



Multi-level assessment of chronic toxicity of estuarine sediments with the amphipod *Gammarus locusta*: I. Biochemical endpoints

Teresa Neuparth*, Ana D. Correia, Filipe O. Costa,
Gláucia Lima, Maria Helena Costa

IMAR – Centro de Modelação Ecológica, DCEA, F.C.T., Univ. Nova de Lisboa,
2829-516 Caparica, Portugal

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Abstract

We report on biomarker responses conducted as part of a multi-level assessment of the chronic toxicity of estuarine sediments to the amphipod *Gammarus locusta*. A companion article accounts for organism and population-level effects. Five moderately contaminated sediments from two Portuguese estuaries, Sado and Tagus, were assessed. Three of them were muddy and two were sandy sediments. The objective was to assess sediments that were not acutely toxic. Three of the sediments met this criterion, the other two were diluted (50% and 75%) with clean sediment until acute toxicity was absent. Following 28-d exposures, the amphipods were analysed for whole-body metal bioaccumulation, metallothionein induction (MT), DNA strand breakage (SB) and lipid peroxidation (LP). Two of the muddy sediments did not cause chronic toxicity. These findings were consistent with responses at organism and population levels that showed higher growth rates and improvement of reproductive traits for amphipods exposed to these two sediments. Two other sediments, one muddy and one sandy, exhibited pronounced chronic toxicity, affecting SB, MT induction (in muddy sediment), survival and reproduction. Potential toxicants involved in these effects were identified. The last sandy sediment exhibited some loss of DNA integrity, however growth was also enhanced. Present results, together with the organism/population-level data, and also benthic

* Corresponding author. Tel.: +351 21 294 8300x10113; fax: +351 21 294 8554.
E-mail address: mtsn@fct.unl.pt (T. Neuparth).

communities information, were analysed under a weight-of-evidence approach. By providing evidence of exposure (or lack of it) to contaminants in sediments, the biomarkers here applied assisted in distinguishing toxicants' impacts in test organisms from the confounding influence of other geochemical features of the sediments.

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1. Introduction

The recognition of the complexity of sediment biogeochemistry and of technical difficulties in the evaluation of the ecological impact of sediment contamination, has led to increasing support for the application of multiple lines of evidence (LOE) in sediment quality assessments, integrated in a weight-of-evidence (WOE) approach (Chapman, McDonald, & Lawrence, 2002; Wenning & Ingersoll, 2002). Sediment toxicity tests are recognized as an essential tool of the WOE approach, although with their inherent strengths and weaknesses. Among the limitations are the recurrent difficulties in discriminating the contaminant-induced impacts in test organisms from those responses attributable to other non-contaminant factors (Wenning & Ingersoll, 2002). In particular, sediment geochemical properties are known not only to regulate contaminants' bioavailability, but also to be able to directly influence responses of test organisms in various ways (Gunnarsson, Granberg, Nilsson, Rosenberg, & Hellman, 1999; USEPA-USACE, 2001; Wenning & Ingersoll, 2002). Most of the response criteria used in chronic toxicity tests (such as those based on growth and reproduction endpoints) lack specificity, and consequently can be affected both by contaminants and other sediment features (e.g., grain size, amount and quality of organic matter). In this context, additional LOE within the toxicity test are required to determine exposure of test organisms to sediment contaminants.

Molecular biomarkers provide evidence of exposure to toxicants, and their detection in natural populations provide information about contaminant bioavailability (Hyne & Maher, 2003; Shugart, 2000). A number of biomarkers have been developed and applied successfully to various invertebrate species (Galloway et al., 2004; Hyne & Maher, 2003; Langston & Bebianno, 1998; Livingstone, 2001), but they have been rarely integrated in conventional sediment toxicity tests and/or linked to population-level effects. However, the application of multiple biomarkers in chronic sediment tests can be advantageous for providing evidence of the cause-effect relationship between exposure to sediment contaminants and ultimate organism and population responses.

Technical difficulties can be one of the reasons for the scarcity of biomarkers in conventional sediment toxicity tests: test organisms must have a short life-cycle in order to assess growth and reproductive effects in a short period and, simultaneously, they must provide large enough biomass for biomarker analysis. In order to fulfil these requirements we selected the amphipod *Gammarus locusta* (L.), a widely dis-

tributed species in coastal Atlantic Europe, which groups a number of advantages for application in ecotoxicological studies (Costa & Costa, 2000). Recently, specific methodologies were developed for application of known biomarkers in ecotoxicological studies with this amphipod, namely metallothionein (MT) induction, lipid peroxidation (LP) (Correia, Lima, Costa, & Livingstone, 2002) and DNA strand breakage (SB) (Costa, Neuparth, Costa, Theodorakis, & Shugart, 2002).

Given the critical role that the DNA molecule plays in the life and reproduction of each organism, a number of studies have focused on biomarkers of DNA damage to detect genotoxicity in aquatic organisms (Shugart, 1998, 2000). Compared to other techniques used to assess DNA damage, detection of DNA strand breakage by agarose gel electrophoresis has the advantage of determining insult to DNA integrity both qualitatively (single strand-breaks versus double strand-breaks) and quantitatively (number of strand breaks). In addition it can also be applied to DNA extracted from whole organisms, thus not requiring manipulation of the amphipods to collect specific tissues (Costa et al., 2002). Malondialdehyde (MDA), a breakdown product of lipid endoperoxides, is an expression of lipid peroxidation and has been used with success in aquatic invertebrates as a general indicator of toxicant stress derived from various types of contamination (Livingstone, 2001). Metallothioneins (MT) are a widely used biomarker of exposure to metallic contaminants (e.g., Cd, Cu, Zn and Hg) which has been applied in numerous aquatic invertebrates, particularly molluscs (Langston & Bebianno, 1998; Livingstone, 2001) and more recently in crustaceans (Barka, Pavillon, & Amiard, 2001; Correia et al., 2002; Galloway et al., 2004; Moksnes, Lindahl, & Haux, 1995).

Our recent research efforts have been directed to the integration of these biomarkers in sediment toxicity tests, by assessing multiple biological effects at several levels of biological organization - from molecular to organism and population levels. This type of approach has been previously tested in laboratory chronic toxicity tests with copper-spiked sediments (Correia, Costa, Neuparth, Diniz, & Costa, 2001; Correia et al., 2002) and we are now aiming to investigate its usefulness in chronic tests with field-contaminated sediments. Therefore, the goal of the current study was to conduct sediment tests with the amphipod *G. locusta*, integrating biomarker alterations (namely MT, SB and LP) with effects on growth, reproductive performance and recruitment. Here we report biomarker responses, while organism and population-level endpoints were analysed in a parallel paper (Costa, Neuparth, Correia, & Costa, 2004). These results were integrated with sediment chemistry and benthic community data in a WOE framework, and discussed in view of the potential of biomarker responses to link sediment contamination with higher-level endpoints (organism/population-level).

2. Materials and methods

2.1. Sediment collection and processing

Control and test sediments were collected from Sado and Tagus estuaries. Fig. 1 indicates the locations of the sediments to be analysed and Table 1 summarizes the

relevant features of the collection sites. Only one sediment was collected in Tagus estuary, all others were collected in the lower Sado estuary. Test sediments from Sado estuary were collected at several points along the north margin, all located in the euhaline section of estuary. Control sediment was collected in the opposite south margin, from a clean reference site, where wild *G. locusta* were also sampled to supply the laboratory culture.

