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Advances in population monitoring of the mangrove 'uçá'-crab (*Ucides cordatus*): reduction of body size variance for better evaluation of population structure and extractive potential

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ABSTRACT

Monitoring focusing on target species is an important tool to better understand biodiversity. The density, size, extractive potential and population structure of *Ucides cordatus* reflects the conservation of the mangrove ecosystem. The Federal Brazilian Institution of Biodiversity Conservation (ICMBio) defined a protocol to standardize and estimate these parameters using an indirect method that does not depend on the capture of individuals of a species. In this protocol are used models to adjust diameter of crabs' gallery *(DG)* measures into largest carapace width *(LC)*. Because this relationship *(LC vs. DG)* can differ according to geographic positions, the present study assessed it in three Brazilian mangrove areas (north, north-east, and south-east regions). Linear models of this relationship were compared between sexes, and also applied as a single model considering these Brazilian localities as a fixed factor and in three independent models for each locality separately. Equations did not differ significantly between sex and could be represented as one to each locality. However, a simpler linear model not including mangroves as fixed factors can be used to represent the entire latitudinal gradient, promoting a homogeneity of the estimation error, due to cover the entire body size (LC) variation of the *Ucides cordatus* crab.

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HIGHLIGHTS

- Body size and population structure of *Ucides cordatus* can be successfully estimated by measurements of the burrows, using an indirect method.
- Indirect method is advantageous in continuous monitoring, avoiding the higher impact promoted by capture in a specific mangrove area.
- Regional models can be more accurate, but a single and simpler model representing the entire latitudinal gradient can promote homogeneity of the estimation error and is more manageable.

Introduction

Mangroves forests fulfil several ecological, environmental and socioeconomic functions, including breeding place, nursery and habitat of many commercial fishery species such as decapod crustaceans (Santos et al. 2016; Pinheiro et al. 2018). Except for Rio Grande do Sul State (the southernmost state of Brazil), the entire Brazilian coastline contains mangrove forests (Schaeffer-Novelli et al. 2000; Souza et al. 2018). This ecosystem comprised ~9,900 km^2 of the Brazilian territory in 2018 (Diniz et al. 2019), accounting for the second largest extent in the world (Spalding et al. 2010). The states of Maranhão, Pará, Amapá and Bahia are the federal units with the most extensive mangrove cover in Brazil, with 85% of its mangrove area (Diniz et al. 2019).

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Ucides cordatus (Linnaeus, 1763), popularly known as 'uçá'-crab, is a semi-terrestrial, large-bodied decapod crustacean belonging to the family Ocypodidae, subfamily Ucidinae, according to Shih et al. (2016). This species is endemic to mangroves and occurs along the west Atlantic coast, with a broad geographic distribution from Florida State (USA) to Laguna city (Santa Catarina State, Brazil) (Melo 1996; Pinheiro et al. 2016). Like other ocypodid crabs, *U. cordatus* promotes mangrove sediment bioturbation (Koch and Wolff 2002; Araujo-Jr. et al., 2016), converts leaf litter to organic matter, alters sediment biochemistry and facilitates the flow of nutrients/energy along the food chain (Christofoletti et al. 2013; Sarker et al. 2021). In this way, it is a key species of the mangrove ecosystem, where it occurs with a high density (Pinheiro et al. 2018) and biomass (Wolff et al. 2000). Moreover, the species has economic interest in many places along the Brazilian coast, being considered one of the main fishing resources of estuarine systems (Dias-Neto 2011; Duarte et al. 2014; Santos et al. 2017). This species is used as food and source of income for traditional communities, especially in the north and north-east regions of Brazil (see Alves and Nishida 2003; Jankowsky et al. 2006; Andrade et al. 2007; Souto 2007; Cavalcante et al. 2011; Dias-Neto 2011; Cordovil et al. 2014; Nascimento et al. 2016, 2017; Fogaça et al. 2018).

Previous evaluations developed by Dias-Neto (2011) show that 'uçá'-crab production decreased by 57% between 1994 and 2007 in the northern region, with an estimated reduction of 28% in the fishing stock of this species throughout the entire Brazilian mangrove ecosystem (Pinheiro et al., 2016). Several Brazilian coastal regions have reported this population decline, which correlates with many factors. Some examples are mangrove habitat destruction, diseases, overfishing and increased mortality due to improper transport (Boeger et al. 2005, 2007; Legat et al. 2006; Andrade et al. 2007; Schmidt 2008a; Pinheiro et al. 2016). Due to this fact, *U. cordatus* was included in the 'National List of Aquatic Invertebrates and Fish Species Overexploited or Threatened with Overexploitation' by federal legislation (MMA 2004). The species faces permissive exploitation that nevertheless follows criteria established by force of law.

According to the historical review presented by Pinheiro and Rodrigues (2011), this species has received a special protection policy with the establishment of specific Brazilian regional laws (IBAMA 2003a: north-northeastern; and IBAMA 2003b: southern-south) and the proposal of the National Management Plan for the Sustainable Use of *U. cordatus* (Dias-Neto 2011). Pinheiro et al. (2016) inform that *U. cordatus* was categorized as 'Near Threatened' (NT) in the Official Assessment of the Risk of Extinction of Brazilian Crustaceans, a fact still recently confirmed in the legislation in force (see MMA, 2022).

