Marine Biology 46, 147-156 (1978)

MARINE BIOLOGY

The Common Mussel *Mytilus edulis* as an Indicator of Trace Metals in Scandinavian Waters. II. Lead, Iron and Manganese

D.J.H. Phillips

Zoology Institute, University of Uppsala; Uppsala, Sweden

Abstract

Concentrations of lead, iron and manganese in whole soft parts of mussels, *Mytilus edulis* (L.), collected from 54 locations in Scandinavian waters were determined. The indicator ability of the mussel for these metals was tested by considering local variations in concentrations of the three metals in relation to known industrial sources. A general agreement with previous published data was reached; the indicator ability of the mussel for lead and iron was supported over the entire range of salinity prevalent in the study area, whereas that for manganese appeared dubious, at least in low-salinity regions. Consideration of the overall profiles of metal contamination revealed similar trends to those previously reported for zinc and cadmium in mussels from the study area, at least for lead and iron. Thus, higher concentrations of lead and iron were found in mussels from low-salinity waters east of Sweden than in mussels from high-salinity waters west of Sweden. The decrease from the high-metal mussel samples to those with low metal concentrations was apparent in the areas of the Sound and Great Belt, coincident with the mixing of Baltic water with water of Kattegat/Skagerrak origin. Concentrations of manganese in mussels followed this trend only weakly, possibly due to the partial regulation of body loads of this element in *M. edulis*. The comparison of lead and iron concentrations in mussels with those reported for water suggested a greater biological availability of these metals in the low-salinity water masses east of Sweden. This availability difference may be related to the low primary productivity of these waters compared to the more typically marine waters to the west of Sweden. The comparison of the concentrations of lead and iron in mussels from the present study with those in mussels from other waters of the world showed Swedish coasts to be severely polluted by lead, particularly on the eastern seaboard; iron concentrations are also rather high in the Baltic samples, but decrease in the Sound and Great Belt to much lower levels, which are maintained in Kattegat and Skagerrak. The profiles for manganese reveal rather higher values in mussels from Scandinavian waters than in those from Britain or New Zealand; however, the uncertainty concerning the indicator ability of *M. edulis* for this element renders the implications of this obscure.

Introduction

The use of the common mussel *Mytilus edulis* as an indicator of environmental contamination by trace metals has been mainly restricted to marine ecosystems to date. The reports of the effects of salinity on the net uptake of metals by this organism (Phillips, 1976a, 1977a; Jackim *et al.*, 1977) suggest that the use of mussels as indicators of metals in estuarine or brackish-water areas may present more of a problem. Similarly, the effects of coexisting trace metals on the net uptake of any one metal by bivalves (Romeril, 1971; Phillips, 1976a; Jackim *et al.*, 1977) raise doubts concerning the ability of these organisms to act as efficient and accurate indicators of the average abundance of certain trace metals in any given environment. Such effects must be clarified if *M. edulis* or a related species is to be used as a worldwide indicator organism, as suggested by Goldberg (1975) and Phillips (1977b).

The present paper reports the concentrations of lead, iron and manganese in whole soft parts of *Mytilus edulis* taken from 54 locations in Scandinavian waters. The ambient annually-averaged salinity throughout the study area varies from 5 to 6‰ S in the waters of the Gulf of Finland and southern Bothnian Sea to 30‰ S in eastern Skagerrak (Segerstråle, 1956, 1957). The concentrations of zinc and cadmium in mussels from the same 54 locations were reported previously (Phillips, 1977c); it was suggested that both zinc and cadmium were more available to mussels in the low-salinity water masses east of Sweden than in the high-salinity waters to the west of Sweden. The present paper considers both the indicator ability of the mussel for lead, iron and manganese (especially as this is affected by salinity) and the availability of these metals to mussels throughout the study area.

Materials and Methods

Details concerning the sampling methods and analytical techniques employed in these studies have been reported previously (Phillips, 1977c) and will be described only briefly here. The sampling procedure used was similar to that suggested by Phillips (1976a); this procedure calls for the sampling of *Mytilus edulis* (L.) of similar sizes from similar depths in the water column at approximately the same season (mid-spring) at all locations. The effects of extraneous sampling variables (see Phillips, 1976a, 1977b) were thus minimised. All mussels were kept in clean seawater from the collection location for 48 h to allow defecation before analysis. The analytical method used was dry-ashing of the whole soft parts from mussel pairs; 10 mussel pairs (20 individuals) from each location were analysed. Pairing of mussels for analysis allows the study of a reasonably large number of individuals from each location whilst retaining some measure of the intralocation variation in trace metal contents of mussels. Dry-ashing was carried out at 390°C for 16 h; samples were subsequently digested with 6.0 N hydrochloric acid for 3 to 4 days. After suitable dilution, samples were analysed by reference to standard salt solutions and use of standard addition methods on a Varian-Techtron AA5 atomic absorption spectrophotometer operated in the flame mode. Final concentrations of metals were calculated on a dry weight basis. This method gives comparable results to those obtained from wet digestion methods (Phillips, unpublished data).

Results

Table 1 shows the concentrations of lead, iron and manganese in *Mytilus edulis* from the 54 study locations in Scandinavian waters; positions of each location have been reported previously (Phillips, 1977c). All results for metal concentrations are quoted as means ± standard deviations of the 10 mussel-pairs analysed from each location. Data for lead and iron in mussels from the Gulf of Finland, the southern Bothnian Sea and the Swedish coast are shown in Fig. 1, and results for these metals in mussels from the Sound and Great Belt are shown in Fig. 2.

The overall concentration profiles for lead and iron were rather similar, with higher concentrations of each metal evident in mussels from the low-salinity regions east of Sweden, especially in those from the Swedish coast. Concentrations of lead and iron decreased rapidly northwards through the Sound and Great Belt (Fig. 2). North of these areas, some small further inputs of metals caused small increases in lead and iron concentrations in mussels, although west coast values never approached typical east coast values over any large region. These profiles for lead and iron are similar to those previously reported for zinc and cadmium in the same mussel samples (Phillips, 1977c), although some local differences were noted. Concentrations of manganese in mussels (Table 1) followed the same trend as those of lead and iron, but the trend for manganese was weaker, with less difference apparent between Swedish east and west coast locations. The concentrations of manganese in mussels were also unexpectedly high in some isolated locations in comparison to those of lead and iron.

