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Heavy Metals in Isopods from the Supra-littoral Zone on the Southern Shore of the Severn Estuary, UK

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ABSTRACT

The concentrations of zinc, cadmium, lead and copper in the tissues of the littoral isopod Ligia oceanica *from three sites near to a primary zinc, lead and cadmium smelting works on the southern shore of the Severn Estuary and an unpolluted site in the Menai Strait, Anglesey, were determined. The concentrations of zinc, cadmium and copper in whole* L. oceanica *from the contaminated sites were significantly higher than in specimens from the uncontaminated site, although the levels were only about one-and-a-half, three to four and twice as great, respectively. The amounts of lead in* L. oceanica *from all four sites were very small. The hepatopancreas was the most important storage organ of heavy metals and, at all sites, contained more than 50% of the total zinc, cadmium and copper in the body.*

The concentrations of heavy metals were compared in the tissues of L. oceanica *and in two 'more terrestrial' isopods,* Oniscus asellus *and* Porcellio scaber, *collected from the same habitat at one of the contaminated sites. The mean concentrations of copper were the same in the hepatopancreas of all the isopods. However, there were large differences in the extent to which zinc, cadmium and lead had been accumulated by this organ in the three species. Analysis of the gut contents of the isopods revealed that all three species had been feeding on leaf litter derived from nearby trees, rather than on seaweed washed up onto the shore. Therefore, it was concluded that the extent to which zinc,*

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cadmium and lead were assimilated by L. oceanica, O. asellus *and* Porcellio scaber *must have been related to differences in their digestive physiology, rather than to choice of food material containing different concentrations of metals.*

INTRODUCTION

Some of the largest industrial concerns in the UK are situated on the shores of the Severn Estuary. These include the steelworks of South Wales and one of the world's largest primary zinc, lead and cadmium smelting works at Avonmouth near Bristol. Effluents from these industries, combined with the low flushing rate in the Estuary of 200 to 400 days (Abdullah *et al.*, 1973; Chester & Stoner, 1975), have resulted in the waters and sediments of the Bristol Channel containing concentrations of heavy metals, particularly cadmium, which are among the highest of any inshore water in the UK (Abdullah *et al.*, 1972; Preston *et al.*, 1972; Preston, 1973*b*; see also Table 1). In recent years, it has been suggested that a tidal barrage could be constructed across the Severn Estuary to produce hydroelectric power. Such a structure would reduce currents within the Bristol Channel and could lead to an increase in the deposition of suspended particles onto which a large proportion of the metals in the waters of the Estuary are adsorbed (Thorne & Nickless, 1981).

It is important to examine the extent to which invertebrates within the

TABLE 1

Concentrations of Heavy Metals in Seawater (μg litre^{-1}) and Sediments (μg g^{-1} Dry Weight) at the Sites from which the Isopods were Collected

	Site	*Zn*	*Cd*	*Pb*	*Cu*
Seawater	Menai Strait	11·3[d]	0·2[d]	1·1[d]	1·4[d]
	Clevedon	35·0[c]	3·8[c]	1·7[c]	2·0[a]
	Severn Beach	90·0[b]	10·8[b]	1·2[b]	5·3[f]
	Portishead	52·0[c]	5·8[c]	2·5[c]	3·0[a]
Sediments	Menai Strait	113[e]	na	116[e]	44·0[e]
	Clevedon	155[g]	1·3[g]	50·1[g]	28·4[g]
	Severn Beach	213[g]	1·5[g]	61·1[g]	45·0[g]
	Portishead	161[g]	2·2[g]	55·9[g]	40·3[g]

na, not available.
[a] Abdullah & Royle (1974).
[b] Butterworth (1970).
[c] Butterworth *et al.* (1972).
[d] Foster (1976).
[e] Icely & Nott (1980).
[f] Khalily (1975).
[g] Thorne & Nickless (1981).