The salinity at the collection sites is very close for all sediments and averages 32‰, with the exception of sediment P that is about 27‰ (Mucha, 1997). At each site, intertidal surface sediments were sampled using a scoop. In the laboratory, sediments were sieved through a 1500 µm screen to remove macrofauna, and stored at 4 °C for a maximum of 72 h before the initiation of the chronic sediment tests. Before the beginning of the assays all test sediments were homogenized for 15 min with the assistance of a mechanic mixer, after which samples of each sediment were collected for geochemical analysis.

2.2. Sediment geochemical analysis

Sediments were analysed for organic matter content (expressed as percentage of total volatile solids – TVS), bulk concentration of trace metals (Cd, Cu, and Zn),

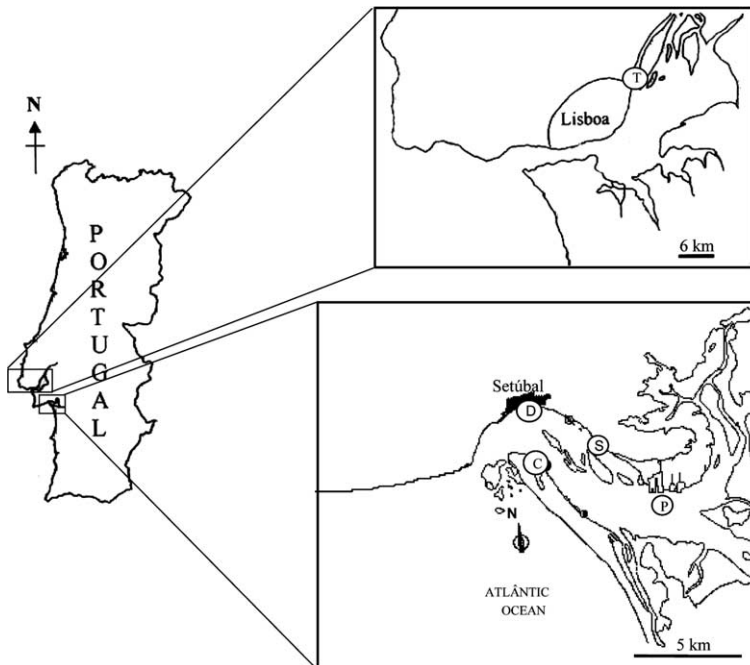


Fig. 1. Sediments' sampling sites in Tagus (above) and Sado (below) estuaries. The sediments from Sado estuary were labelled as C, D, P and S (location for sediments S1 and S2) and the sediment from Tagus estuary as T.

Table 1
Sediments' collection sites, sediment features, and chemical contaminants of each sediment tested in chronic toxicity tests^{a,b,c}

	Control sediment	Chronic test 1		Chronic test 2		
		Sediment T	Sediment P	Sediment S1	Sediment S2	Sediment D
Sediments' collection sites	Clean area of the South margin of Sado estuary	North margin of Tagus estuary near the city of Vila Franca de Xira	North margin of Sado estuary close to a pulp mill effluent	North margin of Sado estuary, near the effluent of a pesticide and fertilizer plant (S1 collected 25 m from the effluent, and S2 30 m upstream from S1)	North margin of Sado estuary, in a dockyard nearby an urban effluent of the city of Setúbal	
Sediment type	Sand	Mud	Mud	Sand	Sand	Mud
TVS (%)	0.7	11.5	8.7	0.4	0.4	12.7
Metals ($\mu\text{g g}^{-1}$ dry wt)						
Cd	BDL	0.31	0.32	0.13	0.12	0.6
Cu	0.21	33	85*	14	11	361**
Zn	20	190*	221*	27	62	217*
PAH and PCB (ng^{-1} dry wt)						
Naphthalene	17	19	41	4	65	5
Acenaphthylene	3	3	13	BDL	21	5
Acenaphthene	BDL	BDL	BDL	BDL	BDL	BDL
Fluorene	BDL	BDL	55*	104*	18	13
Phenanthrene	74	84	303*	1658**	346*	145
Anthracene	BDL	BDL	BDL	BDL	BDL	BDL
Σ Low mol wt. PAH	94	106	412	1848*	368	168
Fluoranthene	90	103	785*	1681*	1411*	355
Pyrene	122	139	686*	2186*	1088*	359
Benzo(a)anthracene	BDL	BDL	490*	1194*	704*	154
Chrysene	47	54	401*	1345*	518*	188
Benzo(b)fluoranthene ^b	81	93	970	1390	1596	335
Benzo(g,h,i)perylene ^b	BDL	BDL	492	BDL	BDL	BDL
Benzo(k)fluoranthene ^b	BDL	BDL	BDL	BDL	BDL	BDL
Indeno(1,2,3-cd)pyrene ^b	BDL	BDL	525	644	657	BDL
Dibenzo(a,h)anthracene	BDL	BDL	BDL	BDL	BDL	BDL
Benzo(a)pyrene	BDL	BDL	551*	794*	905*	183

(continued on next page)

Table 1 (continued)

	Control sediment	Chronic test 1		Chronic test 2		
		Sediment T	Sediment P	Sediment S1	Sediment S2	Sediment D
Sediments' collection sites	Clean area of the South margin of Sado estuary	North margin of Tagus estuary near the city of Vila Franca de Xira	North margin of Sado estuary close to a pulp mill effluent	North margin of Sado estuary, near the effluent of a pesticide and fertilizer plant (S1 collected 25 m from the effluent, and S2 30 m upstream from S1)		North margin of Sado estuary, in a dockyard nearby an urban effluent of the city of Setúbal
\sum High mol wt. PAH	340	389	4900*	9779*	6879*	1574
\sum Total PAH	434	495	5312*	11627*	7247*	1742
Total PCB	0.83	0.83	2.51	0.68	0.89	1.78

^a BDL = below detection limit.

^b ERL and ERM guidelines not available.

^c Values above ERL = *; values above ERM = **.

polynuclear aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCBs). The TVS were determined as the percentage weight loss after ignition of dry sediment at 550 °C for 4 h (Correia & Costa, 2000).

Trace metal analyses were performed on aliquots of the solid fraction that were freeze-dried, homogenized by grinding, and digested with a mixture of acids according to the method described by Rantala & Loring (1977). The digested material was then analysed by air–acetylene flame to determine the concentration of Zn and a pyrolytic graphite furnace equipped with a L'vov platform to establish the concentrations of Cu and Cd. The total PAH were quantified using 16 individual congeners (naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthrene, benzo(g,h,i)perylene, benzo(k)fluoranthene, indeno(1,2,3-cd)pyrene, dibenzo(a,h)anthracene and benzo(a)pyrene). PAH were extracted from frozen sediment samples using soxhlet extraction, after lyophilization and filtration. The sediment extracts were further cleaned up and fractionated by silica column chromatography, concentrated and quantified by capillary gas chromatography/mass spectrometry/electron capture detection (GC-MS/GC-ECD). PCB were extracted from frozen sediment samples by first lyophilizing to remove water. Subsequently, the samples were Soxhlet extracted for 16 h in hexane. The sediment extracts were cleaned up using Florisil and HCl. Separation of PCB compounds from non-polar interferences was accomplished using a gas chromatograph equipped with a fused silica capillary column. The injections of each sample aliquots were made with an autosampler. Chlorobiphenyl congeners (CBs) were identified and quantified on the basis of a synthetic mixture of 19 individual congeners (CB 18, 26, 31, 44, 49, 52, 101, 105, 118, 128, 138, 149, 151, 153, 170, 180, 183, 187, 194).