Discussion and Conclusions

Indicator Ability of Mytilus edulis

The metals studied in the present work differ from each other with respect to the present knowledge of their uptake kinetics in the mussel. Although the ability of *Mytilus edulis* to serve as an accurate indicator of ambient environmental levels of zinc, cadmium and lead has been well-documented (e.g. Schulz-Baldes, 1973, 1974; Phillips, 1976a, b), data concerning the indicator ability of this organism for iron and manganese are less numerous. The establishment of the indicator ability of *M. edulis* for lead, iron and manganese is necessary before

Table 1. *Mytilus edulis*. Concentrations (means ± standard deviations, µg g dry weight^{-1}) of lead, iron and manganese in whole soft parts of mussels from 54 locations in Scandinavian waters

Location	Location ref. no.[a]	Lead	Iron	Manganese
Helsinki, offshore	1	20 ± 4.6	183 ± 66	35.8 ± 13.4
Kopparnäs	2	30 ± 12.7	217 ± 54	34.5 ± 11.1
Saggö, Åland	3	69 ± 14.6	164 ± 29	9.8 ± 1.4
Finbö. Åland	4	95 ± 40.3	145 ± 26	10.5 ± 2.6
Öregrund	5	187 ± 64.9	200 ± 26	8.2 ± 1.1
Edöfjorden	6	128 ± 29.3	169 ± 32	8.7 ± 1.2
Grissleholmen	7	99 ± 28.7	300 ± 105	37.8 ± 14.4
Korsholmen	8	146 ± 55.0	392 ± 92	71.3 ± 19.1
Rånö	9	210 ± 31.0	510 ± 159	56.6 ± 21.9
Landsort	10	113 ± 33.7	241 ± 34	22.3 ± 4.0
Sävösund	11	86 ± 34.0	577 ± 163	47.5 ± 15.2
Risö	12	92 ± 28.8	557 ± 76	91.7 ± 13.4
Utterholmen	13	98 ± 43.5	336 ± 95	79.9 ± 32.8
Oxelösund ironworks	14	264 ± 50.7	1367 ± 385	64.4 ± 27.5
Navekvarn	15	56 ± 15.6	242 ± 61	52.8 ± 24.6
Isö	16	54 ± 16.5	390 ± 67	39.7 ± 13.5
Simpevarp intake	17	97 ± 52.9	140 ± 25	32.3 ± 8.8
Simpevarp, Lillegrund	18	42 ± 16.3	160 ± 29	14.6 ± 4.7
Southern Öland	19	80 ± 23.9	217 ± 70	28.1 ± 3.8
Torhamn	20	51 ± 28.6	145 ± 42	12.6 ± 3.1
Barsebäck	21	99 ± 41.2	184 ± 40	40.9 ± 10.0
Kullen	22	46 ± 23.1	97 ± 13	35.5 ± 7.7
Steninge	23	14 ± 2.7	56 ± 17	30.4 ± 8.7
Ringhals, Viskan	24	17 ± 5.0	76 ± 10	10.7 ± 3.3
Ringhals, reference	25	12 ± 3.6	56 ± 13	7.7 ± 1.3
Onsala	26	14 ± 4.2	59 ± 17	6.9 ± 1.2
Långholmen	27	30 ± 11.2	112 ± 52	11.5 ± 3.3
Rivö	28	24 ± 8.7	59 ± 25	10.0 ± 2.7
Göteborg	29	58 ± 14.7	128 ± 55	12.0 ± 4.3
Stenungsön	30	13 ± 3.7	31 ± 9	6.2 ± 1.1
Stenungsund	31	14 ± 4.2	47 ± 27	7.1 ± 2.0
St. Askerön	32	16 ± 2.6	31 ± 8	7.9 ± 2.1
Flatholmen	33	4 ± 1.3	52 ± 11	14.7 ± 2.5
Brofjorden	34	3 ± 0.7	61 ± 12	9.7 ± 1.1
Fakse Ladeplads	35	66 ± 36.4	60 ± 13	16.1 ± 6.2
Mosede	36	75 ± 32.6	89 ± 28	8.7 ± 0.6
Köbenhavn	37	18 ± 3.6	25 ± 8	8.9 ± 1.4
Taarbäk	38	14 ± 4.2	35 ± 16	9.9 ± 1.3
Niverod	39	9 ± 2.4	111 ± 43	15.8 ± 3.0
Helsingör	40	5 ± 0.8	18 ± 4	9.1 ± 2.5
Risö	41	5 ± 1.1	31 ± 7	31.5 ± 10.0
Nyrup	42	3 ± 0.7	16 ± 4	6.6 ± 2.6
Svallerup	43	10 ± 6.0	26 ± 5	7.6 ± 1.1
Korsör	44	9 ± 3.5	15 ± 3	14.2 ± 4.0
Svinö	45	51 ± 17.5	39 ± 7	10.8 ± 2.8
Nyborg	46	5 ± 0.9	14 ± 4	7.4 ± 1.5
Bogense	47	29 ± 11.3	27 ± 9	9.0 ± 2.0
Gylling Näss	48	54 ± 15.3	50 ± 13	13.9 ± 2.8
Århus	49	32 ± 8.5	27 ± 4	10.1 ± 1.3
Ebeltoft	50	23 ± 7.6	24 ± 7	6.9 ± 1.7
Steilene	51	34 ± 14.9	21 ± 3	6.8 ± 1.2
Ostöya	52	32 ± 5.6	32 ± 9	5.1 ± 0.9
Malmöykalven	53	34 ± 9.1	21 ± 2	8.1 ± 2.0
Hovedöya	54	28 ± 5.1	26 ± 4	4.9 ± 1.0

[a] Location numbers refer to those in the text and are identical to those previously reported (Phillips, 1977c).

conclusions may be reached concerning the results of the present survey.

