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# Cadmium bioaccumulation in two resident limpet species, *Scutellastra granularis* and *Siphonaria capensis*, along the South African coastline

We investigated cadmium (Cd) bioaccumulation in two limpet species, *Scutellastra granularis* and *Siphonaria capensis*, along the South African coastline from three sites: Namaqua National Park, West Coast National Park and Garden Route National Park. Significant spatial variations in Cd accumulation were observed, with the highest concentrations found in limpets from Namaqua National Park (*S. granularis*:  $4.17 \pm 1.99$   $\mu\text{g/g}$ ; *S. capensis*:  $2.92 \pm 1.45$   $\mu\text{g/g}$ ) despite having the lowest water Cd levels ( $0.13 \pm 0.07$   $\mu\text{g/L}$ ). This suggests alternative Cd uptake pathways, such as dietary intake from contaminated algae or sediments. Additionally, larger limpets exhibited higher Cd concentrations, highlighting the importance of considering organism size in biomonitoring studies. The bioconcentration factor analysis further indicated significant site-specific differences, with the highest factor at Namaqua National Park (*S. granularis*:  $32.59 \pm 15.62$ ; *S. capensis*:  $22.81 \pm 11.29$ ). These findings highlight the relationship between environmental exposure and physiological traits in Cd bioaccumulation and the necessity for site-specific assessments and using multiple bioindicator species in environmental monitoring. This study shows the importance of continued research into long-term and spatial variations in metal bioaccumulation in marine ecosystems.

#### Significance:

- This study highlights Cd bioaccumulation in limpets, indicating potential pollution pathways.
- We have demonstrated that *S. granularis* and *S. capensis* can serve as bioindicator species for Cd monitoring.
- Results on spatial significance stress the importance of site-specific monitoring.
- Our results show that organism size matters in pollution assessments.
- There was no correlation between metal concentration in the water and that in the organism.

## Introduction

Coastal regions across the world are subjected to significant metal pollution, resulting from agricultural and industrial activities.<sup>1</sup> With over 70% of South Africa's coastline inhabited, elevated anthropogenic pressures on the nearshore marine environment are becoming more prevalent.<sup>2</sup> Metals naturally occur in the marine environment at low concentrations; however, due to increased anthropogenic pressures, coastal waters are becoming progressively vulnerable to a rise in metal pollution.<sup>3</sup> Metals pose a considerable threat to marine ecosystems due to organism toxicity at low concentrations, environmental persistence and bioaccumulation ability.<sup>4</sup> Bioaccumulation refers to the uptake process of organismal toxicants, such as chemicals and metals, through consumption of contaminated food or direct exposure, be it over short (acute) or long (chronic) periods.<sup>4,5</sup> The degree of metal bioaccumulation is influenced by factors such as the metal bioavailability, the route of uptake, and sequestration or depuration of the toxicant.<sup>6</sup> The greatest threat associated with metal bioaccumulation within the tissues of organisms is biomagnification in the higher trophic levels.<sup>7,8</sup>

Cadmium (Cd) primarily enters water bodies through industrial sources, including zinc (Zn) smelting, electroplating, fossil fuel combustion, plastics, pesticides and oil refining.<sup>9</sup> Research on Cd has intensified globally due to its toxicity at low concentrations, and its ability to biomagnify through trophic levels, thus affecting humans.<sup>1,10-18</sup> Cadmium accumulation occurs in organisms primarily via ingestion, as the metal ions are poorly soluble in water, binding to suspended particulate matter in the ocean, which is ingested and absorbed by filter-feeding organisms.<sup>4</sup> Local studies have demonstrated that gastropods, such as limpets, accumulate metals and can serve as potential bioindicator species.<sup>19,20</sup> Despite the variety of bioindicator species used in South Africa, information on the responses of limpets to metals in the marine environment is limited.

A commonly used approach for environmental biomonitoring is quantifying pollutant loads in organisms that bioaccumulate.<sup>21</sup> Metal concentrations in tissues depend on the uptake, excretion and metabolic capacity to either degrade and/or transform these toxic pollutants.<sup>21</sup> The use of a single bioindicator species when determining metal pollution is not ideal because certain metal concentrations may differ from one species to another.<sup>22</sup> Therefore, different species inhabiting different coastal zones need to be assessed. Recent studies include using the invasive Mediterranean mussel (*Mytilus galloprovincialis*) and endemic brown mussel (*Perna perna*) along the southern and east coasts of South Africa.<sup>3,23-25</sup> Limpets were selected for this study due to their wide distribution, feeding behaviour, being reasonably sessile, and distinct ability to tolerate environmental challenges, making them a key study organism when looking at the effect of environmental changes on intertidal organisms.<sup>19,26</sup> The limpets *Scutellastra granularis* (Linnaeus 1758), a prosobranch found high on the shore, and *Siphonaria capensis* (Quoy and Gaimard 1833), a pulmonate gastropod found in pools and on emergent mid-shore rocks<sup>27,28</sup>, were selected to investigate the variation in Cd uptake and bioaccumulation across key sites along the South African coastline. These

