Brazilian Journal of Biology®

ISSN 1519-6984 (Print)
ISSN 1678-4375 (Online)

Original Article

Characterization and distribution of Teredinidae assemblage in an estuary in Ceará, Brazil's Northeast

Caracterização e distribuição da assembleia de Teredinidae em um estuário no Ceará, Nordeste do Brasil

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Abstract

Teredinids are bivalves mollusks considered the most abundant of invertebrates group of marine wood borers performing an important role in the mangrove environment. This study aimed to characterize the Teredinidae species from the Acaraú River estuary in Ceará and analyse the relationship between the mangrove plant structure and the distribution of Teredinidae, according to gradients estuaries: vertical (flooding) and horizontal (salinity). The collection of mangrove logs with Teredinidae happened in three places within the estuary (inner, median, and upper); in each area, three transects were traced in which three plots were lined off, and a total of 40 logs were collected. Teredinidae species were found and identified: *Nausitora fusticula; Neoteredo reynei; Teredo turnerae; Teredo* cf. *bartschi; Bankia bipennata; Bankia gouldi; Lirodus massa and Lyrodus* cf. *bipartitus.* The *Lyrodus* cf. *bipartitus, Bankia gouldi, and Teredo* cf. *bartschi* species were registered for the first time in Ceará. The distribution and species richness of Teredinidae were directly related to the vertical gradient (flooding) and heterogeneity of the mangrove forest habitat. The data presented here are essential for comprehending the mechanisms responsible for the distribution patterns of the Teredinidae species in the mangrove, contributing to biodiversity conservation in Ceará coastal zones.

Keywords: environmental heterogeneity, mollusk, mangrove.

Resumo

Os teredinídeos são moluscos bivalves considerados o grupo de invertebrados mais abundante de organismos perfuradores de madeira marinha, desempenhando importante papel ecológico nos ambientes de manguezais. O objetivo do estudo foi realizar a caracterização das espécies de Teredinidae do estuário do Rio Acaraú, Ceará e analisar a relação da estrutura vegetal do bosque de mangue com a distribuição dos teredinídeos de acordo com os gradientes estuarinos: vertical (inundação) e horizontal (salinidade). A coleta dos troncos de mangue com teredinídeos aconteceu em três pontos do estuário (interior, médio e superior). Em cada ponto foram traçados três transectos nos quais, foram demarcadas três parcelas das quais foram coletados o total de 40 troncos. Foram encontradas e identificadas 8 espécies de Teredinidae: *Nausitora fusticula*; *Neoteredo reynei*; *Teredo turnerae*; *Teredo* cf. *bartschi*; *Bankia bipennata*; *Bankia gouldi; Lirodus massa* e *Lyrodus* cf. *bipartitus.* As espécies *Lyrodus* cf. *bipartitus, Bankia gouldi* e *Teredo* cf. *bartschi*, foram registradas pela primeira vez no estado. A distribuição e riqueza de espécies de Teredinidae estiveram diretamente relacionadas com o gradiente vertical (inundação) e heterogeneidade de hábitat do bosque de mangue. Os dados aqui apresentados serão importantes para compreensão dos mecanismos responsáveis pelos padrões de distribuição das espécies de Teredinidae nos bosques de mangues, contribuindo para a conservação da biodiversidade em zonas costeiras do Ceará.

Palavras-chave: heterogeneidade ambiental; molusco; manguezal.

1. Introduction

Teredinids are bivalve mollusks popularly known as gusanos (Müller and Lana, 2004). Teredinidae have a wide distribution, from shallow waters to deep sea, and from tropics to polar regions (Borges et al., 2014). Their distribution is directly related to wood availability, salinity, and temperature (Borges et al., 2014). As emergence of salt-tolerant plants, an environment conducive to the evolution of new species, therefore the adaptation of the family Teredinidae is related to the evolution of terrestrial woody systems, in this case the mangroves provide substrate for

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Received: February 15, 2023 – Accepted: August 16, 2023

larval settlement of Teredinidae through their trunks and branches (Kabir et al., 2014).

