64 ± 89.50	79.11 ± 150.34	31.64 ± 89.50			15.82 ± 44.75	31.64 ± 89.50	110.75 ± 142.53		
	A1		31.64 ± 89.50		15.82 ± 44.75	15.82 ± 44.75				79.11 ± 178.21	15.82 ± 44.75				15.82 ± 44.75				31.64 ± 58.59		63.29 ± 135.32	110.75 ± 125.44
	A2	15.82 ± 44.75		15.82 ± 44.75			31.64 ± 89.50				31.64 ± 89.50	79.11 ± 134.26			15.82 ± 44.75					79.11 ± 115.96	332.27 ± 252.59	284.81 ± 259.85
Mysida sp. (CR)	B						15.82 ± 44.75	63.29 ± 67.66		15.82 ± 44.75			31.64 ± 58.59		15.82 ± 44.75			15.82 ± 44.75			31.64 ± 89.50	15.82 ± 44.75
	Vac																					

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Table 4. (*Continued.*)

		Atalaia beach							Farol-Velho beach							Corvinas beach						
Taxa		A	B	C	D	E	F	G	A	B	C	D	E	F	G	A	B	C	D	E	F	G
								15.82 ± 44.75				31.64 ± 58.59			15.82 ± 44.75							47.46 ± 94.18
	A1				31.64 ± 89.50	31.64 ± 89.50	142.40 ± 282.54													47.46 ± 134.26		
	A2					15.82 ± 44.75	15.82 ± 44.75							31.64 ± 89.50	15.82 ± 44.75					15.82 ± 44.75	31.64 ± 58.59	
Ogyrides alphaerostris (CR)	B							15.82 ± 44.75							31.64 ± 89.50							47.46 ± 65.51
	Vac							15.82 ± 44.75													94.93 ± 131.02	
	A1							31.64 ± 89.50				15.82 ± 44.75	15.82 ± 44.75								15.82 ± 44.75	
	A2							31.64 ± 89.50						15.82 ± 44.75	47.46 ± 94.18							31.64 ± 58.59
Kalliapseudes schubartii (CR)	B							15.82 ± 44.75					15.82 ± 44.75	79.11 ± 223.76								
	Vac													15.82 ± 44.75								
	A1																					
	A2							15.82 ± 44.75					15.82 ± 44.75								31.64 ± 58.59	
Excirolana armata (CR)	B	63.69 ± 95.68							15.82 ± 44.75	15.82 ± 44.75						31.64 ± 89.50	15.82 ± 44.75					
	Vac																	15.82 ± 44.75				
	A1		15.82 ± 44.75						15.82 ± 44.75								15.82 ± 44.75	63.29 ± 135.32				
	A2	63.69 ± 95.68	63.29 ± 135.32																			
Excirolana brasiliensis (CR)	B			31.64 ± 89.50					15.82 ± 44.75	94.93 ± 147.46	15.82 ± 44.75						15.82 ± 44.75	63.29 ± 117.19	15.82 ± 44.75			
	Vac										15.82 ± 44.75	31.64 ± 89.50						15.82 ± 44.75	31.64 ± 58.59	15.82 ± 44.75	15.82 ± 44.75	31.64 ± 59.58
	A1	15.82 ± 44.75	94.93 ± 147.46	15.82 ± 44.75					15.82 ± 44.75	15.82 ± 44.75	31.64 ± 89.50							15.82 ± 44.75	94.93 ± 112.20	15.82 ± 44.75		158.22 ± 356.42
	A2	63.69 ± 95.68	63.29 ± 135.32	47.46 ± 94.18						63.29 ± 135.32	63.29 ± 117.19	31.64 ± 89.50						47.46 ± 65.51	63.29 ± 67.66	63.29 ± 67.66		
Sphaeromopsis mourei (CR)	B																					
	Vac																					
	A1																					
	A2																			15.82 ± 44.75		15.82 ± 44.75

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Table 4. (*Continued.*)

