INFLUENCE OF SEDIMENT SPATIAL DISTRIBUTION ON THE DENSITIES OF THE BIVALVE *Anomalocardia flexuosa* (VENERIDAE) ON MANGUE SECO BEACH (NORTHEAST, BRAZIL).

Influência da distribuição espacial do sedimento nas densidades do bivalve *Anomalocardia fleuxosa* (Veneridae) na praia de Mangue Seco (Nordeste, Brasil)

Influencia de la distribución espacial del sedimento en las densidades del bivalvo *Anomalocardia fleuxosa* (Veneridae) en la playa de Mangue Seco (Nordeste, Brasil)

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ABSTRACT

In the present study, the composition and distribution of sediment on Mangue Seco Beach (Pernambuco - Brazil) were evaluated, as well as their influence on the densities in different length classes of the bivalve *Anomalocardia flexuosa*. A total of 34 samples were collected between July and September 2015. Sediments were categorized into three size classes (gravel, sand, and fine sediments), while organisms were divided into four categories (small, medium, large, and total). Observed estimates of sediments and densities, as well as results predicted by Generalized Additive Models, were interpolated using geostatistical methods. The study area exhibited a considerable predominance of sand grains throughout its extent. Longitude was found to be a significant factor in the sediment distribution across all three categories. Reduced quantities of gravel and fine sediments played a relevant role in the distribution and density of *A. flexuosa* in the different length classes. In case there is an interest in directing management strategies towards areas intended for the extraction of large specimens, it is advisable to consider, in addition to geographical coordinates, the regions on the bank with a higher concentration of fine sediments.

Keywords: mollusk; sandy beach; substrate; grain size

RESUMO

No presente estudo, foi avaliada a composição e a distribuição do sedimento na praia de Mangue Seco (Pernambuco – Brasil), e sua influência sobre as densidades em diferentes classes de comprimento do bivalve *Anomalocardia flexuosa*. Um total de 34 amostras foram coletadas no período entre julho e setembro de 2015. Os sedimentos foram categorizados em três classes de tamanho (cascalho, areia e sedimentos finos), enquanto os organismos foram divididos em quatro categorias (pequenos, médios, grandes e total). As estimativas observadas dos sedimentos e das densidades, bem como os resultados previstos pelos Modelos Aditivos Generalizados, foram interpolados por meio de métodos geoestatísticos. A área de estudo apresentou uma

predominância considerável de grãos de areia em toda a sua extensão. A longitude revelou-se como um fator significativo na distribuição dos sedimentos em todas as três categorias. Quantidades reduzidas de cascalho e sedimentos finos exerceram um papel relevante na distribuição e densidade de *A. flexuosa* nas distintas classes de comprimento. Em caso de interesse em direcionar as estratégias de manejo para áreas destinadas à extração de espécimes grandes, é recomendável considerar, além das coordenadas geográficas, as regiões no banco com maior concentração de sedimentos finos.

Palavras-chave: molusco; praia arenosa; substrato; tamanho de grão

RESUMEN

Este estudio evaluó la composición y distribución del sedimento en la playa de Mangue Seco (Pernambuco - Brasil), y su influencia en las densidades en diferentes clases de longitud del bivalvo *Anomalocardia flexuosa*. Se recogieron un total de 34 muestras entre julio y septiembre de 2015. Los sedimentos se clasificaron en tres clases de tamaño (grava, arena y sedimento fino), mientras que los organismos se dividieron en cuatro categorías (pequeño, mediano, grande y total). Las estimaciones de sedimentos y densidad observadas, así como los resultados predichos por los Modelos Aditivos Generalizados, se interpolaron utilizando métodos geoestadísticos. La zona de estudio mostró un predominio considerable de granos de arena en toda su longitud. La longitud resultó ser un factor significativo en la distribución de los sedimentos de las tres categorías. Pequeñas cantidades de grava y sedimentos finos desempeñaron un papel significativo en la distribución y densidad de A. flexuosa en las diferentes clases de longitud. Si existe interés en dirigir las estrategias de gestión hacia zonas destinadas a la extracción de grandes ejemplares, es aconsejable considerar, además de las coordenadas geográficas, las regiones de la orilla con mayor concentración de sedimentos finos.

