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Elevated trace elements in sediments and seagrasses at CO_2 seeps

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ABSTRACT

Seagrasses often occur around shallow marine CO_2 seeps, allowing assessment of trace metal accumulation. Here, we measured Cd, Cu, Hg, Ni, Pb and Zn levels at six CO_2 seeps and six reference sites in the Mediterranean. Some seep sediments had elevated metal concentrations; an extreme example was Cd which was 43x more concentrated at a seep site than its corresponding reference site. Three seeps had metal levels that were predicted to adversely affect marine biota, namely Vulcano (for Hg), Ischia (for Cu) and Paleochori (for Cd and Ni). There were higher-than-sediment levels of Zn and Ni in *Posidonia oceanica* and of Zn in *Cymodocea nodosa*, particularly in roots. High levels of Cu were found in Ischia seep sediments, yet seagrass was abundant there, and the plants contained low levels of Cu. Differences in bioavailability and toxicity of trace elements helps explain why seagrasses can be abundant at some CO_2 seeps but not at others.

Introduction

Around 30% of anthropogenic CO_2 emissions dissolve into the surface ocean causing the pH to fall in a process known as 'ocean acidification' (Caldeira and Wickett, 2003). Seawater acidification poses a threat to marine species and ecosystems, so one of the United Nations Sustainable Development Goals 14 is to 'Minimize and address the impacts of ocean acidification' (United Nations, 2015). Rising CO_2 levels are expected to reduce seascape complexity, alter trophic interactions (Nogueira et al., 2017; Milazzo et al., 2019) and reduce biodiversity (Sunday et al., 2016) causing impacts on a range of ecosystem services (Lemasson et al., 2017).

Trace elements, as the term suggests, normally occur in very low concentrations. At low levels they are not toxic, and some are essential for cellular process that support life (Avelar et al., 2013). At higher concentration, trace elements such as arsenic (As), copper (Cu), mercury (Hg) and lead (Pb) can be harmful to coastal biota (Stumm Morgan, 1995). Element toxicity depends on the chemical form. Arsenic, for example, is toxic in its metalloid form, Hg and Pb are toxic as free ions, and Cu is toxic when reduced to Cu (I) (Tchounwou et al., 2014). Ocean acidification is expected to exacerbate the harmful effects of metal pollution in coastal ecosystems (Ivanina and Sokolova, 2015; Lewis et al., 2016) because lower seawater pH can increase the bioavailability and toxicity of metals both in sediments (Roberts et al., 2013) and in the water column (Millero et al., 2009). Lower pH can release metals to water column that were previously bound to sediment (Atkinson et al., 2007). It can also alter the speciation of elements such as Cu, Ni and Zn resulting in increased toxicity (Lacoue-Labarthe et al., 2009, 2012; Zeng and Chen, 2015). However, levels of toxicity will depend on the rate of metal uptake by marine organisms (Batley et al., 2004). The uptake and availability of Cd, Co, Cu, Hg, Ni, Pb and Zn increase when seawater pH falls from 8.1 to 7.8, which is the change in surface seawater pH that is underway this century (Byrne et al., 1988; Richards et al., 2011). The seawater free ion concentration of Cu, for example is expected to increase by 115% (Pascal et al., 2010; Richards et al., 2011) and Pb by 4.6% (Millero et al., 2009; Dong et al., 2016).

So far, tests on the risks posed by trace metals in ocean acidification conditions have been carried out in laboratory conditions (Besar et al., 2008; Richir and Gobert, 2013; Bravo et al., 2016), which over simplify the complex behaviour of these metals in the marine environment (Millero et al., 2009). Most submarine volcanic seeps have gradients in pH and trace elements providing natural conditions to assess their uptake by marine biota (Renzi et al., 2011; Kadar et al., 2012; Vizzini et al., 2013). While relationships between organisms, environmental factors and trace elements have received much attention at deep-sea hydrothermal vents (Kadar et al., 2007; Cravo et al., 2007), those relationships at coastal CO_2 seeps are little understood.

