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Research Article

Abundance of the sand dollar, *Mellita quinquiesperforata* (Mellitidae) in La Boquilla, Cartagena de Indias, Colombian Caribbean Sea

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ABSTRACT. The sand dollar *Mellita quinquiesperforata* (Leske, 1778) is a lunulate echinoderm inhabiting sandy substrates in the Caribbean Sea's shallow coastal waters. This species functions as an environmental engineer, altering substrate characteristics, yet few studies have examined its abundance, size distribution, or relationship with substrate features. This study examines the impact of climate seasons, months, and substrate features on the relative abundance and size of *M. quinquiesperforata*, based on monthly observations conducted at La Boquilla beach (northern Cartagena de Indias, Colombia) from January to September 2023. According to our observations, aggregations of *M. quinquiesperforata* were observed, with densities ranging from 5 to 87 ind per m². Relative abundance varied significantly with climatic seasons (Kruskal-Wallis test chi-squared = 42.041, *P*-value = $7.427e^{-10}$), with the lowest densities recorded in July (transition season, 5-20 ind m^{-2}) and the highest in April (dry season, 10-45 ind m^{-2}). No individuals were observed during January and February. Aggregations were most prevalent 31-40 m from the low-tide line, where the highest densities were recorded. Size measurements ranged from 0.7 to 9 cm, with an average of 5.76 ± 0.67 cm (n = 2.526), while weights averaged 17.3 ± 5.6 g. Significant differences in size were observed between climatic seasons (chi-squared = 9.4294, *P*-value = 0.008962), months (chi-squared = 58.891, df = 5, *P*-value = $2.06e^{-11}$), and spatial distribution (distance from the low-tide line) (chi-squared = 13.899, *P*-value = 0.0009591). No significant differences were detected in weight. Most individuals collected were adults, suggesting limited recruitment during the study period. Abundance estimates for La Boquilla beach were lower than reported for other South American localities, highlighting potential site-specific differences in environmental or ecological factors affecting *M. quinquiesperforata* populations. These findings contribute to a better understanding of the population dynamics and habitat preferences of this key benthic species in the Caribbean region.

Keywords: *Mellita quinquiesperforata*; relative abundance; sand dollar; size; substrate relationship; Colombian Caribbean Sea

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INTRODUCTION

The intertidal zone is the coastal strip influenced by wave action and tidal fluctuations, undergoing alternating periods of immersion and emergence, which usually features structures such as steps, sandbars, and grooves (Ibarra-Arana & Rocha 2019, Castellar del Valle & Ramírez 2020). This dynamic habitat hosts a diverse array of species that are uniquely adapted to fluctuating conditions of temperature and solar irradiation, shaped by the prevailing climate and tidal regimes (Ibarra-Arana & Rocha 2019). Notably, some of the most socioeconomically and ecologically significant marine coastal ecosystems are situated within the intertidal zone. Among these, sandy beaches are characterized by accumulations of unconsolidated sediments that are transported and molded by currents, waves, wind, and other environmental forces. These ecosystems are particularly sensitive to environmental changes and provide critical habitats for various species to feed, nest, and rest (Morales et al. 2009). Furthermore, sandy beaches support a range of economic activities, including tourism, exploitation of marine resources, and the establishment of human settlements (Morales et al. 2009). Recent environmental changes in these areas are likely to have influenced the population dynamics of biota associated with sandy substrates (Tosic et al. 2019).

The submerged portion of sandy beaches provides a habitat for several echinoderm species, which play a crucial role in sediment mixing and the cycling of organic particles. By burrowing into the most superficial layers of the seabed, these organisms enhance microbial activity and facilitate the regeneration of mineral nutrients (Bell & Frey 1969, Ellers & Telford 1984, Costa 2008, Galván-Villa et al. 2018). Among these species, the sand dollar *Mellita quinquiesperforata* (Leske, 1778) (Fig. 1) is an irregular clypeasteroid echinoid that inhabits sandy substrates with calcareous fragments and soft bottoms at depths of up to 180 m (Lawrence et al. 1998, Francisco & Pauls 2008). It appears to prefer sediments with small grain sizes, likely related to its ability to manipulate fine grains during feeding and movement (Pomoroy et al. 1995). Its distribution spans the Atlantic Ocean coasts, from Massachusetts to southern Brazil, including the Greater Antilles and Colombia (Arévalo 1978, Harold & Telford 1990, Borrero-Pérez et al. 2002, 2012).

M. quinquiesperforata is characterized by a flattened, disc-shaped test with five lunules -one interambulacral and four ambulacral, rounded edges, and a surface covered with numerous short spines. Individuals can reach sizes of up to 160 mm and display coloration ranging from dark to light brown (Borrero-Pérez et al. 2012). The species feeds on microalgae, invertebrates, and organic and inorganic detritus, found on the surface of sediment granules (Lane & Lawrence 1982). Using its spines and tube feet for locomotion, this species constructs shelters with an entrance channel and one or more exit channels (Ellers & Telford 1984, Galván-Villa et al. 2018). In some locations, such as Cartagena de Indias, populations of *M. quinquiesperforata* are harvested and used in the production of handmade jewelry (*pers. obs.*).