Studies already carried out in Brazil with teredinids are mainly concentrated in the South and Southeast regions, with studies addressing larval recruitment and infestation of teredinids species (Varotto and Barreto, 1998; Moraes et al., 2015), new occurrences record (Silva and Tognella, 2013), distribution (Lopes and Narchi, 1993; Maldonado and Skinner, 2016) taxonomic and morphological aspects (Leonel, et al., 2006; De-Carli and Manzi-Decarli, 2012). In the North and Northeast regions, some studies on the occurrence and distribution of species were carried out in the state of Pará (Filho et al., 2008), Alagoas (Freitas and Mello, 2001), Paraíba (Leonel et al., 2002), and Ceará (Vidal and Rocha-Barreira, 2009) accomplished the first record of the occurrence of these families in the state. Another important work is that by Carvalho et al. (2010), with a preliminary study on the *Neoteredo reynei* collected in the estuary of the Pacoti river, Fortaleza.

Despite what was mentioned above, in the Ceará state, little is known about the Teredinidae assemblage distribution and its relationship with the mangrove forests, and more studies need to be carried out. In this sense, the purpose of the study was to characterize Teredinidae species from the estuary of the Acaraú River and analyze the relationship between the plant structure of the mangrove forest and the distribution of teredinids according to the estuaries gradients: vertical (flooding by the tides) and horizontal (salinity).

2. Material and Methods

2.1. Area of study

The study was carried out at three mangrove sites in the River Acaraú estuary in Acaraú, Ceará. The salinity gradient in the waters of the estuary of the Acaraú River varies on average from 35.21 at the mouth to 0.61 in the upper estuary region during high tide and from 24.72 at the mouth and 0.73 in the upper estuary at low tide. The region has a predominantly tropical climate with an average temperature of 27°C, and annual accumulated precipitation of 1139.7 mm (FUNCEME, 2018).

These sites were approximately 3 km apart. The first Site (P1) is located in the lower estuary, in free connection to the open sea 2º50'15.51"S 40º8'25.34"), and the second Site (P2) is located in the middle estuary, subject to a strong mixture of fresh and saltwater (2º51'44.67"S 40º8'16.16"), and the third Site (P3) in the upper estuary, characterized by fresh water, but subjected to the daily influence of the tide (2º52'53.90"S 40º7'34.51"), thus forming an environmental horizontal gradient that goes from the upper region towards the mouth. Data sampling were carried out in September and October 2016, considering the dry period in the study region.

2.2. Field procedures

A vertical flooding gradient characterized the vegetation structure at each established sampling Site. The characterization of the mangrove plant structure was based on the methodology proposed by Maia and Coutinho (2012).

At each of the sites studied (P1, P2, and P3) (in the horizontal gradient), three transects were traced inside the mangrove forest, 50m equidistant from each other. In each transect, three 10x10 m^2 plots were marked off, 5m apart, adding up to 9 plots per Site. The plots were oriented perpendicularly to the river, distributed along a vertical gradient (flooding) where the abiotic factors tidal range and teredinid drying are experienced by exposure to air.

In each plot, the trees were counted and identified as the species, having the Circumference at Chest Height (CCH) (1.30 m above the ground) measured with a tape measure. Only trees with a circumference greater than 2.5 cm had the tree height estimated with the aid of a clinometer. Subsequently, the data from Circumference at Chest Height (CCH) were transformed into Diameter at Chest Height (DCH=CCH/π). For each sampling area, the mean values of height, of DCH, and basal area of individuals ($\pi/4 \times DCH^2$), in addition to the frequency and relative dominance by species (Schaeffer-Novelli and Cintrón,1986) were calculated. The trunks of dead trees were collected within the plots of the sampling design defined for plant analysis of the plant structure of the mangrove forest. The selected logs were fallen or still connected to the trees, but with their plant tissue dead. The temperature and salinity data were verified at the time of sampling in the riverbed using a refractometer and thermo-hygrometer.

2.3. Procedures in the laboratory

The logs were identified for the mangrove species in the laboratory and measured (diameter and length) to calculate the area. With the aid of a chisel and sledgehammer, the logs were fragmented longitudinally to remove the organisms in the galleries without damaging them. The teredinids were initially observed and identified in a stereoscopic microscope at magnifications of up to 400x. Subsequently, the pallets and shells were metalized and photographed using a scanning electron microscope (Inspect S50). The images generated by the Scanning Electronic Microscope (SEM), the identification and characterization of the collected species were carried out with the aid of specialized bibliography (Müller and Lana, 2004; Vidal and Rocha-Barreira, 2009; Turner, 1966).

2.4. Statistic

For the assessment of mangrove vegetation structure, a descriptive analysis was conducted on the parameters obtained in each area of the studied mangrove. To compare the average height, DCH (Diameter at Chest Height), basal area, tree density and abundance of logs between sites (horizontal gradient) and plots (vertical gradient), nonparametric Kruskal-Wallis analysis was used due to the non-normal distribution of the data. When significant differences were detected among the means, post-hoc multiple comparisons using z-values were conducted. Additionally, the abundance of teredinid species was compared across sites (horizontal gradient), plots (vertical gradient), and mangrove log species using the nonparametric Kruskal-Wallis analysis. If significant differences among the means were found, post-hoc multiple comparisons using z-values were also performed.

