Environ Monit Assess (2025) 197:594
https://doi.org/10.1007/s10661-025-14033-2

RESEARCH

Metal concentration in ghost shrimp and contamination levels of sandy beaches contrasted with anthropogenic impacts in Southeast Brazil

Juliano José-Silva · Tailisi H. Trevizani · Alaor A. Almeida · Marcelo A. A. Pinheiro

Received: 16 October 2024 / Accepted: 15 April 2025

Abstract This study evaluates the contrast in the concentration of seven potentially toxic elements (As, Cd, Cr, Cu, Hg, Mn, and Pb) in tissues (G, gonads; H, hepatopancreas; and M, muscle) of the ghost shrimp *Callichirus corruptus*, as a response to sediment contamination in two sandy beaches in Southern Brazil with different anthropogenic status (JUR, Juréia; and STS, Santos). The biotic and abiotic samples were collected with a suction pump and subjected to metal quantification by atomic absorption spectrophotometry technique. In JUR, the sediment had Cr, Cu, and Mn concentrations two times lower when compared to STS ($t \leq 7.80$; $p \leq 0.01$), while STS had Hg concentrations between the Interim Sediment Quality Guideline (ISQG) and probable effect level (PEL) parameters. Three metals (Cd, Cr, and Cu) presented concentrations above the maximum tolerated limit indicated by the Brazilian Health Regulatory Agency (Anvisa), with prawn bioaccumulation up to eight times greater in STS than JUR ($t \geq 4.42$; $p \leq 0.03$). Therefore, this study confirms higher metal concentrations (µg/g) in the biotic (Cd = 7.86 Cr = 11.95 and Mn = 19.38) and abiotic (Cd = 0.45, Cr = 3.13, Cu = 0.59, Hg = 0.49 and Mn = 45.61) compartments of Santos, which has a high human population density and a significant industrial and port complex, in contrast to Juréia, which is located in a highly conservation ecological station. Furthermore, the research presents novel information on trace elements in the sandy sediments of the studied sites. Additionally, it provides unprecedented evidence on metal concentration for *C. corruptus*, which can be used in monitoring programs for sandy beaches due to its metal bioaccumulation potential.

J. José-Silva (✉) · M. A. A. Pinheiro
Institute of Biosciences, São Vicente – Laboratory of Conservation Biology of Crustaceans and Coastal Environments (LBC) – Research Group in Crustacean Biology (CRUSTA), São Paulo State University (UNESP), Praça Infante Dom Henrique, s/nº, Parque Bitaru, São Vicente, SP 11330 - 900, Brazil
e-mail: jj.silva@unesp.br

M. A. A. Pinheiro
e-mail: marcelo.pinheiro@unesp.br

J. José-Silva · M. A. A. Pinheiro
Postgraduate Program in Coastal Environment Biodiversity, UNESP IB/CLP, São Vicente, Brazil
e-mail: marcelo.pinheiro@unesp.br

T. H. Trevizani
Oceanographic Institute – Laboratory of Metals in Marine Organisms (LaMOM) – Cidade Universitária, University of São Paulo (USP), Praça Oceanográfico nº 191, São Paulo, SP 05508 - 120, Brazil
e-mail: tailisi@usp.br

A. A. Almeida
Institute of Biosciences, Botucatu – Center for Toxicological Information and Assistance (CIATox), São Paulo State University (UNESP), Rua Professor Doutor Antonio Celso Wagner Zanin, s/nº, Botucatu, SP 18618 - 689, Brazil
e-mail: alaor.almeida@unesp.br

Published online: 25 April 2025

Keywords Brazil · *Callichirus corruptus* · Crustacean · Keystone species · Marine pollution · Toxicity

Abbreviations

As	Arsenic
ANOVA	Analysis of variance
ANVISA	Brazilian Health Regulatory Agency
Cc	*Callichirus corruptus*
Cd	Cadmium
CETESB	Environmental Company of the State of São Paulo
CIATox	Toxicological Information and Assistance Center
CL	Carapace length
Cr	Chromium
CLP	São Paulo Coastal Campus
CRUSTA	Crustacean Biology Research Group
Cu	Cupper
ESECJI	Juréia-Itatins Ecological Station
G	Gonads
GR	Gravel
H	Hepatopancreas
HCl	Hydrochloric acid
HF	Sulfuric acid
Hg	Mercury
HNO_3	Nitric acid
IB	Institute of Biosciences
IBGE	Brazilian Institute of Geography and Statistics
ISQG	Interim Sediment Quality Guideline
JUR	Juréia
LBC	Laboratory of Conservation Biology of Crustaceans and Coastal Environments
LD	Limits of detection
LQ	Limits of quantification
M	Muscle
MTL	Maximum tolerable limits
Mn	Manganese
MGS	Median grain size
NIST	National Institute of Standards and Technology
OM	Organic matter
Pb	Lead
PEL	Probably effect level
RDSB	Sustainable Development Reserve of Barra do Una
RJ	Rio de Janeiro state
S	South
SA	Sand
SE-A	Upper stratum
SE-B	Lower stratum
SESSV	Santos-São Vicente Estuarine System
SI	Silt
SP	São Paulo state
SRM	Standard reference material
STS	Santos
UNESP	São Paulo State University
W	West
WW	Wet weight

Introduction

Sandy beach environments are subject to intense anthropogenic activity due to high population density in coastal regions, significant coastal development, and consequent pollution (Defeo et al., 2009; McLachlan and Defeo, 2018; Buzzi et al., 2022). Coastal ecosystems have undergone significant physicochemical changes, affecting the distribution of several invertebrate species (Belan, 2004; Wu et al., 2014; Cardoso et al., 2016; Cabrini et al., 2017; Wu et al., 2023), in terms of abundance (Osuala et al., 2018; Koziol et al., 2022) and diversity (Nwabueze et al., 2020; Wu et al., 2023). The unique characteristics of marine and estuarine beaches serve as important natural barriers to pollutants (Karlonienė et al., 2021; Hyndes et al., 2022; Corte et al., 2023) and provide other relevant ecosystem services such as organic and nutrient cycling and water purification (Defeo et al., 2009, 2021; Buzzi et al., 2022; Liang et al., 2024).

Despite the importance of marine coastal ecosystems, studies on pollutants in sandy beaches are scarce (Jonathan et al., 2011; Santhiya et al., 2011; Nagarajan et al., 2013; Corte et al., 2023). Metals stand out among such pollutants due to their wide distribution and association with industrial development (Cajaraville et al., 2000; Costa et al., 2021; Buzzi et al., 2022), which leads to persistence in the environment and toxicity to sediments and biota (Ahearn et al., 2004; Rainbow, 2007; Luoma and Rainbow, 2008; Cesar et al., 2012; Duarte et al., 2017; Pinheiro et al., 2017). Some metals are considered essential (e.g., Cu, Cr, and Mn) as they participate in biological processes, but they become toxic at high concentrations (Duarte et al., 2016). Other elements are non-essential (e.g., As, Cd, Pb, and Hg) and contaminate the environment and biota even at low concentrations (Eisler, 2009; Duarte et al., 2017).

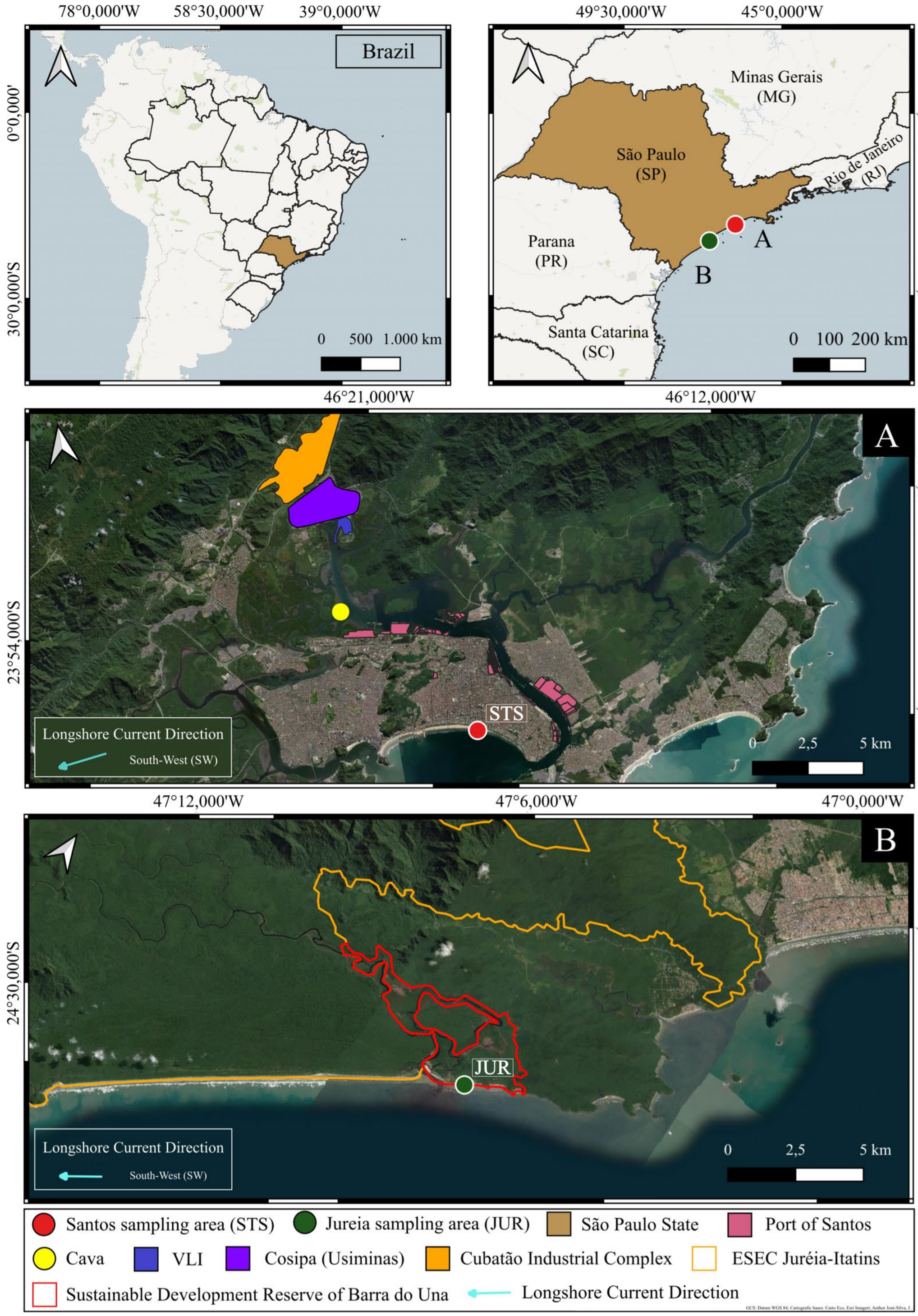
Water acts as a transport matrix for potentially toxic elements, which can dissolve in water and undergo chemical changes, varying widely over time and distance from pollution sources (Harris and Santos, 2000; Raknuzzaman et al., 2016; Lin et al., 2021). These elements are also attracted to sediments, which become persistent and increase toxicity levels (Ahearn et al., 2004; Rainbow, 2007; Vilhena et al., 2013; Banci et al., 2017; Perina et al. 2018). Similarly, these contaminants accumulate in organisms and biomagnify throughout the food chain, causing irreversible damage to local biota (Luoma and Rainbow, 2008; Duarte et al., 2017; Trevizani et al., 2023). Thus, only 1% of pollution is associated with water, while the remaining 99% persists in beach sediments (Gaur et al., 2005; Bartoli et al., 2012; Vetrimurugan et al., 2016).

