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Sidi Ahmed Elemin

sidi.mahmoud@etu.univ-nkc.mr

Université de Nouakchott

Mohammed Fekhaoui

Mohammed V University

Khadijetou El Hacen

Université de Nouakchott

Zeinebou Sidoumou

Université de Nouakchott

Mohamed Avoulwatt

Université de Nouakchott

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Cadmium accumulation and depressed acetylcholinesterase activity in the sentinel clam *Donax rugosus* downdrift of a West African port (N'Diago, Mauritania)

Sidi Ahmed Elemin[1*], Mohammed Fekhaoui[2], Khadijetou El Hacen[1], Zeinebou Sidoumou[1], Mohamed Avoulwatt[1]

[1]EBIOMESN Research Unit, Department of Biology, Faculty of Science and Technology, University of Nouakchott, Nouakchott, Mauritania

[2] Laboratory of Ecotoxicology, Scientific Institute, Mohamed V Agdal University, Avenue Ibn Batouta, Rabat, Morocco

* Corresponding author's e-mail: sidi.mahmoud@etu.univ-nkc.mr

Abstract

The N'Diago port, built from 2016 on the southern Mauritanian Atlantic coast, interrupts a strong southward longshore drift and has reorganized the adjacent sandy shoreline into an updrift accreting sector and a downdrift eroding sector. We tested whether this reorganization coincides with a measurable, contaminant-linked deterioration of the receiving environment, using the dominant intertidal clam Donax rugosus as a sentinel across three zones: an updrift sector, a downdrift sector adjacent to the port, and a morphodynamically stable reference site about 100 km to the north. We measured acetylcholinesterase activity in four organs (gills, mantle, foot, and digestive gland; eight individuals per zone, sampled between January and March 2023), determined tissue cadmium in the same populations, and recorded seawater chemistry, including phosphorus. A permutational multivariate analysis of the four-organ enzyme profile resolved a significant zone effect (pseudo-F = 4.92, 33% of the multivariate variation; p = 0.0002), with homogeneous dispersion among zones (p = 0.16), indicating a difference in location rather than in

scatter. The digestive gland was the only organ whose activity was lowest downdrift (Kruskal–Wallis H = 9.74; p = 0.008; epsilon-squared = 0.42): 0.82 ± 0.62 nmol per minute per milligram protein, against 5.30 ± 3.70 updrift and 2.23 ± 1.40 at the reference site. Only the downdrift–updrift contrast was statistically significant. Cadmium was quantified in all nine downdrift clams (mean 0.34 milligrams per kilogram dry weight) but in none of the updrift or reference clams (Fisher exact $p = 2 \times 10^{-6}$), and seawater phosphorus was highest downdrift. The coincidence of cadmium accumulation, the lowest digestive-gland enzyme activity, and nutrient enrichment in the single downdrift sector is compatible with a localized alteration of environmental quality adjacent to the port. It does not amount to causal proof, as competing explanations cannot be excluded. The study also identifies Donax rugosus as an operational sentinel for sandy West African shores.

Keywords: Port infrastructure; Longshore drift; Sandy-beach biomonitoring; Biomarkers; Trace metals; Mauritania

1. Introduction

Hard coastal infrastructure such as jetties and breakwaters interrupts the longshore transport of sediment and produces a characteristic asymmetry of updrift accretion and downdrift erosion (Dean & Dalrymple, 2002). In sediment-limited arid systems, where little compensatory fluvial supply is available, this asymmetry is amplified and the recovery potential of intertidal communities is correspondingly reduced (Anthony, 2015; Ould Elmoustapha et al., 2007). How such a physical reorganization translates into a change in the quality of the receiving environment, and whether resident organisms record that change, remains far less documented than the geomorphic change itself, particularly on West African sandy coasts.

The N’Diago port, on the southern Mauritanian Atlantic coast, is a suitable setting to address this question. The structure was built from 2016 on a long sandy littoral that carries an active southward

drift, estimated at 200,000–400,000 m³ per year off Nouakchott (Ould Elmoustapha et al., 2007), immediately adjacent to the Diawling National Park, a Ramsar wetland of regional importance. By interrupting the drift, the port drives accretion to the north and erosion to the south (Elemin et al., 2026). This contrast yields three spatially distinct settings, an updrift sector, a downdrift sector, and a reference outside the influence of the port, within which the state of the environment can be compared using a single resident species. Whether the disturbance also reaches the resident intertidal fauna has not been tested.

We use acetylcholinesterase (AChE) activity in Donax rugosus as the primary line of biological evidence. Inhibition of this enzyme is a recognized signature of exposure to organophosphates, carbamates, and several trace metals, including cadmium (Bocquené & Galgani, 1998; Lionetto et al., 2013), although it also responds to thermal, osmotic, and trophic variation through indirect pathways (Pfeifer et al., 2005). Donax rugosus (Linnaeus, 1758) is the dominant bivalve of exposed West African sandy beaches (Ansell, 1983; Defeo & McLachlan, 2005); its sedentary, filter-feeding habit and short life cycle make it an integrator of local conditions, and it occupies the swash-zone habitat most directly modified by port-induced morphodynamic change. To anchor the biomarker in measured exposure rather than in inference, and to reduce the reliance that a single endpoint would impose, we also measured tissue cadmium and seawater chemistry in the same zones.

The study pursues three objectives. The first is to test whether the AChE response in Donax rugosus differs among the three zones and, if so, which tissue carries the signal. The second is to determine whether a contaminant gradient, here tissue cadmium, accompanies the biomarker pattern. The third is to evaluate, through the spatial coincidence of distinct measurements, whether the downdrift sector adjacent to the port shows altered, contaminant-associated environmental

quality, while remaining explicit about the limits that a single-season correlative design places on any causal reading.

