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**Zooplankton from a North Western Mediterranean area as a model of metal transfer in a marine environment**

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**Table 1****Metals concentrations in marine water (mean values of the three sampling sites,  $\mu\text{g L}^{-1}$ )**

<b>0-3 m water depth</b>				
	<b>Spring</b>	<b>Summer</b>	<b>Autumn</b>	<b>Winter</b>
<b>Mn</b>	0.62	0.61	0.41	1.85
<b>Fe</b>	1.21	2.37	1.27	20.26
<b>Al</b>	1.70	1.50	1.65	1.80
<b>Co</b>	2.10	1.45	0.02	0.03
<b>Ni</b>	6.20	10.60	0.26	0.35
<b>Cu</b>	0.36	1.37	0.39	0.34
<b>Zn</b>	4.18	11.43	3.69	2.26
<b>Cd</b>	0.02	0.02	0.02	0.02
<b>Pb</b>	0.49	1.45	2.30	0.80

<b>50 m water depth</b>				
	<b>spring</b>	<b>summer</b>	<b>autumn</b>	<b>winter</b>
<b>Mn</b>	0.60	0.58	0.63	0.65
<b>Fe</b>	1.07	1.60	2.15	4.02
<b>Al</b>	1.25	1.30	2.00	2.61
<b>Co</b>	1.60	1.50	0.02	0.02
<b>Ni</b>	8.70	11.20	0.39	0.28
<b>Cu</b>	0.68	0.93	0.70	0.22
<b>Zn</b>	3.27	8.33	4.70	2.15
<b>Cd</b>	0.02	0.02	0.04	0.02
<b>Pb</b>	0.26	1.11	2.33	0.16

<b>100 m water depth</b>				
	<b>spring</b>	<b>summer</b>	<b>autumn</b>	<b>winter</b>
<b>Mn</b>	0.46	0.35	0.45	0.49
<b>Fe</b>	0.78	0.75	1.07	0.72
<b>Al</b>	1.30	1.05	2.10	2.71
<b>Co</b>	1.10	1.65	0.02	0.02
<b>Ni</b>	9.10	10.40	0.27	0.28
<b>Cu</b>	1.54	0.23	0.34	0.41
<b>Zn</b>	3.30	3.52	0.56	3.12
<b>Cd</b>	0.02	0.02	0.03	0.02
<b>Pb</b>	1.34	2.03	0.50	1.20

**Table 2**  
**Metals concentrations in marine zooplankton (mg Kg<sup>-1</sup>)**

<b>0-3 m water depth</b>				
	<b>Spring</b>	<b>Summer</b>	<b>Autumn</b>	<b>Winter</b>
<b>Al</b>	81.00	62.30	122.79	174.14
<b>As</b>	0.23	0.26	0.41	0.75
<b>Be</b>	0.01	0.01	0.01	0.04
<b>Cd</b>	0.20	0.40	0.41	0.08
<b>Co</b>	0.06	0.08	0.21	0.13
<b>Cr</b>	0.83	0.39	1.61	1.50
<b>Cu</b>	1.90	3.88	14.31	3.72
<b>Fe</b>	109.15	91.03	138.45	354.42
<b>Mn</b>	1.22	1.27	3.26	2.57
<b>Mo</b>	0.15	0.27	0.18	0.11
<b>Ni</b>	1.10	0.88	1.76	1.10
<b>Pb</b>	1.27	1.42	3.46	1.01
<b>Sb</b>	0.10	0.08	0.11	0.02
<b>Se</b>	0.23	0.52	0.32	0.22
<b>Sn</b>	0.07	0.05	0.10	0.24
<b>V</b>	0.31	0.25	0.73	3.06
<b>Zn</b>	22.60	15.68	25.52	11.74

<b>50 m water depth</b>				
<b>Al</b>	440.38	92.91	445.02	621.68
<b>As</b>	0.46	0.14	0.55	0.39
<b>Be</b>	0.02	0.01	0.03	0.01
<b>Cd</b>	0.08	0.05	0.19	0.07
<b>Co</b>	0.23	0.10	0.31	0.08
<b>Cr</b>	7.25	3.23	4.99	2.10
<b>Cu</b>	4.64	1.86	39.7	2.75
<b>Fe</b>	539.44	146.20	659.86	166.24
<b>Mn</b>	5.55	1.96	23.00	2.20
<b>Mo</b>	0.32	0.07	0.45	0.15

<b>Ni</b>	5.48	2.09	3.72	0.85
<b>Pb</b>	12.38	2.60	10.62	4.58
<b>Sb</b>	0.48	0.23	0.41	0.07
<b>Se</b>	0.18	0.12	0.25	0.18
<b>Sn</b>	0.42	0.07	0.86	0.29
<b>V</b>	0.89	0.26	1.28	0.79
<b>Zn</b>	132.33	16.14	51.36	24.85

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**100 m water depth**

<b>Al</b>	1738.23	255.61	648.8	452.66
<b>As</b>	0.65	0.32	0.78	0.40
<b>Be</b>	0.03	0.01	0.04	0.02
<b>Cd</b>	0.16	0.06	0.16	0.08
<b>Co</b>	0.03	0.02	0.38	0.14
<b>Cr</b>	2.87	1.30	3.33	1.19
<b>Cu</b>	3.72	5.91	4.72	1.46
<b>Fe</b>	1741.76	453.45	675.7	320.85
<b>Mn</b>	8.82	5.46	29.85	4.43
<b>Mo</b>	0.16	0.06	0.22	0.05
<b>Ni</b>	2.04	1.23	2.75	1.03
<b>Pb</b>	10.92	10.70	12.02	2.37
<b>Sb</b>	0.59	0.18	0.39	0.06
<b>Se</b>	0.24	0.15	0.25	0.13
<b>Sn</b>	0.28	0.24	0.53	0.07
<b>V</b>	1.18	0.50	1.73	1.11
<b>Zn</b>	79.85	27.43	32.78	15.47

---

**Table 3**  
**Bioaccumulation factors (BAFs) for marine zooplankton**

<b>0-3 m water depth</b>				
	<b>spring</b>	<b>summer</b>	<b>autumn</b>	<b>winter</b>
<b>Mn</b>	1964	2069	7951	1389
<b>Fe</b>	90505	38389	109015	17493
<b>Cu</b>	5349	2837	36692	10941
<b>Zn</b>	5401	1372	6915	5194
<b>Al</b>	47	41	74	96
<b>Ni</b>	177	83	6769	3142
<b>Co</b>	28	56	10500	4333
<b>Pb</b>	2615	978	1506	1257
<b>Cd</b>	10050	22222	17521	3921

<b>50 m water depth</b>				
<b>Mn</b>	9228	3382	36311	3373
<b>Fe</b>	502833	91209	307483	41373
<b>Cu</b>	6870	2002	57105	12298
<b>Zn</b>	40467	1696	10927	11547
<b>Al</b>	352	71	222	238
<b>Ni</b>	629	186	9627	3048
<b>Co</b>	143	66	11666	4210
<b>Cd</b>	4545	3067	4947	3153
<b>Pb</b>	47836	2345	4550	29134

<b>100 m water depth</b>				
<b>Mn</b>	190004	15762	66718	9011
<b>Fe</b>	2245114	601153	629847	448239
<b>Cu</b>	2416	25518	13898	3604
<b>Zn</b>	24226	7799	58327	4951
<b>Al</b>	1337	243	308	167
<b>Ni</b>	224	118	10315	3642
<b>Co</b>	272	147	21839	7216
<b>Cd</b>	7920	3669	6400	4000
<b>Pb</b>	8168	5282	23811	1975

**Table S1**  
**Quantification limit (mg Kg<sup>-1</sup>), reference material values (oyster tissues)**  
**and percentages of recovery.**

<b>Element</b>	<b>LOQ</b>	<b>SRM 1566b</b>	<b>% recovery</b>
Al	0.010	197.2 ± 6.0	82
As	0.010	7.650.65±	103
Be	0.010	-	-
Cd	0.010	2.48±0.08	104
Ce	0.010	-	-
Co	0.010	0.371±0.009	99
Cu	0.010	71.6±1.6	105
Fe	0.010	205.8±6.8	104
Hg	0.034	0.0132±0.0013	102
La	0.010	-	-
Mn	0.010	18.5±0.2	95
Ni	0.010	1.04±0.09	98
Pb	0.010	0.308±0.009	98
Sb	0.010	-	-
Se	0.010	2.06± 0.15	117
V	0.010	0.0577 ± 0.023	102
Zn	0.010	1424±46	105

- These elements were not present in the certified material

1 **Zooplankton from a North Western Mediterranean Area as a model of metal transfer in a**  
2 **marine environment.**

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10

11 **Abstract**

12 We monitored the concentration of 21 trace elements in zooplankton samples collected in a  
13 Northwestern Mediterranean coastal ecosystem (Italy). In the last 20 years, this area has been the  
14 target of important anthropogenic impacts including maritime traffic and substantial industrial  
15 activities. Zooplankton contributes to the transfer of trace metals to higher trophic levels and  
16 constitute one of the recommended groups for the baseline studies of metals in the marine  
17 environment. The essential trace elements (As, Cu, Mn, Zn, Fe, Mo, Co, Cr, Se, Ni) and the  
18 nonessential trace elements (Al, Be, Cd, Pb, Sb, Sn, V) were generally found at concentrations of  
19 no concern in the analyzed zooplankton samples, but showed important variations between seasons  
20 and different water depths. The zooplankton was found to be a significant accumulator of metals,  
21 and bioaccumulation factors were in the range of 28 (Co) to 109015 (Fe) in marine surficial waters,  
22 with increasing values at increasing water depth. Zooplankton is a useful bioindicator to assess  
23 metal contamination and its impact in the marine environment.

24

25

26 **Keywords:** trace elements, zooplankton, Mediterranean Sea, bioaccumulation



## 27 **Introduction**

28 The Mediterranean Sea is characterized by a rich biodiversity, but the presence of chemical and  
29 mining industries in the majority of coastal areas threatens this ecosystem by producing significant  
30 amounts of chemical waste, of which trace metals constitute an important part (EEA, 2006;  
31 Lafaibre, 2008). Some of these trace metals, such as copper (Cu), zinc (Zn), manganese (Mn), iron  
32 (Fe), and chromium (Cr) are essential for the metabolism of the organisms while others, like  
33 cadmium (Cd), lead (Pb), and mercury (Hg), are nonessential. All metals, essential or not, are toxic  
34 above a threshold bioavailability and can be considered as serious pollutants of aquatic  
35 environments because of their toxicity, persistence, and tendency to concentrate in organisms (Ikem  
36 and Egiebor, 2005).