Schulz-Baldes (1974) reported a linear uptake of lead by *Mytilus edulis* with time (40 days) at 8 exposure levels (5 to 5000 µg l^{-1}) of lead in water of 25‰ salinity. The final lead concentrations in the whole soft parts of the mussels were correlated to the exposure level of lead in the water. Uptake of lead from food (the alga *Dunaliella marina*) was also linear with time; uptake via food and water routes occurred at similar rates when exposure concentrations of lead were the same. This author thus concluded that the mussel is an ideal indicator of lead in the marine environment. Phillips (1976b) also supported the abil-

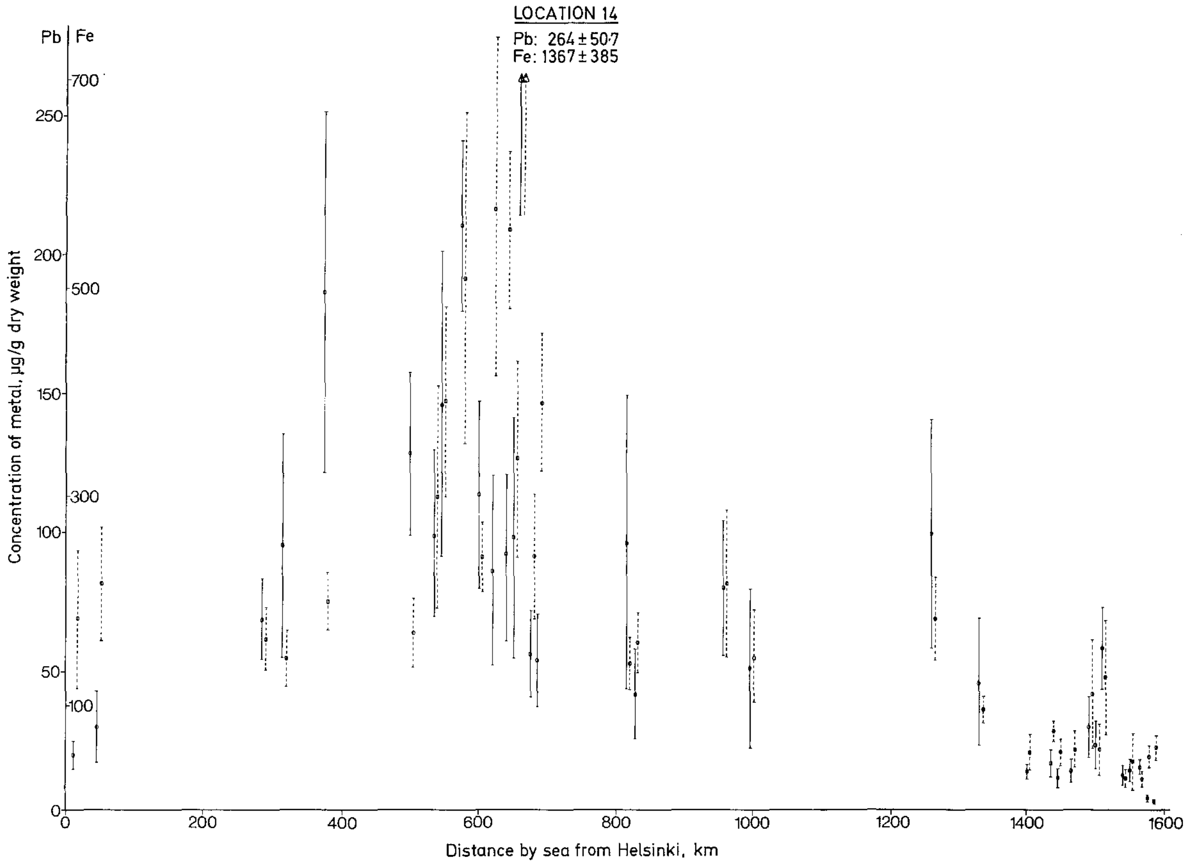

Fig. 1. *Mytilus edulis*. Concentrations (means ± standard deviations, µg g dry weight^{-1}) of lead (continuous lines) and iron (dashed lines) in whole soft parts of mussels from Locations 1-34. (for location names see Table 1)