Here, we investigate metal levels in sediments and seagrasses at

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acidified volcanic seeps as well as at reference sites. We choose seagrasses as they deliver important ecosystem services in coastal habitats (Nordlund et al., 2016). They are also predicted to benefit from rising CO_2 levels within their thermal limits (Koch et al., 2013; Brodie et al., 2014). Seagrass habitats provide food and nurseries for fish, turtles and mammals (Whitfield, 2017) and are important carbon sinks (Fourqurean et al., 2012). The seagrasses also sequester contaminants such as excess nutrients (Costanza et al., 2014) and metals (Bonanno and Orlando-Bonaca, 2017) and so are used as bioindicators (Catsiki and Panayotidis, 1993). The plants take in trace elements via their roots, rhizomes or leaves and can translocate them between these tissue compartments (Ralph et al., 2006). This introduces trace elements into the food web via grazing and decomposition (Lewis and Devereux, 2009).

Seagrass can be abundant at some shallow-water CO_2 seeps (Hall-Spencer et al., 2008; Russell et al., 2013) but are sparse or absent at other seeps (Vizzini et al., 2010, 2013). Studies have shown upregulation of stress-related antioxidant genes in the seagrass *Posidonia oceanica* at some CO_2 seeps (Lauritano et al., 2015) and work on the expression of genes involved in photosynthesis and growth of another common Mediterranean seagrass, *Cymodocea nodosa*, did not reveal beneficial effects of high CO_2 levels near a seep (Olivé et al., 2017). Under laboratory CO_2 enrichment there was significantly increased expression of *C. nodosa* transcripts associated with photosynthesis (Ruocco et al., 2017). So, even though seagrasses can be common at certain CO_2 seeps, toxins may cause stress and stunt their growth.

Laboratory studies have shown that, at elevated CO_2, Cu, Pb and Zn are toxic to the seagrasses *Zostera capricorni* (Ambo-Rappe et al., 2007) and *Halophila ovalis* (Ambo-Rappe et al., 2011). Many volcanic seeps around Greece and Italy have elevated levels of metals and are colonised by seagrass (Vizzini et al., 2010; Apostolaki et al., 2014) yet little is known about the accumulation of these metals in these plants. Here, we expand on work by Vizzini et al. (2013) to quantify the concentrations of trace elements in sediments and seagrass at multiple seep sites around the Mediterranean. Our aim was to find out whether levels of trace elements at volcanic seeps correlated with trace element accumulation in seagrass roots, rhizomes and leaves and whether seagrasses are more tolerant of some metals than others.

Methods

Study sites

We surveyed six sites in the Mediterranean Sea, all of which had seagrasses (*Posidonia oceanica* or *Cymodocea nodosa*) growing on sand in the naturally high salinity and high alkalinity waters of the Mediterranean Sea (Table 1). At each site, a high CO_2 station and a reference station was sampled between May–July 2014. The annual temperature range was around 18–22 °C for all six locations and the CO_2 seeps were at 0–10 m depth with a tidal range of 0.30–0.50 m.

Table 1
Seawater salinity, temperature (T), total alkalinity (A_T), pH and pCO_2 values (mean ± SE, n = 5) at six Mediterranean CO_2 seeps and reference stations between May-July 2014.

Site	Salinity	T (°C)	pH_{TS}	A_T (μmol kg SW^{-1})	$pCO_{2\ (\mu atm)}$
Vulcano					
Reference	35.8	21.6	8.15 ± 0.05	2430.86	321 ± 6.8
CO_2 seep	35.8	22.4	7.93 ± 0.08	2424.08	594 ± 15.8
Ischia					
Reference	35.6	17.7	8.11 ± 0.06	2587.92	408 ± 2.3
CO_2 seep	35.7	17.8	7.68 ± 0.05	2581.34	1233 ± 10.2
Panarea					
Reference	36.0	20.5	8.17 ± 0.05	2498.89	356 ± 4.6
CO_2 seep	36.0	22.3	7.44 ± 0.04	2492.60	2180 ± 2.3
Adamas					
Reference	36.7	22.6	8.18 ± 0.03	2706.84	340 ± 1.6
CO_2 seep	36.7	23.5	7.48 ± 0.04	2696.15	2107 ± 1.8
Paleochori					
Reference	36.0	22.6	8.16 ± 0.01	2702.84	342 ± 1.1
CO_2 seep	36.0	22.8	7.87 ± 0.01	2698.85	883 ± 3.0
Methana					
Reference	36.8	22.8	8.17 ± 0.01	2706.84	337 ± 6.9
CO_2 seep	36.8	23.0	7.77 ± 0.02	2696.25	1006 ± 4.4

Vulcano, Italy

We sampled Levante Bay (38.4 N, 15.0 E) off Vulcano island (Fig. 1A). The underwater gas emissions are 97–98% CO_2 with 2.2% hydrogen sulfide (H_2S) at the seep site, decreasing to <0.005% H_2S towards the north-eastern part of the bay (Capaccioni et al., 2001; Boatta et al., 2013; Milazzo et al., 2014). *Cymodocea nodosa* was absent near the main vents so we collected it on the periphery of the CO_2 seeps at 1 m depth.