Some of the most important sandy beaches in Colombia are located in the Bolívar Department (Gómez-Cubillos et al. 2015). Among these, La Boquilla lies approximately 2 km north of Cartagena de Indias (Llamas 2020). Recent studies have documented change**s** in grain size, sediment type, and substrate composition on these beaches, attributed to increased sediment transport from the Dique channel, coastal population growth, and installation of coastal protection infrastructures (Moreno-Egel et al. 2006, Rangel-Buitrago et al. 2018, Tosic et al. 2019). These processes, combined with the increasingly intense ocean-atmospheric events in the region, exceed the natural recovery capacity of the beach (Maza & Rangel 2015). The resulting impacts include alterations to beach geomorphology and damage to adjacent coastal ecosystems, such as coral reefs, mangroves, and seagrass meadows. At the same time, these environmental changes impact the livelihoods and economic conditions of vulnerable populations residing along the coastal edge (Suárez-Vargas & Rozo-Pinto 2015, Llamas 2020).

Despite recent geomorphological changes on the beaches of Cartagena de Indias and their potential effects on the abundance and distribution of associated fauna, few studies have addressed the status of economically important species such as the sand dollar. Based on the hypothesis that sand dollar abundance is influenced by the predominance of fine sands in the substrate, this study evaluated the potential reduction in the abundance and spatial distribution of this species, as well as in morphometric indicators, at La Boquilla beach. The research also examined the relationship between these variables and substrate characteristics, distance from the tide line, and the local climatic regime. Additionally, a baseline is provided for assessing the future effects of climate change and coastal management on this species.

Figure 1. *Mellita quinquiesperforata.* a) Aboral and b) oral surfaces. Picture by Mariandrea Cuentas and Manuel González.

It is worth noting that, although the results of Coppard et al. (2013) suggest that the sand dollars distributed in the Colombian Caribbean Sea belong to the clade preliminarily designated as *Mellita* sp. 1, all previous studies in this region-from the Panama border to the Guajira Peninsula-have consistently referred to these organisms as *M. quinquiesperforata*, both before and after Coppard's research (e.g. Allain 1976, Nisperuza et al. 2016, Pastrana-Franco et al. 2016, Urrego-Salinas et al. 2016). In this study, we maintain the traditional designation of *M. quinquiesperforata* until further genetic and morphological studies provide more detailed information, descriptions, and comparisons of the *Mellita* species present in this region.

MATERIALS AND METHODS

Study area

Cartagena de Indias is located in the northeast of Colombia (10º25'30"N, 75º32'25"W), at an elevation of 2 m above sea level (m.a.s.l.) (Fig. 2). The city has an average temperature of 27.7°C and an annual average humidity of 79.5%. The regional climate is characterized by three distinct seasons: a rainy season (August-November), a dry season (December-April), and a transition season (May-July) (Alandete & Romero 2016, González et al. 2022). The dry season is characterized by minimal rainfall and intense trade winds blowing from the north or northeast. In contrast, the rainy season is characterized by increased rainfall (averaging 125.7 mm) and a shift in wind direction from north to south (Osorio et al. 2016). During the transition period, wind intensity decreases to its lowest levels, accompanied by the onset of rain. A brief period known as the "Veranillo de San Juan" typically occurs in June and July, characterized by persistent, uniform winds from the north or northeast and a decrease in rainfall (Osorio 2010). The rainfall regime in this region is primarily influenced by geographical position, the trade wind system, and the influence of the Intertropical Convergence Zone (ITCZ).

La Boquilla beach (10°28'23.02"N, 75°29'57.20"W) extends approximately 1.72 km along the coast. It consists primarily of fine and very fine sands, averaging between 0.15 and 0.18 mm in grain sizes that increase in south-to-north direction (Martínez-Cogollo 2022). These sands have a biogenic origin (Arévalo 1978), although influenced by sediments from the Canal del Dique discharge and massive intervention processes (Posada & Henao 2008). The surface water presents an average temperature of 27.4°C and a semi-arid tropical climate throughout the year (Acevedo 2017). The average slope is less than 1°, and the surf zone varies from 150 to 700 m on average (Gómez-Martínez 2021, Escudero-Torres & San Martín-Gómez 2023). La Boquilla is located in a sector of the low-lying coast, highly exposed to wave energy and susceptible to high erosion, with an erosion rate of 6 m yr^{-1}, which is exacerbated by the effects of swells and hurricanes (Posada & Henao 2008). The sand dollar *M. quinquiesperforata* is commonly found near the tide line in the shallow waters of this beach (Arévalo 1978).

