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Spatio-Seasonal Variation in a Swimming Crab Assemblage in a Protected Subtropical Estuary

Rodrigo S. Rodriguez-Lopes [1,2], Esli E. D. Mosna [1,3,*], Pedro G. A. Reis [1] and Marcelo A. A. Pinheiro [1,2,3]

[1] Grupo de Pesquisa em Biologia de Crustáceos (CRUSTA), Departamento de Ciências Biológicas Ambientais, IB/Campus do Litoral Paulista (IB/CLP), Universidade Estadual Paulista (UNESP), São Vicente 11380-972, SP, Brazil; rodrigo.rodriguez@unesp.br (R.S.R.-L.); pedro.a.reis@unesp.br (P.G.A.R.); marcelo.pinheiro@unesp.br (M.A.A.P.)
[2] Programa de Pós-Graduação em Biodiversidade de Ambientes Costeiros (PPG-BAC), UNESP IB/CLP, São Vicente 11330-900, SP, Brazil
[3] Programa de Pós-Graduação em Ecologia, Evolução e Biodiversidade (PPG-EcoEvoBio), UNESP IB/Rio Claro, Rio Claro 13506-900, SP, Brazil
* Correspondence: e.mosna@unesp.br

Abstract

Protected estuaries provide reference conditions for assessing coastal biodiversity, but information on swimming crab assemblages in such systems remains limited. This study evaluated the composition, dominance structure, diversity, body size, and spatio-seasonal variation in *Callinectes* swimming crab assemblages in the Una do Prelado River estuary, within the Barra do Una Sustainable Development Reserve, south-eastern Brazil. Seasonal sampling was conducted at four sites along the estuarine gradient using baited traps. Species composition, abundance, diversity indices and multivariate patterns were analyzed in relation to site and climatic season. A total of 146 individuals from four species were recorded: *Callinectes exasperatus*, *C. danae*, *C. sapidus* and *C. bocourti*. The assemblage was strongly dominated by *C. exasperatus*, which represented 81.5% of the total catch. Species richness was low, consistent with the restricted taxonomic scope and environmental filtering expected in estuaries. Abundance varied more clearly than species composition, with higher catches in autumn and at the intermediate estuarine site. Diversity indices indicated low evenness where *C. exasperatus* was dominant, whereas multivariate analyses detected no significant compositional differences among sites or seasons. As the first study conducted in this protected estuary, our findings provide a baseline for future monitoring of this system. Given the spatial and temporal scope of the study, these results should not be generalized to other protected estuarine systems.

Keywords: *Callinectes*; swimming crabs; estuarine ecology; ecological assembly; species dominance; spatial-seasonal variation; protected estuary

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1. Introduction

Estuaries are transitional coastal ecosystems characterized by the interaction between continental and marine waters, forming environments influenced by physical, chemical, and biological processes [1]. The hydrological complexity of estuaries results in marked environmental gradients that vary spatially and temporally in response to tides, river discharge, precipitation, and local surface runoff [2–4]. Owing to this habitat heterogeneity, expressed through physicochemical gradients such as salinity, pH, and sediment grain size, estuaries provide suitable conditions for feeding, shelter, recruitment, and reproduction for several animal species [5–8].

Crustaceans play relevant ecological roles in estuarine trophic webs, and their life cycles are strongly influenced by environmental conditions that affect growth [9,10], distribution [11–13], ecdysis [14,15], and reproduction [16–18]. Species of the genus *Callinectes* Stimpson, 1860 are frequently recorded in estuarine systems and use different portions of the estuarine gradient throughout their ontogeny. Juveniles occupy shallow areas influenced by salinity and habitat structure [19–21], whereas ovigerous females migrate towards estuary mouths, adjacent coastal waters, or offshore spawning grounds [22–24]. Larval development occurs in oceanic waters, and megalopae return to estuarine habitats to complete their ontogenetic development [25,26].

This broad habitat use reflects the ecological plasticity of *Callinectes* and their importance in coastal and estuarine ecosystems [27–29]. This plasticity is evidenced by their tolerance to environmental variation and occupation of open areas [30,31], vegetated habitats [32–34], and substrates with different sediment characteristics [35–37]. However, environmental heterogeneity does not necessarily result in marked differences in assemblage composition. Instead, spatial and seasonal variation may be reflected in changes in species richness, diversity, abundance, dominance, and constancy of occurrence [38].

Despite the recognized ecological importance of portunid crabs in estuarine and coastal ecosystems, quantitative assessments of *Callinectes* assemblages in relation to environmental variation remain relatively scarce, particularly within protected estuarine systems [39]. Environmental gradients such as salinity, sediment characteristics, organic matter, depth, and water quality may influence habitat use, niche overlap, abundance, and spatial distribution of swimming crabs [11,21,27,40]. Consequently, protected estuaries may support assemblages characterized by low species richness and strong dominance of one or a few ecologically tolerant or widely distributed species, reflecting natural environmental filtering rather than necessarily indicating anthropogenic disturbance. Therefore, quantitative assessments of *Callinectes* assemblages are essential for establishing ecological baselines and supporting long-term biodiversity monitoring in protected estuarine ecosystems.

In this context, the present study characterized the *Callinectes* operational trap-sampled assemblage in the Una do Prelado River Estuary, located within the Barra do Una Sustainable Development Reserve, one of the most important protected coastal areas in the state of São Paulo, south-eastern Brazil. As this estuarine system comprises a marked environmental gradient, variation in salinity, sediment characteristics, and habitat structure may affect species distribution, abundance, and richness. Despite its ecological relevance, information on the *Callinectes* assemblage in this estuarine system is lacking. We therefore evaluated species composition, abundance, body size, ecological descriptors, dominance structure, and their relationships with environmental variables across sampling sites and climatic seasons, providing the first baseline assessment of this assemblage in the reserve.

2. Materials and Methods

2.1. Study Site

The Barra do Una Sustainable Development Reserve (RDS Barra do Una) is part of the Juréia-Itatins Mosaic of Conservation Units (MUCJI) and is located in the municipality of Peruíbe, on the southern coast of São Paulo state, Brazil (24°26′10.91″ S; 47°04′15.75″ W) (Figure 1A). The reserve is a sustainable-use protected area that supports traditional human populations whose permanence is associated with sustainable systems for the use of natural resources. The RDS Barra do Una encompasses beaches, dunes, restinga, hillside forests, and mangrove ecosystems. According to the Köppen climate classification [41], the region has a warm and humid subtropical climate [42].

