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Anthropogenic radionuclides bioaccumulation in Antarctic marine fauna and its ecological relevance

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Abstract The paucity of investigations on the presence of artificial radionuclides and their bioaccumulation in Antarctic fauna is due to the erroneous belief that this area is pristine. We report evidence that significant levels of the artificial radionuclides Sr-90, Cs-137, Am-241 and plutonium isotopes can be found in sponges, bivalves, krill and demersal fish fauna of Terra Nova Bay (Ross Sea), sometimes with a seasonal pattern. Increasing concentrations of Cs-137 were detected in the bivalve *Adamussium colbecki* (Antarctic scallop) during austral summer months, as a result of major trophic activity and changes in metabolic rates. Bioconcentration factors for artificial radionuclides in different Antarctic species are presented and discussed in relation to their different trophic strategies. Unexpectedly high radiocesium bioconcentration factors determined in bivalves suggested the particular role played by filter feeding in bioaccumulation, particularly in summer when radionuclide bioavailability is enhanced. The feeding preference of the trematomiid fish *Trematomus bernacchii* for the scallop *A. colbecki* is confirmed, not only by fish gut content analyses, but also through radiometric results. Transuranics bioaccumulation by sensitive species allowed some interesting comparisons on the different plutonium contamination of the southern hemisphere with respect to the northern one.

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Introduction

For several years the Antarctic ecosystem has been considered as unpolluted, but recent papers on heavy metals (Mauri et al. 1990; Nigro et al. 1997; Stromberg 1997) and organic compounds (Jemenez et al. 1999) in marine animals, and radionuclides mostly in abiotic samples (Hashimoto et al. 1989; Roos et al. 1994), demonstrated that even this remote area has been widely contaminated by anthropic activities (Wolff 1990). In spite of such evidence, no literature data are currently available on radionuclides bioaccumulation in the most common Antarctic species.

In this paper, evidence is reported that artificial radionuclides, spread over Antarctica through atmospheric fallout transport (Koide et al. 1982; Pourchet et al. 1997), are accumulated by the Ross Sea benthic fauna. Detectable concentrations of the anthropogenic radionuclides Sr-90, Cs-137, plutonium isotopes and Am-241 were found in sponges, bivalves and demersal fish fauna, collected between 1989 and 1996 in Terra Nova Bay (Ross Sea). Special attention has been focused on the commonest and most sensitive species, particularly bivalves, because of their ecological role in the littoral food web (Chiantore et al. 1998). In addition, importance has been given to the bioaccumulation capacity of each investigated taxon to assess the retention capacities by different species and the radionuclides' biological pathways in the Antarctic ecosystem. This is of major importance because of the very long half-lives (28–24,000) (110 years) and toxicity of the investigated radioisotopes. As reported by Fisher et al. (1999), ectotherms inhabiting cold waters have slower metabolic rates and higher lipid reserves than do comparable organisms from warmer waters, and it is not known whether these characteristics would influence the bioaccumulation properties or not.

With the aim of providing additional data on bioaccumulation characteristics of polar species, bioconcentration factors (IAEA 1985; Fisher et al. 1999) for americium, cesium, plutonium and strontium isotopes were determined in *Adamussium colbecki* Smith, 1902 (Mollusca, Bivalvia), *Artemisina tubulosa* Koltun, 1964 and *Gellius rudis* Topsent, 1901 (Porifera, Demospongiae), *Euphausia superba* Dana, 1852 (Crustacea, Euphausiacea), *Trematomus bernacchii* Boulenger, 1902 and *Chionodraco hamatus* Lonneberg, 1905 (Osteichthyes, Perciformes), and are herein discussed.

With regard to the paucity of data about bioaccumulation in the Southern Ocean fauna, this is the first attempt to present bioconcentration factors for the most important artificial radionuclides in Antarctic species. The variability of data as a consequence of some natural processes, and the importance of a correct interpretation of results in relation to changing ecological conditions are discussed.

These results add further knowledge to the understanding of trophic relationships and radioactive pollutants transfer within the Antarctic food web, and can be considered as baseline data on polar species for future investigations to be carried out at both environmental and population level in cases of nuclear impact assessments.