		Atalaia beach							Farol-Velho beach							Corvinas beach						
Taxa		A	B	C	D	E	F	G	A	B	C	D	E	F	G	A	B	C	D	E	F	G
Clibanarius simmetricus (CR)	B													15.82 ± 44.75	31.64 ± 89.50							
	Vac																					
	A1														31.64 ± 89.50							
	A2								15.82 ± 44.75						15.82 ± 44.75							
Lepidophtalmus siriboia (CR)	B							31.64 ± 58.59						15.82 ± 44.75							47.46 ± 65.51	
	Vac					47.46 ± 94.18															15.82 ± 44.75	31.64 ± 59.58
	A1											15.82 ± 44.75		15.82 ± 44.75	31.64 ± 89.50						15.82 ± 44.75	
	A2													31.64 ± 58.59	31.64 ± 58.59						79.11 ± 115.96	15.82 ± 44.75
Pinnixa (CR)	B													47.46 ± 134.26								
	Vac						31.64 ± 89.50														47.46 ± 94.18	
	A1				15.82 ± 44.75			15.82 ± 44.75					47.46 ± 94.18						15.82 ± 44.75		15.82 ± 44.75	126.58 ± 234.38
	A2						31.64 ± 89.50	15.82 ± 44.75						47.46 ± 134.26	63.29 ± 179.01						15.82 ± 44.75	15.82 ± 44.75
Lepidopa richmondi (CR)	B											47.46 ± 94.18	15.82 ± 44.75	15.82 ± 44.75					31.64 ± 89.50		15.82 ± 44.75	
	Vac																			47.46 ± 65.51	15.82 ± 44.75	31.64 ± 89.50
	A1			31.64 ± 89.50	15.82 ± 44.75								47.46 ± 134.26	31.64 ± 89.50							15.82 ± 44.75	
	A2							94.93 ± 188.36					63.29 ± 135.32		15.82 ± 44.75						15.82 ± 44.75	110.75 ± 171.67
Harparticoid (CR)	B											63.29 ± 179.01										
	Vac																					
	A1																					
	A2																					
Axiidea (Megalop) (CR)	B										15.82 ± 44.75											
	Vac																					
	A1																					
	A2																					

(*Continued*)

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Table 4. (*Continued.*)

Taxa		Atalaia beach							Farol-Velho beach							Corvinas beach						
		A	B	C	D	E	F	G	A	B	C	D	E	F	G	A	B	C	D	E	F	G
Brachiura (Megalop) (CR)	B													15.82 ± 44.75			15.82 ± 44.75					110.75 ± 313.27
	Vac																					
	A1																					
	A2																					
Cyprideis sp. (CR)	B					47.46 ± 65.51										15.82 ± 44.75	63.29 ± 95.68					
	Vac															63.29 ± 135.32	63.29 ± 177.19	15.82 ± 44.75	47.46 ± 134.26			
	A1				15.82 ± 44.75				15.82 ± 44.75	31.64 ± 59.58	31.64 ± 89.50			47.46 ± 134.26		94.93 ± 147.46	205.69 ± 351.17			15.82 ± 44.75		
	A2		63.29 ± 135.32	31.64 ± 89.50	79.11 ± 115.96	47.46 ± 65.51	31.64 ± 58.59		47.46 ± 94.18	47.46 ± 94.18						316.45 ± 532.76			79.11 ± 178.21			15.82 ± 44.75
Dolichopodidae (larvae) (IN)	B	110.75 ± 184.52							126.58 ± 224.40	47.46 ± 94.18						142.40 ± 105.63						
	Vac															63.29 ± 95.68	15.82 ± 44.75	47.46 ± 134.26				
	A1	63.29 ± 179.01							47.46 ± 94.18							174.05 ± 134.26	15.82 ± 44.75	31.64 ± 58.59				
	A2	63.69 ± 95.68	47.46 ± 134.26						79.11 ± 150.34	47.46 ± 94.18						142.40 ± 207.85	63.29 ± 135.32	15.82 ± 44.75				
Ceratopogonidae (larvae) (IN)	B								63.29 ± 95.68	47.46 ± 94.18						47.46 ± 65.51	300.63 ± 223.76					
	Vac	273.34 ± 265.84	15.82 ± 44.75	31.64 ± 58.59												31.64 ± 58.59	15.82 ± 44.75	47.46 ± 94.18				
	A1		47.46 ± 134.26						31.64 ± 89.50	15.82 ± 44.75	15.82 ± 44.75					268.98 ± 760.81	490.50 ± 751.37					
	A2	174.05 ± 278.46	31.64 ± 89.50						31.64 ± 58.59	15.82 ± 44.75						94.93 ± 147.46	31.64 ± 58.59					
Dysticidae (Larvae) (IN)	B	47.47 ± 94.18							79.11 ± 94.18	79.11 ± 94.18	47.46 ± 94.18					158.22 ± 131.02	79.11 ± 115.96	15.82 ± 44.75				
	Vac															63.29 ± 95.68	31.64 ± 89.50	15.82 ± 44.75				
	A1	110.75 ± 184.52							63.29 ± 135.32							31.64 ± 89.50	348.10 ± 527.36					
	A2	110.75 ± 184.52	79.11 ± 223.76						47.46 ± 65.51	31.64 ± 59.58	15.82 ± 44.75					47.46 ± 94.18	47.46 ± 94.18	110.75 ± 171.67				

B, Before; V, Vacation; A1, After 1; A2, After 2.