Severn Estuary accumulate heavy metals, since these organisms would continue to transport metals released from the sediments to higher trophic levels in food chains, even if industrial discharges into the Bristol Channel were stopped (Preston, 1973*a*; Hardisty *et al.*, 1974*b*). Studies by other authors have shown that molluscs and decapod crustaceans in the Severn Estuary contain higher concentrations of cadmium than the same species from uncontaminated sites (Reynolds & Reynolds, 1971; Butterworth *et al.*, 1972; Nickless *et al.*, 1972; Peden *et al.*, 1973; Hardisty *et al.*, 1974*a*; Stenner & Nickless, 1974; Howard & Nickless, 1975, 1977*a*,*b*; Stenner, 1979; Noel-Lambot *et al.*, 1980). However, the concentrations of heavy metals within isopod crustaceans in these waters have not been determined. It might be expected that isopods within the Severn Estuary would accumulate considerable amounts of these elements since the terrestrial species *Oniscus asellus*, collected from sites contaminated with heavy metals, may contain concentrations of zinc, cadmium, lead and copper in the hepatopancreas which are among the highest so far recorded in the soft tissues of any animal (Hopkin & Martin, 1982*a*,*b*).

In this paper, results are presented on the distribution of zinc, cadmium, lead and copper within the tissues of the littoral isopod *Ligia oceanica* collected from three sites close to a primary zinc, lead and cadmium smelting works at Avonmouth on the southern shore of the Severn Estuary, and from an uncontaminated site on the northern shore of the Menai Strait, Anglesey. The concentrations of zinc, cadmium, lead and copper have also been compared in the tissues and gut contents of *Ligia oceanica* and two 'more terrestrial' species of isopod, *Oniscus asellus* and *Porcellio scaber*, collected from the same habitat at one of the contaminated sites.

The concentrations of copper have been measured previously in *Ligia oceanica* by Wieser (1967, 1968) and in the 'high beach' isopod *Tylos punctatus* by Hayes (1970). However, this paper represents the first study of the concentrations of zinc, cadmium and lead in littoral isopods and is the first report on the levels of heavy metals in isopods from the Severn Estuary.

MATERIALS AND METHODS

Samples of *Ligia oceanica* were collected during October 1981 from the base of cliffs on the northern shore of the Menai Strait near Beaumaris, Anglesey, Wales (British Ordnance Survey Reference Number SH 610 770) and from the littoral zone near Clevedon (ST 391 706), Severn Beach (ST 539 856) and Portishead (ST 476 776) on the southern shore of the Severn Estuary. The Menai Strait is unpolluted whereas the three sites in the Severn Estuary are close to a primary zinc, lead and cadmium smelting works at Avonmouth (Fig. 1) and are contaminated with these elements, particularly cadmium (Table 1).

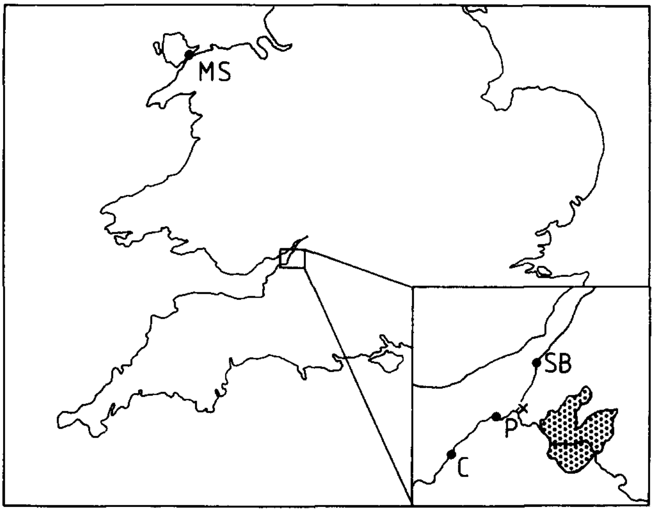

Fig. 1. Sites in the UK from which the isopods were collected. MS, Menai Strait; C, Clevedon; SB, Severn Beach; P, Portishead. The stippled area represents the City of Bristol. The cross marks the position of the primary zinc, lead and cadmium smelting works at Avonmouth.