Considering the abundance similarity matrix of teredinid species, a clustering analysis of the sampled sites and plots was performed using the unweighted pair-group method using arithmetic average (UPGMA) (mode-Q), employing the Bray-Curtis similarity index. To reduce data discrepancies, the original matrices were transformed using the fourth root. To assess variations among environmental gradients, a one-way analysis of similarities (ANOSIM) was conducted. The SIMPER routine was used to identify potential associations of teredinids within the clusters visualized through the analysis. These analyses were conducted using PRIMER software (Plymouth Routines In Multivariate Ecological Research) version 6.0 (Clarke and Gorley, 2006).

The Shannon diversity, Margalef equitability and richness indices of the teredinid assemblage were calculated for the sampled sites and plots using the PAST software version 2.17c. The relationships between Teredinidae richness and abundance and forest structure characteristics (Height, DCH, basal area, and density of mangrove species) were evaluated using a Spearman Correlation Analysis. The BIOENV routine of the PRIMER v6 software was utilized to establish correlations between the ecological descriptors of the community (teredinids) and the structural characteristics of the mangrove forest (DAP, basal area, height, and density).

3. Results

3.1. Plant structure

In the three sites studied, a total of 540 trees were counted, of which 91.5% were alive at the time of sampling. Among the living trees, Site 1 had the highest number of individuals (329), followed by Site 3 (Upper Estuary) with 126 and Site 2 (Median Estuary) with 39 trees.

Four species of mangrove trees were observed*:* *Rhizophora mangle* (L.), *Avicennia germinas* (L.) Stearn, *Avicennia schaueriana* Stapf and Leechm. and *Laguncularia racemosa* (L.) Gaertn. However, *L. racemosa* did not occur at Site 2. Some trees were identified only as *Avicennia* sp, because they are cut and without leaves, which makes it difficult to differentiate between the two species of the genus.

In Sites 1 and 2, *R. mangle* was the most dominant species (with 56% and 88%, respectively), while in Site 3 *A. schaueriana* was the dominant species (50%). Regarding frequency, *R. mangle* was also the most frequent species in Sites 1 and 2 (39% and 69%); in Site 3, *L. racemosa* had the highest frequency (35%).

The average height of the trees in the mangrove forest was 5.5m ± 4.3 SD, ranging from 3.15 to 17.5m. Tree height measurements were significantly higher at Site 2 [Kruskal-Wallis test: H (2, N=494) = 42.66622, p=0.000]. Site 2 had the highest height value (10 m ± 5.1 SD), which is related to the presence of large individuals of *R. mangle* with a height of up to 23 m. Site 1 had the lowest height value (4.99 m ± 3.97 SD), which may be related to the presence of many small trees and threes that were cut, which were more frequent in this area.

The average DCH recorded was 8.64cm ± 9.01, and at Site 2, it was significantly higher [Kruskal-Walllis test: H(2, N=494)=73.274,32 p=0.000]. The highest individual DAP value was from an *Avicennia schaueriana* (75 cm), and the lowest was from *Avicennia germinans* (0.39 cm), both at Site 3. Site 2 had the highest average DCH values (21.13 ± 12.03 SD), and Site 1 had the lowest (6.53 cm ± 6 SD).

The total basal area of the sampled area was 6.04 m^2, presenting a significant difference among the Sites [Kruskal-Wallis test: H (2, N= 494) = 73.27432, p=0.000]. The highest mean basal areas of the trees were found at Site 2 (0.046 m^2), while the lowest were found at Site 1 (0.006 m^2). This result is likely related to the presence of trees with small diameters and heights occurring at a high density at Site 1.

The diversity index calculated from the abundance and richness of mangrove species in the vertical gradient indicate that Site 1 – Lower Estuary has greater diversity and evenness than the other sites sampled.

3.2. Characterization of Teredinidae species

Eight species of Teredinidae were found and identified (Figure 1): *Nausitora fusticula* (Jeffreys,1860), *Neoteredo reynei* (Bartsch,1920), *Teredo turnerae* (Müller and Lana, 2004), *Teredo cf. bartschi* (Clapp, 1923*), Bankia bipennata* (W. Turton, 1819), *Bankia gouldi* (Bartsch, 1908), *Lirodus massa* (Lamy, 1923) and *Lyrodus cf. bipartitus* (Jeffreys, 1860).