species of limpet were used to investigate Cd bioaccumulation due to their different phylogenies (i.e. pulmonate versus patellogastropod) and associated tidal heights along their sympatric distribution in South Africa.

In this study, we describe the spatial patterns of Cd concentrations in South African coastal waters using *S. granularis* and *S. capensis* as quantitative bioindicators. We investigated the effect of weight and size on Cd bioaccumulation. Spatial patterns for each species were used to compare Cd concentrations in water and tissue samples with inferred bioconcentration factors, and these are discussed in terms of background (environmental) concentrations and their sources.

## Materials and methods

### Site selection and animal collection

The study took place in three marine protected areas, chosen in a west–east direction along the South African coastline. The South African coastline is a dynamic environment surrounded by two major ocean currents bringing contrasting environmental conditions.<sup>29</sup> The west coast is a cool temperate ecoregion influenced by the Benguela Current that transports cold nutrient-rich water, whereas the southern coast is classified as warm temperate and influenced by the warm water Agulhas Current.<sup>27–30</sup> Sites selected were two from the west coast: the Namaqua National Park (NNP; 30°51'31.8"S, 17°34'31.1"E) in the Northern Cape and the West Coast National Park (WCNP; 33°08'56.2"S, 17°59'57.9"E) in the Western Cape; and the Garden Route National Park (GRNP; 34°01'14.9"S, 23°52'26.7"E) in the Eastern Cape from the southern coast ecoregion of South Africa (Figure 1). Field fresh samples of similar size (total shell length) were collected from all three sites ( $\Sigma n = 3$  sites  $\times$  2 species  $\times$  10 individuals (replicates) = 60) in January 2020 (Supplementary tables 1–8). The number of individuals collected was determined by both the University of Johannesburg Animal Ethics

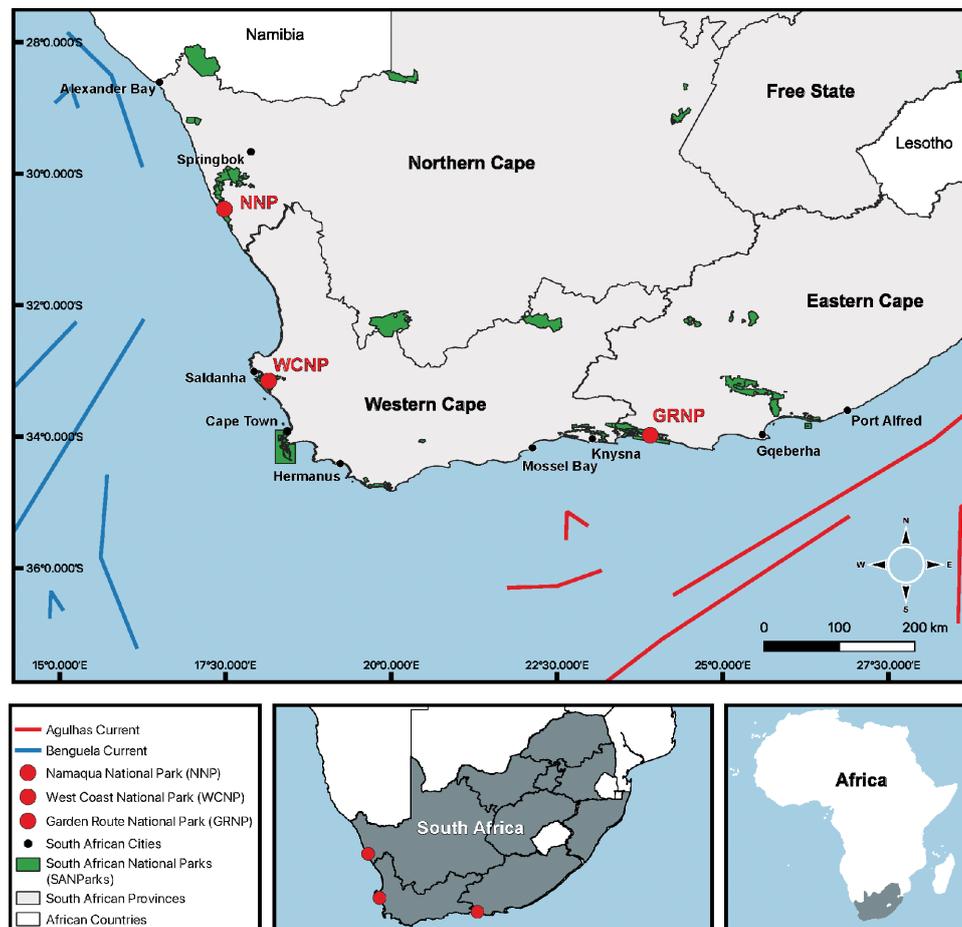
Committee (2019-06-10/Greenfield\_Connell) and the SANParks permitting office (permit number CRC/2020-2021/005--2017/V1). Organisms were collected during low tide (at first daylight). Organisms were carefully removed from the rock surface using either a spatula or by hand and only undamaged individuals were selected. Individuals were classified as undamaged when there was no visible damage on the shell or foot. Field fresh samples collected at each site were flash frozen in liquid nitrogen (–196 °C) and stored at –20 °C for subsequent baseline metal analysis. Water samples ( $\Sigma n = 3$  sites  $\times$  3 water samples (replicates) of 50 mL each = 9) were collected from each site (one sample per day of sampling) and stored at –20 °C for background metal analysis. During collection of water samples, physicochemical parameters (temperature [°C], pH and salinity [PSU]) were recorded using a Thermo Scientific Eutech Elite PCTS multi-parameter meter.