2. Materials and Methods

2.1. Study area and zone selection

The study area lies on the southern Mauritanian Atlantic coast, in the Keur Macène department of the Trarza region (16°23′N, 16°30′W), about 220 km south of Nouakchott. The N'Diago multifunctional port, which comprises a naval base, a fishing port, and a commercial quay, was constructed from 2016 in support of the Grand Tortue Ahmeyim offshore gas project. Since its construction, the port has interrupted the southward drift and driven a marked morphodynamic asymmetry, quantified from 210 shoreline transects with the Digital Shoreline Analysis System: over 2000–2025, 111.35 ha accreted north of the port and 45.47 ha eroded to the south (Elemin et al., 2026). The local regime is dominated by north-westerly Atlantic swell, a semi-diurnal tide, and a unidirectional southward longshore drift, estimated at 200,000–400,000 $m^3\ yr^{-1}$ off Nouakchott (Ould Elmoustapha et al., 2007; Elemin et al., 2026); no estimate specific to the N'Diago sector is available. We selected three sampling zones on the basis of this morphodynamic classification (Elemin et al., 2026): an updrift sector in accretion north of the port (16°28′43.9″N, 16°27′28.4″W); a downdrift sector in chronic erosion adjacent to the port, about 3 km to the south (16°25′27.7″N, 16°28′15.6″W); and a morphodynamically stable reference site at Lguwychiche, about 100 km to the north and roughly midway between the N'Diago port and the Port de l'Amitié at Nouakchott (17°21′59.3″N, 16°07′53.6″W), outside the morphodynamic footprint of the structure (Fig. 1). The morphodynamic contrast serves only to define three comparable sampling settings; it is not itself treated as a measure of environmental quality. Because the sectors were

delimited from the shoreline analysis, the zones compared are not defined independently of the observed morphological response. The reference site, chosen for its apparent stability and its distance from the structure, is not perfectly matched to the port sectors either: it lies further north and further from the mouth of the Senegal River, and its physico-chemical characterization revealed baseline conditions of its own.

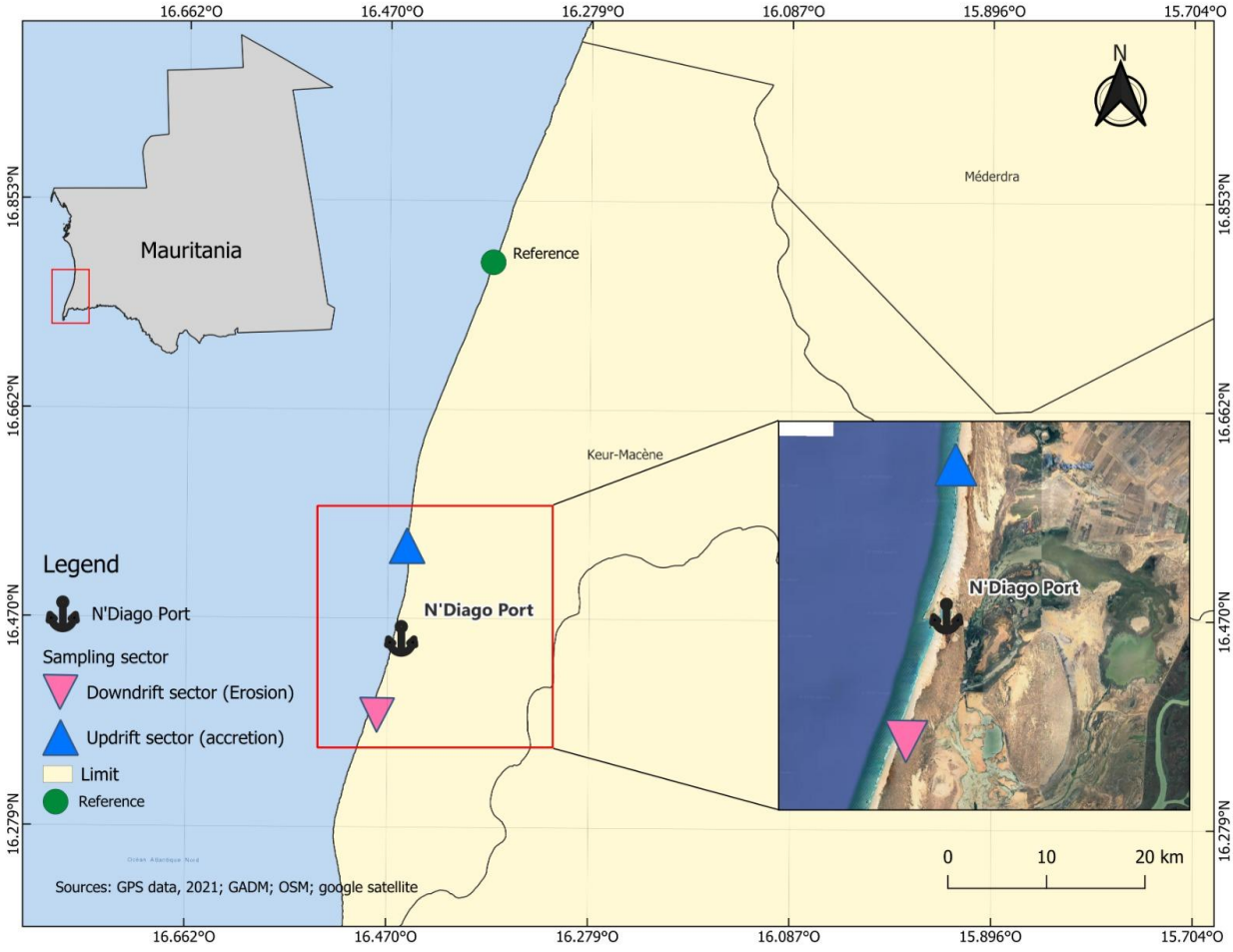

Figure 1. Study area on the southern Mauritanian Atlantic coast

2.2. Species and sampling

We selected Donax rugosus because it is the dominant bivalve of high-energy intertidal sands along the West African Atlantic façade, because its limited mobility makes its biochemical state representative of local conditions, and because its swash-zone niche coincides with the habitat

most affected by port-induced change. Specimens were collected manually at low tide by shallow digging and sieving of the upper 10–20 cm of sediment. Only living individuals with a normal valve-closure response were retained for biochemical analysis. In the downdrift sector, specimens came from two collection points grouped under the single label “downdrift”. Sampling took place in the dry season, between January and March 2023. According to the analysis reports, clams for cadmium determination were collected on 13 January 2023 in the downdrift sector and on 7 and 20 February 2023 in the updrift sector and at the reference site, and seawater was sampled between 9 January and 9 March 2023; clams for the AChE assay were collected on the same dates. The three zones were therefore not sampled on the same day, the downdrift sector having been sampled four to five weeks before the other two. Eight living individuals were retained in the updrift sector, eight at the reference site and twelve in the downdrift sector, all of the same small size class (shell length not measured). On the beach facing the locality of Mouli, about 3 km south of the port in the downdrift sector, empty bivalve shells were very abundant while living D. rugosus were scarce, which made collection harder and partly explains the limited numbers; such shell accumulation may result from local mortality as well as from wave transport and sorting, and is not in itself evidence of mortality on site. Cadmium was determined on specimens distinct from those used for the enzyme assay: six updrift, seven at the reference site and nine downdrift. Comparable sample sizes are commonly used in ecotoxicological studies of Donax on the Atlantic façade (Chahouri et al., 2022; Lamine et al., 2023). The gap of a few weeks between sampling dates means that temporal variability may contribute to the contrast between zones, and the small sample size remains a limitation that calls for seasonal and multi-year replication. Water temperature was recorded in situ at the time of sampling.