Palabras clave: molusco; playa arenosa; sustrato; granulometría

INTRODUCTION

The benthic macroinvertebrates are groups of organisms characterized by their intrinsic relationship with the substrates they inhabit (Day et al., 1989). In sandy habitats, this assemblage consists of permanent and often clumped species (Brown & Mclanchlan, 1990), with the phylum Mollusca prominently featured in this type of environment (Rueda et al., 2009). The analysis of the spatial distribution of mollusks becomes notably relevant due to their species playing a substitutive role in the entire marine benthic community. In this context, bivalves stand out, a class that plays multiple ecological roles and has significant commercial value (Martins et al., 2014).

On the Brazilian coast, several species of bivalves are the subject of commercial exploitation, with a focus on Veneridae *Anomalocardia flexuosa* in the state of Pernambuco (Silva-Cavalcanti & Costa, 2011; Lima et al., 2020). The extraction activity of this bivalve in Pernambuco represents the largest capture of an aquatic organism in the state (Oliveira & Andrade, 2018). This practice is carried out along the entire coast of the state but is predominant in the extractive banks located in the northern region, such as the one at Mangue Seco Beach, possibly the largest *A. flexuosa* extractive bank in the world (Oliveira & Andrade, 2018).

The bivalve *A. flexuosa* is a species that generally inhabits the shallowest sediment layer, preferably the top 5 cm of depth (Lima et al., 2021). In the coastal waters of Brazil, the highest densities of this bivalve are observed in locations with higher sand content (Beasley et al., 2005; Boehs et al., 2008; Rodrigues Maia et al., 2018). The granulometric characteristics of the substrate can influence the distributions and abundances of benthic mollusks. Although, in most cases, this influence occurs due to the explicit relationship these species maintain with the sediment, these characteristics may not be a predominant factor in the zonation patterns of some bivalves (López-Alonso, 2022). The complexity of this distribution may be less pronounced in bivalves of the Veneridae family, to which *A. flexuosa* belongs, since they are substrate generalist species and colonize a wide variety of sediment textures (Alexander et al., 1993).

The variety of sediment types that *A. flexuosa* can inhabit complicates the understanding of the distribution of this species in extractive banks along the Brazilian coast. However, even being a generalist species, it is essential to understand how sand percentages and other granulometric fractions can act as influencing factors in different length classes of this bivalve. Grain size can be a crucial element in habitat selection by different length classes of bivalves, which may prefer a specific grain size as a primary component for their

establishment (Zhang et al., 2022). This information can also be valuable for planning management strategies aimed at adaptation in future cultivation projects of this species.

The application of techniques that contribute to the assessment of the relationship between sediment substrate and *A. flexuosa* densities is of undeniable relevance in elucidating this phenomenon. Among these techniques, one of the most widely used and robust is Generalized Additive Models (GAMs) (Wood, 2017). GAMs are suitable tools for estimating functional relationships, both parametric and smoothed, between predictor variables and the response variable (Pedersen et al., 2019). Therefore, within the scope of this specific study, analyses were conducted to assess the composition and distribution of sediment in Mangue Seco Beach and its influence on the densities of different length classes of *A. flexuosa*.

MATERIAL AND METHODS

STUDY AREA AND DATA COLLECTION

Mangue Seco Beach is located on the northern coast of the state of Pernambuco, in the Northeast of Brazil (Figure 1). The beach bank is predominantly composed of sand, extending over an area of approximately 2.7 km², ranging from the mouth of the Timbó River to the south to the mouth of the Santa Cruz Canal to the north (Lavander et al., 2011; Lima et al., 2020). In this location, the collection activity of the bivalve mollusk *A. flexuosa* is notable. Over the past two decades, the harvesting of this bivalve on Mangue Seco beach has undergone an evolution. Previously, this activity was carried out manually, while currently, it is predominantly conducted using fishing gear (Rodrigues et al., 2013; Lima et al., 2020).