A total of 40 trunks with the presence of galleries of Teredinidae were collected at the three sampling sites, and live teredinids were found in 38. The largest number of logs occurred at Site 3 (19 logs), followed by Site 1 (13 logs), and the lowest abundance was found at Site 2 (6 logs). However, the averages of the logs collected in the sites [Kruskal-Wallis test, H (2, N= 9) =4.057971, p =0.4663] (Figure 2a) and plots [Kruskal-Wallis test, H (2, N= 9) =2.388406, p =0.3037] (Figure 2b) did not differ statistically.

Among the collected logs, *Avicennia* sp. accounted for 63.16%, *Rhizophora mangle* for 23.68%, and *Laguncularia racemosa* for 13.16%. However, no significant differences were observed in the occurrence of logs from these species [Kruskal-Wallis test, H (2, N=27) = 4.964844, p=0.08].

The occurrence of drilling by teredinids in the logs showed no significant difference between sampled sites and plots [Kruskal-Wallis test: H (2, N= 27) =4.964844, p =0.0835]. However, the logs of *Avicennia* sp. were the most drilled into, followed by the logs of *Rhizophora mangle.*

A total of 223 individuals of the Teredinidae were found, 59 at Site 1, 29 at Site 2, and 135 at Site 3. However, no significant differences were observed in abundance along the sampled sites and plots (Table 1). Considering the mangrove plant species, there was also no significant difference between teredinids abundances.

During dissection, we found veliger larvae incubating in the mantle of *Teredo turnerae and Teredo cf. bartschi*. The species *Nausitora fusticula* was the most abundant

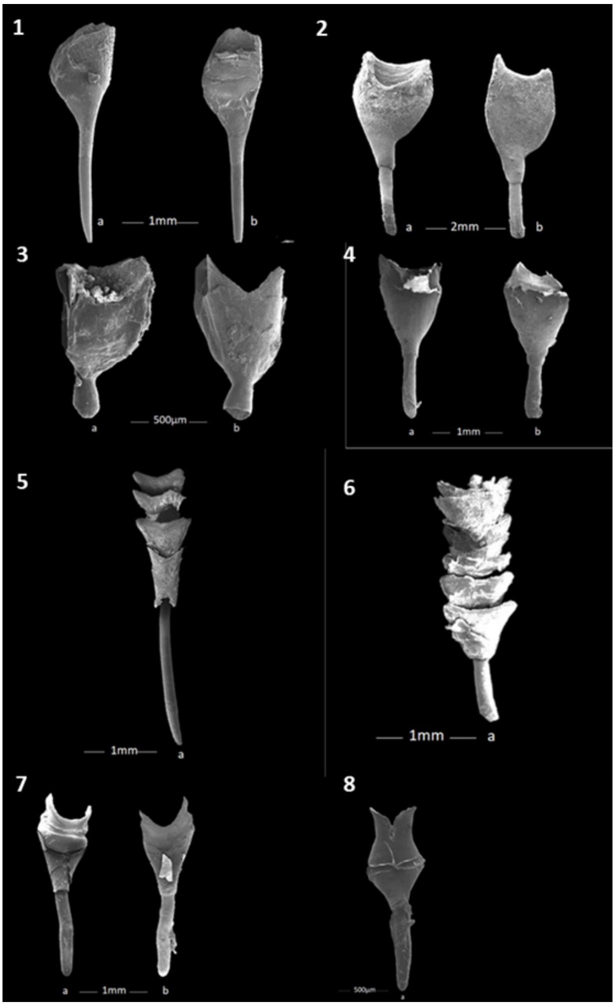

Figure 1. Pallets of the Teredinidae species from the mangrove forests of the Acaraú River estuary. a- outer face of the pallet, b- inner face of the pallet. Caption: 1- Nausitora fusticula; 2- Neoteredo reynei; 3- Teredo turnerae; 4- Teredo cf. bartschi; 5- Bankia bipennata; 6- Bankia gouldi; 7- Lirodus massa; 8- Lyrodus cf. bipartitus.
Source: Authors (2018).

with 117 individuals (52.5%), followed by *Neoteredo reynei* with 77 (34.5%), *Teredo* cf. *bartschi* with 16 (7.2%) and *Teredo turnerae* with 6 (2.7%). The other species showed an abundance of less than 1% of the total number of individuals.

