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Using a classical weight-of-evidence approach for 4-years' monitoring of the impact of an accidental oil spill on sediment quality

Carmen Morales-Caselles [a,c,*], Inmaculada Riba [a,c], Carmen Sarasquete [a,c], T. Ángel DelValls [b,c]

[a] Instituto de Ciencias Marinas de Andalucía (ICMAN-CSIC), Avda. República Saharaui s/n, Puerto Real 11510, Cádiz, Spain
[b] UNESCO UNITWIN/WiCop, Facultad de Ciencias del Mar y Ambientales, Universidad de Cádiz, Polígono Río San Pedro s/n, Puerto Real 11510, Cádiz, Spain
[c] Unidad Asociada de Calidad Ambiental y Patología (CSIC & UCA), Avda. República Saharaui s/n, Puerto Real 11510, Cádiz, Spain

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Abstract

In the present report, the successful application of a Weight of evidence approach (WOE) to sediment quality assessment during a four year impact period following an oil spill is discussed. The study assesses the sediment quality on the Galician Coast (NW Spain) which was impacted by an accidental spill associated with the sinking of the tanker *Prestige* (2002). The assessment is based on three lines of evidence: physicochemical characterization of the sediments; determination of acute toxicity by conducting sediment toxicity tests and benthic alteration including taxonomic identifications along with community descriptive statistics. The data obtained were integrated using a WOE approach by means of two different methodologies: multivariate analysis and ANOVA-based pie charts. Results confirm that PAHs related to the *Prestige* oil spill are the main contaminant associated with biological effects in the area which has since recovered from the initial acute impact. Also, the WOE allowed the identification of metal contamination not previously described in the area responsible for toxicity in sediments analyzed. In addition, the methodology proposed to link the 3 lines of evidence results shows the use for the first time of an objective indice based on factor analysis which allows pollution of the sediments studied to be qualitatively and quantitatively evaluated while demonstrating the WOE approach to be recommendable in monitoring environmental quality.

Keywords: PAHs; Contamination; Toxicity; WOE; Sediment Quality Triad

1. Introduction

Chemical measurements in the environment provide information on contamination (substances present where they would not normally occur, or above natural background concentrations), but they do not provide information on pollution (contamination that causes adverse biological effects in the environment) (Chapman, 2007). Chemical analyses are an important tool in sediment quality assessment, however the information obtained does not report on the consequences that chemicals have on the organisms exposed to them. Biological effects established based on laboratory tests to determine toxic responses in combination with field data on the communities living in the sediments allow it to be established whether there is observable pollution-induced degradation effect a given set of biota (Chapman et al., 1991).

Weight of evidence (WOE) investigations determine possible ecological impacts owing to chemicals or other stressors based on multiple lines of evidence (Chapman, 2007). The classical Sediment Quality Triad (SQT) consists of sediment chemical analysis, examination of the in situ benthic community, and measurements of sediment toxicity (Borgmann et al., 2001). The overall study of these three components provides an assessment of the environmental risk. The SQT approach, accepted internationally as the most comprehensive approach available for assessing contaminated sediments (Chapman and McDonald, 2005), forms part of the WOE framework and is expected to be an integral component of larger-scale assessments (Chapman

* Corresponding author. Instituto de Ciencias Marinas de Andalucía (ICMAN-CSIC), Avda. República Saharaui s/n, Puerto Real 11510, Cádiz, Spain. Tel.: +34 956016740; fax: +34 956016040.
E-mail address: carmen.morales@uca.es (C. Morales-Caselles).

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and Hollert, 2006). This method has been successfully used to assess sediment quality following contaminant spill episodes (DelValls and Chapman, 1998; Chapman, 2000; Borgmann et al., 2001; Riba et al., 2004; Lee et al., 2006). In the present study this methodology was performed in order to determine whether the WOE approach is able to be used as a good tool in assessing sediment quality following the acute impact of an accidental oil spill. In addition the suitability of the application of the WOE procedure as a monitoring instrument in environmental risk assessment is demonstrated.

The broad aim of this study is to determine the quality of oil spill affected sediments by applying a complete methodology, and more specifically to address the following 3 objectives: (a) to monitor the impact of an accidental oil spill using a WOE approach during a 4 year period, (b) to improve methodological aspects in the integration of the 3-LOE results in order to avoid subjectivity thereby defining a new and more objective process of integration, and (c) the determination of pollution, contamination and no impact scenarios for the stations selected and over the 4 year period, including the identification of the contaminants responsible.

2. Materials and methods

2.1. Approach

The case study employed for the improvement of the WOE approach, was that of the impact associated with the sinking of the tanker *Prestige* (November 2002) which spilt around 60,000 tons of heavy fuel oil with the most affected area being the Galician Coast (NW Spain). A first study was carried out with sediment samples collected in the Atlantic Islands National Park (AINP) during 2004, approximately one year after the spill. Fig. 1 shows the area of study and the 10 stations selected for the first survey described in the present paper, 3 stations located in the Ons Island (D07, D09 and D18) and 7 in the Cies Island (D60, D66, D69, D79, FIG, GA1, GA2).

Subsequently surveys were designed for monitoring sediment quality at the distinct stations located in the park and the surrounding area within the four year period. 4 stations were selected in the Cies Island (A, B, C and GA1), located in the AINP, for the period from the beginning of 2004 through to 2006 (3 surveys). The results obtained for the first study carried out in the AINP (beginning of 2004) suggested that the area and its surroundings were probably significantly affected by the spill. This necessitated the selection of a replacement area on the Galician Coast for inclusion in the sediment quality monitoring study. 3 stations (D, E, F) in Corme-Laxe (Fig. 1) were selected and the same WOE approach applied over 2 years, from 2004/2005–2005/2006 (2 surveys).