Concentrations of contaminants in the sediments were compared with the following sediment quality guidelines: (a) effects range low (ERL), that is indicative of contaminant concentration below which adverse effects are rarely observed and (b) effects range median (ERM), that points out the concentration above which biological effects frequently occur (Long, MacDonald, Smith, & Calder, 1995).

2.3. Amphipods

The amphipods used in the chronic sediment tests were juveniles belonging to the 2–4 mm length class (retained between 1000 and 475 µm sieves), obtained from a laboratory culturing system (Neuparth, Costa, & Costa, 2002). The maintenance of this culture system was dependent of amphipods collected from a clean site of Sado estuary where a natural population of *G. locusta* is abundant. Twenty-four hours before the beginning of the experiments, a stock of juveniles was isolated from the main culture and kept at the assay temperature (20 °C) with unlimited food (macroalgae *Ulva* sp.).

2.4. Chronic sediment tests

Two independent chronic toxicity tests were performed in this study, which will be hereafter referred to as chronic test 1 and chronic test 2. Sediments P and T were assayed in chronic test 1, and sediments S1, S2 and D were assayed in chronic test 2.

Previous studies on the acute toxicity of sediments P and T (Costa, Correia, & Costa, 1998) did not reveal acute toxicity. Therefore, only sediments D, S1 and S2 were subjected to screening tests of acute toxicity as described in Costa et al. (1998). Sediments showing acute toxicity were diluted with control sediment as much as required until acute toxicity was absent. Sediment D was not acutely toxic and thus did not need dilution. Sediments S1 and S2 were assayed in the chronic test at concentrations of 25% and 50% (v/v), respectively.

The assays were conducted at 20 °C with 0.45 µm-filtered seawater at $33 \pm 1\%$ salinity, under a 12-h photoperiod. In both chronic tests five replicates per treatment were employed. A 1 cm deep layer of each sediment was placed in the respective aquarium (10-L) the day before the start of the assay. Seawater was added gently, to minimize sediment resuspension, and aeration was provided with plastic tips placed at least 1 cm above the sediment surface. Before addition of the amphipods, the sediment-overlying water system was allowed to equilibrate overnight.

The assays started the following day with the allocation of exactly 70 juveniles to each test chamber. The water was renewed every 10 days (80% of the volume). The organisms were fed with macroalgae *Ulva* sp. on an ad libitum basis, assuring that food was never in shortage. With the exception of the food supply, fresh or frozen *Ulva* sp. in chronic tests 1 and 2, respectively, the procedure was the same in both tests. Test chambers were inspected daily for aeration and feeding requirements and to remove dead animals.

At the end of the 28-d exposure period, the contents of each chamber were gently sieved through 1000 and 250 µm mesh sieves to collect surviving adults and their offspring, respectively. Four to five pools of 4–6 males from each test sediment (pool wet wt. ~0.05 g) were frozen and stored at –80 °C for later quantification of whole body metal bioaccumulation, MT and LP. Fifteen adults (males and non-gravid females) of each tested sediment were sampled for immediate DNA extraction and subsequent analysis of SB.

2.5. Biological responses

2.5.1. Quantification of whole-body trace metals and MT levels

Pools of whole animals (pool wet wt. about 0.05 g) were homogenized at 4 °C in 4 ml of 0.02 M Tris–HCl buffer (pH 8.6) and sub-samples taken for determination of trace metals and MT. Whole-body metal analyses were carried out on dried, HNO₃-digested sub-samples using flame atomic absorption spectrophotometry. Analysis of dogfish muscle (DORM-1) and liver reference (DOLT-1) material (National Research Council of Canada, Canada) was carried out, using the same treatment, in order to validate the metal analyses. The values measured for Cu, Zn and Cd, were within the certified range and the concentrations were expressed as µg g⁻¹ dry wt. of whole body homogenate. MT determination was performed by differential pulse polarography (DPP), essentially as described in [Bebianno & Langston \(1989\)](#). An aliquot of the sub-sample homogenate (2 ml) was centrifuged at 30,000g for 1 h at 4 °C. The cytosol was heat-treated at 80 °C for 10 min to precipitate the high molecular weight proteins, and subsequently centrifuged at

30,000g for 1 h at 4 °C. Aliquots (150–250 µl) of the heat-treated cytosol were taken for quantification of heat-stable MT using DPP with a static mercury drop electrode. A Metrohm 693 VA Processor and the 694 VA Stand was used for that purpose. The Brdicka supporting electrolyte containing 1 M NH₄Cl, 1 M NH₄OH and 2 mM [Co(NH₃)₆]Cl₃ was prepared weekly and stored at 4 °C (Palecek & Pechan, 1971). In the absence of a purified amphipod MT, quantification was by reference to standard additions of rabbit liver MT-1 (Sigma, Portugal). The values obtained were expressed as mg rabbit-MT equivalents g⁻¹ dry wt. of whole body homogenate.

2.5.2. Lipid peroxidation

Malondialdehyde (MDA) was determined by the thiobarbituric acid method of Ohkawa, Ohishi, & Yagi (1979) with minor modifications. Pools of whole animal (0.05–0.08 g wet wt.) were homogenized at 4 °C in 1:4 wet wt./buffer volume ratio in 50 mM NaH₂PO₂/Na₂HPO₄, pH 7.4, containing 15% glycerol (w/v), and centrifuged at 9000g for 15 min at 4 °C. Sub-samples (62.5 µl) of tissue homogenate were treated with 25 µl of 8.1% dodecyl sulphate sodium, 187 µl of 20% trichloroacetic acid (pH 3.5) and 187 µl of thiobarbituric acid. The mixture was made up to 0.5 ml with distilled water and then heated for 60 min in boiling water. After cooling, 125 µl of distilled water and 625 µl of a mixture of *n*-butanol and pyridine (15:1, v/v) were added. The mixture was shaken vigorously before centrifugation at 4000g for 10 min. The organic layer was then recovered and its absorbance measured at 532 nm. MDA concentrations were derived from a standard curve and the values expressed in terms of MDA nmol equivalents per g wet wt. tissue.

2.5.3. DNA strand breakage analysis

DNA was isolated individually from whole amphipods, immediately after the 28-day exposure. An outline of the DNA extraction procedure and DNA strand breakage analysis is presented below, while detailed descriptions are provided in Costa et al. (2002). Briefly, the DNA isolation involved extractions with PCI (phenol:chloroform:isoamyl alcohol, 25:24:1, v/v/v) and subsequently chloroform, before and after digestions with ribonuclease A and proteinase K. Strand breakage analysis comprised electrophoresis of the DNA extracts under alkaline (pH 12) and neutral (pH 8) conditions, thus allowing for determination of total (single and double) and double-stranded breaks in the DNA, respectively. Migration of the DNA within the gel matrix is size dependent, and detection is easily accomplished after staining with ethidium bromide.