Ischia, Italy

At the Castello Aragonese, off Ischia (40°43′50.4″N; 13°57′48.2″E) CO_2 bubbles up in shallow water seeps (Fig. 1A). Here the gas is 90–95% CO_2, 3–6% N_2, 0.6–0.8% O_2, 0.2–0.8% CH_4 and 0.08–0.1% air and the seeps lack H_2S (Tedesco, 1996). Abundant *Posidonia oceanica* meadows were sampled at 0.5 m depth from the seep area and from a reference site (Fig. 2a).

Panarea, Italy

Panarea island (38°38′12.2″N; 15°06′42.5″E) is part of the Aeolian Archipelago in the Southern Tyrrhenian Sea (Fig. 1A). On the main island and on the surrounding seafloor, tectonic faults have many gas seeps (Gabianelli et al., 1990; Voltattorni et al., 2009). The underwater gas emissions around these seeps are 92–95%CO_2, 2.99–6.23% N_2, 0.69–1.2% O_2 and 0.65–3% H_2S (Caramanna et al., 2010). Here *P. oceanica* was sampled at 5 m depth.

Milos Islands, Greece

Adamas thermal springs (36.70 N, 24.46 E) and Paleochori Bay (36.67 N, 24.51 E) are situated on southwest and southeast part of Milos island respectively (Fig. 1B). Milos island is part of an extensive submarine venting, from the intertidal to depths of more than 100 m (Dando et al., 1999). The underwater gas seeps at Adamas and Paleochori are located <1–4 m depth. The released gases are mainly composed of 92.5% CO_2 with some CH_4 and H_2 (Bayraktarov et al., 2013). The underwater gas seeps at Adamas thermal station and Paleochori Bay where *Cymodocea nodosa* meadows were sampled are located at 2 m and 4 m depth respectively (Fig. 2b).

Methana, Greece

The Methana peninsula (37.638428 N; 23.359730 E) is the westernmost volcanic system of the northern Aegean Volcanic Arc (Fig. 1B), derived from the subduction of the African tectonic plate beneath the Eurasian plate. We sampled the area described by Baggini et al. (2014) near Agios Nikolaos village on the NE part of the peninsula. The gases were 90% CO_2, with small amounts of nitrogen, carbon monoxide and methane (D'Alessandro et al., 2008). Here we sampled *Posidonia oceanica* meadows at 8–10 m depth.

Water sampling

Water samples (n = 5) were collected at each CO_2 seep and reference station of all six sites in 100 ml Winkler bottles and were fixed with 20 μl mercuric chloride in the field, stored in dark cool-boxes and transported