The weight-of-evidence approach (WOE) conducted in this study includes three lines of evidence (LOEs) incorporating the following sampling station analyses carried out for each of the 3 distinct surveys described above: (a) sediment contamination: physicochemical characterization of the sediments by analyzing PAHs (acenaphtalene, acenaphtylene, anthracene, benzo(a)anthracene, benzo(a) pyrene, benzo(b)fluoranthene, benzo(g,h,i) perylene, benzo(k)fluoranthene, chrysene, dibenzo(a,h) anthracene, fenanthrene, fluoranthene, fluorene, indene (1,2,3, cd)pyrene, naphthalene, and pyrene), trace metals (Zn, Pb, Cu, Ni, Co and V), grain size and organic carbon (methodologies described in Morales-Caselles et al., 2006); (b) sediment toxicity: by determination of acute toxicity, performing bioassays with bulk sediment such as the amphipod mortality test with *Corophium volutator* (Morales-Caselles et al., 2007) and the polychaeta mortality assay (Casado-Martinez et al., 2006) with *Arenicola marina* as well as two tests using sediment elutriate, these being the commercial assay Microtox® (Morales-Caselles et al., 2007) and embryo–larval sea urchin bioassay (methodology described by Fernández et al, 2006; data obtained from Fernández et al. not published); (c) 'in situ alteration': Benthic alteration was selected and determined by measuring parameters in situ based on taxonomic identifications and community descriptive

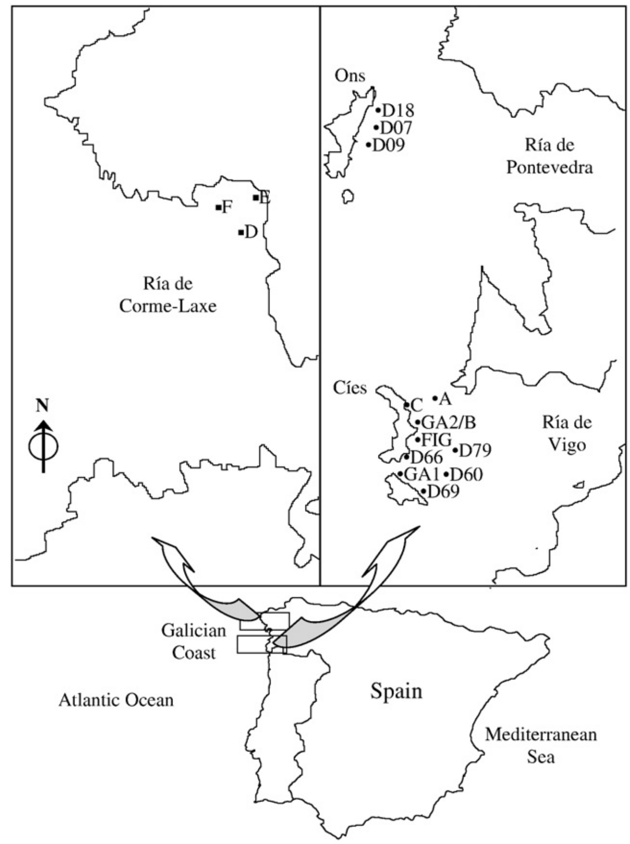

Fig. 1. Map of the coastal area of Galicia (NW Spain) showing the sampling sites in the area of Corme-Laxe (D, E and F) and the Atlantic Island National Park (Ons: D07, D09 and D18; Cíes: GA1, GA2/B, FIG, D60, D66, D69, A and C).

statistics (abundance-biomass analysis, species richness, diversity, dominance and proportions of the major taxonomic groups) (DelValls and Chapman, 1998).

2.2. Data integration

The integration of all LOE data obtained was performed via the two following methodologies: (a) a multivariate analysis approach based on linking all variables obtained in determining the environmental degradation of the studied ecosystems (Riba et al., 2004) and (b) a representation using pie charts using an ANOVA approach and by means of the determination of different factors (Riba et al., 2004).

The multivariate analysis was performed using principal components analysis (PCA) as the extraction procedure, a multivariate statistical technique for examining variable distributions (Riba et al., 2003). The objective of PCA is to derive a reduced number of new variables as linear combinations of the original variables. This provides a description of the structure of the data with minimum loss of information.

For the representation of the pie charts, the factors obtained from the PCA were subjected to ANOVA and Tukey tests which identified significant differences in sensitivity among stations and controls for each factor. In this sense, this new methodology improves and updates this kind of data treatment previously reported by Riba et al. (2003).

3. Results and discussion

Summarized results of the different surveys are shown in Tables 1 and 2. A first approach to assess the impact of the oil spill on the Galician Coast was performed in the AINP a few months after the sinking of the tanker. The multivariate analysis was used in the data set by duplicate to connect and interpret results obtained from the three

Table 1
Summarized results of chemical analysis, the acute toxicity tests and the alteration parameters for our first study of the sediments quality in the Atlantic Islands National Park (D07, D09 and D18 are located in the Ons Island whereas Ga1, D60, D66, D69, D79, FIG and Ga2 are placed in the Cies Island)

	Chemical analysis							Toxicity tests				Benthic alterations					
	Zn (mg kg^{-1})	Pb (mg kg^{-1})	Cu (mg kg^{-1})	Ni (mg kg^{-1})	V (mg kg^{-1})	Hg (mg kg^{-1})	PAH (μg kg^{-1})	Corophium (% mortality)	Arenicola (% mortality)	Microtox IC50	Paracentrotus (% normal)	Species number	Specific richness	Diversity	Molusca (%)	Polychaeta (%)	Crustacea (%)
Ga1	14.78	2.9	12.8	1.71	1.0	0.01	190	15	5	1215	15.0	17	14.3	4.574	22.9	42.86	34.3
D-07	85.3	23.4	250.7	1.04	81.2	0.08	470	25	10	1367	3.3	17	20.5	3.76	23.5	41.17	17.7
D-09	106.9	27.5	159.7	11.7	116	0.07	240	25	15	1694	100.0	12	9.3	3.036	33.3	66.66	0.1
D-18	55.5	14	20.8	3.44	54	0.04	480	45	20	390	15.8	24	18.6	4.089	25.0	62.5	8.3
D-60	100.8	30.5	70.9	16.2	125	0.12	700	20	10	358	100.0	12	21.1	2.386	25.0	58.33	0.1
D-66	14	4.1	16.2	4.6	n.d.	0.06	380	60	15	486	5.0	6	15.4	1.231	33.3	50	16.7
D-69	14.7	2.73	12.8	1.71	n.d.	0.05	480	30	10	450	29.8	7	4.3	2.574	42.9	42.86	14.3
D-79	113.9	29.3	149.4	4.44	13.7	0.09	270	20	15	364	8.7	8	18.6	2.552	50.0	37.5	12.5
FIG	76.2	26.3	18.5	11.8	n.d.	0.04	390	25	5	1006	4.8	3	1.8	1.5	0.1	66.66	33.3
Ga2	3.95	1.14	0.65	0.42	1.0	0.01	2120	50	50	605	80.0	2	1.2	1	0.1	100	0.1

n.d.: not detected.

