Long-term records of trace metal content of western Mediterranean seagrass (*Posidonia oceanica*) meadows: Natural and anthropogenic contributions

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[1] We discuss Al, Ag, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn contents in seagrass *Posidonia oceanica* rhizomes from the Balearic Archipelago for the last 3 decades. Time series of metal concentration in *P. oceanica* were measured by dating rhizomes using retrospective procedures. The highest concentrations of Al ($174.73 \mu\text{g g}^{-1}$), Cd ($3.56 \mu\text{g g}^{-1}$), Cr ($1.34 \mu\text{g g}^{-1}$), Cu ($32.15 \mu\text{g g}^{-1}$), Pb ($8.51 \mu\text{g g}^{-1}$), and Zn ($107.14 \mu\text{g g}^{-1}$) were measured in meadows located around the largest and most densely populated island (Mallorca Island). There was a general tendency for Ag concentration to decrease with time (up to 80% from 1990 to 2005 in sample from Mallorca Island), which could be attributed to a reduction of the anthropogenic sources. Nickel and Zn concentrations were the unique elements that showed a consistent temporal trend in all samples, increasing their concentrations since year 1996 at all studied stations; this trend matched with the time series of UV-absorbing aerosols particles in the air (i.e., aerosols index) over the Mediterranean region (r^2 : 0.78, $p < 0.001$ for Cabrera Island), suggesting that *P. oceanica* could be an efficient recorder of dust events. A comparison of enrichment factors in rhizomes relative to average crustal material indicates that suspended aerosol is also the most likely source for Cr and Fe to *P. oceanica*.

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1. Introduction

[2] Trace metals occur naturally in the ocean, mostly as colloids or absorbed onto organic and inorganic suspended particles, and tend to accumulate in living organisms and bottom sediments. While some trace metals, such as Cd, Co, Cu, Fe, Mn, Ni and Zn play a key biological role in the sea, regulating biochemical function in marine organism, they may be present in excess and, along with other metals (e.g., As, Pb), can negatively affect ecosystem health [Frausto da Silva and Williams, 1991; Morel and Price, 2003]. Identification of the contribution of natural and/or anthropogenic main sources and pathways of trace metals entering the sea, are crucial for understanding the biogeochemical processes occurring in the coastal waters, and to effectively design and implement policies to improve the health of coastal systems.

[3] The coastal zone of the Mediterranean Sea is subject to the input of trace metal mobilized by human activities such as urbanization, tourism, agriculture, aquaculture, industries, marine traffic, etc. For example, while some metals

discharged to water in the Mediterranean could be from industrial origin, such as leather and leather products (Cr, Cu, Pb and Ni), chemical and allied products (Zn), electronic and electric equipment (Pb, Cd), maritime paints and shipyard activities (Cu, Zn), sewage (Ag), etc. [Sañudo-Wilhelmy and Flegal, 1992; Patterson et al., 1998; Howe and Dobson, 2002; Wang et al., 2003; Tovar-Sánchez et al., 2004], other metals like Al, Co, Fe or Mn have mainly a lithogenic origin [Peris et al., 2008]. Atmospheric transport represents the dominant pathway for large-scale transport of trace metals (i.e., Al, Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn) to the Mediterranean Sea [Guieu et al., 1997; Migon, 2005; Guerzoni and Molinaroli, 2005], as riverine inputs are relatively low at the basin scale [Migon, 1993; Migon et al., 2002; Guerzoni and Molinaroli, 2005]. The episodic inputs of Saharan dust have been recognized as particularly important for the transport and deposition of materials to the Mediterranean Sea [Ridame and Guieu, 2002]. Over the last 20 years dust-rain events, from Saharan origin, have increased remarkably in the western Mediterranean region as a consequence of the intensification of meteorological processes (convective and advective synoptic situations) that promote the transport of aerosols from Africa toward the western Mediterranean [Quereda-Sala et al., 1996]. An increased deposition of Saharan

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Figure 1. (a) Map of Balearic Archipelago with sampling sites of *P. oceanica* (black dots). (b) Map of the western Mediterranean with sampling sites of suspended aerosols.

dust to the Mediterranean may result in an increase in the input of metals of which Sahara dust is rich and may also become further enriched by scavenging during atmospheric transport (e.g., Al, Cr, Fe, Mn [Guieu *et al.*, 1997, 2002]). Any increase in metal inputs to the Mediterranean Sea should be reflected in an increase in metal concentrations in living organisms. Sessile organisms like plants (e.g., macroalgae [Olgunoglu and Polat, 2008] and seagrasses [Roméo *et al.*, 1995]), should therefore become excellent biological tracers of metal concentrations in the environment.

[4] *Posidonia oceanica* is a long-lived seagrass species with shoots living for several decades [Marbà *et al.*, 2002], that forms meadows at depths ranging from 1 to 40 m that extend over a total estimated area of 50,000 km² in the Mediterranean Sea [Bethoux and Copin-Montégut, 1986]. It has been well established that *P. oceanica* sequester trace metals from the marine environment and that metal concentrations in their perennial tissues, which remain for decades, can be used as a proxy to trace ambient metal and radionuclide concentrations over long periods of time [Roméo *et al.*, 1995; Pergent-Martini, 1998; Calmet *et al.*, 1988; Baroli *et al.*, 2001; Ancora *et al.*, 2004; Tranchina *et al.*, 2005a, 2005b; Lafabrie *et al.*, 2009]. The growth of *P. oceanica* is highly organized, a regular number of leaves and rhizome internodes being produced at a ratio 1:1 annually at the apical rhizome meristems. Therefore, the age of different rhizomes can be estimated [Duarte *et al.*, 1994]. These findings have highlighted the potential of this seagrass species as a biological indicator of both contamination and environmental variability. Retrospective examination of the long-term variability of elemental composition of plant tissues across regional scales can provide information about the temporal and spatial dynamics of trace metal inputs in the coastal ocean and help discriminate between local and large-scale (e.g., atmospheric) sources.

[5] While several studies have investigated trace metal concentrations in *P. oceanica* over the Mediterranean [e.g., Baroli *et al.*, 2001; Ancora *et al.*, 2004; Tranchina *et al.*, 2005a], information on metal levels in the Balearic Archipelago is very limited.