Photographs of ethidium-bromide stained gels were analysed with the software QWin Lite V2.3 (Leica Microsystems) in order to obtain densitometric profiles of the migration of each DNA sample. Finally the average molecular length (L_n) was computed from these data. The average molecular length is inversely proportional to the number of DNA strand breaks according to the formula:

$$\text{Number of strand breaks per } 10^5 \text{ nucleotides} = 1/L_n \times 100. \quad (1)$$

In order to normalize results among gels, it was required to determine the relative number of total (RNTSB) and double strand breaks (RNDSB). This was accomplished by calculating the difference in the number of strand breaks between every treatment sample and the respective control sediment mean within each gel:

samples from total strand break gel:

$$\text{RNTSB} = 1/L_n(s_{ij}) - 1/L_n(\text{Cm}_j), \quad (2)$$

samples from double strand break gel:

$$\text{RNDSB} = 1/L_n(s_{ij}) - 1/L_n(\text{Cm}_j), \quad (3)$$

where s_{ij} is the sample i from gel j and Cm is the respective control mean from gel j .

Accordingly the relative number of single strand breaks (RNSSB) was determined as follows:

$$\text{RNSSB per } 10^5 \text{ nucleotides} = \text{RNTSB}_i - (2 \times \text{RNDSB}_i), \quad (4)$$

where i is the sample number.

2.6. Statistical analyses

A one-way analysis of variance (ANOVA) was carried out for each studied variable (tissue level of trace metals, MT, LP and SB variables – L_n TSB, L_n DSB, RNTSB, RNDSB and RNSSB) to determine if differences in responses between exposed and control amphipods could be attributed to exposure to contaminated sediments. Significant differences were established at $p < 0.1$. The Fisher's least significant difference test (LSD) was used for multiple comparisons between pairs of means.

2.7. Weight-of-evidence (WOE) approach

Based on Chapman et al. (2002) procedure, a WOE framework was applied to our data in order to assemble and interpret the information derived from the multiple lines of evidence (LOE) produced in this investigation. This approach entailed the setting up of an ordinal ranking system to categorize our LOE, followed by construction of the WOE interpretation matrix.

Table 2 summarizes the ordinal ranking system adopted. The various LOE considered comprise concentrations of sediment contaminants, acute toxicity data, chronic toxicity, and information on benthic community structure obtained from another study (Mucha & Costa, 1999). The LOE obtained from chronic toxicity tests comprised the following endpoints: bioaccumulation of metallic contaminants and biomarker responses (MT, LP and SB) here reported, and organism/population responses reported in part II (Costa et al., 2004). Three categories of responses compared to control treatment were considered: negative, neutral and positive. Within negative and positive categories two levels of intensity were considered: moderate and high.

Table 2

Ordinal ranking scheme applied to sediment quality data in order to build the weight-of-evidence tabular interpretation matrix provided in Table 4

	●●	●	⊖	○	○○
Chemistry (metals–PAHs–PCBs)	One or more contaminants exceed ERM	One or more contaminants exceed ERL	All contaminants are below ERL	–	–
Acute toxicity tests	Mortality higher than 20%	20% ≤ Mortality ≤ 10%	Mortality lower than 10%	–	–
<i>Endpoints from chronic toxicity tests</i>					
Bioaccumulation (Cu–Zn–Cd)	Contaminant uptake higher than control, at least for one of the metals ($p < 0.01$)	Contaminant uptake higher than control, at least for one of the metals ($0.01 \leq p < 0.1$)	No significant increase of contaminants uptake compared to control ($p \geq 0.1$)	–	–
Biomarkers (MT–LP–SB)	Significant induction of biomarker responses compared to control levels ($p < 0.01$)	Significant induction of biomarker responses compared to control levels ($0.01 \leq p < 0.1$)	No significant induction of biomarker responses compared to control levels ($p \geq 0.1$)	Significant reduction of biomarker responses compared to control levels ($0.01 \leq p < 0.1$)	Significant reduction of biomarker responses compared to control levels ($p < 0.01$)
Survival	Significant reduction of survival compared to control ($p < 0.01$)	Significant reduction of survival compared to control ($0.01 \leq p < 0.1$)	No significant difference on survival compared to control ($p \geq 0.1$)	Significant increase of survival compared to control ($0.01 \leq p < 0.1$)	Significant increase of survival compared to control ($p < 0.01$)
Growth	Significant reduction of growth compared to control ($p < 0.01$)	Significant reduction of growth compared to control ($0.01 \leq p < 0.1$)	No significant difference on growth compared to control ($p \geq 0.1$)	Significant increase of growth compared to control ($0.01 \leq p < 0.1$)	Significant increase of growth compared to control ($p < 0.01$)
Reproductive traits	Impairment observed in at least two reproductive traits compared to control	Impairment observed in one reproductive trait compared to control	No symptoms of impairment or improvement in reproductive traits	Improvement observed in one reproductive trait compared to control	Improvement observed in at least two reproductive traits compared to control (continued on next page)

Table 2 (continued)

	●●	●	⊖	○	○○
Benthic community structure	Diversity and/or abundance are lower than control sediment	Diversity and/or abundance are slightly lower than control sediment	Diversity and/or abundance are not lower than control sediment	–	–
Overall assessment (based on Best Professional Judgment)	Severe adverse effects – detrimental effects with large magnitude predicted to these sediments	Moderate adverse effects – possible detrimental effects, but with small magnitude, predicted to these sediments	Neutral effects – no significant effects predicted to these sediments	Moderate beneficial effects – possible advantageous effects but with small magnitude, predicted to these sediments	High beneficial effects – advantageous effects with large magnitude predicted to these sediments

The various LOE differ in the type and relevance of information provided for ecotoxicological assessment of the tested sediments. Therefore, the global evaluation of the quality of each tested sediment required a best professional judgment (BPJ) approach (Chapman et al., 2002). This approach enabled a qualitative analysis of the WOE matrix, attending to the particular information (and its relevance) that can be obtained from each LOE.

3. Results

3.1. Sediment geochemistry

Results of geochemical analyses of sediments are presented on Table 1. All contaminants were below ERM, except copper in sediment D and phenanthrene in sediment S1. As a general trend, trace metal concentrations were higher in sediments D, P and T. Copper concentration exceeded ERM or ERL in sediment D and P, respectively, and zinc levels exceeded ERL either in D, P or T sediments. PAH concentrations were as a rule high in sediments S1, S2 and P. Most individual PAH, high or low molecular weight PAH, and total PAH were higher than ERL in these three sediments. PCB concentrations were low in all tested sediments and in none exceeded ERL.

3.2. Bioaccumulation

Only trace metals were measured in amphipod tissues. The results for whole-body trace metal accumulation are displayed in Table 3. The accumulation of Cu was significantly higher in amphipods exposed to sediments P, S2 and D, with 7%, 21% and 66% higher levels, respectively, compared with the values of control organisms ($p < 0.1$, $p < 0.05$ and $p < 0.01$, respectively).