Table 2
Summarized results of chemical analysis, toxicity test and benthic alteration parameters measured for the study of the sediments quality in the Cies Island 2003–2006 (first survey: GA1−1, A-1, B-1, C-1; second survey: GA1-2, A-2, B-2, C-2; third survey: GA1-3, A-3, B-3, C-3) and Corme-Laxe 2004–2006 (second survey: D-2, E-2, F-2; third survey: D-3, E-3, F-3)

	Chemical analysis							Toxicity tests				Benthic alterations					
	Zn (mg kg^{-1})	Pb (mg kg^{-1})	Cu (mg kg^{-1})	Ni (mg kg^{-1})	V (mg kg^{-1})	Hg (mg kg^{-1})	PAH (μg kg^{-1})	Corophium (% mortality)	Arenicola (% mortality)	Microtox IC50	Paracentrotus (% normal)	Species number	Specific richness	Diversity	Molusca (%)	Polychaeta (%)	Crustacea (%)
GA1-1	14.78	2.9	12.8	1.71	n.d.	n.d.	190	15	5	2486	85	17.0	14.3	4.6	22.9	42.9	37.1
GA1-2	21.2	1.6	6.4	0.32	n.d.	n.d.	74	15	5	3974	89	31.4	43.0	2.0	23.5	32.1	41.0
GA1-3	13.8	2.1	2.19	1.65	n.d.	n.d.	n.d.	10	0	19,762	97	42	39.1	6.1	34.7	18.0	40.5
A-1	76.2	26.3	18.5	11.8	0.53	n.d.	390	25	5	1006	95	3.0	1.8	1.5	0.1	53.0	33.3
A-2	123.8	10.1	11.4	11.8	0.32	n.d.	119	22	10	5231	87	5	12.0	4.3	2.4	21.0	34.5
A-3	377	1.5	5.2	13.3	0.3	0.7	108	23	28	5631	79	7.09	28.5	5.1	15.3	20.0	37.0
B-1	3.95	1.14	0.65	0.42	n.d.	n.d.	2120	50	50	605	20	2	1.2	1.0	0.1	100.0	0.1
B-2	12.7	0.72	0.88	1.31	n.d.	1.01	366	23	35	1523	79	12	5.9	5.2	9.9	56.2	15.4
B-3	91	0.9	1.4	2.4	0.2	0.8	67	20	28	9422	88	47	33.9	5.0	28.4	21.5	41.0
C-1	41.1	7.13	24.9	5.21	0.77	n.d.	420	33	36	723	46	9.0	15.3	2.9	22.2	33.3	33.3
C-2	37.5	6.54	34.5	5.11	0.86	n.d.	239	28	28	4651	68	30.0	50.9	4.5	26.7	26.7	43.3
C-3	164	0.85	1.4	4.5	0.1	0.6	n.d.	17	22	1801	85	25.0	42.4	4.3	39.1	21.7	39.1
D-2	65.7	42.5	21.4	9.18	1.2	13.2	537	30	40	2436	67	9	25.7	2.9	33.3	33.3	33.3
D-3	25	3.7	0.7	1.7	0.34	2	38	10	39	3977	55	10	28.6	3.0	30.0	20.0	50.0
E-2	34	4.31	n.d.	5.66	0.38	2.33	558	36	35	20,827	35	12	66.7	5.0	2.0	30.6	100.0
E-3	19.9	7.3	0.43	1.5	0.35	2.1	52	17	17	21,041	85	12	32.1	3.0	40.1	22.2	51.4
F-2	214	14.6	20	7.07	0.7	5.81	820	40	40	2185	30	15	55.6	2.3	40.0	26.7	33.3
F-3	271	5.9	4.2	5.7	0.36	3.4	323	20	17	4398	76	13	48.2	2.9	15.4	23.1	61.5

lines of evidence investigated. The application of the MAA allows the averaged variables (related to contamination, toxicity and alteration) to be grouped in a new set of factors. In this study physicochemical data (metals — Zn, Pb, Cu, Ni, Hg, V — and PAHs), toxicity (Microtox® test, amphipods assay, polychaetes test and sea urchin test) and alteration (number of species, species richness, diversity and proportions of molluscs, polychaetes and crustaceans) were included. These original variables can be grouped in four new factors which explain 84.0% of the original data variance (Table 3). Negative values obtained in the analysis are as important as the positive values. Values associated with a particular component for which loading was 0.40 or higher were selected to interpret a group of variables. This approximates Comreys' (1973) cut-off of 0.55 corresponding to a good original variable–factor association, while taking into account discontinuities in the magnitudes of loadings approximating the original variables.

The first principal factor, #1 is predominant and accounts for 42.2% of the variance. This factor represents the degradation of the environment associated with the presence of PAHs in the sediment by linking PAHs with the toxicity of *Corphium* and the polychaete *Arenicola marina* as well as infauna alterations. The second factor explains 23.4% of the variance; showing the relationship between the presence of PAHs and the metals Hg and V in the sediment with the adverse effects measured in both the *Arenicola* and sea urchin tests and a slight alteration in the crustaceans and polychaete community. These two factors (#1 and #2), certainly appear as a consequence of the tanker *Prestige* which spilt hydrocarbons containing PAHs and affected the biota resulting in environmental degradation although Factor #2 represents more moderate effects than Factor #1; V is associated with the spill and has an apparently minor effect on biota when compared to PAHs. Factor #3 accounts for a 10.6% of the variance and is related to Cu contamination which is not responsible for biological effects in the environment, whereas factor #4 (7.7%) describes the presence of metal contamination (Zn, Pb, Cu, Ni , V and Hg) which does not produce toxic effects and is not producing degradation in the environment. This metal contamination may be related to basal levels of contaminants or owing to sources other than the *Prestige* oil spill.