While previous works were very localized and focused to assess the degree of metal pollution in the area, our study was designed to elucidate local and regional processes affecting plant metal concentration. The goal of this study is to examine the changes of trace metal composition in rhizomes of *P. oceanica* along coastal waters of the Balearic Islands, western Mediterranean, over the past 3 decades to identify and evaluate the spatial and temporal trends of metal inputs. Then, we evaluate and discuss the possible link between aeolian input and seagrass chemical composition. Because industrial activity in, and nearby, the Balearic Islands is minimal, any enrichment and/or long-term trend in trace metal concentration in *P. oceanica* rhizomes in this region may derive from local point sources or long-distance transport, particularly atmospheric supply. We, therefore, compared metal enrichment and trends in *P. oceanica* rhizomes with metal concentrations in direct measurements of atmospherically suspended aerosols and long-term dynamics of atmospheric aerosols in the region.

2. Methods

[6] The Balearic archipelago (Spain) is located in the western Mediterranean Sea, and it is composed of four major (Mallorca, Menorca, Ibiza and Formentera) and other minor islands (Cabrera and islets) (Figure 1). The Balearic Islands lack significant industrial and riverine inputs and the main human pressure on the coastal water comes from urban activities. Much of the coastal zone is protected (e.g., Minorca Island was declared a Biosphere Reserve in 1993, while Cabrera and small surrounded islets were declared a Spanish national park in 1991). These coastal waters support very extensive *P. oceanica* meadows, growing above iron-poor biogenic carbonate sediments.

[7] *Posidonia oceanica* was sampled during August 2005 to September 2005 and August 2006 to October 2006 in 51 meadows at 3–18 m depth along the coast of the Balearic Islands (Figure 1). At each station, SCUBA divers collected up to three old orthotropic (vertically growing) rhizomes

holding standing leaves. Samples were thoroughly rinsed in ambient seawater, stored in polyethylene bags and frozen. In the laboratory leaves, leaf sheaths and epiphytes were removed from rhizomes. After rinsing with ultrapure water to remove fine sediments particles, rhizomes were carefully cut (using a ceramic knife) in segments of 1 cm of length, corresponding to 1 lepidochronological year period of growth [Marbà and Duarte, 1997]. Previous studies indicated that average vertical rhizome growth of *P. oceanica* along the Balearic Islands was $8.2 \pm 0.14 \text{ mm yr}^{-1}$ (N. Marbà and C. M. Duarte, unpublished manuscript, 2010). Each rhizome segment, previously dried at 60°C for 24 h and weighted, was digested in high-pressure Teflon vessels using a mixture of high-purity acids (suprapur, Merck) HNO_3 (67%) + HCl (13%) + ultrapure water (20%) [Duarte et al., 1995]. Digested samples were transferred into acid cleaned polypropylene tubes and diluted 1:4 (v/v) with ultrapure water. Metal concentrations (Al, Ag, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn) were determined by ICP-AES (Perkin Elmer ICP-AES Optima 5300 DV). Procedural blanks were obtained from acid medium as described above for rhizomes. Detection limits, calculated as three times the standard deviation of the blanks values, were in ng g^{-1} : Ag = 0.09, Al = 0.31, Cd = 0.16, Co = 0.15, Cr = 0.19, Cu = 2.96, Fe = 0.50, Mn = 0.01, Ni = 0.54, Pb = 0.15 and Zn = 1.63. The accuracy of the analytical procedure was checked using a standard reference material (sea lettuce *Ulva lactuca*, CRM 279; Community Bureau of Reference) with recoveries ranging from 93% for Pb to 104% for Ni of certified and indicative values. The trace metal composition during the life span of *P. oceanica* rhizomes (up to 3 decades) was examined for each lepidochronological year (i.e., approximately October to October) in samples from stations 1 to 25. In other cases (from station 26 to station 51), duplicated or triplicate rhizomes were analyzed in two fractions, one corresponding to the 3 youngest lepidochronological years and the other to the rest of rhizome.

[8] Sampling of aerosol was carried out during a cruise on board the R/V *García del CID* in June–July 2006 across the Mediterranean Sea. Samples of coarse ($>20 \mu\text{m}$) suspended aerosols were collected at six stations (latitude N–longitude E; station 1: 38.9033–4.8025; station 2: 38.3086–8.0950; station 3: 37.8845–10.6443; station 4: 37.7626–7.3435; station 5: 38.1211–4.5328; Figure 1) onto an acid-washed cellulose filter (Whatman 41) in a high-volume collector (MCV: CAV-A/HF). A microwave acid digestion procedure [Pekney and Davidson, 2005] followed by ICP-AES was used to measure total trace metal levels in those aerosol filters (Al, Cr, Fe, Mn, Ni, Pb, Cu, and Zn).

[9] The total annual index of atmospheric aerosols was estimated by remote sensing over the Balearic Islands (http://toms.gsfc.nasa.gov/aerosols/aerosols_v8.html). According to the NASA, the Total Ozone Mapping Spectrometer (TOMS) aerosol index is defined as: “a measure of how much the wavelength dependence of backscattered UV radiation from an atmosphere containing aerosols (Mie scattering, Rayleigh scattering, and absorption) differs from that of a pure molecular atmosphere (pure Rayleigh scattering)” (http://toms.gsfc.nasa.gov/aerosols/aerosols_v8.html). This index is related to aerosol optical depth, and indicates the amount of aerosols (e.g., dust, volcanic ash, and smoke) that absorb ultraviolet (UV) radiation in the atmosphere. The aerosol index is calculated daily by using a retrieval algorithm

[Torres et al., 1998, 2002] based on the absorbance measurements (331–360 nm) done by the Earth Probe TOM (Total Ozone Mapping Spectrometer) instrument onboard the Aura satellite system. Because TOMs have been experiencing instrument problems, the aerosol index from 2001 onward should be considered only approximate. Air mass origins for the cruise samples were established using the NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) [Draxler and Rolph, 2003].