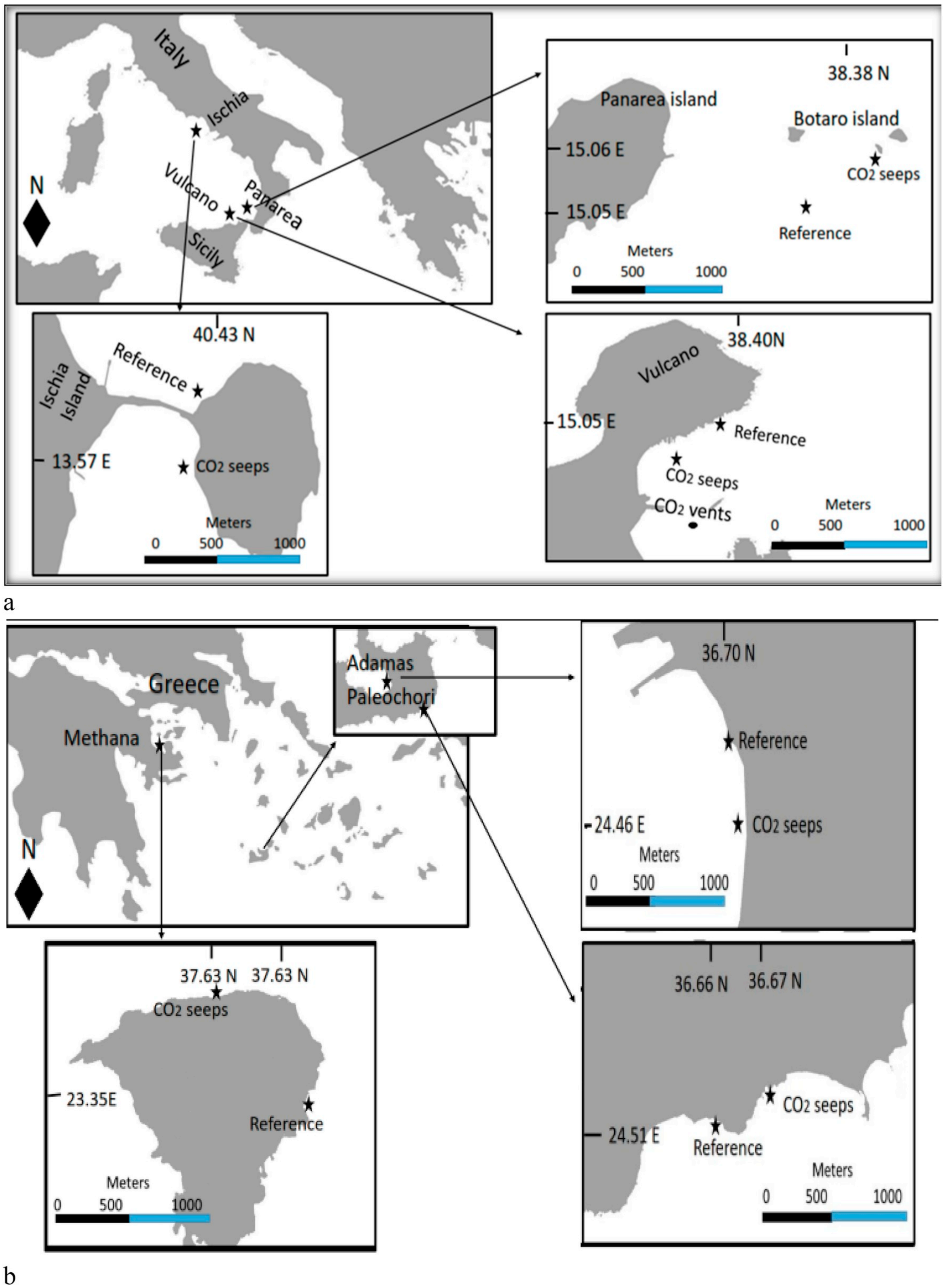

Fig. 1. Study sites in Italy a) and b) Greece, showing reference and CO_2 seep sites, which were all sampled between May to July 2014.

to the laboratory for total alkalinity (A_T) analysis. The pH_{TS} (using pH meter, Titrino Methron, Thermo Scientific) and temperature of the water samples were measured in the field immediately after collection and then measured in the laboratory again during the A_T analysis. In the laboratory 80 ml water samples were analysed for A_T using a Lab Titrino analyser following methods given by Dickson et al. (2007). Sterilized sea water was used as reference materials (CRM Batch 129, accuracy-98.7% Dickson, 2013) for A_T analysis. Temperature, pH_{TS} and A_T data were used to calculate pCO_2 using CO_2SYS program following methods given by Pierrot et al. (2006). Dissociation constants (K_1 and K_2) developed by Mehrbach et al. (1973) and refitted by Dickson and Millero, 1987 and dissociated constant for boric acid (K_B) developed by Dickson et al. (2007) was used in pCO_2 calculation.