The main route of contamination for benthic invertebrates is through gills, direct skin contact, or ingestion of contaminated sediment and food (Rainbow, 2007; Duarte et al., 2016, 2017, 2020), resulting in low environmental preservation status and deleterious effects on the biota (García-Alonso et al., 2011; Castiglioni et al., 2018). Various invertebrate species have been shown to respond physiologically and genetically to different levels of metallic contaminants, reflecting the environmental contamination status of the studied location (Ryu et al., 2011; Rumisha et al., 2012; Cabrini et al., 2017). Therefore, several studies recommend using invertebrates to assess and monitor anthropogenic impacts and have confirmed physiological and genetic alterations (e.g., Goulart and Callisto, 2003; Pinheiro et al., 2012; Duarte et al., 2016, 2017; Pinheiro et al., 2017; Costa et al., 2021). Among the benthic invertebrates of sandy beaches, ghost shrimp deserve special attention as they are considered a "key species" for studying scenarios that promote changes in physicochemical parameters and the local community (Birkeland, 1989; Jones et al., 1994; Valls et al., 2015).

Callichirus corruptus (Hernáez et al., 2022) is a ghost shrimp (Callianassidae) endemic to Brazil, which promotes bioturbation of sandy beach sediments, causing significant changes to their textural and chemical composition (Klerks et al., 2007; Costa et al., 2022). Distributed along the entire Brazilian coast (Hernáez et al., 2022), it excavates burrows and alters the structure of local communities by changing the biogeochemical cycles of the sediment (Posey, 1986; Ziebis et al., 1996; Rodrigues and Shimizu, 1997; Rosa et al., 2018; Constantino et al., 2024). Additionally, its burrows allow a high flow of water and incorporation of organic matter and associated pollutants (Abu-Hilal et al., 1988; Klerks et al., 2007), which interfere with various functional processes of marine sandy beaches (Rodrigues and Shimizu, 1997). This shrimp is also recognized as an important fishery resource due to its widespread use as bait in various coastal areas (Borzone and Souza, 1996). Its popularity can be attributed to its high attractiveness to fish and the ease with which it can be collected on sandy beaches (Peiró and Mantelatto, 2016).

Studies related to metal contamination have already been conducted on mangrove sediments (Pinheiro et al., 2012, 2017; Duarte et al., 2016) and dredging materials (Torres et al., 2009; Buruaem et al., 2013; Kim et al., 2016) from the Santos-São Vicente Estuarine System (SESSV). However, no research has yet assessed the concentration of these elements in the sandy matrix of local beaches. Similarly, there is a gap in studies quantifying metals in crustacean species living in beaches, with intensified studies developed in mangrove areas, especially with "uçá" crab species (*Ucides cordatus*), which is applied as sentinel species of this environmental quality. Therefore, the present study provides novel data on the metal concentration in a shrimp species (*Callichirus corruptus*) from the local beach environment, as well as in the sandy sediment of Santos' beaches (SP), in addition to aligning with Goal 14: Life Below Water, of the UN Sustainable Development Goals (United Nations, 2015).

Considering the significant contrast with human population density and anthropogenic activities along the Brazilian coast, comparing preserved and contaminated areas allows for assessing the effects of different concentrations of potentially toxic elements that cause irreversible damage to the local biota (Duarte et al., 2016, 2017). We hypothesize that the concentration of potentially toxic elements in the sediment and tissues of *C. corruptus* is higher on beaches with greater anthropogenic impact (Santos, SP) compared to an ecological station (Peruíbe, SP), with the following hierarchy of contamination in tissues: hepatopancreas > gonads > muscle.



The objective of this study is to quantify the concentrations of seven potentially toxic elements (As, Cd, Cr, Cu, Hg, Mn, and Pb) in the sediment and in three tissues (gonads, hepatopancreas, and muscle) of the ghost shrimp (*C. corruptus*) and to compare data obtained from two sandy beaches in southeastern

◂**Fig. 1** Location map of two beaches in São Paulo state coast (Brazil), known as Juréia (JUR) and Santos (STS), sampled on April 7 and May 10, 2017. Description: The image consists of four maps. The two smaller maps provide location context: the map on the left illustrates the country and state where the research was conducted, while the map on the right pinpoints the two sampling areas within São Paulo state. Additionally, the image includes two larger maps: the upper map focuses on Santos Beach (STS), highlighting key enterprises and structures in the region, such as the Port of Santos (pink), the Subaquatic Dredged Material Disposal Area (yellow), VLI (lilac), Cosipa (purple), and the Cubatão Industrial Complex (orange). Conversely, the lower map depicts Juréia Beach (JUR), featuring the Juréia-Itatins Ecological Station (ESECJI) (dark yellow line) and the Barra do Una Sustainable Development Reserve (RDSB) (red line)

Brazil with different levels of anthropization: Juréia-Itatins Ecological Station Beach (less impacted environment) vs. Santos Beach (contaminated environment).

Material and methods

Studied areas

Samples were collected from two sandy beaches in southeastern Brazil, both located in the State of São Paulo: (1) Santos Beach (STS) sampled in April 2017 and (2) Juréia Beach (JUR) sampled in May 2017 (Figure 1). Santos Beach is in the municipality of Santos, on the central coast of São Paulo State, which has a high population density (418,000 inhabitants—IBGE, 2022). It hosts one of Brazil's most significant industrial hubs, such as the petrochemical industries (e.g., the Cubatão Industrial Complex), steel industries (e.g., Cosipa), and port transport and logistics (VLI) (Galvão-Filho, 1987; CETESB, 2021), as well as the Port of Santos, the largest in South America (Angeli et al., 2021). Consequently, it experiences various anthropogenic impacts and presents pollution sources, which significantly contaminate ecosystems and their organisms (Oliveira et al., 2008; Torres et al., 2009; Kim et al., 2016; Perina et al., 2018). Juréia Beach, on the other hand, is located in the municipality of Peruíbe, on the southern coast of the same state, located within the Juréia-Itatins Ecological Station (ESECJI) (Law no. 5.649/1987 - São Paulo, 1987; Sanches, 2004) and the Barra do Una Sustainable Development Reserve (RDSB) (Law no. 14.982/2013 - São Paulo, 2013), a Mosaic of Conservation Units (Law No. 12.406/2006 - São Paulo, 2006) governed by state legislation. The human population comprises 162 inhabitants, according to Duarte et al. (2016).

Sediment and crustacean sampling

A sampling area was established at the midpoint of each beach, where sediment and crustacean samples were collected (Figure 2). Twelve shrimps were captured using a simple suction pump positioned over the opening of each burrow, with 5 continuous suctions per burrow (see Rodrigues and Shimizu, 1997). The material (sediment/water) was deposited on a sieve (diameter: 60 cm; mesh: 12 mm). Intact specimens were placed in individual plastic bags, kept in thermal boxes with ice, and transported to the Laboratory of Conservation Biology of Crustaceans and Coastal Environments (LBC), part of the Crustacean Biology Research Group (CRUSTA) at UNESP IB/CLP, São Vicente.

Sediment for analysis was obtained from composite samples using the same suction pump positioned between the openings of three burrows to avoid bioturbation by the shrimp (JUR = 24°26.23′S/04°73.55′W; STS = 23°58.25′S/46°19.36′W). For each sample (n = 6/beach), five sediment columns (45 cm) were suctioned from each beach, with a minimum distance of 5 m between them. They were carefully placed on a plastic sheet, reserving the upper (SE-A: 0 to 15 cm) and lower stratum (SE-B: 30 to 45 cm). Each composite sediment sample (SE-A: n = 3; and SE-B: n = 3; for beach) comprised a mixture of five portions of upper and lower stratum, respectively, which were homogenized and reduced to 1 kg each (see Batley and Simpson, 2016). In the laboratory, each sediment sample was frozen until lyophilization. Three subsamples (15 g per stratum/beach) were kept, placed in labeled Falcon tubes (15 mL), and stored for metal quantification.

For each sediment sample, three replicates (100 g each) were reserved for granulometric analysis by beach following the methods indicated by Negreiros-Fransozo et al. (1991). These replicates were dried in a forced-air oven (60 °C for 72 h) until the dry weight was stabilized, followed by differential sieving into seven granulometric fractions (GR, gravel: ≥ 2 mm; sand (SA): very coarse sand, 2–1 mm; coarse sand, 1–0.5 mm; medium sand, 0.5–0.25 mm;

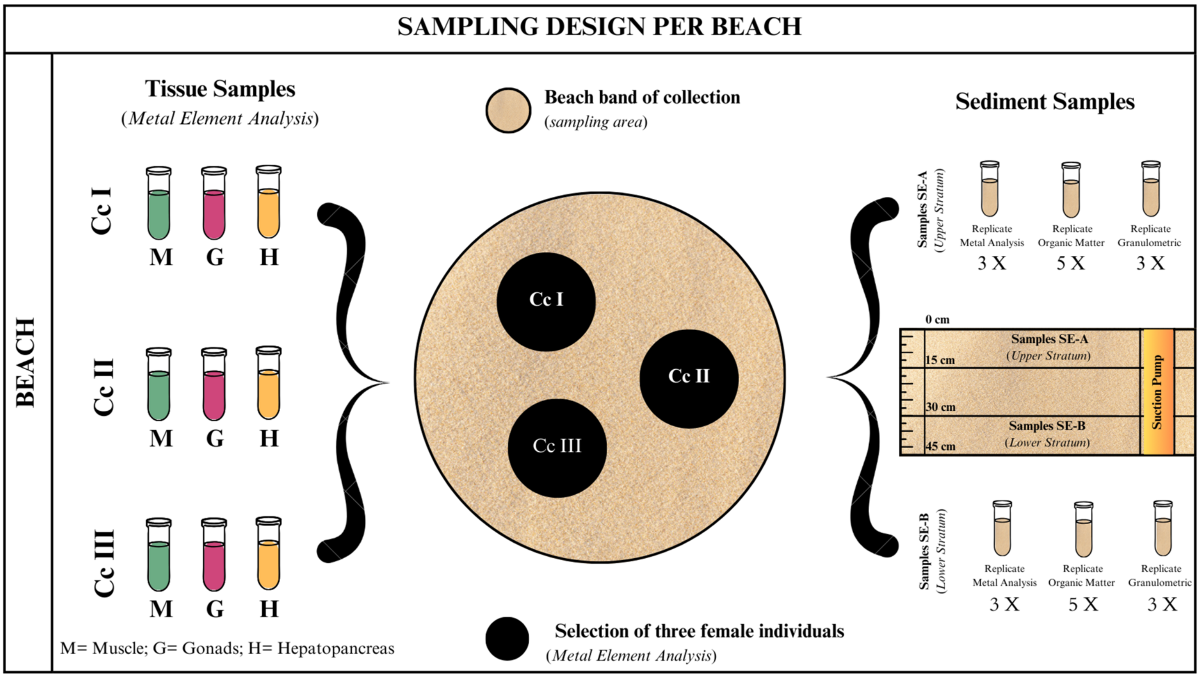


Fig. 2 Sampling design of the study developed in each beach studied in São Paulo state (Brazil), concerning to tissues from *Callichirus corruptus* (Cc) and of sediment stratum (SE-A: upper stratum; and SE-B: lower stratum). Description: the image is a schematic representation of the sampling design. On the left, there are nine test tubes representing three animals, vertically labeled as Cc I, Cc II, and Cc III. The test tubes are color-coded for different tissues: green for muscle, followed by pink for gonads, and yellow for the hepatopancreas. In the center, there is a circle with a sand-like texture containing three smaller circles, each representing one of the animals. On the right, there is a rectangular section of sand, with a 45-cm ruler on its left and a suction pump on its right. Above and below the rectangle are test tubes, symbolizing the sediment replicates from the upper and lower strata, respectively

fine sand, 0.25–0.15 mm; very fine sand, 0.15–0.05 mm; and SI + CL, silt and clay: < 0.05 mm). Each beach's average weight (in grams) was calculated for each granulometric fraction, and the total weight for all fractions was summed to 1000 g. These data were processed using the *Sysgran* program (see Camargo, 2006) for verbal categorization of sediment composition and for the calculation of mean grain size (MGS), expressed by the equation MGS = $(\phi84 - \phi16)/4 + (\phi95 - \phi5)/6.6$ (see Folk & Ward, 1957). In this study, ϕ values were converted to millimeters using the equation MGS (mm) = $1/2\phi$.

For each sample, five replicates (10 g each) of stabilized dry sediment were subjected to a muffle furnace (500 °C for 3 h) to quantify the organic matter (OM) content of the sediment (%) using the ash-free dry weight method.