In this scenario, the evaluation and monitoring of population parameters of *U. cordatus* are important tools for the conservation of the species. The body size and population structure of burrowing decapod crustaceans (e.g. ocypodid and gecarcinid crabs), among them *U. cordatus*, can be estimated by two distinct methods: (1) Direct method, comprising the measurement of body size (*LC*, largest carapace width) with precision calipers; and (2) Indirect method, comprising the measurement of diameter of gallery (*DG*), with posterior conversion to body size using mathematical equations previously obtained for this purpose (see Warren 1990). Schmidt et al. (2008b) verified sample bias in both methods (see review), which can be minimized, and in some cases avoided.

The indirect method is advantageous in monitoring procedures because it does not affect the number of specimens in a specific sampling area, and minimizes the impact on mangrove environments, especially in long duration monitoring (Pinheiro and Almeida 2015). Therefore, it is a more promising alternative to the direct method, where the samples of *U. cordatus* need to be removed from their galleries by manual capture (called 'braceamento') or by traps (called 'redinha'), maximizing the impact for monitoring their populations considering a specific area (Schmidt et al. 2009; Sandrini-Neto and Lana 2012; Schmidt et al. 2013; Santos et al. 2016; Pinheiro et al. 2018).

The increase of studies on *U. cordatus* in the last two decades promoted great accumulated knowledge, which allowed to confirm this mangrove crab as a relevant sentinel species (Pinheiro et al. 2013; Pinheiro and Almeida 2015; Pinheiro et al. 2017; Souza et al. 2022). These studies made it possible to confirm changes in density (active burrows/ m^2 – see Pinheiro et al. 2018), as well as population structure and extractive potential of this species, based on diameter of galleries (*DG*) measurement and conversion to largest carapace width (*LC*) (see Pinheiro and Almeida 2015). These aspects have been recorded once a year in different areas of Brazilian mangroves and allowed to categorize it as pristine or at different levels of anthropic impacts (Duarte et al. 2016; Pinheiro et al. 2017; Souza et al. 2022).

Taking this into consideration, a protocol evolving the 'uçá'-crab was established by the 'Monitoring Network for Benthic Coastal Habitats' (ReBentos), being developed to evaluate the density and population structure of *U. cordatus* (Pinheiro and Almeida 2015). This protocol was rediscussed by the 'Chico Mendes Institute for Conservation and Biodiversity' (ICMBio), incorporating new ideas relevant to create the 'MONITORA' programme (see Ribeiro 2018). This programme aims to carry out continuous monitoring, which can be developed with a minimum cost with regard to operational, infrastructural and training processes, and developed by traditional communities under the supervision of ICMBio. *U. cordatus* was considered a target species, chosen for continuous monitoring of the Brazilian mangroves. This protocol was developed in parallel with another protocol on the arboreal vegetation of this ecosystem. Therefore, the 'uçá'-crab protocol was broadly discussed in many meetings conducted by ICMBio, including specialists of many Brazilian regions, fishermen, traditional communities, environmental agents of ICMBio and other social actors. These stakeholders changed and built a protocol to be recognized, accepted and incorporated to be executed throughout the Brazilian coast. Since 2020, many Federal Conservation Unities (FCUs) have been annually monitored by the 'MONITORA' programme for a better understanding of mangrove characteristics. The purpose was to establish a protocol that could be easily applied, which should help optimize the recording of continuous variables, focusing on reducing possible errors and providing more accurate and reliable data.

Two equations were defined by the 'uçá'-crab protocol to convert *DG* to *LC*, and considered for monitoring distinct Brazilian regions, as previously indicated by Pinheiro & Almeida (2015). According these authors, specific mathematical equations are suggested in function of the considered Brazilian regions: N-NE regions (Schmidt et al. 2008b) and SE-S regions (Pinheiro 2006). This practice was followed due to the probability of differential somatic growth depending on latitude, a fact reported for other decapod crustaceans (Jones and Simons 1983; Castilho et al. 2007; Hirose et al. 2013). The present study aims to test mathematical models that represent the *LC vs. DG* relationship of *U. cordatus* in different Brazilian regions, as well as evaluating whether a single model can be used to express this relationship in monitoring of this species.