### Bioaccumulation analysis

#### Sample preparation and digestion

The water samples (50 mL) were stored in 50-mL Falcon Centrifuge Tubes and filtered using a Millipore sintered glass filtration system (Merck, South Africa) through a gridded cellulose nitrate membrane filter (type 114, 0.45  $\mu$ m). Samples were acidified to 1% with Suprapur® nitric acid (63.01 g/mol HNO<sub>3</sub>; Merck, South Africa).

Whole organism tissue was removed from the shell using a spatula before metal accumulation analysis in accordance with the methods outlined by Boss and Fredeen<sup>31</sup> and Gaines<sup>32</sup>, and adapted from Erasmus et al.<sup>29</sup> Frozen samples were weighed ( $\pm$  0.01 g) to obtain a wet weight, after which the samples were freeze dried (–50 °C at 0.61 mbar) for 48 h using the Martin-Christ LDplus Freeze Dryer (Christ Freeze Dryers, Niedersachsen, Germany). The freeze-dried (whole organism) samples were weighed to obtain a final dry weight, in which the weight was normalised using



**Figure 1:** Map of sampling localities along the west and southern coasts of South Africa. Localities include Namaqua National Park (NNP) and the West Coast National Park (WCNP) along the west coast, and the Garden Route National Park (GRNP) along the southern coast.

the bioconcentration factor calculation, before being digested using the MARS 6 One Touch Technology Microwave (CEM, Charlotte, NC, USA). Before digestion, the Teflon bombs used during processing were cleaned and dried in accordance with the cleaning method, using standard grade HNO<sub>3</sub> (Merck, South Africa) and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>; Merck, South Africa). Standard reference material (SRM; mussel tissue – 2976, 109% recovery), as well as the freeze-dried samples, were individually added to each Teflon bomb along with 5 mL Suprapur® 65% HNO<sub>3</sub> (Merck, South Africa). After digestion, the samples were allowed to cool, before being placed in 15-mL Falcon tubes. Samples were gravimetrically diluted using double distilled water (18.2 Ω) to a total volume of 10 mL.

### Inductively coupled plasma mass spectrometry

Water (diluted by a factor of 10) and tissue samples were analysed using a PerkinElmer NexION® 300 series inductively coupled plasma mass spectrometer (ICP-MS) (PerkinElmer, Waltham, MA, USA). The ICP-MS was calibrated using 0, 0.01, 0.1 and 1 ppb calibration standards, made using the appropriate dilutions from a 100 ppm Cd stock solution (100 mg/L). An internal standard (iridium – 193) was added to each water and tissue sample (100 ppm) before analysis for quality assurance, along with a standard reference material (mussel tissue – 2976), to ensure sufficient recovery and that no drifting occurred during the analysis.