2.3. Dissection and acetylcholinesterase assay

Living specimens were transported at 0–4 °C and held at −20 °C until dissection, which was carried out on dry ice to preserve enzymatic activity. For each individual, we excised the gills, mantle, foot, and digestive gland, decontaminating the tools between organs. Each tissue was weighed and homogenized in 20 mmol L^{-1} phosphate buffer (pH 7.0) containing 0.1% Triton X-100 at a 1:3 (w/v) ratio, following Bocquené and Galgani (1998), using a rotor-stator homogenizer. Homogenates were kept on ice, centrifuged at 14,000 g for 15 min at 4 °C, and the supernatants retained for assay.

AChE activity was measured by the colorimetric method of Ellman et al. (1961), on 18 May 2023 in flat-bottom 96-well microplates; each extract was assayed in technical duplicate, and two columns of each plate were reserved for blanks and controls. Storage at −20 °C therefore lasted about four months for the downdrift sector and about three months for the other two zones; this difference, which could contribute to lowering the activity measured downdrift, is a potential confounding factor. Per well, 10 µL of supernatant was combined with 280 µL of 20 mmol L^{-1} phosphate buffer (pH 7.0), 20 µL of 5,5′-dithiobis(2-nitrobenzoic acid) (DTNB; 0.01 mol L^{-1} in phosphate buffer at pH 9.0), and 10 µL of acetylthiocholine iodide (0.1 mol L^{-1}); the reaction was started by adding the substrate. Absorbance was followed kinetically at 405 nm on a BioTek ELx808 microplate reader, with nine readings 30 s apart over 4 min; the reading temperature of the plates retained ranged from 25.6 to 26.4 °C. Two control wells were included on each plate (DTNB + extract + buffer, and DTNB + substrate + buffer) to correct for non-enzymatic substrate hydrolysis. Activity was normalized to total protein, quantified by the Bradford (1976) method against a bovine serum albumin standard, and expressed in nmol min^{-1} mg $prot^{-1}$, using a molar extinction coefficient for 2-nitro-5-thiobenzoate of 13,600 L mol^{-1} cm^{-1} (0.0136 mL $nmol^{-1}$ cm^{-1}), a total reaction volume of 0.320 mL, and an extract volume of 0.010 mL. Replicates were averaged

to the individual level before analysis. Wells with a negative protein concentration, which is physically impossible, were excluded; this removed the mantle and foot of one updrift individual, which therefore does not enter the multivariate analysis (23 individuals). Because assay temperature modulates enzyme activity (Pfeifer et al., 2005), the sixteen readings from one plate read at 32.9 °C were excluded to keep the assay temperature uniform across zones. They corresponded to four downdrift individuals assayed in a single replicate for all four organs; their exclusion brings the downdrift sample to eight individuals, each keeping two valid replicates per organ. A sensitivity analysis including these four individuals was run to check that the exclusion does not drive the result. Some metals can also produce an apparent inhibition through interaction with the reagents rather than a physiological inhibition (Frasco et al., 2005); this possibility was not specifically controlled and must be kept in mind when interpreting the results.

2.4. Seawater chemistry and tissue metal analysis

Seawater and clam tissue were sampled for elemental analysis alongside the biomarker collection. Seawater was collected in acid-washed bottles and preserved following standard water-sampling guidance (ISO 5667): the aliquot for dissolved elements was filtered through a 0.45 µm membrane and acidified with nitric acid (ρ = 1.4 g mL^{-1}) to pH < 2 (about 0.5 mL per 100 mL), and the aliquot for total elements was acidified to pH ≤ 2. pH, salinity, conductivity, turbidity and dissolved oxygen were measured with a YSI ProDSS multiparameter probe, on two samples in the downdrift sector and one in each of the other two zones. The pH values (6.64–7.61) and dissolved oxygen values (up to 12.2 mg L^{-1}) are unusual for coastal seawater, whose pH is generally close to 8.0–8.2; since sensor calibration is not documented in the analysis reports, these values are interpreted with caution. Phosphorus was determined on three seawater samples in the downdrift sector and two in each of the other zones. The concentrations reported by the laboratory (1.82–16.97 mg kg^{-1},

roughly 60–550 µmol L^{-1}) far exceed the dissolved phosphorus concentrations usually measured in seawater, even in upwelling areas; as the analysed fraction (dissolved or total) is not specified in the reports, they are used to compare zones with one another rather than as absolute concentrations. For tissue analysis, Donax rugosus soft tissue was rinsed in deionized water, dried to constant mass at 60 °C, and homogenized to a fine powder before digestion.

A 0.500 g portion of dried tissue was digested with 8 mL of concentrated nitric acid (HNO_3, 65%) and 2 mL of hydrogen peroxide (H_2O_2, 30%), and the digest was made up to 50 mL with ultrapure water, following the digestion principles of ISO 11885. Phosphorus in seawater and cadmium in the tissue digests were determined by inductively coupled plasma optical emission spectrometry (ICP-OES) with an argon plasma, according to ISO 11885:2007, with cadmium measured at the 214.441 nm line and spectral interferences corrected. Quality control comprised an analytical blank, duplicate analyses (relative standard deviation < 5%), and a fish-protein certified reference material (DORM-4, National Research Council Canada; Willie et al., 2012), for which the measured cadmium concentration (0.294 mg kg^{-1}) agreed with the certified value (0.306 mg kg^{-1}), a recovery of 96.1%. The limit of detection was 0.003 mg kg^{-1} and the limit of quantification 0.010 mg kg^{-1} (dry weight); the reports give concentrations below the limit of quantification as "< 0.01", and these samples were treated as non-quantified, distinct from zeros, and cadmium as a left-censored variable (Section 2.5). They are plotted at half the limit of quantification and are not included in mean calculations. Cadmium is reported on a dry-weight basis and is therefore not directly comparable with regulatory thresholds defined on a wet-weight basis. Phosphorus and cadmium were measured together because their covariation can shed light on the origin of cadmium. Their association may reflect a common anthropogenic source, but it is also a natural property of seawater, cadmium following the distribution of phosphate in the ocean (Boyle et al.,

1976); on a coast subject to the Mauritanian upwelling, a natural joint enrichment must therefore be considered alongside a port-related input.