37 Plankton is a determinant for metal transfer in marine food webs and trace metals are included in  
38 plankton biochemical cycles (Whitfield, 2001). Zooplankton is particularly critical to the  
39 functioning of ocean food webs because of their sheer abundance and vital ecosystem roles.  
40 Zooplankton is mainly composed of copepods, the most abundant animal taxon on the Earth  
41 (Schminke 2007); copepods are the major grazers in ocean food webs, providing the principal  
42 pathway for energy from primary producers to consumers at higher trophic levels (Richardson  
43 2008; Fernández-Severini *et al.*, 2013). Additionally, zooplankton play an important role in the  
44 biogeochemical cycling of trace metals in marine ecosystems. In fact, in surface pelagic waters,  
45 plankton can strongly affect the vertical transport of elements; biogenic particle flux accounts for a  
46 lot of the vertical flux and hence controls the residence times of particle-reactive elements in the sea  
47 (Fisher *et al.*, 1991).

48 Metals may be adsorbed onto organic films or colloidal materials at the particle surface or by  
49 crossing the plankton cell (Fisher and Reinfelder, 1995). Adsorption of metals to plankton varies  
50 greatly in the first trophic levels. In general, plankton with higher surface: volume ratio has higher  
51 concentration factors, especially for non-reactive particles. Once aggregated or incorporated into

52 plankton, elements may be transferred along the web chain and transformed by successive  
53 organisms, either enhancing or alleviating their toxicity (Watras and Bloom, 1992).

54 Metals that are egested by sinking fecal pellets from zooplankton are exported out of the surface  
55 waters, enriching the deep-water dissolved-metal pool through re-mineralization and release (Fisher  
56 *et al.* 1991). Cellular metals regenerated in the dissolved state during grazing may be recycled many  
57 times and re-utilized by the phytoplankton community. In assessing environmental quality with  
58 respect to trace elements in seawater, the bioavailable fraction is of major importance as toxicity is  
59 dependent on the bioavailable exposure concentration (Kahle and Zauke, 2003). This bioavailable  
60 fraction can only be assessed by determining the amount of metals incorporated into organisms,  
61 which is the main goal in biomonitoring (Rainbow, 1993).

62 Because of their wide geographic distribution, trophic position, rapid turnover, huge biomass and  
63 high capacity to accumulate trace metals, zooplanktonic organisms can be used as biomonitors for  
64 trace metals in marine environments (Barka *et al.*, 2001; Kahle and Zauke, 2003; Fang *et al.*, 2006;  
65 Hsiao *et al.*, 2011).

66 Coastal areas receive large amounts of contaminants introduced by domestic, industrial and  
67 agricultural activities, either directly, via rivers or through atmospheric deposition (Usero *et al.*,  
68 2005). Coastal marine ecosystems are important for the fate of contaminants and are therefore worth  
69 studying.

70 Data regarding metal concentrations in zooplankton communities of Mediterranean coastal  
71 environments are very scarce and usually report just a few metals, for example, rare earth elements  
72 (Gulf of Lion, France; Strady *et al.*, 2015); Cu, Pb, and Cd (Toulon Bay, France; Rossi and Jamet,  
73 2008); Zn, Cu, and Cd (estuary of Var, France; Hardstedt–Romeo and Laumond, 1980). No  
74 previous studies have analyzed the concentrations of this many trace elements, reported here, in  
75 zooplankton from a Northwestern Mediterranean area, specifically from an Italian coastal region.

76 The study area is a highly productive coastal region characterized by remarkable commercial  
77 maritime traffic and several industrial plants. Moreover, in the last twenty years, due to its peculiar  
78 geomorphology, the area has been the target of important anthropogenic impacts, such as the  
79 discharges of Leghorn harbor mud (1,873,000 m<sup>3</sup>) contaminated by Cu, Zn and Pb (ARPAT, 2006).  
80 Up until the 1990s, the chloralkali plant of Solvay (Rosignano) built in 1918, discharged about 8000  
81 m<sup>3</sup> h<sup>-1</sup> of industrial effluents directly into the sea (Balestri *et al.*, 2004). Contamination by Hg has  
82 been reported in areas close to this plant (Balestri *et al.*, 2004; Lafabrie *et al.*, 2007a, b). The Arno  
83 River drains a wide inland area, transporting Al, Fe, Hg and other trace elements at high  
84 concentrations towards the sea (Cortecci *et al.*, 2009). In addition, three coastal towns (Pisa,  
85 Leghorn and Cecina), discharge partially treated effluent into the rivers (Renzi *et al.*, 2009).  
86 Furthermore, this coastal area also experiences summer tourism, which leads to a substantial  
87 increase in inhabitants. Therefore, municipal wastewater treatment plants show effluents  
88 characterized by worsened water quality and an increase in the nutrient concentration of marine  
89 water (Renzi *et al.*, 2009).

90 The main objectives of the present study were:

- 91 i) to analyze the concentrations of aluminum (Al), antimony (Sb), arsenic (As), beryllium  
92 (Be), cadmium (Cd), cerium (Ce), cobalt (Co), chromium (Cr), iron (Fe), manganese  
93 (Mn), mercury (Hg), molybdenum (Mo), lanthanum nickel (Ni), lead (Pb), copper (Cu),  
94 selenium (Se), tin (Sn), thallium (Tl), vanadium (V) and zinc (Zn) in zooplankton  
95 samples collected in all four seasons at three different depths.
- 96 ii) to verify if this marine ecosystem, which was heavily influenced in the past by  
97 anthropogenic activities, is still compromised by the presence of high concentrations of  
98 metals
- 99 iii) to evaluate the relevance of zooplankton (and in particular of copepods) as a metal bio-  
100 indicator.

101

## 102 **2. Materials and methods**

### 103 *2.1. Sampling area*

104 The sampling area was located offshore from the Italian coast, at the border between the Northern  
105 Tyrrhenian Sea and the Ligurian Sea (Figure 1). Station 1 (43°29'40" N – 10°01'45" E), Station 2  
106 (43°28'10" N, 10°01'55" E) and Station 3 (43°27'10" N, 10°03'00" E) were located at 12.5  
107 nautical miles off the coast, over the continental shelf towards the strongly impacted neritic zone  
108 close to Solvay-Rosignano. The study area was in fact in the Ligurian Sea, within the “Cetacean  
109 Sanctuary” where the number of cetaceans is at least twice as high as anywhere else in the  
110 Mediterranean (Ambrose, 1999). The Ligurian sea is situated at the north east border of the Western  
111 Mediterranean and is connected to the southern basin (Tyrrhenian Sea) across the Corsica Channel.  
112 The major large-scale feature of the water dynamic of the Ligurian Sea is a cyclonic circulation that  
113 is active all year round, but more intense in winter than in summer, involving both deep and surface  
114 layers (Aliani *et al.*, 2003). Climatic forcing can greatly change the intensity of fluxes, but the  
115 general pattern can be considered permanent (Molinero *et al.*, 2005a, b). Southern waters flowing  
116 towards the Ligurian sea occur by means of two main currents running along each side of Northern  
117 Corsica. The West Corsica Current (WCC) runs along the western side of Corsica while the warm  
118 and salty Tyrrhenian current (TC) goes through the Corsica Channel (Artale *et al.*, 1994) (Figure  
119 S1). The two waters merge at the north of Corsica and flow together along the Ligurian coast  
120 towards the Gulf of Lions. The Tyrrhenian current permits warm species from the south to reach the  
121 Ligurian basin, passing through the Corsica Channel. The investigated sector is characterized by the  
122 large extension of the continental shelf and limited depth (100 m), even at remarkable distances  
123 from the coast (18 miles) (Chiocci and La Monica, 1996).

### 124 *2.2. Sample collection*

125 Zooplankton samples were collected during four expeditions in May, August, and November 2014  
126 and February 2015. The same neritic areas were investigated across all seasons. The three sampling  
127 stations were aligned along a transect parallel to the coast (12.5 NM offshore), as shown in Figure  
128 1. Stations 1 – 3 (Figure 1) were located on the continental shelf above bottom depths ranging from  
129 109 to 114 m. The entire water column was sampled by three hauls: one surface haul, and two  
130 vertical hauls (5 – 50 m, 50 – 100 m depth, respectively); zooplankton samples were taken with a  
131 WP-2 standard net, with a mesh size of 300  $\mu\text{m}$  and a diameter of 60 cm. The horizontal sampling  
132 time was approximately 15 min at a vessel cruising speed of 2 knots, while during the vertical  
133 sampling the net was hauled at  $0.7 \text{ m s}^{-1}$ .

134 Each net was fitted with a flow meter (KC Denmark model 23.090) to measure the volume of water  
135 filtered, which ranged from 14 to 422  $\text{m}^3$ . The net hauls were consistently carried out at night to  
136 minimize variability due to vertical migration. One whole sample of each net was divided into two  
137 aliquots using a Folsom splitter immediately after sampling; one aliquot was used for estimating  
138 biomass and analyzing zooplankton composition, and the second aliquot was immediately frozen at  
139  $-20 \text{ }^\circ\text{C}$  onboard for subsequent analysis of for trace element concentrations (Fang *et al.*, 2014;  
140 Fernandez de Puelles *et al.*, 2014). Samples used for estimating biomass (mg of dry weight  $\text{m}^{-3}$ )  
141 were collected on pre-weighed glass fiber filters and heated at  $60 \text{ }^\circ\text{C}$  for 24-36 h (Lovegrove, 1966).  
142 Samples for composition analysis were fixed in 4% neutralized formaldehyde buffered with borax  
143 and kept in the dark (Boltovskoy, 1981). Subsamples of mesozooplankton were obtained using a  
144 Folsom Plankton Splitter, and at least two subsamples were counted completely to determine the  
145 abundance, presented as  $\text{ind. m}^{-3}$ , of the main zooplankton groups (Boltovskoy, 1981). Considering  
146 the quail-quantitative importance of copepods, the adults were identified to species level and  
147 juvenile stages to genus level, wherever possible (Vives and Shmeleva, 2007, 2010). In addition to  
148 the entire Mediterranean Sea, in the Ligurian and Tyrrhenian Seas, the bulk of copepod populations  
149 are concentrated in the epipelagic layer, up to a depth of 100 m, with abundances decreasing sharply

150 thereafter (Mazzocchi *et al.*, 2007). Moreover, some aspects of biodiversity were evaluated by using  
151 the Shannon-Wiener index ( $H'$ ) (Shannon and Weaver, 1963), calculated on abundance data of  
152 adult copepods at the four sampling seasons.

153 Seawater samples for total dissolved trace metal analysis were collected at depths of 1, 50 and 100  
154 m using 5 L Niskin bottles and stored in a cool box until subjected to filtration. All samples were  
155 kept refrigerated before analysis.