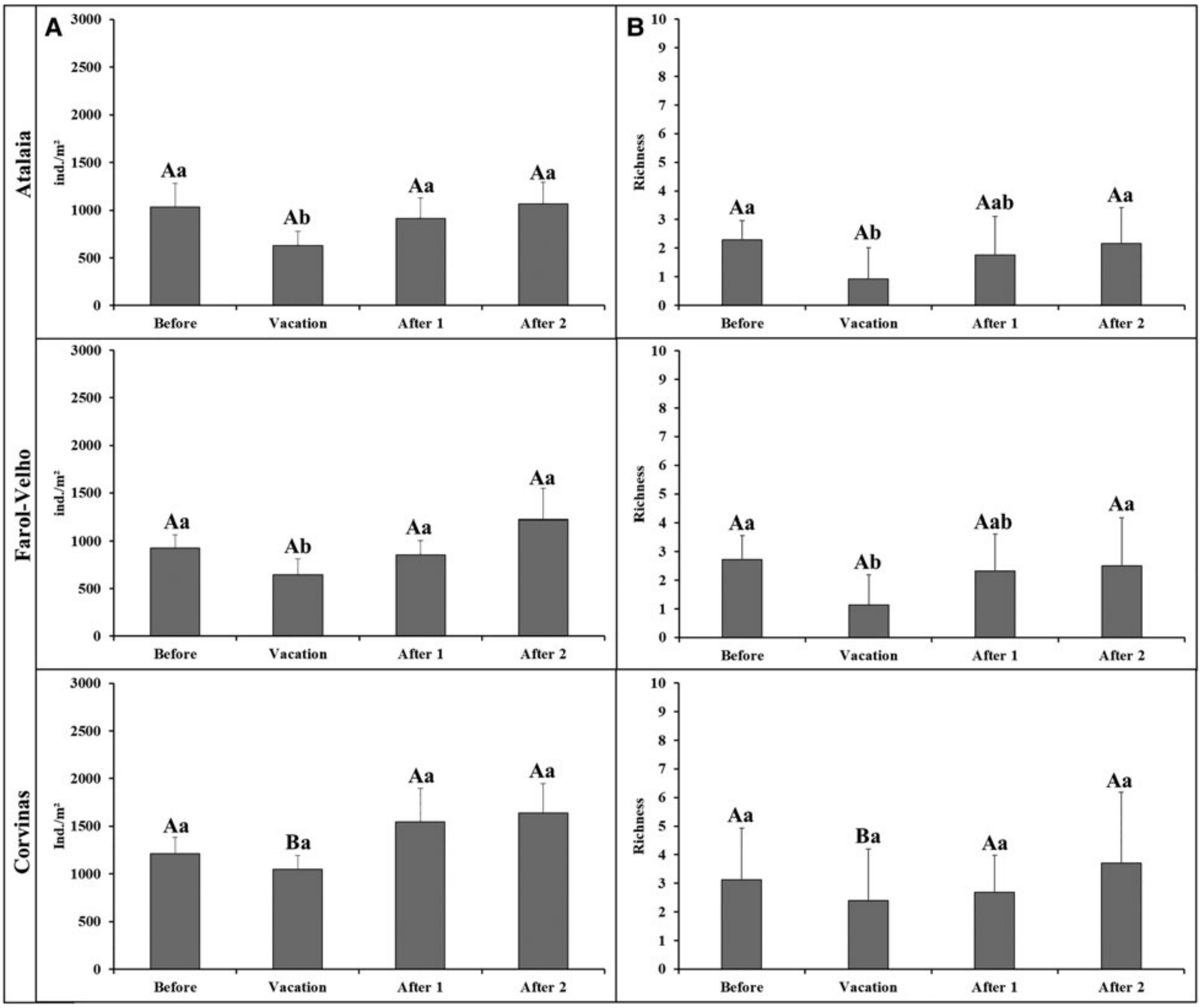

Fig. 5. Mean density (ind. m^{-2} ± SE) (A) and richness (±SE) (B) of macrobenthic community in the study beaches in the different sampling months (Before vacation, during Vacation, After vacation 1 and 2). Different letters indicate significant differences ($P < 0.05$); uppercase letters (A≠B) indicate differences between beaches among months and lowercase letters (a ≠ b) indicate differences between months on each beach.