Zn detected in organisms exposed to sediment P was also higher by about 26% compared to control ($p < 0.1$). No significant bioaccumulation of Cd was observed in amphipods in any of the contaminated sediments, except sediment S2. On the contrary, for sediments P and D significantly lower body-burdens of Cd were detected ($p < 0.01$).

3.3. MT induction and LP

In chronic test 1 no induction of metallothionein (MT) was observed in animals exposed to contaminated sediments (sediments P and T) compared to control levels (1.3 mg MT g⁻¹ dry wt). In contrast, lipid peroxidation (LP) in sediments P and T was about 30% and 40% higher than control (13.5 nmol MDA g⁻¹ wet wt.; $p < 0.05$ and $p < 0.01$, respectively). In chronic test 2, significantly higher MT induction was detected only in amphipods exposed to sediment D compared to control levels of 1.4 mg MT g⁻¹ dry wt. ($p < 0.1$). Effects on LP were observed only in animals from

Table 3
Compilation of biomarker responses of *Gammarus locusta* to tested estuarine sediments^{a,b}

Sediments							
Chronic test 1			Chronic test 2				
	C	T	P	C	S1	S2	D
Bioaccumulation ($\mu\text{g g}^{-1}$ dry wt)							
Cu	59.15.0	53.4 \pm 8.1	63.5 \pm 8.5*	42.4 \pm 3.9	44 \pm 3.6	51.3 \pm 6.7**	70.0 \pm 11.4***
Zn	42.25.5	48.1 \pm 11.4	53.4 \pm 9.3*	60.2 \pm 9.7	52.46.5	53.9 \pm 5.7	78.9 \pm 0.2
Cd	0.21 \pm 0.06	0.18 \pm 0.05	0.08 \pm 0.02***	0.61 \pm 0.2	0.56 \pm 0.15	0.89 \pm 0.29*	0.25 \pm 0.11***
Metallothionein (mg g^{-1} dry wt)							
	1.4 \pm 0.1	1.2 \pm 0.3	1.2 \pm 0.3	1.4 \pm 0.1	1.6 \pm 0.1	1.5 \pm 0.4	1.8 \pm 0.2*
Strand breakage							
L_n TSB	27.9 \pm 5.6	26.6 \pm 8.5	28.5 \pm 7.4	27.1 \pm 8.1	21.8 \pm 7.3**	16.3 \pm 5.4***	19.8 \pm 4.9***
L_n DSB	38.3 \pm 6.3	40.3 \pm 8.7	36.3 \pm 6.0	48.0 \pm 10.8	45.3 \pm 12.1	43.9 \pm 12.9	48.1 \pm 11.5
RNTSB	0.12 \pm 0.67	0.55 \pm 0.37	0.15 \pm 0.96	0.65 \pm 1.8	1.41 \pm 1.64	3.34 \pm 2.12***	1.70 \pm 1.44*
RNSSB	-0.0090.92	0.59 \pm 2.17	-0.27 \pm 1.23	0.54 \pm 1.50	1.081 \pm 1.56	2.70 \pm 2.34***	1.79 \pm 1.78**
Lipid peroxidation (nmol MDA g^{-1} wet wt.)							
	13.5 \pm 0.8	19.3 \pm 2.9***	17.9 \pm 2.2**	24.4 \pm 2.9	33.1 \pm 2.7***	27.7 \pm 5.6	24.9 \pm 4.1

^a L_n TSB and L_n DSB – average molecular length of total and double strand breakage, respectively; RNTSB and RNSSB – relative number of total and single strand breakage, respectively.

^b Asterisks indicate significant effects compared with control: * = $p < 0.1$; ** = $p < 0.05$; *** = $p < 0.01$.

sediment S1, where values were 36% higher than control (24.4 nmol MDA g⁻¹ wet wt., $p < 0.01$) (Table 3).

3.4. DNA integrity

The differences in the relative number of total and single strand breaks (RNTSB and RNSSB) of amphipods exposed to contaminated and control sediments are shown in Table 3. In general, for all the contaminated sediments tested, no effects were observed on double strand breakage parameters (L_n DSB and RND SB).

In chronic test 1, no effects on DNA integrity were detected in exposed amphipods (sediment P and T) compared to control organisms. The RNTSB and RNSSB of amphipods from sediments P and T did not differ from control values ($p > 0.1$). In chronic test 2, the results showed significant differences between amphipods exposed to each of the contaminated sediments (S1, S2 and D) compared to control, when the L_n of TSB was examined ($p < 0.05$, $p < 0.01$ and $p < 0.01$, respectively). Loss of DNA integrity was also observed in the relative number of strand breaks (total and single) determined in organisms exposed to sediments S2 and D (RNTSB - $p < 0.01$ and $p < 0.1$, respectively and RNSSB - $p < 0.01$ and $p < 0.05$, respectively). In sediments S2 and D, amphipods had on average twice as many single strand breaks per 10⁵ nucleotides than control. In amphipods from sediment S1, RNTSB and RNSSB values were also higher than control, but they were not significantly different ($p > 0.1$).

3.5. Weight-of-evidence (WOE) approach

Table 4 provides a WOE interpretation of the results here reported (sediment chemistry, metal bioaccumulation, biomarker responses), together with organism/population endpoints (Costa et al., 2004), and also benthic community information from another study (Mucha & Costa, 1999). Overall, sediments S1, S2 and D, were considered to present a sizeable negative impact. Sediments' S1 and S2 impact may be related in part with PAH toxicity, while copper contamination may have a role in sediment D toxicity. The two remaining sediments – T and P – did not show negative impacts and appear to have a beneficial effect on the test species. However, sediment P has a detrimental ecological impact *in situ*, as indicated by benthic communities' information that could not be detected through toxicity testing. The reasons for these global sediment quality assessments are specified in Section 4 under a BPJ perspective.

4. Discussion

4.1. Biomarker responses

Considering the biomarker responses on the whole, sediments evaluated in chronic test 1 (sediments P and T) did not exhibit contaminant-induced stress in

Table 4

Weight-of-evidence tabular interpretation matrix of toxicity of sediments from Sado and Tagus estuaries analysed in this study: matrix and ordinal ranking scheme (see Table 1) based upon Chapman et al. (2002)^{a,b}

LINES OF EVIDENCE ↓ SEDIMENTS →	Chronic test 1		Chronic test 2		
	Sediment T	Sediment P	Sediment S1	Sediment S2	Sediment D
CHEMISTRY (Metals – PCBs – PAHs) ^a	● - ○ - ○	● - ○ - ●	○ - ○ - ●	○ - ○ - ●	● ● - ○ - ○
ACUTE TOXICITY TESTS	0% dilution ○	0% dilution ○	0% dilution ● ● 50% dilution ●	0% dilution ● ● 50% dilution ○	0% dilution ○
ENDPOINTS FROM CHRONIC TOXICITY TESTS	(0% dilution)	(0% dilution)	(75% dilution)	(50% dilution)	(0% dilution)
Bioaccumulation (Cu - Zn - Cd)	○ - ○ - ○	● - ● - ○	○ - ○ - ○	● - ○ - ●	● ● - ○ - ○
Biomarkers (MT – LP - SB)	○ - ● ● - ○	○ - ● - ○	○ - ● ● - ○	○ - ○ - ● ●	● - ○ - ● ●
Individual/Population Endpoints (survival – growth - reproductive traits) (Costa et al., 2004)	○ - ○ ○ - ○	○ - ○ ○ - ○ ○	○ - ○ - ○	● - ? - ●	● ● - ? - ●
BENTHIC COMMUNITY STRUCTURE (Mucha & Costa, 1999)	NA	● ●	● ●	● ●	NA
OVERALL ASSESSMENT / COMMENTS (based on Best Professional Judgment)	Moderate beneficial effects recorded in chronic toxicity test (high load of organic matter)	- High beneficial effects recorded in chronic toxicity test (high load of organic matter) - Disturbed benthic community (anoxic conditions)	Severe adverse effects (PAH possibly implicated)	Severe adverse effects (PAH possibly implicated)	Moderate adverse effects (Copper probably implicated)

^a Chemistry data refers to full non-diluted sediments.