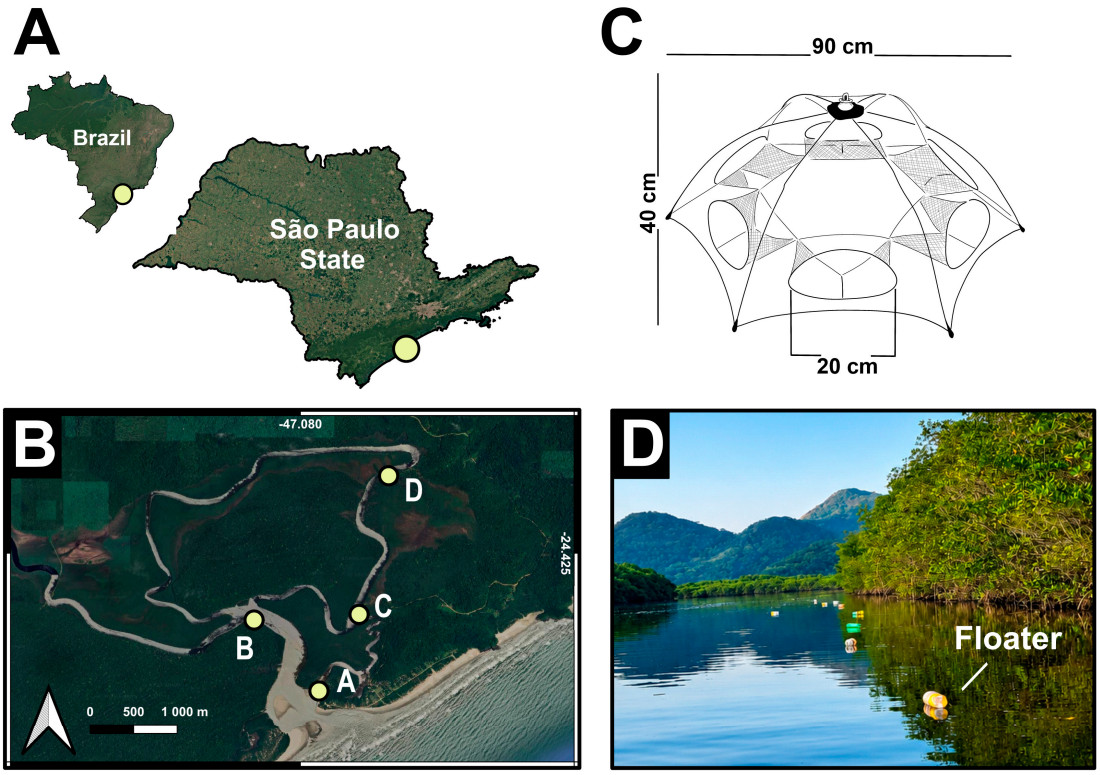

Figure 1. Study area and sampling design in the Una do Prelado River Estuary, Barra do Una Sustainable Development Reserve, south-eastern Brazil. (**A**) Geographic location of the Barra do Una Sustainable Development Reserve in Peruíbe, São Paulo State, Brazil; (**B**) distribution of the four sampling sites (A–D) along the estuarine gradient; (**C**) schematic representation of the baited trap used for swimming crab sampling, measuring 90 cm in diameter and 40 cm in height, with six circular openings of 20 cm diameter and 4 mm mesh; and (**D**) field view of the sampling site, showing the trap deployment system marked by floats.

2.2. Sampling Design

Sampling was carried out seasonally in four sampling sites within the Una do Prelado River Estuary (Table 1; Figure 1B), selected to represent different sectors of the estuarine gradient. The sampling sites were defined to encompass the longitudinal salinity gradient of the estuary. As the estuary has a relatively limited longitudinal extent, these four sites were sufficient to capture the transition between the inner and outer sectors, providing representative coverage of the system's environmental variability. Collections were performed from an aluminum boat equipped with an outboard motor.

At each sampling site, the sampling effort consisted of 10 baited traps deployed for 1 h during the ebbing tide, standardized to the time interval between 5:00 p.m. and 6:00 p.m. The traps were covo-type, measuring 90 cm in diameter and 40 cm in height, with 4 mm mesh and six circular openings, each 20 cm in diameter (Figure 1C). Traps were tied to floats and arranged 5 m apart along a 50 m guide rope, forming a standardized transect (Figure 1D). Fish viscera were used as bait, reflecting the predominantly carnivorous feeding habits of swimming crabs [43].

Due to the protected status of the study area, sampling activities were conducted according to the regulations established for the reserve. Several capture methods are restricted or require specific authorization, and alternative techniques were either prohibited or permitted only for local residents. Therefore, baited traps were selected as the most suitable and feasible method for sampling the *Callinectes* operational trap-sampled assemblage within the reserve.

Table 1. Geographic and environmental characterization of the four sampling sites along the Una do Prelado River Estuary, Barra do Una Sustainable Development Reserve, south-eastern Brazil. Distances from the estuary mouth should be measured along the watercourse rather than as straight-line distance. Local characterization may include estuarine sector, dominant sedimentary condition, vegetation context, mean depth, and other relevant field observations.

Site	Lat.	Long.	Distance from Estuary Mouth (km)	Position in the Estuary	Salinity	Depth (cm)	Sand (%)	Silt + Clay (%)	Organic Matter (%)	General Characterization
A	−24.439524	−47.076810	1.38	Lower estuarine sector	20.5 (17.5–24.4)	40.7 (28.3–45.4)	99.0 (97.7–99.9)	1.0 (0.1–2.3)	0.14 (0.09–0.18)	Shallow sandy sector, with low fine-sediment and organic matter contents.
B	−24.432600	−47.083307	2.26	Intermed-iate estuarine sector	24.5 (14.6–29.5)	41.7 (22.0–55.3)	99.1 (97.5–99.8)	1.0 (0.2–2.5)	0.32 (0.19–0.42)	Sandy sector with the highest mean salinity and low accumulation of fine sediment.
C	−24.436084	−47.093860	4.27	Inner estuarine sector	15.7 (12.9–20.9)	49.5 (32.1–62.3)	92.2 (86.6–96.0)	7.8 (4.0–13.4)	1.73 (0.88–2.85)	Inner sector with greater contribution of fine sediment and organic matter.
D	−24.416375	−47.070271	6.87	Innermost deeper estuarine sector	15.8 (10.1–19.4)	72.7 (54.6–104.2)	89.9 (86.0–92.4)	10.1 (7.6–14.0)	2.01 (1.10–2.50)	Deepest sector, with the highest mean fine-sediment and organic matter contents.

Because baited traps selectively sample active, mobile and bait-responsive individuals, the term "swimming crab operational trap-sampled assemblage" is used here to refer to the operational assemblage of portunid crabs accessible to this sampling method, rather than to the entire estuarine benthic community.

After trap deployment, the boat was moved to the midpoint of each transect to obtain water and sediment samples. Water samples were collected using a 5 L Van Dorn bottle, and the following water-quality parameters were measured—salinity, pH, temperature (°C) and dissolved oxygen content (mg L^{-1})—using a Horiba U-5000G multiparameter probe (Horiba, Ltd., Kyoto, Japan). The depth of each sampling point was obtained using metric markings on the rope of each trap and was recorded at the time of retrieval.

Sediment samples were collected using a Van Veen grab, immediately placed in properly labelled plastic bags, and stored in thermal boxes with crushed ice for transport. Swimming crab specimens captured in each trap were also individually placed in plastic bags and kept refrigerated for transport to the laboratory for subsequent processing.

2.3. Laboratory Processing

The captured specimens were identified to species level using the identification keys proposed by Williams [44,45] and Melo [46]. For each specimen, carapace width (CW, excluding the lateral spines) was measured using a precision calliper (0.01 mm). The number of individuals of each species was recorded by trap, sampling site, and climatic season, enabling estimation of species abundance and dominance at the site–season scale.

In the laboratory, sediment samples were initially manually sieved through a 5 mm mesh to remove allochthonous material (e.g., twigs, roots, and organic debris). After this

sorting, the samples were frozen at −20 °C until the analytical procedures were carried out, as described by Negreiros-Fransozo et al. [47]. Sediment processing included granulometric analysis and quantification of organic matter content.