2.5. Statistical analysis

Analyses were carried out in R (version 4.5.1; R Core Team, 2025) with the vegan, ade4, and FSA packages (figures drawn with ggplot2), and permutation tests used a fixed random seed for exact reproducibility. Because the four organs were measured on the same individuals and are inter-correlated, and because several organ × zone groups departed from normality (Shapiro–Wilk test), the primary test of the AChE response was a permutational multivariate analysis of variance (PERMANOVA; Anderson, 2001; Euclidean distance on the standardized four-organ profile, 4,999 permutations; vegan package), which makes no distributional assumption and treats each individual as a single multivariate unit. Homogeneity of multivariate dispersion among zones was checked with a permutational dispersion test (betadisper; Anderson, 2006) so that a location effect could be distinguished from a difference in scatter. A principal component analysis with a between-class (zone) ordination and a Monte Carlo permutation test (ade4 package) served to visualize the multivariate result. The tissue carrying the signal was then examined univariately with a Kruskal–Wallis test and Dunn post hoc comparisons with Benjamini–Hochberg correction (FSA package); a Welch one-way analysis of variance was reported alongside as an agreement check. The digestive gland met the normality assumption (Shapiro–Wilk $p > 0.15$ in each zone), and the Welch test was chosen because it does not assume equal variances, the standard deviations differing markedly among zones. The univariate tests and the multivariate test are applied to the same measurements: their agreement indicates how robust the result is to the assumptions of each method, not a confirmation by independent data. Tissue cadmium, being left-censored, was analyzed by quantification frequency and a Fisher exact test rather than by analysis of variance.

Seawater phosphorus and physico-chemistry, available at low replication, were summarized descriptively. The significance threshold was $\alpha = 0.05$; effect sizes were reported alongside p-values as R^2 for the multivariate test and epsilon-squared ($\varepsilon^2 = H/(n - 1)$) for the Kruskal–Wallis test, interpreted by conventional benchmarks. For the descriptive convergence index (Fig. 7), each line (digestive-gland AChE inhibition, tissue cadmium and seawater phosphorus) was rescaled from the zone means between the least and the most impaired zone (0 = least, 1 = most), non-quantified cadmium being set to zero.

3. Results

3.1. Seawater chemistry and tissue cadmium

Salinity was comparable across the three zones (34.4–34.9 ‰). The reference site differed from the two port-influenced sectors in being more acidic (pH 6.64 versus 7.39–7.61) and more oxygenated (dissolved oxygen 12.2 versus 7.6–8.3 mg L^{-1}; Table 1). These values rest on one or two readings per zone and are unusual for coastal seawater; with sensor calibration undocumented, they are interpreted with caution. If they reflect real conditions, they are covariates specific to the reference site that could modulate the biological response independently of the port, and the contrast best suited to isolating an effect of the structure is then the one between the updrift and downdrift sectors, whose conditions are more comparable. Seawater phosphorus was highest in the downdrift sector (mean 15.2 mg kg^{-1}, three samples), intermediate updrift (6.4; two samples, 2.5 and 10.3), and lowest at the reference site (1.9; two samples) (Fig. 2). This ranking is compatible with enrichment in the sector adjacent to the port, but the low replication, the spread of the updrift values and concentrations far above those usually measured for dissolved phosphorus in seawater mean that it should be read as a relative ranking among zones, the analysed fraction not being specified.

Table 1. Seawater physico-chemistry and phosphorus by zone (descriptive). Salinity in ‰; dissolved O_2 in mg L^{-1}; conductivity in µS cm^{-1}; phosphorus as mean (range), mg kg^{-1}.

Zone	pH	Salinity (‰)	Dissolved O_2 (mg L^{-1})	Conductivity (µS cm^{-1})	Phosphorus (mg kg^{-1})
Updrift	7.61	34.9	7.57	53,100	6.4 (2.5–10.3)
Reference	6.64	34.4	12.18	52,000	1.9 (1.8–2.0)
Downdrift	7.39	34.65	8.25	54,000	15.2 (13.9–17.0)

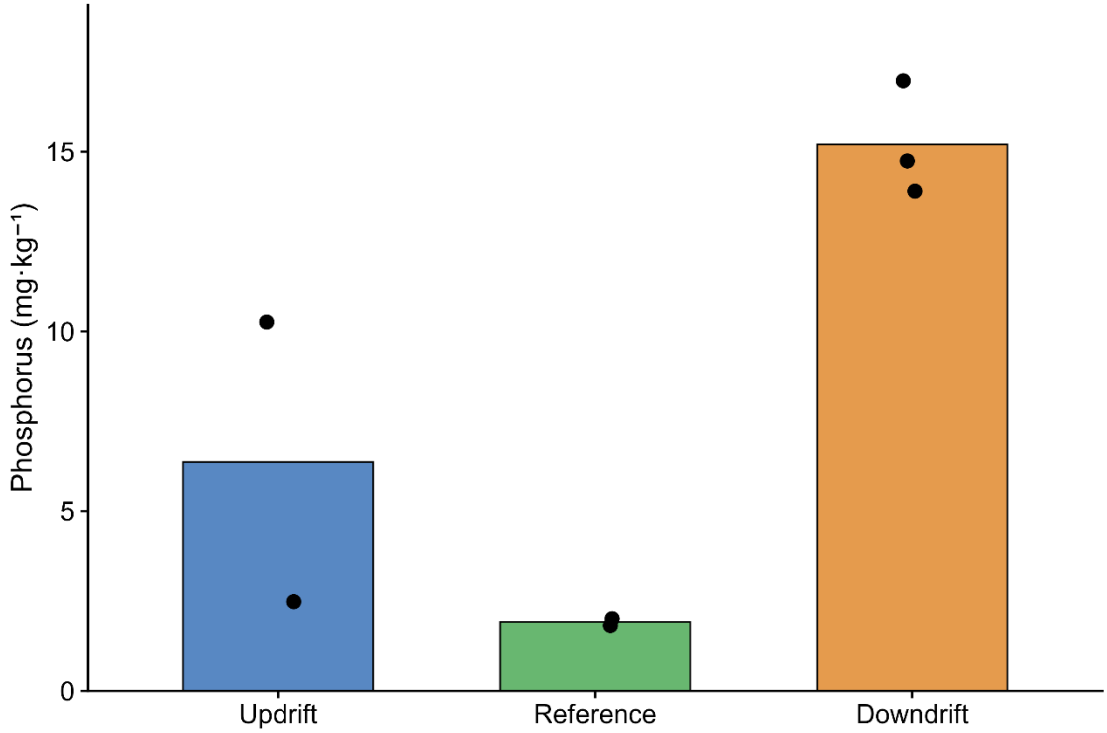

Figure 2. Seawater phosphorus by zone (bars are zone means; points are individual samples, two to three per zone; descriptive data). Enrichment is highest in the downdrift sector adjacent to the port.