Sand dollar abundance

In the central sector of La Boquilla beach, the abundance of sand dollars was estimated monthly from January to September 2023, based on available sampling logistics. Sampling was conducted using a band transect measuring 150 m in length (parallel to the coastline) and 50 m in width (extending seaward),

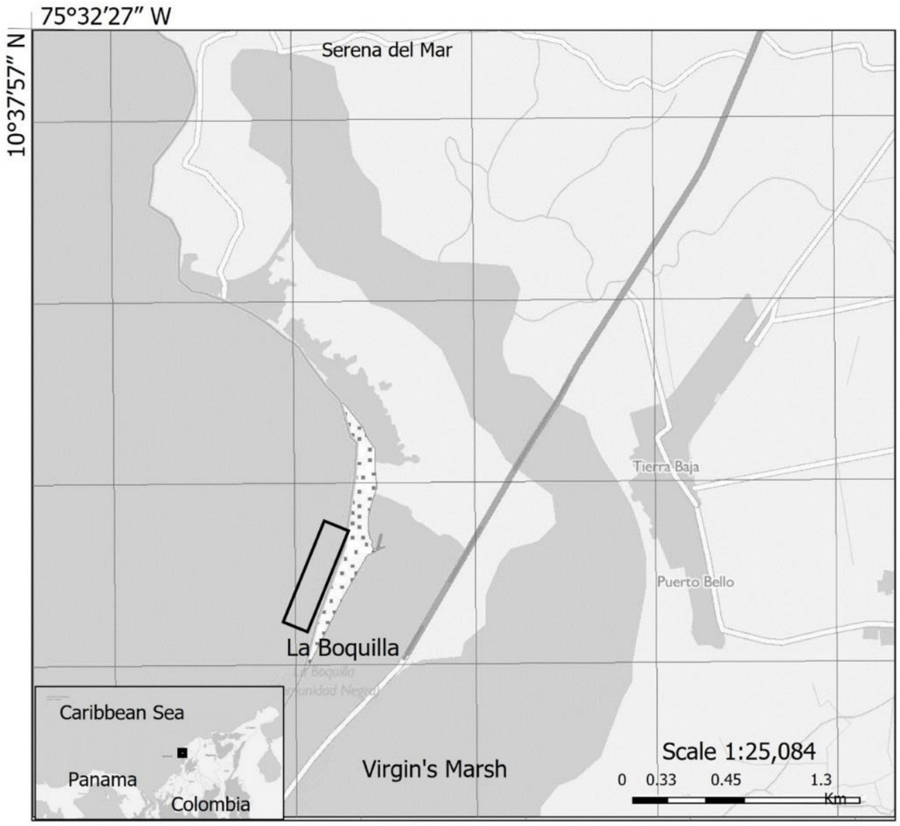

Figure 2. Sampling area (rectangle). Central sector of La Boquilla beach, north border of Cartagena de Indias (Caribbean Sea).

located 20 m from the low tide line (LTL). This transect was subdivided into nine sectors, each containing 23 quadrants (1 m^2), where all sand dollars were counted. Observations of abundance were classified based on the distance of the quadrant location from the LTL into three categories: 20-30, 31-40, and 41-50 m. Once, these data displayed a non-normal distribution (Shapiro-Wilk test, P = 2.2e-16, n = 1,863) and non-homogeneity of variances (Fligner-Killeen test, χ^2 = 40.069; $P = 1.991^{e-09}$) across climatic seasons, months (χ^2 = 73.069, $P = 1.201^{e-12}$) and strips defined by distance from the LTL (x^2 = 120.23, $P = 2.2^{e-16}$), the abundance variability for this factors was evaluated through nonparametric variability analysis (Kruskal-Wallis test).

Within each quadrant, all sand dollars present on the top substrate layer were directly collected using a Hoocozi spoon or by hand, without causing major disturbance to the substrate. Individuals were freshly weighed (g), and their sizes (cm) were measured. Size (cm) was determined as the distance from the edge of the interambulacral lunula to its opposite end (Borrero-Pérez et al. 2012). According to Tavares & Borzone (2006), individuals were categorized as juveniles if their size was less than 4 cm, the approximate size at which *M. quinquiesperforata* reaches sexual maturity as indicated by the presence of genital pores (Lane & Lawrence 1980). Individuals larger than 4 cm were categorized as adults (Borzone et al. 1997). After measurements were taken, all individuals were returned to the sea to minimize any potential impact on the population.

Size data presented a non-normal distribution (Shapiro-Wilk test, $P = 2.2^{e-16}$), and non-homogeneity of variances between climatic seasons (χ^2 = 9.7534, df = 2, P = 0.007622), months (x^2 = 13.667, df = 5, P = 0.01787) and sampling strips (χ^2 = 7.8685, df = 2, P = 0.01956) as indicated by the Fligner-Killeen test. Similarly, weight data did not meet the assumptions of normality (Shapiro-Wilks test, W = 0.99104, $P = 2.402^{e-10}$), homogeneity of variances across climatic seasons (Fligner-Killeen test, χ^2 = 1.4108, df = 2, P = 0.4939), or months (χ^2 = 19.399, df = 4, P = 0.0006559); but homogeneity of variances was observed across strips defined by the distance from the LTL (χ^2 = 0.020922, df = 2, *P* = 0.9896). Subsequently, the body weight-to-size ratio (K) was calculated as K = W L^{-1}, where W represents the body weight (g) and L is the body size (cm). These last estimations were first analyzed using a scatter plot and a linear model.