[10] Because metal concentrations along rhizomes exhibited wide temporal fluctuations, we used median values to characterize the metal composition of each station. Differences in *P. oceanica* metal concentration across islands were statistically tested using Analysis of Variance, and differences between paired islands identified with Tukey-Kramer test. The magnitude of temporal fluctuations in *P. oceanica* metal concentrations was quantified using the coefficient of variation (CV). Significant temporal shifts in *P. oceanica* metal (e.g., Ag) concentration among islands were tested using *t* test. We used cross correlation analysis to demonstrate the coupling between average temporal trends in Zn and Ni for each island and atmospheric aerosol index despite the existence of time lags in seagrass response. Metal concentrations were calculated with respect to dry weight.

3. Results

[11] The length of orthotropic rhizomes studied ranged from 4.5 to 32 cm, which represent between 4 (station 11) and 29 (station 22) years old. Hence metal contents were analyzed in a total of 292 rhizomes sections, the oldest formed in 1976. Median, minimum and maximum metal (Al, Ag, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn) concentrations in rhizomes collected in 51 meadows around the Balearic Islands (Figure 1) are shown in Table S1 (available as auxiliary material).¹ The lowest median metal contents characterized Formentera (Al: $1.32 \mu\text{g g}^{-1}$, Cd: $0.41 \mu\text{g g}^{-1}$, Cu: $4.31 \mu\text{g g}^{-1}$, Fe: $15.85 \mu\text{g g}^{-1}$, Mn: $1.30 \mu\text{g g}^{-1}$ and Pb: $0.05 \mu\text{g g}^{-1}$) and Ibiza (Cr: $0.01 \mu\text{g g}^{-1}$, Ni: $0.97 \mu\text{g g}^{-1}$ and Zn: $4.02 \mu\text{g g}^{-1}$) meadows. Although the lowest concentrations of Ag and Co were found, occasionally, in rhizomes from stations 17 ($1.24 \mu\text{g g}^{-1}$, Mallorca) and 42 ($0.02 \mu\text{g g}^{-1}$, Menorca), respectively, very low concentrations were also measured in samples from Formentera (e.g., St 7: $2.43 \mu\text{g g}^{-1}$ Ag and St 28: $0.04 \mu\text{g g}^{-1}$ Co). The highest concentrations of Al ($174.73 \mu\text{g g}^{-1}$), Cd ($3.56 \mu\text{g g}^{-1}$), Cr ($1.34 \mu\text{g g}^{-1}$), Cu ($32.15 \mu\text{g g}^{-1}$), Pb ($8.51 \mu\text{g g}^{-1}$) and Zn ($107.14 \mu\text{g g}^{-1}$) were measured in meadows located around the Mallorca Island. On the other hand, the highest median concentrations of Ag ($27.58 \mu\text{g g}^{-1}$), Fe ($624.09 \mu\text{g g}^{-1}$) and Mn ($31.66 \mu\text{g g}^{-1}$) were measured at the north of Menorca Island (station 43).

[12] Except for Al, concentrations of all metals in *P. oceanica* varied significantly among islands (ANOVA with comparisons for all pairs using Tukey-Kramer test; Table S2). Concentrations of Cu, Ag and Mn showed the highest spatial variations (ANOVA and Tukey-Kramer test, $p < 0.001$; Table S2).

¹Auxiliary materials are available in the HTML. doi:10.1029/2009JG001076.

Figure 2. Concentrations, at different stations, of Ag, Cr, Cu, and Cd of *P. oceanica* from the Mallorca and Ibiza islands as a function of lepidochronological years. Concentrations of Cr at stations 10 and 11 were below detection limit. Note that different scale is used for station 14.

[13] Interannual fluctuations of metal concentrations in *P. oceanica* rhizomes were broadly variable, CV: Al (19–129%), Cd (18–69%), Co (27–140%), Cr (16–231%), Cu (12–96%), Fe (26–102%), Mn (6–71%), Pb (40–258%) (Figures 2–4 and Figures S1–S3). After excluding values at station 14 in Mallorca Island, where concentrations were

generally higher for almost all analyzed elements, probably due to a local source, the lowest temporal variations in metal concentrations were found around the smallest and less impacted islands, Cabrera (CV: 57, 31, 65 and 55%, for Al, Cd, Fe and Mn, respectively) and Formentera (CV: 53, 51% for Co and Cu, respectively). Only Cr (CV: 85%) and

Figure 3. Concentrations, at different stations, of Mn, Co, Fe, and Al of *P. oceanica* from the Mallorca and Ibiza islands as a function of lepidochronological years. Concentrations of Co at stations 5, 17, and 23 were below detection limit. Note that different scale is used for station 14.

Pb (CV: 69%) showed the lowest variations at Ibiza and Mallorca, respectively. No temporal trends of these metals concentrations were observed in the studied meadows.

[14] Ag, Ni and Zn concentrations also showed interannual changes along the rhizomes and variations among

different meadows, thus the highest variations of Ag (CV: 97%) were shown at Cabrera, while Ni (CV: 165%) and Zn (CV: 113%) varied greatly at Ibiza Island. A temporal sustained decreasing trend of Ag concentration was observed in most rhizomes from Mallorca and Ibiza islands since year

Figure 4. Concentrations, at different stations, of Ni, Zn, and Pb of *P. oceanica* from the Mallorca and Ibiza islands as a function of lepidochronological years. Dashed line is the annually aerosols index estimated by satellite on the Balearic Archipelago region. Note that different scale is used for station 14.

1995 (Figures 2 and S1). A *t* test indicated that Ag contents in the rhizome were significantly lower ($p < 0.0001$) after 1995 (5.44 ± 0.30 versus 9.75 ± 0.55 and 6.66 ± 0.37 versus 10.80 ± 0.49 at Mallorca and Ibiza, respectively). Conversely, Nickel and Zn concentrations in all *P. oceanica* rhizomes increased since year 1996 at all studied stations (Figures 4 and S3), although the largest increase was detected since 2000–2002.

4. Discussion

4.1. *P. oceanica* Trace Metal Characterization in the Balearic Archipelago

[15] Chemical composition of *P. oceanica* over the Balearic archipelago shows the lowest metal contents in plants from Formentera and Cabrera islands. These islands are the smallest and less inhabited islands of the archipelago and consequently those supporting the least anthropogenic pressure on their coastal system. In contrast, the highest concentrations were measured in meadows located around Mallorca and Menorca islands, the largest and most densely

populated islands of the archipelago. The metal enrichment in rhizomes from station 43 (Menorca) cannot easily be attributed to anthropogenic causes since this meadow is located in a marine reserve where no sewage or submarine outfalls were identified.