The isopods were rinsed in distilled water for a few seconds to remove particles of sediment from the body surface. The hepatopancreas and gut were removed from each individual and placed on small pieces of Millipore filter paper which had been dried and weighed. These, together with the rest of the body, including the exoskeleton (rest), were placed in petri dishes and dried overnight at 70 °C. After cooling to room temperature, the samples were weighed on a microbalance. The animals were not starved before dissection.

The samples were digested in 2 ml of boiling, concentrated Aristar grade nitric acid (BDH Chemicals, Poole, Dorset, UK) and diluted to

TABLE 2

Concentrations of Heavy Metals ($\mu g\ g^{-1}$ Dry Weight, Mean ± Standard Error) in *Ligia oceanica* from an Uncontaminated Site on the Northern Shore of the Menai Strait and Three Sites on the Southern Shore of the Severn Estuary. tdw = tissue dry weight (mg)

Site	*tdw*	*Zn*	*Cd*	*Pb*	*Cu*
Menai Strait ($n = 36$)					
Hepatopancreas	9·71 ± 0·92	588 ± 35	14·1 ± 0·7	< 1	497 ± 33
Gut	3·34 ± 0·32	102 ± 5	5·96 ± 0·54	< 3	81·4 ± 6·2
Rest	87·03 ± 7·41	65·7 ± 1·4	0·49 ± 0·04	0·80 ± 0·17	55·4 ± 1·9
Total	99·64 ± 8·51	116^{a} ± 3	1·94^{a} ± 0·07	≥ 0·69	97·9^{a} ± 4·2
Clevedon ($n = 35$)					
Hepatopancreas	7·26 ± 0·56	856 ± 60	45·0 ± 2·9	< 1	1 272 ± 47
Gut	4·03 ± 0·34	76·7 ± 17·4	17·4 ± 1·8	< 3	153 ± 14
Rest	72·91 ± 6·16	79·7 ± 7·6	1·38 ± 0·14	2·7 ± 0·6	88·5 ± 3·3
Total	83·94 ± 6·83	147^{b} ± 9	5·84^{b} ± 0·28	≥ 2·4	193^{bd} ± 5
Severn Beach ($n = 22$)					
Hepatopancreas	8·06 ± 0·68	892 ± 71	60·3 ± 4·7	< 1	1 514 ± 90
Gut	2·93 ± 0·30	140 ± 13	30·7 ± 2·2	< 3	142 ± 22
Rest	62·32 ± 4·43	63·3 ± 2·0	0·71 ± 0·07	< 0·2	78 ± 3
Total	72·90 ± 5·23	155^{b} ± 8	8·13^{bc} ± 2·23	< 0·2	233^{c} ± 9
Portishead ($n = 36$)					
Hepatopancreas	6·87 ± 0·56	1 205 ± 75	74·1 ± 1·1	5·6 ± 0·8	1 690 ± 88
Gut	4·86 ± 0·74	140 ± 9	28·9 ± 3·7	24·5 ± 3·3	59·9 ± 7·8
Rest	69·50 ± 5·57	65·2 ± 2·1	1·81 ± 0·22	0·75 ± 0·05	65·2 ± 2·7
Total	80·66 ± 6·42	166^{b} ± 7	8·96^{c} ± 0·67	2·8 ± 0·4	200^{d} ± 6

Total concentrations of each metal followed by the same letter are not significantly different from others in the same column ($p \leq 0{\cdot}05$, Duncan's New Multiple Range Test).

10 ml with deionised distilled water. Blank digests of Millipore filter paper were also prepared. The digests were analysed for zinc, cadmium, lead and copper by flame (Varian AA775) or flameless (Varian AA6 and CRA90, or Varian AA775 and GTA95) atomic absorption spectrophotometry (AAS). In all cases, correction for non-atomic absorption was made automatically with a deuterium or hydrogen lamp (for further details see Hopkin & Martin, 1982*a*). In some cases, concentrations of lead in the digests were below the detection limit of the flameless spectrophotometer. Thus, figures in Table 2 prefixed by < have been calculated on the assumption that the digests contained concentrations of lead which were just below the detection limit of the analytical techniques. In most cases, these are probably an overestimate but they represent a maximum value which can be compared with other tissues in which lead was detected.