Table 5. Results of PERMANOVA analysis and pairwise test regarding macrobenthic community structures of the study beaches

Factors	df		*Pseudo* -F		*p (perm)*	
Month	3		3.7		**	
Beach	2		0.8		0.5	
Sampling Levels (Beach)	18		10.6		**	
Month × Beach	6		4.9		**	
Month × Sampling Levels (Beach)	54		2.1		**	
Residue	588					
Pair-wise test						
	BF × V	BF × A1	BF × A2	V × A1	V × A2	A1 × A2
Atalaia (Ata)	**	0.3	0.7	0.1	**	0.2
Farol-Velho (FV)	**	0.2	0.7	**	**	0.1
Corvinas (Cor)	0.5	0.1	0.1	0.2	0.5	0.2
	Ata × FV		Ata × Cor		FV × Cor	
Before (BF)	0.9		0.8		0.9	
Vacation (V)	0.1		**		**	
After 1 (A1)	0.4		0.1		0.4	
After 2 (A2)	0.9		0.2		0.3	

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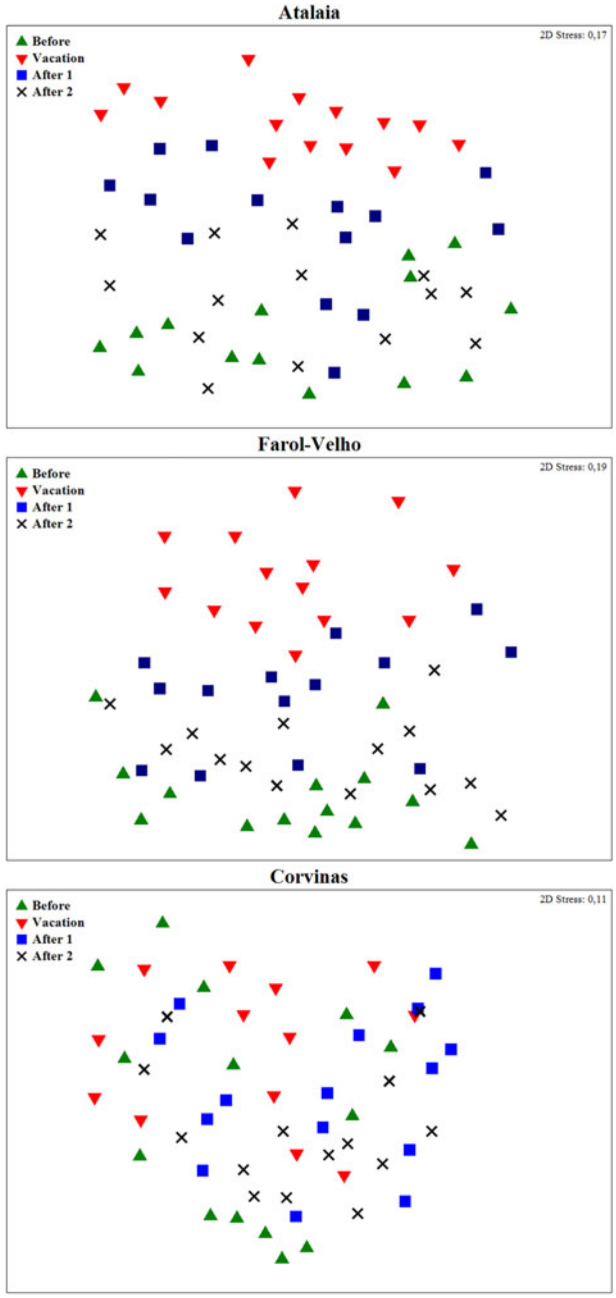

Fig. 6. nMDS for month × beach combinations for macrobenthic community in the study beaches.

in Amazonian beaches are likely to have higher impacts during the vacation periods in the benthic fauna, as shown by a previous study (Santos *et al*., 2021*a*). In that study Santos *et al*. (2021*a*) showed that the meiofauna community is sensitive to recreational activities, and these impacts may be related to changes in substrate characteristics, especially to compaction.