[16] Mean values of metal concentrations in rhizomes collected in the Balearic Archipelago are in agreement with ranges reported for other areas in the Mediterranean Sea, except for Co whose concentrations (0.22 – $0.86 \mu\text{g g}^{-1}$) were 1 order of magnitude lower than reported for other Mediterranean areas (1.7 – $12.1 \mu\text{g g}^{-1}$) (Table 1). Iron concentrations were often observed to be below the threshold ($100 \mu\text{g g}^{-1}$ Fe) for iron sufficiency in angiosperms, as expected for carbonate sediments away from anthropogenic Fe inputs [Duarte *et al.*, 1995], thus suggesting that Fe supply may often limit the growth of *P. oceanica* in the Balearic Islands [Holmer *et al.*, 2005; Marbà *et al.*, 2007]. The finding of low Fe concentration in rhizomes agrees with previous observations relative to leaves of *P. oceanica* from the same region [Fourqurean *et al.*, 2007]. To our knowledge this is the first study that measures Ag and Al concentrations in

Table 1. Mean Values $\pm$ SD of Metal Concentrations in Rhizomes of Different Coastal Areas of the Mediterranean Sea^a

Reference ^b	Location	Ag	Al	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Zn
1	Mallorca, Spain	8.28 $\pm$ 5.84	40.79 $\pm$ 92.4	1.11 $\pm$ 0.77	0.44 $\pm$ 0.67	0.51 $\pm$ 0.66	13.62 $\pm$ 7.98	161.90 $\pm$ 281.23	7.53 $\pm$ 10.25	10.21 $\pm$ 11.79	4.26 $\pm$ 4.35	35.61 $\pm$ 32.89
	Menorca, Spain	16.08 $\pm$ 10.53	43.25 $\pm$ 92.4	1.13 $\pm$ 0.45	0.22 $\pm$ 0.25	0.31 $\pm$ 0.29	15.22 $\pm$ 5.15	190.92 $\pm$ 199.35	9.25 $\pm$ 11.8	17.05 $\pm$ 13.83	0.65 $\pm$ 1.15	49.32 $\pm$ 25.60
	Ibiza, Spain	9.05 $\pm$ 4.27	52.42 $\pm$ 46.39	1.03 $\pm$ 0.48	0.29 $\pm$ 0.28	0.36 $\pm$ 0.32	11.51 $\pm$ 5.98	184.76 $\pm$ 144.92	9.61 $\pm$ 6.82	7.11 $\pm$ 10.4	2.65 $\pm$ 3.02	28.00 $\pm$ 28.58
	Formentera, Spain	4.66 $\pm$ 2.29	19.28 $\pm$ 15.29	0.96 $\pm$ 0.33	0.37 $\pm$ 0.25	0.24 $\pm$ 0.25	9.41 $\pm$ 4.44	48.49 $\pm$ 39.52	4.22 $\pm$ 2.35	10.35 $\pm$ 12.46	0.45 $\pm$ 0.41	41.15 $\pm$ 25.5
	Cabrera, Spain	5.23 $\pm$ 5.1	30.95 $\pm$ 17.76	0.72 $\pm$ 0.22	0.86 $\pm$ 1.4	1.06 $\pm$ 2.44	10.88 $\pm$ 10.19	68.02 $\pm$ 44.44	16.16 $\pm$ 8.81	3.66 $\pm$ 3.26	8.89 $\pm$ 27.49	23.44 $\pm$ 10.46
2	Sicily, Italy			0.97 $\pm$ 0.12			9.3 $\pm$ 5.9				6.7 $\pm$ 1.9	65 $\pm$ 26
				1.15 $\pm$ 0.39			4.1 $\pm$ 0.7				3.5 $\pm$ 0.7	63 $\pm$ 18
				0.73 $\pm$ 0.38			2.6 $\pm$ 1.1				4.5 $\pm$ 1.2	150 $\pm$ 110
3	Sardinia, Italy			2.25 $\pm$ 0.018			7.9 $\pm$ 1.1				6.0 $\pm$ 0.6	172 $\pm$ 117
	Ischia, Italy			0.8 $\pm$ 0.2			5.4 $\pm$ 1.4	90 $\pm$ 120			0.8 $\pm$ 0.2	
	Corsica, France			0.8 $\pm$ 0.1			12.8 $\pm$ 1.5	370 $\pm$ 80			2.3 $\pm$ 0.2	
	Corsica, France			2.4 $\pm$ 0.4			14.9 $\pm$ 1.3	120 $\pm$ 20			2.4 $\pm$ 0.3	
	Cortiou, France			1.1 $\pm$ 0.1			15.3 $\pm$ 0.3	110 $\pm$ 10			1.3 $\pm$ 0.2	
4	Gulf of Naples, Italy			0.25–1.6			6.0–62	100–600	4–23		0.15–1.25	20–220
	Corsica, France			5.38 $\pm$ 0.14	12.07 $\pm$ 0.52	1.27 $\pm$ 0.23				60.3 $\pm$ 3.67	1.47 $\pm$ 0.03	
	Toscana, Italy			3.39 $\pm$ 0.12	5.73 $\pm$ 0.03	0.27 $\pm$ 0.07				28.90 $\pm$ 0.65	1.4 $\pm$ 0.25	
	Sardinia, Italy			2.10 $\pm$ 0.10	1.7 $\pm$ 0.06	0.2 $\pm$ 0.06				27.47 $\pm$ 1.1	1.8 $\pm$ 0.0	

^aUnits are in $\mu\text{g g}^{-1}$ dry weight.^bReferences: 1, this work; 2, Tranchina et al. [2005a]; 3, Baroli et al. [2001]; 4, Ancora et al. [2004]; 5, Lafabrie et al. [2007].

P. oceanica, therefore comparison with other Mediterranean regions is not possible.

[17] The concentrations of Al, Co, Cr and Pb in *P. oceanica* rhizomes exhibited the widest interannual fluctuations. The temporal changes in the concentration of these metals in *P. oceanica* rhizomes were not consistent at regional scale (Figures 2–4 and Figures S1–S3). Individual increases of concentrations like those detected for Al, Cr, Fe and Mn at station 22 in the section of rhizome dated in 1999 (Figures 2 and 3), or the higher concentrations of all elements measured along the rhizome of station 14, could be due to local, point source contamination from undetected or uncontrolled sewages or shipyard activities.