During the sampling period, the salinity levels at the sampling sites showed a variation ranging from 30 to 41. The temperature ranged between 30°C and 35°C. Interestingly, there was no recorded rainfall during the sampling months, resulting in elevated salinity levels within the estuary.

No significant differences were observed in the abundance of teredinids species between the sites (horizontal gradient). Considering the plots (vertical gradient), only the species *Nausitora fusticula* was significantly more abundant in plot 1 (Table 1) Only *Neoteredo reynei, Lyrodus massa,* and *Bankia gouldi* showed significant differences in abundance among the drilled mangrove species. *Neoteredo reynei* occurred mainly in trunks of *Avicennia sp*. and *Rhizophora mangle*, and *Lyrodus massa* and *Bankia gouldi* occurred only in trunks of *Laguncularia racemosa.*

A negative correlation was observed between *Bankia bipennata* and the height of the mangrove forest (Spearman Correlation, $r = -0.74$, $p < 0.05$). *Teredo bartschi, Lyrodus massa* and *Bankia gouldi* exhibited a significant correlation with the density of *Avicennia* sp. and *Laguncularia racemosa.*

The ecological descriptors did not show significant differences between Sites, plots, and mangrove species (Table 1); however, some observations of this index must be considered. Margalef richness was highest in *Laguncularia racemosa*, with all eight species of Teredinidae drilling their logs. Although most of the logs collected are of the species *Avicennia sp*., the diversity indexes were higher in fragments of *L. racemosa* and *R. mangle*. Despite the great abundance of the dominant species *N. reynei* and *N. fusticula*, evenness was higher than 0.80 in the three observed mangrove species.

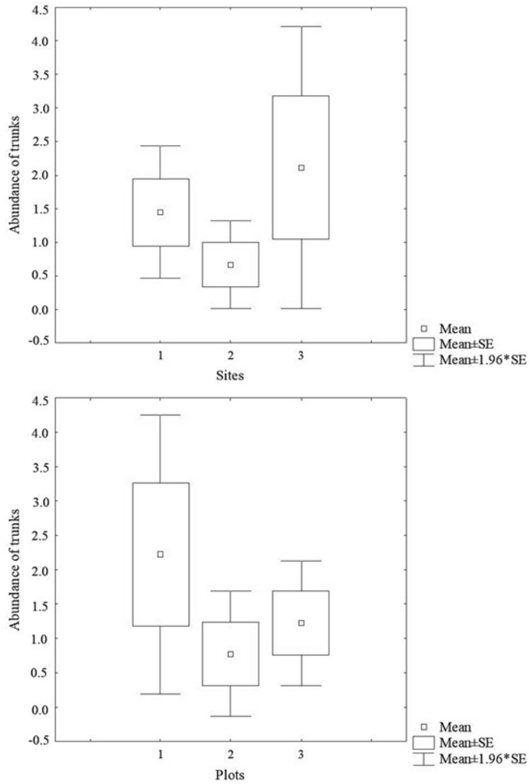

Figure 2. Abundance of drilled mangrove trunks observed at (a) sites (Site 1 - Lower Estuary, Site 2 - Middle Estuary, Site 3 - Upper Estuary) and (b) sampling plots in the Acaraú River Estuary, Ceará, Brazil. SE (Standard error).

Regarding the sampling sites (horizontal gradient), Site 1 (lower estuary) showed higher values of Margalef richness and Shannon diversity; at this Site, eight species of Teredinidae were recorded. The lowest richness and diversity were observed at Site 3 (Upper Estuary), where five of the eight species of Teredinidae occurred. Considering the sampled plots (vertical gradient), Margalef richness and Shannon diversity were higher in plots closer to the water (plot 1), and plot 3 (furthest from the water) showed greater evenness.

The cluster analysis showed the formation of 2 groups considering the sites and plots sampled (ANOSIM, Global R = 0.58, p= 0.01) (Figure 3).

In the first group, plots 1 (near the water) of all sites and plot 2 of Site 1 (lower estuary) were combined (62.91% similarity, $p<0.05$). These areas corresponded to the most flooded by the tidal cycle. The second group gathered the other plots (similarity of 62.95%, $p<0.05$), showing the formation of 2 subgroups, one with plots 2 (intermediate zone) of sites 2 and 3 (similarity of 94.94%, $p<0.05$), and another with plots 3 (away from the river) from all sites (83.2% similarity, $p<0.05$).