Materials and methods

Mangrove areas

Climate data were obtained in meteorological stations (MS) located near the mangrove areas in the study, characterized by distinct latitude, tidal amplitude, rainfall and temperature in these Brazilian regions (Figure 1). Tidal amplitude, temperature and rainfall were registered daily as part of a decennial data record, obtained from 1 January 2010 to 31 December 2019, in weather stations as follows: (1) northern Brazil (N-PA) – MS.1032: Vigia de Nazaré city, Pará State (0°50′46″S, 48°08′33″W), with macrotidal regimen (5.0 ± 0.4 m, until 5.6 m), the highest temperatures (26.3 ± 1.7°C, from 18–31.0°C) and high rainfall level (1,968 ± 690 mm y^{-1}, from 1,078.1–3,141.1 mm y^{-1}); (2) north-eastern Brazil (NE-BA) – MS.4082: Santo Amaro city, Bahia State (12°39′14″S, 38°44′44″W), with mesotidal regimen (3.0 ± 0.1 m, until 3.2 m), moderate temperatures (25.9 ± 4.3°C, from 16.0–39.0°C) and medium rainfall level (645 ± 257 mm y^{-1}, from 390–1,231 mm y^{-1}); and (3) south-eastern Brazil (SE-SP) – Station MS.749: Peruíbe city, São Paulo State (24°26′02″S, 47°05′59″W), with microtidal regimen (1.5 ± 0.1 m, until 1.6 m), the lowest temperatures (23.1 ± 5.2°C, from 6.0–38.0°C) and high rainfall level (1,452 ± 210 mm y^{-1}, from 1,082–1,762 mm y^{-1}). It is important to note that according to genetic analyses developed by Oliveira-Neto (2007a, 2007b) and Buranelli et al. (2019), *U. cordatus* comprises the same population along the Brazilian coast. Despite this wide latitudinal distribution and expressive climatic contrast among these three mangrove areas, all these mangrove areas were classified as *Am* (tropical monsoon climate) according to Alvares et al. (2014), using the Köppen climate classification (Köppen 1936). This fact suggests a seasonal (monsoon) winds, alternating rainy and dry seasons, temperature in the coldest month ≥18°C (annual average: 20–28°C y^{-1}), and rainfall in the driest month <60 mm (annual rainfall: 1,000–3,500 mm y^{-1}).

Data record

Open burrows with biogenic activities of *U. cordatus* (e.g. trails, faeces and sediment deposits) were recognized in each mangrove area according to their external morphology, indicated by Santos et al. (2009) and Pinheiro and Almeida (2015). Furthermore, the burrows of this species were recognized due its inclined opening in relation to the sediment, with

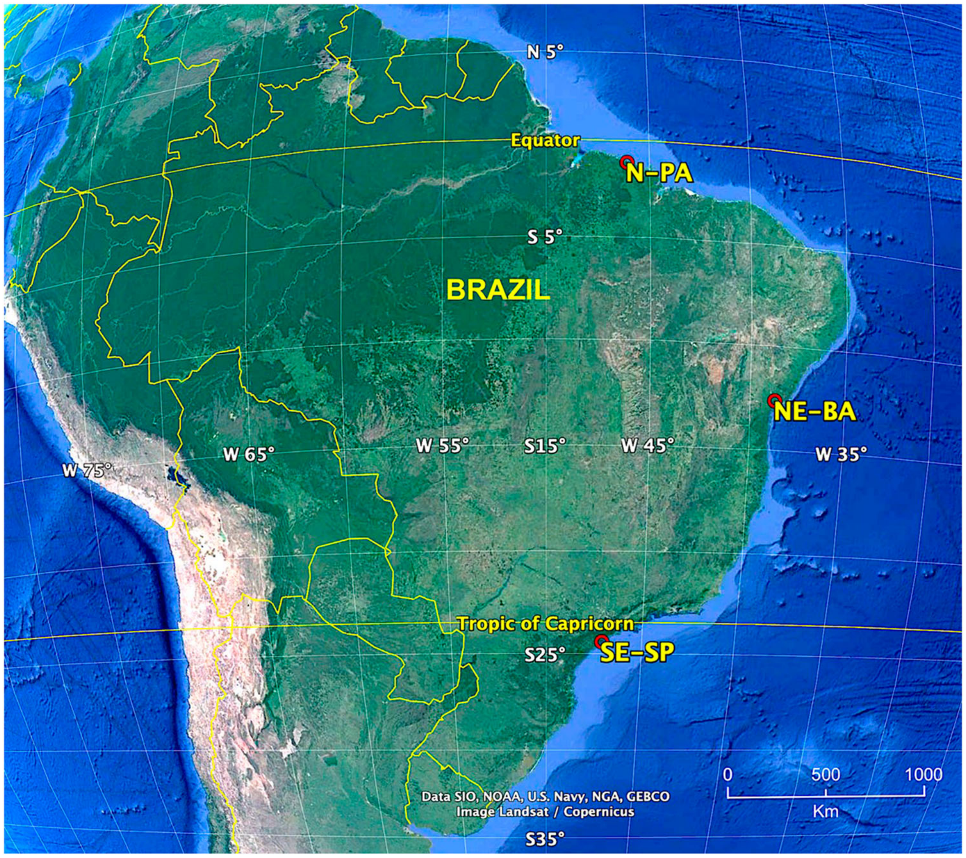

Figure 1. Map with three Brazilian sampling areas: north region (N-PA), Vigia de Nazaré, PA: 0°51′20″S, 48°08′24″W); north-east region (NE-BA), Acupe, BA: 12°39′14″S, 38°44′44″W); and south-east region (SE-SP), Peruíbe, SP: 24°26′02″S, 47°05′59″W). Source: Google ® Earth Data SIO, NOAA, U.S. Navy, NGA, GEBCO – Landsat/Copernicus.

the first 30 cm of its tunnel running parallel to surface, and posteriorly deep down in perpendicular until reaching more than 50 cm (Pülmanns et al. 2014).