[18] Concentrations of some metals (i.e., Ag, Ni and Zn) in *P. oceanica* rhizomes showed consistent temporal trends. Thus, while Ag concentration decrease with time from 1990 to 2005, Zn and Ni increased their concentrations since year 1996 at all studied stations. The major sources of Ag in the environment are waste from human activities (mainly from the photographic industry and photo-processing wastes in sewage sludge), and sewages outfalls have been considered the principal source of anthropogenic silver in coastal water [Sañudo-Wilhelmy and Flegal, 1992; Howe and Dobson, 2002; Wang et al., 2003; Tovar-Sánchez et al., 2004]. The decrease of Ag content in rhizomes of *P. oceanica* observed during the last decades could reflect the decrease of Ag inputs to the environment as a consequence of the progressive reduction in the use of photographic films caused by the development of digital technology.

[19] The quasi-synoptic increase in Ni and Zn concentrations in meadows across the Balearic Islands cannot be explained by local inputs. Indeed, only changes in the atmospheric deposition of these elements with aerosols could possibly explain this marked and synoptic trend in plants across such a large area. To test the hypothesis that Ni and Zn composition of *P. oceanica* reflects atmospheric deposition, we examined the relationship between the total annual index (from 1997 to 2004) of atmosphere aerosols estimated daily by remote sensing over the Balearic Islands (http://toms.gsfc.nasa.gov/aerosols/aerosols_v8.html) and the Ni and Zn composition of *P. oceanica* (Figures 4 and S3). Remarkably similar trends were observed between the suspended particles in the air and the Ni and Zn content in rhizomes, suggesting that the increasing Zn and Ni concentrations in *P. oceanica* result from inputs associated with aerosols deposition. Actually, the average annual concentration of Ni and Zn in *P. oceanica* rhizomes measured at each island, but Ibiza, was significantly positively correlated with the total atmospheric annual index recorded 3 years before (cross-correlation analysis, $p < 0.05$; Table S3). The best correlations were obtained for Zn (r^2 : 0.78, $p < 0.01$) and Ni (r^2 : 0.85, $p < 0.05$), at Mallorca and Cabrera, respectively. The fact that metal concentration in *P. oceanica* rhizomes was measured during lepidochronological years (October to October) while atmospheric index was estimated for chronological years (January to January), and the slow growth of this seagrass species might explain the time lag observed in *P. oceanica* metal concentration response. An increasing trend of Zn concentration in *P. oceanica* rhizomes between years 1990 and 1999 was also reported in a different area of the Mediterranean (Gulf of Naples, Italy [Ancora et al., 2004]). Although in this study the sources were not

Figure 5. Crustal enrichment factor (EF_{crustal}) for elements in the rhizomes of *P. oceanica* over all islands of the Balearic Archipelago (solid boxes), in suspended aerosols on the western Mediterranean (dashed boxes), and in European anthropogenic and crustal dominated aerosols on the Mediterranean (stars and triangles, respectively) [Guerzoni et al., 1999]. The line within the box is the median, and the error bars indicate the 5th and 95th percentiles. Solid circles show outlying points, and n is the number of EF_{crustal} values for rhizomes of *P. oceanica*.

identified, our results indicate a wide regional influence of aerosols depositions on the Zn composition of *P. oceanica*.

4.2. Natural and Anthropogenic Contribution

[20] The metal concentrations normalized to a crustal reference (i.e., Al) are usually used to estimate the relative contributions of anthropogenic and natural sources. Thus, in order to estimate the degree to which the trace metals measured in *P. oceanica* are enriched relative to putative aerosols sources we calculated the crustal enrichment factor (EF_{crustal}) following the equation [Taylor, 1964; Ikegawa et al., 1999]:

$$EF_{\text{crustal}} = (Me/Al)_{P.oceanica} / (Me/Al)_{\text{crust}};$$

where Me and Al are the concentrations of each studied metal and Al, in *P. oceanica* and in average crustal material, respectively. By convention, average EF_{crustal} values of any element <10 suggest that crustal material, derived in this case from the Sahara desert, is the probably source for that element [Duce et al., 1975; Ikegawa et al., 1999; Chester et al., 1999]. We are aware that EF_{crustal} is mostly applicable to mineral matter. Although, in this case we assume that the uptake and dissolution processes, of many elements in *P. oceanica*, are congruent with the dissolution and uptake of the reference element (i.e., Al). This assumption is supported by the use of this plant as a proxy to trace ambient metal concentration [e.g., Roméo et al., 1995; Pergent-Martini, 1998; Baroli et al., 2001; Tranchina et al., 2005a]. EF_{crustal} values suggest that Cr (median: 5.0) and Fe (median: 5.8) in rhizomes of *P. oceanica* from the Balearic Islands are likely derived from a crustal source (Figure 5). The other elements showed slightly (median values for Mn: 20.3 and Co: 22.9) or higher (Ni > Pb > Cu > Zn > Cd > Ag) values, indicating that

they are enriched relative to crustal sources. In order to evaluate the connection between aeolian input and *P. oceanica* chemical composition, we measured the chemical composition of collected aerosols suspended particles in the western Mediterranean (Figure 1). Concentrations of Al, Cr, Cu, Fe, Mn, Ni, Pb and Zn, in the aerosols were 279.8–1403.5, 0.6–2.3, 2.6–19.4, 147.7–814.8, 5.1–25.8, 2.0–7.0, 1.2–6.0, and 11.0–14.9 ng/m^3 , respectively.

[21] A comparison of the EF_{crustal} calculated for *P. oceanica* with that of aerosols collected in this work, and those reported for anthropogenic and Saharan dominated aerosols in the Mediterranean [Guerzoni et al., 1999] indicate that Pb, Ni, Zn and Cd are more clearly influenced by aerosols with an anthropogenic component than by a Saharan component (Figure 5). To support this statement, we have estimated the air mass origins for our suspended aerosols samples using the NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) [Draxler and Rolph, 2003] (Figure S4). The back trajectories (for the 48 h preceding sample collections) indicate that aerosols particles collected during our sampling date come from northwestern Europe, and therefore they probably have an anthropogenic load. On the other hand, the ratios of these metals to Al in aerosols were, except for Pb, lower than those in the plants (Figure 5), which suggest the presence of local sources of these metals enriching *P. oceanica* tissues. Lead from anthropogenic European aerosols clustered with Pb composition of *P. oceanica*, suggesting that these aerosols might also be a source.