The macrobenthic fauna of the present study was dominated by polychaetes. The dominance of polychaetes is a general pattern in intertidal habitats of the Amazonian coast (Rosa Filho *et al*., 2006, 2009, 2011; Beasley *et al*., 2010; Braga *et al*., 2011, 2013; Morais & Lee, 2013; Santos & Aviz, 2018, 2020, 2021; Santos *et al*., 2020, 2021*b*, 2021). Thus, the impact of recreational activities in this study was mainly evidenced by changes in density and taxonomic composition of Polychaeta assemblages. In fact, the use of Polychaeta as indicators of human impact has intensified, due to their significant presence, both in quantitative and qualitative terms, when compared with other benthic fauna organisms (Amaral *et al*., 1998, Feres *et al*., 2008).

In the present study, a sharp reduction in polychaete densities was observed in the beaches with high compaction (>20 kgf cm^{-2}) during vacation. It has been shown that recreational activity has a negative effect on beach communities probably due to sediment compaction, which might hamper burrowing and thus reduce the probability of survival of organisms (Ugolini *et al*., 2008). Therefore, sites with high compaction, reflecting firmer substrates, may be unfavourable to a wide range of small-sized burrowers and sessile and semi-sessile infaunal polychaetes, because compaction increases the energy costs of burrowing (Brown & Trueman, 1991; Hsu *et al*., 2009; Che & Dorgan, 2010; Dorgan, 2015). Considering this fact, the presence of a high abundance of polychaetes might be indicative of less-compacted sediments.

Some polychaete species, such as *Thoracophelia papillata*, *Scolelepis squamata* and *Paraonis* sp., seem to be rather sensitive to high values of sediment compaction caused by recreational activities, as indicated by their relatively higher abundance at Corvinas beach compared with the other beaches. Furthermore, they also had changes in density throughout the study months, reflecting changes in impact intensity. *T. papillata*, *S. squamata* and *Paraonis* sp. are probably more vulnerable to trampling and vehicle traffic because they are shallow burrowers and have no hard structures such as shells and carapaces as protection against physical disturbance (MacCord & Amaral, 2005). The decline in these taxa was more evident at Atalaia and Farol-Velho beaches, where their densities were minimal or even absent. Similar results were found in the highly urbanized sectors of sandy beaches of Rio de Janeiro (Brazil) by Machado *et al*. (2017), who observed

Table 6. Multiple regression results showing correlations and levels of significance of each significant predictor environmental variable used for modelling sandy beach community attributes

Model results						
	R	R^2		$F_{(3.80)}$		P
Density (ind. m^{-2})	0.58	0.32		14.04		**
Richness (total taxa)	0.6	0.34		15.57		**
Dependent variables						
	Density			Richness		
Independent variables	β		P	β	t	P
Compaction	−0.23	0.22	**	0.4	2.79	**
Vehicles	−0.23	−1.7	**	−0.5	−3.76	**
Beachgoers	−0.42	−2.72	**	−0.42	−2.78	**
Organic matter	0.15	1.51	0.13	0.31	3.4	0.1
Mean grain size	−0.08	−0.83	0.40	−0.08	−0.87	0.38
Sorting	−0.11	−1.1	0.27	−0.12	−1.34	0.18

*P < 0.05; β – standardized coefficients.

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Table 7. The results of the SIMPER analysis, showing the mean abundances (ind. $m^{-2} \pm SE$) and similarity of the species that most contributed to the samples between study beaches and months

Atalaia

Groups: Before × Vacation	Average dissimilarity = 94.19			
	Before	Vacation		
Species	Av.Abund	Av.Abund	Contrib%	Cum.%
Scolelepis squamata	0.37	0.09	11.91	11.91
Paraonis sp.	0.19	0.13	11.61	23.51
Thoracophelia papillata	0.22	0.18	9.44	32.96
Donax striatus	0.19	0.11	9	41.96
Nephtys simoni	0.16	0.14	8.33	50.29
Groups: Before × After 1	**Average dissimilarity = 72.74**			
	Before	After 1	Contrib%	Cum.%
Species	Av.Abund	Av.Abund		
Scolelepis squamata	0.19	0.43	12.85	12.85
Donax striatus	0.37	0.13	10.42	23.28
Thoracophelia papillata	0.22	0.18	8.07	31.34
Nephtys simoni	0.19	0.16	7.4	38.74
Paraonis sp.	0.16	0.17	6.98	45.72
Ceratopogonidae (larvae)	0.19	0.02	4.51	50.23