According to the percentage similarity test (SIMPER), the abundances of *Neoteredo reynei*, *Nausitora fusticula*, *Teredo* cf. *bartschi*, and *Teredo turnarae* contributed with 85.3% to the similarity in the grouping of the most flooded

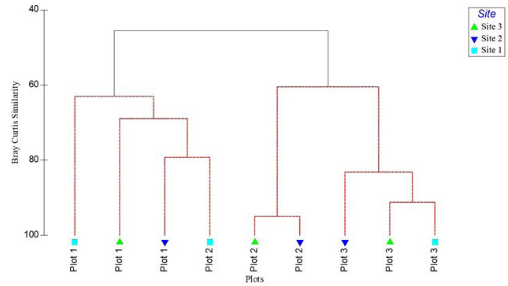

Figure 3. Dendrogram showing the cluster analysis of sampled sites (Inner Estuary - Site 1, Median Estuary - Site 2, and Upper Estuary - Site 3) and plots (Plot 1 - near the river, Plot 2 – intermediate zone, and Plot 3 - away from the river) in the Acaraú River estuary, Ceará,Brazil. The analysis was based on the Bray-Curtis similarity index, considering the abundance values of Teredinidae species. **Source:** Authors (2018).

sampling areas (Group 1). In group 2 with the other plots, 100% of the formation of this group was attributed to *Neoterdo reynei* and *Nausitora fusticula.*

Considering the structure of the mangrove forest, the densities of *Avicennia* sp and *Laguncularia racemosa* are the factors that best explain the distribution of teredinids in the study area, according to the BIO-ENV test.

4. Discussion

In Brazil, 22 species of teredinids are known (Müller and Lana, 2004), of which six had already been recorded for the coast of Ceará by Vidal and Rocha-Barreira (2009). The present study recorded eight species in the Acaraú river estuary, Ceará, where three species (*Lyrodus* cf. *bipartitus*; *Bankia gouldi* and *Teredo* cf. *bartschi*) were recorded for the first time in the state of Ceará, also being the first record for Brazil of *Lyrodus* cf. *bipartite*. The species *Bankia gouldi* had not yet been registered for the North and Northeast regions of the country, being previously known for Rio de Janeiro (Maldonado and Skinner, 2016), São Paulo (Migotto et al., 1993; Lopes and Narchi, 1993) and Paraná (Müller and Lana, 1986). *Teredo* cf. *bartschi* was registered for the states of Pará (Santos et al., 2005), Alagoas (Freitas and Mello, 2001), and Paraíba (Leonel et al., 2002, 2006).

The occurrence of *Nausitora fusticula* and *Neoteredo reynei* was recorded for the North and Northeast coast of Brazil in studies carried out in the states of Pará (Santos et al., 2005; Filho et al., 2008), Alagoas (Freitas and Mello, 2001), Paraíba (Leonel et al., 2002) and Ceará (Vidal and Rocha-Barreira, 2009). These species are abundant and can be considered typical of Brazilian mangroves. *Lyrodus massa*, *Teredo turnerae*, and *Bankia bipennata* had already been described for Ceará by Vidal and Rocha Barreira (2009) in the Jaguaribe River estuary on the east coast of Ceará State, in the municipality of Aracati.

One of the main factors for recording these new occurrences of teredinids in the Acaraú River is due to the shortage of studies on this group in Ceará, in addition to the difficulty in collecting and processing

Table 1. Results of the Kruskal-Wallis nonparametric test for the abundance of teredinid species and community ecological descriptors between the sites, plots, and mangrove species in the Acaraú River estuary, Ceará, Brazil.

Sampling Sites	**Nº of Teredinids species**		**Abundance of Teredinids**		**Margalef's Wealth**		**Evenness**		**Shannon's Diversity**	
	Average	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**
1	1.85	1.21	4.54	2.76	0.53	0.63	0.88	0.10	0.39	0.49
2	1.67	1.21	4.83	5.00	0.41	0.55	0.89	0.14	0.30	0.48
3	1.63	0.68	7.11	9.47	0.44	0.42	0.73	0.23	0.30	0.33
Kruskal-Wallis test	H =0.26, p=0.8772		H=0.17, p=0.91		H=0.14, p =0.93		H=1.90, p =0.39		H=0.22, p =0.89	
Plot	Nº of Teredinids species		Abundance of Teredinids		Margalef's Wealth		Evenness		Shannon's Diversity	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
1	2.00	1.12	8.20	9.06	0.53	0.52	0.73	0.20	0.42	0.44
2	1.43	0.79	3.57	2.44	0.37	0.51	0.87	0.07	0.22	0.38
3	1.36	0.50	3.09	2.47	0.38	0.51	0.96	0.07	0.24	0.34
Kruskal-Wallis test (H)	H =3.49, p =0.17		H=4.09, p =0.13		H=0.83, p =0.66		H=5.49, p =0.06		H=1.91, p =0.38	
Mangrove species	Nº of Teredinids species		Abundance of Teredinids		Margalef's Wealth		Evenness		Shannon's Diversity	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Avicennia sp	1.58	0.65	5.83	7.26	0.41	0.35	0.80	0.22	0.30	0.34
Laguncularia racemose	2.40	1.67	8.80	11.01	0.79	0.87	0.84	0.21	0.57	0.62
Rhizophora mangle	1.67	1.12	4.33	3.97	0.39	0.52	0.80	0.07	0.28	0.43
Kruskal-Wallis test (H)	H=1.25, p =0.53		H=0.64, p =0.72		H=0.88, p =0.64		H=0.44, p =0.80		H=1.18, p =0.55	