Materials and methods

The activities of the Italian programme at the base of Terra Nova Bay in Victoria Land are carried out only during summer time and for this reason our samples were collected between December and February of each year in the period 1987–1996. During this period, most ecosystem activities and animal metabolic processes tend to increase after the long winter rest. We therefore considered this season the most sensitive period for radioecological investigations. Sampling activities covered a wide area of Terra Nova Bay and forelying Ross Sea (between approximately latitudes 74° and 75°S and longitude 164°E; one sample of krill was collected at 175°E during navigation).

Nineteen samples of six different species were collected: in particular, specimens of *Adamussium colbecki* (Mollusca, Bivalvia) were collected by dredge, as well as *Artemisina tubulosa* and *G. rudis* (Porifera, Demospongiae), and *T. bernacchii* and *C. hamatus* (Osteichthyes, Perciformes) by trawls; one sample of *E. superba* (Crustacea, Euphausiacea) was collected by a megaplankton net (500 μm mesh) during the oceanographic cruise from New Zealand to Antarctica in 1994. All species and related sampling sites are reported in Table 1.

Bivalves and fish were firstly analysed for sex and biometric parameters, and dissected into their principal anatomical components. The edible part of some bivalve specimens was accurately washed with isoosmotic artificial marine water to remove abiotic particles from external surfaces and avoid sediment contamination. Fish gut contents were weighed and analysed both at macroscopic and microscopic levels. All specimens were then oven-dried (105 °C) until constant weight was reached, finely ground and submitted to radioanalytical procedures for the radiometric determinations of alpha-, beta- and gamma-emitting radionuclides. Dry weight/wet weight percentages were calculated for the determination of the organism's Bioconcentration Factor (C.F.), which is defined as the ratio between activity concentration of organism sample ($Bq \cdot kg^{-1}$ wet weight) and that of seawater ($Bq \cdot l^{-1}$) (IAEA 1985; Fisher et al. 1999). The C.F. indicates how many times the organism concentrates the pollutant from the surrounding medium, and can be considered a direct representation of the bioaccumulation properties of the animal relative to background environmental conditions.

Direct gamma spectrometry for Cs-137 determinations on ground samples was carried out using high-resolution PGT Silena and EG&G-Ortec HPGe detectors, Sr-90 by an ASPN beta scintillation counter, and plutonium isotopes and Am-241 by alpha spectrometry carried out by means of two EG&G-Ortec silicon chambers. Americium, plutonium and strontium were analysed after the application of a new radiochemical separation technique (Jia et al. 1998). This sensitive and reliable technique allowed the sequential determination of the three elements from the same sample. We were therefore able to detect the transuranics and the beta emitter from small quantities of dry material after the Cs-137 determination. Mean sample weights ranged between 300 g (gamma spectrometry) and 50 g (radiochemical separations of alpha and beta emitters). Each sample was made up of several different individuals to maintain the population variability. Counting times varied between 1 day and 1 week in relation to the sample quantities and signal intensities.

All sample treatments, radioanalytical methodologies and instrument characteristics have been fully described elsewhere (Jia et al. 1998; Nonnis Marzano et al. 1998). In addition, quality control was assured by several analyses made on certified biotic and abiotic samples (IAEA 307, IAEA 367, IAEA 368) supplied by the IAEA (International Atomic Energy Agency).

Table 1 Sampling sites and species collected during PNRA scientific expeditions at Terra Nova Bay (Ross Sea)

Species	Taxon	Latitude (S)	Longitude (E)	Date
Artemisina tubulosa	Porifera	74°43′	164°08′	Jan. 1994
Gellius rudis	Porifera	74°43′	164°08′	Jan. 1994
Adamussium colbecki	Mollusca	74°43′	164°08′	Feb. 1989
		74°42′	164°06′	Jan. 1990
		74°41′	164°08′	Jan. 1990
		74°42′	164°07′	Dec. 1990
		74°42′	164°09′	Jan. 1994
		74°43′	164°09′	Feb. 1995
Euphausia superba	Crustacea	74°36′	175°00′	Nov. 1994
Trematomus bernacchii	Osteichthyes	74°42′	164°06′	Feb. 1989
		74°41′	164°08′	Jan. 1990
		74°42′	164°07′	Dec. 1990
		74°42′	164°09′	Jan. 1994
		74°43′	164°09′	Dec. 1994
		74°43′	164°09′	Jan. 1995
Chionodraco hamatus	Osteichthyes	74°42′	164°06′	Feb. 1989
		74°41′	164°08′	Jan. 1990
		74°42′	164°09′	Jan. 1994
		74°43′	164°09′	Jan. 1995