Twelve specimens of *L. oceanica* and six specimens of *O. asellus* and *P. scaber* were collected during October 1983 from beneath large stones above the high water spring tide level at the Portishead site. These isopods were dissected into four fractions— hepatopancreas, gut, gut contents and 'rest'—and were analysed in the same manner as the specimens of *L. oceanica* collected during October 1981. The guts of all the specimens of *O. asellus* and *P. scaber* examined were full, but only six of the guts removed from the specimens of *L. oceanica* contained food material. Fresh preparations of gut contents from each species were also examined by light microscopy. Samples of deciduous leaf litter (mainly oak) and seaweed (*Ascophyllum*) collected from the site were dried, milled, digested in boiling Aristar grade nitric acid and analysed by flame or flameless AAS.

RESULTS

Ligia oceanica

The concentrations of zinc, cadmium and copper in whole *L. oceanica* from the three sites in the Severn Estuary were significantly higher than in specimens from the Menai Strait, although the levels were only about one-and-a-half, three to four and twice as great, respectively (Table 2). The amounts of lead in *L. oceanica* from all four sites were very small. The relatively large amounts of lead in the guts of *L. oceanica* from Portishead

TABLE 3

Concentrations of Heavy Metals ($\mu g\ g^{-1}$ Dry Weight, Mean ± Standard Error) in the Gut Contents of the Isopods from the Supra-littoral Zone at the Portishead Site. See Table 5 for the Concentrations of Heavy Metals in the Tissues of These Animals

Species	*Dry weight (mg)*	*Zn*	*Cd*	*Pb*	*Cu*
Ligia oceanica ($n = 6$)	4·420 ± 0·380	159 ± 14	13·0 ± 0·8	45·2 ± 5·0	22·7 ± 1·4
Oniscus asellus ($n = 6$)	1·395 ± 0·269	145 ± 17	14·2 ± 3·2	66·0 ± 10·6	28·6 ± 3·6
Porcellio scaber ($n = 6$)	0·880 ± 0·155	123 ± 19	9·00 ± 1·49	93·6 ± 10·7	30·1 ± 1·7

(Table 2) were probably associated with food material in the lumen (see Tables 3 and 4). The hepatopancreas was the most important storage organ of heavy metals and, at all sites, contained more than 50 % of the total zinc, cadmium and copper in the whole body.

Comparisons between *Ligia oceanica*, *Oniscus asellus* and *Porcellio scaber*

Two observations suggested that the major proportion of the diets of *L. oceanica*, *O. asellus* and *P. scaber* at the Portishead site consisted of deciduous leaf litter from nearby trees, rather than seaweed washed up onto the shore. First, fresh preparations of the gut contents of all three species were identical in appearance and contained fragments of plant material which could have been derived only from higher plant tissue (vascular bundles, etc.). Secondly, the concentrations of metals in the gut contents were more closely related to those of leaf litter than to seaweed (Tables 3 and 4). This relationship was most obvious in the case of lead

TABLE 4

Concentrations of Heavy Metals ($\mu g\ g^{-1}$ Dry Weight) in Deciduous Leaf Litter and Seaweed from the Supra-littoral Zone at the Portishead Site

	Zn	*Cd*	*Pb*	*Cu*
Seaweed	238	2·7	0·64	22·2
Litter	174	6·0	89·5	20·0

TABLE 5

Concentrations of Heavy Metals ($\mu g\ g^{-1}$ Dry Weight, Mean ± Standard Error) in Three Species of Isopod from the Supra-littoral Zone at the Portishead Site. tdw = tissue dry weight (mg)