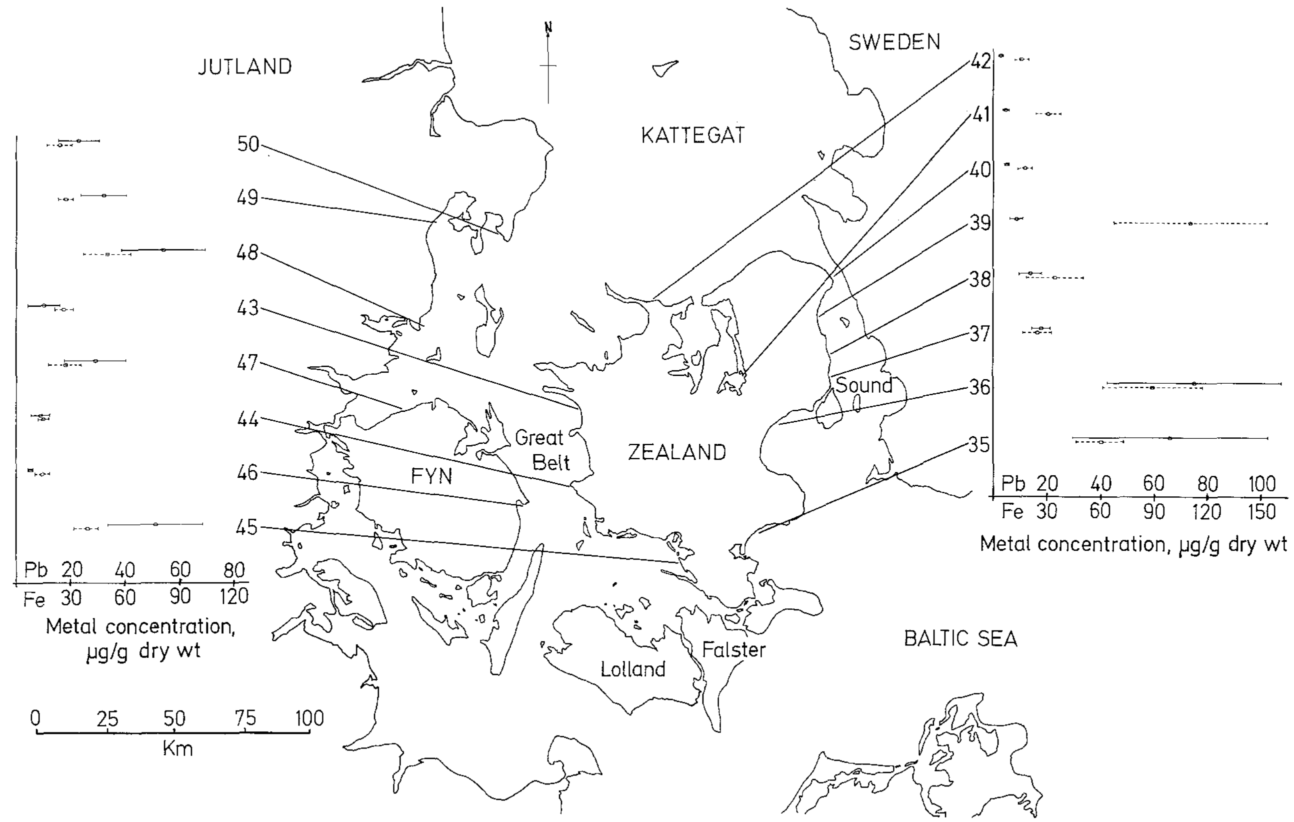

Fig. 2. *Mytilus edulis*. Concentrations (means ± standard deviations, µg g dry weight^{-1}) of lead (continuous lines) and iron (dashed lines) in whole soft parts of mussels from Danish coasts, Locations 35-50

ity of *M. edulis* to act as an indicator of lead pollution in marine ecosystems; in this case, lead concentrations in mussels from Port Phillip Bay in Australia were compared to known industrial sources of this element in the catchment of the same bay. However, significant effects of environmental variables have been reported for lead uptake in *M. edulis* (Phillips, 1976a). Variables shown to affect lead kinetics in this mussel included season, size and position in the water column of the organisms, salinity, and water temperature. Of these, salinity is the parameter which is most likely to have affected the results of the present survey, as the other perturbing parameters either differ little between the locations studied here or were eliminated by adherence to a strict sampling regime (see above and Phillips, 1976a).

The published data for iron in *Mytilus edulis* are not as easily interpreted as those for lead. Hobden (1967) suggested the existence of two stores of iron in the mussel. The "permanent store" was considered to be that remaining after starvation of mussels for 5 months in the laboratory, and was similar in magnitude to the lowest levels of iron found in mussels from Southampton and 5 other locations in southern England (25 mussels total, at least 3 of which were probably *M. galloprovincialis* rather than *M. edulis*; see Ahmad and Beardmore, 1976). Concentrations of iron in this permanent store were quoted as 20 to 25 µg g wet weight^{-1} (equivalent to 154 to 192 µg g dry weight^{-1} assuming a typical dry weight:wet weight ratio of 13%). A highly-labile "temporary store" of iron was also postulated, existing at least partly in particulate form; this store was suggested to be of indefinite size. Data from the present study reveal the existence of many samples of mussels, particularly from Kattegat and Skagerrak, containing mean levels of iron lower than those of Hobden's "permanent store". Other authors have also observed lower iron concentrations in *M. edulis* than Hobden's lower limit, e.g. Boyden (1975) reported 87 to 154 µg iron g dry weight^{-1} in mussels from Poole Harbour in England, and Nielsen and Nathan (1975) found mean values of 64 to 377 µg iron g dry weight^{-1} for samples of mussels from New Zealand coasts (see also Table 2 of present paper). It is evident that although the lower level of iron found by Hobden (1967) in mussels may have been that irreversibly bound (or at least of long half-life) in the tissues, the attempted extrapolation of results from local regions to mussels elsewhere was inadvisable.

In a later paper, Hobden (1969) considered the uptake of "soluble" Fe^{59} from citrated seawater by *Mytilus edulis*. Uptake was reported to cease after 3 to 7 days exposure, and the amounts of iron absorbed appeared independent of the exposure concentration in solution. However, Winter (1972) reported a continued uptake of iron (added as ferric hydroxide flakes to the aquarium water) over 5 months by mussels. This author also found a good correlation between added concentrations of iron and the final levels of this element in whole soft parts of mussels, although the final concentration factors derived from his paper are anomalously high due to the decrease in organism condition throughout the test period. George *et al.* (1976) found that the uptake of particulate ferric hydroxide from seawater by *M. edulis* varied in linear proportion to the external exposure concentration of iron in the range 7.4 to 500 µg l^{-1}. Uptake rates of iron for whole soft parts were constant throughout 25 days exposure, although those for individual tissues showed some tendency to equilibrium, presumably by the transfer of iron from these tissues to a growing store elsewhere (possibly in the byssus gland). The uptake of Fe^{59} from food (the alga *Dunaliella tertiolecta*) also supported the indicator ability of the mussel for iron (George, unpublished data; personal communication).

The uptake curves for the uptake of Fe^{59} from water by *Mytilus edulis* reported by Pentreath (1973) were more typical exponential curves; each tissue studied reached an equilibrium level for iron after 21 to 42 days exposure. The differences between the results of Hobden (1969) and those of the other authors cited above may have been due to the use by the former author of citrated seawater to "solubilise" Fe^{59}. As iron in seawater exists almost totally in particulate form (see below), the results of authors using particulate iron may be accepted to more closely represent the situation in the environment. The evidence available at present therefore supports the ability of the mussel to monitor the environmental abundance of this element. However, the effects of environmental variables on the uptake of iron by mussels are almost totally unknown. Bellamy *et al.* (1972) reported that the concentration of iron in *M. edulis* was age-dependent; however, this variable was eliminated during sampling in the present study. No data are available on the effects of salinity on the uptake of iron by the mussel.

The only data known concerning the uptake of manganese by *Mytilus edulis* are those of Pentreath (1973) for Mn^{54}. The uptake curves reported for Mn^{54} were similar to those for Fe^{59} in the same paper, although the steady-state concentration factors for individual tissues differed for the two nuclides, as did their tissue distributions. Pentreath (1973) also reported changes in the concentration and tissue distribution of the stable isotope of manganese with season in the mussel; no other published work is known on the effects of any environmental or sampling variable on the net uptake of manganese by the mussel.