Lastly, the relationship between relative abundance (density ind m^{-2}) and environmental factors, including climatic season and the distance from the sampling site to the LTL, was evaluated using nonparametric Kruskal-Wallis tests (Quinn & Keough 2002). Likewise, the influence of environmental factors on size, weight, and K values was evaluated using nonparametric tests. Statistical analyses were conducted using statistical tools available in Excel (Microsoft Corporation, 2018) and R Studio (Posit Software PBC, 2023).

Granulometric analysis of the sediment

A surface sediment sample was collected from the north, center, and south borders of the transect during the three climatic seasons (dry, rainy, and transition; n = 27) using a Hoocozi spoon. Each sample was placed in a sealed bag and transported to the laboratory for analysis. Samples were initially air-dried for 3-5 days in aluminum trays, turned, and mixed periodically. Subsequently, the samples were oven-dried at 70°C for 24 h.

A 100 g subsample of each dried sediment was passed through a series of sieves with mesh sizes of 3.35, 1.7, 0.600, 0.25, 0.125, and 0.75 mm for 10 min. The sediment retained on each sieve was transferred to Petri dishes and weighed using an analytical balance. The grain size composition of each sample was determined based on the percentage importance of each grain size and the dominant grain size. Finally, Pearson correlation analysis (Quinn & Keough 2002) was used to evaluate the statistical relationship between sediment grain size variables and the mean abundance of *M. quinquiesperforata*.

RESULTS

Density and distribution of *M. quinquiesperforata*

A total of 2,524 ind of *M. quinquiesperforata* were recorded during the study period (January-September 2023) based on 207 quadrants (1 m^2) deployed monthly at La Boquilla beach, for a total of 1,863 (n) samples. No specimens were found during January and February. The overall mean relative abundance was estimated at 1.36 ± 6.99 ind m^{-2}, with values ranging from 0 to 87 ind m^{-2} (Table 1).

A nonparametric variability analysis (Kruskal-Wallis test) revealed significant differences in abundance medians across climatic seasons (χ^2 = 42.041; *P* = 7.427^{e-10}), months (χ^2 = 71.67; *P* = 2.284^{e-12}), and the strips defined by the distance from LTL (χ^2 = 122.46; *P* = 2.2^{e-16}). The highest general abundance was recorded during the transition season (2.48 ± 9.42 ind m^{-2}), exceeding the values observed during the dry season (0.96 ± 6.10 ind m^{-2}) and rainy season (0.46 ± 2.68 ind m^{-2}).

Regarding distance from the LTL, the 31-40 m strip consistently maintained average abundances above 2 ind m^{-2} during April to August. This strip also exhibited the highest average abundance for the study (3.41 ± 10.96 ind m^{-2}).

Patch distribution of *M. quinquiesperforata*

Observations indicate that *M. quinquiesperforata* exhibits a patchy or aggregated distribution, with individuals clustering in small portions of the substrate surface. This pattern is evident, as 94% of the sampled surface (1,755 out of 1,863 quadrats) contained no individuals. In contrast, in the remaining quadrats (108), abundance ranged from 5 to 87 ind m^{-2} (Table 2).

Most quadrats with *M. quinquiesperforata* presence contained 5 to 20 ind, whereas only about 15 quadrats showed densities between 50 and 87 ind (Table 2). To further explore abundance patterns, subsequent analyses were conducted exclusively on quadrats where *M. quinquiesperforata* was present.

The Kruskal-Wallis test showed statistically significant differences in average abundance across the climatic seasons (χ^2= 42.041; *P* = 7.427^{e-10}). The average abundance of *M. quinquiesperforata* within the patches was highest during the dry season (29.4 ± 17.7 ind m^{-2}), followed by the transition season (23.0 ± 18.9 ind m^{-2}) and the rainy season (13.7 ± 5.7 ind m^{-2}).

Significant differences were detected in the median abundances of *M. quinquiesperforata* across the evaluated months (Kruskal-Wallis test, χ^2 = 23.669; *P* = 0.0002513). The highest abundance was recorded in April (33.1 ± 21.4 ind m^{-2}), while the lowest was observed in July (13.7 ± 5.7 ind m^{-2}). However, no significant differences were detected in abundance estimates between the strips defined by the distance from the LTL (Kruskal-Wallis test; χ^2= 0.90283; *P* = 0.6367).

Despite the lack of statistical significance, the average abundance was highest in the 31-40 m strip (24.1 ± 18.8 ind m^{-2}), followed by the 20-30 m strip (21.7 ± 14.1 ind m^{-2}) and the 41-50 m strip (12.7 ± 3.1 ind m^{-2}) across all climatic seasons (Table 2).

Table 1. Overall average abundance (ind m^{-2}) of *Mellita quinquiesperforata* at La Boquilla beach (north Cartagena de Indias, Colombian Caribbean) during January-September 2023. SD: standard deviation.