Initially, each burrow had its diameter (*DG*) measured with an adapted precision caliper (0.05 mm) (see Pinheiro and Almeida 2015), positioned in parallel to the sediment. The *U. cordatus* specimen was then manually removed from its burrow by an experienced crab-catcher (see Pinheiro and Fiscarelli 2001; Fiscarelli and Pinheiro 2002; Machado et al. 2018) and sexed by the inspection of its abdominal morphology and counting of the number of pleopods (males: elongated and narrow abdomen, with 2 pairs of pleopods; females: broad and semioval abdomen, with 4 pairs of pleopods – see Pinheiro and Fiscarelli 2001). Then, the specimen had its body size measured (*LC*, largest carapace width) with a standard precision caliper (0.05 mm).

Data treatment and statistical analysis

The *DG vs. LC* relationship is usually expressed by *DG* (dependent variable) as a function of *LC* (independent variable). However, in this study, due to the conversion of the diameter of gallery (*DG*) to largest carapace width (*LC*), we propose an inverse approach that addresses the *LC vs. DG* relationship. In this sense, the empirical points of this relationship were submitted to plot charts for better evaluation of data dispersion in each Brazilian region (mangrove area), with a posterior residual analysis to remove spurious points that reduce fitting by a specific mathematical equation (Sokal and Rohlf 2012).

This dataset resulted in 719 empirical points, comprising the sum of all Brazilian regions (Figure 2), as follows: north region – Pará (N-PA: $n = 198$); north-east region – Bahia (NE-BA: $n = 302$); and south-east region – São Paulo (SE-SP: $n = 219$). Considering that only São Paulo (SE-SP) data had information on the sex of *U. cordatus* specimens occupying the burrows, only this area was used to assess the effect of sex in the relationship. Thus, data recorded for the relationship *LC vs. DG* of this mangrove area were previously inspected by sex in a normal Q-Q graphic to confirm the normality of residuals, and enabling it to be represented by regression analysis using a simple linear regression ($Y = bX + a$). Subsequently these equations

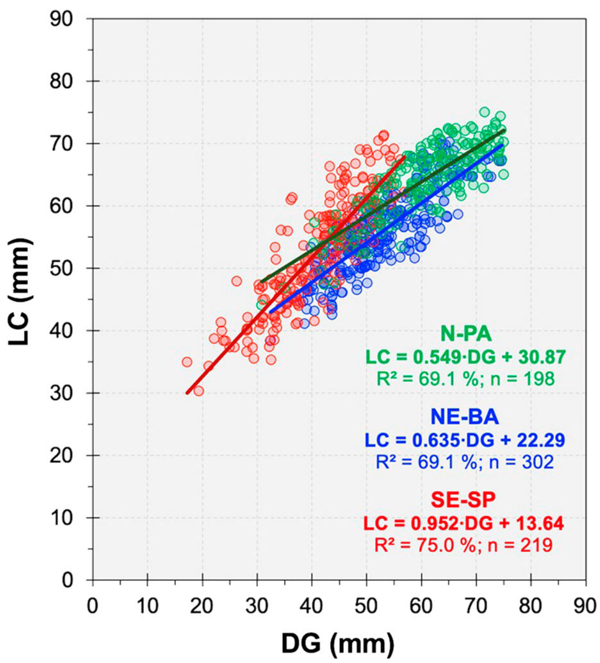

Figure 2. Dispersion graph of the *LC vs. DG* relationship according to Brazilian regions. Dispersion graph of the *LC vs. DG* relationship (*DG*, diameter of gallery; *LC*, largest carapace width), represented by empirical points obtained in post-residual analysis according to Brazilian regions (N-PA, north region – Pará State; NE-BA, north-east region – Bahia State; and SE-SP, south-east region – São Paulo State), with adjustment of linear equations representing each one. Where: *n*, total of individuals in each Brazilian region; and R^2, coefficient of determination.

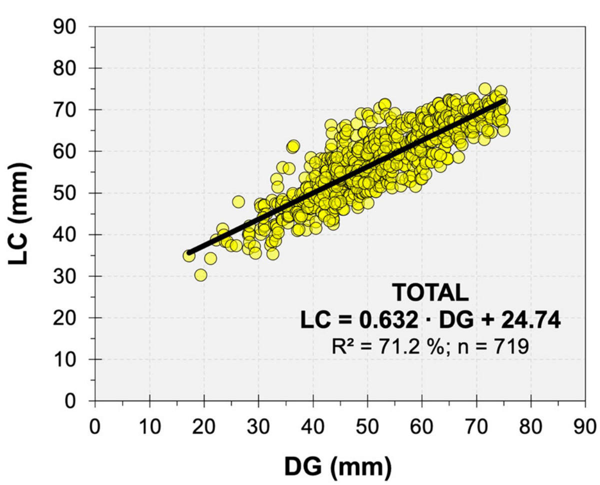

Figure 3. Dispersion graph of the *LC vs. DG* relationship regardless of Brazilian regions. Dispersion graph of the *LC vs. DG* relationship (*DG*, diameter of gallery; *LC*, largest carapace width), representing the total of empirical points ($n = 719$) regardless of Brazilian regions (north, north-east and south-east), with adjustment of linear equations representing each one. Where: *DG*, diameter of gallery; *LC*, largest carapace width; *n*, total of individuals analyzed; and R^2, coefficient of determination.

were subjected to ANCOVA, with comparison between constant values (*a*, intercept; and *b*, slope), verifying a possible representation by only one equation, according to Davanso et al. (2016) and Moraes et al. (2018).