Farol-Velho

Groups: Before × Vacation	Average dissimilarity = 94.24			
	Before	Vacation		
Species	Av.Abund	Av.Abund	Contrib%	Cum.%
Scolelepis squamata	0.26	0.07	9.79	9.79
Paraonis sp.	0.23	0.15	9.5	19.29
Thoracophelia papillata	0.21	0.2	8.96	28.26
Donax striatus	0.23	0.16	7.37	35.63
Nephtys simoni	0.15	0.11	6.11	41.74
Dysticidae (Larvae)	0.19	0	5.63	47.36
Phoxocephalidae sp.	0.11	0.09	5.31	52.67
Groups: Before × After 1	**Average dissimilarity = 82.59**			
	Before	After 1	Contrib%	Cum.%
Species	Av.Abund	Av.Abund		
Nephtys simoni	0.21	0.25	8.18	8.18
Thoracophelia papillata	0.23	0.21	8.12	16.3
Scolelepis squamata	0.09	0.29	6.66	22.96
Donax striatus	0.23	0.13	5.91	28.86
Paraonis sp.	0.26	0.07	5.72	34.58
Petricolaria sp.	0.15	0.18	5.7	40.28
Dysticidae (Larvae)	0.19	0.04	4.66	44.94
Armandia sp.	0.1	0.09	4.19	49.13
Orbiniia sp.	0.1	0.12	4.08	53.2

Corvinas

Groups: Before × Vacation	Average dissimilarity = 61.41			
	Before	Vacation		
Species	Av.Abund	Av.Abund	Contrib%	Cum.%
Thoracophelia papillata	0.26	0.23	8.2	8.2
Paraonis sp.	0.24	0.2	6.92	15.12
Scolelepis squamata	0.2	0.14	6.51	21.63
Donax striatus	0.21	0.16	6.47	28.1
Ceratopogonidae (larvae)	0.17	0.2	5.52	33.63
Dysticidae (Larvae)	0.23	0.09	5.02	38.65
Nephtys simoni	0.26	0.09	4.88	43.53
Armandia sp.	0.19	0.06	4.67	48.2
Phoxocephalidae sp.	0.08	0.16	4.5	52.7
Groups: Before × After 1	**Average dissimilarity = 60.23**			
	Before	After 1	Contrib%	Cum.%
Species	Av.Abund	Av.Abund		
Scolelepis squamata	0.23	0.28	7.34	7.34
Thoracophelia papillata	0.26	0.19	7.11	14.45
Paraonis sp.	0.24	0.23	6.46	20.9
Ceratopogonidae (larvae)	0.21	0.18	6.4	27.3
Dolichopodidae (larvae)	0.12	0.18	5.79	33.09
Laeonereis cuvieri	0.05	0.31	5.68	38.77
Excirolana armata	0.1	0.21	5.36	44.13
Dysticidae (Larvae)	0.2	0.13	5.18	49.31
Nephtys simoni	0.26	0.11	4.86	54.17