Tissue cadmium showed a clear spatial pattern. It was below the limit of quantification in every updrift (0/6) and reference (0/7) specimen but was quantified in all nine downdrift specimens, with a mean of 0.34 mg kg^{-1} dry weight (range 0.12–0.86) (Fig. 3). The contrast in quantification frequency between the downdrift sector and the other two zones was highly significant (Fisher

exact $p = 2 \times 10^{-6}$; Table 2). The downdrift sector is therefore the only zone in which Donax rugosus accumulated quantifiable cadmium.

Table 2. Tissue cadmium (dry weight) and quantification frequency by zone. LOQ, limit of quantification; n, number of individuals analyzed; dry wt, dry weight.

Zone	n	Quantified	Mean (range), mg kg^{-1} dry wt
Updrift	6	0/6	< LOQ (0.010)
Reference	7	0/7	< LOQ (0.010)
Downdrift	9	9/9	0.34 (0.12–0.86)

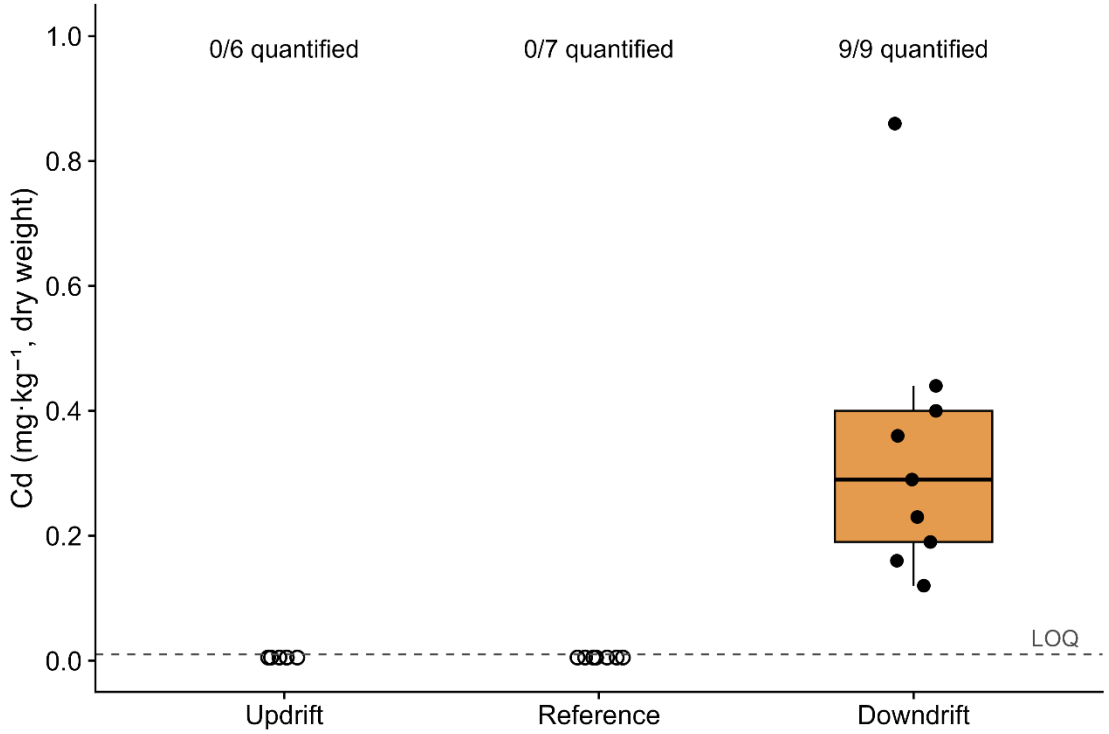

Figure 3. Tissue cadmium in *Donax rugosus* by zone (dry weight). Points are the samples; the non-quantified samples (< 0.01 mg kg^{-1}) of the updrift and reference sectors are plotted at half the limit of quantification (LOQ, dashed line). Fisher exact test on quantification frequency: $p = 2 \times 10^{-6}$.

3.2. Multivariate structure of the acetylcholinesterase response

Across the twelve zone × organ combinations, mean AChE activity varied widely, and the four organs did not respond in parallel (Fig. 4; Table 3). The standardized four-organ profile differed significantly among zones (pseudo-F = 4.92; R^2 = 0.33; p = 0.0002; 23 individuals; Table 4), so that zone accounted for about a third of the multivariate variation. Multivariate dispersion did not differ among zones (permutational dispersion test: F = 2.00; p = 0.16), indicating that the result reflects a difference in the position of the zone groups rather than in their scatter. The between-class analysis confirmed this separation (Monte Carlo permutation test p = 0.0002; Fig. 5): the updrift sector separated clearly from the other two zones, whose ellipses partly overlapped.

Table 3. Descriptive acetylcholinesterase activity (nmol min^{-1} mg $prot^{-1}$; mean ± SD and coefficient of variation, CV) by organ and zone (n = 8 per zone, except mantle and foot updrift, n = 7). SD, standard deviation.

Organ	Zone	Mean	SD	CV (%)
Gills	Updrift	1.51	0.88	57.9
Gills	Reference	2.38	0.82	34.5
Gills	Downdrift	1.14	0.99	86.9
Mantle	Updrift	2.06	0.41	20.2
Mantle	Reference	0.72	0.39	55.2
Mantle	Downdrift	2.78	3.67	131.8
Foot	Updrift	2.63	1.39	52.9
Foot	Reference	0.53	0.52	96.9
Foot	Downdrift	1.03	1.13	109.2
Digestive gland	Updrift	5.30	3.70	69.8
Digestive gland	Reference	2.23	1.40	63.0
Digestive gland	Downdrift	0.82	0.62	75.8