For granulometric analysis, the samples were thawed and dried in a ventilated oven at 70 °C for 72 h until a constant weight was obtained. Three 100 g subsamples were taken per sampling site and season. Each subsample was subjected to mechanical sieving using a Granutest® (Telastem Peneiras para Análise Ltda., São Paulo, Brazil) sieve shaker at intensity 8 for 5 min. Sediment fractions were classified according to the Wentworth [48] grain-size scale as follows: VCS, very coarse sand (2.0–1.0 mm); CS, coarse sand (1.0–0.5 mm); MS, medium sand (0.50–0.25 mm); FS, fine sand (0.25–0.15 mm); VFS, very fine sand (0.15–0.05 mm); and S + C, silt + clay (<0.05 mm). The sand fractions were also summed to obtain total sand, whereas the finest fraction was represented by silt + clay.

Organic matter content was determined using the loss-on-ignition technique, expressed as ash-free dry weight. Three 10 g sediment subsamples were used per sampling site and season. Each subsample, after drying and weight stabilization, was placed in a porcelain crucible and incinerated in a muffle furnace at 500 °C for 3 h. The percentage of organic matter was calculated as the difference between the weights before and after incineration.

2.4. Data Analysis

Water parameters, including temperature, salinity, dissolved oxygen, and pH, were registered at each sampling site and for each climatic season. Depth was recorded from the traps installed along each transect. For descriptive analyses and graphical representation, environmental variables were summarized by sampling site and climatic season, using means and measures of dispersion when appropriate.

Operational trap-sampled assemblage structure was assessed using a species abundance matrix, species richness and absolute abundance of each species per sampling site and climatic season. The number of individuals captured per trap per hour (CPUE) was used to standardize abundance according to trap deployment time. The dominance of *Callinectes exasperatus* was calculated as the percentage contribution of this species to the total number of individuals recorded in each site–season combination. Species constancy [49] was estimated from the frequency of occurrence of each species across the site–season sampling units, while other ecological indices (Margalef richness, Shannon–Wiener diversity, and Pielou evenness) were calculated following Krebs [50].

Shannon–Wiener diversity was calculated using natural logarithms and expressed in nits ind.$^{-1}$. Shannon effective diversity was obtained as exp(H′), representing the number of equally abundant species equivalent to the observed Shannon diversity. Pairwise differences in Shannon–Wiener diversity (H′) among sampling sites were tested using Hutcheson's *t*-tests, which compare diversity estimates while accounting for their associated variances [51]. Because all pairwise comparisons among sites were evaluated, *p*-values were adjusted using the Holm sequential Bonferroni correction to control for multiple testing [52]. Because of the low number of individuals recorded at some sampling sites, these comparisons were interpreted cautiously and used as complementary support for the descriptive diversity patterns. In each case, the formulae are presented in the Supplementary Material (Table S1). A sample-based species accumulation curve and an individual-based rarefaction curve were also generated to assess whether the observed richness approached an asymptotic pattern as sampling effort increased [53,54].

Normality was initially assessed using the Shapiro–Wilk test, and homogeneity of variances was assessed using Levene's test. Since parametric assumptions were not met, comparisons of body size among species and sampling sites were performed using the non-

parametric Kruskal–Wallis test, followed by Dunn's post hoc test for multiple comparisons when significant differences were detected [55].

To assess assemblage structure, a species abundance matrix was constructed using each sampling site × climatic season combination as the sampling unit. Dissimilarity between samples was calculated using the Bray–Curtis index. Samples without recorded individuals were retained in descriptive analyses but removed from multivariate analyses based on Bray–Curtis dissimilarity. Assemblage composition was ordinated using non-metric multidimensional scaling (nMDS) to visualize general similarity patterns among sampling sites and seasons. The quality of the ordination was evaluated using the stress value [56]. Furthermore, an exploratory distance-based redundancy analysis (dbRDA) was performed as a complementary analysis to assess whether the measured environmental gradients were associated with community composition. Because the environmental variables were summarized at the site–season scale and the number of independent samples was limited, the dbRDA was interpreted with caution and presented as a supplementary analysis.

Differences in operational trap-sampled assemblage composition among sampling sites and climatic seasons were tested using permutational multivariate analysis of variance (PERMANOVA), with 9999 permutations and Bray–Curtis dissimilarity [57]. The homogeneity of multivariate dispersions among groups was assessed using the betadisper procedure [58], to verify whether any apparent differences detected by PERMANOVA could be related to variation in within-group dispersion. Because the study was based on a limited number of site–season combinations, multivariate results were interpreted cautiously and used primarily to assess whether compositional differentiation was detectable at the sampling scale analysed.

Exploratory relationships between environmental variables, abundance and the dominance of *C. exasperatus* were evaluated graphically and, when appropriate, using Spearman rank correlations [59]. These analyses were treated as exploratory because environmental measurements were summarized at the site–season scale and the number of independent site–season combinations were limited.

All analyses were performed in R version 4.5.0 [60], primarily using the *vegan* package for ecological and multivariate analyses [61].

3. Results

3.1. Environmental and Sedimentary Variation

Environmental variables recorded in the Una do Prelado River Estuary showed clear spatial and seasonal variation, although responses differed among variables. Temperature varied mainly among climatic seasons, with a stronger seasonal effect ($F = 66.73$; $p < 0.001$), whereas differences among sampling sites were not significant ($F = 0.052$; $p = 0.98$). Thus, water temperature reflected seasonal oscillation rather than a consistent longitudinal gradient along the estuary (Figure 2A).

Salinity showed a spatial tendency, although this variation was not significant at the 5% level ($F = 3.31$; $p = 0.056$). Higher values occurred mainly at the more marine-influenced sites A and B, whereas lower values were recorded towards the inner sectors, especially at sites C and D (Figure 2B). The pH varied seasonally ($F = 14.57$; $p < 0.001$), but not among sampling sites ($F = 0.108$; $p = 0.95$), again indicating a stronger temporal than spatial signal (Figure 2C). Dissolved oxygen showed no marked spatial or seasonal variation ($p > 0.05$), with values remaining within a relatively narrow range among sites and seasons (Figure 2D).