### 156 *2.3. Detection of trace elements*

#### 157 *2.3.1 Zooplankton*

158 The zooplankton samples were placed in a small nylon sieve and thoroughly rinsed with Milli-Q  
159 water to remove salts. Samples were divided into two sub-samples, one for Hg quantification with a  
160 Direct Mercury Analyzer (DMA-80 Analyzer from Milestone, Shelton, CT, USA) and the other one  
161 for detecting all the other metals by Inductively Coupled Plasma - Mass Spectrometry (ICP-MS  
162 Xseries II, Thermo Scientific, Bremen, Germany). The Direct Mercury Analyzer performs thermal  
163 decomposition, catalytic reduction, amalgamation, desorption and atomic absorption spectroscopy  
164 without having to pre-treat the samples. Between 0.05 g and 0.1 g of samples were directly weighed  
165 on graphite shuttles and processed for Hg content.

166 Determination of Al, Sb, As, Be, Cd, Ce, Co, Cr, Cu, Fe, Mn, Mo, La, Pb, Ni, Se, Sn, Tl, V and Zn,  
167 was performed after wet digestion using acids and oxidants ( $\text{HNO}_3$  and  $\text{H}_2\text{O}_2$ ) of the highest quality  
168 grade (Suprapure). In this case, between 1.5 and 2.0 g of samples were subjected to microwave  
169 digestion (microwave oven ETHOS 1 from Milestone, Shelton, CT, USA) with 7 mL of  $\text{HNO}_3$   
170 (70% v/v) and 1.5 mL of  $\text{H}_2\text{O}_2$  (30% v/v). Ultrapure water was added to samples to reach a final  
171 weight of 50 g (Arium611VF system from Sartorius Stedim Italy S.p.A., Antella - Bagno a Ripoli,  
172 FI, Italy). Multi-elemental determination was performed by ICP-MS after daily optimization of  
173 instrumental parameters and using an external standard calibration curve; Rhodium and Germanium  
174 were used as internal standards. Analytical performances were verified by processing Certified

175 Reference Materials (Oyster Tissue -SRM 1566b from the National Institute of Standard and  
176 Technology), along with blank reagents in each analytical session. The limit of quantification  
177 (LOQ) for each element, the reference material values and the percentages of recovery obtained are  
178 shown in Table S1.

### 179 2.3.2 Seawaters

180 The direct introduction of seawater to a Mass Spectrometer can cause a number of serious  
181 problems. The high content of dissolved solids (approximately 3.5%) in seawater can suppress  
182 analyte signals due to inter-element interferences, and clog the interface sampler and skimmer  
183 cones. Therefore, a chelating polymer resin, the SPR-IDA Reagent (Suspended Particulate Reagent  
184 – Iminodiacetate, by Cetac Technologies, Omaha, USA) was used for pre concentration/ matrix  
185 elimination of seawater. The reagent consists of 10 micron-diameter polymer beads derivatized with  
186 the chelating agent iminodiacetate. A 15 mL sample of seawater was directly added to a pre-cleaned  
187 15 mL volume polypropylene centrifuge tube. A 100  $\mu\text{L}$  aliquot of a 10% suspension of SPR-IDA  
188 reagent beads was then pipetted directly into the sample. Tubes were covered with parafilm and the  
189 contents were mixed thoroughly. Samples were then spiked with 0.5  $\mu\text{g/L}$  yttrium, which functions  
190 as an internal standard, helping to correct for any volume differences in the blanks, samples, and  
191 spiked samples. High-purity ammonium hydroxide ( $\text{NH}_4\text{OH}$ , 29%) was added in two steps (25  $\mu\text{L}$  +  
192 20  $\mu\text{L}$ ) to adjust the pH to approximately 8. The SPR-IDA beads were then allowed to settle for  
193 approximately 1 hour. Samples were then placed in a centrifuge and spun at 2000 rpm for 10 min.  
194 The supernatant liquid was then carefully poured off to minimize any loss of beads. The beads were  
195 mostly compacted at the bottom of the tube. A solution of deionized water, adjusted to pH 8 with  
196 high purity  $\text{NH}_4\text{OH}$ , was then added to the 15 mL mark of the sample tube and the contents were  
197 mixed. The beads were again allowed to settle, centrifuged, and the resulting supernatant liquid  
198 carefully poured off and discarded. A 0.5 mL aliquot of 7% v/v absolute high-purity nitric acid

199 (Suprapure) was then added to the bead residue to extract any bound metal ions. The extract was  
200 then diluted to 3 mL with deionized water and analyzed by ICP-MS. The following metals were  
201 then quantified in seawater: Al, Cd, Co, Cu, Fe, Mn, Ni, Pb, Zn.

#### 202 *2.4 Bioaccumulation factors (BAFs)*

203 The bioaccumulation factor (BAF) is the ratio of a chemical concentration in an organism to the  
204 concentration in water. BAFs were estimated for Al, Cd, Co, Cu, Fe, Mn, Ni, Pb, and Zn, the same  
205 elements that were quantified both in seawaters and in plankton.

206 All metal concentrations in seawater are reported in  $\mu\text{g L}^{-1}$ , while in zooplankton, the values are  
207 expressed in  $\text{mg kg}^{-1}$ . For estimation of BAFs, the metal levels in zooplankton were converted in  $\mu\text{g}$   
208  $\text{kg}^{-1}$ .

#### 209 *2.5 Merging data from the different stations*

210 Data were tested for normality and equality of variance. The mean zooplankton abundance and  
211 biomass from each sampling station at the same season were compared using the *Kruskal-Wallis*  
212 *test*, to determine if it was acceptable to combine these datasets. Statistical analyses were carried out  
213 using the R software, Version 3.1.2 (R Core Team, 2014),  $p < 0.05$  was considered as statistically  
214 significant.

215 There were no significant differences between the three stations for each season (*Kruskal-Wallis*  $X^2$   
216  $= 0.024$ ,  $df = 2$ ,  $p = 0.988$ ). Based on these estimates, it was decided that it was acceptable to merge  
217 the datasets from the three sampling stations (Figure 1), and thereby enable concise and  
218 comprehensible representations of the results.

### 219 **3. Results and discussion**

#### 220 *3.1. Zooplankton communities*

221 The zooplankton communities of the three sampling sites (Figure 1) showed very comparable  
222 compositions, so we presented their mean values (Figure 2) to facilitate data discussion.



223 The analyzed zooplankton presented the highest biomass value in winter (mean values over areas  
224  $19.1 \text{ mg m}^{-3}$ ), followed by autumn ( $16.2 \text{ mg m}^{-3}$ ), spring ( $4.6 \text{ mg m}^{-3}$ ) and summer ( $1.07 \text{ mg m}^{-3}$ ).  
225 Differences between seasons were evident for the most abundant groups of mesozooplankton, with  
226 copepods being the most abundant group (69% in spring, 56% in summer, 77% in autumn and 82%,  
227 in winter) (Figure 3), being indicative of the general pattern of zooplankton annual distribution. In  
228 addition, 14 zooplankton taxa were found but only 8 (>1%) were considered to be important in the  
229 mesozooplankton community. Cladocerans followed copepods in abundance (7% and 14%, in  
230 spring and summer, respectively). This group, along with thaliaceans showed similar abundances  
231 during both seasons. Misydacea/Euphausiacea were more abundant in autumn and winter (6% and  
232 9%, respectively) than in spring and summer, when they decreased drastically (to just 1%). Instead,  
233 the chaetognaths showed the highest values in autumn and spring (5% and 4%, respectively). Other  
234 groups, such as pteropods (5%) and siphonophores (4%) were more abundant in summer than in the  
235 cold seasons. Finally, meroplankton larvae, mainly represented by gastropoda and decapod larvae,  
236 were relatively abundant, but only during the summer (3%).

### 237 *3.2. Abundance and diversity of copepods*

238 More than 130 copepod species belonging to 29 families and 52 genera were recorded during the  
239 four surveys. The greatest number of species was found in spring (66), whereas the lowest number  
240 (50) was found in autumn. Richness species (d) and species diversity ( $H'$ ) indices (Figure 3a, b)  
241 showed similar spatial trends throughout the study area, with the exception of autumn, where d  
242 reaches the minimum value. The seasonal trend of diversity, calculated on the integrated water  
243 column at a depth of 5 – 100 m, showed the lowest Shannon-Wiener index values (range: 1.93-  
244 2.59) in February, corresponding to the maximum of abundance, and the highest values in summer  
245 (range: 3.056-3.063). The highest richness species was recorded during the summer (range: 8.098-  
246 8.514), in which there was the lowest copepod abundance (range: 6.319-7.319).

247 *Clausocalanus*, *Oithona* and *Acartia* were the most common genera found throughout the year  
248 (48%, 20%, and 13%, respectively). The abundance of copepods found at all stations during the  
249 February expedition ranged from 614 to 2361 ind./m<sup>3</sup>, and was significantly higher than during  
250 November (141.54 and 694.56 ind./m<sup>3</sup>)

251 In spring 2014, the genera *Clausocalanus* (mainly *Clausocalanus pergens* and *Clausocalanus*  
252 *arcuicornis*) and *Centropages typicus* clearly dominated the biomass of the copepods in the water  
253 off the Tuscan coast. Indeed, in the superficial hauls the percentages of *Clausocalanus* spp. and *C.*  
254 *typicus* were 32.96% and 30.21%, respectively. Moreover, *Farranula rostrata*, rarely found in the 5  
255 – 50 m and 50 – 100 m layers, were abundant on the surface (14.51%). The dominant cladoceran  
256 species was *Evadne spinifera* (118.04 ind.m<sup>-3</sup> ± 41.8).

257 During summer 2014, throughout the whole water column, the maximum distribution of the  
258 copepods *Clausocalanus arcuicornis*, *Clausocalanus furcatus*, *Temora stylifera* and *Nannocalanus*  
259 *minor* was 61.77%, with a peak of 78.05% in the 50 – 100 m layer. *Penilia avirostris* (205.8 ind. m<sup>-3</sup>  
260 ± 76.2) dominated among the cladocerans, followed by *Pseudoevadne tergestina* and *Evadne*  
261 *spinifera*.

262 *Clausocalanus paululus*, *Clausocalanus furcatus*, *Calocalanus styliremis* and *Oithona plumifera*  
263 were the most common species in autumn 2014, constituting 46% of the copepod biomass (with a  
264 peak abundance of 71.58% in the 5 – 50 m layer).

265 In winter 2015, when the maximum abundance of copepods was observed, copepods such as  
266 *Acartia negligens*, *Clausocalanus lividus*, *Clausocalanus mastigophorus* and *Oithona decipiens*  
267 were predominant (39.24%), although some other larger copepods, such as *Centropages typicus*,  
268 *Calanus helgolandicus* and *Temora stylifera* were also highly abundant, particularly in the 5 – 50 m  
269 layer.