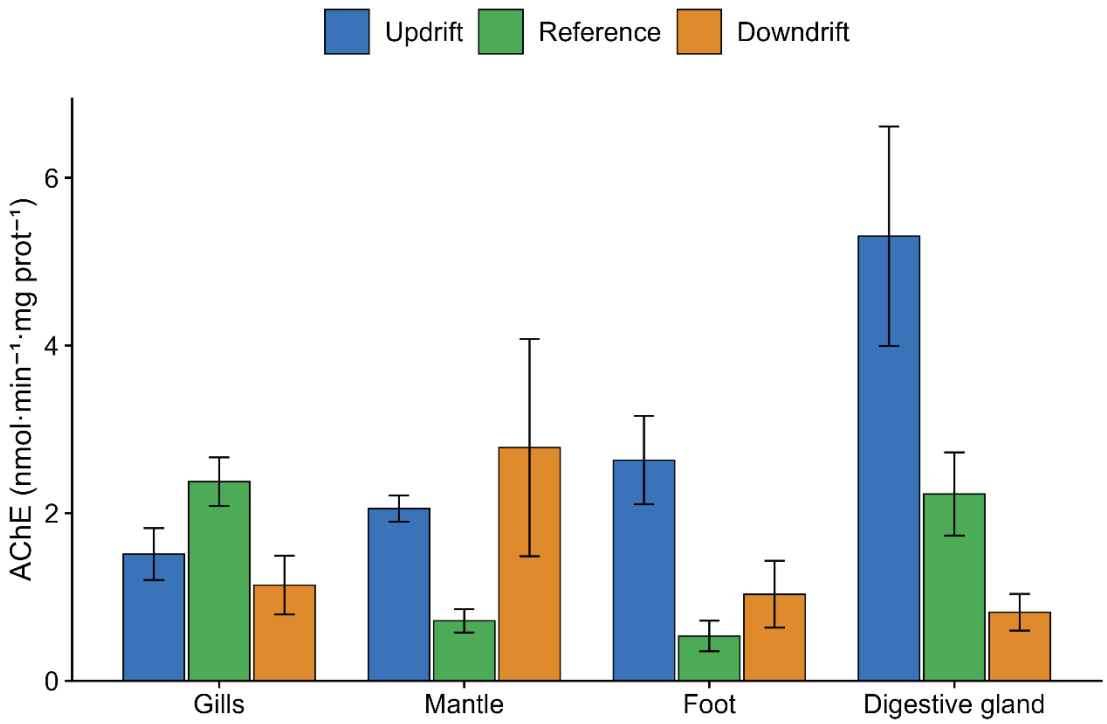

Figure 4. Tissue-specific AChE activity (mean ± standard error; n = 7–8 per zone) by zone and organ. The four organs do not follow a common cross-zone pattern; the digestive gland shows the largest inter-zone contrast, highest updrift and lowest downdrift.

Table 4. Summary of statistical tests of the zone effect on the acetylcholinesterase response and on tissue cadmium. ANOVA, analysis of variance; MANOVA, multivariate analysis of variance.

Test	Statistic	p-value	Effect size
Permutational MANOVA (four-organ profile)	pseudo-F = 4.92	0.0002	$R^2 = 0.33$
Permutational dispersion test	F = 2.00	0.16	—
Between-class permutation test	—	0.0002	—
Digestive gland, Kruskal–Wallis	H = 9.74	0.008	$\varepsilon^2 = 0.42$
Digestive gland, Welch ANOVA	F = 8.05	0.007	—
Tissue cadmium, Fisher exact	—	2×10^{-6}	—

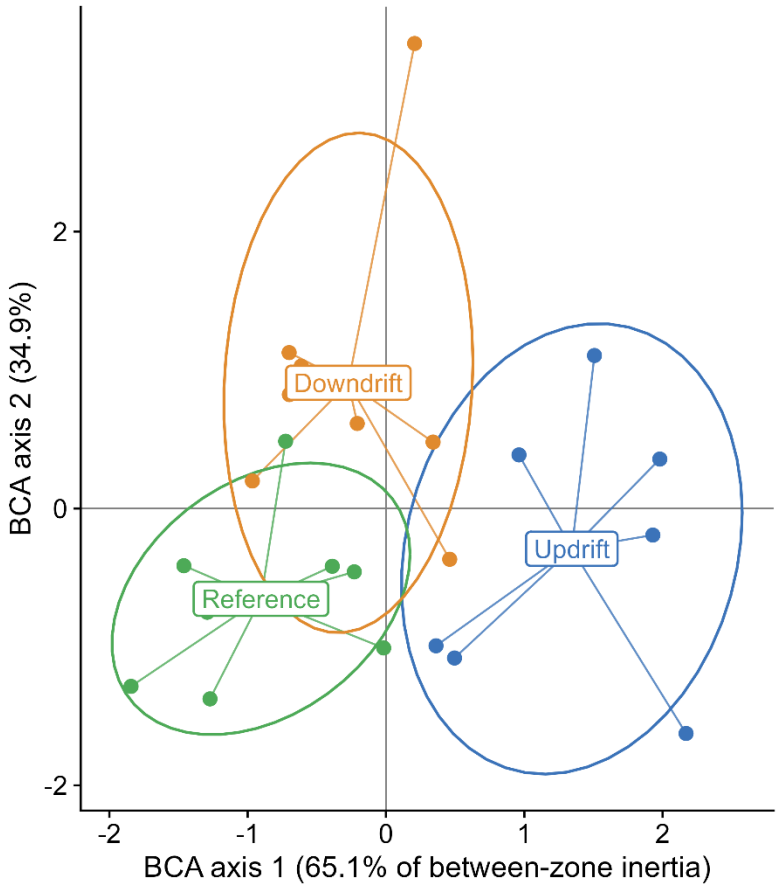

Figure 5. Between-class analysis (BCA) of the standardized four-organ AChE profile of *Donax rugosus*. Each point is one individual, ellipses summarize within-zone dispersion, and labelled boxes mark zone centroids; the updrift sector separates from the other two zones, whose ellipses partly overlap (Monte Carlo permutation test p = 0.0002).

3.3. Organ-level response and digestive-gland activity

Examined organ by organ, the zone effect was significant for the digestive gland (Kruskal–Wallis H = 9.74; p = 0.008; $\varepsilon^2 = 0.42$), the foot (H = 10.52; p = 0.005; $\varepsilon^2 = 0.48$) and the mantle (H = 8.40; p = 0.015; $\varepsilon^2 = 0.38$), including after Benjamini–Hochberg correction for the four organs (adjusted p from 0.015 to 0.020), but not for the gills (H = 5.70; p = 0.058). The direction of the effect differed between organs, however. In the foot and mantle it reflected the low activity at the reference site (updrift–reference comparison: p = 0.004 and p = 0.011 after correction), whereas

the digestive gland was the only organ whose activity was lowest in the downdrift sector. For this tissue, the Welch ANOVA agreed with the Kruskal–Wallis test ($F = 8.05$; $p = 0.007$), the digestive gland meeting the normality assumption (Section 2.5). The result does not depend on excluding the four downdrift individuals read at 32.9 °C: including them raises the downdrift sample to twelve individuals and mean digestive-gland activity to 1.20 ± 0.94 nmol min^{-1} mg $prot^{-1}$, and the Kruskal–Wallis test remains significant ($H = 9.04$; $p = 0.011$).