### Bioconcentration factor

The bioconcentration factor (BCF) was determined according to the method of Abel<sup>33</sup>. This method determines the ratio between the Cd concentration in organisms and water samples ( $C_{\text{Organism dry weight}}/C_{\text{Water}}$ ), where the  $C_{\text{Organism dry weight}}$  (µg/g dry weight) and  $C_{\text{Water}}$  (µg/L) are the fractions of the element within the organism and the environment (water). The median concentration values of the element present in each organism and the water were used to calculate the BCF.

### Statistical analysis

Statistical analyses were conducted using RStudio (v. 4.0.3). All data met the assumptions of normality and homogeneity of variance, following Levene's and Shapiro–Wilk tests, respectively.<sup>34</sup> Following testing of assumptions, one-way analyses of variance were performed on Cd concentration in water samples (factors: site, three levels and fixed, significance set at  $p < 0.05$ ), Cd concentration in tissue samples (factors: site, three levels and fixed, significance set at  $p < 0.05$ ), and bioconcentration factor (factors: site, three levels and fixed, significance set at  $p < 0.05$ ) for each species. Where there were significant factors, a pairwise comparison was performed using Tukey's honestly significant difference test.<sup>34</sup> All statistical analyses were performed using the *car* and *tidyverse* packages in RStudio.<sup>35,36</sup> Barplots (±SEM) were created using the *ggplot2* and *plyr* packages in RStudio.<sup>37,38</sup>

## Results

### Environmental water quality parameters

The physicochemical parameters – temperature (°C), pH and salinity (PSU) – that were measured in situ at the three sites are shown in Table 1. The measured parameters showed great variation across the sites between sampling periods at each site (high SD values) as well as among the

sites themselves. Temperature showed significant variation across sites ( $F_{(2,8)} = 91.5, p = 3.2e^{-05}$ ). Water temperature was significantly higher at GRNP than at both west coast sites (NNP and WCNP, Table 1). Water temperature also varied significantly between the two west coast sites (NNP and WCNP), with significantly lower temperatures recorded at NNP. All other water quality parameters (pH and salinity) were not significantly different across the three sites ( $p > 0.05$ , Table 1).

### Cadmium concentrations versus weight and size

Cadmium concentrations in whole body tissues (without shell) were plotted against the wet weight (g) and size (mm) for both species of limpets, *S. granularis* and *S. capensis*; the results are illustrated in Figure 2A (weight) and 2B (size). Concentration of Cd in whole body limpets showed no significant change with increasing weight of either species ( $F_{(3,56)} = 0.0482, p = 0.986$ ; Figure 2A). With increasing weight, both *S. granularis* and *S. capensis* showed no significant change in their individual Cd concentrations, with  $R^2$  values of 0.001 and 0.002, respectively. In contrast, concentration of Cd in whole body limpets showed a significant change with increasing size ( $F_{(3,56)} = 5.347, p = 0.003$ ; Figure 2B). Both *S. capensis* and *S. granularis* showed increases in Cd concentrations with an increase in size. *S. capensis* showed a slightly stronger correlation between size and concentration than *S. granularis* ( $R^2 = 0.26$  and  $R^2 = 0.20$  respectively).

### Cadmium concentration in water from the southern and west coasts

Cadmium concentrations within water samples collected at each respective site during the sampling of *S. granularis* and *S. capensis* are shown in Figure 3. No statistically significant differences in Cd concentrations were present in water samples between the three sites ( $F_{(2,8)} = 1.837, p = 0.239$ ; Figure 3, Supplementary table 3), with the concentration ranging from 0.13 µg/L at NNP on the west coast to 0.24 µg/L at GRNP on the southern coast.

### Cadmium concentrations in field-fresh *S. granularis* and *S. capensis*

The measured concentrations of Cd in both *S. granularis* and *S. capensis* are presented in Supplementary table 6 and Figure 4A. Cd concentrations

Table 1: Mean (±SD) water quality measures taken in situ at each sampling site during each day of sampling ( $n = 3$ )

	Namaqua National Park	West Coast National Park	Garden Route National Park
Temperature (°C)	16.18 ± 2.01 <sup>ab</sup>	16.47 ± 0.06 <sup>ac</sup>	19.40 ± 0.17 <sup>bc</sup>
pH	8.01 ± 0.10	7.06 ± 0.69	7.71 ± 0.31
Salinity (PSU)	33.17 ± 1.17	38.33 ± 2.52	35.33 ± 3.21

Common superscripts indicate statistically significant differences in water quality parameters across sites ( $p < 0.05$ )