The results from locations in the present study known to be exposed to industrial discharges of lead and iron can be used to test the indicator ability of the mussel in local regions throughout the study area. Mussels from Locations 9, 14, 21 and 29 (see Table 1) may be considered as those affected directly by lead and iron from industry at Nynäshamn, Oxelösund ironworks, Malmö and Göteborg, respectively. Each of these samples was found to contain higher concentrations of both lead and iron than those in samples taken at adjacent sites further north and/or south along the Swedish coast. These results suggest that the mussel is capable of reflecting local differences in lead and iron abundance throughout the study area. Data from studies of lead and iron in sediments close to Locations 9 and 14 (Edgren, 1973, 1976) agree well with the profiles of contamination seen in the present mussel studies.

The situation for manganese is more complex. Contamination profiles for manganese in sediments (Edgren, 1973, 1976) suggest that this element is less restricted to industrial areas; possibly higher concentrations of manganese are available from natural sources and the local effects of industry are less pronounced. The manganese profile in mussels revealed peaks in concentration at Locations 8, 12, 21 and 29 (see Table 1) which may possibly be related to industrial sources of this element at Locations 9, 14, 21 and 29. However, the lack of precise matching in Swedish east coast locations prevents strong conclusions on the indicator ability of *Mytilus edulis* for this metal.

The data from the present study thus agree with previous literature on the indicator ability of the mussel for lead, iron and manganese. The mussel appears to be a capable indicator of lead and iron (although the effects of environmental variables on iron kinetics in the mussel are unknown); by contrast, the ability of the mussel to act as an accurate indicator of the environmental abundance of manganese is suspect. Phillips (1976a, b) has suggested that *Mytilus edulis* is not capable of acting as an accurate indicator of copper due to the effects of other metals on the net uptake of this element. It now appears from the present work that manganese may be regulated to some extent by the mussel, at least in waters of low salinity. It is interesting that another commonly-used indicator organism, the alga *Fucus vesiculosus,* also partially regulates manganese (Morris and Bale, 1975).

Availability of Metals Throughout the Study Area

Lead and iron exist predominantly in particulate form in seawater. Preston *et al.* (1972) reported geometric mean values for the percentage particulate:total metal in waters of the British Isles of 64 and 93 to 99% for lead and iron, respectively. Head (1971) reported values of 96.2 to 96.5% for the same fraction for iron in Southampton Water. Sillén (1961) suggested that the particulate species of iron in seawater is $Fe_2O_3H_2O$. Few data are available on lead speciation in seawater; although lead methylation has been observed with the production of tetramethyl-lead from inorganic lead nitrate or lead chloride (Wong *et al.,* 1975), the extent and importance of this molecule in the environment remain to be elucidated.

The predominance of lead and iron in the same phase of seawater explains the general similarity between the profiles for these metals in mussels from all locations in the present study. The mussel may be expected to take up both metals simultaneously from ingested particulate material, although the exact availability of each metal will be determined by the size range of the particulates in which it is present. However, these profiles for lead and iron also show similarities to the profiles for zinc and cadmium reported previously (Phillips, 1977c), i.e., mussels from low-salinity waters east of Sweden contain higher concentrations of both metals than do those from high-salinity waters to the west of Sweden. The major decrease in concentrations of lead and iron in mussels occurs in the areas of the Sound and Great Belt (Fig. 2), coincident with the mixing of Baltic water with water of Kattegat/Skagerrak origin. Further metal inputs exist north of this region, both in Denmark (Locations 47-50) and in Sweden (Locations 27-29), although the values for lead in mussels attain similar levels in samples from the north-west of Sweden as in those from north-eastern Denmark.

The concentrations of manganese in mussels from these studies must be interpreted cautiously. Table 1 shows that the manganese profile differs considerably from the profiles for lead and iron in some regions. The peaks for manganese are in general less broad, and the differences between different geographical areas are less obvious. In addition, although some of the samples studied in Baltic waters revealed high concentrations of manganese, other samples (e.g. those from Locations 3-6, 18 and 20) contained concentrations of this element similar to those found in mussels from the west coast of Sweden. The divergence between results from the two coasts seen for lead and iron is, therefore, not entirely reflected in the results for manganese. This result is somewhat surprising, as manganese also exists in particulate form in seawater. Preston *et al.* (1972) reported geometric means of 68 to 81% for the ratio of particulate:total manganese in British waters, and Sillén (1961) suggested the existence of unchanged particulate hydroxides such as $Mn(OH)_3$ or $Mn(OH)_4$ in seawater. There is no reason to suspect lower inputs of manganese into Baltic waters than those for lead or iron (although possibly a higher proportion of the total manganese present derives from natural sources; see above), and the mussel would be expected to ingest manganese simultaneously to the ingestion of lead and iron. The profiles for manganese are reminiscent of those for copper in mussels from Port Phillip Bay in Australia (Phillips, 1976b) in that the peaks (at least in Swedish east-coast samples) show little relation to known industrial areas. It is possible that the uptake of manganese by the mussel is responsive to the presence of other metals, as was discovered for copper (Phillips, 1976a), or perhaps an unusual effect of salinity exists on the net uptake of manganese by the mussel. Whatever the explanation for the divergence between the results for manganese and those for lead and iron, it appears that the indicator ability of *Mytilus edulis* for manganese should be studied in the laboratory before strong conclusions may be reached concerning field results.

As noted previously for zinc and cadmium (Phillips, 1977c), the increased concentrations of lead and iron in mussels from the low-salinity waters of the Gulf of Finland, southern Bothnian Sea, and the Baltic Sea compared to those in mussels from the high-salinity Kattegat and Skagerrak areas are not correlated to higher levels of lead and iron in water samples from the former areas. Although the large temporal variation in concentrations of metals in water (see Grimshaw *et al.*, 1976; Phillips, 1977b) makes the accurate elucidation of interlocation differences difficult, the available data (Sen Gupta, 1972; Gustavsson, 1976) suggest that the concentrations of lead and iron in surface water vary little throughout the study area, possibly increasing slightly in Kattegat and Skagerrak. The differences in the concentrations of these metals in mussels taken from waters to the east and to the west of Sweden must, therefore, be based on differences in the biological availability of these metals in the two regions.