Tissue fraction	*tdw*	*Zn*	*Cd*	*Pb*	*Cu*
Ligia oceanica ($n = 12$)					
Hepatopancreas	8·941 ± 1·024	1 422 ± 190	82·8 ± 16·4	3·16 ± 0·76	1 852 ± 270
Gut	1·676 ± 0·188	77·0 ± 10·8	34·9 ± 3·4	< 3	37·1 ± 6·3
Rest	84·43 ± 6·66	56·8 ± 1·6	1·01 ± 0·13	0·73 ± 0·11	53·9 ± 1·55
Total	94·98 ± 7·33	173 ± 9	8·20 ± 0·80	0·90 ± 0·11	203 ± 6
Oniscus asellus ($n = 6$)					
Hepatopancreas	1·463 ± 0·294	963 ± 174	508 ± 96	370 ± 82	2 144 ± 254
Gut	0·651 ± 0·160	167 ± 13	12·2 ± 2·2	23·1 ± 4·9	42·8 ± 5·8
Rest	15·90 ± 1·59	52·5 ± 1·4	0·579 ± 0·078	11·3 ± 1·1	57·2 ± 4·1
Total	18·02 ± 1·96	124 ± 11	36·3 ± 6·0	37·8 ± 6·2	196 ± 18
Porcellio scaber ($n = 6$)					
Hepatopancreas	1·622 ± 0·104	3 874 ± 587	128 ± 27	83·1 ± 16·1	2 569 ± 497
Gut	0·713 ± 0·058	116 ± 13	14·9 ± 8·1	73·9 ± 18·6	30·6 ± 4·9
Rest	16·95 ± 0·97	68·0 ± 2·7	0·675 ± 0·099	10·5 ± 0·4	54·8 ± 2·6
Total	19·28 ± 1·09	367 ± 43	11·5 ± 2·1	18·8 ± 1·8	243 ± 32

which was present in similar concentrations in leaf litter (89·5 μg g^{-1}, Table 4) and the gut contents of the isopods (45·2, 66·0 and 93·6 μg g^{-1}, Table 3) but which occurred in only trace amounts in seaweed (0·64 μg g^{-1}, Table 4). Such comparisons are legitimate since fragments of food in the anterior chamber of the gut, which make up the great majority of the gut contents, are not extensively attacked by digestive enzymes until they reach the much smaller 'papillate region' towards the posterior end of the digestive tract. For a full description of the structure and function of the digestive system of terrestrial isopods, see Hassall (1977), Hassall & Jennings (1975), Hopkin & Martin (1984) and Wieser (1979).

A comparison between the concentrations of zinc, cadmium, lead and copper in *L. oceanica*, *O. asellus* and *P. scaber* collected from the same habitat at the Portishead site showed that copper had been accumulated by the three species to the same relative extent, but that there were large differences in the degree to which the isopods had retained zinc, cadmium and lead in the body (Table 5). Since the three species had been eating similar food, the degree to which zinc, cadmium and lead were assimilated by *L. oceanica*, *O. asellus* and *P. scaber* must have been due to differences in their digestive physiology, rather than to choice of food material containing different concentrations of metals.

The minimum amount of leaf litter which *L. oceanica*, *O. asellus* and *P. scaber* could have eaten during their lifespan can be calculated by assuming that the isopods extracted all the copper from the food as it passed through the gut. For example, the specimens of *L. oceanica* from Portishead must have eaten a mean of at least 935 mg dry weight of leaf material containing 20·0 μg g^{-1} of copper (Table 4) to account for the 19·3 μg of copper in their bodies (Table 6). Using this principle, the relative net assimilation of zinc, cadmium, lead and copper in *L. oceanica*, *O. asellus* and *P. scaber* can be determined (Table 6).

These calculations show that copper was assimilated from leaf litter by all the isopods with a relatively much greater efficiency than zinc, cadmium or lead (Table 6). Furthermore, the large differences in the net assimilation rates for zinc, cadmium and lead in *L. oceanica*, *O. asellus* and *P. scaber* were not consistent between species. For example, *O. asellus* retained about four times more of the cadmium which passed through its gut than *P. scaber* whereas *P. scaber* assimilated more than twice as much zinc from the food as *O. asellus*. Consequently, although there were no significant differences between the concentrations of copper

TABLE 6

Assimilation of Zinc, Cadmium and Lead from Leaf Litter, Relative to Copper, by Isopods from the Supra-littoral Zone at the Portishead Site. M_a, Mean Amount of Metal in Whole Animals (μg); M_p, Amount of Metal Eaten with the Food (μg); P, Proportion of Potentially Available Metal Assimilated ($M_a/M_p \times 100$). The Figure in Parentheses After Each Species is the Amount of Leaf Litter (Dry Weight) which the Isopods would have to have Consumed to Account for the Total Amount of Copper in Their Bodies. The Weights of the Isopods are given in Table 5