270 During all seasons the dominant copepods species are herbivorous.

271 3.2 Trace elements in seawater

272 The three sampling sites (Figure 1) showed very comparable concentrations, so we presented their  
273 mean values (Table 1) to facilitate data discussion.

274 The temporal and spatial distributions of dissolved Mn, Fe, Cu, Zn, Al, Ni Co, Cd and Pb are shown  
275 in Figure 4. In surface water, the average metal concentrations were in the following order:  
276 Zn>Ni>Fe>Al>Pb>Co>Mn>Cu>Cd, while at 50 m of water depth, the order was  
277 Ni>Zn>Fe>Al>Pb>Co> Cu>Mn> Cd and at 100 m water depth, the order was Ni> Zn> Al>Pb>  
278 Fe>Co>Mn> Cu>Cd.

279 Cd concentrations ranged from 0.02 to 0.04  $\mu\text{g L}^{-1}$  and did not show significant variations between  
280 seasons or water depths. Pb was in the range of 0.16 to 2.33  $\mu\text{g L}^{-1}$  with slight variations between  
281 seasons (the highest values in autumn) and water depths. Zn, Ni and Fe were the nutrient trace  
282 elements with the highest concentrations in seawater, and their levels seemed to be strongly  
283 influenced by the seasons. In fact, the highest levels of Zn and Ni were recorded in summer, both in  
284 surficial water and at 50 m water depth, while the highest concentration of Fe was in winter. Cu  
285 concentrations ranged from 0.22 to 1.54  $\mu\text{g L}^{-1}$  and did not show variations between water depths  
286 (Table 1); the highest Cu concentration was registered in summer (Figure 4). Co concentrations  
287 ranged from 0.02 to 1.65  $\mu\text{g L}^{-1}$  and Mn from 0.35 to 1.84  $\mu\text{g L}^{-1}$ , both elements had slight  
288 variations between water depths and seasons (Figure 4, Table 1). Al concentration was relatively  
289 low (1.50-1.80  $\mu\text{g L}^{-1}$ ) and relatively constant in the analyzed waters, in line with previous findings  
290 in the Mediterranean Sea (Caschetto and Wollast, 1979).

291 Trace metals in coastal waters are usually higher than concentrations in the open ocean, owing to  
292 metal inputs from continental sources, such as ground water and coastal sediments (Sunda, 2012). In  
293 the Mediterranean Sea, nutrient-like metals usually exhibit surface concentrations higher than those  
294 of the Pacific and Atlantic Oceans and their vertical profiles are more or less homogenous, differing  
295 from the distribution observed in the open ocean, where there are depleted surface layers and  
296 increasing concentrations with depth (Voutsinou-Taliadouri *et al.*, 2000). This peculiarity is due to

297 limited recycling of nutrients in this semi-closed sea and to trace metal-enriched source waters  
298 derived from rivers. The concentrations we detected in seawater were comparable or lower than  
299 those recently detected in the Mediterranean Sea (e.g. Safaa, 2015; Ebling and Landing, 2015).  
300 However, measuring metal concentrations in water does not provide information on the risks posed  
301 by metal bioaccumulation or biomagnification (Ricart *et al.*, 2010; Maceda-Veiga *et al.*, 2013).

### 302 *3.2 Trace elements in zooplankton, nonessential elements*

#### 303 *3.2.1 Cadmium and lead*

304 In marine zooplankton, Cd and Pb levels ranged from 0.05 to 0.41 mg kg<sup>-1</sup> and from 1.01 to 12.38  
305 mg kg<sup>-1</sup>, respectively (Figure 5, Table 2). It is well known that the distribution of Cd in seawater is  
306 regulated by marine biogeochemical processes, such as uptake by phytoplankton in surface waters,  
307 consequential decomposition of organic matter produced, and demineralization in deep waters  
308 (Paimpillil *et al.*, 2010). Since Cd has no significant physiological role, it is probably adsorbed on  
309 the surface of zooplanktonic debris or fecal pellets during its transportation to bottom waters  
310 (Kremling and Pohl, 1989). Pb is known to form colloids in seawater that could be adsorbed onto  
311 planktonic debris (Paimpillil *et al.*, 2010). Pb concentrations in zooplankton increased with  
312 increasing water depths, while Cd appeared to be uninfluenced by this parameter (Table 2). In  
313 comparison with other findings in other marine environments of the world, such as Taiwan, India,  
314 and Argentina, (Fang *et al.*, 2006; Pempkoviak *et al.*, 2006; Fernandez-Severini *et al.*, 2013) Cd  
315 concentrations were lower, but of the same magnitude as those reported in the Seine estuary  
316 (France) by Miramand and coauthors (2001). Pb levels registered in zooplankton were comparable  
317 or lower with previous findings in Mediterranean coastal areas (Rossi and Jamet, 2008). The  
318 highest Pb concentrations in zooplankton were registered in autumn, at all the three water depths  
319 considered (Table 2).

#### 320 *3.2.2 Aluminum and vanadium*

321 To our knowledge, these two nonessential elements have not been previously investigated in  
322 zooplankton from the Mediterranean Sea. Despite some reports of a role of Al in physiological  
323 processes, there is no clear evidence that it plays an essential function in organisms (Pérez-  
324 Granados and Vaquero 2002). In surface seawater, Al remains for just 4 weeks to 4 years (Orians  
325 and Bruland, 1986). Processes removing Al from seawater include passive scavenging into particles  
326 (Vink and Measures, 2001), and biological absorption is the predominant mechanism of biological  
327 scavenging of dissolved Al (Li *et al.*, 2013). Al levels in zooplankton ranged from 62.30 to  
328 1738.23 mg kg<sup>-1</sup> and increased with increasing water depths, with the highest Al concentrations  
329 registered in spring (Figure 5, Table 2).

330 Vanadium enters the aquatic system through multiple routes, including release of flying ash and  
331 through run-off from naturally V-rich soils, irrigated areas and industrial plants (Mackey *et al.*,  
332 1996). V concentrations were low in zooplankton, ranging from 0.25 to 1.73 mg kg<sup>-1</sup>, and as for Al,  
333 concentrations increased with water depth (Table 2).

### 334 3.2.3 Antimony, beryllium, tin

335 Antimony is found at very low levels throughout the environment (ATSDR, 1992), usually < 1 mg  
336 kg<sup>-1</sup> in soil and water. Data on Sb concentrations in marine environments are very scarce, but in  
337 marine plants, especially algae, results are generally in the range of 0.1 to 0.2 mg kg<sup>-1</sup> (Filella *et al.*,  
338 2007). In zooplankton, we found Sb concentrations ranging from 0.02 to 0.59 mg kg<sup>-1</sup>, with the  
339 lowest levels in winter and the highest in spring (Table 2).

340 Beryllium occurs in rocks and minerals at concentrations ranging from 0.038 to 11.4 mg kg<sup>-1</sup> (Drury  
341 *et al.*, 1978). In most natural waters, the majority of Be is adsorbed to suspended matter or in the  
342 sediment, rather than dissolved. Be is not significantly bioconcentrated from water by aquatic  
343 species (US EPA, 1980). According to the environmental low levels, Be was under the LOQ in

344 marine zooplankton collected in surficial water and at 50 m depth, while detectable levels were  
345 found at 100 m depth (0.02 to 0.04 mg kg<sup>-1</sup>).

346 Tin and its compounds are significant and controversial chemicals in the environment, and are  
347 generally considered as being relatively immobile in food chains. Coastal regions are hot spots for  
348 environmental contamination by organotin compounds due to their proximity to harbor areas, as  
349 well as to industrial and domestic points of effluent discharge (WHO, 2005). Sn concentrations  
350 were found to be low in the study area, but always detectable in zooplankton, ranging from 0.05 to  
351 0.42 mg kg<sup>-1</sup>, with the lowest levels in surficial samples and in the summer (Figure 6, Table 2). We  
352 were unable to find any literature on Sb, V and Sn in zooplankton, but the detected levels can be  
353 considered low and of no concern.

354 Moreover, the nonessential elements Hg and Tl and the rare earth elements La and Ce were below  
355 the LOQ (0.037 mg kg<sup>-1</sup>, Hg; 0.010 mg kg<sup>-1</sup>, La, Ce and Tl) of the analytical methods.

### 356 *3.3 Trace elements in zooplankton, essential elements*

#### 357 *3.3.1 Copper, manganese, iron and zinc*

358 Some marine organisms are known to concentrate significant amounts of copper in seawater, such  
359 as crustaceans that require this element as a component of enzymes and haemocyanin (Paimpillil *et*  
360 *al.*, 2010). Zooplankton, and especially copepods, do not express haemocyanin, and the requirement  
361 of Cu is thus restricted to enzyme activity, which are important for life-history processes, such as  
362 egg production and growth (Paimpillil *et al.*, 2010). Cu levels in the analyzed zooplankton ranged  
363 from 1.90 to 39.70 mg kg<sup>-1</sup> (Figure 6, Table 2), the highest values were registered in autumn, and  
364 increased with water depth. These levels were in accordance with those registered from other  
365 marine environments of the world in areas of low anthropogenic impact (Fernandèz-Severini *et al.*,  
366 2013).

367 Manganese is a naturally occurring metal in seawater and can be significantly bioconcentrated by  
368 aquatic biota at lower trophic levels (WHO, 2004). In zooplankton samples, this element ranged

369 from 1.22 to 29.85 mg kg<sup>-1</sup> and like Cu, the highest values were registered in autumn, and were  
370 influenced by water depth (Figure 6, Table 2). The values were one order of magnitude lower than  
371 those recorded in more contaminated marine areas, e.g. in the Bay of Bengal (Paimpillil *et al.*,  
372 2010), in the northern coast of Taiwan (Hsiao *et al.*, 2011), and in the Gulf of Gdansk (Fialkowski *et*  
373 *al.*, 2003).

374 Iron is an essential trace element for the biological requirements of marine plankton, and was the  
375 element with the highest concentration of the essential elements analyzed. In fact, Fe levels reached  
376 levels of 354.42 mg kg<sup>-1</sup> in surficial water and the Fe concentration was strongly influenced by  
377 water depth (Figure 6), reaching levels of 1741.76 mg kg<sup>-1</sup> at 100 m of depth.

378 These three essential elements- copper, manganese, and iron- showed nutrient-like vertical  
379 distributions, being depleted in surface waters due to uptake by the biota and increased in  
380 concentration with increasing depths as a result of the remineralization of sinking organic matter.