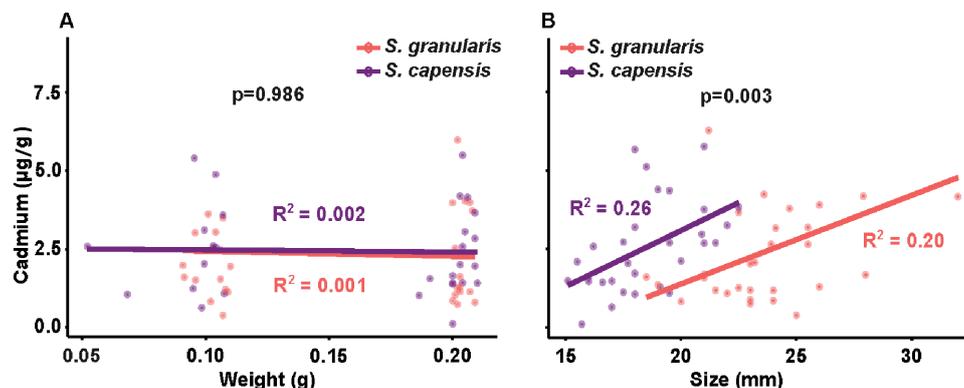
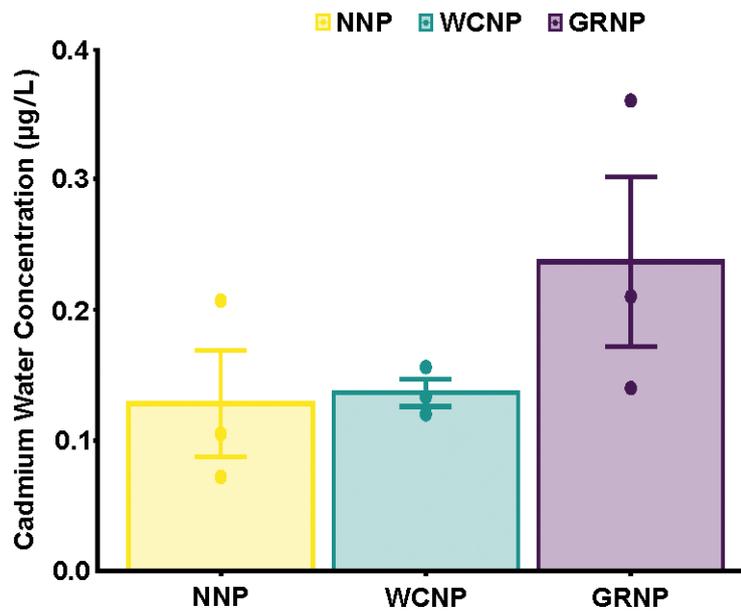
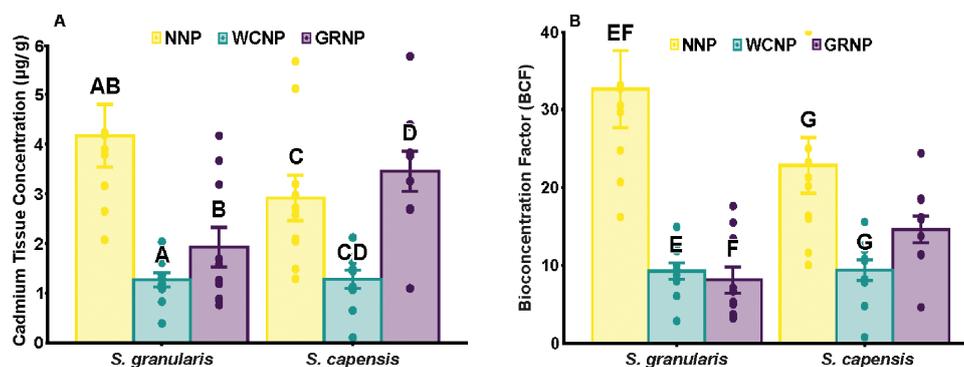


Figure 2: General linear model showing the relationship between cadmium concentration (µg/g) and the weight (A) and size (B) of *Scutellastra granularis* and *Siphonaria capensis*.



**Figure 3:** Mean ( $\pm$ SEM) levels of cadmium in water samples ( $n = 3$  per site) collected from Namaqua National Park (NNP), West Coast National Park (WCNP) and Garden Route National Park (GRNP).