Species		*Zn*	*Cd*	*Pb*	*Cu*
Ligia oceanica (965 mg)	M_a	16·4	0·778	0·085	19·3
	M_p	168	5·79	86·4	19·3
	P	9·76%	13·4%	0·001%	100%
Oniscus asellus (176·5 mg)	M_a	2·23	0·654	0·681	3·53
	M_p	30·7	1·06	15·8	3·53
	P	7·26%	61·7%	4·31%	100%
Porcellio scaber (234 mg)	M_a	7·08	0·222	0·362	4·68
	M_p	40·7	1·40	20·9	4·68
	P	17·4%	15·9%	1·73%	100%

in the hepatopancreas of the isopods, there were large and inconsistent differences in the concentrations of zinc, cadmium and lead in this organ of the three species. For example, the concentrations of cadmium and lead were about four times greater in the hepatopancreas of *O. asellus* than in the hepatopancreas of *P. scaber* even though the concentrations of zinc in this organ of *P. scaber* were about four times greater than in the hepatopancreas of *O. asellus* (Table 5).

DISCUSSION

Ligia oceanica

L. oceanica is important in the transfer of heavy metals, particularly cadmium, from vegetation to higher organisms in food chains on the shores of the Severn Estuary. A predator of *L. oceanica*, such as the shore crab *Carcinus maenas* (Nicholls, 1931*a*), would take in some three to four times more cadmium when feeding on *L. oceanica* at the sites studied in this paper than it would feeding on the isopod in an uncontaminated site. *L. oceanica* may also transfer metals to marine predators from leaf litter which has blown onto the shore line. At Portishead, such material contained 140 times more lead than seaweed from the same habitat (Table 4).

L. oceanica manages to survive in large numbers on the southern shore of the Severn Estuary in spite of the pollution of its habitat by heavy metals. However, more detailed observations need to be made on the growth, fecundity, survival and physiology of the isopods from these sites before it can be determined whether *L. oceanica* suffers any ill effects from the elevated levels of zinc, cadmium and copper in its tissues. It has been suggested that the high levels of cadmium in the Severn Estuary may be inhibiting carbohydrate metabolism in limpets (Shore *et al.*, 1975), causing a reduction in the growth rate of flounders (Hardisty *et al.*, 1974*a*) and be preventing dog whelks from colonising the shore between Clevedon and the mouth of the River Avon (Butterworth *et al.*, 1972). Clearly, further studies are urgently required on the effects of pollution by heavy metals on organisms within the Severn Estuary before the full ecological consequences of a tidal barrage can be predicted.

Comparisons between *Ligia oceanica*, *Oniscus asellus* and *Porcellio scaber*

Copper is required by terrestrial isopods as an essential part of the oxygen-carrying blood protein, haemocyanin (Bonaventura & Bonaventura, 1980; Terwilliger, 1982). When isopods moved onto land, their only source of this element was the food in the gut. Unlike their marine ancestors, they could no longer obtain copper from seawater across the respiratory surfaces. Since uncontaminated leaf litter contains only about 10 $\mu g\, g^{-1}$ dry weight of copper (Hopkin & Martin, 1982*a*), the systems for the uptake of this element by the digestive epithelia had to be very efficient. However, in sites where the food contained higher concentrations of copper, the isopods may have assimilated the metal in excess of their requirements. Instead of excreting copper across the digestive epithelia, which would have involved the expenditure of considerable amounts of energy, they appear to store excess copper, within insoluble granules associated with sulphur and calcium, in the S cells of the hepatopancreas (Wieser, 1967; Donadey & Besse, 1972; Hopkin & Martin, 1982*b*). Indeed, it can be calculated from the figures in Table 6 that the isopods could have assimilated all the copper which passed into the body with the food. For example, even if it were assumed that the specimens of *P. scaber* from Portishead were 500 days old, and that they had assimilated copper from their food with an efficiency of

100 %, they would still have to have eaten at least 5 % of their body weight per day in leaf litter to account for the 4·68 μg of copper in their bodies (Table 6). This rate of consumption is within the range of 1 to 10 % of body weight per day quoted in a review of this topic by Wieser (1979).