Season	Month	Strip	Average	SD	n
Dry			0.96	6.10	828
	January		0	0	207
		20-30	0	0	69
		31-40	0	0	69
		41-50	0	0	69
	February		0	0	207
		20-30	0	0	69
		31-40	0	0	69
		41-50	0	0	69
	March		1.72	8.07	207
		20-30	0	0	69
		31-40	5.16	13.40	69
		41-50	0	0	69
	April		2.12	8.96	207
		20-30	3.14	10.24	69
		31-40	3.20	11.46	69
		41-50	0	0	69
Transition			2.48	9.42	621
	May		4.32	13.53	207
		20-30	0	0	69
		31-40	12.96	20.99	69
		41-50	0	0	69
	June		1.81	6.57	207
		20-30	2.20	6.72	69
		31-40	3.23	8.95	69
		41-50	0	0	69
	July		1.30	5.97	207
		20-30	0	0	69
		31-40	3.90	9.88	69
		41-50	0	0	69
Rain			0.46	2.68	414
	August		0.93	3.74	207
		20-30	0	0	69
		31-40	2.23	5.70	69
		41-50	0.55	2.65	69
	September		0	0	207
		20-30	0	0	69
		31-40	0	0	69
		41-50	0	0	69
Total			**1.35**	**6.95**	**1.863**

Sediment grain size

Granulometric analysis of 27 sediment samples from La Boquilla beach revealed that the surface sediments are predominantly composed of fine sands (51-82%) with grain sizes ranging from 125 to 250 µm. Additionally, 8-44% of each sample consisted of very fine sands, with grain sizes ranging from 75 to 125 µm.

Table 2. Average size of aggregations or patches (ind m^{-2}) of *Mellita quinquiesperforata* at La Boquilla beach (north Cartagena de Indias, Colombian Caribbean) during January-September 2023. SD: standard deviation.

Season	Month	Strip	Average	SD	n
Dry			29.41	17.70	27
	March	31-40	29.67	17.79	12
	April		29.20	18.25	15
		20-30	27.13	16.57	8
		31-40	31.57	21.09	7
Transition			22.96	18.87	67
	May	31-40	33.11	21.43	27
	June		17.05	12.31	22
		20-30	16.89	10.22	9
		31-40	17.15	13.99	13
	July	31-40	14.94	14.68	18
Rain	August		13.71	5.68	14
		31-40	14.00	6.29	11
		41-50	**12.67**	**3.06**	**3**
Total			**23.37**	**17.92**	**108**

Correlation analysis indicated a relationship between the proportion of specific grain sizes and the overall average abundance of *M. quinquiesperforata*. A positive correlation was observed with grain size measuring 0.075-125 µm (t = 3.44; df = 25; P-value = 0.002605; r = 0.5559) whereas a negative correlation was found for grains measuring 0.125-0.25 µm (t = -2.77; df = 25; P-value = 0.01042; r = -0.4846) (Table 3). These results suggest that the distribution of finer sediment fractions may influence the abundance of sand dollars.

Size of *M. quinquiesperforata*

A total of 2,526 ind of *M. quinquiesperforata* were collected from January to September 2023, with an average size of 5.76 ± 0.68 cm, ranging from 0.7 to 9 cm in length. The variability analysis using the Kruskal-Wallis test revealed significant differences in size across climatic seasons (χ^2 = 9.7534, df = 2, P = 0.008962), months (χ^2 = 58.891, df = 5, P = 2.06^{e-11}) and sampling stripes (χ^2 = 13.899, df = 2, P = 0.0009591). However, average size estimates were relatively consistent across seasons: dry (n = 794, 5.71 ± 0.67 cm), transition (n = 1,539, 5.79 ± 0.66 cm), and rainy (n = 193, 5.75 ± 0.69 cm). Similarly, the average size of sand dollars ranged from 5.56 ± 0.66 cm (March, n = 347) to 5.89 ± 0.60 cm (June, n = 375).

When comparing average sizes across sampling strips defined by the distance from the LTL, slight differences were observed. Sand dollars collected in the 20-30 m strip (n = 369, 5.88 ± 0.61 cm) were slightly

Table 3. Correlation (Cor) analysis (Pearson test) between grain size importance (%) and sand dollar density at La Boquilla, overall and inside the patches. *Fligner-Killeen test between seasons (degrees of freedom: 2). Results in bold correspond to significant correlation estimates between grain sizes and sand dollar average density. Correlation (%) grain size-density within patches (average).