**Figure 4:** (A) Mean ( $\pm$ SEM) levels of cadmium in *Scutellastra granularis* and *Siphonaria capensis* ( $n = 10$ ) collected from Namaqua National Park (NNP), West Coast National Park (WCNP) and Garden Route National Park (GRNP). (B) Bioconcentration factor variation in *S. granularis* and *S. capensis* ( $n = 10$ ) using cadmium concentrations in water and tissue samples collected from each site (NNP, WCNP and GRNP).

from whole body *S. granularis* tissue were significantly different between sites ( $F_{(2, 29)} = 11.978, p = 0.0002$ ; Supplementary table 6). At NNP, *S. granularis* accumulated significantly higher concentrations of Cd than at both other sites, WCNP and GRNP (Figure 4A). A similar trend was observed in *S. capensis*, which showed spatial variances in Cd concentrations across all three sites ( $F_{(2, 29)} = 9.522, p = 0.0007$ ; Supplementary table 6). Limpets collected from NNP had significantly higher Cd concentrations ( $p < 0.01$ ) than those collected and analysed from the WCNP (Figure 4A). Dissimilarly, along the southern coast at GRNP, *S. capensis* had the highest Cd concentrations out of the three sites, being significantly higher than at WCNP ( $p < 0.001$ ).

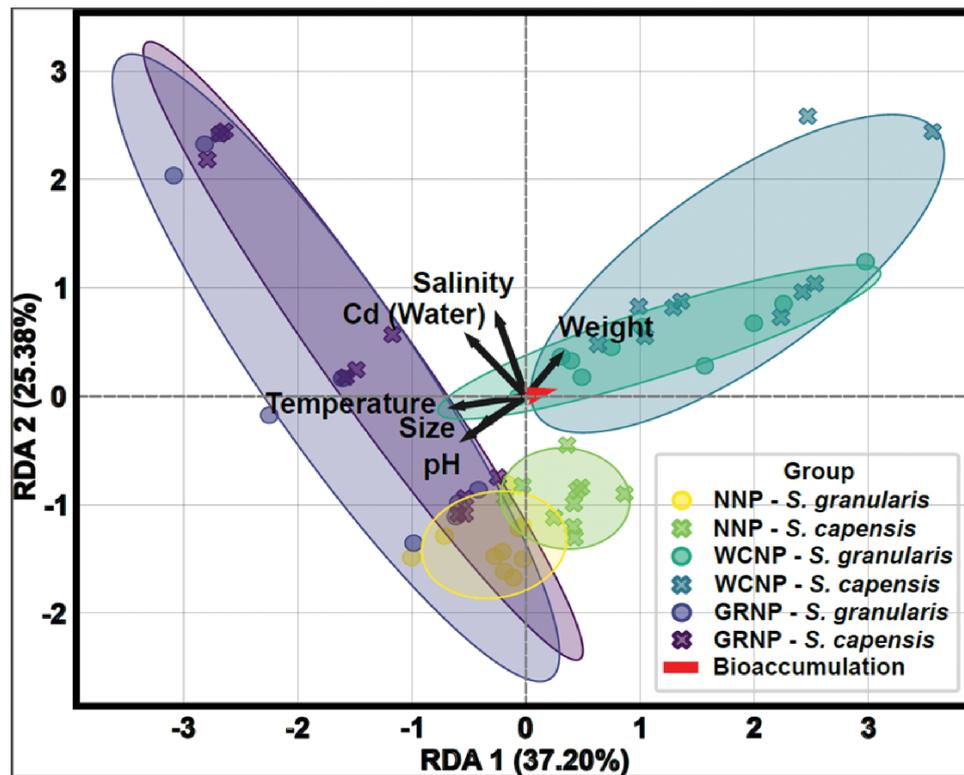
A redundancy analysis (RDA) triplot is shown in Figure 5. Individual *S. granularis* and *S. capensis* from each site are represented by ellipses (encompassing 95% of the sample area), with environmental variables depicted as arrows indicating their direction and strength of influence. The RDA explains 62.58% of the total variation in Cd bioaccumulation attributable to environmental variables, with RDA 1 (x-axis) accounting for 37.20% and RDA 2 (y-axis) for 25.38% of the variance in bioaccumulation.

The plot indicates that temperature, pH and limpet size (length) are the strongest positive drivers of Cd bioaccumulation in both species in GRNP along the southern coast. Both *S. granularis* and *S. capensis* from GRNP exhibit the largest ellipses, indicating greater individual variation in bioaccumulation levels. In contrast, individuals from WCNP show tighter ellipses, reflecting less variation in bioaccumulation. For these populations,

weight and Cd concentration in water are the most influential positive drivers, suggesting a strong relationship between individual weight and Cd bioaccumulation. Finally, both species from NNP display the tightest ellipses, indicating minimal intra-site variation in bioaccumulation. Bioaccumulation is also positively influenced by pH and size (length) and negatively influenced by salinity and Cd levels in water.