Zinc is an integral part of many enzymes, including carbonic anhydrase, which is a catalyst in the formation of calcium carbonate (Maren, 1967). Zinc is present at much higher levels in leaf litter than copper (concentrations of zinc in excess of 200 $\mu g\,g^{-1}$ dry weight are not uncommon in leaf litter from uncontaminated sites, Hopkin & Martin, 1982*a*) and the capacity of the hepatopancreas to store this metal would soon be exceeded if all the zinc taken in with the food were retained. Thus, the net uptake of zinc must be regulated, although it is not at present clear whether this is achieved by excluding the metal from the digestive epithelia, or excreting zinc after it has been assimilated. The exoskeleton of *P. scaber* is much more heavily calcified than those of *L. oceanica* and *O. asellus*. Therefore, the greater assimilation of zinc by *P. scaber* may be due to the need to store more of this metal in the hepatopancreas as a reserve to be used during moulting when there is a large demand for carbonic anhydrase for the calcification of the new exoskeleton.

It has been proposed by Hopkin & Martin (1984) that the assimilation efficiency of lead in terrestrial isopods is low because very little of the metal in the food is released into solution in the lumen of the gut by the digestive fluids, which are only mildly acidic (pH 6·0 to 7·0, Nicholls, 1931*b*; Hartenstein, 1964). It would take only small differences in the pHs of the gut contents between species to account for the small percentage differences in the proportions of lead which were assimilated by *L. oceanica*, *O. asellus* and *P. scaber* (Table 6).

Non-essential elements are thought to enter animals by following the same biochemical pathways as essential elements with which they are chemically similar. For example, lead released into solution in the gut of terrestrial isopods is probably taken up by the digestive epithelia, along the same pathways as calcium (Beeby, 1978). In marine decapod Crustacea, cadmium is assimilated via the same biochemical routes as copper and/or zinc and is stored in cysteine-rich, low molecular weight proteins called metallothioneins (Overnell & Trewhella, 1979; Rainbow & Scott, 1979; Overnell, 1982). However, if cadmium followed the same pathways in terrestrial isopods, then the ratios of the concentrations of cadmium and zinc, or cadmium and copper, should be consistent between species. This is not the case in *L. oceanica*, *O. asellus* and *P. scaber* from

Portishead (Table 5). Consequently, there may be mechanisms which have evolved specifically for the exclusion or excretion of cadmium which have been developed to a higher degree in *L. oceanica* and *P. scaber*, which only assimilate 13·4 % and 15·9 % of the cadmium taken in with the food, respectively, than in *O. asellus*, which assimilates 61·7 % (Table 6). If further research were to prove this speculation correct, it would be the first demonstration of a system which existed specifically for the 'detoxification' of a non-essential element in a living organism.

The ability of terrestrial isopods to accumulate zinc, cadmium, lead and copper to such high concentrations has led some authors to suggest that woodlice may be good 'biological monitors' of environmental contamination by heavy metals (Wieser *et al.*, 1976; Coughtrey *et al.*, 1977; Martin & Coughtrey, 1982). The results of the present study (Table 6) emphasise that if *L. oceanica*, *O. asellus* or *P. scaber* are to be used as 'indicators' of pollution by zinc, cadmium or lead, the same species must be compared at different sites.

O. asellus will tolerate concentrations of zinc and cadmium in the hepatopancreas of up to about 1·5% and 0·5% of the dry weight, respectively before this organ becomes deformed and the animals die (Hopkin & Martin, 1982*b*, 1984). If these critical toxic concentrations of zinc and cadmium in the hepatopancreas are similar in all terrestrial isopods, then the resistance of *L. oceanica*, *O. asellus* and *P. scaber* to contamination of their food will be related to the relative assimilation rates of these elements. For example, *L. oceanica* and *P. scaber* may be able to survive in an environment in which the concentrations of cadmium in leaf litter were much higher than would be toxic to *O. asellus* because they assimilate cadmium from the food to a much lesser extent (Table 6).

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