Groups: Before × After 2	Average dissimilarity = 71.75				Groups: Before × After 2	Average dissimilarity = 70.04				Groups: Before × After 2	Average dissimilarity = 59.97			
	Before	After 2	Contrib%	Cum.%		Before	After 2	Contrib%	Cum.%		Before	After 2	Contrib%	Cum.%
Species	Av.Abund	Av.Abund			Species	Av.Abund	Av.Abund			Species	Av.Abund	Av.Abund		
Thoracophelia papillata	0.22	0.29	10.25	10.25	*Thoracophelia papillata*	0.23	0.45	11.67	11.67	*Laeonereis cuvieri*	0.05	0.51	6.93	6.93
Donax striatus	0.37	0.13	9.09	19.35	*Paraonis* sp.	0.26	0.43	10.54	22.22	*Paraonis* sp.	0.24	0.36	6.56	13.48
Nephtys simoni	0.19	0.27	8.76	28.11	*Nephtys simoni*	0.21	0.23	7.35	29.57	*Nephtys simoni*	0.26	0.33	6.27	19.76
Cyprideis sp.	0.05	0.21	7.58	35.69	*Donax striatus*	0.23	0.16	6.57	36.14	*Thoracophelia papillata*	0.26	0.21	6.27	26.03
Paraonis sp.	0.16	0.25	7.07	42.76	Dysticidae (Larvae)	0.19	0.11	6.28	42.42	Phoxocephalidae sp.	0.08	0.36	5.54	31.56
Scolelepis squamata	0.19	0.18	6.31	49.07	*Thoracophelia papillata*	0.09	0.2	4.69	47.11	*Scolelepis squamata*	0.23	0.27	5.53	37.09
Ceratopogonidae (larvae)	0.19	0.09	5.72	54.78	*Petricolaria* sp.	0.15	0.06	3.69	50.8	Dysticidae (Larvae)	0.2	0.16	5.39	42.48
										Ceratopogonidae (larvae)	0.21	0.1	5.1	47.59
										Dolichopodidae (larvae)	0.12	0.13	4.69	52.27
Groups: Vacation × After 1	Average dissimilarity = 84.25				Groups: Vacation × After 1	Average dissimilarity = 89.32				Groups: Vacation × After 1	Average dissimilarity = 61.8			
	Vacation	After 1	Contrib%	Cum.%		Vacation	After 1	Contrib%	Cum.%		Vacation	After 1	Contrib%	Cum.%
Species	Av.Abund	Av.Abund			Species	Av.Abund	Av.Abund			Species	Av.Abund	Av.Abund		
Scolelepis squamata	0.15	0.43	18.4	18.4	*Nephtys simoni*	0.2	0.25	10.82	10.82	*Thoracophelia papillata*	0.23	0.19	7.44	7.44
Paraonis sp.	0.14	0.17	10.71	29.11	*Thoracophelia papillata*	0.16	0.21	10.32	21.14	*Laeonereis cuvieri*	0.14	0.31	7.17	14.61
Nephtys simoni	0.16	0.16	9.81	38.92	*Scolelepis squamata*	0.14	0.29	10.31	31.45	*Scolelepis squamata*	0.09	0.28	7.03	21.64
Thoracophelia papillata	0.18	0.18	9.73	48.65	*Donax striatus*	0.15	0.13	7.04	38.49	*Paraonis* sp.	0.2	0.23	6.8	28.45
Donax striatus	0.09	0.13	6.32	54.97	*Petricolaria* sp.	0.11	0.18	6.79	45.28	Dolichopodidae (larvae)	0.1	0.18	6.24	34.69
					Laeonereis cuvieri	0.1	0.14	6.25	51.53	*Excirolana armata*	0.13	0.21	6.11	40.8
										Ceratopogonidae (larvae)	0.16	0.18	6.03	46.83
										Donax striatus	0.2	0.13	5.3	52.13
Groups: Vacation × After 2	Average dissimilarity = 85.96				Groups: Vacation × After 2	Average dissimilarity = 83.11				Groups: Vacation × After 2	Average dissimilarity = 71			
	Vacation	After 2	Contrib%	Cum.%		Vacation	After 2	Contrib%	Cum.%		Vacation	After 2	Contrib%	Cum.%
Species	Av.Abund	Av.Abund			Species	Av.Abund	Av.Abund			Species	Av.Abund	Av.Abund		
Thoracophelia papillata	0.18	0.29	13.07	13.07	*Thoracophelia papillata*	0.16	0.45	15.35	15.35	*Laeonereis cuvieri*	0.14	0.51	8.23	8.23

(*Continued*)

Table 7. (*Continued.*)

Atalaia					Farol-Velho					Corvinas				
Groups: Before × Vacation	Average dissimilarity = 94.19				Groups: Before × Vacation	Average dissimilarity = 94.24				Groups: Before × Vacation	Average dissimilarity = 61.41			
	Before	Vacation	Contrib%	Cum.%		Before	Vacation	Contrib%	Cum.%		Before	Vacation	Contrib%	Cum.%
Species	Av.Abund	Av.Abund			Species	Av.Abund	Av.Abund			Species	Av.Abund	Av.Abund		
Nephtys simoni	0.16	0.27	11.16	24.23	*Paraonis* sp.	0.07	0.43	11.37	26.72	Phoxocephalidae sp.	0.16	0.36	7.29	15.52
Cyprideis sp.	0	0.21	9.73	33.97	*Nephtys simoni*	0.2	0.23	8.99	35.71	*Paraonis* sp.	0.2	0.36	6.83	22.35
Paraonis sp.	0.14	0.25	9.5	43.47	*Donax striatus*	0.15	0.16	7.93	43.64	*Thoracophelia papillata*	0.23	0.21	6.43	28.79
Scolelepis squamata	0.15	0.18	7.97	51.44	*Scolelepis squamata*	0.14	0.2	7.77	51.41	*Nephtys simoni*	0.09	0.33	5.79	34.58
										Cyprideis sp.	0.13	0.16	5.24	39.82
										Dysticidae (Larvae)	0.14	0.16	5.22	45.04
										Dolichopodidae (larvae)	0.1	0.13	4.75	49.8
										Ceratopogonidae (larvae)	0.16	0.1	4.61	54.41
Groups: After 1 × After 2	Average dissimilarity = 74.89				Groups: After 1 × After 2	Average dissimilarity = 71.24				Groups: After 1 × After 2	Average dissimilarity = 68.62			
	After 1	After 2	Contrib%	Cum.%		After 1	After 2	Contrib%	Cum.%		After 1	After 2	Contrib%	Cum.%
Species	Av.Abund	Av.Abund			Species	Av.Abund	Av.Abund			Species	Av.Abund	Av.Abund		
Scolelepis squamata	0.43	0.18	12.57	12.57	*Thoracophelia papillata*	0.21	0.45	11.93	11.93	*Laeonereis cuvieri*	0.31	0.51	9.33	9.33
Thoracophelia papillata	0.18	0.29	10.87	23.45	*Paraonis* sp.	0.07	0.43	8.73	20.67	*Scolelepis squamata*	0.28	0.27	6.99	16.31
Paraonis sp.	0.17	0.25	8.28	31.72	*Nephtys simoni*	0.25	0.23	8.42	29.09	*Paraonis* sp.	0.23	0.36	6.71	23.02
Nephtys simoni	0.16	0.27	8.04	39.77	*Scolelepis squamata*	0.29	0.2	8.24	37.33	Phoxocephalidae sp.	0.12	0.36	6.19	29.21
Cyprideis sp.	0.02	0.21	7.57	47.34	*Donax striatus*	0.13	0.16	4.63	41.96	Dolichopodidae (larvae)	0.18	0.13	6.02	35.23
					Petricolaria sp.	0.18	0.06	4.37	46.33	*Excirolana armata*	0.21	0.2	5.86	41.09
					Laeonereis cuvieri	0.14	0.08	3.79	50.12	*Thoracophelia papillata*	0.19	0.21	5.68	46.77
										Nephtys simoni	0.11	0.33	5.63	52.4