Generalized Linear Models (GLMs) were fitted to assess the relationship between the response variable *LC* and its covariables *DG* and Mangrove area (MA). To explore the possibility of using a single equation to monitor *U. cordatus* in the field based only on galleries measurements, two models were adjusted: one with all variables, and a second one without the MA term. To determine the best model, we used the Second-Order Information Criterion (AICc), and the model that resulted in the lower AICc was selected (Sugiura, 1978; DelSole and Tippett, 2021). Due to the continuous nature of the data, we also tested which distributional family was the best fit for these models, Gaussian or Gamma (both with link function identity). The AICc was also used to select the best family. The analyses were performed in the software R version 4.0.3 (R Core Team 2021). The GLMs were fitted with the package *mgcv* (Wood, 2017), and the AICc values were estimated with function *AICc()* from *MuMin* package (Barton, 2009).

In another approach the equations obtained to each Brazilian region (N-PA, NE-BA and SE-SP), as well as the one representing the entire data set (TOT), were used to obtain estimated body size (LC_e) and the corresponding difference with respect to real body size (LC_r) for each crab analyzed. These data were submitted to residual analysis as follows: $DIF = ABS\ (LC_e - LC_r)$, where *ABS* is the absolute value of the difference between *LCe* (estimated body size) and *LCr* (real body size) for each animal analyzed. The variance of the *DIF* variable was calculated for each mangrove area (MA: N-PA, NE-BA and SE-SP) and the total data of them (TOT), with a comparison by relative variance expressed in percentage: $\sigma^2_{\text{Relative}} = ([(\sigma^2_{MA} - \sigma^2_{TOT}) \cdot 100]/\sigma^2_{MA})$; and considering as the most suitable that equation with minimum $\sigma^2_{\text{Relative}}$ in estimation of *LC* as a function of *DG*.

Results

The residual analysis (see Table I) of data of each mangrove under study reduced spurious records (8.8% in SE-SP to 34.4% in N-PA), consequently increasing the equation adjustment (16.4% in N-PA to 52.4% in NE-BA). Crabs' largest widths (*LC*) ranged from 30.3–75.0 mm (mean ± standard deviation: 57.2 ± 8.5 mm; CV = 14.8%), and DGs ranged from 17.2–75.2 mm (51.4 ± 11.3 mm; CV = 22.0%) (Table II). *LC* amplitude was similar across mangrove areas (44.7 mm),

Table I. Biometric variables of the *LC vs. DG* relationship (*LC*, largest carapace width; and *DG*, burrow diameter) in each Brazilian region under study (N-PA, north region – Pará State; NE-BA, north-east – Bahia State; and SE-SP, south-east – São Paulo State), and for the three Brazilian regions together by linear function ($Y = bX + a$) and the power function ($Y = aX^b$), respectively.

Brazilian Region (Mangrove Area)	Data Matrix	*n*	Mathematical Regression	R^2 (%)	PPD/PEA (%)
N-PA	ORG	302	$LC = 0.561 \cdot DG + 28.85$	57.8	−34.4 / + 16.4
	PAN	198	$LC = 0.549 \cdot DG + 30.87$	69.1	
NE-BA	ORG	378	$LC = 0.415 \cdot DG + 33.68$	32.9	−20.1 / + 52.4
	PAN	302	$LC = 0.635 \cdot DG + 22.29$	69.1	
SE-SP	ORG	240	$LC = 0.528 \cdot DG + 23.26$	43.0	−8.8 / + 42.7
	PAN	219	$LC = 0.952 \cdot DG + 13.64$	75.0	
Total (linear function)		**719**	$\mathbf{LC = 0.632 \cdot DG + 24.74}$	**71.2**	**–**
Total (power function)		**719**	$\mathbf{LC = 6.29 \cdot DG^{0.561}}$	**73.0**	**–**

Where: *n*, number of ordinated pairs (*X*, *Y*); ORG, original data matrix; PAN, post-analysis matrix; PEA, percentage of equation adjustment; PPD, percentage of points discarded from the original matrix; and R^2, coefficient of determination.

Table II. Biometric variables of the *LC vs. DG* relationship (*LC*, largest carapace width; and *DG*, diameter of gallery) in each Brazilian region under study (N-PA, north region – Pará State; NE-BA, north-east – Bahia State; and SE-SP, south-east – São Paulo State).

Variables	Brazilian Region (Mangrove Area)	*n*	Min-Max (Amplitude)	*x* ± sd	CV (%)
DG (mm)	N-PA	198	30.8–75.2 (44.4)	60.7 ± 9.2 c	15.1
	NE-BA	302	32.5–74.6 (42.1)	52.6 ± 8.3 b	15.8
	SE-SP	219	17.2–56.9 (39.7)	41.3 ± 8.3 a	20.0
	Total	**719**	**17.2–75.2 (57.7)**	**51.4 ± 11.3**	**22.0**
LC (mm)	N-PA	198	44.0–75.0 (31.0)	64.2 ± 6.0 c	9.4
	NE-BA	302	38.4–70.2 (31.8)	55.7 ± 6.4 b	11.4
	SE-SP	219	30.3–71.3 (41.0)	52.9 ± 9.1 a	17.1
	Total	**719**	**30.3–75.0 (44.7)**	**57.2 ± 8.5**	**14.8**

Where: *n*, number of ordinated pairs (*X*, *Y*); Min-Max, minimum – maximum values (amplitude value); *x*, mean value; sd, standard deviation; and CV, coefficient of variation. Mean values of the same variable followed by the same letter do not differ statistically ($P > 0.05$).

whereas for diameter of gallery (*DG*) it was more expressive (57.7 mm), with narrower ranges *DG* in S-SP (39.7 mm) and N-PA (44.4 mm), respectively.