[22] As indicated above, the coupling between temporal variations in Ni and Zn concentrations along *Posidonia* rhizomes and the annual record of suspended particles in the air point out an influence of aerosol deposition on the composition of *P. oceanica* (Figures 4 and S3). However, the observation that the concentration of these two elements in *P. oceanica* cannot be explained by a normal crust event and the fact that other elements of crustal origin (e.g., Fe, Mn) do not show the same temporal trend as aerosols records represents apparently a paradox. This could be explained by (1) total Ni and Zn concentrations in aerosol deposition at the northwestern Mediterranean are higher than those expected regarding the EF_{crust} [Guieu et al., 1997]. Although the causes are not yet known, additional sources of Zn to the Mediterranean (from local or regional anthropogenic origin), or underestimation of aerosols concentration (e.g., significant gaseous contribution) have been suggested [Migon, 2005; Guieu et al., 1997]. In fact, the Ni and Zn EF values of European anthropogenic dominated aerosols reported by Guerzoni et al. [1999] and plotted in Figure 5 were only 1 order of magnitude lower (Ni: 15–21 and Zn: 63–120) than those calculated for *P. oceanica* (median and range: 251.5 and 6.5–6.7 10^5 for Ni, 1001.6 and 81.8–15.8 10^5 for Zn), supporting this possibility; (2) differential translocation, use and storage of trace metals in seagrass organs, as some metals, such as Fe, may play a key role as limiting element and be translocated from rhizomes to leaves and used to produce new plant tissues, whereas some others, in excess of biological demand or with no biological function, may remain in the rhizomes; and (3) our aerosols EF calculation might be underestimated since we used filters of big pore size (Whatmann 41) which collect only large suspended aerosols particles ($>20 \mu\text{m}$).

The small aerosols fraction ($<20\ \mu\text{m}$) could contribute significantly to the total atmospheric deposition and could even have a different chemical composition.

[23] Although aerosol deposition in the Mediterranean Sea has increased since 1996, concentrations of lithogenic elements (i.e., Fe and Mn) in *P. oceanica* rhizomes do not exhibit an increasing trend. *Posidonia* in the Balearic Islands grows on carbonate-rich and iron-poor sediments and it is iron deficient, as demonstrated by Fe-addition experiments [Holmer et al., 2005; Marbà et al., 2007]. Iron additions to *P. oceanica* meadows enhance clonal growth and, thus, production of new shoots, without increasing Fe concentrations in plant tissues [Marbà et al., 2007]. Therefore, the growth response to increased Fe inputs is expected to dilute the concentration possibly accounting for the lack of increase of Fe concentrations in *P. oceanica* meadows in the Balearic Island compared to the increase in aerosol deposition since 1996. An increased Fe deposition to the region, from increased atmospheric dust transport, may have improved the condition of *P. oceanica* meadows in the region, as Fe inputs have been experimentally shown to reduce seagrass population decline in the Balearic Islands [Marbà et al., 2007]. Manganese is also a micronutrient essential for plant growth [Barker and Pilbeam, 2006]; however, there is no information on the nutritional status of *P. oceanica* relative to this element. Some trace metals (Zn, Cd, Mn and Ni) can be mobilized within plants, such wheat, toward new growing leaves [Page and Feller, 2005]. Therefore, an increase of Zn and Ni in *P. oceanica* rhizomes during the recent years could be an artifact derived from translocation toward rhizome meristem, i.e., recently produced rhizome segments. Yet, if this was indeed the cause, a greater increase would be expected for Fe, the main limiting trace element to *P. oceanica* in these waters [Holmer et al., 2005; Marbà et al., 2007], whereas no such trend was observed. Moreover, increasing trends were observed at the same time (1996) in both young and old rhizomes, further indicating the influence of an external cause. Hence, our results suggest that aerosols deposition may have been the main source of Zn and Ni to *P. oceanica* rhizomes in the Balearic Islands over the last 2 decades.

5. Conclusion

[24] Our results show that metal concentrations vary few orders of magnitude within *P. oceanica* rhizomes across the Balearic Islands. In addition, metal concentrations show also large, order-of-magnitude temporal variability within any meadow, indicating that the balance between metal supply and, for the essential elements, plant incorporation and allocation patterns can vary greatly. Whereas the internal dynamics of metal mobilization within the plants may play an important role in the variability of some essential metals, such as Fe and Co, for some others (e.g., Ag) the anthropogenic activity might represent the main cause of variability. Temporal changes in metal concentrations appear to be caused, in the case of Ni and Zn, by changes in atmospheric inputs, driven by a recent increase in the load of events over the Mediterranean. A comparison of the EF_{crustal} calculated for atmospheric aerosols collected over the W Mediterranean Sea and for the seagrass rhizomes reveals an anthropogenic influence for some metals (i.e., Ni, Pb, Cu,

Zn and Cd). Atmospheric inputs appear to be the dominant source of Fe to these seagrass meadows, which are strongly Fe-limited, in agreement with the observation that nitrogen in the tissues of these *Posidonia oceanica* meadows is also predominantly of atmospheric origin [Papadimitriou et al., 2005]. These observations evidence on the importance of atmospheric inputs for the functioning and health of seagrass meadows around the Mediterranean Sea. Moreover, our results clearly indicate that metal concentrations in *P. oceanica* provide a convenient record of metal changes in the environment, enhancing the value of this plant as an indicator of the past and present environmental conditions in the coastal Mediterranean Sea.