Results

The overall radioactive biocontamination of Terra Nova Bay appeared low and generally consistent over a long period of time (1989–1996). However, several exceptions emerged during the summer, especially for Cs-137, which was the commonest radionuclide in each sample. In fact, in spite of the expected general low contamination, some interesting results on the radiocesium uptake by sponges, bivalves and fish were detected. Some data concerning radiocesium in bivalves and fish collected during single campaigns have been reported elsewhere (Nonnis Marzano and Triulzi 1994a; Triulzi et al. 1995; Nonnis Marzano et al. 1998). Ranges of concentrations in all species investigated are reported in Table 2, with the aim of comparing the retention capacities by different taxa and the potential transfer within an Antarctic trophic web. Most of these results are unpublished.

As can be observed, Cs-137 is the most abundant radionuclide and the only one detected in all samples, although in very small amounts in krill. It is noteworthy that krill populations have a very short life-cycle compared to the other taxa, and no accumulation of radiocesium occurs. Levels of contamination are actually too low in the water medium (average value 0.50 Bq/m^3) (Nonnis Marzano et al. 1998) and its life-cycle is too short to reach detectable retention.

Higher concentrations were measured in benthic communities (Fig. 1), because of the strict dependance on the sediment layer, which is the final point of pollution accumulation and resuspension (Fowler et al. 1987; Fisher et al. 1999). In fact, unexpected major concentrations as high as 2–3 Bq/kg dry weight (dw) were found in sponges and bivalves, thanks to their filter-feeding habitus. No differences between washed and unwashed samples of bivalves were observed. Radiocontamination of *T. bernacchii* was twice as high as *C. hamatus*. Moreover, fish radiocontamination was lower than that of invertebrates, hardly reaching 0.50 Bq/kg dw (Table 2).

Figure 2 indicates the ranges of bioconcentration factors measured in sponges, edible parts of molluscs and different tissues of fish fauna. Sponge and mollusc values are quite pronounced and much higher than those recommended by the IAEA (1985) reference database and other publications on temperate and Arctic species (Nonnis Marzano and Triulzi 1994b; Fisher et al. 1999). Relevant differences emerged in fish tissues: the values measured in different tissues of *C. hamatus*

Table 2 Ranges of concentrations (Bq/kg dry weight) of cesium, strontium, plutonium and americium isotopes in the different species. Bioconcentration factors for Cs-137 in total organism are reported *in parentheses* on second line of each taxon (*nd* not determined)

Species	Taxon	Cs-137	Sr-90	Pu-239	Pu-238	Am-241
Artemisina tubulosa, *Gellius rudis*[a]	Porifera	1.38–2.10 (365–812)	nd	nd	nd	nd
Euphausia superba	Crustacea	< 0.11	nd	nd	nd	nd
Adamussium colbecki (edible part)	Mollusca	0.20–2.87 (159–925)	0.11	0.015–0.045	0.007–0.013	0.0087
Trematomus bernacchii	Osteichthyes	0.18–0.47 (140–290)	0.08	0.022	0.0053	0.0006
Chionodraco hamatus	Osteichthyes	0.15–0.25 (143–145)	0.03	0.010	0.0025	nd

[a] Sponge samples of the two species were gathered together to reach analytical dry weight