Table 3
Sorted rotated factor loadings (pattern) of 17 variables for the four principal factors resulting from the multivariate analysis of the single results obtained from the chemical analysis, the acute toxicity tests and the alteration parameters for the study of the sediments quality in the Atlantic Islands National Park

	Factor 1	Factor 2	Factor 3	Factor 4
	42.21	23.43	10.64	7.73
Zn	–	–	–	0.91
Pb	–	–	–	0.81
Cu	–	–	0.47	0.47
Ni	–	–	–	0.80
V	–	0.63	–	0.55
Hg	–	0.32	–	0.73
PAHs	0.65	0.54	–	–
Corophium bioassay	0.30	–	–	–
Arenicola bioassay	0.54	0.59	–	–
Microtox test	–	–	–	–
Paracentrotus assay	–	0.90	–	–
Number of species	0.89	–	–	–
Specific richness	0.94	–	–	–
Diversity	0.79	–	–	–
% Molusca	0.96	–	–	–
% Polychaeta	0.77	0.48	–	–
% Crustacea	–	0.91	–	–

Fig. 2 shows the factors' scores for each of the 10 studied stations. Factor #1 defined as representing the environmental degradation caused by the PAHs bound to the sediments is prevalent in the stations FIG (1.8) and GA2 (2.0). indicating high pollution levels due to PAHs in these sites. Factor #2 which indicates pollution by PAHs and V is prevalent in the station D09 (1.4) from the Ons island and D60 (1.2) and GA2 (1.4) from Cies. Factor #3, defined as representing Cu contamination with no effects has a positive loading in the samples from Ons D07 (1.5) and D09 (1.2) and FIG (0.4), GA1 (0.9) in Cies, whereas Factor #4 describes the presence of metals (Zn, Pb, Cu, Ni , V and Hg) in the sediments from Ons D07 (0.1) and D09 (0.8), Cies D60 (1.4), D79 (0.8) and FIG (1.2). These results show how in 2004 the Atlantic Islands National Park was significantly affected by the oil spill and the way in which station GA1 has proved to be a suitable site of reference for the present research.

With the aim of identifying the cause of pollution (or lack thereof) in each study site, an ANOVA analysis was conducted by using the factor scores obtained in the MAA. Fig. 3 shows the pie charts stemming from ANOVA results, using GA1 as the negative control.

In this first approach in which the sediment status was established (in 2004) following the spill, significant pollution caused by PAHs at the stations FIG and GA2 was detected. Pollution provoked by a mixture of PAHs and V affecting both the Ons: D09 and the Cies Islands: D60, FIG, GA2 was also detected. High levels of pollution were especially identified in the station GA2 on the Cies island. A source of metals (Zn, Pb, Cu, Ni, Hg and V) was identified initially, whose presence was thought not to be in connection with the oil spills but instead is probably related to background levels or contamination which does not cause biological effects. Such levels appear at D07, D09 and the stations from Cies Islands D60, D79 and FIG. In FIG the presence of metals has been correlated with alteration in one of the analyses, but no toxicity was exhibited; perhaps meaning that alteration of the macrofauna was caused by other sources, possibly physical, such as the assessed beach cleaning after the spill. Previous studies have demonstrated that the *Prestige* oil spill caused Zn contamination in the surrounding water column (Prego and Cobelo-García, 2003). Contamination by copper and lead was also observed in the uppermost layer in the shipwreck area of the Northeast Atlantic Ocean (Prego and Cobelo-García, 2004; Cobelo-Garcia et al., 2004), however, this contamination with Cu is not likely to be related because levels of Cu in the fuel oil were relatively low (3.39 mg kg^{-1}) suggesting Cu inputs from the nearby Ria de Vigo. Previous studies have shown the presence of trace metal contamination in the Rias, close to the AINP (Carballeira et al., 1997; Pérez-López et al., 2003) this also possibly explains the presence of metals on the Cies and Ons Islands.

The application of the WOE approach has shown that some months after the spill there was a significant impact which provoked degradation of the ecosystem in part of the sediment from study sites located in the Atlantic Islands National Park. A source of metals, which in some cases are affecting the environment or are considered a potential risk has been detected. Results suggested that further studies should be done in order to clarify whether the affected AINP and surrounding sites have recovered. With this aim in mind, the WOE investigations have been applied to selected sites in the Cies Island (AINP) and Corme-Laxe, with the fresh approach of monitoring over a four year period in order to assess the recovery of an area affected by an oil spill.

Sediments from GA1 turned out to be the cleanest given it did present toxicity or in situ alteration making this station an appropriate selection as the reference site in the following assessments. The WOE-monitoring focused on two areas with the following procedures applied separately: (a) assessing the Cies Island sediment quality monitoring from the beginning of 2004 to 2006, and (b) studying the Corme-Laxe sediment status from the end of 2004 to 2006. In this sense, this study