381 Zinc is another essential element, and in tissues of aquatic organisms, Zn levels usually greatly  
382 exceed those required for normal metabolism; much of the excess is bound to macromolecules or  
383 present as insoluble metal inclusions in tissues (Eisler, 1993). The zinc levels in zooplankton  
384 reflected the occurrence of zinc in marine environment and in fact, this element is concentrated  
385 more effectively than copper. High accumulation of Zn in zooplankton may be due to its co-  
386 precipitation with calcium carbonate (Paimpillil *et al.*, 2010). Diet is the most significant source of  
387 Zn to aquatic organisms and is significantly more important than Zn uptake from seawater (Eisler,  
388 1993). The concentration of Zn in zooplankton was in the range of 14.47 to 132.33 mg kg<sup>-1</sup>, much  
389 lower than values recorded in contaminated coastal areas (Paimpillil *et al.*, 2010).

### 390 3.3.2 Arsenic, chromium and selenium

391 Arsenic is a metalloid which can be toxic in its inorganic form, and innocuous in some organic  
392 forms such as arsenobetaine. Studies have suggested that inorganic arsenic is an essential dietary  
393 nutrient; although its physiological role has not been clearly defined, it has been suggested that

394 arsenic could play a role in methionine metabolism (Uthus, 2003). Water contains mainly inorganic  
395 As, and aquatic organisms accumulate, retain, and transform arsenic species inside their bodies  
396 when exposed to it through their diet and other sources such as water, soil, particles (Sharma and  
397 Sohn, 2009). As biomagnification is inconsistent, and total As accumulation usually decreased by  
398 one order of magnitude with each trophic level (Maher et al., 2011). Our findings have shown that  
399 As levels in zooplankton were low, considering that concentrations reported were usually between  
400 0.2 to 24.4 mg kg<sup>-1</sup> (Rahman *et al.*, 2012) and we found values from 0.14 to 0.78 mg kg<sup>-1</sup>.

401 In the open sea, chromium is involved in biogeochemical cycles, with biologically mediated Cr  
402 removal in the surface layers and elevated Cr levels in deeper waters because of mobilization of Cr  
403 upon breakdown of sinking biogenic particles (Campbell and Yeats, 1981). Published data for Cr  
404 content in zooplankton are very scarce, but the concentrations we found between 0.39 to 7.25 mg  
405 kg<sup>-1</sup> (the highest values in autumn) were much lower than those recorded for Cr in polluted marine  
406 ecosystems, such as the northern coast of Taiwan (Hsiao *et al.*, 2011) and west coast of India  
407 (Kadam *et al.*, 2015).

408 Selenium has been an element of concern in aquatic environments for many years due to its  
409 potential toxicity (Purkerson *et al.*, 2003). The lower trophic levels, such as phytoplankton and  
410 bacteria bioaccumulate dissolved Se, and higher trophic levels such as zooplankton and fish  
411 accumulate Se through ingestion (Kehrig *et al.* 2009). It has been reported that little or no  
412 bioaccumulation of Se occurs along a marine food chain from algae to herbivores and carnivores  
413 (Schneider *et al.*, 2015). We found Se concentrations ranging from 0.12 to 0.52 mg kg<sup>-1</sup> in  
414 zooplankton, levels which were not influenced by seasons or water depth (Figure 6, Table 2). These  
415 concentrations were one order of magnitude lower than those detected in other marine areas  
416 (Purkerson *et al.*, 2003).

### 417 3.3.3 Cobalt, molybdenum and nickel



418 Cobalt is a particle-reactive metal and is scavenged by suspended particulate matter in coastal areas  
419 (Paimpillil *et al.*, 2010). We found Co concentrations ranging from 0.06 to 0.38 mg kg<sup>-1</sup>, with the  
420 highest levels recorded in autumn.

421 The element molybdenum is found in all living organisms and is considered an essential or  
422 beneficial micronutrient. Concentrations < 2.00 mg kg<sup>-1</sup> were recorded in marine zooplankton  
423 (Eisler, 1989). In the analyzed samples, Mo content was very low and ranged from 0.06 to 0.32 mg  
424 kg<sup>-1</sup>. Similarly to Co, the highest values of Mo were registered in autumn.

425 Nickel is a required nutritionally for many eukaryotic and prokaryotic organisms and occurs in  
426 aquatic systems as soluble salts adsorbed on clay particles or organic matter (detritus, algae,  
427 bacteria), or associated with organic particles, such as humic and fulvic acids and proteins  
428 (Thomson, 1982). Absorption processes may be reversed leading to the release of nickel from the  
429 sediment; there is no biomagnification of Ni along the food chain, at least in aquatic ecosystems,  
430 (WHO 1991). In the analyzed samples, Ni ranged from 0.85 to 5.48 mg kg<sup>-1</sup> (Table 2),  
431 corresponding to the mean of 4 mg kg<sup>-1</sup> found in marine compartments (Eisler, 1988).

432 Aquatic organisms have developed different strategies to deal with metals; the tissue concentrations  
433 are more or less under homeostatic control for essential elements such as copper or zinc, whereas  
434 the nonessential do not appear to be regulated very strongly (e.g., cadmium or lead). The role of  
435 essential trace metals, such as iron, copper and zinc in the growth of marine zooplankton still need  
436 to be deeply investigated, but being essential for life, the most common types of plankton contained  
437 a regular number of trace metals in their chemical make-up, such as zinc, iron, and copper  
438 (Paimpillil *et al.*, 2010). Trace element concentrations in marine zooplankton are in a state of  
439 dynamic equilibrium, depending on both uptake and elimination processes occurring  
440 simultaneously. In fact, regulation occur by matching metal excretion to metal uptake so that the  
441 internal body concentration of the metal remains constant, or by storing part of the metal in a

442 physiologically inactive pool. Marine organisms employ both strategies and in many cases effective  
443 regulation and/or detoxification is achieved by combining the two methods (CIESM, 2002).

444 Earlier investigations on the vertical transport of trace metals by zooplankton suggested that greater  
445 availability of food in the surface layers resulted in a more rapid breakdown of zooplankton, and  
446 thus less time was available for adsorption of metals from the water by the exoskeleton (Martin,  
447 1970). It was suggested that more of these elements were adsorbed to copepod exoskeletons at  
448 greater depths because food-dependent molting rates were lower and more time was available for  
449 elemental adsorption to take place (Martin, 1970). Consequently, the adsorption of dissolved metals  
450 to copepod exoskeletons constitutes an important pathway of trace metal accumulation in deep  
451 seawaters (Martin 1970; Sick and Baptist 1979). In our study, increases in the concentrations of  
452 trace elements, such as Al, Pb, Cu, Fe, Mn were found in the samples from greater depths,  
453 according to the previous findings of Martin (1970).

#### 454 3.3.4 Bioaccumulation factor (BAF)

455 Bioaccumulation of naturally occurring substances occurs along a continuum of exposure, and trace  
456 amounts of metals, both essential and nonessential, can be found in all biota (Mc Geer *et al.*, 2003)  
457 The bioaccumulation factor (BAF) is the ratio of a chemical concentration in an organism to the  
458 concentration in water; the concentration in the aquatic organism results from all possible routes of  
459 exposure, such as dietary absorption and transport across the respiratory surface (Gobas and  
460 Morrison, 2000). The metals considered in our study for estimation of BAFs were Al, Cd, Co, Cu,  
461 Fe, Mn, Ni, Pb, and Zn (Table 3). Given the wide range of concentrations considered in the BAF  
462 dataset, values were converted to log scale to aid visual comparisons (Figure 7).

463  
464 The data shown in Table 3 and Figure 7 confirm the high potential of the zooplankton as  
465 bioaccumulators of metals. The average BAF in zooplankton from surficial waters are in the  
466 following order Fe> Cd> Cu>Zn>Co>Mn>Ni>Pb>Al. At increasing water depths, an increase in

467 BAFs for the essential elements Fe, Cu, Zn, and Mn was observed, while BAFs were fairly constant  
468 for Ni and Co. The three nonessential elements Al, Pb and Cd showed a different trend in  
469 bioaccumulation, as Al and Pb bioaccumulation increased with water depth while Cd BAF  
470 decreased (Figure S2).

471 Bioaccumulation of trace elements in zooplankton could be due to low rates of efflux and relatively  
472 high rates of assimilation efficiency, as the zooplankton may be slow to metabolize or excrete the  
473 metals, the elements may bioaccumulate within the organism (Fernández-Severini *et al.*, 2013).  
474 Many aquatic invertebrates show accumulation patterns for most trace metals that include some  
475 storage of accumulated metal in its detoxified form somewhere in the body (Rainbow, 2002). Trace  
476 elements typically have an affinity for sulphur and nitrogen (Nieboer and Richardson, 1980), and  
477 proteins are made up of amino acids, most of which contain sulphur and/or nitrogen, and there are  
478 therefore numerous potential binding sites for trace metals within cells (Rainbow, 1997). It should  
479 be considered that toxicity is related to a threshold concentration of metabolically-available metal  
480 and not to the total metal concentration in an organism.

481 Even if the BAFs for most of the analyzed elements reveal the high potential of marine zooplankton  
482 as a bioaccumulator, many processes are involved in the bioaccumulation of metals in zooplankton,  
483 such as bioavailability, the amount of dissolved metal uptake, the physiological efficiency of the  
484 organism to excrete metals, as well as on the feeding rate and prey availability (Rainbow, 1997).

## 485 **Conclusions**

486 The study area which, a decade ago, was heavily influenced by metals derived from industrial  
487 activities does not presently show metal levels of particular concern for the aquatic ecosystem,  
488 probably due to the reduced anthropogenic inflows and to an improvement of industrial wastewater  
489 treatments. Mesozooplankton biomass, species composition and biodiversity values measured in the  
490 present study are similar to previous reports in areas with a negligible metal pollution and

491 anthropogenic impact, for example, in the Mallorca channel (Fernández de Puelles *et al.*, 2003,  
492 2007, 2014), the Tyrrhenian Sea (Brugnano *et al.*, 2012), the Ligurian Sea (Razouls and  
493 Kouwenberg, 1993) or in the Sicily channel (Brugnano *et al.*, 2010). However, the most abundant  
494 copepods, such as *Clausocalanus* and *Oithona*, showed a widespread distribution in the  
495 Mediterranean sea, which may indicate a tolerant characteristic within different hydrographic  
496 conditions (Gaudy, 1985) and their ability to adapt to fluctuating environmental states (Mazzocchi  
497 and Ribera d'Alcala, 1995). In seawater, the trace element concentrations were comparable or lower  
498 than those recently detected in the Mediterranean Sea, while the examined zooplankton showed a  
499 great ability to accumulate concentrations of metals by several thousand times, compared to  
500 concentrations detected in marine water, in particular the essential elements Fe, Cu, Zn, Co and Mn  
501 and the nonessential element Cd. No unusual patterns in the taxonomic composition and abundance  
502 of the zooplankton were found, but the abundance of the zooplankton taxa varied according to the  
503 season of the year, and as such the metal concentrations in these organisms were related to the  
504 seasons. In fact, for many trace elements (Al, As, Cr, Cu, Fe, Mn, Pb, Ni, V and Zn) the highest  
505 metal concentrations were detected in winter and autumn, the seasons with the highest biomass  
506 values, with a predominance of copepods.