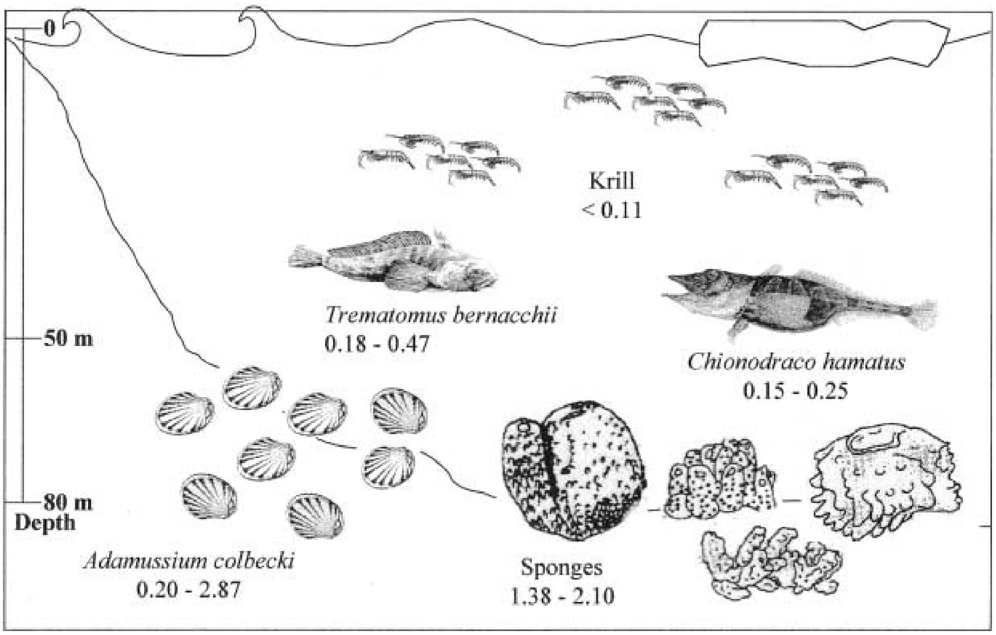

Fig. 1 Concentrations of Cs-137 (Bq/kg dry weight) potentially available within an Antarctic trophic web

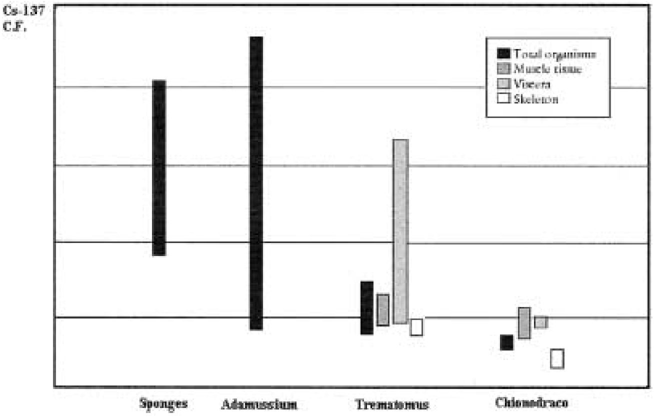

Fig. 2 Ranges of Cs-137 bioconcentration factors in the different taxa. The data illustrate how many times total organism and tissues can concentrate the radionuclide from surrounding water

are consistent and in good agreement with the recommended value of 100–150 (IAEA 1985; Fisher et al. 1999), while the data for *T. bernacchii* are much higher, particularly in viscera.

Significant variations are observed according to a seasonal pattern: in Fig. 3 a representation of the different Cs-137 concentrations during the Antarctic summer season is illustrated, gathering data from different sampling dates.

Such variations are particularly remarkable for *Adamussium colbecki*: data ranged between 0.20 Bq/kg dw in December and 2.5–3.0 Bq/kg dw during the following January, related to the greater food availability (Cattaneo-Vietti et al. 1997; Albertelli et al. 1998).

Furthermore, radiometric analyses on 30 single individuals seemed to vary independently by shell length and soft part weight. In fact, statistical regression indexes were very low ($r^2 = 0.02$–0.05) and not correlated with dimensional classes.

The high values of C.F. found in the viscera of *T. bernacchii* (Fig. 2) and the seasonal concentration pattern observed in this fish seem related to *Adamussium colbecki* fluctuations (Fig. 3), probably because the scallop is the favourite food source for this benthic fish, especially in areas abundantly populated by the bivalve (Vacchi et al. 1994; Vacchi and La Mesa 1995). A direct prey-predator relationship between the two species has recently been evidenced by Vacchi et al. (1998, 1999). Also, in this study, large quantities of bivalves with entire, unbroken shells were largely predominant in the stomach contents and suggested a major contamination brought by these bivalves rather than real bioaccumulation by the fish.