Processing of crustacean tissue samples

In the laboratory, each shrimp's carapace length (CL), from the postero-orbital margin to the posterior margin of the cephalothorax, was measured with a precision analogic caliper (0.05 mm). After blotting with absorbent paper, the total wet weight was recorded using a precision digital balance (0.01 g).

For metal analysis, three females per beach were separated due to their large size compared to males of this genus (Hernáez et al., 2019). They were dissected with scissors and tweezers to remove the three tissues under study (muscle, hepatopancreas, and gonads). Due to the small size of the first chelipeds in ghost shrimps, the muscle was removed from the abdomen. At the same time, gonads and hepatopancreas were extracted after a median-dorsal longitudinal incision of each specimen. Each tissue was placed in labeled Falcon tubes (15 mL) and frozen until analysis.

Quantitative analysis of metals

Tissue samples (muscular, gonadal, and hepatopancreatic) were immediately frozen after removal. All sediment samples ($n = 6$/beach) and each shrimp tissue sample ($n = 3$/tissue/beach) were lyophilized using a VirTis BenchTop Pro®–Scientific Products® equipment. Subsequently, samples underwent specific digestion and metal quantification procedures. For the analysis of the seven metals (As, Cd, Cr, Cu, Hg, Mn, and Pb), minimum masses were used for raw dried macerated sediment samples (1 g), dried macerated gonads, hepatopancreas (0.5 g each), and dried macerated muscle (2 g). Samples were mineralized after homogenization and weighed, followed by the addition of 6 mL of 65% HNO3 PA (Merck®) in a PTFE® reaction vessel, performing microwave digestion in a PROVECTO® DGT 100 plus, with a previously validated heating program specific to each matrix type. Calibration curves were obtained using certified primary standards (Fluka®, Merck®, and Sigma/Aldrich®) for each chemical element. Certified reference materials were used following NIST standards: SRM 1646a for sediment samples and SRM 1566b for tissue samples. Specific standard curves were defined according to detection and quantification limits using a hydride generator for Hg determination (Table 1). Qualitative/quantitative metal readings in samples were conducted with a GBC-AA 932 atomic absorption spectrophotometer, optimized according to the manufacturer's recommendations for each chemical element. All processes were conducted at the Toxicological Information and Assistance Center (CIATox) laboratory, IB/UNESP Botucatu.

Table 1 Limits of detection (LDs) and limits of quantification by atomic absorption technique (LQs) for seven potentially toxic elements (As, arsenic; Cd, cadmium; Cr, chromium; Cu, copper; Hg, mercury; Mn, manganese; Pb, lead) studied, as well the percentual (%) of recovery in tissues and sediments samples, according the methodology for quantifying metallic concentration (μg/g)

Metals	LD	LQ	% recovery of tissues	% recovery of sediments
As	0.400	4.00	95	97
Cd	0.010	0.20	102	101
Cr	0.050	2.00	96	98
Cu	0.020	1.00	98	99
Hg	0.005	0.05	105	101
Mn	0.020	1.00	99	101
Pb	0.050	0.50	98	101

Statistical analysis

Results were organized in spreadsheets and submitted to *R Studio 2023.12.1 + 402* in the R environment (R Core Team, 2023) for graph construction and statistical analysis. Metal concentrations (μg/g) recorded in dried sediment and dried shrimp tissues were subjected to homogeneity of variances (Levene's test) and normality (Shapiro-Wilk test). After confirming data as homoscedastic and normal ($p > 0.05$), variables were subjected to a parametric test (t test) comparing means of the same variable between the two beaches (STS vs. JUR).

Sediment contamination assessment for each beach per metallic element and its concentration in dried shrimp tissues were determined by comparing each metal concentration with regulatory threshold levels. For sediment, metal concentrations were compared to ISQG (Interim Sediment Quality Guidelines) and PEL (Probable Effect Levels) values provided by the Canadian Environmental Quality Guidelines (CCME, 2002). For shrimp, given that the entire animal is consumed, the sum of metal concentrations in the three analyzed dried tissues was compared to the maximum tolerable limit (MTL) for crustaceans provided by the Brazilian Health Regulatory Agency (ANVISA) (Brazil, 2022).

The hierarchy of metal concentration in dried shrimp tissues was established for each beach by comparing the mean values recorded for gonads, hepatopancreas, and muscle of the species based on ANOVA results and confirmed by Tukey's post hoc test. All statistical analyses were conducted with a minimum significance level of 5%.

Results

Shrimp biometrics

The females of *C. corruptus* at Juréia Beach (JUR) had a carapace length (CL) of 12.0 ± 1.5 mm (mean

± standard deviation), which did not statistically differ from those at Santos Beach (STS), which measured 13.6 ± 1.1 mm (t = 2.37; p = 0.08). This was also observed with the wet weight (WW) of these specimens, which did not differ between beaches: JUR: 4.7 ± 2.6 g; STS: 14.1 ± 4.9 g (t = 2.91; p = 0.06).

Mean grain size (MGS) and organic matter (OM) in sediment samples

The sediment from Santos Beach (STS) was classified as very fine sand (MGS: 0.078 ± 0.001 mm) with an organic matter content of 0.137 ± 0.049%. In contrast, sediment from Juréia (JUR) was classified as fine sand (MGS = 0.129 ± 0.002 mm) and had an organic matter content of 0.032 ± 0.006%. Statistical analysis revealed that the sediment from STS is significantly finer (t = 53.32; $p \leq 0.01$) and contains a higher organic matter content (t = 6.62; $p \leq 0.01$).

Metal concentration in sediment

All potentially toxic elements showed a normal distribution ($W \geq 0.89$; $p \geq 0.33$) and homoscedastic variance ($L \geq 0.13$; $p \geq 0.12$), allowing their concentrations to be evaluated by parametric tests. The concentration of potentially toxic elements did not differ significantly between sediment strata (SE-A = SE-B) both for JUR (Cr, Cu, and Mn: $t \leq 2.51$; $p \geq 0.13$) and STS (Cd, Cr, Cu, Hg, and Mn: $t \leq 1.59$; $p \geq 0.09$). Therefore, these samples could be evaluated without differentiating strata (n = 6/beach).

In STS, 71.4% of the studied potentially toxic elements was recorded (n = 5: Cd, Cr, Cu, Hg, and Mn), while only 42.9% occurred in JUR (n = 3: Cr, Cu, and Mn) (Table 2). The metallic element richness was 1.7 times higher in STS. The concentrations of Cu, Cr, and Mn were also significantly higher in STS than in JUR ($t \leq 7.80$; $p \leq 0.01$), varying from 1.5 to 3.8 times. In JUR, the hierarchical order of metallic element concentration in sediment was Mn > Cr > Cu, similar to that observed for STS, where two other non-essential potentially toxic elements were added: Mn > Cr > Cu > Cd > Hg.

Except for the Hg concentration in STS sediment (0.15 μg/g), categorized as contaminated, the other potentially toxic elements presented concentrations below ISQG and PEL and were considered safe for both beaches.

Table 2 Concentrations (mean ± standard deviation, in μg/g) of each metallic element (Cd, cadmium; Cr, chromium; Cu, copper; Hg, mercury; Mn, manganese) registered in the beach sediment samples (n = 6/beach) of Juréia (JUR) and Santos (STS), in São Paulo state coast (Brazil), obtained in May and April 2017, respectively. Quality parameters of the sediment are represented by ISQG (Interim Sediment Quality Guidelines) and PEL (probable effect levels), according to CCME (Canadian Environmental Quality Guidelines), where Min, minimum; Max, maximum; x, mean; s, standard deviation; t, t test

Metal	Beach	Concentration of metals (μg/g)			t	CCME (2002)	
		Min	*Max*	$x \pm s$		ISQG	PEL
Cd	JUR	-	-	< LDM	-	0.70	4.20
	STS	0.25	0.61	0.45 ± 0.16			
Cr	JUR	1.21	2.74	1.79 ± 0.58a[a]	3.90	52	160
	STS	2.48	4.22	3.13 ± 0.61b			
Cu	JUR	0.26	0.56	0.39 ± 0.11a	3.84	19	108
	STS	0.49	0.67	0.59 ± 0.07b			
Hg	JUR	-	-	< LDM	-	0.1	0.7
	STS	0	0.49	0.15 ± 0.23			
Mn	JUR	9.49	17.31	12.03 ± 3.03a	7.80	-	-
	STS	34.66	61.12	45.61 ± 10.10b			

[a]Mean concentration in the same metal, followed by distinct lowercase letters, differed significantly between the beaches studied ($p \leq 0.05$)

Table 3 Concentrations (mean ± standard deviation, in µg/g) of each metallic element (Cd, cadmium; Cr, chromium; Cu, copper; Mn, manganese) by *C. corruptus* tissues (n = 9/tissue: G, gonads; H, hepatopancreas; and M, muscle) obtained in two studied sandy beaches (JUR, Juréia and STS, Santos), in São Paulo state coast (Brazil), obtained in May and April 2017, respectively

Metal	Local	Concentration of metals (µg/g)				Brazil (2013)
		G	*H*	*M*	*Total*	
Cd	JUR	0.25 ± 0.08 A(a)[a]	0.73 ± 0.16 B(a)	< LDM	0.98 ± 0.11a	0.5
	STS	4.93 ± 0.77B(b)	1.66 ± 0.33 A(b)	1.27 ± 0.77 A	7.86 ± 1.42b	
Cr	JUR	1.62 ± 0.93 A(a)	1.04 ± 0.41 A(a)	1.47 ± 0.35 A(a)	4.12 ± 1.04a	0.5
	STS	7.80 ± 1.87B(b)	2.43 ± 2.21 A(a)	1.72 ± 0.54 A(a)	11.95 ± 2.88b	
Cu	JUR	25.44 ± 9.60 A(a)	108.74 ± 120.20 A(a)	23.13 ± 5.94 A(a)	157.31 ± 130.00a	30.0
	STS	109.66 ± 51.69 A(a)	145.33 ± 233.15 A(a)	32.45 ± 10.08 A(a)	339.69 ± 203.42a	
Mn	JUR	1.07 ± 0.07 A(a)	1.01 ± 0.44 A(a)	3.37 ± 0.74B(a)	5.45 ± 0.65a	–
	STS	11.94 ± 2.99B(b)	2.72 ± 0.73 A(b)	4.73 ± 2.36 A(a)	19.38 ± 4.89b	

[a]Mean concentrations of the same metal, followed by distinct lowercase letters, differed significantly between studied beaches ($p \leq 0.05$) and those of a same metal and beach, followed by distinct uppercase letters, contrasting significatively among the tissues studied ($p \leq 0.02$). Brazil (2013) presents the maximum allowable contamination limit for metals in crustaceans established by the "Agência Nacional de Vigilância Sanitária" (Anvisa)

Concentration of metals in dried shrimp tissues

Four potentially toxic elements (Cd, Cr, Cu, and Mn) were recorded in shrimp tissues (Table 3). Copper was the metal with the highest concentration in all evaluated tissues, ranging from 13.61 to 321.7 µg/g, although its total average concentration in the three tissues did not differ significantly between STS (339.6 ± 203.4 µg/g) and JUR (157.3 ± 130.0 µg/g) (t = 1.30; p = 0.21). This was also the case for each tissue when analyzed separately ($t \leq 2.77$; $p \geq 0.10$). For the other potentially toxic elements (Cd, Cr, and Mn), the total average concentrations in shrimp from STS were three to eight times higher than in JUR ($t \geq 4.42$; $p \leq 0.03$).

There was a differential accumulation of Cd, Cu, Cr, and Mn in the tissues of *C. corruptus* at the studied beaches. In gonads, Cd, Cr, and Mn accumulation differed significantly ($t \geq 5.12$; $p \leq 0.01$). It was up to 10 times higher in shrimp from STS than from JUR. This was also observed in the hepatopancreas, with a significant contrast in the accumulation of Cd and Mn. The means in STS were higher than in JUR ($t \geq 3.45$; $p \leq 0.03$), although there was no significant difference between the means of Cu and Cr between both beaches ($t \leq 1.07$; $p \geq 0.40$). For muscle, there was no significant difference between the beaches for Cr, Cu, and Mn ($t \leq 1.30$; $p \geq 0.25$).