These differences in metal availability may be clearly seen by use of the calibration curve calculated for lead in *Mytilus edulis* by Schulz-Baldes (1974). This calibration curve allows the prediction of lead concentrations in water if the content of lead in mussels from that water is known. Application of this method to the present data predicts average concentrations of lead in water at Ringhals (Location 25) of 0.4 to 0.5 $\mu g\ l^{-1}$ and at Forsmark (Location 5) of 4.0 to 5.0 $\mu g\ l^{-1}$. In fact, these concentrations would be even more divergent than the data of Schulz-Baldes (1974) suggest, as salinity affects the direct uptake of lead from water by the mussel. Phillips (1976a) found that mussels took up 1.64 to 1.82 times as much lead at 35‰ S than at 15‰ S. As the contribution of direct uptake of lead from solution to the total body load of lead in the mussel is unknown, no accurate adjustment to these values can be made; however, it is apparent that the concentration of lead in water at Forsmark should be more than 10 times greater than that at Ringhals. Gustavsson (1976) reported average concentrations of lead in water of <1 to 2 $\mu g\ l^{-1}$ at Ringhals and <1 $\mu g\ l^{-1}$ at Forsmark; thus, the calibration curve of Schulz-Baldes (1974) is not obeyed, at least at the east coast station (Forsmark). The reason for this deviation must be the greater biological availability of lead in the low-salinity waters. Although no such calibration curve exists for iron in mussels, it may be calculated by comparison of iron concentrations in water with those in the mussel that this element is also more available to mussels on the east coast of Sweden than to those on the west coast. The situation for manganese is more complex, as not all mussels from the east coast of Sweden contained higher concentrations of this metal than did those from Kattegat or eastern Skagerrak. The general lack of data concerning the indicator ability of *M. edulis* for manganese, and the uncertainty concerning the concentrations of this element in water, preclude conclusions in the present work on the relative abundance of manganese in Scandinavian waters.

The present lack of knowledge on metal speciation in Scandinavian waters and the lack of data concerning the concentrations of metals in phytoplankton throughout the study area make speculation on the basis of the above differences in biological availability difficult. It is possible that, although the total concentrations of lead and iron in water are approximately the same throughout the study area, a greater proportion of the total metal in the low-salinity waters is available to mussels compared to the situation in the high-salinity areas. This may be valid for either the metals in solution, or those adsorbed to inorganic particulate material, or both. Alternatively, salinity effects may alter the concentration factors of metals in phytoplankton (Myers *et al.*, 1975; Styron *et al.*, 1976), thus leading to a higher availability of metals in low-salinity areas than in high-salinity locations.

The similarities between the availability differences for lead and iron studied here, and those for zinc and cadmium reported previously (Phillips, 1977c), suggest some type of non-specific change in availability of pollutants with study area, however, and it may be considered unlikely that either of the above mechanisms would extend to several metals to produce similar quantitative effects. It is interesting in this connection that Jensen *et al.* (1972) reported that levels of DDT and PCBs in herring (*Clupea harengus*) and cod (*Gadus morrhua*) were 5 to 10 times greater in Baltic samples than in those from the Swedish west coast; however, a later report (Jensen *et al.*, 1975) on littoral eel (*Anguilla anguilla*) and pike (*Esox lucius*) could not confirm this distinction for inshore waters. Conceivably many pollutants are more available to biota in the Baltic area due to the lower primary productivity here compared to the Swedish west-coast waters; the available pollutants would thus be taken up by a smaller phytoplankton biomass, to produce higher concentrations in both phytoplankters and secondary consumers. The effects of plankton biomass on the availability of pollutants and on their food-chain amplification have been documented for pesticides by several authors (e.g. Jensen *et al.*, 1970, 1972; Olsson *et al.*, 1973; Olsson, 1974); in addition, Bryan (1973) suggested that the dilution of available metals in the phytoplankton biomass was responsible for the seasonality of trace metals observed in the scallops *Pecten maximus* and *Chlamys opercularis* from the English Channel.

Comparison of Metals in Mussels from Scandinavian Waters to Those in Mussels from Elsewhere in the World

Table 2 shows published data concerning the concentrations of lead, iron and manganese in *Mytilus edulis* from coastal waters of the world. Comparison of data from the present study to other published values can afford only an approximate idea of the relative pollution of the different water masses, as the sampling regimes for most studies were different from that of the present study. However, the data suggest that the low-salinity waters east of Sweden (the Gulf of Finland, southern Bothnian Sea and Baltic Sea proper) are severely polluted by lead, i.e., a high biological availability of lead exists in this area. A study of Table 1 and Fig. 1 reveals that high levels of lead in mussels were found particularly for locations on the Swedish coast; concentrations of lead in mussels from the Gulf of Finland were much lower, and those in mussels from Åland were intermediate. This trend is repeated for results for lead from the west coast of Sweden compared to Danish coasts, although the absolute levels of lead in mussels from these areas are lower than for the Swedish east coast.

Studies of industrial and storm-water discharges suggest that the majority of the lead entering the coastal waters of Sweden is derived from storm-water and must originate from the use of lead additives in petrol (Edgren, personal communication). Further decreases in the lead content of petrol in Sweden will be necessary to improve this situation. The concentrations of iron in mussels are also highest in samples from the low-salinity waters east of Sweden, and are comparable here to those in mussels from industrialised areas elsewhere in the world. Levels of iron in mussels from the Sound and Great Belt, Kattegat and Skagerrak are lower by a factor of approximately 5 to 10 and present much less of a problem. The concentrations of manganese in mussels weakly follow the same trend as those of lead and iron. Although the manganese levels appear rather high in mussels from Scandinavian waters compared to those reported for mussels from Britain or New Zealand, the implications of this are obscure, particularly as the indicator ability of *Mytilus edulis* for manganese could not be definitely established.