Digestive-gland activity was 5.30 ± 3.70 nmol min^{-1} mg $prot^{-1}$ in the updrift sector, 2.23 ± 1.40 at the reference site and 0.82 ± 0.62 in the downdrift sector (Fig. 6), about six times lower downdrift than updrift and nearly three times lower than at the reference. Dunn comparisons with Benjamini–Hochberg correction placed the downdrift sector significantly below the updrift sector ($p = 0.006$); the difference between the downdrift sector and the reference site was not significant ($p = 0.12$), nor was the updrift–reference difference ($p = 0.18$). The only statistically established contrast therefore opposes the downdrift and updrift sectors; the reference site occupies an intermediate position that does not differ significantly from either, and the data do not describe a gradient declining with distance from the port. The downdrift sector thus combines the lowest digestive-gland AChE activity with the only quantifiable tissue cadmium.

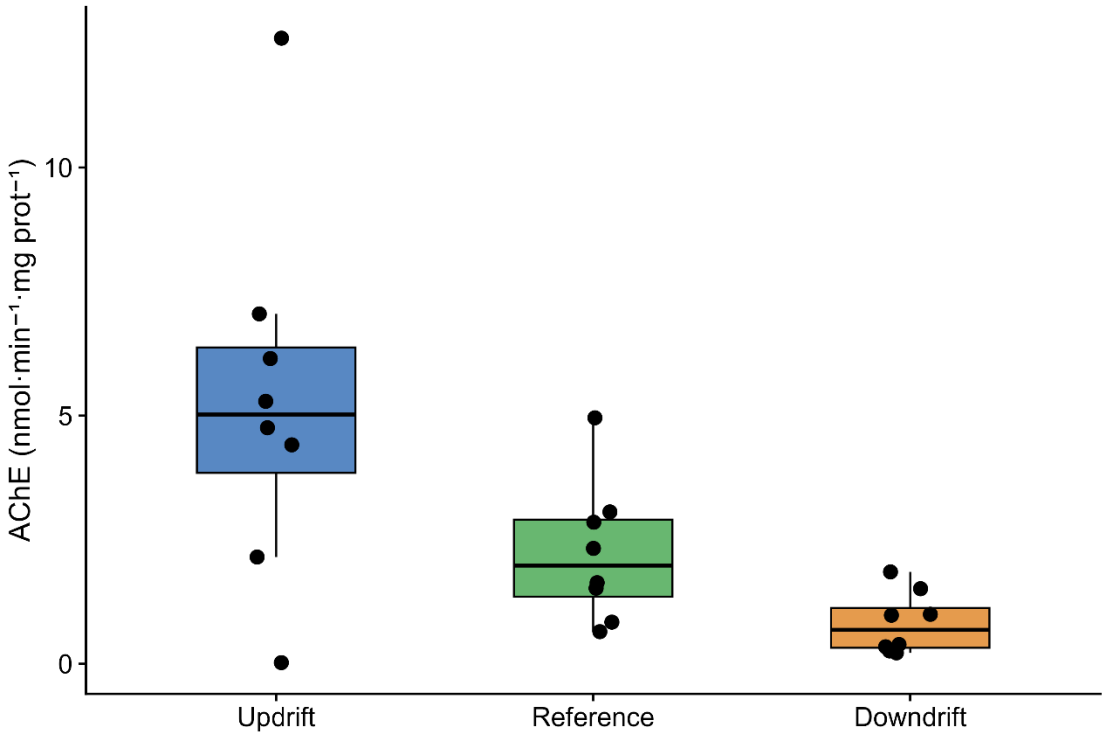

Figure 6. Digestive-gland AChE activity by zone. Boxes show medians and interquartile ranges and points are individuals (n = 8 per zone); activity is lowest in the downdrift sector (Kruskal–Wallis p = 0.008; Dunn downdrift–updrift p = 0.006).

3.4. Convergence of the lines of evidence

The three measurements that resolve among zones, namely tissue cadmium, digestive-gland AChE, and seawater phosphorus, reach their respective extremes in the same sector: cadmium is quantifiable only downdrift, digestive-gland AChE is lowest downdrift, and phosphorus is highest downdrift. This coincidence can be represented by an index rescaled from 0 to 1, on which each of the three measurements reaches its maximum in the downdrift sector (Fig. 7). The index is descriptive: it accounts neither for within-zone variability nor for the statistical significance of the differences, the enzyme activity at the reference site not differing significantly from either of the other two zones. The three measurements are of different natures and were obtained on distinct samples, so their coincidence is not the property of a single measurement; they nevertheless come

from a single sampling season and may share a common cause. Taken together, they indicate that the downdrift sector differs from the other two zones in a direction compatible with degraded environmental quality, without excluding the competing explanations discussed in Section 4.

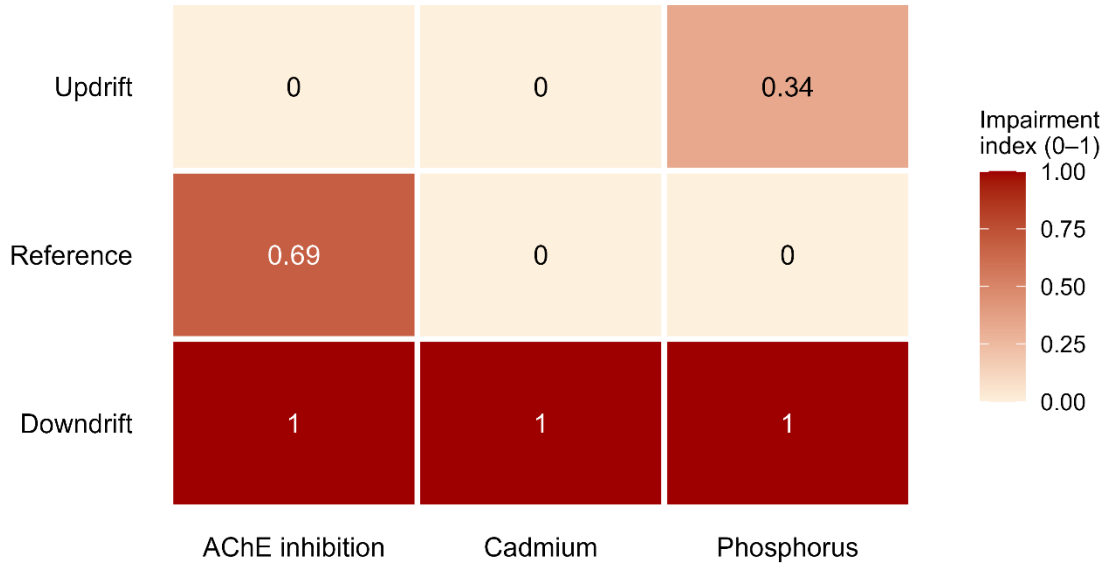

Figure 7. Descriptive convergence index. Each line (digestive-gland AChE inhibition, tissue cadmium, seawater phosphorus) is rescaled from the zone means between the least (0) and the most (1) impaired zone; all three reach their maximum in the downdrift sector.