#### Bioconcentration factor of cadmium in *S. granularis* and *S. capensis*

The results obtained show the BCF of Cd in both *S. granularis* and *S. capensis* and are presented in Supplementary table 8 and Figure 4B. Spatial differences in the BCF of Cd in *S. granularis* were significant ( $F_{(2, 29)} = 20.120, p < 0.001$ ). As seen in the Cd concentrations of *S. granularis*, the BCF spatial variance showed the same pattern. *S. granularis* from NNP showed the greatest BCF, differing significantly from those from both WCNP and GRNP ( $p < 0.001$ , Figure 4B). No difference was observed in the BCF of *S. granularis* between WCNP and GRNP ( $p > 0.05$ ). Unlike in the Cd concentrations observed in *S. capensis* (Figure 4A), a dissimilar trend was observed in the BCF values across sites, although significant spatial differences were observed ( $F_{(2, 29)} = 7.86, p = 0.002$ ; Figure 4B, Supplementary table 8): *S. capensis* from NNP exhibited the greatest BCF, differing significantly with limpets sampled from WCNP ( $p < 0.01$ , Figure 4B). No other significant spatial differences were observed in *S. capensis* between NNP and GRNP, nor between NNP and GRNP ( $p > 0.05$ , Figure 4B).



**Figure 5:** Redundancy analysis (RDA) triplot showing bioaccumulation of cadmium (Cd) in *Scutellastra granularis* and *Siphonaria capensis* and the effect of environmental variables (drivers). Sites and species are represented by ellipses and drivers (environmental variables) by arrows. The ellipse for each group is set to 95% inclusion. The triplot explains 62.58% of the variation, with 37.20% on the x-axis (DRA 1) and 25.38% on the y-axis (RDA 2).

## Discussion

While metal contaminants occur naturally in the marine environment at low concentrations, anthropogenic influence on the marine environment has exacerbated the situation.<sup>39,40</sup> The results from this study reveal significant bioaccumulation of Cd in two limpet species, *S. granularis* and *S. capensis*, collected from different coastal regions in South Africa. Comparing Cd concentrations in both limpet species to that found in water samples analysed indicates that Cd is strongly accumulated in both species from their respective surrounding environments, as indicated by the BCF results. Cadmium is known as a toxic metal, even at low concentrations, and as such is considered non-essential for biological function. Metalloproteins such as metallothionein are produced and upregulated in limpets as a response to cadmium-induced oxidative stress, serving as a protective mechanism against metal toxicity.<sup>11,13,41</sup> Potential sources of Cd in the marine environment come from the emissions of industrial combustion processes, metallurgical industries, road transport, and waste streams, all of which occur along the west and southern coasts of South Africa.<sup>20,29,42,43</sup> Water samples analysed for Cd showed variation between the southern coast site (GRNP) and the two west coast sites (NNP and WCNP). Studies conducted by Reinecke et al.<sup>19,41</sup> indicated Cd concentrations along the South African coastline varied considerably spatially and temporally. Degger et al.<sup>40</sup> measured unexpectedly high metal concentrations (Cd and Zn) in brown mussels (*P. perna*) along the southern coast at Tsitsikamma National Park (within GRNP) compared to localities with known anthropogenic activities and influence (such as WCNP). High concentrations of metals in the study by Degger et al.<sup>40</sup> follow a similar pattern shown in the data from the present study (both the water and organisms). This is indicative of long-term exposure, resulting from freshwater input through geogenic weathering and frequent upwelling that occur along South Africa's southern coast.<sup>29</sup> *S. capensis* showed the greatest Cd accumulation at Namaqua National Park (NNP), with both species having the greatest metal uptake at this site despite lower Cd concentrations in the corresponding water samples. Additionally, these limpets possess physiological traits that enhance Cd retention, such as slower excretion rates or higher binding affinities in tissue proteins.<sup>21,44</sup>

This finding suggests similarity with previous studies, indicating that bioaccumulation in marine organisms occurs through various pathways, including dietary intake and sediment interaction.<sup>4,29</sup>