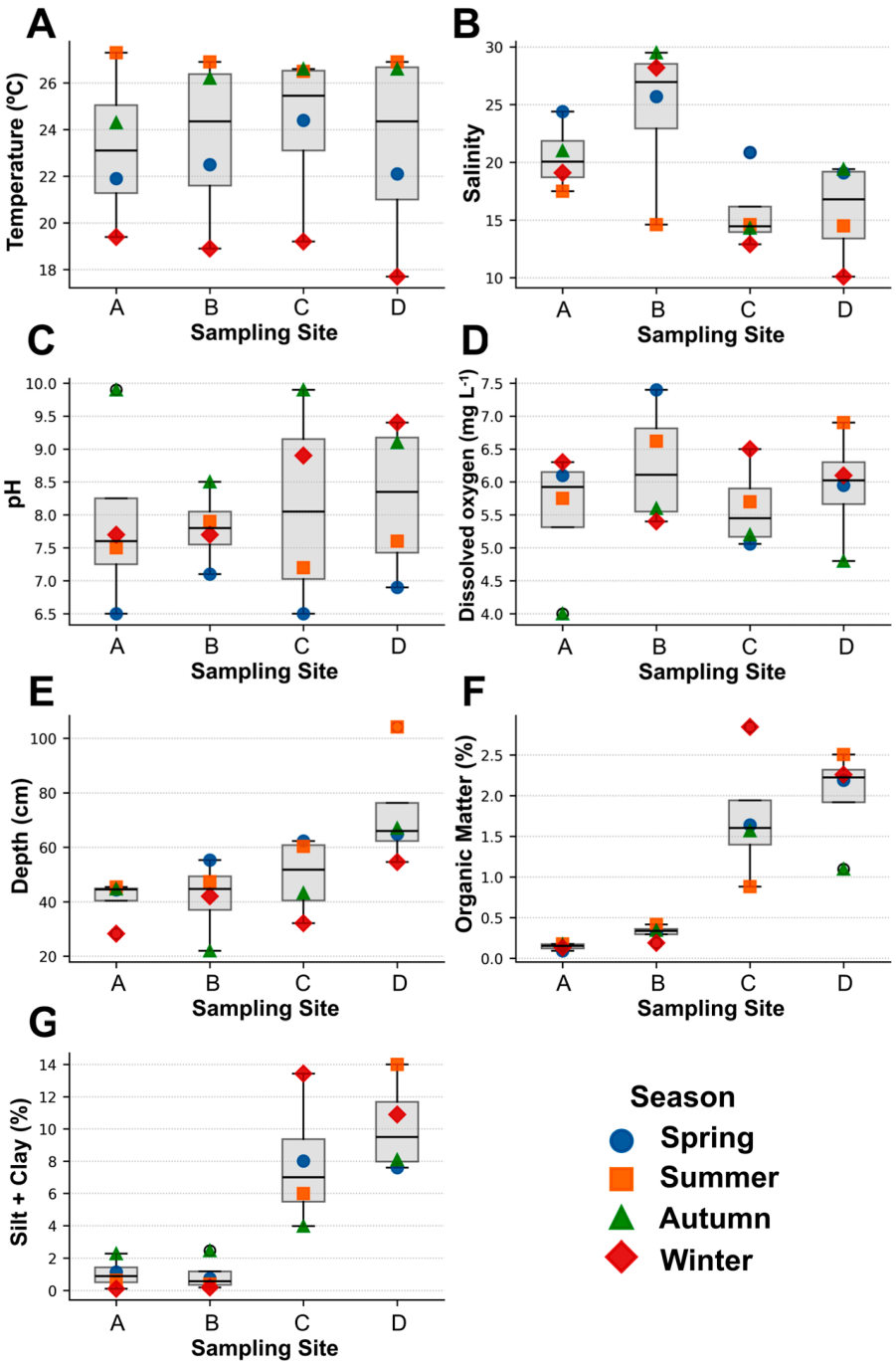

Figure 2. Spatial and seasonal variation in environmental and sedimentary variables recorded in the Una do Prelado River Estuary, Barra do Una Sustainable Development Reserve, south-eastern Brazil. Boxplots show variation among sampling sites for (**A**) temperature, (**B**) salinity, (**C**) pH, (**D**) dissolved oxygen, (**E**) depth, (**F**) organic matter, and (**G**) silt + clay fraction, while symbols indicate the climatic seasons sampled: spring, summer, autumn, and winter.

Depth varied among sampling sites ($F = 3.73$; $p < 0.05$), reflecting local differences in channel morphology. The shallowest mean values were recorded in the outer estuarine sectors (sites A and B), at 40.7 and 41.7 cm, respectively, whereas greater depths occurred in the inner estuarine sectors (sites C and D), at 49.5 and 72.7 cm, respectively (Figure 2E).

Sediment was predominantly sandy throughout the estuary, but fine sediments increased towards the inner sector. Sand accounted for more than 97% of the sediment at sites A and B, while the silt + clay fraction reached maximum values of only 2.3% and 2.5%, respectively. In contrast, sites C and D showed maximum silt + clay values of 13.4% and

14.0%, approximately six times higher than those recorded in the more external sectors (Figure 2G). Organic matter followed the same spatial pattern, increasing from mean values of 0.1% and 0.3% at sites A and B to 1.7% and 2.0% at sites C and D, respectively (Figure 2F). Therefore, although sandy sediment predominated along the estuary, the inner sectors were characterized by greater accumulation of fine particles and organic matter.

3.2. Species Composition, Abundance and Body Size

A total of 146 swimming crabs belonging to the genus *Callinectes* were recorded in the Una do Prelado River Estuary. Four species were identified: *Callinectes exasperatus* (Gerstaecker, 1856), *Callinectes danae* Smith, 1869, *Callinectes sapidus* Rathbun, 1896 and *Callinectes bocourti* A. Milne-Edwards, 1879 (Figure 3). The operational trap-sampled assemblage was strongly dominated by *C. exasperatus*, with 119 individuals, corresponding to 81.5% of the total catch. The remaining species were much less abundant: *C. danae* accounted for 15 individuals (10.3%), *C. sapidus* for nine individuals (6.2%), and *C. bocourti* for only three individuals (2.1%) (Table 2; Figure 4C).