507 Monitoring programs are mainly designed to discern spatial and temporal patterns in contaminant  
508 concentrations in the environment, and bio indicators are organisms that can be used to provide  
509 information on the variation of pollutants over time and space. Accumulated metal concentrations  
510 in zooplankton provide a great deal of information of applied relevance in terms of the geographical  
511 and temporal variation in the bioavailabilities of essential and nonessential trace elements in the  
512 environment. Due to its wide occurrence, abundant species and sensitive responses, zooplankton  
513 has shown to play a key role as a highly suitable candidate bio indicator in the bio monitoring of  
514 metal in marine ecosystem.

515 This study has provided a novel insight into metal distribution in zooplankton, which are the main  
516 food constituents of most fish of the coastal waters, and thus play an important role in the transfer  
517 of metals through the food chain.

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526 Project IZSPLV 14/14 RC).

527

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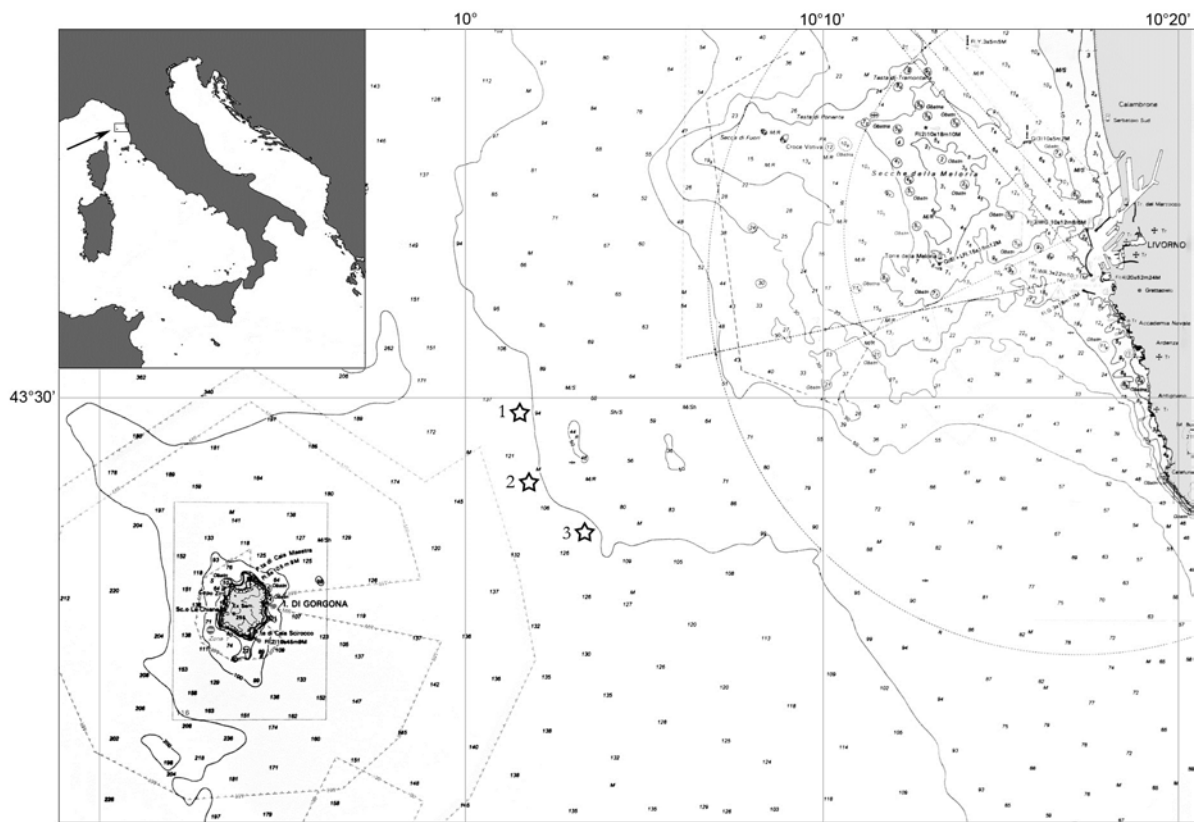
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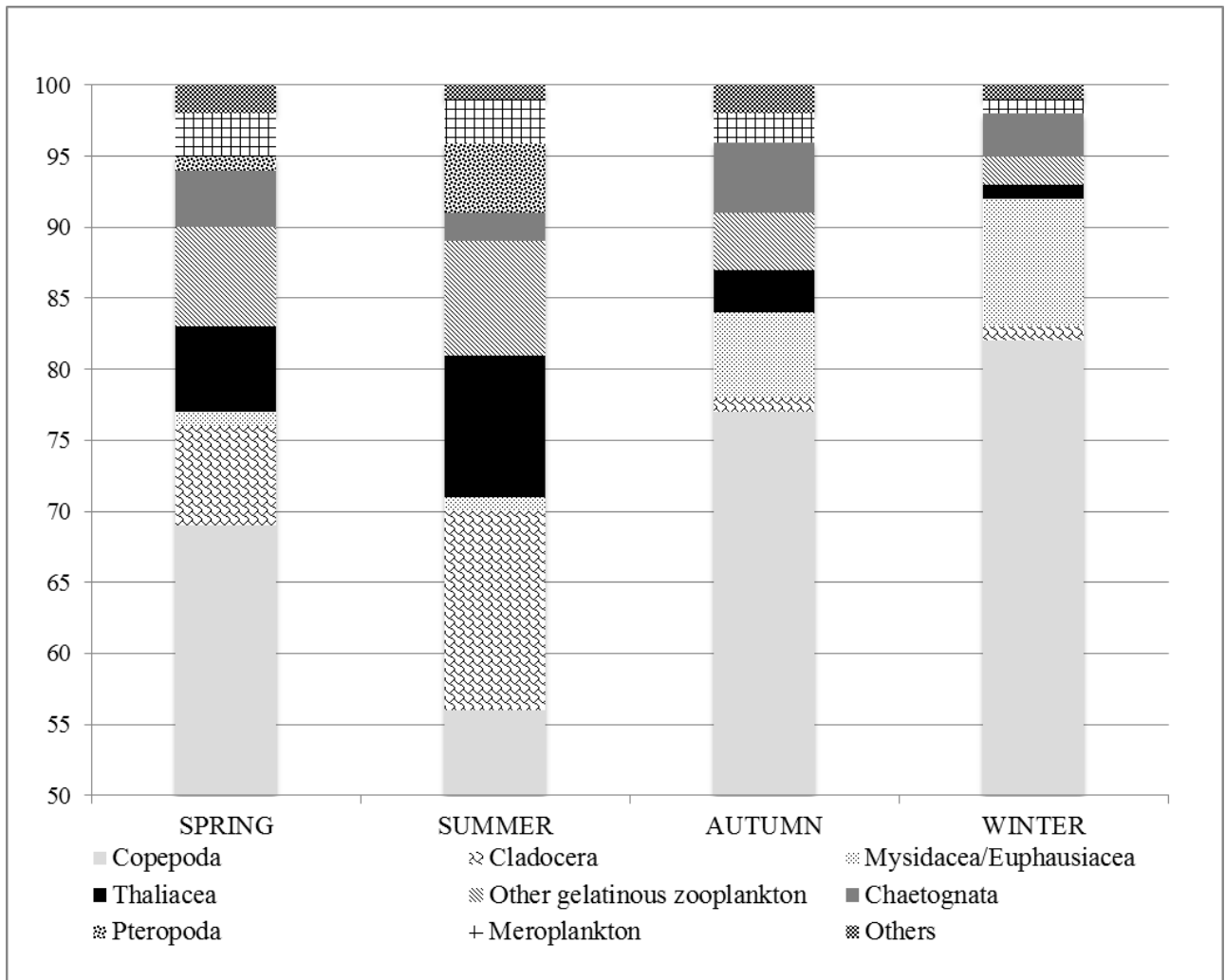
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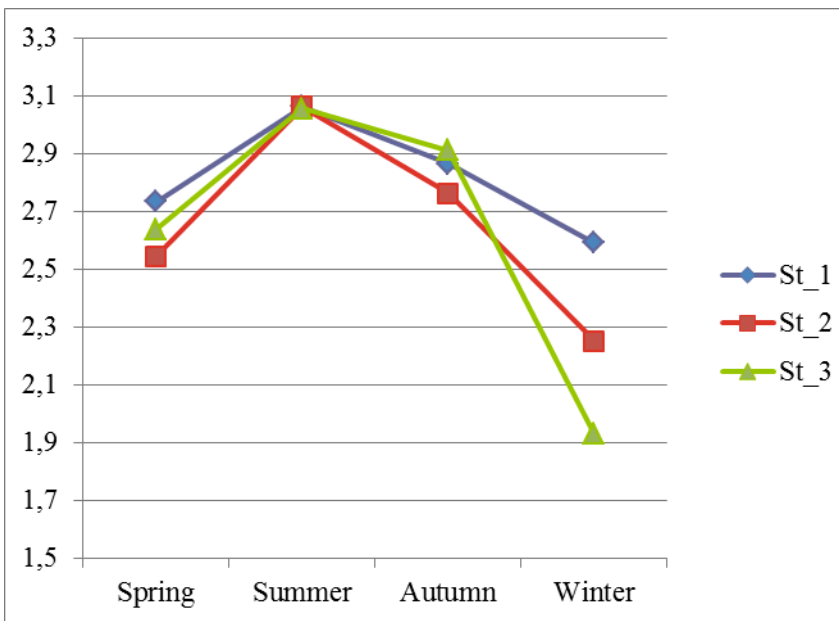
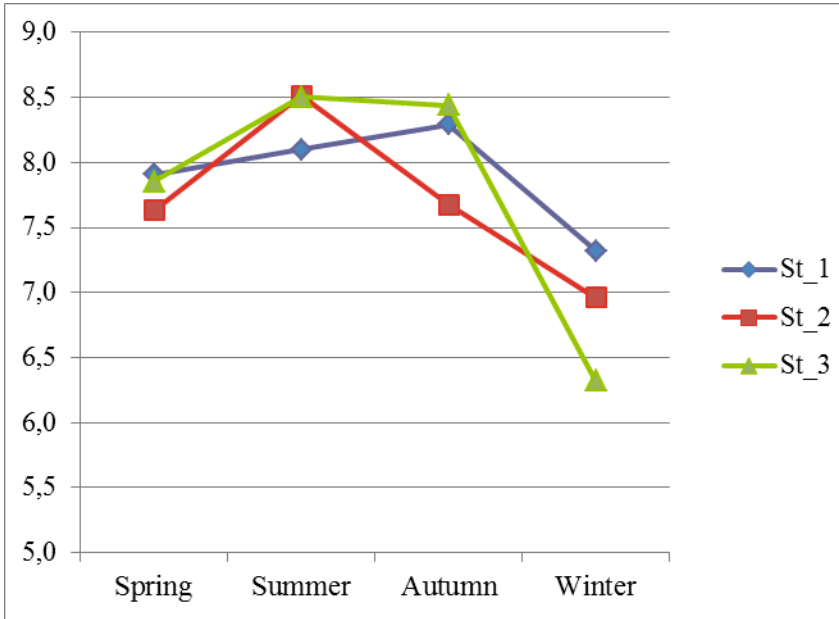
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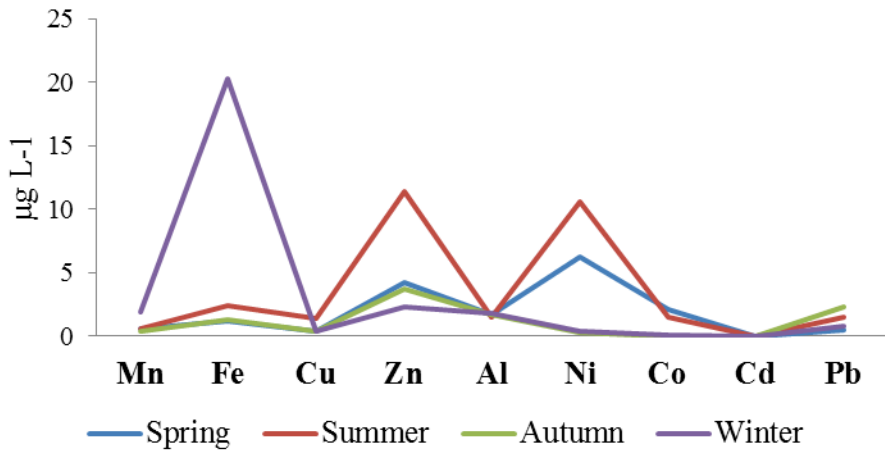
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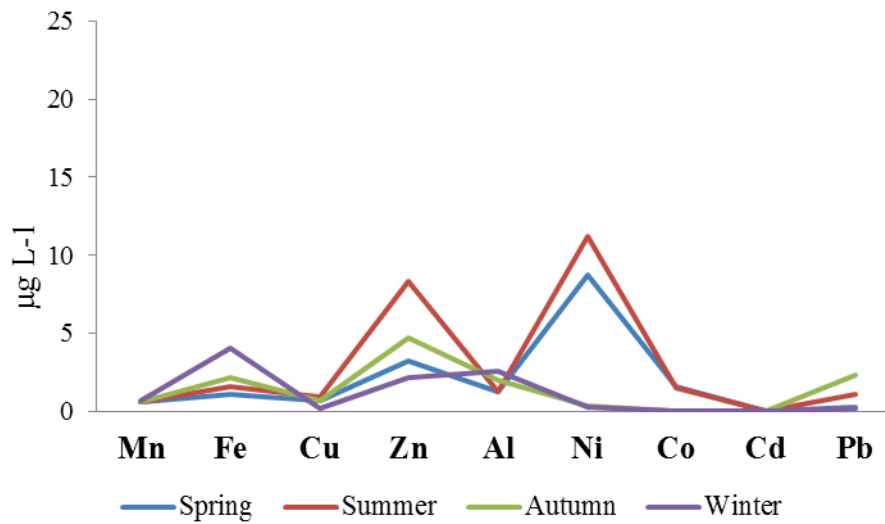