Regarding the maximum tolerable limits (MTL) of metals as established by ANVISA (Brazil, 2022), all shrimp tissue samples (n = 18) showed Cr contamination regardless of the beach, while for Cd, it was 61.1% (JUR: 55.6% > STS: 33.3%) and for Cu, it was 50% (STS: 88.9% > JUR: 44.4%). ANVISA does not present an MTL for Mn in crustaceans, making it impossible to evaluate the contamination percentage of this metal or compare the beaches.

Comparing the tissues of *C. corruptus*, the highest accumulation of Cd, Cr, and Mn occurred in the gonads of shrimp from Santos ($F \geq 3.86$; $p \leq 0.02$), with concentrations 2.5 to 4.6 times higher than those of the other studied tissues. In Juréia, the highest Cd accumulation occurred in the hepatopancreas ($F \geq 4.59$; p = 0.02), surpassing the concentration recorded in the gonads by 3.5 times. There was also significant Mn accumulation in the muscle ($F \geq 5.61$; $p \leq 0.02$), about 3.1 times higher than the concentrations in the other analyzed tissues. Thus, in STS, the hierarchy of Cd, Cr, and Cu accumulation in the tissues was G > H > M, contrasting with JUR, which was the inverse (H > M > G). However, the total average concentration of each metal in tissues showed a similar accumulation hierarchy for shrimp from Juréia (Cu > Mn = Cr > Cd) compared to those from Santos (Cu > Mn > Cr > Cd).

Discussion

The sediments from the studied beaches exhibited a distinct contrast in the concentrations of Cr, Cu, and Mn, which were consistently higher at Santos Beach (STS) than Juréia Beach (JUR). Cadmium (Cd) and mercury (Hg) were detected exclusively at Santos Beach. Notably, mercury levels at Santos Beach fell between the Interim Sediment Quality Guidelines (ISQG) and probable effect levels (PEL), indicating a threshold for the absence of adverse effects on associated biota. This observation underscores Santos as an area with higher environmental impact due to its greater human population density and the historical influence of anthropogenic activities, such as industrial (Cosipa, Cubatão Industrial Complex, VLI see Figure 1) and port complexes, relative to Juréia, which is situated within a less impacted area. The study also confirms the metal accumulation capacity of the ghost shrimp (*C. corruptus*), with variations observed among the analyzed dried tissues, particularly in the hepatopancreas, but also in the gonads and muscles. Human consumption of this crustacean from Santos Beach is not recommended due to elevated concentrations of Cd, Cr, and Cu, which exceed the levels set by the Brazilian Health Regulatory Agency (ANVISA). Cadmium is of significant concern.

Abiotic variables: metal concentration in sediment

The concentrations of the five potentially toxic elements (Cd, Cr, Cu, Hg, and Mn) were higher in sediments from Santos Beach than in those from Juréia Beach. This finding aligns with our hypothesis and is consistent with previous studies conducted in adjacent coastal environments. Notably, Banci et al. (2017) reported that sediment metal concentrations in mangrove areas were up to 2.4 times higher in Cubatão (Santos-São Vicente Estuarine System) compared to Juréia (Ecological Station), particularly for chromium (6.1 vs. 3.0 μg/g) and copper (3.3 vs. 1.4 μg/g). In the present study, average concentrations were lower for these two metals, likely due to differences in particle size between the sediments of these beaches. However, chromium concentrations (3.1 vs. 1.8 μg/g) and copper (0.6 vs. 0.4 μg/g) remained higher at Santos Beach compared to Juréia Beach. The elements Cr and Cu were found in higher concentrations in Santos, which may be related to the presence of the Port of Santos and untreated industrial effluents (Gonçalves et al., 2013; Angeli et al., 2021).

Surface estuarine sediments, especially from port channels, can exhibit even higher metal concentrations. For instance, Bordon et al. (2011) reported metal levels in the Santos Port Channel as follows: Cr (20.0 μg/g), Hg (0.3 μg/g), and Mn (272.5 μg/g), which are up to 33 times higher than those found in the sandy sediments of Santos Beach (3.13, 0.15, and 45.61 μg/g, respectively). The concentrations in dredging sediments from the Santos Port Channel are comparable to those in the region's mangroves (Buruaem et al., 2013; Cesar et al., 2014; Kim et al., 2016; Perina et al., 2018), regarding Mn (348.50 μg/g), Cd (0.1 to 3.1 μg/g), Cr (18.0 to 32.20 μg/g), Hg (0.3 to 0.5 μg/g), and Cu (12.6 to 15.7 μg/g). These values reflect similar magnitudes to those observed in the sandy sediments of the studied beaches. The highest concentrations of metals in surface estuarine sediments can be attributed to the average grain size and organic matter content (Perina et al., 2018), as sediments with smaller average grain sizes (MGS) and higher percentages of organic matter (OM) tend to exhibit higher metal concentrations (Uchimiya et al., 2010), as explained in detail in the paragraph below.

In these studies, metal concentrations in sediments are associated with particle size and organic matter content, with higher concentrations in finer and more organic sediments (Martinčić, et al., 1990). Martinčić, et al. (1990) and Uchimiya et al. (2010) confirmed that Cd, Cu, Pb, and Zn concentrations in dredging sediments showed a significant negative association with mean grain size (MGS) and organic matter content (OM) ($n = 19$; $r \geq -0.90$; $p > 0.01$). This is attributed to the high mobility, deposition, and complexation of metals in mangrove sediments, which are three to four times more organic than continental sediments (Jennerjahn and Ittekkot, 1997). Thus, OM and MGS are key factors influencing metal redistribution in sediments (Rahman et al., 2024).

The variation in metal concentrations across studies is linked to sediment particle size and organic matter content. Mangrove sediments, with higher organic matter content (6–15%) and smaller mean grain size (MGS < 0.063 mm), contain a significant percentage of finer-grained sediment (silt and clay, 38–51%), according to review of articles (Jennerjahn and Ittekkot, 1997; Sanders et al., 2012; Gomes et al., 2013; Tue et al., 2018; Allais et al., 2024). In dredging sediment studies, metals are associated with finer sediment fractions, particularly silt and clay (MGS < 0.063 mm), with percentages ranging from 80 to 95% and OM% between 8 and 19%, according to review articles (Kronvang and Cristiansen, 1986; Oyarzún et al., 1987; Holland and Elmore, 2008; Torres et al., 2009; Buruaem et al., 2013; Hamouche and Zentar, 2020). For the sediments analyzed in the study, sand was the predominant granulometric fraction at both beaches, differing in classification as very fine sand (MGS: 0.078 ± 0.001 mm) in Santos and fine sand (MGS: 0.128 ± 0.002 mm) in Juréia.

The organic matter (OM) content in the sediments of STS (0.137 ± 0.049 %) and JUR (0.032 ± 0.006 %) beaches also influences the concentration of potentially toxic elements (Sauve et al., 1998). Santos Beach is categorized as a low-energy dissipative beach due to its embayment and lower hydrodynamic activity, which allows for more significant organic matter deposition (Hernáez et al., 2019), which promotes metal complexation. In contrast, Juréia Beach has high-energy dissipative morphodynamics (Souza, 2012), where stronger longshore drift currents reduce sedimentation and organic matter incorporation, leading to lower metal retention.

At Juréia sediment beach, the hierarchy of average concentration for essential potentially toxic elements was Mn > Cr > Cu, whereas Santos Beach exhibited Mn > Cr > Cu > Hg > Cd. This hierarchy is consistent with previous studies in the same region (e.g., Bordon et al., 2011: Mn > Cu > Cr > Hg > Cd; Cesar et al., 2014: Mn > Cr > Cu; Perina et al., 2018: Cr > Cu > Hg > Cd), although there were some inversions, especially for Hg and Cd at lower concentrations.

Contamination of coastal environments by potentially toxic elements is related to historical occupation and human population density, particularly in port regions and industrial complexes, such as in the municipality of Santos (Torres et al., 2009; Pinheiro et al., 2017). The Port of Santos (Figure 1), with industries like (VLI), plays a significant role in generating concentrations of Cu and Cr, which are highly adsorbed by sediments due to fuels (Costa, 2004; Angeli et al., 2021). Kim et al. (2016) noted that these metals (Cu, Cr, and Pb) frequently occur at high concentrations in untreated or poorly treated industrial effluents, likely due to the high number of petrochemical industries (Cubatão Industrial Complex) and steel industry (Cosipa) (*see* Figure 1) in the Santos-São Vicente Estuarine System (CETESB, 2021).

Mercury in Santos Beach sediment is particularly concerning due to its high frequency in the analyzed samples (66%) and concentrations between ISQG and PEL values (0.1 and 0.7 μg/g, respectively), reflecting its high toxicity. Mercury contamination in Santos is associated with port activities (Hortellani et al., 2008) and industrial sources, such as petrochemicals, fertilizers, and landfills (Perina et al., 2018).

A global comparison of metallic element concentrations in sandy beaches reveals that the sediments in the present study showed lower values for Cr and Cu compared to other locations (Table 4). However, the average Cd concentration in Santos Beach (0.45 μg/g) is comparable to that of other urban beaches, ranging

Table 4 Concentration (mean, in μg/g) of metals (Cd, cadmium; Cr, chromium; Cu, copper; Hg, mercury; Mn, manganese) in sandy beach sediments around the world. Higher concentration values of each metal are represented in bold face

Beach	Country	Concentration of metals (μg/g)					Type of metal digestion	Authors (year)
		Cd	Cr	Cu	Hg	Mn		
Acapulco	Mexico	-	17.9	42.8	-	26.6	HCl	Jonathan et al. (2011)
Aqba	Jordan	7.8	92.1	14.0	-	321.5	HNO_3, $HC1O_4$ and HF	Abu-Hilal et al. (1988)
Chennai	India	0.3	14.1	4.0	-	46.8	HCl and HNO_3	Santhiya et al. (2011)
Durnford	South Africa	0.4	11.4	5.0	-	107.1	HNO_3 and HCl	Vetrimurugan et al. (2016)
Espinho	Portugal	-	44.0	371.4	-	476.1	HCl, HNO_3 and HF	Vidinha et al. (2006)
Kerela	India	3.6	80.9	76.7	-	-	HNO_3	Suresh et al. (2015)
Miri City	Malaysia	-	126.2	42.9	-	26.6	HNO_3 and HCl	Nagarajan et al. (2013)
Rio del Plata	Uruguay	0.3	15.1	-	-	-	HCl	Castiglioni et al. (2018)
Juréia	Brazil	-	1.8	0.4	-	12.0	HNO_3	Present study
Santos	Brazil	0.5	3.1	0.6	0.2	45.6	HNO_3	Present study

from 0.30 µg/g (Chennai, India—Santhiya et al., 2011; Montevideo Bay—Castiglioni et al., 2018) to 0.40 µg/g (Richards Bay, South Africa—Vetrimurugan et al., 2016). Conversely, Kerala Beach in India (Suresh et al., 2015) exhibited a Cd concentration of 3.60 µg/g, approximately seven times higher than that at Santos Beach. The average Mn concentration at Santos Beach (45.61 µg/g) was like that of Chennai Beach, India (46.80 µg/g—Santhiya et al., 2011). However, concentrations at beaches under intense port influence and with high levels of untreated domestic and industrial waste can be seven to 10 times higher (Abu-Hilal et al., 1988; Vidinha et al., 2006).

Biotic variables: concentration of potentially toxic elements in *C. corruptus*

At Santos Beach, the highest concentrations of four potentially toxic elements (Cd, Cr, Cu, and Mn) were recorded in the tissues of the shrimp *C. corruptus*. These concentrations were up to eight times higher than those at Juréia Beach, particularly for Cd, Cr, and Cu, which exceeded the maximum tolerable limit (MTL) established by ANVISA (Brazil, 2022) at both beaches. Copper is an essential metal for decapod crustaceans, primarily associated with hemocyanin, a hemolymph protein responsible for oxygen transport (Rainbow, 2002; Terwilliger, 2015). In addition to its role in respiration, hemocyanin helps maintain relatively stable copper concentrations in crustaceans, facilitating the transport and accumulation of this metal in other tissues (Rtal and Truchot, 1996). The higher Cu concentrations in shrimps from Santos Beach (339.69 µg/g) compared to Juréia (157.31 µg/g) clearly illustrate this phenomenon. Excess copper was immobilized in the hepatopancreas of *C. corruptus*, regardless of the beach (JUR: 108.74 µg/g; STS: 145.33 µg/g). Such high copper concentrations in the hepatopancreas have been previously reported for other decapod crustaceans, including the lobster *Homarus gammarus* (Clark, 2001).