Source: Authors (2018).

the logs, which is limiting for these studies. Introduction of species is also a possibility to be considered, as some studies have shown

Is Teredinidae species expanding their distribution area due to global warming or human transport in ballast water or associated with wooden structures (Maldonado and Skinner, 2016). Thus, Lyrodus cf. bipartitus can be considered a cryptic species for Brazil, since its type locality is not precise, but it is considered native to the Indo-Pacific region (Simberloff et al., 1997) and was recently recorded in Venezuela (Velásquez et al., 2017).

In the present work, the species *Nausitora fusticula* was the most abundant, present mainly in the plots closer to the water, corroborating the results of Leonel et al. (2002), who observed the occurrence of *Nausitora fusticula* in brackish waters, within a wide salinity gradient, strengthening the idea of adapting to salinity variation. Freitas and Mello (2001) reveal that the species *Nausitora fusticula* tolerates between 0.04 and 27 of salinity, occurring both in estuarine areas within the forest that are little flooded and on the margins of the mangrove covered by water during variation of tides and salinities.

According to Müller and Lana (2004), *Neoteredo reynei* is considered a tropical and subtropical amphi-Atlantic species with a preference for brackish waters and estuarine. A wide tolerance to salinity variation was also observed by Freitas and Mello (2001) and De-Carli and Manzi-Decarli (2012). Differently from the other observed species, specimens of *Bankia gouldi* were collected only at Site 1 (lower estuary), a region that receives more significant marine influence. This result agrees with the study by Müller and Lana (1986), who consider that the species is typically marine and stenohaline.

Teredo cf. *bartschi* in the present study occurred at the three sites sampled, although a slight increase in the number of individuals of this species was observed towards the sea. This organism is characterized as a marine euryhaline species and is usually found at the mouth of the estuary (Freitas and Mello, 2001). According to Leonel et al. (2002), *T. bartschi* increases in number when the water temperature and salinity increase, these conditions probably favor the establishment of larvae and spawning.

In the estuary of the Acaraú River, *Teredo turnerae* was the fourth most abundant, occurring only in the plots closest to the water. According to Macintosh et al. (2012), the species is typical of warm tropical waters.

The wood substratum is one of the most important resources and the primary stimulus for the infestation of the Teredinidae assemblage. In mangrove environments, the amount of wood available for drilling by Teredinidae, in general, is huge (Lopes and Narchi, 1997). The mangrove swamp of the Acaraú River estuary can be considered underdeveloped, considering the structural characteristics of the forest observed in this study. Thus, the low abundance of Teredinids in the plots and the sampled sites may be related to the degree of development of the mangrove forest and the low number of dead mangrove trees found.

The greatest availability of logs was observed in the upper and lower estuaries. The intermediate stages of development of the mangrove forest at these sites may be the main factor contributing to the accumulation of dead wood; however, the presence of a cut observed in these places may also influence the availability of trunks. Although the lower estuary had the highest number of dead trees, it did not have the greatest amount of available logs; in this case, the slope of the terrain and the tidal flow may have favored the transport of fallen logs to other regions. According to Tyberghein et al. (2012), environmental factors such as flooding, topography, and soil cause environmental heterogeneity, which in turn can generate an increase in diversity. The diversity index reinforces the idea of environmental heterogeneity between the sites sampled.

In addition to the low rate of available trunks, the selection of the size of large logs (84 cm) may have influenced the sampling, as colonization by Teredinidae may also occur with smaller logs. In the study carried out in the state of Pará by Filho et al. (2008), they found that drilling by Teredinids was lower in large fragments of wood because it may take longer to be colonized than in smaller fragments.