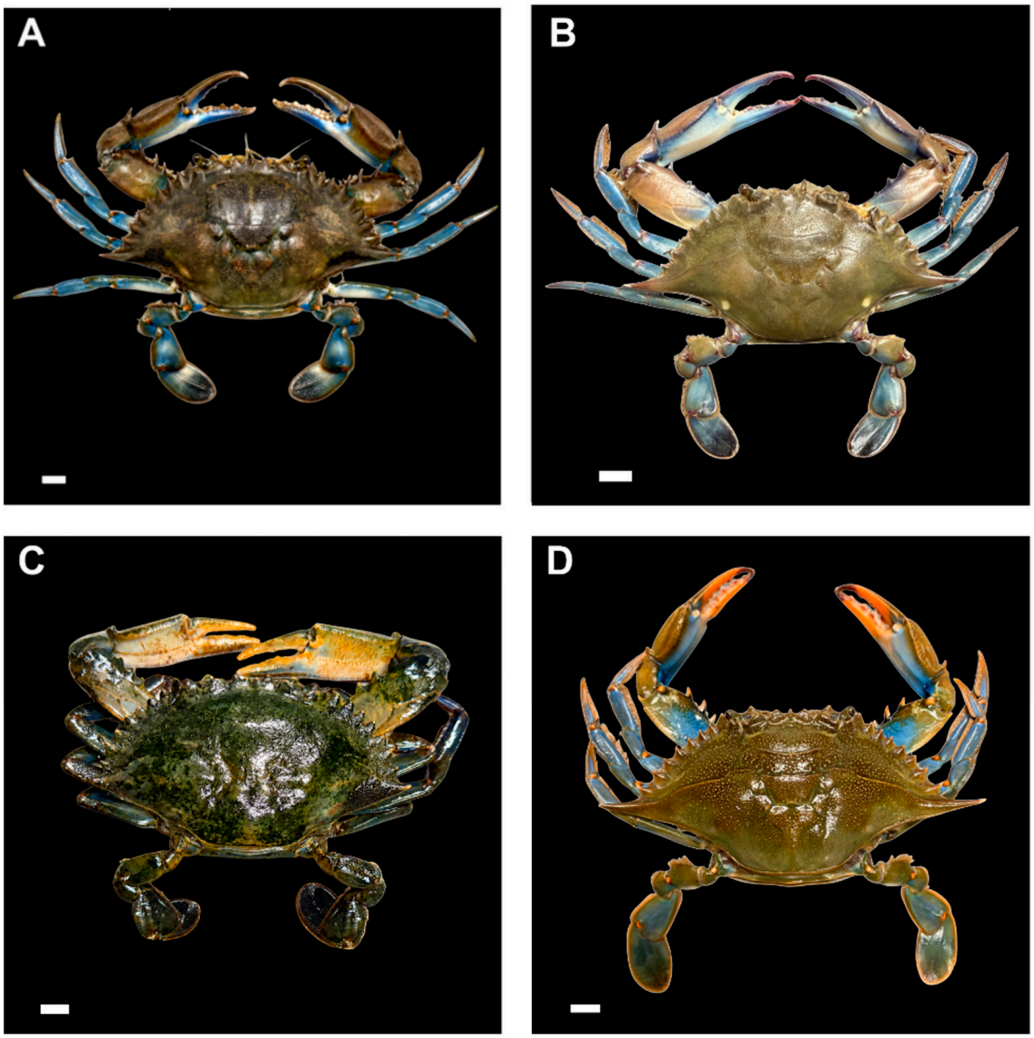

Figure 3. Representative specimens of *Callinectes* swimming crabs recorded in the Barra do Una Sustainable Development Reserve, south-eastern Brazil. (**A**) *Callinectes bocourti* A. Milne-Edwards, 1879; (**B**) *Callinectes danae* Smith, 1869; (**C**) *Callinectes exasperatus* (Gerstaecker, 1856); and (**D**) *Callinectes sapidus* Rathbun, 1896. Scale bars = 10 mm.

Table 2. Number of individuals and descriptive statistics of carapace width of *Callinectes* species sampled in the Una do Prelado River Estuary, Barra do Una Sustainable Development Reserve, south-eastern Brazil. N indicates the number of individuals; CW, carapace width; Min, minimum value; Max, maximum value; and SD, standard deviation. Different lowercase letters indicate significant differences in carapace width among species based on the Kruskal–Wallis test followed by Dunn's post hoc test ($p < 0.05$). The total row summarizes pooled measurements and was not included in post hoc comparisons.

Species	N	Carapace Width (mm)		
		Min	Max	$x \pm$ SD
C. bocourti	3	89.6	103.4	102.3 ± 11.1^{b}
C. danae	15	23.1	87.1	53.7 ± 20.9^{a}
C. exasperatus	119	59.6	106.1	83.8 ± 9.7^{b}
C. sapidus	9	27.1	129.1	95.9 ± 30.5^{b}
Total	146	23.1	129.1	83.9 ± 18.1

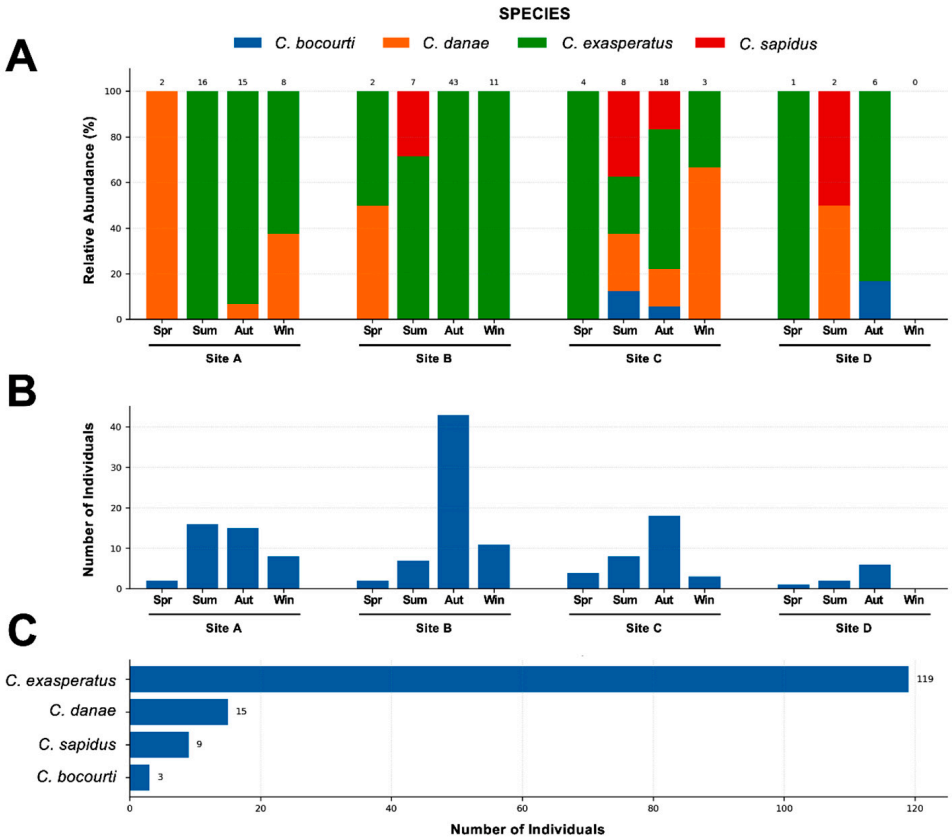

Figure 4. Seasonal and spatial patterns in the composition, abundance, and dominance of *Callinectes* swimming crabs in the Una do Prelado River Estuary, Barra do Una Sustainable Development Reserve, south-eastern Brazil. (**A**) Relative species composition by sampling site and climatic season, with numbers above bars indicating the total number of individuals recorded in each site–season combination; (**B**) total abundance of *Callinectes* crabs by sampling site and climatic season; and (**C**) overall abundance of the recorded species, highlighting the numerical dominance of *Callinectes exasperatus* in the assemblage.

The dominance of *C. exasperatus* was not restricted to a single site or climatic season. This species occurred in most site–season combinations and formed the numerical core of the operational trap-sampled assemblage. In contrast, *C. danae* occupied an intermediate position, whereas *C. sapidus* and *C. bocourti* occurred sporadically and contributed little to the total abundance (Figure 4A,C).

Total abundance varied more clearly than operational trap-sampled assemblage composition. Seasonally, abundance was highest in autumn and lowest in spring, whereas spatially it was concentrated mainly at site B (Table 3). This seasonal peak was largely driven by sampling site B in autumn, when 43 individuals were captured, representing the highest site–season abundance recorded during the study (Figure 4B). Thus, the main spatial pattern was a concentration of abundance at sampling site B, especially in autumn, rather than an increase in species richness.

Table 3. Ecological indices of the *Callinectes* operational trap-sampled assemblage in the Una do Prelado River Estuary, Barra do Una Sustainable Development Reserve, south-eastern Brazil, according to climatic season and sampling site. Seasonal variation is shown in section A and spatial variation in section B. N indicates the number of individuals; S, species richness; D, Margalef richness index; H′, Shannon–Wiener diversity index; and J′, Pielou evenness index.

(A) Season	**N**	**S**	**D**	**H′**	**J**
Spring	9	2	0.46	0.64	0.92
Summer	33	4	0.86	0.89	0.64
Autumn	82	4	0.68	0.46	0.33
Winter	22	2	0.32	0.54	0.77
(B) Site	**N**	**S**	**D**	**H′**	**J**
A	41	2	0.27	0.42	0.60
B	63	3	0.48	0.22	0.20
C	33	4	0.85	1.13	0.82
D	9	4	1.36	1.00	0.72

Carapace width differed significantly among species (Kruskal–Wallis, KW = 32.98; $p < 0.05$). *Callinectes danae* had the smallest mean carapace width (53.7 ± 20.9 mm), which differed from those of the other species in the post hoc comparisons. *Callinectes exasperatus*, the dominant species in the assemblage, presented intermediate values (83.8 ± 9.7 mm), whereas *C. sapidus* and *C. bocourti* had larger mean values (*C. sapidus*: 95.9 ± 30.5 mm; *C. bocourti*: 102.3 ± 11.1 mm), although both were represented by fewer individuals, and these values should be interpreted with caution, without inferring differences at the population level. Considering all specimens pooled, carapace width ranged from 23.1 to 129.1 mm, with a mean of 83.9 ± 18.1 mm (Table 2).

3.3. Diversity, Dominance and Sampling Coverage

Considering all samples pooled, the *Callinectes* assemblage in the RDS Barra do Una comprised four species and 146 individuals, with an overall Shannon–Wiener diversity of H′ = 0.652 nits ind.$^{-1}$ and Pielou evenness of J′ = 0.470. The corresponding Shannon effective diversity was 1.92 species, indicating that, despite the occurrence of four species, the operational trap-sampled assemblage was numerically equivalent to fewer than two equally abundant species due to the strong dominance of *C. exasperatus*.

The ecological indices confirmed the low richness and strong dominance indicated by the abundance data. Seasonal richness ranged from two to four species, with the highest values recorded in summer and autumn (four species each) and the lowest in spring and winter (two species each). Although autumn had the highest abundance, it did not exhibit the highest diversity due to the strong dominance of *C. exasperatus*. Shannon–Wiener diversity was highest in summer (H′ = 0.89 nits ind.$^{-1}$) and lowest in autumn (H′ = 0.46 nits ind.$^{-1}$), whereas Pielou evenness was highest in spring (J′ = 0.92) and lowest in autumn (J′ = 0.33) (Table 3; Figure S1).

Spatially, richness was highest at sampling sites C and D, with four species each, followed by sampling site B with three species and sampling site A with two species. However, richness at sampling site D should be interpreted cautiously, since only nine individuals were captured there during the entire study. Sampling site C showed the highest Shannon–Wiener diversity ($H' = 1.13$ nits ind.$^{-1}$) and high evenness ($J' = 0.82$). In contrast, sampling site B, despite having the highest abundance, showed the lowest diversity ($H' = 0.22$ nits ind.$^{-1}$) and evenness ($J' = 0.20$), reflecting the strong numerical dominance of *C. exasperatus* (Table 3; Figure S1).

Pairwise comparisons of Shannon–Wiener diversity using Hutcheson's *t*-tests indicated that sampling site C had significantly higher diversity than sampling site A ($t = 5.13$; $df = 71.62$; Holm-adjusted $p < 0.001$) and sampling site B ($t = 6.43$; $df = 81.32$; Holm-adjusted $p < 0.001$), whereas the remaining pairwise comparisons were not significant.

The relationship between relative abundance and species constancy reinforced the same pattern. *Callinectes exasperatus* was the only species showing both high abundance and high frequency among site–season sampling units, whereas *C. danae* occupied an intermediate position and *C. sapidus* and *C. bocourti* were poorly represented (Figure S2). Species accumulation and rarefaction curves also supported a species-poor assemblage, approaching the observed richness of four species based on 146 individuals sampled, considering that only one type of trap and effort was used (Figure S3).

3.4. Multivariate Assemblage Structure

The nMDS ordination based on Bray–Curtis dissimilarity showed broad overlap among sampling sites and climatic seasons, with no clear group separation in the ordination space (Figure 5). The low stress value (0.116) indicated an adequate two-dimensional representation of the dissimilarities among site–season sampling units. The site–season unit without captured individuals (sampling site D—Winter) was excluded from the Bray–Curtis analysis. In addition, the dbRDA analysis provided only weak support for the environmental structuring of the assemblage sampled by the operational traps, with no environmental variable showing a significant effect in the marginal testes (Table S2; Figure S4).

PERMANOVA did not detect differences in operational trap-sampled assemblage composition among sampling sites ($R^2 = 0.125$; pseudo-$F = 0.551$; $p = 0.778$) or climatic seasons ($R^2 = 0.264$; pseudo-$F = 1.159$; $p = 0.379$). Considering the limited number of site-station units, as well as the low abundance of rare species, this result should be interpreted as a limited compositional differentiation, visible at the sampling scale presented, and not as an inference of ecological stability or absence of spatial and seasonal variation. Most variation remained in the residual component ($R^2 = 0.607$), indicating that the spatial and seasonal factors tested explained little of the compositional variation at the sampling scale analysed (Table 4). Homogeneity of multivariate dispersions was also confirmed for sampling sites ($F = 0.477$; $p = 0.705$) and climatic seasons ($F = 0.253$; $p = 0.858$), indicating that the non-significant PERMANOVA results were not attributable to unequal within-group dispersion.

Overall, the *Callinectes* operational trap-sampled assemblage was compositionally simple, with the clearest biological pattern being the high abundance, strong dominance, and broad occurrence of *C. exasperatus*. Spatial and seasonal variation was therefore more evident in abundance and dominance than in operational trap-sampled assemblage composition, despite the environmental and sedimentary gradients recorded along the estuary.

Table 4. Summary of the permutational multivariate analysis of variance (PERMANOVA) used to test variation in Callinectes operational trap-sampled assemblage composition among sampling sites and climatic seasons in the Una do Prelado River Estuary, Barra do Una Sustainable Development Reserve, south-eastern Brazil. The analysis was based on Bray–Curtis dissimilarity and 9999 permutations. df indicates degrees of freedom; SS, sum of squares; R^2, proportion of ex-plained variation; pseudo-F, PERMANOVA test statistic; and *p*, permutation-based probability value.

Source of Variation	df	SQ	R^2	F	*p*
Site	3	0.47	0.13	0.62	0.78
Season	3	0.93	0.28	1.26	0.30
Residual	8	1.20	0.60	--	--
Total	14	3.40	1.00	--	--