^b ? = Inconclusive results – see Costa et al. (2004) for discussion.

the amphipod *G. locusta*. By comparison with control organisms, no adverse effects were detected on MT induction and DNA integrity. Whereas in sediment T only Zn concentrations raise some concern, in sediment P several contaminants (Cu, Zn and PAH) exceeded the ERL, and therefore biomarker responses might be anticipated. The fact that bioaccumulation of Cu and Zn was only little higher than control levels (approximately one fold higher than control), and apparently insufficient to induce MT, indicates low bioavailability of metallic contaminants in sediments P. The lower levels observed for Cd body-burdens, compared to control in this sediment (and also in sediment D), most likely resulted from interactions with the essential metals Cu and/or Zn that were bioaccumulated by *G. locusta*. These interactions can take place at different stages of absorption, distribution in the organism, and excretion of the above-mentioned metals (Brzoska & Moniuszko-Jakoniuk, 2001). Increased Zn supply may reduce Cd absorption and accumulation and prevent or reduce the adverse action of Cd (Brzoska & Moniuszko-Jakoniuk, 2001).

The high content of organic matter of sediment P (8.7% TVS) possibly caused low bioavailability of both metals and PAH to *G. locusta*, reducing or eliminating the potential negative impacts that would be anticipated from contaminant concentrations alone. Either metallic or organic contaminants may become unavailable to biota in sediments with high organic content, due to the strong sorption affinity of contaminants to sediment organic carbon matrix (Gunnarsson et al., 1999; Lawrence & Mason, 2001). Previous results from laboratory studies with *G. locusta* where the sediment-Cu LC50s increased considerably and directly with sediment organic carbon content (Correia & Costa, 2000), also support this premise. Low contaminant bioavailability as a result of binding at the organic carbon matrix may also explain the absence of adverse effects recorded at organism/population level in sediment P. Actually amphipods exposed to this sediment exhibited high individual performance, in particular a significant improvement of individual growth and pregnancy ratio compared to control animals. Similar stimulating effects on growth were also observed in sediment T, although not as significant as in sediment P (Costa et al., 2004).

As opposed to these results, the higher levels of lipid peroxidation detected in animals exposed to sediments P and T, would indicate occurrence of toxicant-induced stress. Although these sediments differ in contamination levels, they have in common the high level of organic content (8.7% and 11.5% TVS, respectively), a feature that was the most likely cause for the growth stimulation observed in amphipods exposed to both sediments. As there is no other evidence showing contaminant-induced insult from all remaining parameters, composite data suggest that LP resulted from other causes than oxidative stress derived from exposure to oxyradical-generating compounds (e.g., Cu or Zn and/or PAH). Effectively, these LP results are congruent with known evidence that endogenous variables (e.g., nutritional status, age, sex, growth and reproduction) may themselves influence the peroxidation status of organisms (Viarengo, Canesi, Pertica, & Livingstone, 1991), including *G. locusta* (Correia, Costa, Luis, & Livingstone, 2003), therefore contributing to confound contaminant-induced effects. Earlier studies with *G. locusta* revealed that increases in LP could be attributed to the improvement of the physiological condition of animals and not directly to damage derived from exposure to copper (Correia, 2002).

Results from chronic test 2 showed that sediments S2 and D generated chronic toxicity to the amphipod *G. locusta*. According to DNA damage data, sediments S2 and D can produce DNA strand breakage, mainly single strand breaks. The loss of DNA integrity was observed by the significantly higher L_n TSB, RNTSB and RNSSB in animals exposed to both sediments, but it was much more pronounced in sediment S2. The detection of these adverse effects in amphipods from sediments S2 and D provide evidence of exposure and bioavailability of genotoxins in both sediments. Although the complex chemical nature of sediments may make unclear which were the compound(s) responsible for the DNA damage observed, the approach here followed may help identify probable candidates. Compound analyses of the various parameters provide significant weight-of-evidence that copper may have contributed to the detrimental effects observed in amphipods exposed to this sediment D: (1) high concentration of Cu, namely exceeding ERM, (2) significant Cu bioaccumulation and (3) MT induction. Although copper is an essential metal, it may become toxic if intracellular concentrations exceed the organisms' requirements and its detoxification capability (Livingstone, 2001; Schenk, Davis, & Griffin, 1999; Viarengo, 1989). The available scientific evidence indicates the potential of copper and other trace metals as genotoxicants (Bolognesi, Landini, Roggieri, Fabbri, & Viarengo, 1999; Jha, Cheung, Foulkes, Hill, & Depledge, 2000). Moreover in previous studies with *G. locusta*, Cu has been shown to induce MT (Correia et al., 2002) and DNA single strand breaks (Costa et al., 2002).

Effects of MT induction were only observed in amphipods exposed to sediment D. A positive correlation was also detected between MT concentration and whole-body levels of Cu ($r = 0.5035$, $p < 0.05$), indicating that induction of MT was closely associated with Cu in sediment D. The simultaneous presence of SB and MT in animals exposed to sediment D, and the absence of MT induction in amphipods from sediment S2 suggests that the dynamics of toxicity differed in the latter. Although not as high as in sediment D, there was still some significant bioaccumulation of Cu in sediment S2, and also levels of Cd significantly higher compared to control. In this respect it is noteworthy that precisely in amphipods from sediment S2, which apparently lacked MT "protection", DNA damage was especially severe. Although other possible interpretations for these observations cannot be discounted, the most plausible is that effects on DNA integrity were caused mainly by other genotoxicants, which are not detoxified by MT. The high levels of PAHs (over ERL) in sediment S2 are particularly relevant in a sandy sediment where the bioavailable fraction of organic contaminants is potentially higher compared to muddy sediments.

Chronic toxicity of sediments S2 and D was also recorded at the organism/population levels. As described in Costa et al. (2004), an extensive impaired condition was observed in amphipods exposed to these sediments that was expressed by lower survival, an unbalanced sex ratio, low proportion of gravid females, and the lowest number of offspring, by comparison with control amphipods. Hence, the biochemical endpoints are on the whole in agreement with changes seen at higher-levels of biological organization (specially evident in SB), providing more

conclusive evidence on the prevalence of contaminant-induced stress in these sediments.

Concerning sediment S1, no MT induction was detected and the loss of DNA integrity was not as high and clear as in amphipods exposed to S2 and D (significant effects were only observed in L_n TSB). Similar to what was observed in the first chronic toxicity test, effects on LP were also detected in amphipods exposed to this sediment. For the reasons previously mentioned this response is again interpreted as related to the higher average length observed in S1 amphipods. Despite the high level of contamination and acute toxicity of this sediment, the 75% dilution with control sediment was effective in almost eliminating chronic toxicity. However, this dilution may be just near the toxicity threshold, as residual traces of toxicity and some evidence of stimulating effects on growth suggest occurrence of hormesis. Hormesis is a biological response to sub-inhibitory doses of stressor characterized by stimulatory effects on biological indicators of insulted organisms, particularly growth, compared to non-stressed control organisms (Stebbing, 1982, 1997). The event of hormesis has been documented in vertebrates and invertebrates in response to a variety of stressors (Calabrese, Baldwin, & Holland, 1999). As shown in a previous study, where evidence was found of copper-induced hormesis in *G. locusta*, stimulatory effects of low doses of toxicant can be coupled with induction of LP (Correia, 2002) and MT (Correia et al., 2001). The toxicity of sediment S1 was apparent even at 50% dilution. By further diluting this sediment with control sediment, contaminant concentrations were reduced possibly to a hormetic level, with stimulatory effects on growth and LP, but not on MT.

4.2. Weight-of-evidence (WOE) approach

In summary, by way of a WOE interpretation of the multiple biological effects examined, the following conclusions can be drawn from this investigation:

- (1) Sediments enriched on organic matter may have a significant positive impact in *G. locusta*'s growth in chronic bioassays (e.g., sediments T and P). These potential effects should be considered in advance when designing either acute or chronic bioassays with benthic organisms, where multiple-level assessments may play a useful role.
- (2) On the whole, sediments T and P did not reveal contaminant-induced stress to the amphipod *G. locusta*. Despite sediment P shown some chemical contamination, the high organic content of this sediment may have had some influence in reducing the bioavailability of toxicants and consequently eliminating symptoms of toxicity. On the other hand, the same factor probably promoted growth and fecundity of *G. locusta*. All previous (Costa et al., 1998) and current tests with sediment P failed to show toxicity. However, these findings do not match with benthic macrofauna studies that recorded a disturbed community in the sediment collection site (Mucha & Costa, 1999). The development of extreme anoxic conditions under high loads of organic matter has been proposed as explanation for this impoverished benthic community (Mucha & Costa, 1999).

- (3) As opposed to sediment P, results from the second chronic test show that a high content of organic matter in the sediment is not necessarily a shield from contaminant insult. That is the case for sediment D, which despite being the sediment with the highest organic content tested, was also one of the sediments that exhibited pronounced toxicity for several endpoints. Although other possibilities cannot be discounted, there is some WOE that the origin of the sediment D toxicity is associated with copper, namely considering the sediment copper above ERM, bioaccumulation of copper and induction of MT.
- (4) The origin of the sediments S1 and S2 toxicity is apparently related with the nearby industrial effluent at the sampling site, as evidenced by reduction of sediment toxicity as a function of the distance from the effluent – S1 more toxic than S2. The high levels of PAH detected in these sediments probably played a role in the serious detrimental effects recorded. The current findings of severe toxicity match with data showing a highly disturbed benthic community at these sediments' collection site (Mucha & Costa, 1999).
- (5) A presumed hormetic response occurred after exposure of the amphipods to serial dilutions of sediment S1. The phenomenon of hormesis has relevance to ecological risk assessment (Calabrese & Baldwin, 1999; Chapman, 2002). The application of multiple-level assessments and WOE approaches in chronic toxicity tests is likely to improve the ability to detect and understand better this relevant phenomenon.
- (6) Sediments' dilutions contribute to establish more clearly dose–responses and enable ranking of sediment toxicity, which in this study was $S1 > S2 > D$. Sediment S1 was the most toxic since a 75% dilution was required to eliminate acute toxicity and reduce chronic toxicity to the putative hormetic response. Sediment S2 was the second most toxic sediment since it still exhibited chronic toxicity after a 50% dilution, and sediment D was the least toxic of the three sediments given that it only showed chronic toxicity, but not acute toxicity when tested in full.

This study illustrated how integration of biochemical markers in chronic sediment tests within a WOE framework, can help backing-up interpretation of organism and population-level responses. By providing evidence of exposure (or lack of it) to contaminants in sediments under examination, the biomarkers here applied assisted in the identification of the grounds for organism-level responses. Namely they contributed to distinguish responses induced by sediment contaminants from those responses derived from other factors, such as for example the amount of organic matter in the sediment.

Further research is encouraged in the use of a multi-level assessment of chronic sediment toxicity, for example the inclusion of the biomarkers tested here, and eventually other potential biochemical endpoints, in long-term tests where responses are determined on a time-course basis. This will enable a better understanding of pathways of contaminant metabolism, detoxication and toxic action, allowing to follow more closely the whole toxicological process up to the organism/population levels.

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References

- Barka, S., Pavillon, J. F., & Amiard, J. C. (2001). Influence of different essential and non-essential metals on MTLP levels in the copepod *Tigriopus brevicornis*. *Comparative Biochemistry and Physiology*, *128C*, 479–493.
- Bebianno, M. J., & Langston, W. J. (1989). Quantification of metallothioneins in marine invertebrates using different pulse polarography. *Portugaliae Electrochimica Acta*, *7*, 59–64.
- Bolognesi, C., Landini, E., Roggieri, P., Fabbri, R., & Viarengo, A. (1999). Genotoxicity biomarkers in the assessment of heavy metal effects in mussels: experimental studies. *Environmental and Molecular Mutagenesis*, *33*, 287–292.
- Brzoska, M. M., & Moniuszko-Jakoniuk, J. (2001). Interactions between cadmium and zinc in the organism. *Food and Chemical Toxicology*, *39*, 967–980.
- Calabrese, E. J., & Baldwin, L. A. (1999). The marginalization of hormesis. *Toxicologic Pathology*, *27*, 187–194.
- Calabrese, E. J., Baldwin, L. A., & Holland, C. D. (1999). Hormesis: a highly generalizable and reproducible phenomenon with important implications for risk assessment. *Risk Analysis*, *19*, 261–281.
- Chapman, P. M. (2002). Ecological risk assessment (ERA) and hormesis. *The Science of the Total Environment*, *288*, 131–140.
- Chapman, P. M., McDonald, B. G., & Lawrence, G. S. (2002). Weight-of-evidence issues and frameworks for sediment quality (and other) assessments. *Human and Ecological Risk Assessment*, *8*, 1489–1515.
- Correia, A. D. (2002). Integrated ecotoxicological research with *Gammarus locusta* (L.): Biochemical and cellular responses and links to organism-level endpoints. Ph.D. thesis, Universidade Nova de Lisboa, Lisboa, Portugal.
- Correia, A. D., Costa, F. O., Neuparth, T., Diniz, M. E., & Costa, M. H. (2001). Sub-lethal effects of copper spiked sediments on the marine amphipod *Gammarus locusta*: evidence of hormesis?. *Ecotoxicology and Environmental Restoration*, *4*, 32–38.
- Correia, A. D., & Costa, M. H. (2000). Effects of sediment geochemical properties on the toxicity of copper-spiked sediments to the marine amphipod *Gammarus locusta*. *The Science of the Total Environment*, *247*, 99–106.
- Correia, A. D., Costa, M. H., Luis, O. J., & Livingstone, D. R. (2003). Age-related changes in antioxidant enzymes activities, fatty acid composition and lipid peroxidation in whole body *Gammarus locusta* (Crustacea: Amphipoda). *Journal of Experimental Marine Biology and Ecology*, *289*, 83–101.
- Correia, A. D., Lima, G., Costa, M. H., & Livingstone, D. R. (2002). Studies on biomarkers of copper exposure and toxicity in the marine amphipod *Gammarus locusta* (Crustacea) I: induction of metallothionein and lipid peroxidation. *Biomarkers*, *7*, 422–437.
- Costa, F. O., Correia, A. D., & Costa, M. H. (1998). Acute marine sediment toxicity: a potential new test with the amphipod *Gammarus locusta*. *Ecotoxicology and Environmental Safety*, *40*, 81–87.
- Costa, F. O., & Costa, M. H. (2000). Review of the ecology of *Gammarus locusta* (L.). *Polish Archives of Hydrobiology*, *48*, 541–559.