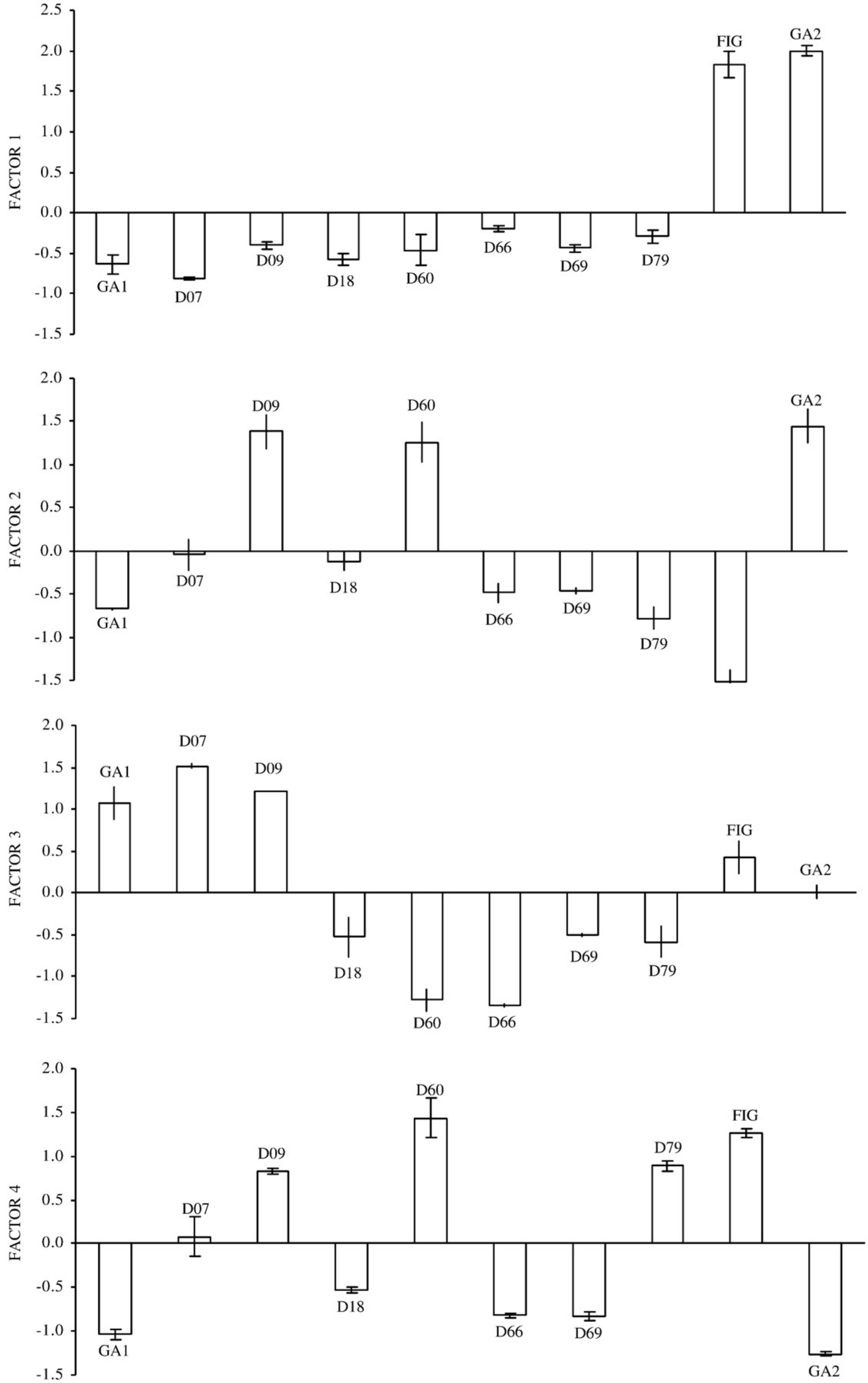

Fig. 2. Estimated factor scores for the four factors in each of the 10 cases. The factor scores quantify the prevalence of each factor for every station and is used to establish the definition of each factor.

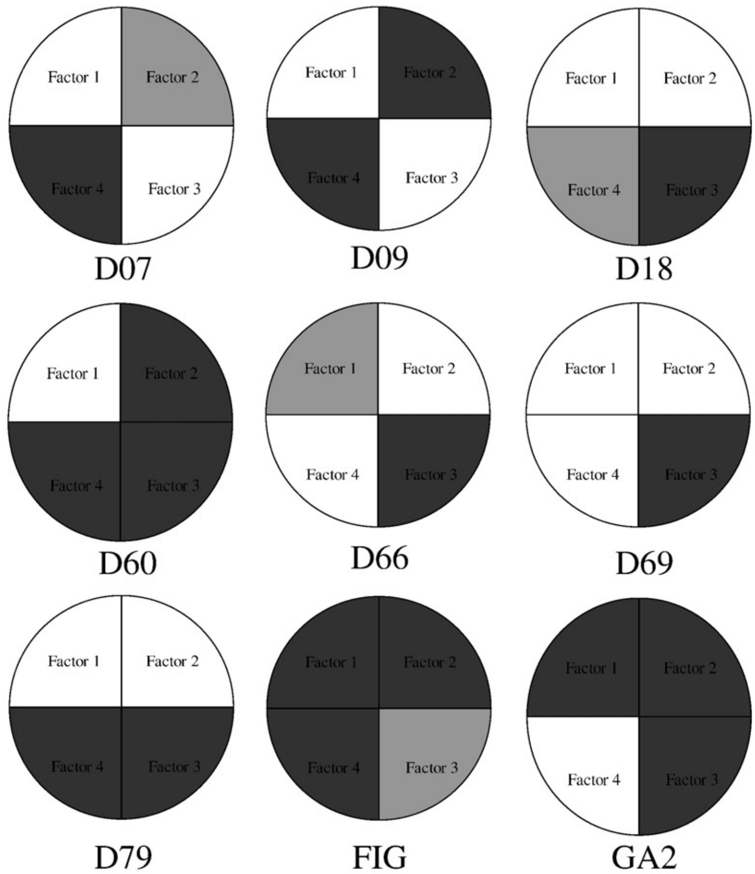

Fig. 3. Pie charts representing the significant differences of the factors score in every study site — Atlantic Islands National Park (2003) — related to the reference site GA1 (black: $p<0.01$; grey: $0.01<p>0.05$; white: no significant differences, $p>0.05$). Factor #1: PAHs-pollution; Factor #2: PAHs–Hg–V-pollution; Factor #3: Cu-contamination; Factor #4: Zn–Pb–Cu–Ni–V–Hg-contamination.

was designed to monitor the recovery or persistence of the pollution caused by the oil spill over time using an improved WOE approach based on the classical SQT.

3.1. Cíes Island (2004–2006)

The sediment quality assessment at the Cies Island (AINP) has been carried out for the same 3 sites in distinct sampling campaigns from 2003 to 2006. Results from the first survey (2004) correspond to GA1-1, A-1, B-1 and C-1; data from the second survey (2004–2005) are referred to as GA1-2, A-2, B-2 and C-2 , with the results obtained in the third survey (2005–2006) corresponding to Ga1-3, A-3, B-3 and C-3. The MAA was carried out by treating each set of data as an independent case in order to track the monitoring of the sediment quality in each station.