that the impact occurred especially on soft-bodied organisms, such as Nemertea and the polychaete *Hemipodia californiensis* (Hartman, 1938), a species that is usually abundant in that region. Also, similar to the results obtained for *Thoracophelia furcifera* (Ehlers, 1897) on two urbanized beaches of the south coast of Brazil (Vieira *et al*., 2012), the low density of *T. papillata* found in our study suggests that this species does not tolerate great intensity of trampling and vehicle traffic, even if these only occur during a restricted period of the year in the Amazon region.

Recreational activities observed on Amazonian beaches can be classified as pulse disturbances (Santos *et al*., 2021*a*), however, pulse disturbances can produce either a pulse or a press response in the community (Glasby & Underwood, 1996; Bravo *et al*., 2015). Recreational activities on Amazonian sandy beaches caused a discrete pulse disturbance affecting the macrobenthic community during the Vacation month, but the communities returned to density and richness values similar to their initial condition (before period) in the second month after the Vacation (i.e., After 2 period). A similar pattern was found in a previous study in the same Amazonian beaches where the meiofauna community density and richness values returned to similar conditions soon after the Vacation ended (within a month) (Santos *et al*., 2021*a*). Thus, although the macrobenthic fauna showed high susceptibility to recreational activities, they also showed high resilience. However, the consequence of intensive use by beach visitors in urbanized areas could result in a long-term loss of biodiversity which might become irreversible (Reyes-Martínez *et al*., 2015).

Conclusions

The results reported in this pioneer study evaluating the effect of recreational activities in macrobenthic community of Amazonian macrotidal sandy beaches showed a similar pattern to those found in previous studies on other sandy beaches worldwide. Thus, the hypothesis that recreational activities trigger changes in benthic macrofaunal structure and composition, reducing species diversity, richness and abundance in the community was confirmed. Furthermore, the vulnerability of some taxa studied here, particularly the polychaetes *T. papillata*, *S. squamata* and *Paraonis* sp., indicates that they may be potential indicators of recreational activity impacts, and can be used as tools to investigate impacts associated with recreational activities (trampling and vehicle traffic).

The beaches studied here along the Amazonian coast are attractive recreational sites that are intensively visited every vacation period and holidays. This study shows that on these beaches, recreational activities may have adverse effects on intertidal benthic assemblages. Long-term studies are required to determine the status of communities under the influence of tourism disturbances. This study also highlights the importance of establishing and implementing effective management actions to mitigate the consequences of recreational activities on sandy beaches. Management plans and conservation strategies should include: (1) the development of protected areas with restricted access and use; (2) control of number of visitors and their decentralization (Machado *et al*., 2017). The above-mentioned actions, together with the prohibition of vehicles in the intertidal zone, should be implemented on Amazonian sandy beaches.

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Data. Data will be made available on reasonable request.

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