In total, 34 samples were collected (Figure 1) from July to September 2015, using a PVC cylinder with a diameter of 19 cm, inserted to a depth of 10 cm. The collected material was transported to the laboratory, where specimens of *A. flexuosa* were measured in the anteroposterior direction of the shell, with the assistance of a precision manual caliper with a precision of 0.02 mm and quantified. Densities were calculated for both the total aggregate and for different length categories, namely: small (up to 10 mm), medium (greater than 10 mm and less than 20 mm), and large (greater than 20 mm), following the guidelines outlined by Lima et al. (2022). The sediments in each sample were dried in an oven at 60°C for 48 hours, followed by homogenization and selection of 100g of material. The separated sediments were sieved using a sieve shaker (ROTAP) and classified into three size categories: gravel (> 2 mm), sand (2 mm – 0.053 mm), and fines (< 0.053 mm).
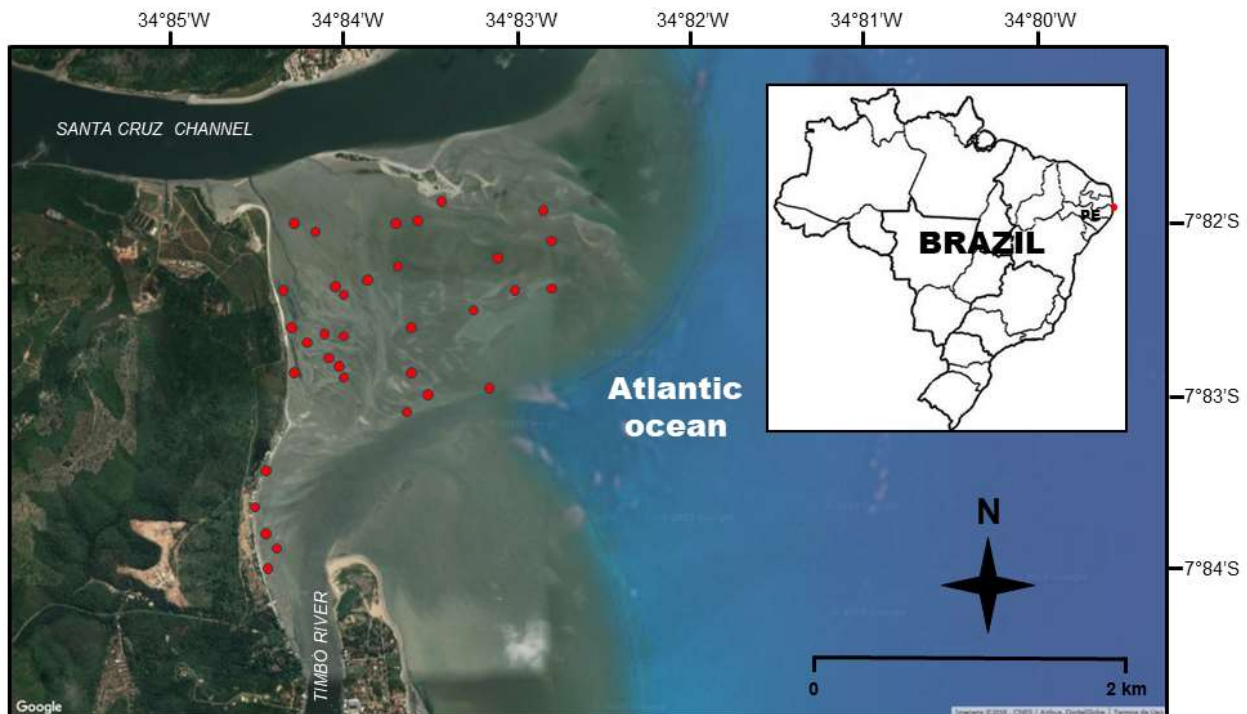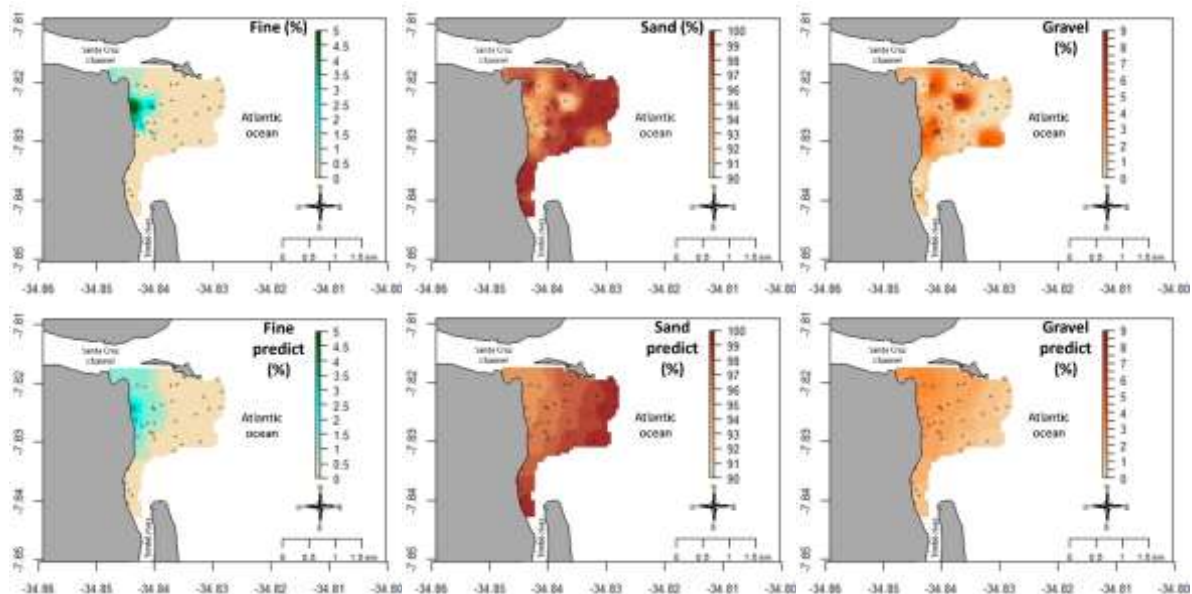