Beta emitters and transuranic radioisotopes were detected only in the most abundant samples because of analytical difficulties and the considerable effort necessary to obtain consistent and certified data with so low a contamination (Table 2). For *Adamussium colbecki*, its role as ''sentinel organism'' (Nigro et al. 1997) and, more generally, as bioindicator of low level radiocontamination, was confirmed by results on plutonium

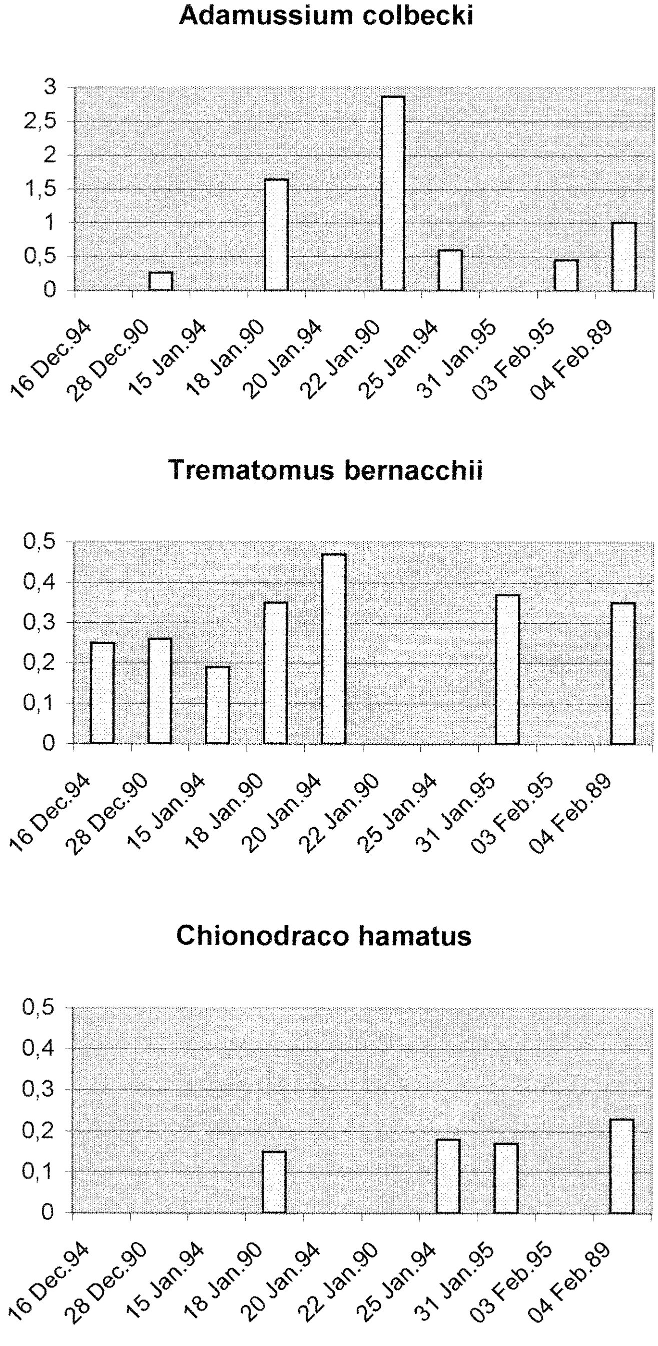

Fig. 3 Trends of Cs-137 concentrations (Bq/kg dry weight) in bivalves and fish collected throughout Antarctic summer. Data from different expeditions were gathered together with the aim of assessing possible seasonal fluctuations

isotopes. The Pu-238/Pu-239 ratio in molluscs and fish was 0.24–0.29.

Concentration factors for transuranics were calculated using regional seawater concentration values (Nonnis Marzano et al. 1999) not corresponding to the biotic samples. Ranges of values in bivalves and total fish were 500–2500 for Pu-239, 700–4000 for Pu-238, and 350–4350 for Am-241. These data are reported for an order of magnitude estimate.

Discussion

In spite of the general idea that radionuclide concentrations in Antarctic biota are often barely detectable and below the level of instrumental detection, measurable concentrations of cesium, strontium, plutonium and americium isotopes were found in almost all investigated taxonomic groups. Cs-137 is the most represented radionuclide in each single taxon, in accordance with its worldwide distribution and abundance (Pourchet et al. 1997).

Some interesting aspects of the ecology of polar species emerge from the radiocesium data. In particular, despite differences in the respective modes of feeding, the filter-feeding habit of Porifera and bivalves seems to be the major factor contributing to Cs-137 bioaccumulation, and suggests the particular bioavailability of this monocationic radioisotope during the austral summer months connected to higher particulate matter production. In comparison, Bondavalli (1994) and Fiori (1998) reported Cs-137 concentrations ranging between 1.0 and 3.5 Bq/kg dw in *Mytilus galloprovincialis* and *Crassostrea gigas* collected in very eutrophicated Mediterranean lagoons.