	Grain size (mm)						
	3.35	**1.7**	**0.600**	**0.25**	**0.125**	**0.075**	**<0.075**
Overall density							
t	-0.811	-1.188	-0.772	-2.053	-2.770	3.440	1.566
P-value	0.425	0.246	0.448	0.051	**0.010**	**0.003**	0.130
Cor	-0.160	-0.231	-0.152	-0.380	**-0.485**	**0.556**	0.299
Patches inside density							
t	0.399	-0.070	0.220	-0.673	-2.412	1.617	2.584
P-value	0.694	0.945	0.827	0.507	**0.024**	**0.119**	**0.016**
Cor	0.079	-0.014	0.044	-0.133	**-0.434**	**0.308**	**0.459**
Normality							
N	27	27	27	27	27	27	27
Shapiro-Wilk (W)	0.5302	0.705	0.691	0.845	0.928	0.945	0.385
P-value	$3.46e^{-08}$	4,57E-03	2,90E-03	0.001	**0.062**	**0.157**	1.38E-09
Lilliefors (D)	0.407	0.274	0.268	0.177	**0.158**	**0.115**	0.378
P-value	$8.85e^{-13}$	$1.61e^{-05}$	$2.81e^{-05}$	0.030	**0.082**	**0.478**	$6.24e^{-11}$
Variance Homogeneity* (χ^2)	2.546	3.447	0.402	4.492	**1.511**	**3.374**	6.249

larger on average than those from the 31-40 m (n = 2,119, 5.74 ± 0.67 cm) and 41-50 m strip (n = 38, 5.72 ± 0.71). Among the collected specimens, less than 1% were subadults, approximately 30% belonged to young adults (4.0-6.5 cm), and 7% were mature adults (>6.5 cm). The size frequency distribution remained consistent across the three climatic periods and sampled months.

Weight of *M. quinquiesperforata*

Between April and August 2023, a total of 2,176 ind of *M. quinquiesperforata* were weighed, yielding an average body weight of 17.28 ± 5.59 g, with a range of 2.0 and 40.0 g. Nonparametric variability analysis (Kruskal-Wallis test) showed no significant differences in weight estimates across climatic seasons (χ^2 = 2.8621, df = 2, P = 0.2391), months (χ^2 = 2.9881, df = 4, P =0.5598) or LTL-defined strips (χ^2= 0.097768, df = 2, P = 0.9523). Overall, 60% of individuals presented body weights ranging from 11 to 23 g, while only 4% weighed between 30 and 40 g, and 2% weighed less than 5 g. This weight distribution remained consistent across all sampled periods, with adults more prevalent than juveniles during all months.

The weight/size ratio (K) ranged from 0.57 to 5.33, with an average of 2.94 ± 0.72. These data met the assumptions of normal distribution (Shapiro-Wilk test, W = 0.99, P-value = 0.2125), and homogeneity of variances across climatic seasons (Fligner-Killeen test, χ^2 = 3.7216, df = 2, P-value = 0.1555) and LTL-defined strips (χ^2 = 5.7944, df = 2, P-value = 0.05518), but not across months (χ^2= 28.676, df = 4, P-value = 9.095^{e-06}).

One-way ANOVA analysis revealed no significant differences in K values across climatic seasons (F = 2.718, P = 0.0662), months (F = 2.235, P = 0.063), and strips (F = 0.311, P = 0.732). Two-way ANOVA also revealed no significant interactions between these factors and the K values. The linear equation describes the relationship between body weight and size: y = 7,0796x - 23,785. This linear model suggests a proportional relationship between body weight and size across the sampled population.

DISCUSSION

Abundance and distribution of *M. quinquiesperforata*

In the Colombian Caribbean, three species of Mellitidae have been reported: *M. quinquiesperforata* (Leske, 1778), *Leodia sexiesperforata* (Leske, 1778), and *Encope michelini* (L. Agassiz, 1841). However, the latter is probably *E. emarginata* (Leske, 1778), according to Coppard & Lessios (2017). These species have been documented in Cartagena de Indias (Arévalo 1978), Santa Marta, Cispatá, and nearby localities (Borrero-Pérez et al. 2012). In 1978, Arévalo collected 2,365 ind of *M. quinquiesperforata* from the beaches in Cartagena, ranging from Bocagrande to Manzanillo (Arévalo 1978) (Table 4).

Table 4. Abundance estimates of the *Mellita quinquiesperforata* species were made across their distribution area.

Species	Reference	Locality	Methods	Abundance
M. quinquiesperforata	Salsman & Tolbert (1965)	Panama City	Manual collection	44-821 ind m^{-2}
M. quinquiesperforata	Arévalo (1978)	Cartagena de Indias (Colombia). From Bocagrande to Manzanillo beach	Opportunistic collecting	2,365 ind /15 km
M. quinquiesperforata	Mahieu & Gamba (1980)	Tocuyo de La Costa (Venezuela)	Manual collection	52 ind m^{-2}
M. quinquiesperforata	Lane & Lawrence (1980)	Tampa Bay, Florida	Manual collection	6-489 ind m^{-2}
M. quinquiesperforata	Pauls et al. (1988)	Playa Tucacas (Brazil)	Manual collection	28.3 ind m^{-2}
M. quinquiesperforata	Borzone (1992)	Patos Lagoon (Brazil)	Manual collection	12-50 ind m^{-2}
M. quinquiesperforata	Penchaszadeh & Molinet (1994)	Quizandal Beach (Venezuela)	Handmade. 1-4 m deep April-May 1979-82	2,570 ind m^{-2} for juveniles, 87 ind m^{-2} for adults
E. michelini	Galindo-Anaya et al. (2020)	Cispatá (Colombia)	Handmade	405 ind /114 m^2, 0.58 ± 0.14 ind m^{-2}
M. quinquiesperforata	Silva et al. (2021)	Santos Beach, (Brazil)	5.5 km beach strips (10 m wide) at the intertidal zone	0.0001-0.0084 ind m^{-2}
M. quinquiesperforata	This study	Cartagena, La Boquilla (Colombia)	1,864 1m^2 quadrants	2,524 /1,864 m^2 1.36 ± 6.99 ind m^{-2}