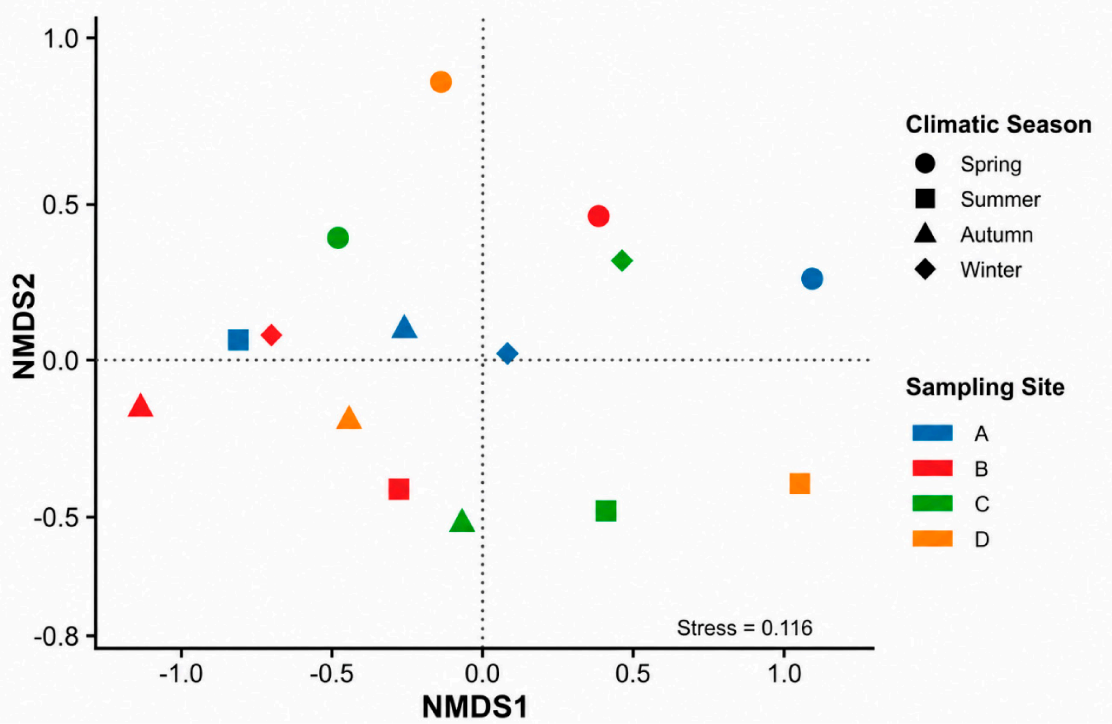

Figure 5. Non-metric multidimensional scaling (nMDS) ordination of *Callinectes* operational trap-sampled assemblage composition in the Una do Prelado River Estuary, Barra do Una Sustainable Development Reserve, south-eastern Brazil. The ordination was based on Bray–Curtis dissimilarities calculated from the species-abundance matrix, with each point representing a site–season sampling unit. Colors denote sampling sites, whereas symbols denote climatic seasons. The site–season unit with no captured individuals was excluded from the Bray–Curtis analysis. The stress value and PERMANOVA probabilities are shown within the plot.

4. Discussion

Our findings show that the swimming crab operational trap-sampled assemblage in the Barra do Una Sustainable Development Reserve (RDS Barra do Una) was characterized by low species richness, strong numerical dominance of *Callinectes exasperatus* and broad spatial and seasonal overlap in assemblage composition. Throughout the estuary, environmental and sedimentary gradients related to salinity, temperature, depth, dissolved oxygen, sediment composition and organic matter were evident. These variables are commonly associated with the distribution of *Callinectes* species in estuarine systems [11,21]. However, in the present study, these gradients were not reflected in significant spatial or seasonal differences in operational trap-sampled assemblage composition, indicating a compositionally simple and broadly overlapping assemblage within the estuarine sector

analysed. Therefore, the environmental gradient should be interpreted mainly as the ecological background of the study area, rather than as direct evidence of strong compositional structuring at the scale sampled.

Although the observed richness for the Una do Prelado River estuary was relatively low, with only four *Callinectes* species recorded, this value falls within the range reported for several Brazilian estuarine systems, where three to five portunid species have been recorded [11,62,63]. Higher richness has been reported in broader and more heterogeneous estuarine systems, such as the Cananéia-Iguape Estuarine-Lagoon Complex, where ten Portunidae species were recorded [28], and the Santos–São Vicente Estuarine Bay Complex, where seven to ten portunid species have been reported [64,65]. These differences are not surprising, since richness depends not only on environmental conditions, but also on spatial extent, habitat diversity, sampling effort, capture method and temporal coverage. Baited traps are efficient for sampling active swimming crabs, but their catches may be influenced by gear design, mesh size, bait attractiveness, soak time, escape behaviour and crab mobility [66–70]. For instance, studies using monthly sampling and longer trap-immersion periods [11] tend to record a broader portion of the local fauna than seasonal surveys with shorter capture periods. Thus, the low richness recorded here should not be interpreted by itself as evidence of an impoverished assemblage, but rather as a local baseline for this protected estuarine sector and for the sampling design used.

Local assemblage patterns are especially relevant to future monitoring strategies in protected areas [71], where assessments should consider not only species richness but also assemblage structure, temporal changes, dominant taxa, and management capacity [72]. Protected areas are often expected to harbor high biodiversity, but this expectation must be treated with caution in estuarine systems. A protected estuary may also contain a species-poor assemblage strongly dominated by a tolerant or widely distributed species, particularly when local environmental conditions favor a restricted set of taxa. Therefore, the value of the RDS Barra do Una as a reference system is not weakened by the low richness observed. On the contrary, documenting this natural pattern of dominance provides an important benchmark for detecting future changes in abundance, constancy of occurrence and assemblage structure. In species-poor assemblages, abundance, dominance and constancy of occurrence may provide more sensitive monitoring signals than richness alone, because richness can remain stable while assemblage identity, dominance structure and relative abundance change substantially [73–78].

The predominance of *C. exasperatus* was the most distinctive biological pattern observed in the Una do Prelado River Estuary. Although ecological information on *C. exasperatus* remains comparatively limited, available studies indicate that this species occurs in tropical and subtropical estuarine systems of the western Atlantic, usually within multi-species *Callinectes* assemblages and often at lower abundance than other congeners [11,79–81]. This pattern contrasts with several studies in Brazilian estuarine systems, where *C. danae* is frequently reported as one of the most abundant and widely distributed portunid species [11,28,62,64,82,83]. In the Cachoeira River estuary, for example, *C. danae* was the most abundant species and the only one recorded at all sampling sites, whereas *C. exasperatus* occurred along the estuary but was mainly associated with marginal areas [11]. In the present study, the opposite tendency was observed: *C. exasperatus* accounted for most individuals, occurred broadly across the estuary and formed the numerical core of the operational trap-sampled assemblage, whereas the other species were less abundant and more sporadic. However, the dominance of *C. exasperatus* should be interpreted with caution, considering that other factors such as trap selectivity, organism mobility, and differential habitat use by species may influence this pattern, but were not directly tested in the present study [66–70].

The widespread occurrence of *C. exasperatus* likely contributed to the lack of clear compositional separation among sampling sites and climatic seasons. When one species accounts for most individuals and occurs across most site–season combinations, differences among sampling sites or climatic seasons tend to appear more as variation in abundance and dominance than as true species replacement. This interpretation is consistent with the autumn abundance peak, especially at sampling site B, which increased the total number of crabs but did not generate a statistically distinct assemblage composition. Thus, the main ecological signal was not a spatial or seasonal turnover in species composition, but the persistence of a dominant species across a heterogeneous estuarine setting.

Differences among swimming crab assemblages in estuarine systems may result from several non-exclusive factors, including local habitat configuration, estuarine morphology, sampling scale and methodological differences among studies. In the Cachoeira River estuary, the distribution of *Callinectes* species varied along the salinity gradient and across the estuary's transverse profile, indicating responses to both longitudinal variation and marginal-channel habitat heterogeneity [11]. In the Laguna Estuarine System, the distribution of demographic groups of *C. danae* and *C. sapidus* was associated with salinity, pH, dissolved oxygen and turbidity, showing that environmental gradients can structure *Callinectes* assemblages when species or demographic groups respond differently to local conditions [21]. In the RDS Barra do Una, however, the measured environmental gradients did not translate into significant spatial or seasonal changes in operational trap-sampled assemblage composition, suggesting that the sampled sector maintained a largely overlapping composition structured mainly by the high occurrence and dominance of *C. exasperatus*.

For brachyuran crustacean assemblages in estuarine systems, compositional patterns alone may not capture the full biological heterogeneity of the system, because body-size variation and the formation of ontogenetic groups are important descriptors of local population and assemblage structure [21]. In the present study, carapace width differed significantly among species, primarily due to the smaller size of *C. danae*. *Callinectes exasperatus* showed intermediate values, whereas *C. sapidus* and *C. bocourti* had larger mean carapace widths, although both were represented by few individuals. Because *C. sapidus* and *C. bocourti* had low sample sizes, their mean size values should be interpreted descriptively rather than as strong population-level patterns. The partial overlap in size range among *C. exasperatus*, *C. sapidus* and *C. bocourti* is consistent with information reported in the literature for these species [46,63]. Likewise, any spatial difference in body size should be interpreted carefully, since it may reflect differences in the relative contribution of species and size classes among sites rather than clear spatial segregation at the operational trap-sampled assemblage level.