- Costa, F. O., Neuparth, T., Costa, M. H., Theodorakis, C. W., & Shugart, L. R. (2002). Detection of DNA strand breakage in a marine amphipod by agarose gel electrophoresis: exposure to X-rays and copper. *Biomarkers*, 7, 451–463.
- Costa, F.O., Neuparth, T., Correia, A.D., Costa, M.H., 2004. Multi-level assessment of chronic toxicity of estuarine sediments with the amphipod *Gammarus locusta*: II. Organism and population-level endpoints. *Marine Environmental Research*, doi:10.1016/j.marenvres.2004.08.005.
- Galloway, T. S., Brown, R. J., Browne, M. A., Dissanayake, A., Lowe, D., Jones, M. B., & Depledge, M. H. (2004). A multibiomarker approach to environmental assessment. *Environmental Science and Technology*, 38, 1723–1731.
- Gunnarsson, J. S., Granberg, M. E., Nilsson, H. C., Rosenberg, R., & Hellman, B. (1999). Influence of sediment-organic matter quality on growth and polychlorobiphenyl bioavailability in echinodermata (*Amphiura filiformis*). *Environmental Toxicology and Chemistry*, 18, 1534–1543.
- Hyne, R. V., & Maher, W. A. (2003). Invertebrate biomarkers: links to toxicosis that predict population decline. *Ecotoxicology and Environmental Safety*, 54, 366–374.
- Jha, A. N., Cheung, V. V., Foulkes, M. E., Hill, S. J., & Depledge, M. H. (2000). Detection of genotoxins in the marine environment: adoption and evaluation of an integrated approach using the embryo-larval stages of the marine mussel, *Mytilus edulis*. *Mutation Research*, 464, 213–228.
- Langston, W. J., & Bebianno, M. J. (1998). *Metal metabolism in aquatic environments*. London: Chapman and Hall.
- Lawrence, A. L., & Mason, R. P. (2001). Factors controlling the bioaccumulation of mercury and methylmercury by the estuarine amphipod *Leptocheirus plumulosus*. *Environmental Pollution*, 11, 217–231.
- Livingstone, D. R. (2001). Contaminant-stimulated reactive oxygen species production and oxidative damage in aquatic organisms. *Marine Pollution Bulletin*, 42, 656–666.
- Long, E. R., MacDonald, D. D., Smith, S. L., & Calder, F. D. (1995). Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. *Environmental Management*, 19, 81–97.
- Moksnes, P. O., Lindahl, U., & Haux, C. (1995). Metallothionein as a bioindicator of heavy metal exposure in the tropical shrimp, *Penaeus vannamei*: a study of dose-dependent induction. *Marine Environmental Research*, 39, 143–146.
- Mucha, A. P. (1997). *Estudo das comunidades macrozoobênticas em biótopos litorais de energia distinta. Sua relação com gradientes de carbono e nutrientes*. Lisboa: Tese de Mestrado, Universidade Nova de Lisboa.
- Mucha, A. P., & Costa, M. H. (1999). Macrozoobenthic community structure in two Portuguese estuaries: relationship with organic enrichment and nutrient gradients. *Acta Oecologica*, 20, 363–373.
- Neuparth, T., Costa, F. O., & Costa, M. H. (2002). Effects of temperature and salinity on life history of the marine amphipod *Gammarus locusta*. Implications for ecotoxicological testing. *Ecotoxicology*, 11, 61–73.
- Ohkawa, H., Ohishi, N., & Yagi, K. (1979). Assay for lipid peroxides in animal tissues by thiobarbituric acid reaction. *Analytical Biochemistry*, 95, 351–358.
- Palecek, E., & Pechan, Z. (1971). Estimation of nanogram quantities of proteins by pulse polarographic techniques. *Analytical Biochemistry*, 42, 59–71.
- Rantala, R. T. T., & Loring, D. H. (1977). A rapid determination of 10 elements in marine suspended particulate matter by atomic absorption. *Atomic Absorption Newsletter*, 16, 51–52.
- Schenk, D., Davis, K. B., & Griffin, B. R. (1999). Relationship between expression of hepatic metallothionein and sublethal stress in channel catfish following acute exposure to copper sulphate. *Aquaculture*, 177, 367–379.
- Shugart, L. R. (1998). Structural damage to DNA in response to toxicant exposure. In V. Forbes (Ed.), *Genetics and ecotoxicology* (pp. 151–167). Washington, DC: Taylor & Francis.
- Shugart, L. R. (2000). DNA damage as a biomarker of exposure. *Ecotoxicology*, 9, 329–340.
- Stebbing, A. R. D. (1982). Hormesis - the stimulation of growth by low levels of inhibitors. *The Science of the Total Environment*, 22, 213–234.

- Stebbing, A. R. D. (1997). A theory for growth hormesis. *Belle Newsletter*, 6, 1–11.
- USEPA-USACE (2001). Method for assessing the chronic toxicity of marine and estuarine sediment-associated contaminants with the amphipod *Leptocheirus plumulosus*. United States Environmental Protection Agency, EPA/600/R-01/020, Washington, DC.
- Viarengo, A. (1989). Heavy metals in marine invertebrates: mechanisms of regulation and toxicity at the cellular level. *CRC Critical Reviews in Aquatic Sciences*, 1, 295–317.
- Viarengo, A., Canesi, L., Pertica, M., & Livingstone, D. R. (1991). Seasonal variations in the antioxidant defence systems and lipid peroxidation of the digestive gland of mussels. *Comparative Biochemistry and Physiology*, 100C, 187–190.
- Wenning, R. J., & Ingersoll, C. G. (2002). Summary of SETAC Pellston workshop on use of sediment quality guidelines and related tools for the assessment of contaminated sediments, 17–22 August 2002, Fairmont, Montana, USA. Society of Environmental Toxicology and Chemistry (SETAC), Pensacola, FL, USA.