4. Discussion

The central result is the spatial coincidence, in the downdrift sector, of three signals: cadmium bioaccumulation in Donax rugosus, depression of digestive-gland AChE, and seawater phosphorus enrichment. Cadmium is a documented inhibitor of cholinesterases in bivalves (Lionetto et al., 2013), so the co-occurrence of quantifiable tissue cadmium and the lowest digestive-gland activity in the same sector is mechanistically coherent. The digestive gland, functionally comparable to the vertebrate liver and repeatedly identified as the most contaminant-sensitive bivalve tissue (Cajaraville et al., 2000; Moore et al., 2004), is the compartment in which this depression is expressed, consistent with its role in metal handling and detoxification.

The cross-zone pattern of the digestive gland is not a monotonic decline with distance from the port: activity is highest updrift, intermediate at the reference, and lowest downdrift. Only the downdrift–updrift contrast is statistically established; the reference site differs significantly from neither sector, so the data do not describe a three-step gradient. The reference site is also not a perfectly matched control: its lower pH and higher oxygen, if real, point to a somewhat different micro-environment, and in the foot and mantle it is the reference site, not the downdrift sector, that shows the lowest activity. The enzyme response is therefore not distributed uniformly across the organism, and the specificity of the digestive gland with respect to the downdrift sector is compatible with localized exposure rather than generalized stress, without on its own ruling out other factors. The high updrift activity, which does not differ significantly from that of the reference, can be read as variation within the normal range rather than as evidence of an effect updrift.

The downdrift sector adjacent to the port carries a cadmium burden absent from the other two zones and shows the lowest digestive-gland AChE activity. They do not, on their own, demonstrate that the port is the chemical source of the cadmium. Several non-exclusive sources may contribute: port-related inputs (antifouling hull coatings, hydrocarbon and fuel residues, discharges and handling operations), fishing activity concentrated in this sector, continental inputs through the river–sea interface, remobilization of phosphate-associated cadmium, natural enrichment linked to upwelling (Boyle et al., 1976), and a morphosedimentary process in which the eroding cell may act as a depositional trap concentrating fine, contaminant-bearing particles in low-energy areas. Cadmium is naturally abundant in the upwelling waters of the region: on the Senegalese coast, Sidoumou et al. (2006) measured 2.4–13.8 μg g^{-1} dry weight in four bivalves, values they relate to upwelling, and the concentrations quantified here in downdrift D. rugosus are well below them,

which calls for caution in comparisons across species and sites. The spatial coincidence of phosphorus enrichment and cadmium quantification suggests a common source or correlated transport processes, but the design does not allow these pathways to be ranked. We therefore frame the conclusion as a localized alteration of environmental quality coinciding with the port-influenced downdrift sector, rather than as a demonstrated causal chain from port operation to tissue cadmium.

Several limitations qualify the strength of the inference and set the priorities for further work. Sampling covers a single dry season, and the downdrift sector was sampled four to five weeks before the other two, so seasonal variation in AChE, which tracks reproductive condition, temperature, and food availability in bivalves (Pfeifer et al., 2005), is not captured and temporal variability cannot be excluded. The contaminant and the biomarker were measured on different individuals within each zone, and cadmium was measured on whole soft tissue, so the linkage holds at the zone level, not at the individual level. Cadmium was determined on a dry-weight basis, which precludes direct comparison with wet-weight regulatory limits and any statement about consumption safety. Sediment chemistry was not measured, so the depositional-trap hypothesis cannot yet be tested. Other explanations for the enzyme depression must also be considered. AChE is first of all the reference biomarker for organophosphate and carbamate insecticides, widely used in the irrigated rice schemes of the Senegal River basin, where they pose a high risk to aquatic organisms (Jepson et al., 2014); exposure to these compounds, not measured here, could produce a comparable depression. The downdrift specimens were also stored about one month longer than those from the other zones before the assay, which could contribute to lowering the measured activity. On the shore facing Mouli, empty bivalve shells were abundant while living D. rugosus were scarce; this is compatible with an unfavourable environment, but shell accumulation can also

result from wave transport and sorting, and it was not quantified. These constraints limit what can be inferred from the observed coincidence.

Within these limits, Donax rugosus performed as an informative sentinel. It is abundant on exposed sandy beaches, it occupies the intertidal sand directly exposed to port-induced change, and it can be collected without specialized equipment, an advantage that the classical rocky-substrate sentinels of temperate monitoring do not offer on these shores. The specific response of the digestive gland gives a concrete, organ-level focus for subsequent monitoring on West African sandy coasts.

5. Conclusions

Using Donax rugosus as a sentinel across three zones around the N'Diago port, we found that the downdrift sector adjacent to the port combines tissue cadmium quantified in every specimen, the lowest digestive-gland AChE activity, significantly below that of the updrift sector, and the highest seawater phosphorus. The coincidence of these signals in a single sector is compatible with a localized alteration of coastal environmental quality, without constituting causal proof: the design rests on a single sampling season and small samples, and competing explanations cannot be excluded. Multi-year seasonal replication, paired sediment–tissue chemistry, measurement of organophosphate and carbamate pesticides, and a wet-weight cadmium determination are the most direct extensions needed to convert this diagnostic signal into a causal account. The specific response of the digestive gland gives that future monitoring a concrete, organ-level target.

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Conflict of Interest Statement

The authors declare no competing financial or non-financial interests that could have influenced the work reported in this manuscript.

Ethics declarations:

Ethical approval and participant consent were not required for this study, as no human participants, human tissues, or clinical trials were involved.

Author Contributions

S.A.E.: Conceptualization (lead); Methodology (lead); Investigation (equal); Formal analysis (lead); Writing – original draft (lead). M.F.: Methodology (supporting); Investigation (equal); Data curation (lead); Writing – review and editing (equal). K.E.H.: Formal analysis (supporting); Validation (lead); Visualization (lead); Writing – review and editing (equal). Z.S.: Investigation (supporting); Resources (lead); Writing – review and editing (supporting). M.A.: Resources (supporting); Supervision (lead); Project administration (lead); Writing – review and editing (equal).

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