The ecological indices reinforced the same general interpretation derived from the abundance data. The operational trap-sampled assemblage showed low overall diversity and evenness, and the Shannon effective diversity indicated that the four recorded species were functionally equivalent to fewer than two equally abundant species. This result provides strong numerical evidence of dominance, rather than simply reflecting a descriptive impression. Seasonally, autumn had the highest total abundance but not the highest diversity, as the abundance peak was largely attributable to *C. exasperatus*. In contrast, summer showed higher richness and diversity, although with lower abundance. Spatially, sampling site C showed the highest Shannon–Wiener diversity and high evenness, whereas sampling site B had the highest abundance but the lowest diversity and evenness. The richness recorded at sampling site D must be interpreted with caution, since only 9 individuals were captured there throughout the study.

The species accumulation and rarefaction curves supported the interpretation of a species-poor assemblage under the sampling effort applied. The approach to the observed richness of four species suggests that the dominant components of the local *Callinectes* operational trap-sampled assemblage were sampled, but it does not preclude the possibility that rare species could be detected with greater sampling effort, longer temporal coverage, or additional capture methods. This point is important because estuarine swimming crab assemblages may include species with low abundance, seasonal occurrence or restricted habitat use. Because different sampling gears, habitats and effort levels may detect different fractions of estuarine assemblages, trap-based surveys should be interpreted as baselines for the catchable component of the assemblage rather than as definitive inventories of all species potentially occurring in the broader protected area. Differences in sampling gears, habitat coverage, and effort among studies may result in the detection of different fractions of estuarine assemblages [53,54,68,84,85].

Although several environmental variables were assessed, a substantial proportion of operational trap-sampled assemblage variation remained unexplained by the spatial and seasonal factors considered. In estuarine systems, additional ecological processes, such as recruitment, reproductive cycles, habitat use, and movement between habitats, can strongly influence the abundance and distribution of fish and invertebrates, especially in habitats that function as nurseries, feeding areas, or growth areas [86]. These processes may be particularly important for swimming crabs, whose life cycles involve changes in habitat use among juveniles, adults and reproductive females. Therefore, future studies should incorporate sex, maturity stage, reproductive condition and size-class structure, especially for *C. exasperatus*, which was the dominant species throughout the study. Such information would allow a more refined evaluation of whether the observed dominance reflects recruitment, adult habitat use, seasonal movement or a persistent local population structure.

Overall, the swimming crab operational trap-sampled assemblage of the Una do Prelado River Estuary was characterized by low richness, strong dominance and limited compositional differentiation among sampling sites and climatic seasons. The main observed pattern was the widespread occurrence and numerical dominance of *C. exasperatus*, whereas the remaining species contributed modestly to total abundance and occurred less frequently. For monitoring purposes, these results suggest that changes in abundance, dominance and constancy of *C. exasperatus* may be more sensitive indicators of temporal change than richness or multivariate composition alone. These findings reinforce the need to use protected estuarine areas as ecological reference systems, because local assemblage structure, dominant species and temporal changes can provide baseline information for future monitoring and conservation assessments [71,72]. Future studies combining greater sampling effort, longer time series, complementary sampling gears and demographic information will be essential to clarify the ecological processes that maintain the dominance of *C. exasperatus* in this protected estuarine system.

5. Conclusions

The present study recorded four species of swimming crabs belonging to the genus *Callinectes* in the RDS Barra do Una, revealing a species-poor operational trap-sampled assemblage with strong numerical dominance of *C. exasperatus*. This dominance represents the clearest ecological pattern identified in the study, indicating that the assemblage was not structured by an even distribution of species, but rather by the marked prevalence of a single taxon.

Although no significant differences in operational trap-sampled assemblage composition were detected among sampling sites or climatic seasons, this should be interpreted

as limited compositional variation during the study period, rather than as evidence of long-term spatiotemporal stability. At the same time, the observed distributional patterns of species occurrence suggest some variation along the estuarine gradient, probably reflecting local environmental heterogeneity, especially in relation to salinity, depth, sediment characteristics, and organic matter content. These patterns should be interpreted with caution, since the low abundance of the less frequent species limits stronger inferences about their habitat preferences.

The broad occurrence of *C. exasperatus* across the estuary and throughout the seasonal cycle indicates broad occurrence within the trap-sampled assemblage under the environmental conditions recorded in the system. This pattern may contribute to its numerical dominance in the RDS Barra do Una estuary and reinforces the importance of this species as a useful component for future monitoring of swimming crab assemblages in protected estuarine areas.

Despite the ecological and socioeconomic relevance of portunid crabs, information on the ecology and distribution of *C. exasperatus* remains limited in Brazilian estuaries. Therefore, the present study adds baseline information on the composition, dominance structure, and environmental context of a swimming crab assemblage within a sustainable-use protected area. Future studies with increased temporal replication, complementary sampling methods, and population-level analyses will be important to further investigate the ecological processes potentially associated with the dominance of *C. exasperatus* and the persistence of rarer *Callinectes* species in estuarine systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d18080464/s1, Figure S1. Descriptive ecological indices of the *Callinectes* assemblage by sampling site and climatic season in the Una do Prelado River Estuary, Barra do Una Sustainable Development Reserve, south-eastern Brazil. Panels show (A) observed species richness, (B) Shannon effective diversity, (C) Pielou evenness, and (D) dominance of *Callinectes exasperatus*. Numbers above bars in panel A indicate the total number of individuals recorded in each site–season combination. Figure S2. Relationship between relative abundance and constancy of occurrence of *Callinectes* species recorded in the Una do Prelado River Estuary, Barra do Una Sustainable Development Reserve, south-eastern Brazil. Each point represents one species, positioned according to its relative abundance in the total catch and its frequency of occurrence among site–season sampling units. Vertical reference lines indicate the conventional limits used to distinguish accidental, accessory, and constant species. Figure S3. Sampling sufficiency of the *Callinectes* assemblage recorded in the Una do Prelado River Estuary, Barra do Una Sustainable Development Reserve, south-eastern Brazil. (A) Sample-based species accumulation curve, with the shaded area representing the 95% randomization interval; (B) individual-based rarefaction curve showing expected species richness as a function of the number of individuals sampled. The observed total richness was four species, based on 146 individuals. Figure S4. Distance-based redundancy analysis (dbRDA) of the *Callinectes* operational trap-assemblage in the Una do Prelado River estuary, Barra do Una Sustainable Development Reserve, southeastern Brazil. The ordination was based on Bray–Curtis dissimilarities calculated from the species-abundance matrix, with each point representing a site–season sampling unit. Colors denote sampling sites, whereas symbols denote climatic seasons. The site–season unit with no captured individuals was excluded from the Bray–Curtis analysis. Table S1. Summary of ecological indices used and their respective equations, where: N, number of individuals sampled; p_i, proportion of individuals of species i in relation to the total sample; S, total number of species; x_i and y_i represent the abundance of the species in the two samples compared. Table S2. (A) Results of the distance-based redundancy analysis (dbRDA) testing the association between environmental variables and the *Callinectes* operational trap-sampled assemblage; (B) the values for each axis.

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