For the non-essential metals that exceeded the MTL (Cd and Cr), *C. corruptus* specimens from Santos exhibited concentrations up to eight times higher than those from Juréia (Cd: 7.86 vs. 0.98 µg/g; Cr: 11.95 vs. 4.12 µg/g). Cadmium concentrations were highest in the gonads of shrimps from Santos (4.93 µg/g), followed by the hepatopancreas and muscle (1.27 µg/g), while in Juréia, cadmium levels were much lower and not detectable in the muscle, accumulating only in the hepatopancreas (0.73 µg/g) and gonads (0.25 µg/g). According to Vig (2003) and Cabrini et al. (2018), Cd is highly toxic to biota and ranks third in hierarchical toxicity among eight metals (Luoma and Rainbow, 2008). This metal is generally found at higher concentrations in the base of the food chain, in producers and primary consumers (Bargagli, 1998; Sun et al., 2020) and is depurated in brachyuran crustaceans during molting (Reichmuth et al., 2010).

Chromium was found at high concentrations at both beaches (JUR: 4.12 µg/g; STS: 11.95 µg/g). In Santos, the highest concentration was observed in the gonads, whereas in Juréia, it bioaccumulated more in the hepatopancreas of shrimps. Chromium has no biological function and has been reported to reduce survival and fecundity and even inhibit growth (Ochiai, 1995; Cabrini et al., 2018; Honig et al., 1980).

When comparing the same tissues in shrimps from the two studied beaches, the concentrations of Cr, Cu, and Mn in the hepatopancreas and muscle did not exhibit significant differences between individuals from JUR and STS. This finding suggests that the hepatopancreas effectively fulfils its biological detoxification role in *C. corruptus*, as supported by studies such as Ahearn et al. (2004), Zhu et al. (2018), and Rodrigues et al. (2022). The absence of significant differences in metal concentrations in the muscle between individuals from Santos and Juréia can be attributed to the biological functions of these elements, particularly manganese. Mn is an essential metal that participates in key metabolic pathways such as glycolysis and the Krebs cycle (Napierska and Skorkowski, 2001), which explains the higher concentrations observed in muscle tissues with high energy demands (Thibodeaux et al., 2009). Copper, on the other hand, is a critical component of hemocyanin, the oxygen-transport pigment in the hemolymph, which plays a vital role in supporting the metabolism of these animals (Terwilliger, 2015).

The hierarchy of metal accumulation in *C. corruptus* tissues followed H > M > G for the four elements (Cd, Cr, Cu, and Mn) at Juréia Beach. At Santos Beach, the hierarchy was G > H > M for three metals (Cd, Cr, and Mn). Pinheiro et al. (2012) reported a similar sequence (H > M) for tissues of the crab *Ucides cordatus*, endemic to mangroves, though they did not analyze metal concentrations in gonads. The highest concentration of potentially toxic elements in crustaceans typically occurs in the hepatopancreas (Ahearn et al., 2004), which serves as the primary detoxification organ (Metian et al., 2010; Zhu et al., 2018; Rodrigues et al., 2022). This observation was confirmed in the present study based on the proportions and hierarchy of contamination among the tissues of *C. corruptus*, especially in Juréia. At Santos, metal contamination surpassed the detoxification capacity of the hepatopancreas, leading to greater bioconcentration in the gonads and even in the muscle of the shrimps.

Luoma and Rainbow (2008) and Liao et al. (2022) attribute this phenomenon to the biochemical composition of the hepatopancreas, which includes (1) lipids, particularly during the fattening phase of decapod crustaceans when the hepatopancreas enlarges (Wu et al., 2008; Lobato et al., 2013); (2) metallothioneins, sulfur-rich proteins responsible for sequestering potentially toxic elements, regulating metal homeostasis, and redistributing these elements to other tissues (Pourang et al., 2004; Liao et al., 2022; Baudrimont et al., 2003); and (3) glutathione-S-transferase, isoenzymes with detoxifying capacity that convert xenobiotic compounds into less toxic forms (Habig and Jakoby, 1981; Lobato et al., 2013). The higher metal accumulation in the ovaries of female *C. corruptus* from Santos can be attributed to increased lipid content due to vitellogenesis, which characterizes the ovaries of decapod crustaceans (Jeckel et al., 1996). The hepatopancreas's detoxification capacity, with redistribution to other tissues, has been documented for other decapod crustacean species (Metian et al., 2010; Zhu et al., 2018; Rodrigues et al., 2022) and may potentially cause reproductive damage (as suggested for *Ucides cordatus* by Duarte et al., 2016, 2017).

The high metallic concentrations found in ghost shrimps are likely due to their contact with external and interstitial water in their burrows, branchial respiration, and feeding (Morrison et al., 2011). This was particularly evident for *C. corruptus* at Santos Beach, where Cd and Cr concentrations (7.9 and 11.9 µg/g, respectively) were up to five times higher than those recorded for *Callichirus laurae* (1.7 and 3.2 µg/g, respectively) in Aqaba, Jordan (Abu-Hilal et al., 1988), due to the port activity in that location. Conversely, bioconcentrations of Cu and Mn were similar between these species, as they are essential metals for crustacean metabolism (Baden and Eriksson, 2006), especially in antioxidant defense (Frías-Espericueta et al., 2022).

The maintenance of the bioconcentration hierarchy of potentially toxic elements by *C. corruptus* (Cu > Mn > Cr > Cd) at both beaches shows some similarity with results obtained by Cabrini et al. (2018) for two species of mole crabs (Hippidae) on the beaches of the State of Rio de Janeiro (RJ) (*see* Figure 1). Like ghost shrimps, Hippidae are filter-feeding decapod crustaceans associated with similar abiotic matrices (water and sediment). The metal hierarchies in their tissues are Cu > Cr > Cd and Cu > Cd > Cr, respectively. The high bioconcentration of copper (an essential metal) and low concentrations of cadmium and chromium (non-essential metals) observed in this study are consistent with findings from these studies. Similarly, the bioconcentration hierarchy for *Callichirus laurae* studied by Abu-Hilal et al. (1988) on Aqaba Beach (Jordan) was Cu > Mn > Cr > Cd.

Conclusion

The concentration of potentially toxic elements in the sediment of Santos Beach is notably higher compared to Juréia Beach. This is particularly concerning due to mercury levels falling between the ISQG and TEL parameters, suggesting potential risks. The elevated levels of pollutants in Santos Beach are likely associated with the high population density in the region, which contributes to pollution from various sources, including industrial effluents from the industrial complex and polycyclic aromatic hydrocarbons from ships at the Port of Santos, impacting the Santos-São Vicente Estuarine System.

The bioconcentration of potentially toxic elements in specimens of *C. corruptus* from Santos is also significantly higher than in those from Juréia. Notably, the concentrations of three metals (Cd, Cr, and Mn) exceed the maximum tolerable limits established by the Brazilian Health Regulatory Agency (Brazil, 2022). The absence of contrast in the concentrations of Cr, Cu, and Mn in the muscle tissue between individuals from both beaches suggests that these elements are essential for the physiology of these shrimps. The similar concentrations observed in individuals from both less-impacted and more-impacted environments likely reflect the indispensable metabolic roles of these elements. In Juréia, the metal concentration in ghost shrimps follows a hierarchy (H > M > G) like that reported for other decapod crustaceans. The hepatopancreas, known for its role in metal detoxification, appears to be operating beyond its capacity in Santos. Consequently, metals are being transported to other tissues, with significant accumulation observed in the gonads (ovaries) of females due to their high lipid content. This pattern is comparable to what occurs in the hepatopancreas and may have detrimental effects on the species in the study area.

These findings provide new insights into the concentration of potentially toxic elements in *C. corruptus* and highlight the importance of sandy beach conservation, as exemplified by the Juréia-Itatins Ecological Station.

Acknowledgements The authors thank to Michael T. Angeloni and Marcio C. A. João for helping during the field sampling.

Author contribution Juliano José-Silva: Writing – original draft, Visualization, Investigation, Formal analysis. Tailisi H. Trevizani: Writing – review & editing, Visualization. Alaor A. Almeida: Writing – review & editing, Data curation, Methodology, Conceptualization. Marcelo A. A. Pinheiro: Writing – review & editing, Data curation, Methodology, Conceptualization, Supervision, Funding acquisition, Formal analysis.

Funding "Fundação de Amparo à Pesquisa do Estado de São Paulo – FAPESP" e Fundação Grupo Boticário (FAPESP/FGB no. 2014/50438 - 5) provided indirect financial support to Marcelo A. A. Pinheiro and "Centro de Informação e Assistência Toxicológica – CIATOX" of IB/UNESP Botucatu provided metal analysis and use of the atomic absorption spectrophotometry. "Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq" granted Research Productivity Fellowship to Marcelo A. A. Pinheiro (CNPq no. 303286/2016 - 4).

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

Abu-Hilal, A., Badran, M., & de Vaugelas, J. (1988). Distribution of trace elements in *Callichirus laurae* burrows and nearby sediments in the gulf of Aqaba, Jordan (Red Sea). *Marine Environmental Research, 25*(4), 233–248. https://doi.org/10.1016/0141-1136(88)90014-1

Ahearn, G. A., Mandal, P. K., & Mandal, A. (2004). Mechanisms of heavy-metal sequestration and detoxification in crustaceans: a review. *Journal of Comparative Physiology. B, Biochemical, Systemic, and Environmental Physiology*, *174*(6), 439–452. https://doi.org/10.1007/s00360-004-0438-0

Allais, L., Thibodeau, B., Khan, N. S., Crowe, S. A., Cannicci, S., & Not, C. (2024). Salinity, mineralogy, porosity, and hydrodynamics as drivers of carbon burial in urban mangroves from a megacity. *The Science of the Total Environment, 912*(168955), 168955. https://doi.org/10.1016/j.scitotenv.2023.168955

Angeli, J. L. F., Sartoretto, J. R., Kim, B. S. M., de Lima Ferreira, P. A., de Mahiques, M. M., & Figueira, R. C. L. (2021). Trace element fluxes during the "Anthropocene" in a large South American industrial and port area (Santos and São Vicente estuarine system, SE, Brazil). *Environmental Monitoring and Assessment, 193*(9), 594. https://doi.org/10.1007/s10661-021-09378-3

Baden, S., & Eriksson, S. (2006). Role, routes and effects of manganese in crustaceans. In *Oceanography and Marine Biology* (pp. 61–84). CRC Press. https://doi.org/10.1201/9781420006391.ch2

Bargagli, R. (1998). Cadmium in marine organisms from the Tyrrheniansea: No evidence of pollution or biomagnification. *Oebalia, 19*, 13–25.

Bartoli, G., Papa, S., Sagnella, E., & Fioretto, A. (2012). Heavy metal content in sediments along the Calore river: Relationships with physical-chemical characteristics. *Journal of Environmental Management, 95*(Suppl), S9-14. https://doi.org/10.1016/j.jenvman.2011.02.013

Batley, G. E., & Simpson, S. L. (2016). Sediment sampling, sample preparation and general analysis. *Sediment quality assessment*, *2*(15),15–46.

Baudrimont, M., Andres, S., Durrieu, G., & Boudou, A. (2003). The key role of metallothioneins in the bivalve *Corbicula fluminea* during the depuration phase, after in situ exposure to Cd and Zn. *Aquatic Toxicology (Amsterdam, Netherlands), 63*(2), 89–102. https://doi.org/10.1016/s0166-445x(02)00134-0

Belan, T. A. (2004). Marine environmental quality assessment using polychaete taxocene characteristics in Vancouver Harbour. *Marine Environmental Research, 57*(1–2), 89–101. https://doi.org/10.1016/S0141-1136(03)00062-X

Birkeland, C. (1989). The Faustian traits of the crown-of-thorns starfish. *American scientist, 77*(2), 63–154.