Comparing the results of the three areas (Table II), *U. cordatus* specimens in the N-PA were the largest ones, followed by individuals from NE-BA and those from SE-SP, which had the smallest size ($F = 69.13$; $P = 1 \cdot 10^{-4}$). The same biometric pattern was observed in *DG* ($F = 126.89$; $P = 1 \cdot 10^{-4}$). Thus, both variables presented the same size hierarchy: N-PA > NE-BA > SE-SP.

Data recorded for the SE-SP mangrove ($n = 219$) were used to test the effect of sex on the *LC vs. DG* relationship, obtaining the following equations: $LC_{Males} = 0.919 \cdot DG + 15.51$ ($n = 173$; $R^2 = 73.4\%$; $F = 472.50$; $P = 2.2 \cdot 10^{-16}$); and $LC_{Females} = 0.965 \cdot DG + 11.32$ ($n = 46$; $R^2 = 76.9\%$; $F = 146.40$; $P = 1.4 \cdot 10^{-15}$). The slope values ('b') of these equations did not differ ($F = 0.24$; $P = 0.627$), despite intercept values ('a') being statistically distinct ($F = 10.19$; $P = 1.6 \cdot 10^{-3}$), although numerically similar (see Discussion). This fact indicated that only one equation disregarding the sex effect can be used ($F = 0.237$; $P = 0.627$): $LC = 0.952 \cdot DG + 13.64$ ($n = 219$; $R^2 = 75.0\%$; $F = 649.85$; $P < 2.2 \cdot 10^{-16}$). This absence of a sex effect in the *LC vs. DG* relationship was extrapolated to the other mangrove regions, each one of them represented by one equation. These three equations were compared using covariance analysis (see Table III), which confirmed a difference among them in relation to intercept ('a') and slope ('b').

Table III. Analysis of covariance (ANCOVA) with 'a' and 'b' values and contrast between *LC vs. DG* equations (*LC*, largest carapace width; and DG, diameter of gallery) established for each Brazilian region/Mangrove area (MA) under study (N-PA, north region – Pará State; NE-BA, north-east region – Bahia State; and SE-SP, south-east region – São Paulo State) and interaction (DG:MA).

Interaction of the Brazilian Regions	Const.	Effect or Interaction	*df*	Sum Sq.	Mean Sq.	*F*	*P*
N-PA *vs.* NE-BA	a	MA	1	0.385	0.385	1728.8	$<2 \cdot 10^{-16}$ ***
	b	DG:MA	1	0.023	0.023	6.519	0.011 *
N-PA *vs.* SE-SP	a	MA	1	3870	3870	198.1	$<2 \cdot 10^{-16}$ ***
	b	DG:MA	1	669	669	36.59	$2.81 \cdot 10^{-9}$ ***
NE-BA *vs.* SE-SP	a	MA	1	1.003	1.003	175	$<2 \cdot 10^{-16}$ ***
	b	DG:MA	1	0.040	0.040	7.03	0.0083 **

****$P = 0.001$; **$P = 0.01$; *$P = 0.05$.

Where: Const., constants; *df*, degrees of freedom; Sum Sq., sum of squares; Mean Sq., mean squares; *F*, *F*-test; *P*, significance level.

Table IV. Gaussian and Gamma models (link function identity) fitted for response variable.

Model Family	Response Variable	Parameters	AICc	Pseudo-R^2
Gaussian	*LC*	*DG + MA*	4067.071*	0.769
		DG	4225.644	0.711
Gamma	*LC*	*DG + MA*	4095.408	0.769
		DG	4247.037	0.713

Where: LC, Largest carapace width; DG; Diameter of gallery; MA, Mangrove area. * Best model.

Table V. ANOVA table extracted from the best model.

Terms	DF	Deviance	Residual DF	Residual Deviance
DG	1	36737	717	14894
MA	2	3015	715	11879

Fixed factor *LC* (largest carapace width), covariates *DG* (diameter of gallery) and *MA* (mangrove areas).

The total dataset ($n = 719$) was used to fit the GLMs. From the four fitted GLMs, the model that contained both covariates (i.e. *DG* and *MA*) and the Gaussian distributional family presented the lowest AICc, therefore was selected as the best model (Table IV). It rejects the null hypothesis; therefore, MA may not be removed. The ANOVA table for the best model was provided (Table V).

The conversion using the linear equation obtained for each Brazilian region (mangrove area) resulted in variances from between 17.1 (NE-PA) and 29.8 (SE-SP), with N-PA occupying an intermediate position (see Table VI). The equation involving the clustering of all data (TOT) showed a more reduced variance ($\sigma^2 = 11.4$), minimizing the difference between actual and estimated *LC* when compared with regional equations (see inside parentheses), as follows: TOT *vs.* SE-SP (61.8%) > TOT *vs.* N-PA (55.2%) > TOT *vs.* NE-BA (33.3%). Moreover, the percentage obtained between the relation of each region's σ^2 in relation to the $\Delta\sigma^2$ of the same area, was similar between the values obtained for the total equation and each area's equation (Table VI).

Table VI. Statistical summary of the absolute difference (*DIF*, in millimetres) that expresses the difference between estimated body size (*LCe*) and real body size (*LCr*), with estimated values obtained by *LC vs. DG* equations for each Brazilian region (*N-PA*, north region – Pará State; *NE-BA*, north-east – Bahia State; and *SE-SP*, south-east – São Paulo State) and total data set (*TOT*).

	DIF (mm)			
Brazilian Mangrove Region	*n*	*x*	*sd*	σ^2
N-PA	198	6.5	5.0	25.4
NE-BA	302	5.1	4.1	17.1
SE-SP	219	7.1	5.5	29.8
TOT	719	4.4	3.4	11.4
Estimate Comparison	$\Delta\sigma^2$		$\sigma^2_{Relative}$ (%)	
N-PA x TOT	25.4–11.4 = 14.0		55.2	
NE-BA x TOT	17.1–11.4 = 5.7		33.3	
SE-SP x TOT	29.8–11.4 = 18.4		61.8	
MEAN x TOT	24.1–11.4 = 12.7		52.7	

Where: *DG*, diameter of gallery; *DIF*, absolute value of the difference between estimated and real body size; *LC*, largest carapace width; *sd*, standard deviation; σ^2, variance; *x*, mean; $\Delta^{\sigma 2}$, difference between the estimated variance for each region and the estimated variance for the total dataset; *MEAN*, $\Delta\sigma^2$ mean obtained for each mangrove region; and $\sigma^2_{Relative}$ (%), relative variance expressed in percentage, between σ^2 to each mangrove region in relation σ^2 to grouped data (*TOT*).

Discussion

The long extent of the Brazilian coast comprises contrasting environmental factors that promote biological changes such as those observed in biometric relationships in animal species (González et al. 2016; Khalil et al. 2021). The GLM models indicated that fitting an equation for each different region would be more accurate in estimating the *LC* from the *DG* values obtained in the field. However, we believe that the use of a single model representing the entire latitudinal gradient would be more practical in the light of a conservation monitoring programme that will take place nationwide, carried out by local agents.

As we stated before, this study is part of a monitoring programme in development, and the agents will be individuals from the local communities, such as fishermen and other estuarine extractors. Although training will be provided to these agents, the several different collectors, under different circumstances, will lead to error in estimates, which is already expected. We also have to consider the intrinsic error in the estimated values of *LC* from the *DG* measures, in relation to the real *LC* values. However, with the grouped data we observed a lower variance due to the homogenization of the estimated error, even considering that we would be assuming a lower fit in favour of a simpler approach.

The increased and more stable temperature and photoperiod registered in equatorial/tropical zones (e.g. *N*-PA and NE-BA) contrast with the subtropical Brazilian zone (e.g. SE-SP), where a seasonal oscillation of these environmental parameters is more evident (see Williams and Middleton 2008; Hernández-Rojas et al. 2020). Nonetheless, using the total data set to estimate crab size as a function of burrow diameter resulted in lower variance between real and estimated crab size, allowing to express the *LC vs. DG* relationship on a national level.

The use of a biometric relationship requires a good knowledge of the variables under study, aiming to obtain the simplest mathematical model that allows the best conversion between them. In this aspect, it is especially relevant when these models are applicable, as in the present case, where the aim is to convert *DG* into *LC*, and with the latter to assess the population structure and extractive potential of *U. cordatus*. Thus, models that are useful in this conversion gain greater adherence with the traditional community (e.g. 'uçá'-crab catchers), in a federal participatory monitoring, as proposed by the protocols developed by Pinheiro and Almeida (2015) and ICMBio, as already mentioned.

In the present study, the percentage of data discarded by residual analysis (see *PPD* variation in Table I: 8.8–34.4%) can be explained by errors during data recording (e.g. measurement or reading inaccuracies of the caliper). This fact was verified with the *DG* variable, with a reduction if the records are made by a caliper adapted with stainless steel rods, extremely indicated in this process (see Pinheiro and Almeida 2015). Residual analysis promoted a significant increase in the determination coefficient (R^2) when the *LC vs. DG* data set was fitted by linear equation (see *PEA* variation in Table I: 16.4–52.4%), but there was no correspondence between *PPD* and *PEA*. In this sense, this previous mathematical procedure was essential to regression diagnosis, promoting a better expression between what was observed and predicted by the models (Webb 1973; Martin et al. 2017).

Latitudinal distribution of *U. cordatus* in Brazil is quite wide (~12° latitude), where environmental factors (especially temperature, rainfall and tidal regime) present a contrast among the mangrove areas studied. In this sense, temperature and photoperiod are considered relevant abiotic factors modulating these processes (see Sastry 1983, for review), although endogenous and biotic factors (e.g. genetic aspects – Farhadi et al. 2021, for review; and food availability – Pinheiro et al. 2005; Robertson 2021), can act alone or together and change biological parameters related to age, sex, size and reproduction (Sastry 1983; Hartnoll 2006).

Many authors confirm a differential effect varying according to latitudinal distribution (Hartnoll 1982; Jones and Simons 1983; Bauer 1992; Defeo and Cardoso 2004; Bakke et al. 2018). Despite temperature and photoperiod being the main environmental factors affecting growth and reproduction (Hartnoll 1982), tidal regimes in estuarine systems also modulate biological processes, especially the reproduction. This aspect is particularly verified for larval release in decapod crustaceans, where the tidal regime regulates the chronology of their life cycle (Nagelkerken et al. 2008; Schmidt et al. 2012; Gallep and Robert 2022). Due to this contrasting effect (mainly in a continental country such as Brazil), *U. cordatus* presents a higher energy investment in growth in the southernmost region in Brazil (subtropical), compared with areas further north in this country (equatorial/tropical), where it reaches maturity earlier and has a longer time to reproduce (Hines 1989; Castiglioni et al. 2011; Marochi et al. 2013; Takano et al. 2016). Mainly in decapod crustaceans this fact occurs due to the antagonism between these two biological processes (growth *vs.* reproduction – Adiyodi 1985; Pinheiro et al. 2005; Nagaraju 2011), due to competition between these biological processes for stored energy (especially glycogen) in the hepatopancreas of these animals (Kyomo 1988; Colpo and López-Greco 2018; Garcia-Bento et al. 2020; Griffen et al. 2022).

Regarding somatic growth, in south-eastern Brazil the somatic growth rate (*k*) of *U. cordatus* varied from 0.26–0.28 (see Pinheiro et al., 2005), about two times greater than that estimated by Diele and Koch (2010) in northern Brazil (*k*: 0.15–0.18). This was likely due to higher temperatures between the Tropic of Cancer and the equator line and higher investment in reproductive aspects. The opposite pattern occurred in the south-eastern region, where high latitudes might stimulate growth. Thus, individuals might reach sexual maturity earlier and be smaller than those inhabiting higher latitudes (Hartnoll 1982; Jones and Simons 1983; Lardies et al. 1998; Wehrtmann et al. 2012). According to Timofeev (2001), Bergmann's rule in marine crustaceans indicates that a crustacean's lifespan increases with the decrease of temperature (= higher latitudes), the same occurring with the growth in most crustaceans throughout life, reaching greater size compared with those from warmer areas (= lower latitudes). However, *U. cordatus* did not follow this rule – the same has been verified with other brachyuran species (see *Chionoecetes opilio* by Orensanz et al. 2007).

A GLM analysis was performed in the present study, where sex was not included as a valid variable because it is not so relevant. This aspect could be confirmed when linear models of *LC* vs. *DG* relationship were compared in function of sex, with no statistically significant difference for the slopes, but with a subtle numerical difference for the origin index (a-values), but biologically negligible. This aspect is confirmed when these equations are used to estimate *LC* to each sex along the variation of *DG* variable (30–80 mm), reaching values of estimated body size differences (LC males – LC females), ranging from 0.51–2.81 mm *LC*. In fact, sex of 'uçá'-crab was not a relevant variable suggested by Pinheiro & Almeida (2015) and ICMBio for the 'MONITORA' programme, despite a possible sex recognition (e.g. traces in sediment, faeces size, etc.) during recording of *DG* measurements with calipers. Due to these facts, sex was not considered a valid variable to be included in the GLM model, but MA (mangrove areas) was. The GLM model with the MA covariate explained 77% of *LC* variation, while the model that did not include the areas explained 71%. This difference in the fit leads us to believe in the usage of a single equation to represent the aforementioned biometric relationship. This simpler equation can be easily used by traditional fishermen, that actively aid in this participative monitoring process proposed, on the supervision of ICMBio environmental analysts and university partners duly trained in this protocol.

In the present case, the use of a simpler and single model for the entire Brazilian coast makes it possible to homogenize the estimation error in comparison to those arising from the different regional models, given that not all of them cover the entire body size (*LC*) variation of the 'uçá'-crab. Adaptations to the protocol for the *Ucides cordatus* ('MONITORA' programme – ICMBio) can optimize the actions of temporal monitoring of the population structure and extractive potential of this sentinel species to maintain the environmental quality of Brazilian mangroves.

CRediT authorship contribution statement

Marcelo Antonio Amaro Pinheiro: Conceptualization; Data collection and curation; Statistical analysis; Funding acquisition; Investigation; Methodology; Writing – original and final draft, review and editing; Validation. Fernanda Vargas Barbi de Souza: Data col lection and curation; Visualization; Writing – original draft; Validation. Julia Fernandes Perroca: Statistical Analysis; Writing – final draft, review and editing; Vali dation. Mauro Marcio Tavares da Silva: Data collection and curation; Funding acquisition; Investigation; Writing – original draft; Validation. Raimundo Luiz Morais de Sousa: Data collection and curation; Visual ization; Writing – original draft; Validation. Thais Arrais Mota: Data collection and curation; Visualization; Writing – original draft; Validation. Sérgio Schwarz da Rocha: Data collection and curation; Funding acqui sition; Investigation; Visualization; Writing – original draft, review and editing; Validation.

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