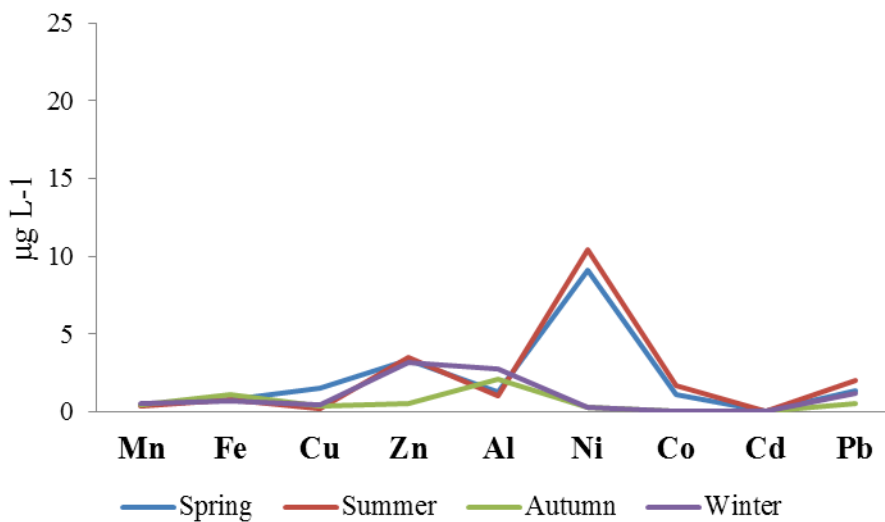
### Trace elements in surficial seawater