Bordon, I. C. A. C., Sarkis, J. E. S., Gobbato, G. M., Hortellani, M. A., & Peixoto, C. M. (2011). Metal concentration in sediments from the Santos estuarine system: A recent assessment. *Journal of the Brazilian Chemical Society, 22*(10), 1858–1865. https://doi.org/10.1590/s0103-50532011001000005

Borzone, C. A., & Souza, J. R. B. (1996). A extração de corrupto, *Callichirus major* (Decapoda: Callianassidae), para uso como isca em praias do litoral do Paraná: Características da pesca. *Revista Nerítica, 10*(1–2), 69–79.

Brazil, (2022). Estabelece os limites máximos tolerados (LMT) de contaminantes em alimentos. Instrução Normativa Anvisa nº 160, de 1° de julho de 2022. https://antigo.

Anvisa.gov.br/documents/10181/2718376/IN_160_2022_.pdf. Acessed June 20, 2023.

Buruaem, L. M., de Castro, Í. B., Hortellani, M. A., Taniguchi, S., Fillmann, G., Sasaki, S. T., Varella Petti, M. A., de Sarkis, J. E. S., Bícego, M. C., Maranho, L. A., Davanso, M. B., Nonato, E. F., Cesar, A., Costa-Lotufo, L. V., & Abessa, D. M. de S. (2013). Integrated quality assessment of sediments from harbour areas in Santos-São Vicente Estuarine system, Southern Brazil. *Estuarine, Coastal and Shelf Science, 130*, 179–189. https://doi.org/10.1016/j.ecss.2013.06.006

Buzzi, N. S., Menéndez, M. C., Truchet, D. M., Delgado, A. L., & Severini, M. D. F. (2022). An overview on metal pollution on touristic sandy beaches: Is the COVID-19 pandemic an opportunity to improve coastal management? *Marine Pollution Bulletin, 174*(113275), 113275. https://doi.org/10.1016/j.marpolbul.2021.113275

Cabrini, T. M. B., Barboza, C. A. M., Skinner, V. B., Hauser-Davis, R. A., Rocha, R. C., Saint'Pierre, T. D., Valentin, J. L., & Cardoso, R. S. (2017). Heavy metal contamination in sandy beach macrofauna communities from the Rio de Janeiro coast, Southeastern Brazil. *Environmental Pollution (Barking, Essex: 1987)*, *221*, 116–129. https://doi.org/10.1016/j.envpol.2016.11.053

Cabrini, T. M. B., Barboza, C. A. M., Skinner, V. B., Hauser-Davis, R. A., Rocha, R. C., Saint'Pierre, T. D., Valentin, J. L., & Cardoso, R. S. (2018). Investigating heavy metal bioaccumulation by macrofauna species from different feeding guilds from sandy beaches in Rio de Janeiro, Brazil. *Ecotoxicology and Environmental Safety, 162*, 655–662. https://doi.org/10.1016/j.ecoenv.2018.06.077

Cajaraville, M. P., Bebianno, M. J., Blasco, J., Porte, C., Sarasquete, C., & Viarengo, A. (2000). The use of biomarkers to assess the impact of pollution in coastal environments of the Iberian Peninsula: A practical approach. *The Science of the Total Environment, 247*(2–3), 295–311. https://doi.org/10.1016/s0048-9697(99)00499-4

Camargo, M. G. (2006). SysGran: Um sistema de código aberto para análises granulométricas do sedimento. *Revista Brasileira de Geociências, 36*(2), 371–378.

Cardoso, R. S., Barboza, C. A., Skinner, V. B., & Cabrini, T. M. (2016). Crustaceans as ecological indicators of metropolitan sandy beaches health. *Ecological Indicators, 62*, 154–162.

Castiglioni, D., Rezende, C. E., Muniz, P., Muir, A. I., & García-Alonso, J. (2018). Trace metals bioavailability approach in intertidal estuarine sediments and bioaccumulation in associated nereidid polychaetes. *Bulletin of Environmental Contamination and Toxicology, 100*(4), 472–476. https://doi.org/10.1007/s00128-018-2301-0

CCME – Canadian Canadian Council of Ministers of the Environment. (2002). Canadian sediment quality guidelines for the protection of aquatic life: summary tables. Updated. In: Canadian environmental quality guidelines, 1999, Canadian Council of Ministers of the Environment, Winnipeg. http://www.popstoolkit.com/Tools/SitePrioritization/Files/Guidelines/SedQ%20aquatic%20life.pdf. Accessed June 20, 2023.

Cesar, A., Choueri, R. B., Gusso-Choueri, P. K., & Pereira, C. D. S. (2012). Integrative approach for the environmental quality assessment of aquatic ecosystems: A critical review. *Global Journal of Enviromental. Science Technologic, 2*, 2–9.

Cesar, A., Lia, L. R. B., Pereira, C. D. S., Santos, A. R., Cortez, F. S., Choueri, R. B., De Orte, M. R., & Rachid, B. R. F. (2014). Environmental assessment of dredged sediment in the major Latin American seaport (Santos, São Paulo-Brazil): An integrated approach. *The Science of the Total Environment, 497–498*, 679–687. https://doi.org/10.1016/j.scitotenv.2014.08.037

Cetesb – Companhia Ambiental do Estado de São Paulo. (2021). Qualidade das águas costeiras do estado de São Paulo – São Paulo: Relatório Anual de Águas Costeiras de 2020, 107-108p. https://cetesb.sp.gov.br/aguas-costeiras/wpcontent/uploads/sites/2/2021/07/Relatorio-de-Qualidade-da-Aguas-Costeiras-no-Estado-de-Sao-Paulo-2020.pdf. Accessed 12 Jul 2023.

Clark, R. B. (2001). *Marine polution* (p. 237). Oxford University Press.

Constantino, W. D., Ferreira, K. A., Zalmon, I. R., & Soares-Gomes, A. (2024). Short-term changes in the spatial distribution of the ghost shrimp *Callichirus corruptus* (Decapoda: Axiidea, Callichiridae) from southwestern Atlantic. *Marine Biology, 171*(1), 37.

Corte, G. N., Esmaeili, Y. S., Maria, T. F., Costa, L., Mattos, G., Checon, H. H., & Barboza, C. A. D. M. (2023). The science we need for the beaches we want: frontiers of the flourishing Brazilian ecological sandy beach research. *Frontiers in Marine Science*, *10*. https://doi.org/10.3389/fmars.2023.1200979

Costa, L. L., Constantino, W. D., de Aquino Ferreira, K., Zalmon, I. R., & Soares-Gomes, A. (2022). Sandy beach ecology in the Anthropocene: Ghost shrimp (Crustacea: Callianassidae) as a study model. *Estuarine, Coastal and Shelf Science, 275*(107999), 107999. https://doi.org/10.1016/j.ecss.2022.107999

Costa, L. L., Soares-Gomes, A., & Zalmon, I. R. (2021). Burrow occupation rates and spatial distribution within habitat of the ghost crab *Ocypode quadrata* (Fabricius, 1787): Implications for impact assessments. *Regional Studies in Marine Science, 44*(101699), 101699. https://doi.org/10.1016/j.rsma.2021.101699

Costa, M. F. (2004). Oceanografia: um cenário tropical. Recife: *Editora Bagaço*, *1*, 761.

da Banci, K. R. S., Mori, G. M., Oliveira, M. A. de, Paganelli, F. L., Pereira, M. R., & Pinheiro, M. A. A. (2017). Can environmental pollution by metals change genetic diversity? *Ucides cordatus* (Linnaeus, 1763) as a study case in Southeastern Brazilian mangroves. *Marine Pollution Bulletin, 116*(1–2), 440–447 . https://doi.org/10.1016/j.marpolbul.2017.01.039

Defeo, O., McLachlan, A., Schoeman, D. S., Schlacher, T. A., Dugan, J., Jones, A., Lastra, M., & Scapini, F. (2009). Threats to sandy beach ecosystems: A review. *Estuarine, Coastal and Shelf Science, 81*(1), 1–12. https://doi.org/10.1016/j.ecss.2008.09.022

Defeo, O. M., McLachlan, A., Armitage, D., Elliott, M., & Pittman, J. (2021). Sandy beach social ecological systems at risk: Regime shifts, collapses and governance challenges. *Frontiers in Marine Science, 19*(10), 564–573.

de Duarte, L. F. A., Souza, C. A., Nobre, C. R., Pereira, C. D. S., & Pinheiro, M. A. A. (2016). Multi-level biological responses in *Ucides cordatus* (Linnaeus, 1763) (Brachyura, Ucididae) as indicators of conservation status in mangrove areas from the western Atlantic. *Ecotoxicology and Environmental Safety, 133*, 176–187. https://doi.org/10.1016/j.ecoenv.2016.07.018

Duarte, L. F. A, Blasco, J., Catharino, M. G. M., Moreira, E. G., Trombini, C., Nobre, C. R., & Pereira, C. D. S. (2020). Lead toxicity on a sentinel species subpopulation inhabiting mangroves with different status conservation. *Chemosphere, 251*, 126394. https://doi.org/10.1016/j.chemosphere.2020.126394

Duarte, L. F. A., de Souza, C. A., Pereira, C. D. S., & Pinheiro, M. A. A. (2017). Metal toxicity assessment by sentinel species of mangroves: In situ case study integrating chemical and biomarkers analyses. *Ecotoxicology and Environmental Safety, 145*, 367–376. https://doi.org/10.1016/j.ecoenv.2017.07.051

Eisler, R. (2009). *Compendium of Trace Metals and Marine Biota: Volume 1: Plants and Invertebrates*. Elsevier Science & Technology, *1*, 399–477.

Folk, R. L., & Ward, W. C. (1957). Brazos River bar: A study in the significance of grain size parameters. *Journal of Sedimentary Petrology, 27*, 3–26.

Frías-Espericueta, M. G., Bautista-Covarrubias, J. C., Osuna-Martínez, C. C., Delgado-Alvarez, C., Bojórquez, C., Aguilar-Juárez, M., Roos-Muñoz, S., Osuna-López, I., & Páez-Osuna, F. (2022). Metals and oxidative stress in aquatic decapod crustaceans: A review with special reference to shrimp and crabs. *Aquatic Toxicology (Amsterdam, Netherlands), 242*(106024), 106024. https://doi.org/10.1016/j.aquatox.2021.106024

Galvão-Filho, J. B. (1987). Controle da poluição ambiental: Cubatão, filosofia e conceito. *Revista Ambiente, 1*(2), 70–73.

García-Alonso, J., Greenway, G. M., Munshi, A., Gómez, J. C., Mazik, K., Knight, A. W., Hardege, J. D., & Elliott, M. (2011). Biological responses to contaminants in estuaries: Disentangling complex relationships. *Marine Environmental Research, 71*(4), 295–30.

Gaur, V. K., Gupta, S. K., Pandey, S. D., Gopal, K., & Misra, V. (2005). Distribution of heavy metals in sediment and water of river Gomti. *Environmental Monitoring and Assessment, 102*(1–3), 419–433. https://doi.org/10.1007/s10661-005-6395-6

Gomes, J. D., Abrunhosa, F. A., Simith, D. J. de B., & Asp, N. E. (2013). Mangrove sedimentary characteristics and implications for crab *Ucides cordatus* (Crustacea, Decapoda, Ucididae) distribution in an estuarine area of the Amazonian region. *Acta Amazonica, 43*(4), 481–488. https://doi.org/10.1590/s0044-59672013000400010

Gonçalves, C., Figueira, R. C. L., Sartoretto, J. R., Salaroli, A. B., Ribeiro, A. P., Ferreira, P. A. L., & Mahiques, M. M. (2013). Reconstruction of historical trends in potentially toxic elements from sediment cores collected in Bertioga Channel, southeastern Brazil. *Brazilian Journal of Oceanography, 61*(2), 149–160.