The BCF indicated Cd had been accumulated in whole tissue samples of *S. granularis* and *S. capensis* in comparison to the concentration of Cd in the environment.<sup>33</sup> Whole tissue samples of both species varied significantly in their accumulation of Cd in relation to their sampling site. This accumulation, however, does not correlate with Cd concentrations from water sampled. Interestingly, despite higher water Cd levels at GRNP, the BCF was highest at NNP for *S. granularis*, suggesting species-specific and site-specific bioaccumulation dynamics, seasonal and exposure level variation.<sup>45</sup> High Cd concentrations at GRNP, as discussed previously, are a direct result of both the freshwater input from geogenic weathering in the region and from upwelling events that are known to occur along the southern coast of South Africa at GRNP.<sup>29,40</sup> The significantly high BCFs at NNP are a direct result of the significantly high concentrations of Cd detected in whole tissue samples of *S. granularis* and *S. capensis*, despite the lower concentrations of Cd in the water. This result is indicative of either a short-term but high-dose exposure to Cd or a different means of uptake in both limpet species other than directly from the water column.<sup>40,46</sup> Elevated metal levels along the west coast, observed at NNP and WCNP, are a direct result of the mining and port activities, as well as the iron and crude oil facilities in the surrounding areas, which lead to elevated pollution of local coastal waters, affecting the inhabitants of these waters.<sup>20,29,42</sup>

The anatomy and physiology of the limpets is also known to play a primary role in the uptake and accumulation of metals. Difference in body size of individuals of the same species has been shown to result in varying metal tissue concentrations.<sup>22,29,47,48</sup> The size of marine ectotherms is related to their metabolic activities in relation to their life history stage.<sup>9</sup> Various metals, such as copper, iron and zinc, in moderate concentrations, are essential to an organism's growth and development; however, non-essential metals such as Cd lead to reduced growth and development, even at low concentrations.<sup>9</sup> Limpet size was positively

correlated with tissue Cd concentration, indicating that larger individuals tend to accumulate more Cd, potentially due to prolonged exposure and greater overall uptake over time.<sup>8,48</sup> This size-related bioaccumulation trend has been observed in other marine invertebrates and highlights the importance of considering organism size in biomonitoring studies.<sup>19,49</sup>

The physiological and anatomical differences between *S. granularis* and *S. capensis* likely contribute to the observed differences in Cd bioaccumulation. *S. granularis*, a prosobranch, and *S. capensis*, a pulmonate gastropod, exhibit distinct respiratory and excretory mechanisms that influence metal uptake and storage.<sup>44</sup> Pulmonate gastropods, such as *S. capensis*, exhibit higher rates of metal accumulation due to their ability to absorb metals through their foot and mantle cavity, in addition to dietary intake.<sup>21,44</sup> Comparative studies have shown that bioaccumulation patterns in marine organisms can vary widely based on local environmental conditions and the species involved. Research on the brown mussel (*P. perna*) has demonstrated significant spatial variation in metal concentrations along the South African coastline, similar to the patterns observed in this study.<sup>40</sup> These findings underscore the importance of site-specific assessments and the use of multiple bioindicator species to accurately gauge environmental metal pollution levels.<sup>20,21</sup>

## Conclusion

This study provides insight into the spatial patterns of Cd bioaccumulation in two limpet species, *S. granularis* and *S. capensis*, along the South African coastline. The findings from both limpet species showed significant spatial variation in Cd accumulation, with *S. granularis* having the highest Cd levels at NNP despite lower Cd concentrations in corresponding water samples. This suggests alternative pathways for Cd uptake, such as dietary intake from contaminated algae or sediments. Additionally, larger individuals from both species exhibited higher Cd concentrations, likely due to greater exposure duration, emphasising the importance of considering organism size in biomonitoring studies. The BCF analysis further indicated that the BCF of Cd in *S. granularis* and *S. capensis* was highest at NNP, highlighting the complex interplay between environmental exposure and physiological traits in Cd bioaccumulation. These findings emphasise the need for site-specific assessments and the use of multiple bioindicator species to effectively assess environmental metal pollution levels in marine ecosystems. Future research should focus on the long-term monitoring of these species across a greater seasonal and spatial gradient, and the exploration of additional environmental factors influencing metal bioaccumulation.

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## Data availability

All the data supporting the results of this study are included in the article itself and in the [supplementary material](#).

## Declarations

We have no competing interests to declare. We have no AI or LLM use to declare. This research forms part of Liam J. Connell's PhD thesis. Clearance for this study was granted by both the University of Johannesburg Animal Ethics Committee (2019-06-10/Greenfield\_Connell) and the SANParks permitting office (permit number CRC/2020-2021/005--2017/V1).

## Authors' contributions

L.J.C.: Conceptualisation, methodology, investigation, sample analysis, formal analysis, validation, data curation, writing – original draft, writing –

review and editing, project leadership, project administration. K.B.: Investigation, sample analysis, validation, writing – review and editing. R.G.: Validation, writing – review and editing, supervision, project leadership, project administration, funding acquisition. All authors read and approved the final manuscript.

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