In Table 4 the MAA carried out on original variable data , including replicates is shown. The application of the statistical analysis shows that the 19 original variables can be grouped in four new factors. These factors explain 88.5% of the original data variance. The first Factor (#1) accounts for 50.75 % of the variance and corresponds to the toxicity and in situ alteration due to PAHs and the presence of Pb responsible for environmental degradation (pollution); Factor #2 (18.3%) depicts Pb, Cu, Ni and V contamination for which no toxicity or other effects on biota is appreciable; Factor #3 (10.9%) is also related to contamination by Zn, Pb, Ni and Hg having no associated biological effects while Factor #4 (8.6%) shows a degree of toxicity and environmental degradation due to PAHs contamination.

Fig. 4 shows the factor scores in the 12 cases. Factor #1, which defines pollution due to PAHs and Pb, has a positive loading in A-1 (2.0) and B-1 (2.2). These 2 cases correspond to first sampling carried

Table 4
Sorted rotated factor loadings (pattern) of 17 variables for the four principal factors resulting from the multivariate analysis of the single results obtained from the chemical analysis, the acute toxicity tests and the alteration parameters for the study of the sediments quality in the Cies Island 2003–2006

	Factor 1	Factor 2	Factor 3	Factor 4
	50.73	18.26	10.93	8.62
Zn	–	–	0.88	–
Pb	0.41	0.71	0.32	–
Cu	–	0.83	–	–
Ni	–	0.43	0.86	–
V	–	0.82	–	–
Hg	–	–	0.37	–
PAH	0.73	–	–	0.63
Corophium bioassay	0.63	–	–	0.72
Arenicola bioassay	–	–	–	0.92
Microtox test	0.62	–	–	0.53
Paracentrotus assay	0.38	–	–	0.89
Number of species	0.91	–	–	0.31
Specific richness	0.95	–	–	–
Diversity	0.91	–	–	–
% Molusca	0.97	–	–	–
% Polychaeta	0.76	–	–	–
% Crustacea	0.70	–	–	0.57

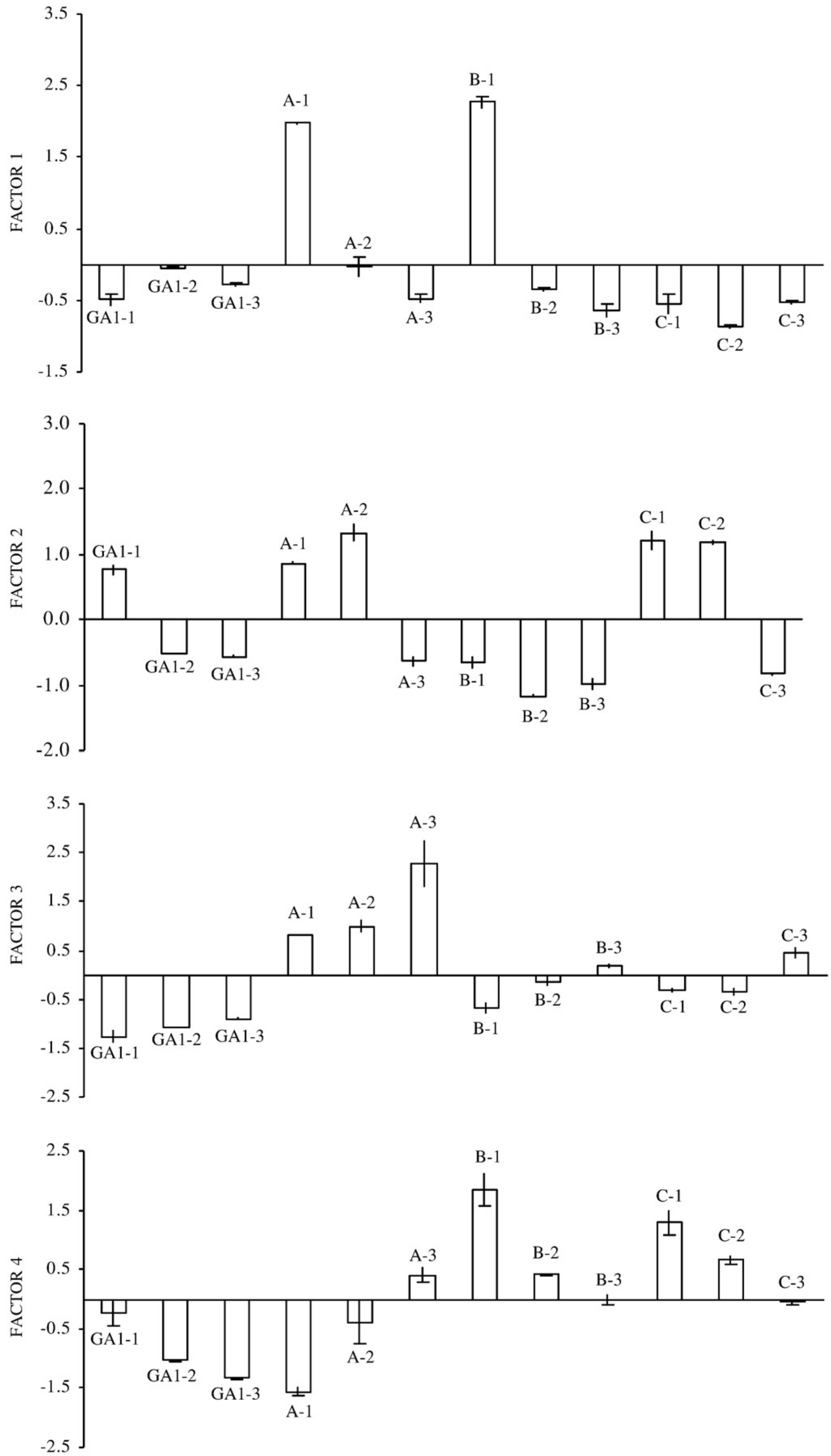

Fig. 4. Estimated factor scores for the four factors in each of the 12 cases.

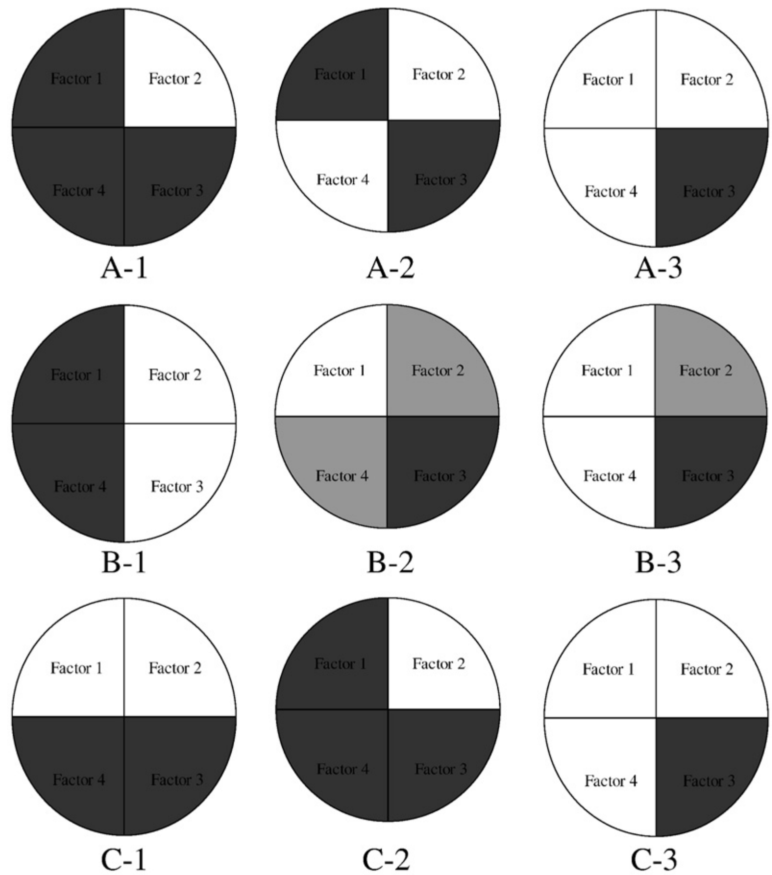

Fig. 5. Pie charts showing the significant differences of the factors score in every study site — Cies (2003–2006) — related to the reference site GA1 (black: $p<0.01$; grey: $0.01<p>$ 0.05; white: no significant differences, $p>0.05$). Factor #1: PAHs–Pb-pollution; Factor #2: Pb–Cu–Ni–V-contamination; Factor #3: Zn–Pb–Ni–Hg-contamination; Factor #4: PAHs-pollution.

out in the Cies Islands. We can see how the score for factor #1 at these 2 stations (A and B) decreases with time in the following surveys, in response to sediment recovery from the effects of initial pollution levels in the studied sites . Factor #2 and #3 demonstrate contamination by metals which was not associated with degradation in most of the stations. Factor #4, related to PAH toxicity, decreases in the stations B and C with time although slight persistence is evident in station A.

Fig. 5 shows the prevalence of each factor in every station according to the statistical differences obtained in the ANOVA analysis, in comparison with the reference site. The prevalence of Factor #1 and Factor #4 which are related to PAHs pollution decreased in all stations over the period 2004–2006 giving the impression that the AINP has been undergoing a process of recovery during the 4 years following the oil spill. On the other hand the significant differences found for Factor #1 and Factor #2 did not reflect such a recovery process during this period. This is perhaps related to the persistence of metal contamination in the 3 study sites, suggesting that this contamination was present prior to the spill in the studied area.

On the whole, the analysis performed in the Cies Island for the period 2004–2006 has shown an important decrease of the initial degradation provoked by the accidental oil spill. At the start of 2004 initial pollution due to PAHs bound to sediments was detected which affected the sediment quality in stations A, B and C. This contamination and its biological effects decreased in the following surveys and currently these sediments seem not to be degraded. The presence of metals contamination was detected in the stations despite this not having produced environmental biological effects. It is possible that these metals may not be available to organisms in their present form, but that if environmental conditions eventually changed, they may become a threat to the environment.

Table 5

Sorted rotated factor loadings (pattern) of 17 variables for the four principal factors resulting from the multivariate analysis of the single results obtained from the chemical analysis, the acute toxicity tests and the alteration parameters for the study of the sediments quality in Corme-Laxe 2004–2006

	Factor 1	Factor 2
	41.32	21.64
Zn	0.55	–
Pb	0.79	–
Cu	0.70	0.59
Ni	0.94	–
V	0.64	0.72
Hg	0.88	–
PAH	0.89	–
Corophium bioassay	0.88	–
Arenicola bioassay	0.83	–
Microtox test	–	0.87
Paracentrotus assay	0.72	–
Number of species	0.50	–
Specific richness	–	0.92
Diversity	–	–
% Molusca	–	–
% Polychaeta	–	0.78
% Crustacea	0.49	–

3.2. Corme-Laxe (end of 2004–2006)

The sediment quality evaluation was performed at the same sites during distinct surveys in the period from the end of 2004 to 2006. Results from the first survey (2004–2005) correspond to GA1-2, D-2, E-2 and F-2; data from the second campaign are referred to as GA1-3, D-3, E-3 and F-3.

The multivariate approach was conducted as described above. After applying the principal factors analysis the 17 variables were grouped in two new factors (Table 5). These factors explain 62.96 % of the original data variance. The first factor, #1 is predominant and explains a 41.3 % of the variance. It links the pollution caused by PAHs and metals (Zn, Pb, Cu, Ni, V and Hg) bound to sediment by relating these contaminants with the toxicity (amphipods, polychaete, sea urchin) and alteration (number of species and percentage of crustacea). The second factor, #2, explains 21.6 % of the variance and depicts the relationship between certain metals (Cu and V) with alteration (specific richness, % of polychaete) and potential toxicity (Microtox® test). Fig. 6 shows the factor scores for the 8 cases. Factor #1, which is defined as the pollution caused by PAHs and the metals Zn, Pb, Cu, Ni, V and Hg, has a positive loading in D-2 (1.7), E-2 (0.3), F-2 (1.5) and F-3 (0.1). The three first cases correspond to the first Corme-Laxe survey (2004–2005) whereas F-3 corresponds to the second station F survey (2005–2006). We can see how the score for factor 1 in D, E, and F decreased as time went on, while remaining positive for station F, this indicating that sediments from these stations have recovered but that degradation persists in station F. Factor #2 shows metal contamination by Cu and V linked to alteration and potential toxicity having a positive loading for D-2 (0.8). The factor score decreased with time in stations D and F whereas station E presented an increase despite it not having a positive loading. Fig. 7 shows the prevalence of each factor in every station according to the statistical differences obtained in the ANOVA analyses in comparison with the reference site (GA1). The significant differences in Factor #1 compared with the reference station did not decrease during the 2004–2006 period with respect to the stations D, E and F, meaning that although recovery was detected in the MAA analysis, D and E are not as clean as the reference station, whereas site F continued to present degradation due to a mixture of various contaminants including PAHs and metals. On the other hand the potential pollution due to the metals Cu and V (Factor #2) present in D and E, was not apparent for the final survey, insofar as significant differences compared with the control GA1 were concerned.