Figure 1. Extractive reserve of Mangue Seco Beach on the northern coast of the state of Pernambuco (Northeast - Brazil) and collection points.

Data Analysis

In describing the percentages of sediment size classes and densities within different length classes of the bivalve and aggregate, descriptive analyses were applied, including means, minimum, and maximum values. To model the distributions of the three grain size classes, we employed Generalized Additive Models (GAMs), using longitude and latitude as explanatory variables, as well as the four density groups of *A. flexuosa*. The latter had longitude, latitude, and the three sediment divisions (gravel, sand, and fines) as explanatory variables. In all GAMs models, parametric and smoothed forms of variables were assessed, along with their interactions. However, due to the limited data, some of these interactions did not converge. Model selection was based on residual diagnostics and the Akaike Information Criterion - AIC (Akaike, 1974). Observed estimates of the percentages of the three sediment size classes and densities in the four bivalve length classes, along with results predicted by the best GAMs models, were interpolated using geostatistical methods, employing calculations based on inverse distance. All analyses were conducted using R 4.3.1 Statistical Environment software (R Core Team, 2024). For GAMs-based modeling, the mgcv package was used (Wood, 2022), while gstat (Pebesma & Graeler, 2017) was utilized for geostatistical calculations.

RESULTS

The percentages of the three sediment granulometry categories analyzed in the coastal area of Mangue Seco Beach revealed higher contents of sand, gravel, and fines, respectively (Figure 2). The average percentage of fines found was 0.56%, with a minimum value of 0.02% and a maximum of 4.73%. For the sand fraction, the mean was 97.55%, with values ranging from a minimum of 96.16% to a maximum of 99.96%, while the gravel fraction showed an average percentage of 1.88%, with a minimum of 0.00 and a maximum of 8.67%. In the GAMs, the explained deviations were higher in the fines, sand, and gravel fractions, respectively (Table 1). Longitude showed significance in the sediment distribution in all three categories, while latitude had an impact on the sand fraction, and the smoothing resulting from the interaction between these two coordinates influenced the fines and sand categories. The model predictions interpolations highlighted that the longitudinal variable exerted the greatest influence on the different sediment granulometry categories analyzed, and compared to fines and sand fractions, the result for the gravel category was the least reliable (Figure 2 - lower panels).
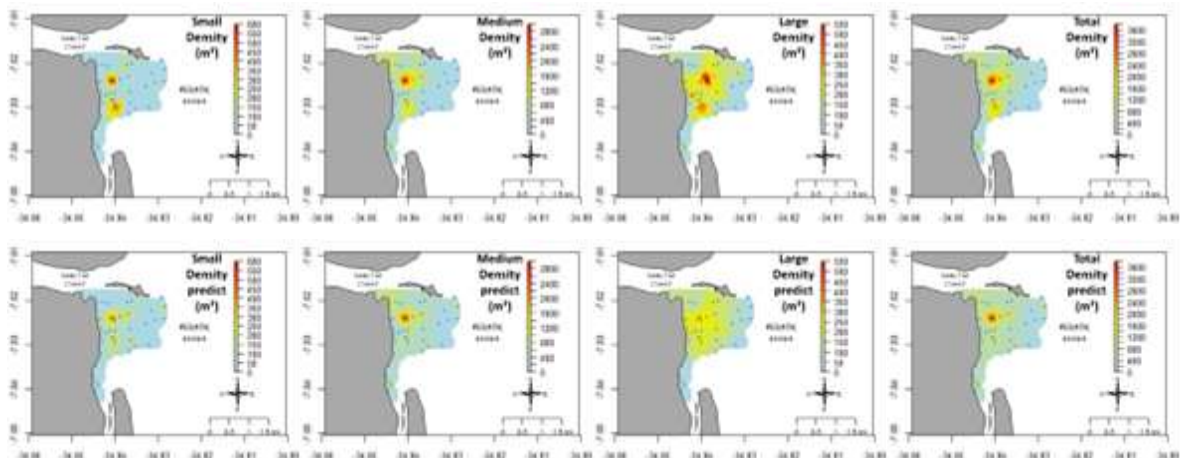