In this study, exploratory measurements made during June and July 2022 along the same beaches referred to by Arévalo (1978) did not detect a single individual of *M. quinquiesperforata*. The species was only observed at La Boquilla beach. These results are likely due to the urban intervention in the area and its effects on beach dynamics and sand size composition. Subsequent systematic monthly surveys, conducted using 1 m² quadrats between January and September 2023 in the central sector of La Boquilla, resulted in the collection of data from 2,524 ind across a sampled area of 1,864 m².

The average abundance of *M. quinquiesperforata* in Cartagena (1.36 ± 6.99 ind m^{-2}) contrasts with the historical distribution in the area (Arévalo 1978) and highlights La Boquilla beach as the current primary location. These findings suggest potential shifts in habitat suitability or population dynamics for this species in the region, likely driven by environmental or anthropogenic factors.

Although the number of individuals collected in both studies is similar, notable differences exist in methodology and spatial coverage. Arévalo (1978) sampled an area of approximately 15 km², whereas this study focused on a smaller area of approximately 4 km². Also, the time and methods used to sample the individuals varied. Arévalo's study was based on the opportunistic collection of individuals, likely associated with punctual observations conducted for other purposes in the region. In contrast, the present study implemented systematic sampling, specifically designed to survey a defined area (4 km) during field campaigns exclusively planned for this research. Consequently, the relative abundance estimated in this study for *M. quinquiesperforata* in Cartagena might be considered higher than that estimated from Arévalo's data in the 1970s. However, the relative abundance reported here is lower than that estimated for most other localities, as well as for other Mellitidae species (Table 4). Only the abundance estimates in this study are higher than those reported for Santos Beach, Brazil (0.0001-0.0084 ind m^{-2}, 2015-2018, Silva et al. 2021), where sampling was conducted along 5.5 km beach strips (10 m wide) at the intertidal zone.

During the last two centuries, Cartagena de Indias's littoral border has undergone several morphological changes due to the impacts of mangrove loss and coral reef degradation, uncontrolled urbanization, and the effects of sea level rise linked to climate change. For example, cartographic and historical analyses of coastal landscape evidence indicate that erosion exceeds accretion during this period (Gonzalez-Rodriguez et al. 2021). Additionally, the substrate on the littoral border exhibited visible changes. For example, according to Arévalo (1978), the substrate of sand beaches along Cartagena de Indias during the 1970s was dominated by grains of 0.250-0.063 mm in size, composed of fragments of coral, shell, and foraminifera. For this study, sand samples collected at La Boquilla were predominantly composed of fine sands (51-82%) and very fine sands (8-44%), with grain sizes ranging from 0.075 to 0.250 mm. These geomorphological modifications experienced by Cartagena's beaches since 1978, driven by uncontrolled urban development, the construction and maintenance of coastal protection structures (Moreno-Egel et al. 2006, Castellar & Ramirez 2020) and the loss of mangrove areas, along with the cumulative effects of these processes on sediment transport and deposition increased by ocean/atmosphere events (Posada & Henao 2008), may explain the observed reduction in the abundance of *M. quinquiesperforata* in Cartagena de Indias. These findings underscore the need to monitor the composition and dynamics of sediment, as well as the relationship between the sediment and biota associated with local beach areas.

Sand dollar abundance is closely related to the characteristics of the substrate they inhabit, particularly grain size. In a laboratory experiment, Pomory et al. (1995) tested sand dollars of the species *Mellita tenuis* in compartments containing different grain sizes. They observed a preference for substrates with grain sizes of 250-499 and 125-249 µm. Although individuals were capable of moving across all tested sediment grain size classes, they exhibited a preference for the smaller grains. These preferences are likely linked to their ability to handle finer particles more efficiently and to maximize organic matter intake (Pomory et al. 1995, Challener et al. 2009). Similarly, Salsman & Tolbert (1965) described a patchy distribution for *M. tenuis* (Clark 1940), typically associated with sand channels and depressions where finer sediments accumulate. Consistent with these findings, punctual observations conducted in 2022 on Cartagena's beaches (before the current study) revealed the absence of individuals in the strip from the low-tide line to 20 m offshore.

The present study found that the grain size composition at sites with *M. quinquiesperforata* presence exhibited little variation between locations and climatic periods sampled, with fine and very fine sand particles predominating. Finally, the average abundance of this species showed a slight positive relationship with the proportion of fine and very fine particles in the substrate samples, emphasizing the role of sediment characteristics in shaping their distribution.

Climatic season and abundance of *M. quinquiesperforata*

The abundance of *M. quinquiesperforata* in La Boquilla was influenced by the climatic season. In this study, the highest overall abundance of this species was recorded in April, while the species was not detected during January, February, and September. Although available studies indicate geographic variability in the reproductive patterns of *Mellita* species (Salsman & Tolbert 1965, Lane & Lawrence 1980, Harold & Telford 1990), assessment of *M. quinquiesperforata* reproductive activity, particularly in Brazil, report the continuous presence of fertile adults and premature juveniles throughout the year (Tavares & Borzone 2006, Mello et al. 2020). Consistent with these findings, the present results showed a greater presence of adults than juveniles across all sampled months.

Thus, the observed seasonal variation in sand dollar abundance at La Boquilla beach is likely related to environmental factors rather than the reproductive cycle of the species. The low abundance estimates in this study may be attributed to undersampling caused by the depth at which sand dollars burrow into the substrate or their distance from the shoreline. During the dry season, increased winds and reduced rainfall typically result in a decrease in suspended solids in the water column. However, laboratory experiments continue to seek to clarify the relationship between environmental factors and the diel or seasonal behavior of sand dollar species (Cleveland & Pomory 2022).

In this study, sand dollars were collected manually or using a Hoocozi spoon, with sampling restricted to the top sediment layer, often under conditions of strong waves and high tides. The size of the patches, i.e. the average abundance within quadrants with *M. quinquiesperforata* presence, showed a different trend compared to overall abundance estimates. The highest patch density was observed in May (33.1 ± 21.4 ind m^{-2}, n = 27), while the lowest occurred in August (13.7 ± 5.7 ind m^{-2}, n = 14), indicating that higher patch densities do not necessarily coincide with higher overall abundance across the sampled area.

It is possible that during January and February, sand dollars were buried deeper within the substrate or located farther away from the tide line, rendering them less detectable by the applied sampling methods. Available descriptions refer to sand dollars burrowing just under the substrate surface (e.g. Yeo et al. 2013). Still, several also cite that this depth can change in response to changes in salinity, tidal force, or surface current intensity. In contrast, others relate the burrowing depth to the size of the organisms (Fink 2016). These findings underscore the need for additional research to elucidate the impact of environmental factors on the distribution and behavior of *M. quinquiesperforata* in shallow coastal ecosystems.

Size comparisons of *M. quinquiesperforata*

The size range of *M. quinquiesperforata* observed in Cartagena (0.7-9 cm) is similar to values reported in other studies. For instance, Salsman & Tolbert (1965) recorded sizes from 1.2-6.3 cm in Panama City (Florida), while Lane & Lawrence (1980) documented individuals from >0.1-11 cm in Tampa Bay, Florida. Similarly, Costa (2008) reported a size range of 0.35-8.26 cm for specimens collected in Ceará, Brazil (n = 4,134).

The average size estimated in the present study (5.76 ± 0.68 cm, n = 2,526) was slightly larger than the average size reported for Tampa Bay (4.6 cm; Lane & Lawrence 1980), which suggests that size variability in *M. quinquiesperforata* may be influenced by local environmental conditions and population dynamics across regions.

CONCLUSIONS

According to the observations described here, *M. quinquiesperforata* may have a seasonal presence on the La Boquilla beaches, particularly during the transition season around June and August. Fine and very fine sand particles predominate at sites with this species, with little variation between locations and climatic periods sampled. Although it has been previously reported along Cartagena de Indias beaches, its presence is now limited to the La Boquilla Sector, likely in response to historical changes in substrate features and massive urbanization at the coastal edge, which highlights some of the environmental stressors for this resource in this locality. Additionally, the current abundance of sand dollars is lower than previously reported for other areas and this region. These results partially support the hypothesis that *M. quinquiesperforata* abundance depends on the predominance of fine sands, but also present a seasonal pattern likely related to the local climate regime. Regarding the age composition, the aggregations of *M. quinquiesperforata* correspond mostly to adult individuals. These observations underscore the importance of ongoing and intensified monitoring of benthic fauna in intertidal ecosystems at Cartagena de Indias, as well as their relationship with substrate characteristics.

RECOMMENDATIONS

Considering the ecological roles of echinoid species in sand littoral substrates and their vulnerability to the effects of climate change, it is essential to enhance year-round monitoring efforts for *M. quinquiesperforata*. Additionally, approaches regarding the reproductive cycle, larval stages, and environmental factors driving their settlement on the substrate are required, particularly considering the spatial location of the juveniles' recruitment process and potential strategies for protecting these ecosystems. Further research into these subjects will provide valuable information to understand the behavior of *M. quinquiesperforata* better, and inform elements for its conservation and management.

Credit author contribution

M. Cuentas-Pérez & M. González-Anaya: supported the acquisition, identification, and measurement of specimens using their funds, and they also managed the acquisition of technical equipment for fieldwork; R. Sarmiento-Devia, M. Benavides-Serrato & P. Romero-Murillo: supported and advised the data analysis and discussion, as well as the field and lab work. All authors have read and accepted the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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