Acknowledgements. It is a pleasure to acknowledge with thanks the many people who gave their time and effort in Scandinavia to help with mussel sampling for this work. Professor U. Grimås is owed particular thanks for continued support

Table 2. *Mytilus edulis*. Concentrations (means or ranges, µg g dry weight^{-1}) of lead, iron and manganese in whole soft parts of mussels from various waters throughout the world. A dry weight:wet weight ratio of 13% was used where authors quoted results by wet weight and gave no conversion ratio

Sampling location	Lead	Iron	Manganese	Source
Tasman Bay, New Zealand	12	1960	27	Brooks and Rumsby (1965)[a]
Lee-on-Solent, UK	9	1700	3.5	Segar *et al.* (1971)
East coast of UK	118-343	100-3400	-	Bellamy *et al.* (1972)
Bristol Channel, UK	1-30	-	-	Nickless *et al.* (1972)
Weser Estuary, FRG	-	80-230	-	Winter (1972)
Weser Estuary and German Bight	1.3-9.7	-	-	Schulz-Baldes (1973)
Hardangerfjord, Norway	15-3100	-	-	Stenner and Nickless (1974)
Skjerstadfjord, Norway	2-6	-	-	
Poole Harbour, UK	7-19	87-154	3-5	Boyden (1975)
Coasts of New Zealand	1-15	64-377	-	Nielsen and Nathan (1975)
Atlantic coasts of Spain and Portugal	2-15	-	-	Stenner and Nickless (1975)
River Ythan Estuary, UK	-	510	-	George *et al.* (1976)
Port Phillip Bay, Australia	5.5-77	-	-	Phillips (1976b)
Trondheimsfjord, Norway	-	122-1623	-	Lande (1977)
Lower Medway Estuary, UK	6-17	-	-	Wharfe and Van den Broek (1977)
Scandinavia, low salinity[b]	20-264	60-1366	8.2-92	This study
The Sound and Great Belt	4.5-99	14-184	7.4-41	
Kattegat and Skagerrak	3.0-58	16-128	6.2-35	

[a] Species quoted as *Mytilus edulis aoteanus*.

[b] Gulf of Finland, southern Bothnian Sea, Baltic Sea proper.

and encouragement. This work was funded by the National Environment Protection Board of Sweden as a special project.

Literature Cited

Ahmad, M. and J.A. Beardmore: Genetic evidence that the "Padstow mussel" is *Mytilus galloprovincialis*. Mar. Biol. *35*, 139-147 (1976)

Bellamy, D.J., D.M. John, D.J. Jones, A. Starkie and A. Whittick: The place of ecological monitoring in the study of pollution of the marine environment. *In:* Marine pollution and sea life, Ed. by M. Ruivo. pp 421-425. London: Fishing News (Books) Ltd. 1972

Boyden, C.R.: Distribution of some trace metals in Poole Harbour, Dorset. Mar. Pollut. Bull. *6* (12), 180-187 (1975)

Brooks, R.R. and M.G. Rumsby: The biogeochemistry of trace element uptake by some New Zealand bivalves. Limnol. Oceanogr. *10*, 521-528 (1965)

Bryan, G.W.: The occurrence and seasonal variation of trace metals in the scallops *Pecten maximus* (L.) and *Chlamys opercularis* (L.). J. mar. biol. Ass. U.K. *53*, 145-166 (1973)

Edgren, M.: Recipientundersökningar rörande lokalisering av kraftverk till Nynäshamn. Report in Swedish, from Statens Naturvårdsverk Undersökningslaboratoriet. Radioekologiska sektionen, 9 November 1973. (Copies available from: The Secretary, Statens Naturvårdsverk Undersökningslaboratoriet, 170 11 Drottningholm, Stockholm, Sweden)

\- Metaller och närsalter i sediment och vattenburen partikulär substans. Report in Swedish, from Statens Naturvårdsverk Undersökningslaboratoriet, 25 November 1976. (Copies available from The Secretary, Statens Naturvårdsverk Undersökningslaboratoriet, 170 11 Drottningholm, Stockholm, Sweden)

George, S.G., B.J.S. Pirie and T.L. Coombs: The kinetics of accumulation and excretion of ferric hydroxide in *Mytilus edulis* (L.) and its distribution in the tissues. J. exp. mar. Biol. Ecol. *23*, 71-84 (1976)

Goldberg, E.D.: The mussel watch — a first step in global marine monitoring. Mar. Pollut. Bull. *6* (6), p. 111 (1975)

Grimshaw, D.L., J. Lewin and R. Fuge: Seasonal and short-term variations in the concentration and supply of dissolved zinc to polluted aquatic environments. Envir. Pollut. *11*, 1-7 (1976)

Gustavsson, I.: The concentration of heavy metals in the receiving waters off the nuclear power plants of Sweden (1976). (Report No. SNV PM 785E, in English, available from: The Secretary, Statens Naturvårdsverk, Villavägen 3, 752 36 Uppsala, Sweden)

Head, P.C.: Observations on the concentration of iron in sea water, with particular reference to Southampton Water. J. mar. biol. Ass. U.K. *51*, 891-903 (1971)

Hobden, D.J.: Iron metabolism in *Mytilus edulis*. I. Variation in total content and distribution. J. mar. biol. Ass. U.K. *47*, 597-606 (1967)

\- Iron metabolism in *Mytilus edulis*. II. Uptake and distribution of radioactive iron. J. mar. biol. Ass. U.K. *49*, 661-668 (1969)

Jackim, E., G. Morrison and R. Steele: Effects of environmental factors on radiocadmium uptake by four species of marine bivalves. Mar. Biol. *40*, 303-308 (1977)

Jensen, S., A.G. Johnels, T. Odsjö, M. Olsson and G. Otterlind: PCB-occurrence in Swedish wildlife. *In:* Proceedings of the PCB Conference, Wenner-Gren Centre, Stockholm, September 29, 1970. (Copies available from The Research Secretariat, Statens Naturvårdsverk, Fack, 171 20 Solna, Sweden)

– –, M. Olsson and G. Otterlind: DDT and PCB in herring and cod from the Baltic, the Kattegat, and the Skagerrak. Ambio spec. Rep. *1*, 71-85 (1972)

M. Olsson and R. Vaz: Levels of DDT and PCB in littoral fishes along the Swedish coast. *In:* Proceedings of the Third Soviet-Swedish Symposium on the Baltic Pollution, Stockholm, Sweden. September, 1975. (Copies available from The Secretary, Statens Naturvårdsverk, 171 20 Solna, Sweden)

Lande, E.: Heavy metal pollution in Trondheimsfjorden, Norway, and the recorded effects on the fauna and flora. Envir. Pollut. *12*, 187-198 (1977)

Morris, A.W. and A.J. Bale: The accumulation of cadmium, copper, manganese and zinc by *Fucus vesiculosus* in the Bristol Channel. Estuar. cstl mar. Sci. *3*, 153-163 (1975)

Myers, V.B., R.L. Iverson and R.C. Harriss: The effect of salinity and dissolved organic matter on surface charge characteristics of some euryhaline phytoplankton. J. exp. mar. Biol. Ecol. *17*, 59-68 (1975)

Nickless, G., R. Stenner and N. Terrille: Distribution of cadmium, lead and zinc in the Bristol Channel. Mar. Pollut. Bull. *3* (12), 188-190 (1972)

Nielsen, S.A. and A. Nathan: Heavy metal levels in New Zealand molluscs. N.Z. Jl mar. Freshwat. Res. *9*, 467-481 (1975)

Olsson, M.: Time and space dependence of pollutant levels in aquatic biota. Field studies. *In:* Proceedings of the International Conference on Transport of Persistent Chemicals in Aquatic Ecosystems, Ottawa, Canada, 1974. (Copies available from The Secretary, Statens Naturvårdsverk, 171 20 Solna, Sweden)

-, S. Jensen and L. Renberg: PCB in coastal areas of the Baltic. *In:* PCB Conference II, Publication 4E of the National Environment Protection Board of Sweden (1973). (Copies available from The Research Secretariat, Statens Naturvårdsverk, Fack, 171 20 Solna, Sweden)

Pentreath, R.J.: The accumulation from water of Zn^{65}, Mn^{54}, Co^{58} and Fe^{59} by the mussel, *Mytilus edulis*. J. mar. biol. Ass. U.K. *53*, 127-143 (1973)

Phillips, D.J.H.: The common mussel *Mytilus edulis* as an indicator of pollution by zinc, cadmium, lead and copper. I. Effects of environmental variables on uptake of metals. Mar. Biol. *38*, 59-69 (1976a)

- The common mussel *Mytilus edulis* as an indicator of pollution by zinc, cadmium, lead and copper. II. Relationship of metals in the mussel to those discharged by industry. Mar. Biol. *38*, 71-80 (1976b)

- Effects of salinity on the net uptake of zinc by the common mussel *Mytilus edulis*. Mar. Biol. *41*, 79-88 (1977a)

- The use of biological indicator organisms to monitor trace metal pollution in marine and estuarine environments — a review. Envir. Pollut. *13*, 281-317 (1977b)

- The common mussel *Mytilus edulis* as an indicator of trace metals in Scandinavian waters. I. Zinc and cadmium. Mar. Biol. *43*, 283-291 (1977c)

Preston, A., D.F. Jefferies, J.W.R. Dutton, B.R. Harvey and A.K. Steele: British Isles coastal waters: the concentrations of selected heavy metals in sea water, suspended matter and biological indicators — a pilot survey. Envir. Pollut. *3*, 69-82 (1972)

Romeril, M.G.: The uptake and distribution of Zn^{65} in oysters. Mar. Biol. *9*, 347-354 (1971)

Schulz-Baldes, M.: Die Miesmuschel *Mytilus edulis* als Indikator für die Bleikonzentration im Weserästuar und in der Deutschen Bucht. Mar. Biol. *21*, 98-102 (1973)

- Lead uptake from sea water and food, and lead loss in the common mussel *Mytilus edulis*. Mar. Biol. *25*, 177-193 (1974)

Segar, D.A., J.D. Collins and J.P. Riley: The distribution of the major and some minor elements in marine animals. Part II. Molluscs. J. mar. biol. Ass. U.K. *51*, 131-136 (1971)

Segerstråle, S.G.: The Tvärminne excursion. A confrontation with the brackish Baltic. Limnologorum Conventus *13*, 46-72 (1956)

- Baltic Sea. Mem. geol. Soc. Am. *67*, 751-800 (1957)

Sen Gupta, R.: On some trace metals in the Baltic. Ambio *1*, 226-230 (1972)

Sillên, L.G.: The physical chemistry of sea water. *In:* Oceanography, pp 549-581. Ed. by M. Sears. Washington, D.C.: American Association for the Advancement of Science, 1961. (Publs Am. Ass. Advmt Sci. No. 67)

Stenner, R.D. and G. Nickless: Distribution of some heavy metals in organisms in Hardangerfjord and Skjerstadfjord, Norway. Wat. Air Soil Pollut. *3*, 279-291 (1974)

-- Heavy metals in organisms of the Atlantic coast of south-west Spain and Portugal. Mar. Pollut. Bull. *6* (6), 89-92 (1975)

Styron, C.E., T.M. Hagan, D.R. Campbell, J. Harvin, N.K. Whittenburg, G.A. Baughman, M.E. Bransford, W.H. Saunders, D.C. Williams, C. Woodle, N.K. Dixon and C.R. McNeill: Effects of temperature and salinity on growth and uptake of Zn^{65} and Cs^{137} for six marine algae. J. mar. biol. Ass. U.K. *56*, 13-20 (1976)

Wharfe, J.R. and W.L.F. Van den Broek: Heavy metals in macroinvertebrates and fish from the lower Medway estuary, Kent. Mar. Pollut. Bull. *8* (2), 31-34 (1977)

Winter, J.E.: Long-term laboratory experiments on the influence of ferric hydroxide flakes on the filter-feeding behaviour, growth, iron content and mortality in *Mytilus edulis* L. *In:* Marine pollution and sea life, Ed. by M. Ruivo. pp 392-396. London: Fishing News (Books) Ltd. 1972

Wong, P.T.S., Y.K. Chau and P.L. Luxon: Methylation of lead in the environment. Nature, Lond. *253*, 263-264 (1975)

David J.H. Phillips
Fisheries Research Station
100 A Shek Pai Wan Road
Aberdeen
Hong Kong

Date of final manuscript acceptance: December 9, 1977. Communicated by T.M. Fenchel, Aarhus