Figure 2. Interpolations of sand, clay, and gravel percentages (upper panels) and their predictions with the best-selected model (lower panels) in the extractive bank of Mangue Seco Beach on the northern coast of the state of Pernambuco (Northeast - Brazil).

The average, minimum, and maximum densities for the bivalve length categories were 57 ind/m² (0 – 132 ind/m²) for the small group, 366 ind/m² (0 – 2788 ind/m²) for the medium group, 132 ind/m² (0 – 529 ind/m²) for the large group, and a total of 559 ind/m² (0 – 3635 ind/m²). Overall, the distribution of bivalves concentrated in longitudes closer to the coast and latitudes closer to the Santa Cruz Channel outlet (Figure 3). However, in the selected GAMs, geographic coordinates were incorporated only for the large length category, and in all models, the explanatory power exceeded 68% (Table 2).

Table 1. Selected Generalized Additive Models (GAMs) for the distributions of fine, sand, and gravel percentages considering longitude and latitude variables in the extractive bank of Mangue Seco Beach on the northern coast of the state of Pernambuco (Northeast - Brazil). Term type: P – parametric terms S– smooth terms; EDF – estimated degrees of freedom; p-values in bold indicate significant differences.

Size sediment	Terms	Term type	EDF	F-value	t-value	p-value	Deviance explained
Fine	longitude	P	-	-	-3.902	**0.001**	65%
	latitude	P	-	-	-0.939	0.357	
	longitude, latitude	S	10.01	2.513	-	**0.024**	
Sand	longitude	P	-	-	-245.500	**<0.001**	33%
	latitude	P	-	-	-140.200	**<0.001**	
	longitude, latitude	S	3.56	2.609	-	**0.048**	
Gravel	longitude	P	-	-	-4.897	**<0.001**	12%
	latitude	P	-	-	-1.999	0.055	
	longitude, latitude	S	2.46	1.074	-	0.320	

In the small category, the smoothed term involving the interaction between sand and gravel showed relevance in its distribution. In the distributions of medium-sized bivalves, as well as in the aggregate (total), no significant interactions between variables were observed, with only the smoothed terms related to sediment size categories being incorporated, all showing significance for the medium category, except for fine sediments in the case of the total. In the large category, in addition to geographic coordinates, the parametric term related to fine sediments was found to be significant.

Figure 3. Interpolations of *Anomalocardia flexuosa* densities by length classes (small, medium, large) and aggregate (total) (top panels) and their predictions with the best-selected model (bottom panels) in the extractive bank of Mangue Seco Beach on the northern coast of Pernambuco state (Northeast - Brazil)

Table 2. Selected Generalized Additive Models (GAMs) for *Anomalocardia flexuosa* densities considering the variables longitude, latitude, and percentages of fines, sand, and gravel in the bank of Mangue Seco Beach (Pernambuco - Brazil). Term type: P – parametric terms S – smooth terms; EDF – estimated degrees of freedom; p-values in bold indicate significant differences.