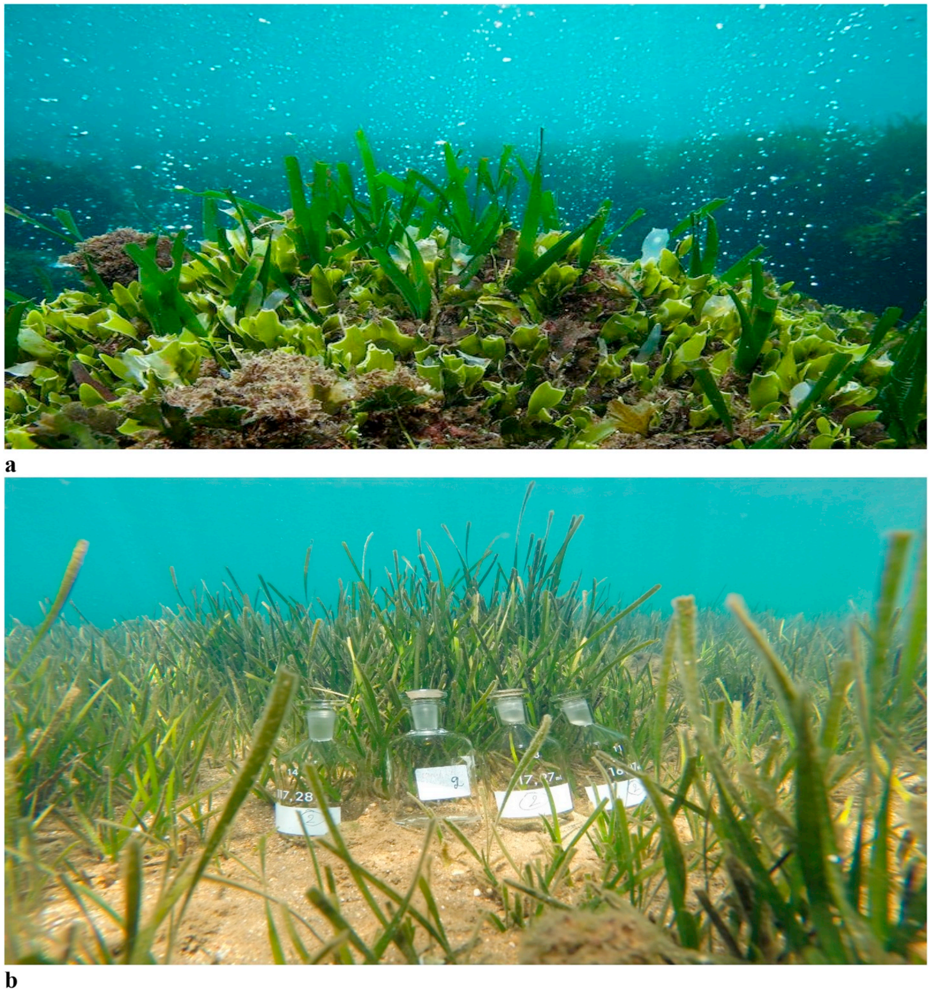

Fig. 2. a) Gas bubbling out of *Posidonia oceanica* meadows at CO_2 seeps off Ischia (Italy) and b) *Cymodocea nodosa* meadows at Adamas seeps (Greece). The leaf length of *P. oceanica* and *C. nodosa* were 15.4 cm and 24.3 cm respectively. Photo credits for a) *Posidonia oceanica*, and b) *Cymodocea nodosa* meadows at Italy and Greece: Jason Hall Spencer, University of Plymouth, UK and Thanos Dailianis of Hellenic Centre for Marine Research, Greece respectively

Sediment & seagrass sampling

Sediment samples (n = 5) were collected 1 m apart from six CO_2 seeps and six reference stations by SCUBA diving. A 10-cm long and 2 cm diameter syringe with the tip cut off to was used to suck up the upper 5 cm of sand. The sediment samples were stored in plastic bags in dark boxes and transferred to the laboratory. They were then dried at 40 °C until a constant weight was achieved and then analysed for the grain size following dry sieving at Half Phi intervals (Blott and Pye, 2001). After grain size analysis the fine and very fine of sediment fraction (<180-63 μm) were collected and stored in plastic bottles for trace metal analysis.

Samples (n = 5, whole plants) of *Cymodocea nodosa* (from Vulcano, Adamas and Paleochori islands) and *Posidonia oceanica* (from Ischia, Panarea and Methana) were collected by SCUBA diving at each station. The plants were rinsed well to remove sediment, scraped to remove leaf epiphytes and leaf scales were removed from rhizomes (*P. oceanica*) by hand and with soft tooth-brush and then washed with distilled water, air-dried and stored in polybags until analyses. Seagrass leaves, roots and rhizomes were oven dried at 40 °C and powdered in a mortar and stored till further analysis.

Analytical methods

Total trace elements (Cd, Cu, Hg, Ni, Pb and Zn) concentrations were determined using Aqua Regia Soluble Total method (Modified by Laboratory of the Government Chemist (LGC) UK from ISO11466). Dried sediment (0.25 g) was put into digestion tubes (Tecator type). Cold and concentrated acids in the order: 4.5 ml Hydrochloric acid (HCl): 1.5 mL Nitric acid (HNO_3) was added to the tubes. The digestion tubes were left to pre-digest, for 1 h then heated for 2 h at 95–100 °C. After cooling, the digest was filtered quantitatively into a volumetric flask and diluted using 2% HNO_3 (25 ml volume).

For dried seagrass (leaves, rhizomes and roots), 0.25 g of sample was added to 6 mL of HNO_3 following the same procedure as metals and the volume was made up to 25 mL. Similarly, blanks and standards (LGC Reference Materials, UK, recovery-95%) used for sediments (LCG6156) and plants (LGC7162) were prepared using the same method. Analysis of Cd, Co, Cu, Hg, Pb and Zn was performed using an ICP-MS (Thermo Scientific, iCAP 7000 Series) and an ICP-AES (Thermo Scientific, X Series-2) in triplicate with analytical detection precision of 99.5%.

All acids were analytical grade. Normal precautions for metal analysis were observed throughout the analytical procedures. HCL (37%w/w) and HNO_3 (69% w/w) were Ultrapure type (Ultrapure, Fischer Chemicals, USA). All glassware was soaked overnight in 10% HNO_3 and washed with distilled water and oven dried before use.

Data analysis

To assess the sediment quality of all six locations we used Sediment

Quality Guidelines Quotient (SQG-Q, Long and MacDonald, 1998). Among the environmental quality indices in the literature, this was chosen for its simplicity, comparability and robustness as reported by Caeiro et al. (2005). The SQG-Q consists of two values: a threshold effects level (TEL) and a probable effect level (PEL) (MacDonald et al., 1996). TEL and PEL, represent concentrations below which adverse biological effects occur rarely and frequently.

The SQG-Q was calculated as follows

$$SQG\text{-}Q = (\Sigma^{n}{}_{i=1}\ PEL\text{-}Q_i)/n$$

Where $PEL\text{-}Q_i$ = contaminant/PEL. The PEL-Qi represents the probable effect level quotient (PEL-Q) of the i contaminant and n represents the total number of contaminants (trace metals). Using the SQG-Q index, the sediments were divided into three categories as established by MacDonald et al. (2000). SQG-Q ≤ 0.1- low potential for adverse biological effects; 0.1< SQG-Q<1- moderate potential for adverse biological effects; SQG-Q≥1- high potential for adverse biological effects.

To assess bio-accumulation of elements, we calculated the Bio Sediment Accumulation Factor (BSAF), which is defined as the ratio between metal concentration in the organism and that in the sediment (Lau et al., 1998; Szefer et al., 1999), given by:

$$BSAF = Mp/Ms$$

Where Mp is the concentration of the element in the seagrass and Ms is the concentration of the element in the sediment (Fergusson 1990). BSAF is a key factor in expressing the efficiency of seagrass species to absorb elements from sediments and concentrate specific element in its roots, rhizomes or leaves. Higher BSAF values (>1) indicate a greater capability of accumulation (EPA, 2007).

Statistics

A three-way ANOVA was used to test for significant differences in trace element concentration among locations (Ischia, Panarea and Methana for *P. oceanica* and Adamas, Paleochori and Vulcano for *C. nodosa*), compartments (sediments and leaves, rhizomes, roots) and stations (CO_2 seeps, Reference). All data were first checked for normality and homogeneity of variances. When variances were not homogenous, data were ln(x+1) transformed. When there were significant effects, the Holm-Sidak test was performed for a posteriori comparison among factor levels. Pearson's correlation co-efficient was applied to identify correlations between trace element concentration in sediment and seagrass compartments, after testing for normality of distribution on raw or log transformed data. When normality was not achieved, non-parametric Spearman's rank correlation coefficient was applied. All statistical tests were conducted with a significance level of $\alpha = 0.05$ and data were reported as mean ± standard error (SE).

Results

Dissolved CO_2 concentrations were highest (and pH lowest) at each of the seeps; reference sites had normal CO_2 and pH levels. Salinity, temperature and total alkalinity were not affected by the seeps (Table 1).

Grain size analysis showed that 99% of the sediment particles sampled at all locations were sand. Most sediment trace element levels were significantly higher in the sediments of seeps than at reference stations, except Ischia (Figs. 3 and 4). Large differences were found for Ni (5.3-fold) and Zn (2.39-fold) at Panarea, Cd (42.6-fold) at Paleochori and Cu (8.9- fold) at Adamas seep sediments, compared to reference stations. Mercury was only observed at Italian CO_2 seeps, with 1.4-fold higher levels in the seep sediments at Vulcano than at Ischia and Panarea. Zinc sediment concentrations were similar at all locations but were 1.7-fold lower at Methana than at Ischia. However, Zn levels at the seeps of Panarea were 2.3-fold higher than at reference sites. The environmental quality of seep sediments for trace elements derived from the Sediment Quality Guidelines Quotient was mainly 'Moderate', although it was in the 'Low' to 'Moderate' range for reference stations. 'Adverse' biological effects were considered likely due to high levels of Hg at Vulcano, Cu at Ischia plus Ni and Cd at Paleochori (Table 2).

We were especially interested in results from Ischia as *P. oceanica* was abundant within the main CO_2 seep area (Fig. 2a). The sediment at this seep has the highest Cu (32-fold), Zn (2-fold) and Pb (1.5-fold) concentrations than other two seep locations sampled for *P. oceanica*, but the seagrass tissues had low levels of these metals (Fig. 3). On the other hand, *P. oceanica* at the Ischia seeps had higher concentrations of Cd (1.9-fold), Hg (1.2-fold), Ni (3-fold) and Zn (4-fold) than the sediment (Fig. 3). The concentrations of Ni at Paleochori, Pb at Vulcano and Zn at Adamas seeps were 18-fold, 4-fold and 3-fold higher in the sediment than in *C. nodosa* (Fig. 4). Trace element levels were generally significantly higher in the roots than rhizomes and leaves of *P. oceanica* and *C. nodosa* at all seep locations (Figs. 3 and 4). Exceptions were Cd (8-fold) concentrations within the rhizomes, Zn (42-fold) and Cu (5-fold) within the leaves of *P. oceanica* and Cd (6-fold), Pb (4-fold) and Hg (3-fold) within leaves of *C. nodosa* (Figs. 3 and 4).

Significant differences between the three sampling sites in the levels of trace elements in sediment and tissues were observed for *P. oceanica* (Table 3). Element concentrations measured in sediments and *P. oceanica* compartments differed significantly except for Cu (sediment-leaves) and Zn (sediment-roots), whereas within *P. oceanica* compartments all elements, except Pb (roots-leaves) has significant differences at all three sites. The accumulation of elements in *P. oceanica* plant parts did not show consistent common patterns for the three sampling sites. Hg and Cu were generally higher in roots and leaves than in rhizomes in all reference and seep sites. Zn was much higher in the leaves than in other plant parts at Ischia and Panarea. On the other hand, Cd was higher in the rhizomes of *P. oceanica* in reference and seep sites of Ischia and Panarea (Fig. 3).

Significant variation was observed in trace element levels for *C. nodosa* between the three sites, except for Cu at Adamas vs Paleochori, Ni at Vulcano vs Adamas and Pb at Vulcano vs Paleochori (Table 4). Element levels measured in sediment and in *C. nodosa* compartments differed significantly, except for Cu (sediment vs rhizomes). The accumulation of elements in *C. nodosa* plant parts did not show highly

Table 2
Sediment Quality Guidelines-quotient (SQG-Q) of sediment calculated with Probable Effects Level for Reference and CO_2 seep sites in Greece and Italy. SQG-Q <0.1 (low effect), <0.1 SQG-Q>1 (moderate effect), SQG-Q>1 (adverse biological effects). Numbers in bold indicate possible adverse effects of trace elements.

Location	Element	SQG-Q		Effects	
		Reference	CO_2 seeps	Reference	CO_2 seeps
Vulcano	Cu	0.08	0.33	Low	Moderate
	Hg	0.32	**1.18**	Moderate	**Adverse**
	Ni	0.13	0.21	Moderate	Moderate
	Zn	0.09	0.13	Low	Moderate
Ischia	Cu	0.93	**1.06**	Moderate	**Adverse**
	Hg	0.64	0.86	Moderate	Moderate
	Pb	0.11	0.13	Moderate	Moderate
	Zn	0.12	0.10	Moderate	Moderate
Panarea	Cd	0.10	0.16	Low	Moderate
	Cu	0.06	0.11	Low	Moderate
	Hg	0.79	0.84	Moderate	Moderate
	Ni	0.03	0.18	Low	Moderate
	Pb	0.09	0.57	Low	Moderate
	Zn	0.05	0.12	Low	Moderate
Adamas	Cd	0.21	0.21	Moderate	Moderate
	Ni	0.31	0.41	Moderate	Moderate
Paleochori	Cd	0.04	**1.84**	Low	**Adverse**
	Ni	0.71	**1.01**	Moderate	**Adverse**
Methana	Ni	0.11	0.16	Moderate	Moderate
	Pb	0.05	0.42	Low	Moderate

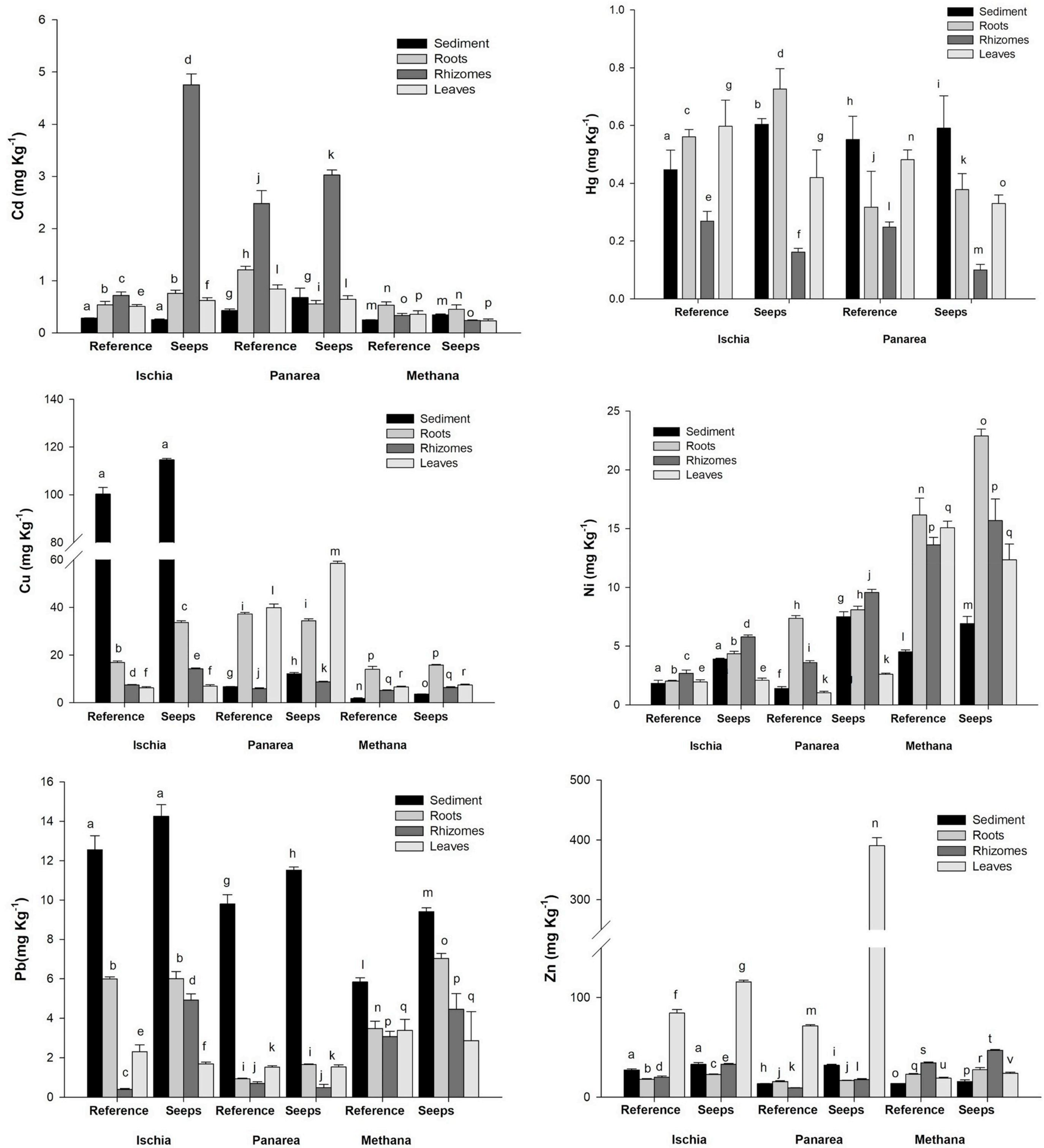

Fig. 3. Element concentrations (mean ± SE, n = 5) of Cd, Cu, Hg, Ni, Pb and Zn in *Posidonia oceanica* plant compartments and sediment at reference and CO_2 seep sites off Italy and Greece. