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Cadmium pathways in an exploited intertidal ecosystem with chronic cadmium inputs (Marennes-Oléron, Atlantic coast, France)

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ABSTRACT: The Marennes-Oléron Bay is subject to chronic pollution by cadmium (Cd) from the Gironde watershed. An ecosystem approach was used to study the fate of cadmium in the different biological compartments. The median Cd concentration was 0.4 µg g^{-1} dry weight for the 63 benthic species measured. When combined with the respective biomasses for the different species studied, we estimated that 7 kg of Cd is partitioned into the soft tissues of the benthic species in the bay. The majority of this cadmium was distributed between primary producers, mainly microphytobenthos (40%), and suspension-feeders, mainly oysters (40%). All other benthic species measured were associated with negligible masses of Cd. Two trophic levels contained 98% of the Cd: 3 kg was partitioned into primary producers (of which 77% is associated with the microphytobenthos) and 3.2 kg of Cd was distributed among all suspension feeders. The carnivores, including scavengers, concentrated less than 0.2 kg of Cd, suggesting an absence of biomagnification of Cd in the trophic food web of the bay. The microphytobenthic compartment was estimated to control the largest quantity of Cd (ca. 188 kg yr^{-1}), suggesting an important role for the microphytobenthos in the biogeochemical cycle of Cd in the bay. The quantities of Cd associated with annual biological production in other biological compartments were low: 2 kg yr^{-1} for eelgrass which could represent a vector of Cd transfer to winter populations of Brent geese and 1.4 kg yr^{-1} for all suspension feeders, principally the cultivated Pacific oysters (64%) representing a vector of Cd transfer to humans. An ecosystem-wide budget for the quantities of Cd present in all the biological and physical compartments showed that the majority of Cd (1 t) is trapped in the upper 5 cm of the bay sediments, representing a potential risk for the oyster and shellfish cultivation in the bay.

KEY WORDS: Macrophytes · Microphytobenthos · Macrofauna · Cadmium · Bioaccumulation · Trophic food web · Marennes-Oléron Bay

INTRODUCTION

The Marennes-Oléron Bay represents the coastal endpoint of a continuum of Cd pollution which begins 450 km upstream, in a small tributary of the Lot River, called the 'Riou Mort' (Jouanneau et al. 1990, Lapaquellerie et al. 1995, Grousset et al. 1999) (Fig. 1). The cadmium contamination originates from a discharge of mine treatment waste by the ore processing plant 'Vieille Montagne' that is located on the Riou Mort river, in Decazeville (Aveyron, France) (Grousset et al. 1999). This processing plant has been discharging waste into the tributary for many decades, up to 60 kg of cadmium per day. In addition, runoff, enriched in cadmium from the unstabilised and exposed tailings of the processing plant, flows directly into the Riou Mort. In 1986, the pro-

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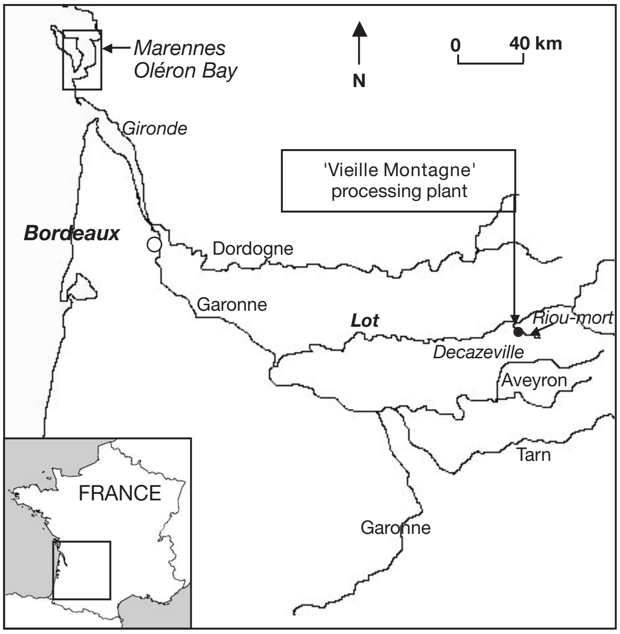

Fig. 1. Location of the major Cd output linked to mining activities within tributaries of the Garonne River, 450 km upstream of the Marennes-Oléron Bay.

cessing plant stopped metal production, the tailings were isolated, and the runoff water treated. Nonetheless, the remaining cadmium mass trapped in the sediments of the Lot River was estimated to be nearly 200 t in 1991 (Lapaquellerie et al. 1995). The Garonne River and Gironde Estuary, which are downstream from the Riou Mort and the Lot River, have been contaminated through the flux of eroded, contaminated bottom sediments (Latouche 1988, Boutier et al. 2000). Even if the Cd fluxes have decreased since 1985 as distance from the Gironde Estuary increased (RNO 2000), they remain important, and are currently estimated at 4 to 5 t of dissolved cadmium per year. In the estuarine environment, cadmium sorbed on sediment particles may desorb as the water salinity increases (Latouche 1988, Lapaquellerie et al. 1996, Boutier et al. 2000). Thus, in the plume of the Gironde Estuary Cd is preferentially in a dissolved form that has a higher bioavailability for living organisms, including shellfish species that were commercially-grown in the estuary, such as the Pacific oyster, *Crassostrea gigas*. Since 1996, high cadmium concentrations measured in oysters from this estuary have led to a prohibition on the commercialisation of this bivalve for the entire Gironde estuarine zone (RNO 2000).

Depending on meteorological conditions in the Gulf of Biscay and the fluvial flow, a portion of the Gironde estuarine plume reaches Marennes-Oléron Bay (Lazure & Jégou 1998), and 400 to 500 kg of dissolved Cd enters the Marennes-Oléron Bay each year through the 'Pertuis d'Antioche' (Antioche Straits) north of the island of Oléron (Boutier et al. 2000). The bay is a well-studied system in terms of biological compartments (Sauriau et al. 1989, Sautour & Castel 1998) and hydrological (Héral et al. 1984, Soletchnick et al. 1998) and sedimentary processes (Raillard & Ménesguen 1994), making it suitable for studies of the fate of Cd at the ecosystem level. It has been the focus of study for many years because of its importance in the shellfish industry in France (Héral et al. 1989, Goulletquer & Héral 1997). Marennes-Oléron Bay, which has an annual production of 30 000 t of oysters from a stock of more than 100 000 t, is also a major zone for oyster-spat collection, and a site traditionally important in the refining of oysters in 'claires' located in salt-marsh ponds (Goulletquer & Héral 1997). The bay has a large ecological status as demonstrated by a recent macrofaunal inventory which enumerated more than 300 macrofauna species in the bay (de Montaudouin & Sauriau 2000). In addition, the bay is an important regional centre of tourism, where the population increases by 10-fold during the summer season (to about 100 000 people).

Until recently, the fate of Cd in the Marennes-Oléron Bay was only investigated in the context of monitoring studies for the Cd content in *Crassostrea gigas*. Since 1979, this oyster species has been used as a bioindicator species in a long-term monitoring study as part of the French National Monitoring Network (RNO-*Réseau National d'Observation*: www.ifremer.fr/envlit/index.htm) for the quality of the marine environment (RNO 1988, 2000, 2004). No other data on the amount of Cd contamination has been available for other species in the bay. The present study implements an ecosystem approach in place of bioindicator species. With this approach, a large number of representative species from the different trophic compartments in the bay are analysed for Cd content to study the distribution of Cd in the food web of the bay. The objectives of this study were: (1) to calculate the quantities of Cd partitioned at a given time into each biological component from primary to secondary producers, (2) to calculate the partitioning of Cd by each trophic level, and (3) to evaluate the role of different organisms in terms of identifying which biological compartments are likely to mobilise important quantities of Cd within the trophic networks of the Marennes-Oléron Bay.

MATERIALS AND METHODS

Description of the Marennes-Oléron Bay. The Marennes-Oléron Bay is located on the south-western Atlantic coast of France, north of the Gironde Estuary and south of the Charente River estuary (Fig. 1). The bay is bounded to the west by Oléron Island, to the north by a line extending from Saumonards Point on Oléron Island to Fouras on the continental side (west to east) and to the south by Maumusson Strait (Fig. 2). Dissolved Cd concentrations in the bay are in the order of 20 ng l^{-1} (B. Boutier pers. comm.), and the concentrations of particulate Cd are 0.26 µg g^{-1} (Pigeot 2001). The total surface area, including the intertidal and subtidal zones, is in the order of 180 km^2 (Sauriau et al. 1989, Soletchnik et al. 1998); the intertidal zone has a surface area of 96 km^2 (Soletchnik et al. 1998). In this bay, the major portion of the biomass (including cultivated shellfish) is located in the intertidal zone and thus, for the purposes of our study, we have concentrated our sampling efforts in this zone.

Sediments of the bay range from pure mud to sandy mud with some limited areas of rocky outcrops (see Sauriau et al. 1989 for a detailed map). The intertidal zone includes: (1) bare mudflats dominated by microphytobenthos which consists mostly of pennate diatoms (Cariou-Le Gall & Blanchard 1995), (2) some meadows of dwarf eelgrass, *Zostera noltii*, mainly located on the Oléron Island (Guillaumont 1991, Sauriau & Kang 2000) and covering a surface area of 8.65 km^2 (Pigeot 2001), (3) the upper shore, which forms a border some dozens of meters wide in the most protected zones of the bay, and covers about 1.2 km^2 where the halophytes *Atriplex* (= *Halimione*) *portulacoides* and *Sarcocornia* (= *Arthrocnenum*) *perennis* predominate, and (4) shellfishery zones, located in the lower portion of the intertidal area (on-bottom and off-bottom oyster cultivation zones and mussel poles), and covering a surface area of 30 km^2 (Fig. 2).

Species sampling at Château Oléron station. We sampled a number of different species, mostly in spring of 1997 (70 % of the samples); the remainder were collected in spring 1998 and 1999. All species were collected by hand at low tide from the rocky and sandy-mud substrates at Château d'Oléron (Fig. 2); this station is representative of the bay with respect to its sedimentary features (predominance of sandy-mud facies) and also for the cadmium concentrations in the oysters (RNO 1995, 2000) which remained stable over the 1997–1999 sampling period in the range of 1 to 4 µg g^{-1} dry weight (RNO 2000, 2004). Species have been sampled in the 3 levels of the mid-littoral zone. Those organisms that only live at precise locations within 1 level were only sampled at that 1 level; species that occur in several levels of the mid-littoral zone were sampled from the level where they had the highest biomass. In total, 63 macroscopic plant and animal species were collected. Microphytobenthos was sampled from sandy-mud sediments from the mid-littoral zone. The types of organisms sampled were: (1) primary producers (microphytobenthos, dif-

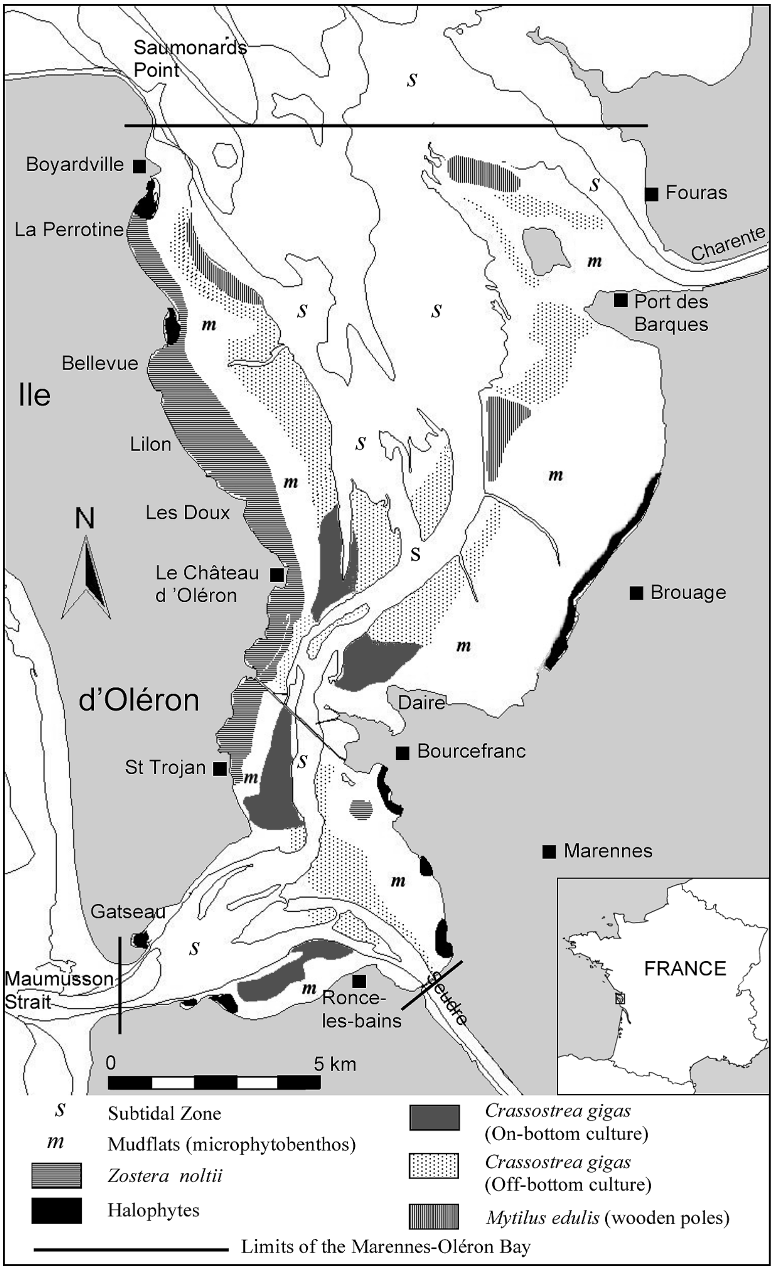

Fig. 2. Marennes-Oléron Bay at low tide, showing the extent of bare mudflats, eelgrass meadows, oyster parks (with off-bottom and on-bottom cultures), mussel poles and salt-marsh vegetation areas

ferent green, brown and red macroalgae and salt marsh plants (leaves and rhizomes were separated) and (2) the consumers as represented by 10 taxa (Porifera, Cnidaria, Polychaeta, Polyplacophora, Gastropoda, Bivalvia, Crustacea, Echinodermata, Ascidia and Teleostei). The 49 consumers are all metazoans and belong to 8 trophic groups, to which 2 other groups for the suprabenthic species were added: the carnivores and the omnivores (Table 1). In addition, the principal subtidal species have been sampled by dredging or trawling in the central channel of the Marennes-Oléron Bay. All species were analysed without depuration.

Separation of the microphytobenthos from the sediments. A sufficient biomass of microphytobenthos for the analyses was collected using the method described by Riera et al. (1996). Surface sediments (1 l from the upper 2 mm) were collected from the mudflats by gently scraping the surface with a plastic spatula. After the sample was transported back to the laboratory, the mud was placed into trays, and covered with a 63 µm nylon mesh. A silica gel with granules greater than 63 µm in diameter was then spread onto the nylon mesh. This assemblage was placed under artificial light for 48 h to allow benthic diatoms to migrate from the sediment into the silica gel. After the migration period was complete, the gel was sieved using a second 63 µm mesh and the diatoms recovered by centrifugation of the filtrate.

Cadmium analyses. Upon returning to the laboratory, all species were cleaned and any epiphytes removed, and the samples were frozen (–20°C) until

Table 1. Concentrations (±SD) of cadmium (µg g^{-1} dry weight) in intertidal organisms from the Château d'Oléron station (45° 53' N, 1° 11' W) in spring 1997, 1998 and 1999 (n = number of replicates). Trophic level: primary producers (pp) and consumers (sus = suspension feeders, car = carnivores, omn = omnivores, her = herbivores, dep = deposit-feeders, sca = scavengers, sdf = suspension-deposit feeders, omn = suprabenthic omnivores, det = detritivores, car = suprabenthic carnivores). Reference sources (Ref.): 1, Purchon (1968); 2, Newell (1979); 3, Turquier (1989); 4, Fish & Fish (1996)

Taxon	Species	Year	Trophic level	Ref.	Midlittoral level	n	[Cd] ± SD (µg g^{-1} dry wt)
	Microphytobenthos	1997	pp		Intermediate	5	1.222 ± 0.130
Chlorophyta	*Enteromorpha intestinalis*	1997	pp		Intermediate	5	0.100 ± 0.014
	Ulva lactuca	1997	pp		Intermediate	5	0.200 ± 0.043
Pheophyta	*Ascophyllum nodosum*	1997	pp		Intermediate	5	0.114 ± 0.037
	Fucus serratus	1998	pp		Lower	3	0.564 ± 0.109
	Fucus vesiculosus	1997	pp		Intermediate	5	0.057 ± 0.012
Rhodophyta	*Ceramium ciliatum*	1998	pp		Intermediate	3	1.771 ± 0.317
	Gigartina acicularis	1997	pp		Lower	5	0.082 ± 0.029
	Gracilaria verrucosa	1997	pp		Intermediate	5	0.276 ± 0.076
	Laurencia pinnatifida	1997	pp		Lower	5	0.128 ± 0.015
	Porphyra umbilicalis	1997	pp		Lower	5	0.100 ± 0.010
Spermaphyta	*Sarcocornia perennis* Leaves & stem	1999	pp		Upper	3	0.013 ± 0.002
	Atriplex portulacoides Leaves & stem	1999	pp		Upper	3	0.099 ± 0.054
	Zostera noltii	1997	pp		Intermediate	5	
	Leaves						0.678 ± 0.478
	Rhizomes & roots						1.228 ± 0.582
Porifera	*Halichondria bowerbanki*	1997	sus	3	Lower	5	0.227 ± 0.087
Cnideria	*Actinia equina*	1997	car	2	Upper	3	0.009 ± 0.002
	Anemonia viridis	1997	car	2	Lower	5	0.025 ± 0.007
Polychaeta	*Hediste diversicolor*	1998	omn	4	Intermediate	3	0.077 ± 0.033
	Marphysa sanguinea	1998	car	4	Intermediate	3	0.182 ± 0.097
Polyplacophora	*Lepidochiton cinereus*	1998	her	1	Intermediate	3	0.561 ± 0.114
Gastropoda	*Archidoris pseudoargus*	1997	car	4	Lower	3	2.656 ± 0.194
	Crepidula fornicata	1997	sus	1	Lower	5	0.750 ± 0.319
	Gibbula cineraria	1998	her	1	Lower	3	0.572 ± 0.065
	Gibbula umbilicalis	1997	her	1	Intermediate	3	0.441 ± 0.059
	Hydrobia ulvae	1998	dep	1	Intermediate	3	0.048 ± 0.005
	Littorina littorea	1997	her	1	Intermediate	5	1.159 ± 0.253
	Littorina obtusata	1997	her	1	Upper	5	2.613 ± 0.221
	Nassarius incrassatus	1998	car	1	Intermediate	5	5.063 ± 0.938
	Nassarius reticulatus	1997	sca	4	Lower	3	5.213 ± 2.080

Table 1 (continued)

Taxon	Species	Year	Trophic level	Ref.	Midlittoral level	n	[Cd] ± SD ($\mu g\ g^{-1}$ dry wt)
	Nucella lapillus	1998	car	1	Lower	3	9.541 ± 3.752
	Ocenebra erinacea	1997	car	3	Intermediate	5	5.822 ± 1.389
	Ocinebrellus inornatus	1998	car	3	Lower	3	6.108 ± 0.742
	Osilinus lineatus	1997	her	1	Upper	5	0.261 ± 0.041
	Patella vulgata	1997	her	1	Intermediate	5	5.215 ± 1.897
Bivalvia	*Cerastoderma edule*	1997	sus	1	Intermediate	5	0.460 ± 0.163
	Chlamys varia	1997	sus	2	Lower	5	11.805 ± 3.250
	Crassostrea gigas	1997	sus	3	Lower	5	1.474 ± 0.617
	Macoma balthica	1997	sdf	1	Intermediate	3	0.101 ± 0.004
	Modiolus barbatus	1997	sus	2	Lower	3	8.275 ± 2.439
	Mytilus edulis	1997	sus	1	Lower	5	2.520 ± 0.124
	Mytilus galloprovincialis	1997	sus	2	Intermediate	3	2.633 ± 1.063
	Ostrea edulis	1998	sus	1	Lower	3	2.531 ± 0.245
	Scrobicularia plana	1998	sdf	1	Intermediate	3	0.385 ± 0.112
	Tapes decussatus	1997	sus	3	Intermediate	5	0.471 ± 0.173
	Tapes philippinarum	1997	sus	3	Intermediate	2	0.329 ± 0.001
Crustacea	*Balanus perforatus*	1998	sus	3	Lower	3	2.394 ± 0.177
	Carcinus maenas	1997	car	3	Lower	5	0.297 ± 0.086
	Chtamalus stellatus	1998	sus	3	Upper	3	0.062 ± 0.007
	Clibanarius erythropus	1997	omn	4	Lower	5	0.619 ± 0.484
	Elminius modestus	1998	sus	3	Intermediate	5	0.100 ± 0.030
	Galathea squamifera	1998	sus	2	Lower	3	0.568 ± 0.089
	Hemigrapsus penicillatus	1998	car	3	Intermediate	3	0.066 ± 0.007
	Necora puber	1997	car	3	Lower	7	0.248 ± 0.039
	Orchestia gammarellus	1997	det	4	Upper	3	0.309 ± 0.085
	Pachygrapsus marmoratus	1997	car	3	Intermediate	3	0.041 ± 0.011
	Palaemon elegans	1997	omn	4	Intermediate	3	0.018 ± 0.001
	Pilumnus hirtellus	1997	car	3	Lower	5	0.419 ± 0.165
	Porcellana platycheles	1997	sus	2	Lower	5	0.145 ± 0.049
	Xantho pillipes	1998	her	4	Lower	3	0.210 ± 0.082
Echinodermata	*Asterina gibbosa*	1998	omn	4	Intermediate	3	1.846 ± 0.213
	Psammechinus miliaris	1997	omn	4	Lower	3	0.291 ± 0.254
Urochordata	*Dendrodoa grossularia*	1998	sus	2	Lower	3	0.403 ± 0.021
Teleostei	*Anguilla anguilla*	1997	car	4	Intermediate	3	0.082 ± 0.037
	Gobius paganellus	1997	car	4	Intermediate	3	0.021 ± 0.005

analysis. After thawing, only molluscs were de-shelled and their soft tissues were analysed. All other species were analysed in total except for *Zostera noltii*, in which leaves and rhizomes (+roots) were analysed separately and halophytes (*Atriplex portulacoides* and *Sarcocornia perennis*), in which only aboveground parts (leaves + stems) were analysed. Replicates (3 or 5) containing 1 or several adult individuals (depending on the average size of the species) of the same size were analysed to estimate a mean Cd and standard deviation. Tissues were dried for several days at 80°C to a constant weight and then homogenised. Three aliquots (approximately 300 mg per aliquot) of each homogenised and dried tissues were digested in a solution of 4 ml of 65% HNO_3 and 1 ml of 70% $HClO_4$ at 80°C until the solution became clear. After evaporation, the residues were re-dissolved into 10 ml 0.3 N HNO_3. Cd was determined by flame or graphite furnace atomic absorption spectrophotometry (FAAS or GF-AAS) with a deuterium background correction. Two reference tissues, dogfish liver DOLT-2 (NRCC) and the MA-A2 fish tissue standard (IAEA), were treated and analysed in the same way as the other tissues. The results for the standard reference materials were in good agreement with the certified values reported. The detection limit for Cd was 0.005 $\mu g\ g^{-1}$ dry wt.

Estimation of the biomasses by stratified random sampling. Of the 63 species considered in this study, only the biomasses of some mollusc species were previously known: Pacific oysters *Crassostrea gigas* and European mussels *Mytilus edulis* from cultivated stocks estimates (P. Goulletquer, O. Le Moine pers. comm.). Biomass estimates of other species (*Cerastoderma edule*, *Chlamys varia*, *Hydrobia ulvae*, *Macoma balthica*, *Crepidula fornicata*, *Nassarius reticulatus*, *Srobicularia plana*, *Tapes decussatus* and *Littorina littorea*) were taken from an earlier estimate of stocks of non-cultivated species present on soft-bottom sediments of the bay (Sauriau 1987, Sauriau et al. 1989, 1998).

Estimates for the stocks of non-cultivated species on rocky substrates and for plant groups, eelgrasses and halophytes, present along the shoreline, were made specifically for the present study. The sampling protocol was based on a stratified sampling strategy (Cochran 1977) with specific strata definition, estimates of their area, random sampling in a minimum of 2 stations per strata, and then sampling by unit surface area (details are given below). The calculations of variance used the formulas for a stratified random protocol (Cochran 1977).

Biomass assessment of intertidal animal species on hard substrates: Hard substrates in the Marennes-Oléron Bay are mostly the low walls present in the oyster bed cultivation zones (Goulletquer & Héral 1997, Pigeot 2001). Six strata were defined by the tidal level of the oyster cultivation zones and linked to the tidal coefficient (<30, 30–40, 40–60, 60–80, 80–100, >100). Tidal coefficients range from 20 to 120 according to SHOM (*Service Hydrographique de la Marine*, *Brest*), 20 and 120 being related to extreme neap tide levels and extreme spring tide levels, respectively. Each stratum contained between 2 and 5 randomly selected sampling stations. Within each station, 2 linear meters of low wall were sampled. All the motile and attached epiflora and epifauna, as well as those located in the immediate surroundings (at a distance of 20 cm maximum on either side of the section of the wall being sampled), were collected. The organisms collected from each sampling station were sorted by species in the laboratory, and the biomass of each species was evaluated. This protocol was used in 4 sectors of the oyster cultivation zone: Château d'Oléron, Daire, Saint Trojan and Ronce-les-Bains (Fig. 2). Finally, the shellfishery exploitation registry '*Cadastre ostréicole des Affaires Maritimes - Marennes*' was used to make estimates of the total length of these low walls for each bathymetric stratum and for each of the 4 sectors, using the Arcview GIS softwave, release 3.2.

Biomass assessment of intertidal plants on soft-bottom substrates: The biomasses of the shore halophytes (*Atriplex portulacoides* and *Sarcocornia perennis*) were evaluated on 3 geographic strata (La Perrotine, Gatseau and Brouage, Fig. 2). On each strata, 3 samples of 0.25 m^2 each were made and the 2 dominant species *Atriplex portulacoides* (80% of the total surface) and *Sarcocornia perennis* (20%) were sampled. In the laboratory, the plants were weighed after the mud was removed. The ratio of the dry to wet weight was measured to establish a value for the dry biomass per unit surface area of each plant species. The surface occupied by the halophytes was determined using aerial pictures with a scale of 1:25 000.

For the eelgrass, *Zostera noltii*, living on the upper part of the shore, we evaluated the covered surface in the same way as the shore halophytes but used a SPOT satellite image obtained in September 1986 (Guillaumont 1991). The biomass was evaluated in 6 geographic strata (La Perrotine, Bellevue, Lilon, Les Doux, Le Château and Saint Trojan, Fig. 2) in which 6 quadrants, of 0.25 m^2 each, were randomly sampled. In each quadrant, all the *Z. noltii* plants were collected. In the laboratory, the plants were washed, weighed wet, dried in an oven for 48 h and then reweighed (dry weight).

Estimation of cadmium partitioned in organisms and associated with annual biological production: The quantities of cadmium partitioned (Q in g) into the population of a given species, were evaluated in the following manner:

$$Q = [\mathrm{Cd}] \times \mathrm{DB} \times 10^{-6}$$

where [Cd] (in µg g^{-1} of dry weight) is the concentration of cadmium and DB (in g) is the dry biomass of a given species for the entire bay.

The variance estimate of Q was evaluated following a formula for 2 independent random variables (Seber 1982) as:

$$V([\mathrm{Cd}] \times \mathrm{DB}) = V([\mathrm{Cd}]) \times V(\mathrm{DB}) + (E([\mathrm{Cd}]))^2 \times V(\mathrm{DB}) + V([\mathrm{Cd}]) \times (E(\mathrm{DB}))^2$$

where E([Cd]) and E(DB) are the mean values of cadmium concentration and dry weight biomass for a given species for the entire bay, respectively.

Evaluation of the quantity of cadmium associated with the annual production of living matter for the population of a given species (F in g yr^{-1}) was estimated as follows:

$$F = Q \times P/B$$

where Q is the quantity of Cd partitioned into the population of a given species and P/B is the productivity (the production P of a given species divided by its wet biomass B at a given instant). P/B data were taken from the literature (e.g. Leguerrier et al. 2003 and references therein).

RESULTS AND DISCUSSION

Cadmium concentrations in sampled species

The median of the measured Cd concentrations in the organisms was 0.4 µg g^{-1} dry wt for the 63 species from the Marennes-Oléron Bay. The concentrations of cadmium in the different benthic and suprabenthic

Table 2. Dry biomass (mean ± SD in t) of the principal intertidal taxa and species of the Marennes-Oléron Bay ranked in decreasing order. Reference sources (Ref.): 1, P. Goulletquer & O. Le Moine (pers. comm.); 2, Sauriau (1987); 3, this study

Species	Dry biomass	Ref.	Species	Dry biomass	Ref.
Microphytobenthos	1918.0 ± 383.0	3	*Modiolus barbatus*	0.4 ± 0.1	3
Crassostrea gigas			*Chlamys varia*	0.4 ± 0.1	3
Natural and cultivated	1835.2 ± 428.8	1	*Clibanarius erythropus*	0.3 ± 0.1	3
Atriplex portulacoides			*Pilumnus hirtellus*	0.3 ± 0.1	3
Leaves & stem	1022.5 ± 200.0	3	*Patella vulgata*	0.3 ± 0.1	3
Zostera noltii			*Gibbula umbilicalis*	0.2 ± 0.1	3
Leaves	279.0 ± 70.0	3	*Ulva lactuca*	0.2 ± 0.1	3
Rhizomes & roots	306.0 ± 96.0	3	*Galathea squamifera*	0.1 ± 0.1	3
Cerastoderma edule	273.4 ± 62.5	2	*Hediste diversicolor*	0.1 ± 0.1	3
Sarcocornia perennis			*Osilinus lineatus*	0.1 ± 0.1	3
Leaves & stem	209.9 ± 40.0	3	*Marphysa sanguinea*	0.1 ± 0.1	3
Mytilus edulis			*Enteromorpha intestinalis*	<0.1	3
natural and cultivated	121.4 ± 21.2	1	*Necora puber*	<0.1	3
Hydrobia ulvae	85.1 ± 9.2	2	*Nucella lapillus*	<0.1	3
Macoma balthica	67.6 ± 11.2	2	*Porphyra umbilicalis*	<0.1	3
Scrobicularia plana	45.8 ± 15.2	2	*Anguilla anguilla*	<0.1	3
Crepidula fornicata	29.2 ± 8.9	2	*Littorina obtusata*	<0.1	3
Nassarius reticulatus	27.1 ± 10.2	2	*Asterina gibbosa*	<0.1	3
Fucus vesiculosus	25.0 ± 17.4	3	*Lepidochiton cinereus*	<0.1	3
Tapes decussatus	21.7 ± 7.6	2	*Archidoris pseudoargus*	<0.1	3
Tapes philippinarum	10.9 ± 2.5	3	*Chtamalus stellatus*	<0.1	3
Fucus serratus	8.9 ± 8.2	3	*Ceramium ciliatum*	<0.1	3
Pachygrapsus marmoratus	5.8 ± 1.2	3	*Gobius paganellus*	<0.1	3
Ascophyllum nodosum	3.3 ± 3.2	3	*Dendrodoa grossularia*	<0.1	3
Porcellana platycheles	2.8 ± 0.4	3	*Mytilus galloprovincialis*	<0.1	3
Ocinebrellus inornatus	2.4 ± 0.3	3	*Ostrea edulis*	<0.1	3
Carcinus maenas	2.3 ± 0.5	3	*Balanus perforatus*	<0.1	3
Halichondria bowerbanki	1.7 ± 1.0	3	*Gibbula cineraria*	<0.1	3
Littorina littorea	1.4 ± 0.8	3	*Gigartina acicularis*	<0.1	3
Nassarius incrassatus	1.4 ± 0.9	3	*Laurencia pinnatifida*	<0.1	3
Elminius modestus	1.3 ± 0.3	3	*Orchestra gammarellus*	<0.1	3
Xantho pillipes	0.7 ± 0.2	3	*Palaemon elegans*	<0.1	3
Hemigrapsus penicillatus	0.6 ± 0.2	3	*Psammechinus miliaris*	<0.1	3
Ocenebra erinacea	0.4 ± 0.1	3	*Actinia equina*	<0.1	3
Anemonia viridis	0.4 ± 0.1	3	*Gracilaria verrucosa*	<0.1	3

organisms at the Château d'Oléron station in the spring seasons of 1997, 1998 and 1999 were distinguished by 3 main groups (Table 1). The majority of benthic and suprabenthic organisms had relatively low concentrations, that is, less then 1 µg g^{-1} dry wt. Eleven species had concentrations between 1 and 3 µg g^{-1} dry wt. For primary producers, there were microphytobenthos and 2 macrophytes (*Ceramium ciliatum*, *Zostera noltii*). For animal species there were 3 gastropods (*Archidoris pseudoargus*, *Littorina littorea* and *L. btusata*), 4 bivalves (*Crassostrea gigas*, *Mytilus edulis*, *M. galloprovincialis* and *Ostrea edulis*), 1 crustacean (*Balanus perforatus*) and 1 echinoderm (*Asterina gibbosa*). Six gastropods (*Nassarius incrassatus*, *N. reticulatus*, *Nucella lapillus*, *Ocenebra erinacea*, *Ocinebrellus inornatus* and *Patella vulgata*) and 2 bivalves (*Chlamys varia* and *Modiolus barbatus*) had concentrations higher than 5 µg g^{-1} dry wt, and up to 10 µg g^{-1} dry wt.

Estimation of the biomass of intertidal species

The total dry biomass for the 63 benthic and suprabenthic organisms of the Marennes-Oléron Bay was about 8800 t (Table 2). Six species (the 2 cultivated bivalves *Crassostrea gigas* and *Mytilus edulis*, the shore halophytes *Atriplex portulacoïdes* and *Sarcocornia perennis*, the dwarf eelgrass *Zostera noltii*, and the cockle *Cerastoderma edule*) plus the microphytobenthos represented more than 96% of the total dry biomass; each has a dry biomass (DB) greater than 100 t. Eight other species, which are all found on sandy-mud substrates, with the exception of 1 brown algae (*Fucus serratus*), had DB values between 10 and 100 t. These 14 species, plus microphytobenthos, amounted to 8771 t of dry material, or more than 99.5% of the total DB. The remaining 0.5% of the total dry biomass constituted 10 species living on rocky substrates and the remaining 39 species sampled had DB values lower than 1 t each.

Table 3. Quantities of cadmium fixed (Q ± SD in g) by the principal intertidal taxa and species of the Marennes-Oléron Bay, ranked in decreasing order

Species	Cd fixed (g)
Crassostrea gigas	
Natural and cultivated	2705.1 ± 1108.0
Microphytobenthos	2343.8 ± 383.0
Zostera noltii	565.6 ± 256.7
Leaves	189.2 ± 141.0
Rhizomes & roots	376.4 ± 214.0
Mytilus edulis	
Natural and cultivated	305.9 ± 54.6
Nassarius reticulatus	141.3 ± 80.4
Cerastoderma edule	125.8 ± 54.0
Atriplex portulacoides	
Leaves & stem	101.2 ± 59.6
Crepidula fornicata	22.2 ± 11.8
Scrobicularia plana	17.6 ± 8.0
Ocinebrellus inornatus	14.9 ± 2.6
Tapes decussatus	10.2 ± 5.4
Nassarius incrassatus	7.3 ± 4.6
Macoma balthica	6.8 ± 1.2
Fucus serratus	5.0 ± 4.8
Macoma balthica	6.8 ± 1.2
Chlamys varia	4.4 ± 1.5
Hydrobia ulvae	4.1 ± 0.6
Tapes philippinarum	3.6 ± 2.5
Modiolus barbatus	3.0 ± 1.2
Sarcocornia perennis	
Leaves & stem	2.7 ± 0.7
Ocenebra erinacea	2.5 ± 0.7
Littorina littorea	1.7 ± 1.0
Fucus vesiculosus	1.4 ± 1.1
Patella vulgata	1.4 ± 0.6
Carcinus maenas	0.7 ± 0.3
Nucella lapillus	0.6 ± 0.3
Porcellana platycheles	0.4 ± 0.1
Halichondria bowerbanki	0.4 ± 0.3
Ascophyllum nodosum	0.4 ± 0.4
Pachygrapsus marmoratus	0.2 ± 0.1
Clibanarius erythropus	0.2 ± 0.2
Xantho pillipes	0.1 ± 0.1
Pilumnus hirtellus	0.1 ± 0.1
Elminius modestus	0.1 ± 0.1
Archidoris pseudoargus	0.1 ± 0.1
Asterina gibbosa	0.1 ± 0.1
Gibbula umbilicalis	0.1 ± 0.1
Galathea squamifera	0.1 ± 0.1
Littorina obtusata	<0.1
Psammechinus miliaris	<0.1
Hemigrapsus penicillatus	<0.1
Ostrea edulis	<0.1
Balanus perforatus	<0.1
Anguilla anguilla	<0.1
Osilinus lineatus	<0.1
Necora puber	<0.1
Mytilus galloprovincialis	<0.1
Lepidochiton cinereus	<0.1
Ceramium ciliatum	<0.1
Marphysa sanguinea	<0.1
Anemonia viridis	<0.1
Dendrodoa grossularia	<0.1
Gibbula cineraria	<0.1
Enteromorpha intestinalis	<0.1
Porphyra umbilicalis	<0.1
Tapes decussatus	<0.1
Gigartina acicularis	<0.1
Orchestra gammarellus	<0.1
Gobius paganellus	<0.1
Palaemon elegans	<0.1
Chtamalus stellatus	<0.1
Actinia equina	<0.1
Laurencia pinnatifida	<0.1
Ulva lactuca	<0.1

Quantities of cadmium in the phytobenthos and zoobenthos

The quantity of cadmium in the biomass of the 63 principal benthic, suprabenthic and intertidal species, as well as in the microphytobenthos of the Marennes-Oléron Bay was 6.3 kg with a standard deviation of 1.2 kg (Table 3). Ninety-eight percent of this cadmium was within 6 species, plus the microphytobenthos, and all of them contained quantities of cadmium higher than 0.1 kg. These species were the 2 cultivated bivalve species (*Crassostrea gigas* and *Mytilus edulis*), the dwarf eelgrass *Zostera noltii*, the cockle *Cerastoderma edule*, 1 of the 2 principal shore halophytes (*Atriplex portulacoïdes*) and the reticulated dog whelk (*Nassarius reticulatus*). If we add the quantity of cadmium in the 7 taxa above to that accumulated by the following 5: *Crepidula fornicata*, *Ocinebrellus inornatus*, *Scrobicularia plana*, *Tapes decussatus* and *Patella vulgata* (all of which have biomass accumulations between 0.1 and 0.01 kg of Cd), then these species account for over 99 % of the cadmium partitioned into the benthic biomass. Thus, 11 benthic species plus the microphytobenthos alone accounted for the majority of the cadmium.

Species contamination

The initial data available from the RNO on the quality of the marine environment demonstrated that there are chronic levels of cadmium pollution in the Marennes-Oléron Bay (RNO 1988, 1995, 2000). Oysters collected from this bay contained Cd concentrations systematically higher than those generally measured in oysters sampled from other French coastal regions: the measured values have shown a tendency to decrease since 1985, and have returned to concentrations below 5 μg g^{-1} dry wt since the mid-1990s (RNO 2000, 2004). The maximum allowable Cd in bivalves is 1 µg g^{-1} wet wt (European Community regulation CEE/466/2001 on 8 March 2001, applicable 5 April 2002) above which the consumption and commercialisation of shellfish is forbidden. Thus, using a ratio of wet to dry wt of near 5, some other species analysed from the bay (scallops, mussels, limpets, dog whelks) also exceeded the maximum allowable Cd in bivalves. The majority (71%) of the species analysed, notably the fish, crustacean and echinoderm species most likely to be consumed by humans, had Cd concentrations below 1 µg g^{-1} dry wt (Table 1). These results are in the same range as concentrations measured in these taxa in other industrialised coastal zones (Bryan 1984).

Nineteen species in the Marennes-Oléron Bay had Cd concentrations higher than 1 µg g^{-1} dry wt. Among these, only 4 species, or groups of species, were not molluscs: the red algae *Ceramium ciliatum*, the starfish *Asterina gibbosa*, the barnacle *Balanus perforatus*, which had a concentration among the lowest measured for barnacles collected from Cd contaminated zones (Phillips & Rainbow 1988), and the microphytobenthos. To the best of our knowledge, this is the first time that Cd analyses have been made on the microphytobenthos of the Marennes-Oléron Bay, a biological compartment that is very abundant on all bare mudflats of this bay (Guarini et al. 1998, Blanchard et al. 2000). This microphytobenthos had a Cd concentration (1.22 µg g^{-1} dry wt) close to that measured in the planktonic diatoms collected from the Seine Bay (which is also subjected to chronic Cd pollution) and of planktonic diatoms collected in the Marennes-Oléron Bay (Miramand et al. 1993, 2001a).

The mollusc species with Cd concentrations higher than 1 µg g^{-1} dry wt included neogastropods (*Nassarius incrassatus*, *N. reticulatus*, *Nucella lapillus*, *Ocenebra erinacea*, *Ocinebrellus inornatus*), filibranch bivalves (*Chlamys varia*, *Crassostrea gigas*, *Modiolus barbatus*, *Mytilus edulis*, *M. galloprovincialis*, *Ostrea edulis*), the nudibranch *Archidoris pseudoargus*, 2 littorina species (*Littorina littorea* and *L. obtusata*) and the limpet *Patella vulgata*. Most of these species are known to bioaccumulate Cd (Bryan 1984, Phillips 1977, Langston & Zhou 1987). Among the molluscs, the bioaccumulation of cadmium does not seem to be linked to their taxonomic group, nor even trophic behaviour (Table 1). For example, among the archeogastropods, *Patella vulgata* had Cd concentrations an order of magnitude higher than *Gibbula umbilicalis* (Kruskal-Wallis rank test, $p < 0.03$, see Table 1 Gastropoda section). The concentration of Cd measured for species belonging to the same taxa is not linked to their trophic level within the benthic food web and we observe large differences in the concentrations measured for species with the same feeding behaviour. This is, for instance, most apparent for grazers and for the filter feeders including facultative suspension-feeders. Within bivalves, a clear split appears between the filibranchs (*Mytilus galloprovincialis*, *M. edulis*, *Modiolus barbatus*, *Crassostrea gigas*, *Chlamys varia* with significant differences between species, Kruskal-Wallis rank test $p < 0.01$, which had systematically greater concentrations than the median) and the eulamellibranchs (*Cerastoderma edule*, *Tapes decussatus*, *T. philippinarum*, *Macoma balthica*, *Scrobicularia plana* with no significant differences between species, Kruskal-Wallis rank test $p > 0.05$, and all with low concentrations, near the median) since highly significant differences occurred between the 2 groups (Kruskal-Wallis rank test, $p < 0.001$, see Table 1 Bivalvia section). Thus, it seems unreasonable to group all the bivalves together or to separate trophic groups among bivalves on the basis of their bioaccumulation of cadmium.

Contamination at the ecosystem level

The quantity of Cd partitioned into the principal benthic species of the bay appears variable within 7 main species. The largest fraction are the intertidal species, which account for about 6.4 kg of Cd (Table 3). Studies of subtidal species stocks in the Marennes-Oléron Bay (Sauriau 1987 and renewed for *Crepidula fornicata* by Sauriau et al. 1998) estimated that approximately 0.5 kg of cadmium was partitioned into subtidal fauna (Table 4). Thus, a total of 7 kg of Cd may be contained in all benthic species living in the bay. At the ecosystem level, only a few species or groups of species seem to be relevant for the partitioning of Cd (Fig. 3). These are essentially the Pacific oysters *Crassostrea gigas* and the microphytobenthos, each representing about 40% of the total. Five other species also play an important role in Cd partitioning: eelgrass *Zostera noltii* at 9%, mussels *Mytilus edulis* at 5%, dog whelks *Nassarius reticulatus*, cockles *Cerastoderma edule* and halophytes *Atriplex portulacoides* at 2% each. In conclusion, there are 6 spe-

Table 4. Quantities of cadmium fixed ($Q \pm$ SD in g) by the principal benthic subtidal species in the Marennes-Oléron Bay, ranked in decreasing order. DB: dry biomass (t) for each species; [Cd]: concentration of cadmium

Species	DB (t)	[Cd] (µg g^{-1} DB)	Q (g of Cd)
Chlamys varia	15.6 ± 7.9	11.8 ± 3.2	184.1 ± 105.0
Nassarius reticulatus	28.7 ± 5.3	5.2 ± 2.1	149.2 ± 66.3
Mytilus edulis	33.5 ± 18.9	2.5 ± 0.1	83.7 ± 47.4
Crepidula fornicata	49.2 ± 28.6	0.7 ± 0.3	34.4 ± 24.9

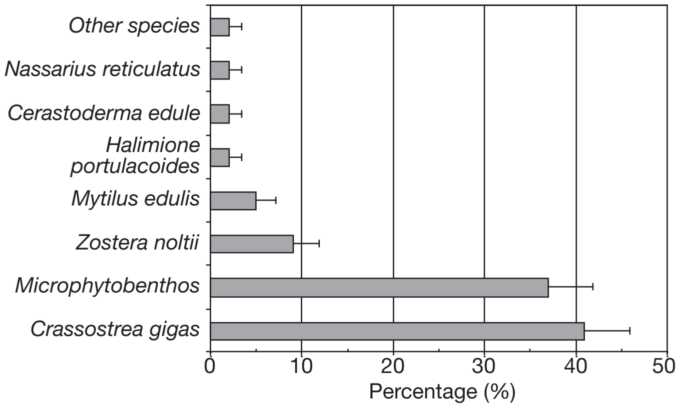

Fig. 3. Percentages of Cd partitioned among the benthic species in the Marennes-Oléron Bay

cies and 1 group of species (microphytobenthos) which contain up to 98% of the Cd present in the benthic species of the Marennes-Oléron Bay. At the ecosystem level, all the other benthic species are considered negligible for the partitioning of Cd. Individually, each of them represents less than 0.1% of the total Cd partitioned into the organisms of the benthic ecosystem.

Transfers within the trophic foodweb

For the Marennes-Oléron Bay, almost all the partitioned Cd (97%) is associated with only 2 trophic levels: the primary producers (3 kg of Cd) and the filter feeders (3.2 kg of Cd) (Fig. 4, Table 3). By comparison, the quantities of Cd partitioned by the other trophic levels appear negligible. In particular, the Cd mass partitioned into the carnivores (< 0.2 kg) was small, and most (84%) of this cadmium was associated with the reticulated dog whelk *Nassarius reticulatus*. Based on this observation, there is a clear absence of biomagnification of Cd in the trophic network at the ecosystem level. This has also been observed in numerous other studies, which consider the biomagnification of this metal at the species level only (Bryan 1984). Yet, in the present study, a biomagnification of Cd was described for short food chains with just 2 trophic levels, for example between the microphytobenthos and the suspension feeders.

The quantities of Cd associated with the annual production of biomass for the principal benthic and suprabenthic intertidal species of the Marennes-Oléron Bay have been estimated (Table 5). These estimates are considered to represent the uptake of Cd in the ecosystem during biological production and thus, the quantities of Cd which are potentially available to be transferred within the trophic network. The intertidal mudflats of the Marennes-Oléron Bay are central to an intense microphytobenthic primary production where the sedimentary chlorophyll levels are frequently higher than 100 mg chl *a* m^{-2} (Guarini et al. 1998) and the net production (actual production less the losses caused by suspension, grazing, etc.) has been measured at 1 g C m^{-2} d^{-1} (Blanchard et al. 1998), resulting in an annual production of 300 g C m^{-2} yr^{-1}. This intense production explains the central role occupied by the microphytobenthos in the trophic network of the intertidal areas of the Marennes-Oléron Bay (Leguerrier et al. 2003). The microphytobenthos is

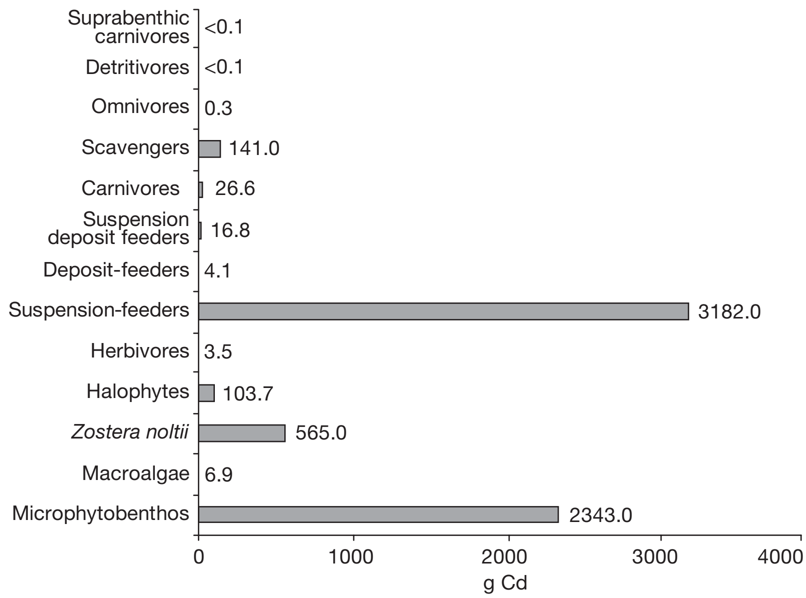

Fig. 4. Cd masses (g) estimated for the major benthic trophic groups within the Marennes-Oléron Bay

Table 5. Estimated quantities of cadmium associated with the annual biomass production (*P/B*) of the principal benthic species in different zones of the Marennes-Oléron Bay

Zone	Surface (km^2)	Principal species	*P/B* (yr^{-1})	Cd (kg yr^{-1})
Shellfishery areas	30.00	*Crassostrea gigas*, *Mytilus edulis*, *Fucus serratus*, *Ocenebra erinacea*, *Patella vulgata*	0.33	1.4.00
Bare mudflats	96.00	Microphytobenthos	80.00	188.00
Seagrass meadows	8.65	*Zostera noltii*	3.40	1.90
Upper shore	1.20	*Atriplex portulacoïdes*, *Sarcocornia perennis*	0.60	<0.10

the most important source of food for the majority of deposit feeder species which also make up the largest portion of the intertidal benthic population in the Marennes-Oléron Bay (Riera et al. 1996). The estimate for the quantities of Cd associated with the annual production in the microphytobenthic compartment (approximately 188 kg yr^{-1} [200 ng of Cd cm^{-2} yr^{-1}]) exceeded the other benthic compartments by 2 orders of magnitude (Table 5). Stable isotope tracer studies have shown that microphytobenthos are a trophic resource available to the commercially exploited suspension feeders in the bay, such as oysters, mussels and cockles (Riera et al. 1996, Sauriau & Kang 2000). Therefore, the role of microphytobenthos in the cycling of Cd in mudflat zones should be taken into account in future biogeochemical models in order to determine how the microphytobenthic compartment participates in Cd transfer processes to suspension and deposit feeders.

Humans are the most important consumers of shellfish sourced from the bay, and thus Cd contamination of oysters represents a potentially non-negligible source of contamination of human consumers by Cd. The quantity of Cd associated with the biomass production of suspension feeders was approximately 1.4 kg yr^{-1}, which is relatively low. However, Cd associated with the oysters represented the major portion of this pool (64 %). In order to exceed the weekly tolerable dosage (WTD) of Cd in humans, recommended by the JECFA (7 µg kg^{-1} bodyweight, Joint Expert Committee for Food Additives, FAO-WHO), it would be necessary to consume, on average, almost 3.6 kg of oysters per week (Miramand et al. 2001b). This quantity is higher than that known to be consumed, even by the large consumers of shellfish from the Charente-Maritime region, who consume up to 38.5 kg yr^{-1}, of which only 24.8 kg correspond to oysters (Anonymous 1994).

The eelgrass meadows are a possible vector of Cd to some migratory bird populations. Marennes-Oléron Bay is an overwintering location for a large population of Brent geese *Branta bernicla*, a bird that specialises in grazing on eelgrass (Charman 1979). The Cd associated with the eelgrass meadows was estimated at more than 2 kg yr^{-1} (Table 5), which when divided by the surface area of all the eelgrass meadows in the bay represented 23 ng of Cd cm^{-2} yr^{-1}. This result is consistent with estimates of Wassermann et al. (1991) from Arcachon Bay, France. Considering a daily consumption of 100 g of eelgrass per bird, this represents a weekly consumption of approximately 63 µg of Cd, which when calculated relative to the average weight of a Brent goose (2 kg) is almost 20 times higher than the WTD recommended for Cd in humans. However, Cd accumulation has not yet been studied in these birds, or the other overwintering wading birds, which may represent a potential pathway to export Cd out of the bay.

Ecosystem-wide budget of Cd in the Marennes-Oléron Bay

Using the quantities of Cd partitioned by the different benthic species and communities of the Marennes-Oléron Bay (Tables 4 & 5), an ecosystem-wide budget of the quantities of Cd present in each of the biological and physical compartments in the bay has been estimated (Table 6).

One compartment, the nekton, has not been studied yet. The quantities of Cd partitioned by fish and cephalopods living in the Marennes-Oléron Bay remain unclear because of their seasonal migrations. In the Marennes-Oléron Bay, mullet *Liza ramada* and cuttlefish *Sepia officinalis* represent the majority of the nektonic biomass in the bay. Using an average Cd concentration of 0.02 µg g^{-1} dry wt (measured in several species, Pigeot 2001) and a maximum biomass of 10 000 t, the quantity of Cd partitioned by fish may be estimated at approximately 40 g, which can be considered negligible relative to the other compartments. The amount of Cd parti-

Table 6. Global budget[a] of cadmium estimated for the Marennes-Oléron Bay

Primary compartments	Secondary compartments	Cd total (kg)
Water	Dissolved	13
	Particulate	7
Pelagos	Phytoplankton[b]	0.2–0.4
	Zooplankton[c]	0.01–0.05
	Nekton	>0.2
Benthos	Microphytobenthos	2.3
	Other primary producers	0.7
	Filter feeders	3.2
	Other consumers	0.2
Sediment[d]		1000

[a]Calculations used the following values from the literature: average volume of the basin 574 million m^3 (Soletchnik et al. 1998); average turbidity of 100 mg l^{-1} (Sornin et al. 1986); average dissolved Cd concentration of 20 ng l^{-1} (B. Boutier pers. comm.) and an average particulate Cd concentration of 0.26 µg g^{-1} (Pigeot 2001)

[b]Phytoplankton average springtime concentration of 5 µg chl *a* l^{-1} (Héral et al. 1984); measured concentration of Cd in pelagic diatoms 1.19 µg g^{-1} dry wt (Miramand et al. 2001a)

[c]Zooplankton estimated biomass of 9.86 mg of C m^{-3} (Sautour & Castel 1998); measured Cd concentration in zooplankton 1.17 µg g^{-1} dry wt (Miramand et al. 2001a)

[d]Sediments: sedimentation rate in the basin was 1 cm of compacted mud per year (Raillard et al. 1994) even if locally the sediment dynamics depend on the geomorphology of the mudflat (Gouleau et al. 2000); mudflat surface area of 96 km^2 with an average mud density of 1.4 (Gouleau et al. 2000); average measured Cd concentration of 0.14 µg g^{-1} dry wt (Gonzalez et al. 1991)

tioned by the cephalopods was estimated at 0.2 kg applying an approximate biomass of 1000 t and an average concentration of 0.02 µg Cd g^{-1} dry wt measured in cuttlefish collected off La Rochelle, just beyond the northern limit of the bay (Bustamante et al. 1998). A similar calculation could be done for epibentic crustaceans with an average concentration higher than 1 µg Cd g^{-1} dry wt but biomasses lower than 100 to 500 t. Thus, the total quantity of Cd partitioned by the pelagic compartments of the bay is between 0.5 and 0.6 kg, which would be considered low at the scale of the whole bay, when compared to the water column (20 kg) and to the benthos (6.4 kg) (Table 6).

Overall, the largest pool of cadmium was associated with the upper 5 cm of sediments (equivalent to about 5 yr of deposition) (Table 6). Cohesive sediments of Marennes-Oléron Bay intertidal areas may function as either a geochemical sink for Cd, or as a source, through long-term tidal erosion-sedimentation cycles (Gouleau et al. 2000), biodeposition by oysters and mussels (Sornin et al. 1983, 1986) and infauna bioturbation (El Ghobary & Dumon 1984). Gonzalez et al. (1991) have estimated that the diffusive flux of Cd from the sediments of the bay to the water column is, on average, 150 ng of Cd cm^{-2} yr^{-1}. Fluxes of Cd out of the sediments could be enhanced by the activities of benthic deposit-feeders (meiofauna: Green & Chandler 1994 and macrofauna: Watson et al. 1993). However, spatial variability in species composition and density (Sauriau et al. 1989), predominance of upwards vs downward sediment reworking depending on specific feeding behaviour (e.g. Rasmussen et al. 2000) and the balance between stabilising effects of microphytobenthic biofilms on surface sediments vs destabilising effects by deposit-feeder reworking (Orvain et al. 2004), may add a significant degree of variability in the final estimates. In addition, cadmium trapped upstream from the bay, in the bottom sediments of the Garonne River, could be released during future dredging projects behind the numerous hydroelectric dams installed on this river, and therefore increase the flux of Cd to the Marennes-Oléron Bay. An integrated ecosystem study of Cd transport along the entire continuum, from the source (the Lot River) through the Gironde Estuary to the Marennes-Oléron Bay, seems necessary, as even small changes in Cd partitioning among the largest compartments may have major negative consequences to the biota and could also adversely affect the socioeconomic structures of the Marennes-Oléron Bay.

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