Size bivalve	Terms	Term type	EDF	F-value	t-value	p-value	Deviance explained
Small	Fine	P	-	-	0.056	0.956	72%
	Sand, Gravel	S	12.58	2.356	-	0.036	
Medium	Fine	S	7.75	6.095	-	<0.001	75%
	Sand	S	2.60	3.467	-	0.037	
	Gravel	S	0.61	14.204	-	0.008	
Large	Fine	P	-	-	5.630	<0.001	72%
	Sand	P	-	-	1.416	0.171	
	Gravel	P	-	-	-1.110	0.279	
Total	longitude, latitude	S	9.11	3.015	-	0.011	69%
	Fine	S	2.65	3.167	-	0.050	
	Sand	S	7.04	4.439	-	0.003	
	Gravel	S	0.61	12.802	-	0.010	

DISCUSSION

The higher percentage of sand is in line with previous findings, in which the Mangue Seco Beach was classified as predominantly sandy (Lavander et al., 2011). However, it is noteworthy that sand predominates in this study without a subdivision of this fraction into more specific categories such as fine, medium, and coarse sand. This information, if available, could significantly enhance the understanding of the site's granulometric composition, given the high proportion of sand found. Nevertheless, it appears that substantial percentages of fine and coarse sand are present (Lavander et al., 2011).

The highest percentages of fine particles are concentrated near longitude -34°84' and river mouths, especially the Santa Cruz Channel. The studied bank exhibits characteristics of a tidal flat, where the input of fine-grained sediments prevails, driven by tides rather than other hydrodynamic forces (Klein, 1985). The origin of these fine sediments is largely attributed to river transport (Gao, 2019). It is believed that the predominant input of fine sediments at the site comes largely from the Santa Cruz Channel to the north, which constitutes the largest estuarine complex in the state of Pernambuco (Moura, 2009). The deposition of clayey sediments is indicative of areas subject to intense tidal influence (Gao, 2019). Therefore, it is reasonable to infer that tidal action on the bank is more pronounced near the Santa Cruz Channel, with the additional protection provided by the Coroa do Avião islet, which acts as a natural barrier. Conversely, at the mouth of the Timbó River, wave action is likely to exert a more significant influence, thus explaining the low proportion of clay and, consequently, the predominance of waves as the dominant force responsible for the transport of fine-grained sediments to more distant coastal regions (King, 1972).

The settings of the models chosen for bivalve length class densities were similar only for medium category and total, confirming the hypothesis that the percentages of granulometric fractions may interfere in distinct ways depending on animal lengths. Small proportions of fine sediments or gravel were intervening factors in the densities of *A. flexuosa* in the mentioned bank. The distribution patterns of animals by length class, in relation to grain size, in this study partially corroborated with the results obtained for the bivalve mollusk

Amarilladesma mactroides on a sandy beach in the South Atlantic (Fiori & Carcedo, 2015). Large individuals of *A. flexuosa* exhibited a more selective distribution compared to other classes, opting for sandy sediments containing proportions of fine sediments, while *A. mactroides* were predominantly observed in locations with medium to fine grain sand (Fiori & Carcedo, 2015). In small and medium-sized animals, positive relationships were observed with a higher proportion of gravel, although lower bivalve abundances are more commonly found in high-energy hydrodynamic zones characterized by gravelly sediments (Fersi et al., 2023). This less restrictive recruitment of animals is relevant, as bivalves have the ability to occupy a wide range of grain sizes, but subsequent success is conditioned by sediment fractions that allow for rapid burial during movements between different locations (Fiori & Carcedo, 2015).

The extractive bank at Mangue Seco Beach is composed of high proportions of sand grains along its entire length. Small amounts of gravel are distributed with more significant longitudinal variations, as well as fine sediments (silt and clay), which are also influenced by the interaction between latitude and longitude, possibly resulting from the transport and deposition of these grains near the Santa Cruz Channel. Despite the predominance of sandy sediments, the less abundant fractions played a significant role in the distribution and density of *A. flexuosa*. Different sediment size categories can affect the different length classes of the bivalve, which is crucial for identifying exclusion areas or more suitable capture locations. Although the length class distributions overlapped in most collections, if there is an interest in directing management towards areas of large specimen extraction, in addition to geographic coordinates, it is advisable to observe areas on the bank with a higher presence of fine sediments. The results presented here also contribute to the success of species cultivation activities, as the substrate chosen for different length classes of specimens should consider grain size.

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