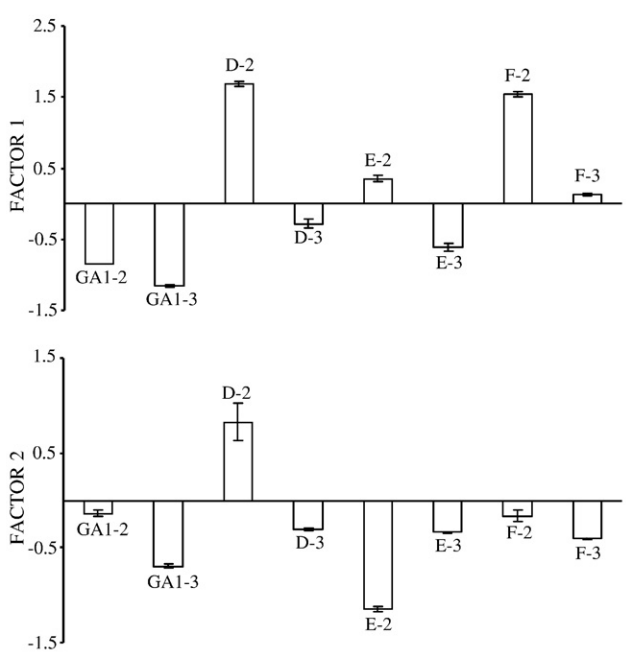

Fig. 6. Estimated factor scores for the two factors in each of the 8 cases.

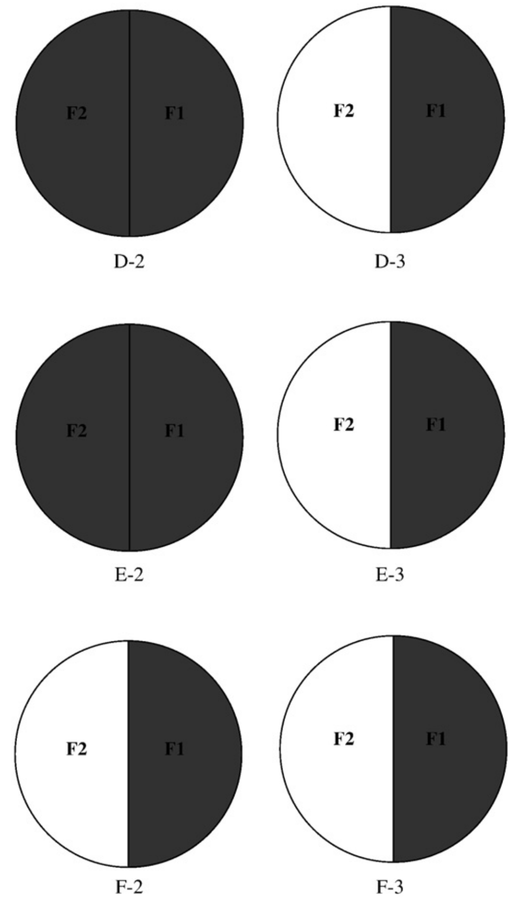

Fig. 7. Pie charts showing the significant differences of the factors score in every study site — Corme-Laxe (2004–2006) — related to the reference site GA1 (black: $p<0.01$; grey: $0.01<p>0.05$; white: no significant differences $p>0.05$). Factor #1: PAHs–Zn– Pb–Ni–Cu–V–Hg-pollution; Factor #2: Cu–V-pollution.

The Corme-Laxe study showed that the presence of both PAHs and a mixture of metals Zn, Pb, Cu, Ni, V and Hg initially caused environmental degradation at the stations D, E and F. The recovery of the stations in D and E (MAA) show that the source of the PAHs pollution is related to the *Prestige* oil spill. However, the presence of metals with different characteristics from those bound to the original fuel oil from the *Prestige,* suggest the possible existence of another source or sources of contamination in the area. Previous studies have shown that the neighbouring Rias and coastal waters act as a source of dissolved and particulate trace metals (Cobelo-García et al., 2005). Research results obtained show sediments from the stations D and E to have recovered whereas degradation remains at the F site nearest to the coast, highlighting the influence of the mentioned causes different than the *Prestige*. Initial potential degradation caused by Cu and V was also detected, although not present for the final survey.

4. Conclusions

The WOE approach employed in this study has been applied to 3 lines of evidence (contamination, toxicity and alteration) in addressing 3 distinct objectives. First of all a revision of the sediment quality following the *Prestige* oil spill has been carried out in the Atlantic Islands, an area with a high ecological relevance. This was achieved by applying a multivariate and ANOVA analyses. In order to assess the development of the quality of the sediments affected by the spill a set of stations was studied using the same time-dependent methodology for the Cies Island (2004–2006) and in Corme-Laxe (2004–2006). Results obtained have identified PAHs related to the *Prestige* oil spill as the main contaminant in the sites studied on the Galician Coast. A source of metals has been identified in the Atlantic Islands National Park which seems not to be producing biological effects although further research of this input of metals should be carried out especially for the Ons Island. In Corme-Laxe an additional source or sources of a mixture of contaminants was also detected. Pollution has decreased in recent years in both the Atlantic Islands National Park and Corme-Laxe areas , although there is still some degradation present in some areas, particularly in Corme-Laxe.

The information obtained in this study has demonstrated that WOE is a suitable tool for monitoring environmental risk assessment allowing sources and fate of contaminants to be differentiated in addition to their potential risk. The innovative application of the classical WOE methodology has proved useful in obtaining more objective results and its use is recommended in the design and implementation of monitoring programs in areas that have suffered contamination episodes through the selecting of appropriate lines of evidence on a case by case basis.

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