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References

- Ancora, S., N. Bianchi, A. Butini, M. C. Buia, M. C. Gambi, and C. Leonzio (2004), *Posidonia oceanica* as a biomonitor of trace elements in the Gulf of Naples: Temporal trends by lepidochronology, *Environ. Toxicol. Chem.*, 23(5), 1093–1099, doi:10.1897/02-590.
- Barker, A. V., and D. J. Pilbeam (2006), *Handbook of Plant Nutrition*, 613 pp., CRC Press, Boca Raton, Fla.
- Baroli, M., A. Christin, A. Cosse, G. De Falco, V. Gazal, and G. Pergent-Martini (2001), Concentrations of trace metals (Cd, Cu, Fe, Pb) in *Posidonia oceanica* seagrass of Liscia Bay, Sardinia (Italy), in *Mediterranean Ecosystems: Structures and Processes*, edited by F. M. Faranda, L. Guglielmo, and G. Spezie, Springer, New York.
- Bethoux, J. P., and G. Copin-Montégut (1986), Biological fixation of atmospheric nitrogen in the Mediterranean Sea, *Limnol. Oceanogr.*, 31, 1353–1358.
- Calmet, D., C. F. Boudouresque, and A. Meinesz (1988), Memorization of nuclear atmospheric tests by rhizomes and scales of the Mediterranean seagrass *Posidonia oceanica* (Linnaeus) Delile, *Aquat. Bot.*, 30(4), 279–294, doi:10.1016/0304-3770(88)90061-7.
- Chester, R., M. Nimmo, and M. R. Preston (1999), The trace metal chemistry of atmospheric dry deposition samples collected at Cap Ferrat: A coastal site in the western Mediterranean, *Mar. Chem.*, 68, 15–30, doi:10.1016/S0304-4203(99)00062-6.
- Draxler, R. R., and G. D. Rolph (2003), HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model, NOAA Air Resour. Lab., Silver Spring, Md. (Available at <http://www.arl.noaa.gov/ready/hysplit4.html>).
- Duarte, C. M., et al. (1994), Reconstruction of seagrass dynamics: Age determinations and associated tools for the seagrass ecologist, *Mar. Ecol. Prog. Ser.*, 107, 195–209, doi:10.3354/meps107195.
- Duarte, C. M., M. Merino, and M. Gallegos (1995), Evidence of iron deficiency in seagrass growing above carbonate sediments, *Limnol. Oceanogr.*, 40(95), 1153–1158.
- Duce, R. A., G. L. Hoffman, and W. H. Zoller (1975), Atmospheric trace metals at remote Northern and Southern Hemisphere sites: Pollution or natural?, *Science*, 187, 59–61, doi:10.1126/science.187.4171.59.
- Fourqurean, J. W., N. Marbà, C. M. Duarte, E. Diaz-Almela, and S. Ruiz-Halpern (2007), Spatial and temporal variation in the elemental and stable isotopic content of the seagrasses *Posidonia oceanica* and *Cymodocea nodosa* from the Illes Balears, Spain, *Mar. Biol. Berlin*, 151, 219–232, doi:10.1007/s00227-006-0473-3.
- Frausto da Silva, J. J. R., and R. J. P. Williams (1991), *The Biological Chemistry of the Elements—The Inorganic Chemistry of Life*, Clarendon, Oxford, U. K.
- Guerzoni, S., and E. Molinaroli (2005), Input of various chemicals transported by Saharan dust and depositing at the sea surface in the Mediterranean Sea, in *The Handbook of Environmental Chemistry*, part 5K, pp. 237–268, Springer, Berlin.