Goulart, M., & Callisto, M. (2003). Bioindicadores de Qualidade de Água como Ferramenta em Estudos de Impacto Ambiental. *Rev. FAPAM, 2*(1), 156–164.

Habig, W. H., & Jakoby, W. B. (1981). Assays for differentiation of glutathione S-transferases. *Methods in Enzymology, 77*, 398–405. https://doi.org/10.1016/s0076-6879(81)77053-8

Hamouche, F., & Zentar, R. (2020). Effects of organic matter on physical properties of dredged marine sediments. *Waste and Biomass Valorization, 11*(1), 389–401. https://doi.org/10.1007/s12649-018-0387-6

Harris, R. R., & Santos, M. C. F. (2000). Heavy metal contamination and physiological variability in the Brazilian mangrove crabs *Ucides cordatus* and *Callinectes danae* (Crustacea: Decapoda). *Marine Biology, 137*(4), 691–703. https://doi.org/10.1007/s002270000382

Hernáez, P., Hereman, M. J., Pimenta, C. E. R., Rio, J. P. P., João, M. C. A., & Pinheiro, M. A. A. (2019). La efectividad de una ley de protección al servicio de la conservación de un recurso marino: El ejemplo del camarón fantasma *Callichirus major* (Decapoda, Callianassidae) de la costa de Brasil. *Iheringia. Serie Zoologia, 109*(0). https://doi.org/10.1590/1678-4766e2019001

Hernaéz, P., Miranda, M. S., Rio, J. P. P., & Pinheiro, M. A. A. (2022). A new species of the ghost shrimp genus *Callichirus* Stimpson, 1866 (Decapoda: Axiidea: Callichiridae) from the southwestern Atlantic, long confounded with *C. major* (Say, 1818), with neotype designation and an illustrated key to the western Atlantic species. *Journal.of Naural. History, 56*, 533–563.

Holland, K. T., & Elmore, P. A. (2008). A review of heterogeneous sediments in coastal environments. *Earth-Science Reviews, 89*(3–4), 116–134. https://doi.org/10.1016/j.earscirev.2008.03.003

Honig, R. A., McGinniss, M. J., Buikema, A. L., Jr., & Cairns, J., Jr. (1980). Toxicity tests of aquatic pollutants using *Chilomonas paramecium* Ehrenberg (Flagellata) populations. *Bulletin of Environmental Contamination and Toxicology, 25*(2), 169–175. https://doi.org/10.1007/bf01985506

Hortellani, M. A., Sarkis, J. E., Abessa, D., & Sousa, E. C. (2008). Avaliação da contaminação por elementos metálicos em sedimentos do Estuário Santos-São Vicente. *Química Nova, 31*(1), 10–19.

Hyndes, G. A., Berdan, E. L., Duarte, C., Dugan, J. E., Emery, K. A., Hamback, P. A., Henderson, C. J., Hubbard, D. M., Lastra, M., Mateo, M. A., Olds, A., & Schlacher, T. A. (2022). The role of inputs of marine wrack and carrionin sandy-beach ecosystems: A global review. *Biological Reviews, 97*, 2127–2161.

Jeckel, W. H., Roth, R. R., & Ricci, L. (1996). Patterns of trace-metal distribution in tissues of *Pleoticus muelleri* (Crustacea: Decapoda: Solenoceridae). *Marine Biology, 125*(2), 297–306. https://doi.org/10.1007/bf00346310

Jennerjahn, T., & Ittekkot, V. (1997). Organic matter in sediments in the mangrove areas and adjacent continental margins of Brazil. 1. *Amino acids and hexosamines. Oceanology Acta, 20*, 359–369.

Jonathan, M. P., Roy, P. D., Thangadurai, N., Srinivasalu, S., Rodríguez-Espinosa, P. F., Sarkar, S. K., Lakshumanan, C., Navarrete-López, M., & Muñoz-Sevilla, N. P. (2011). Metal concentrations in water and sediments from tourist beaches of Acapulco. *Mexico. Marine Pollution Bulletin, 62*(4), 845–850. https://doi.org/10.1016/j.marpolbul.2011.02.042

Jones, C. G., Lawton, J. H., & Shachak, M. (1994). Organisms as ecosystem engineers. *Oikos, 69*(3), 130–147.

Karlonienė, D., Pupienis, D., Jarmalavičius, D., Dubikaltinienė, A., & Žilinskas, G. (2021). The impact of coastal geodynamic processes on the distribution of trace metal content in Sandy Beach sediments, southeastern Baltic Sea coast (Lithuania). *Applied Sciences (Basel, Switzerland), 11*(3), 1106. https://doi.org/10.3390/app11031106

Kim, B. S. M., Salaroli, A. B., de Ferreira, P. A. L., Sartoretto, J. R., Mahiques, M. M. de, & Figueira, R. C. L. (2016). Spatial distribution and enrichment assessment of heavy metals in surface sediments from Baixada Santista. Southeastern Brazil. *Marine Pollution Bulletin, 103*(1–2), 333–338. https://doi.org/10.1016/j.marpolbul.2015.12.041

Klerks, P. L., Felder, D. L., Strasser, K., & Swarzenski, P. W. (2007). Effects of ghost shrimp on zinc and cadmium in sediments from Tampa Bay. *FL. Marine Chemistry, 104*(1–2), 17–26. https://doi.org/10.1016/j.marchem.2006.12.014

Kozioł, A., Paso, K. G., & Kuciel, S. (2022). Properties and recyclability of abandoned fishing net-based plastic debris. *Catalysts (Basel, Switzerland), 12*(9), 948. https://doi.org/10.3390/catal12090948

Kronvang, K. B., & Christiansen, C. (1986). The paths of the suspended particulate inorganic and organic matter in a small urban estuary: The Aarhus Harbour Estuary. *Hydrology Research, 17*(1), 31–46. https://doi.org/10.2166/nh.1986.0003

Liang, J., Shu, M.-Y., Huang, H.-R., Ma, C.-W., & Kim, S.-K. (2024). Using benthic indices to assess the ecological quality of sandy beaches and the impact of urbanisation on Sandy Beach ecosystems. *Journal of Marine Science and Engineering, 12*(3), 487. https://doi.org/10.3390/jmse12030487

Liao, Z.-H., Chuang, H.-C., Huang, H.-T., Wang, P.-H., Chen, B.-Y., Lee, P.-T., Wu, Y.-S., & Nan, F.-H. (2022). Bioaccumulation of arsenic and immunotoxic effect in white shrimp (*Penaeus vannamei*) exposed to trivalent arsenic. *Fish & Shellfish Immunology, 122*, 376–385. https://doi.org/10.1016/j.fsi.2022.02.029

Lin, H., Cui, J., & Bai, X. (2021). Feature extraction of marine water pollution based on data mining. *Symmetry, 13*(2), 355. https://doi.org/10.3390/sym13020355

Lobato, R. O., Nunes, S. M., Wasielesky, W., Fattorini, D., Regoli, F., Monserrat, J. M., & Ventura-Lima, J. (2013). The role of lipoic acid in the protection against of metallic pollutant effects in the shrimp *Litopenaeus vannamei* (Crustacea, Decapoda). *Comparative Biochemistry and Physiology. Part A, Molecular & Integrative Physiology*, *165*(4), 491–497. https://doi.org/10.1016/j.cbpa.2013.03.015

Luoma, S. N., & Rainbow, P. S. (2008). *Metal contamination in aquatic environments: science and lateral management* (Vol. 99). Cambridge University Press.

Martinčić, D., Kwokal, Ž, & Branica, M. (1990). Distribution of zinc, lead, cadmium and copper between different size fractions of sediments I: The Limski Kanal (North Adriatic Sea). *Science Total Environmental, 95*, 201–215.

Mclachlan, A., & Defeo, O. (2018). *The ecology of sandy shores* (Vol. 572). Academic Press.

Metian, M., Hédouin, L., Eltayeb, M. M., Lacoue-Labarthe, T., Teyssié, J.-L., Mugnier, C., Bustamante, P., & Warnau, M. (2010). Metal and metalloid bioaccumulation in the Pacific blue shrimp *Litopenaeus stylirostris* (Stimpson) from New Caledonia: Laboratory and field studies. *Marine Pollution Bulletin, 61*(7–12), 576–584. https://doi.org/10.1016/j.marpolbul.2010.06.035

Morrison, G., Greening, H., & Yates, K. K. (2011). Sediment contaminants and benthic habitat quality. In *Integrating Science and Resource Management in* (Vol. 1348, pp. 203–234).

Nagarajan, R., Jonathan, M. P., Roy, P. D., Wai-Hwa, L., Prasanna, M. V., Sarkar, S. K., & Navarrete-López, M. (2013). Metal concentrations in sediments from tourist beaches of Miri City, Sarawak, Malaysia (Borneo Island). *Marine Pollution Bulletin, 73*(1), 369–373. https://doi.org/10.1016/j.marpolbul.2013.05.036

Napierska, D., & Skorkowski, E. F. (2001). Isolation and some properties of malic enzyme from the abdomen muscle of Antarctic krill *Euphausia superba*. *Bulletin of the Sea Fisheries Institute, 1*(152), 31–44.

Negreiros-Fransozo, M. L., Fransozo, A., Pinheiro, M. A. A., Mantelatto, F. L., & Santos, S. (1991). Caracterização Física e Química da Enseada da Fortaleza, Ubatuba. *SP. Revista Brasileira de Geociências, 21*(2), 114–120.

Nwabueze, J. C., Sogbanmu, T. O., & Ugwumba, A. A. A. (2020). Physicochemical characteristics, animal species diversity and oxidative stress responses in dominant fish from an impacted site on the Lagos Lagoon. *Nigeria. Ife Journal of Science, 22*(2), 81–93. https://doi.org/10.4314/ijs.v22i2.8

Ochiai, E.-I. (1995). Toxicity of heavy metals and biological defense: Principles and applications in bioinorganic chemistry-VII. *Journal of Chemical Education, 72*(6), 479. https://doi.org/10.1021/ed072p479

Oliveira, A. J. F. C., Pinheiro, M. A. A., & Fontes, R. F. C. (2008). *Panorama Ambiental da Baixada Santista* (Vol. 127). UNESP.

Osuala, F. I., Abiodun, O. A., Igwo-Ezikpe, M. N., Oguejiofor, U., & Salami, O. (2018). Evaluation of sixteen priority polycyclic aromatic hydrocarbons in sediment and impacts on benthic marcoinvertebrate community structure of the Lagos Lagoon. *NISEB Journal*, *3*

Oyarzún, C., Carrasco, F. D., & Gallardo, V. A. (1987). Some characteristics of macrobenthic fauna from the organic-enriched sediments at Talcahuano. *Chile. Cahiers de Biologie Marine., 28*, 429–446.

Peiró, D. F., & Mantelatto, F. L. (2016). Capítulo 6: Avaliação do calianassídeo *Callichirus major* (Say, 1818) sensu lato. *Livro vermelho dos crustáceos do Brasil: Avaliação, 2012–2014*, 103–112.

Perina, F. C., Torres, R. J., Mozeto, A. A., Nascimento, M. R. L., & Abessa, D. M. S. (2018). Sediment quality assessment of the tributaries of the Santos-São Vicente Estuarine System-Brazil. *Ecotoxicology and Environmental Contamination, 13*(2), 25–38.

Pinheiro, M. A. A., Souza, C. A., Zanotto, F. P., Torres, R. A., & Pereira, C. D. S. (2017). Chapter 10. The crab *Ucides cordatus* (Malacostraca, Decapoda, Brachyura) and other related taxa as environmental sentinels for assessment and monitoring of tropical mangroves from south America. In *Issues in Toxicology* (pp. 212–242). Royal Society of Chemistry.