### 50 m water depth



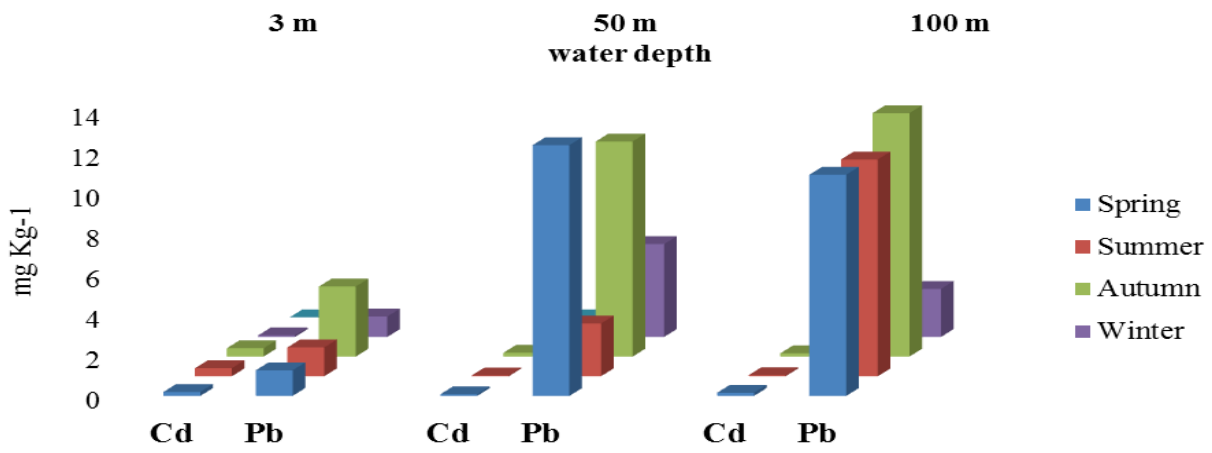
### 100 m water depth



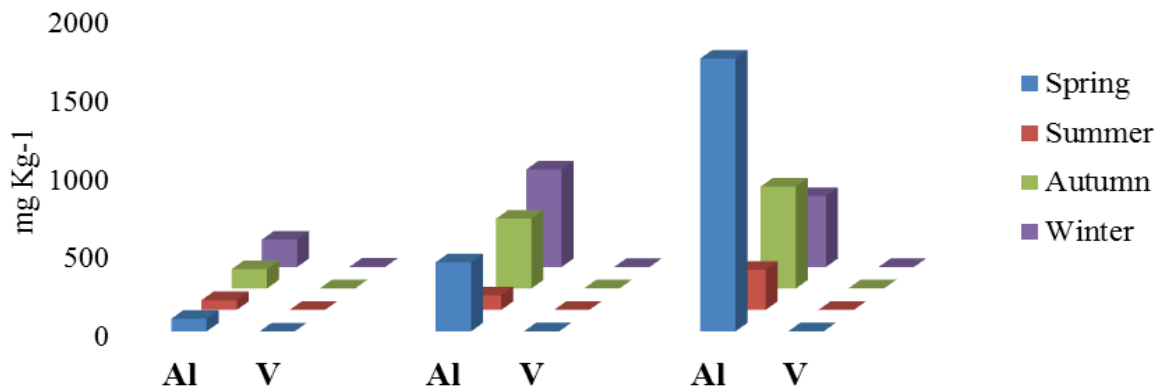




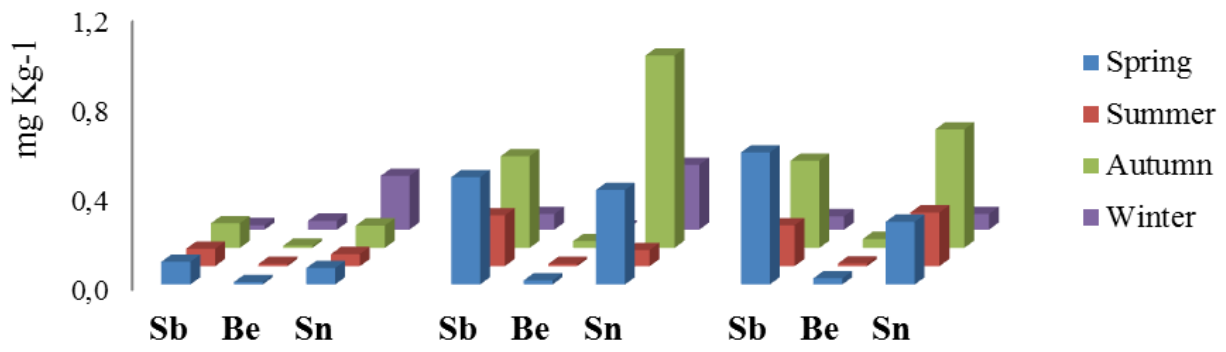
### Cadmium and lead



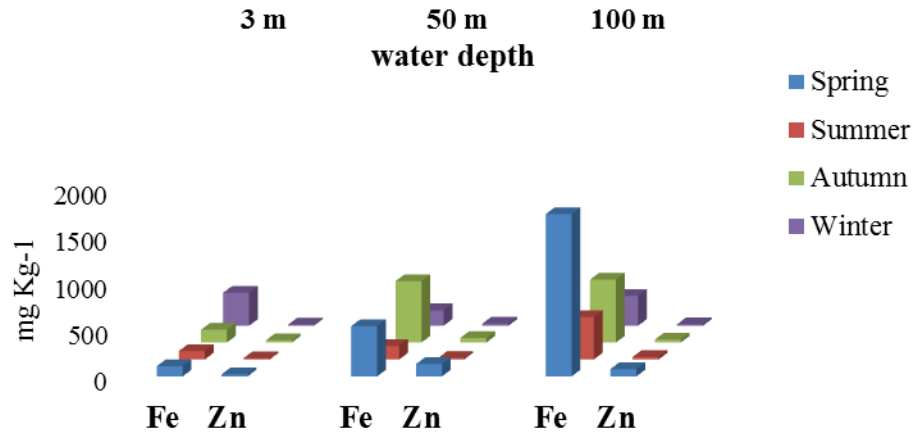
### Aluminum and vanadium



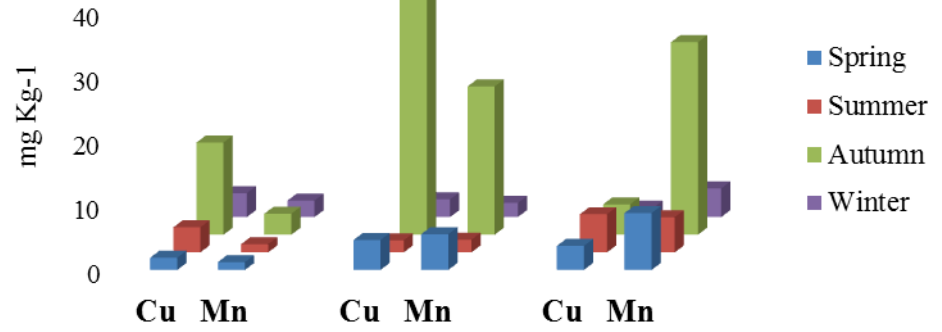
## Antimony, berillium and tin



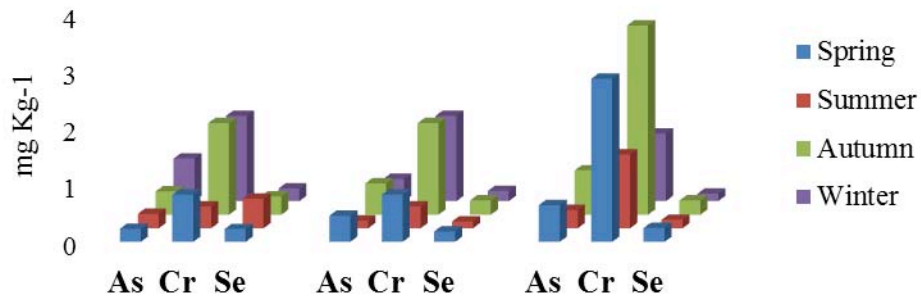
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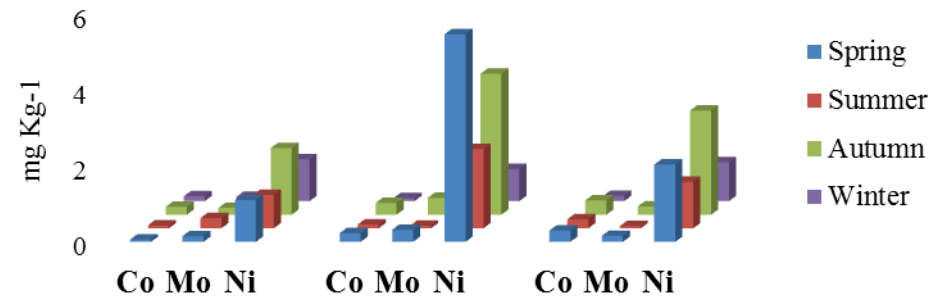
### Copper and manganese

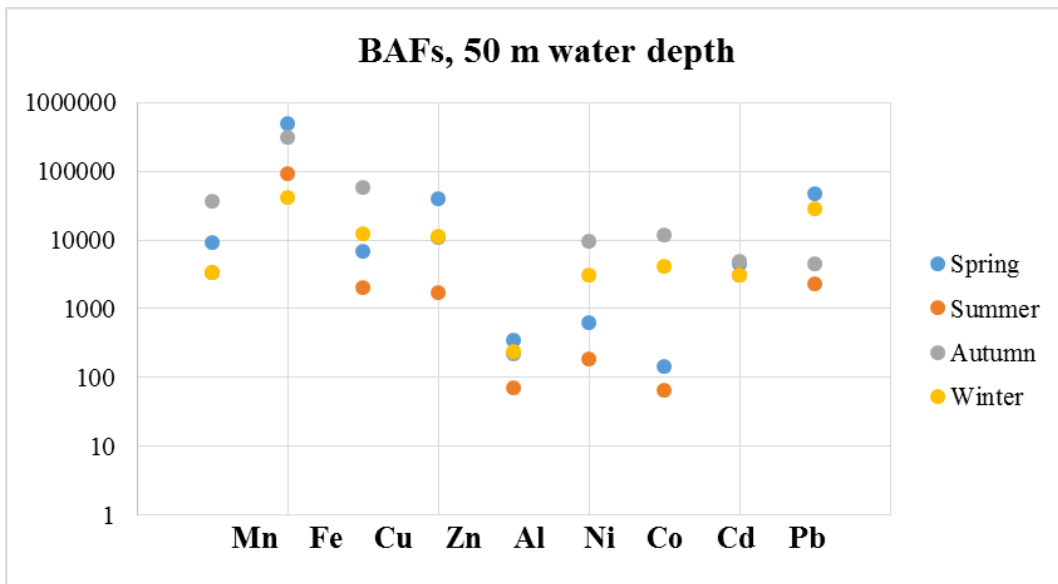
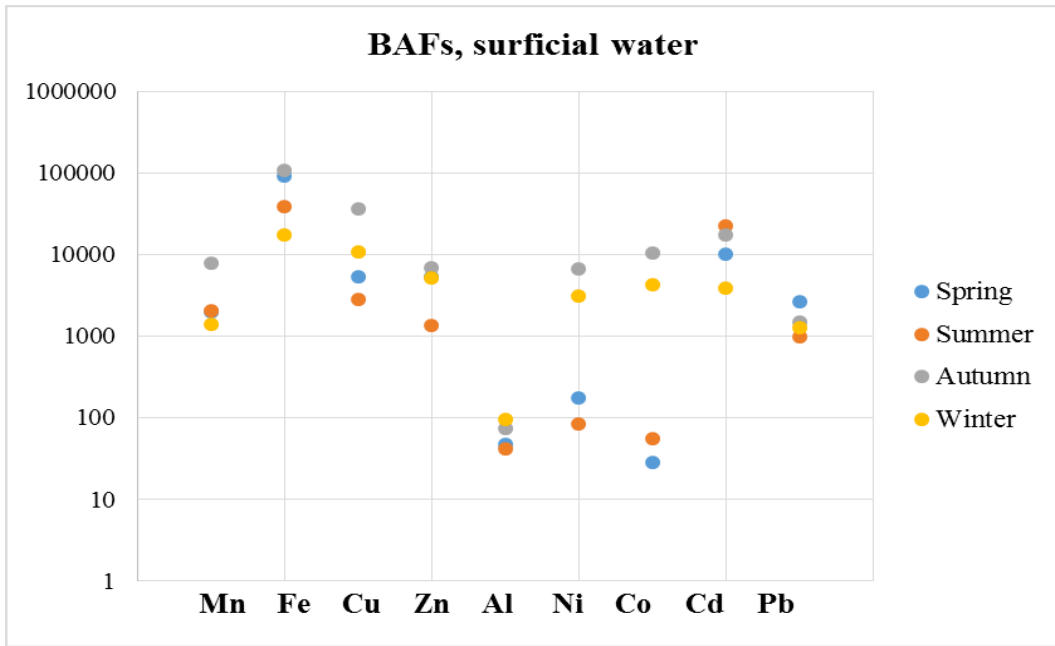


### Arsenic, chromium and selenium

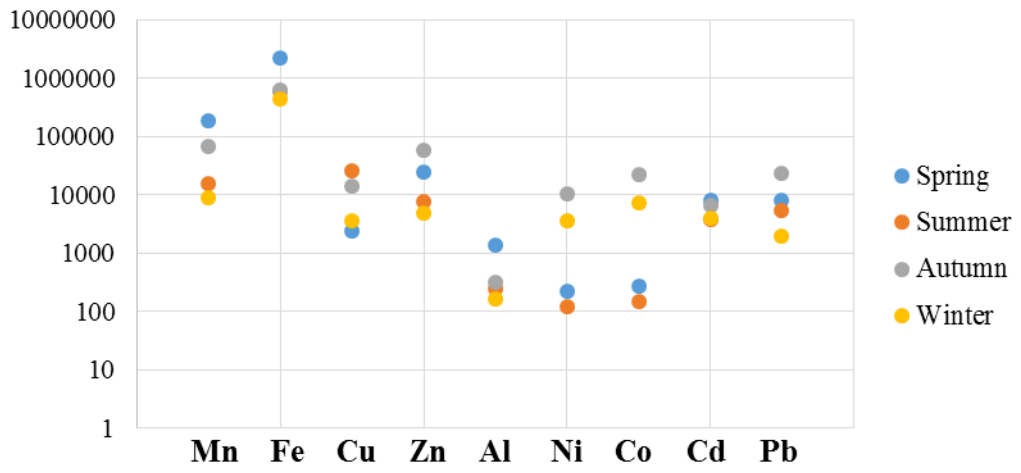


### Cobalt, molybdenum and nickel





### BAFs, 100 m water depth



## **Figure captions**

### **Figure 1**

Ligurian Sea (Western Mediterranean): study area and location of sampling station.

### **Figure S1**

Map of the western Mediterranean indicating the study area and mean circulation patterns: NC, Northern Current; WCC, Western Corsica Current; ECC, Eastern Corsica Current.

### **Figure S2**

Trends in BAFs zooplankton of Mediterranean Sea

### **Figure 2**

Zooplankton community composition (biomass) by taxonomic group and season for the samples from 2014 to 2015.

### **Figure 3**

Seasonal copepods community at every sampling station: a) species richness (d) and b) Shannon – Wiener index  $H'$  ( $\log e$ ), for each season.

### **Figure 4**

Metals levels ( $\mu\text{g L}^{-1}$ ) in seawater at different water depths and seasons

### **Figure 5**

Nonessential elements in marine zooplankton

### **Figure 6**

Essential trace elements in marine zooplankton

### **Figure 7**

Bioaccumulation factors (BAFs) for marine zooplankton at different water depths