- Guerzoni, S., et al. (1999), The role of atmospheric deposition in the biogeochemistry of the Mediterranean Sea, *Prog. Oceanogr.*, **44**, 147–190, doi:10.1016/S0079-6611(99)00024-5.
- Guieu, C., R. Chester, M. Nimmo, J.-M. Martin, S. Guerzoni, E. Nicolas, J. Mateu, and S. Keyse (1997), Atmospheric input of dissolved and particulate metals to the northwestern Mediterranean, *Deep Sea Res., Part II*, **44**, 655–674, doi:10.1016/S0967-0645(97)88508-6.
- Guieu, C., M.-D. Loÿe-Pilot, C. Ridame, and C. Thomas (2002), Chemical characterization of the Saharan dust end-member: Some biogeochemical implications for the western Mediterranean Sea, *J. Geophys. Res.*, **107** (D15), 4258, doi:10.1029/2001JD000582.
- Holmer, M., C. M. Duarte, and N. Marbà (2005), Iron additions reduce sulfate reduction rates and improve seagrass growth on organic-enriched carbonate sediments, *Ecosystems*, **8**, 721–730, doi:10.1007/s10021-003-0180-6.
- Howe, P. D., and S. Dobson (2002), Silver and silver compounds: Environmental aspects, in *Concise International Chemical Assessment Document, Rep. 44*, Int. Programme on Chem. Safety, Geneva. (Available at <http://www.inchem.org/documents/cicads/cicads/cicad44.htm>)
- Ikegawa, M., M. Kimura, K. Honda, I. Akabane, K. Makita, H. Motoyama, Y. Fujii, and Y. Itokawa (1999), Geographical variations of major and trace elements in east Antarctica, *Atmos. Environ.*, **33**, 1457–1467, doi:10.1016/S1352-2310(98)00243-X.
- Lafabrie, C., G. Pergent, R. Kantin, C. Pergent-Martini, and J.-L. Gonzalez (2007), Trace metals assessment in water, sediment, mussel and seagrass species—Validation of the use of *Posidonia oceanica* as a metal biomonitor, *Chemosphere*, **68**, 2033–2039, doi:10.1016/j.chemosphere.2007.02.039.
- Lafabrie, C., G. Pergent, and C. Pergent-Martini (2009), Utilization of the seagrass *Posidonia oceanica* to evaluate the spatial dispersion of metal contamination, *Sci. Total Environ.*, **407**, 2440–2446, doi:10.1016/j.scitotenv.2008.11.001.
- Marbà, N., and C. M. Duarte (1997), Interannual changes in seagrass (*Posidonia oceanica*) growth and environmental change in the Spanish Mediterranean littoral zone, *Limnol. Oceanogr.*, **42**(5), 800–810.
- Marbà, N., C. M. Duarte, M. Holmer, R. Martínez, G. Basterretxea, A. Orfila, A. Jordi, and J. Tintoré (2002), Assessing the effectiveness of protection on *Posidonia oceanica* populations in the Cabrera National Park (Spain), *Environ. Conserv.*, **29**, 509–518, doi:10.1017/S037689290200036X.
- Marbà, N., M. L. Calleja, C. M. Duarte, E. Alvarez, E. Diaz-Almela, and M. Holmer (2007), Iron additions reduce sulfide intrusion and reverse seagrass (*Posidonia oceanica*) decline in carbonate sediments, *Ecosystems*, **10**, 745–756, doi:10.1007/s10021-007-9053-8.
- Migon, C. (1993), Riverine and atmospheric inputs of heavy metals to the Ligurian Sea, *Sci. Total Environ.*, **138**, 289–299, doi:10.1016/0048-9697(93)90422-3.
- Migon, C. (2005), Trace metals in the Mediterranean Sea, in *The Handbook of Environmental Chemistry*, part 5K, Springer, Berlin.
- Migon, C., V. Sandroni, J.-C. Marty, B. Gasser, and J.-C. Miquel (2002), Transfer of atmospheric matter through the euphotic layer in the north-western Mediterranean: Seasonal pattern and driven forces, *Deep Sea Res., Part II*, **49**, 2125–2141, doi:10.1016/S0967-0645(02)00031-0.
- Morel, F. M. M., and N. M. Price (2003), The biogeochemical cycles of trace metals in the oceans, *Science*, **300**, 944–947, doi:10.1126/science.1083545.
- Olgunoglu, M. P., and S. Polat (2008), Trace metals in marine macroalgae samples from the Iskenderun Bay, Turkey, *Fresen Environ. Bull.*, **17**, 589–595.
- Page, V. U., and R. S. Feller (2005), Selective transport of zinc, manganese, nickel, cobalt and cadmium in the root system and transfer to the leaves in young wheat plants, *Ann. Bot.*, **96**, 425–434, doi:10.1093/aob/mci189.
- Papadimitriou, S., H. Kennedy, D. P. Kennedy, C. M. Duarte, and N. Marbà (2005), Sources of organic matter in seagrass-colonized sediments: A stable isotope study of the silt and clay fraction from *Posidonia oceanica* meadows in the western Mediterranean, *Org. Geochem.*, **36**, 949–961, doi:10.1016/j.orggeochem.2004.12.002.
- Patterson, J. W., R. A. Minear, E. Gasca, and C. Petropoulou (1998), Industrial discharges of metals to water, in *Metals in Surface Waters*, edited by H. E. Allen, A. W. Garrison, and G. W. Luther III, pp. 37–65, Ann Arbor Press, Chelsea, Mich.
- Pekney, N. J., and C. I. Davidson (2005), Determination of trace elements in ambient aerosol samples, *Anal. Chim. Acta*, **540**, 269–277, doi:10.1016/j.aca.2005.03.065.
- Pergent-Martini, C. (1998), *Posidonia oceanica*: A biological indicator of past and present mercury contamination, *Mar. Environ. Res.*, **45**(2), 101, doi:10.1016/S0141-1136(97)00023-8.
- Peris, M., L. Recatalá, C. Micó, R. Sánchez, and J. Sánchez (2008), Increasing the knowledge of heavy metal contents and sources in agricultural soils of the European Mediterranean region, *Water Air Soil Pollut.*, **192**, 25–37, doi:10.1007/s11270-008-9631-1.
- Quereda-Sala, J., J. Olcina-Cantos, and E. Montón-Chiva (1996), Red dust rain within the Spanish Mediterranean area, *Clim. Change*, **32**, 215–228, doi:10.1007/BF00143711.
- Ridame, C., and C. Guieu (2002), Saharan input of phosphate to the oligotrophic water of the open western Mediterranean Sea, *Limnol. Oceanogr.*, **47**(3), 856–869.
- Roméo, M., M. Gnassia-Barelli, T. Juhel, and A. Meisnesz (1995), Memorisation of heavy metals by scales of the seagrass *Posidonia oceanica*, collected in the NW Mediterranean, *Mar. Ecol. Prog. Ser.*, **120**, 211–218, doi:10.3354/meps120211.
- Sañudo-Wilhelmy, S. A., and A. R. Flegal (1992), Anthropogenic silver in the southern California bight: A new tracer of sewage in coastal waters, *Environ. Sci. Technol.*, **26**, 2147–2151, doi:10.1021/es00035a012.
- Taylor, S. R. (1964), Abundance of chemical elements in the continental crust: A new table, *Geochim. Cosmochim. Acta*, **28**, 1273–1285, doi:10.1016/0016-7037(64)90129-2.
- Torres, O., P. K. Bhartia, J. R. Herman, and Z. Ahmad (1998), Derivation of aerosol properties from satellite measurements of backscattered ultraviolet radiation: Theoretical basis, *J. Geophys. Res.*, **103**(D14), 17,099–17,110, doi:10.1029/98JD00900.
- Torres, O., P. K. Bhartia, J. R. Herman, A. Sinyuk, and B. Holben (2002), A long term record of aerosol optical thickness from TOMS observations and comparison to AERONET measurements, *J. Atmos. Sci.*, **59**, 398–413, doi:10.1175/1520-0469(2002)059<0398:ALTROA>2.0.CO;2.
- Tovar-Sánchez, A., S. A. Sañudo-Wilhelm, and A. R. Flegal (2004), Temporal and spatial variations in the biogeochemical cycling of cobalt in two urban estuaries: Hudson River Estuary and San Francisco Bay, *Estuarine Coastal Shelf Sci.*, **60**, 717–728, doi:10.1016/j.ecss.2004.03.010.
- Tranchina, L., M. Brai, F. D'Agostino, A. Bartolotta, and G. Rizzo (2005a), Trace metal in “*Posidonia oceanica*” seagrass from south-eastern Sicily, *Chem. Ecol.*, **21**(2), 109–118, doi:10.1080/02757540500092990.
- Tranchina, L., S. Muccichè, A. Bartolotta, M. Brai, and R. N. Mantegna (2005b), *Posidonia oceanica* as a historical monitor device of lead concentration in marine environment, *Environ. Sci. Technol.*, **39**, 3006–3012, doi:10.1021/es048870u.
- Wang, J., C. P. Huang, and D. Pirestani (2003), Interactions of silver with wastewater constituents, *Water Res.*, **37**, 4444–4452, doi:10.1016/S0043-1354(03)00407-X.

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