Pinheiro, M. A. A., Silva, P. P. G. E., Duarte, L. F. A., Almeida, A. A., & Zanotto, F. P. (2012). Accumulation of six metals in the mangrove crab *Ucides cordatus* (Crustacea: Ucididae) and its food source, the red mangrove *Rhizophora mangle* (Angiosperma: Rhizophoraceae). *Ecotoxicology and Environmental Safety, 81*, 114–121. https://doi.org/10.1016/j.ecoenv.2012.05.004

Posey, M. H. (1986). Changes in a benthic community associated with dense beds of a burrowing deposit feeder, *Callianassa californiensis*. *Marine Ecology Progress Series, 31*, 15–22. https://doi.org/10.3354/meps031015

Pourang, N., Dennis, J. H., & Ghourchian, H. (2004). Tissue distribution and redistribution of trace elements in shrimp species with the emphasis on the roles of metallothionein. *Ecotoxicology (London, England), 13*(6), 519–533. https://doi.org/10.1023/b:ectx.0000037189.80775.9c

R Core Team. R (2023). A language and environment for statistical computing. *Vienna: R Foundation for Statistical Computing*. https://www.r-project.org/

Rahman, M., & Ali, M. S. (2024). Properties of dredged material and potential scope of its beneficial use: A case study of the Pussur River in Bangladesh. *Water Science and Engineering, 17*(4), 336–343. https://doi.org/10.1016/j.wse.2023.12.005

Rainbow, P. S. (2002). Trace metal concentrations in aquatic invertebrates: why and so what? *Environmental Pollution (Barking, Essex: 1987)*, *120*(3), 497–507. https://doi.org/10.1016/s0269-7491(02)00238-5

Rainbow, P. S. (2007). Trace metal bioaccumulation: Models, metabolic availability and toxicity. *Environment International, 33*(4), 576–582. https://doi.org/10.1016/j.envint.2006.05.007

Raknuzzaman, M., Ahmed, M. K., Islam, M. S., Habibullah-Al-Mamun, M., Tokumura, M., Sekine, M., & Masunaga, S. (2016). Trace metal contamination in commercial fish and crustaceans collected from coastal area of Bangladesh and health risk assessment. *Environmental Science and Pollution Research International, 23*(17), 17298–17310. https://doi.org/10.1007/s11356-016-6918-4

Reichmuth, J. M., Weis, P., & Weis, J. S. (2010). Bioaccumulation and depuration of metals in blue crabs (*Callinectes sapidus* Rathbun) from a contaminated and clean estuary. *Environmental Pollution (Barking, Essex: 1987)*, *158*(2), 361–368. https://doi.org/10.1016/j.envpol.2009.09.009

Rodrigues, S. A., & Shimizu, R. M. (1997). Autoecologia de *Callichirus major* (SAY, 1818). *Oecologia Brasiliensis, 03*(01), 155–170. https://doi.org/10.4257/oeco.1997.0301.10

Rodrigues, P., Ferrari, R. G., Kato, L. S., Hauser-Davis, R. A., & Conte-Junior, C. A. (2022). A systematic review on metal dynamics and marine toxicity risk assessment using crustaceans as bioindicators. *Biological Trace Element Research, 200*(2), 881–903. https://doi.org/10.1007/s12011-021-02685-3

Rosa, L. C., Freire, K. M., & Souza, M. J. (2018). Spatial distribution and population dynamics of *Callichirus major* (Crustacea, Callianassidae) in a tropical sandy beach, northeastern Brazil. *Invertebrate Biology, 137*(4), 308–318.

Rtal, A., & Truchot, J. P. (1996). Haemolymph transport and tissue accumulation of exogenous copper in the shore crab, Carcinus maenas. *Marine pollution bulletin, 32*(11), 802–811. https://doi.org/10.1016/S0025-326X(96)00043-4

Rumisha, C., Elskens, M., Leermakers, M., & Kochzius, M. (2012). Trace metal pollution and its influence on the community structure of soft bottom molluscs inintertidal areas of the Dar es Salaam coast. *Tanzania. Marine Polluion. Buletim, 64*, 521–531.

Ryu, J., Khim, J. S., Kang, S.-G., Kang, D., Lee, C.-H., & Koh, C.-H. (2011). The impact of heavy metal pollution gradients in sediments on benthic macrofauna at population and community levels. *Environmental Pollution (Barking, Essex: 1987)*, *159*(10), 2622–2629. https://doi.org/10.1016/j.envpol.2011.05.034

Sanches, R. A. (2004). Caiçaras e a Estação Ecológica de Juréia–Itatins: litoral sul de São Paulo. *São Paulo: Annablume / FAPESP*, *1*, 29–33.

Sanders, C. J., Smoak, J. M., Waters, M. N., Sanders, L. M., Brandini, N., & Patchineelam, S. R. (2012). Organic matter content and particle size modifications in mangrove sediments as responses to sea level rise. *Marine Environmental Research, 77*, 150–155. https://doi.org/10.1016/j.marenvres.2012.02.004

Santhiya, G., Lakshumanan, C., Jonathan, M. P., Roy, P. D., Navarrete-Lopez, M., Srinivasalu, S., Uma-Maheswari, B., & Krishnakumar, P. (2011). Metal enrichment in beach sediments from Chennai Metropolis, SE coast of India. *Marine Pollution Bulletin, 62*(11), 2537–2542. https://doi.org/10.1016/j.marpolbul.2011.08.019

São Paulo. Lei nº 5.649, de 28 de abril de. (1987). Cria a Estação Ecológica da Juréia-Itatins e dá outras providências. *Diário Oficial Estado de São Paulo, 97*(79), 1.

São Paulo. Lei nº 12.406, de 12 de dezembro de. (2006). Altera a Lei n. 5.649, de 28 de abril de 1987, que criou a Estação Ecológica da Juréia–Itatins, exclui, reclassifica e incorpora áreas que especifica, institui o Mosaico de Unidades de Conservação da Juréia–Itatins, regulamenta ocupações. *Diário Oficial Estado de São Paulo, 116*(236), 1.

São Paulo., Lei nº 14.982, de 08 de abril de. (2013). Altera os limites da Estação Ecológica da Jureia- Itatins na forma que especifica, e dá outras providências. *Diário Oficial Estado de São Paulo, 123*(65), 1.

Sauve, S., Mcbride, M., & Hendershot, W. (1998). Soil solution speciation of lead (II): Effects of organic matter and pH. *Soil Science Society American. Journal, 62*(3), 618–621.

Souza, C. R. de G. (2012). Praias arenosas oceânicas do estado de São Paulo (Brasil): síntese dos conhecimentos sobre morfodinâmica, sedimentologia, transporte costeiro e erosão costeira. *Geography Department University of Sao Paulo*, 307–371. https://doi.org/10.7154/rdg.2012.0112.0015

Sun, T., Wu, H., Wang, X., Ji, C., Shan, X., & Li, F. (2020). Evaluation on the biomagnification or biodilution of trace metals in global marine food webs by meta-analysis. *Environmental pollution, 264,* 113856. https://doi.org/10.1016/j.envpol.2019.113856

Suresh, G., Ramasamy, V., Sundarrajan, M., & Paramasivam, K. (2015). Spatial and vertical distributions of heavy metals and their potential toxicity levels in various beach sediments from high-background-radiation area, Kerala. *India. Marine Pollution Bulletin, 91*(1), 389–400. https://doi.org/10.1016/j.marpolbul.2014.11.007

Terwilliger, N. B. (2015). Oxygen transport proteins in Crustacea: hemocyanin and hemoglobin. In *Chang TS, Thiel, M. Physiology: The Natural History of the Crustacean* (Vol. 528). Oxford University Press.

Thibodeaux, L. K., Burnett, K. G., & Burnett, L. E. (2009). Energy metabolism and metabolic depression during exercise in *Callinectes sapidus*, the Atlantic blue crab: Effects of the bacterial pathogen *Vibrio campbellii*. *Journal of Experimental Biology, 212*(21), 3428–3439.

Torres, R. J., Abessa, D. M. S., Santos, F. C., Maranho, L. A., Davanso, M. B., do Nascimento, M. R. L., & Mozeto, A. A. (2009). Effects of dredging operations on sediment quality: Contaminant mobilization in dredged sediments from the Port of Santos, SP. *Brazil. Journal of Soils and Sediments, 9*(5), 420–432. https://doi.org/10.1007/s11368-009-0121-x

Trevizani, T. H., Domit, C., Santos, M. C. O., & Figueira, R. C. L. (2023). Bioaccumulation of heavy metals in estuaries in the southwest Atlantic Ocean. *Environmental Science and Pollution Research, 30*, 26703–26717. https://doi.org/10.1007/s11356-022-23974-x

Tue, N. T., Nguyen, P. T., Quan, D. M., Dung, L. V., Quy, T. D., Nhuan, M. T., & Thai, N. D. (2018). Sedimentary composition and organic carbon sources in mangrove forests along the coast of northeast Vietnam. *Regional Studies in Marine Science, 17*, 87–94. https://doi.org/10.1016/j.rsma.2017.12.001

Uchimiya, M., Lima, I. M., Klasson, K. T., & Wartelle, L. H. (2010). Contaminant immobilization and nutrient release by biochar soil amendment: Roles of natural organic matter. *Chemosphere, 80*(8), 935–940. https://doi.org/10.1016/j.chemosphere.2010.05.020

United Nations. (2015). Transforming our world: the 2030 Agenda for Sustainable Development. https://sustainabledevelopment.un.org/post2015. Accessed 4 Apr 2023.

Valls, A., Coll, M., & Christensen, V. (2015). Keystone species: Toward an operational concept for marine biodiversity conservation. *Ecological Monographs, 85*(1), 29–47. https://doi.org/10.1890/14-0306.1

Vetrimurugan, E., Jonathan, M. P., Roy, P. D., Shruti, V. C., & Ndwandwe, O. M. (2016). Bioavailable metals in tourist beaches of Richards Bay, Kwazulu-Natal. *South Africa. Marine Pollution Bulletin, 105*(1), 430–436. https://doi.org/10.1016/j.marpolbul.2016.01.045

Vidinha, J. M., Rocha, F., Patinha, C., Silva, E., & Andrade, C. (2006). Heavy metals contents on beach and dune sediments from Espinho to Mondego Cape (Portugal)—influence of human activities. *Journal of Geochemical Exploration, 88*(1–3), 404–407. https://doi.org/10.1016/j.gexplo.2005.08.085

Vig, K. (2003). Bioavailability and toxicity of cadmium to microorganisms and their activities in soil: A review. *Advances in Environmental Research, 8*(1), 121–135. https://doi.org/10.1016/s1093-0191(02)00135-1

Vilhena, M. S. P., Costa, M. L., & Berredo, J. F. (2013). Accumulation and transfer of Hg, As, Se, and other metals in the sediment-vegetation-crab-human food chain in the coastal zone of the northern Brazilian state of Pará (Amazonia). *Environmental Geochemistry and Health, 35*(4), 477–494. https://doi.org/10.1007/s10653-013-9509-z

Wu, B., Song, J., & Li, X. (2014). Evaluation of potential relationships between benthic community structure and toxic metals in Laizhou Bay. *Marine Pollution Bulletin, 87*(1–2), 247–256. https://doi.org/10.1016/j.marpolbul.2014.07.052

Wu, J.-P., Chen, H.-C., & Huang, D.-J. (2008). Histopathological and biochemical evidence of hepatopancreatic toxicity caused by cadmium and zinc in the white shrimp. *Litopenaeus vannamei. Chemosphere, 73*(7), 1019–1026. https://doi.org/10.1016/j.chemosphere.2008.08.019

Wu, M., Lin, Y. P., Ruiz-Fernandez, A. C., & Sahu, B. K. (2023). Coastal environmental and ecological data analysis. *Frontiers in Marine. Science., 9*, e1126086.

Zhu, Q.-H., Zhou, Z.-K., Tu, D.-D., Zhou, Y.-L., Wang, C., Liu, Z.-P., Gu, W.-B., Chen, Y.-Y., & Shu, M.-A. (2018). Effect of cadmium exposure on hepatopancreas and gills of the estuary mud crab (*Scylla paramamosain*): Histopathological changes and expression characterization of stress response genes. *Aquatic Toxicology (Amsterdam, Netherlands), 195*, 1–7. https://doi.org/10.1016/j.aquatox.2017.11.020

Ziebis, W., Forster, S., Huettel, M., & Jorgensen, B. B.(1996). Complex burrows of the mud shrimp Callianassa truncata and their geochemical impact in the sea bed. *Nature, 382*, 619–622. https://doi.org/10.1038/382619a0