It was observed that the density of plants correlated with the abundance of teredinids along the sampling sites, which highlights the close relationship between the structure of the forest and the occurrence of teredinids. The highest abundance of Teredinidae was found at Site 3 (upper estuary), represented mainly by *Nausitora fusticula* and *Neoteredo reynei*. This greater abundance may be related to the availability of logs in this area. According to Rimmer et al. (1983), the relationship between the abundance of Teredinidae and the amount of available wood is very strong, since the wood substratum is the main stimulus for the settlement of larvae of drilling species.

The vertical gradient of flooding by the action of the tide also influences the colonization success of Teredinidae since the longer the wood is in contact with seawater, the greater number of larvae can settle and start penetration (Moraes et al., 2015).

In the present study, the logs of *Avicennia* spp. were the most drilled; the great availability of trees of *Avicennia* sp. in the studied area may also have influenced the greater occurrence of drillings. A similar result was found by Leonel et al. (2006), who hypothesized that the greater infestation by Teredinidae in *A. schaueriana* is related to the low hardness of the wood since it was less resistant to opening to remove animals. The live roots of *Rhizophora stylosa* are able to prevent the larval settlement of teredinids by producing tannin, but when severely damaged or when they die, tannin levels tend to decrease, and attack by teredinids becomes possible (Hendy and Cragg, 2017).

However, considering the abundance, the highest values were found at Site 3, further away from the estuary mouth, differing from the observations of several authors (Barreto et al., 2000; Junqueira et al., 1989; Lopes and Narchi, 1993), who observed a decreasing infestation with increasing distance from the mouths of the rivers, highlighting the role of salinity in the distribution of teredinids in this environment. Similar results were observed by Rosa et al. (2020) in studies carried out at Lagoa Araruama in Rio de Janeiro where the absence of Cladocera was attributed to the high level of salinity inside the lagoon. The salinity condition observed in the dry period of the region, as well as the predominance of euryhaline species, such as *Nausitora fusticula and Neoteredo reynei*, seem to determine this differentiated condition in the Acaraú River estuary. In the studies carried out by Medeiros et al. (2015), in the Apodi/Mossoró River estuary, revealed that the highest densities of *Donax striatus* occurred on beaches far from the estuarine region where the salinity level was higher. Salinity as a factor in the distribution of organisms was also recorded in the studies by Magalhães et al. (2006), in the Caeté River Estuary with the species *Pseudodiaptomus richardi and Pseudodiaptomus acutus.*

The results of the present study indicate that the diversity of Teredinidae is directly related to the heterogeneity of habitat, as the characteristics of the forest influenced the occurrence and abundance of the species. Mangrove forests that present a great diversity of species significantly interfere in the spatial distribution of teredinidae assemblages; these environments provide greater variations in food and shelter for wood borers (Rimmer et al., 1983). According to studies by Freitas and Mello (2001), in the estuarine region of the Manguaba River, located on the north coast of the State of Alagoas, the distribution of Teredinidae in mangroves is conditioned by the presence of wood, but also related to other species. Factors such as flooding and salinity levels contribute to the spatial distribution of teredos in these environments. Flooding favors the colonization of submerged logs by larvae, while low or high salinities can determine the establishment of teredinids in the environment (Barreto et al., 2000; Moraes et al., 2015).

In the present study, the environmental factor of flooding directly influenced the diversity of Teredinidae since the teredinids established themselves along a vertical gradient of flooding. According to Moraes et al. (2015), the vertical gradient of flooding, caused by the action of the tide, provides the settlement of Teredinidae larvae in the logs during the period they are submerged.

However, the effect of the horizontal salinity gradient was unclear in the present study. Barreto et al. (2000) reveal that low salinity affects the survival of teredinid species and concluded that, with the reduction of this environmental component, there is an increase in the mortality of species of the group. As this is a limiting factor in the development of Teredinids, it is likely that higher salinities also affect the survival of individuals of some species.

5. Conclusion

Teredinidae diversity is related to habitat heterogeneity, as the characteristics of the most heterogeneous forest influence the occurrence and diversity of species. The vertical flooding gradient influenced the diversity of Teredinidae since the teredinids settled along the gradient.

The effect of the horizontal salinity gradient was unclear in the present study, probably because the salinities were high along the entire horizontal gradient. Further studies with greater temporal replication in estuaries of the semi-arid coast of northeastern Brazil are suggested.

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