Wide fluctuations of the concentration factors were observed. Data were very inconsistent, ranging between 100 and 900 (kilograms wet organism/liter seawater). Such values are unexpected and very far from the average value of 30–100 recommended by IAEA (1985), Nonnis Marzano and Triulzi (1994b) and Fisher et al. (1999) for similar species of temperate seas.

The availability of particulate matter at bottom level increases during austral summer (Fabiano et al. 1997; Albertelli et al. 1998) and greatly affects animal metabolism (Cattaneo-Vietti et al. 1997). Particularly for *Adamussium*, its valve-clapping activity appears to be very effective in stirring up the sediment substrate, and this could lead to a concentration of particulate radionuclides. Similar phenomena have already been observed for heavy metals retention by the same bivalves of the same area (Mauri et al. 1990; Nigro et al. 1997). These authors suggested the usefulness of *Adamussium colbecki* as sentinel organism for monitoring the Antarctic environment. Ecological, ethological and biochemical characteristics of this species contribute to the general enhancement of pollutant concentrations with respect to other taxa (Nigro et al. 1992, 1997; Regoli et al. 1997).

It is noteworthy that the general consideration that Cs-137 is mostly a soluble isotope dissolved in pelagic waters must be partially disregarded and revised. In fact, the particulate matter, both as sinking and resuspended material, seems to play a major role in the summer cycling of the radionuclide between biotic and abiotic substrates. In particular, the grazing activity of euphausiids on phytoplankton does not affect the radiocontamination of this taxonomic group because of the short life-cycle and fast renewal of the plankton population. The krill likely acts as a vector in the radionuclide transfer path from the pelagos to the benthos, as first described by Fowler et al. (1987) in the Mediterranean.

However, the benthic filter feeders act as strong bioconcentrators due to their long life-span, low P/B and high filtering activity. Also, the high concentration measured in *T. bernacchii* can be linked to its dietary preferences (Vacchi et al. 1998, 1999). Therefore, radiocesium increase in total fish during summer time is mostly due to internal organ and intestinal contamination brought by undigested bivalves rather than real muscle tissue bioaccumulation. Calculations of C.F. support this statement. In fact, wide variations of contamination in *T. bernacchii* viscera seemed to reflect the C.F. fluctuations of *Adamussium colbecki*. In contrast, *Chionodraco hamatus* preys on different, less contaminated invertebrates, mostly copepods and euphausiids as well as small fish, and therefore radionuclide accumulation is lower. However, it should be noted that this icefish does not feed during the Antarctic summer because of spawning activities and scarce literature is available on the trophic characteristics of this and congeneric species (Takahashi and Nemoto 1984; Schwarzbach 1988).

For Sr-90 and the transuranics, despite the low concentrations detected, they were monitored in most matrices because of the scarce literature data available. As previously described for radiocesium, the trophic link and direct pollutant transfer from *Adamussium colbecki* to *T. bernacchii* is also proved for Sr-90 and the transuranics. In addition, an interesting result emerged from the plutonium data: the Pu-238/Pu-239 ratio in molluscs and fish is 0.24–0.29 and this value was 5–7 times higher than what has been detected in the Mediterranean and Irish areas (Nonnis Marzano et al. 1999; Ryan et al. 1999). The results suggest a different Pu-238 origin, since the Pu-238/Pu-239 weapons fallout ratio is typically 0.033–0.037 (Ryan et al. 1999). In particular, our data in animal species confirm previous investigations by Roos et al. (1994) that reported an increasing fraction of Pu-238 deposited over Antarctica, as a result of the re-entry burn-up in the southern hemisphere of a transit satellite bearing the SNAP 9 A nuclear reactor.

As with radiocesium, bioconcentration factors for transuranics were also very high. Ranges of values in bivalves and fish were between 5×10^2 and 4×10^3. It should be remembered that these data are reported with an order of magnitude estimate and will need further assessments.

In conclusion, future radioecological and other environmental studies should be encouraged and address the assessment of the bioaccumulation capabilities of more filter-feeders and scavengers of the Antarctic benthos. An extended survey of several other zoological taxa would be of major interest for evaluation of possible future contamination events.

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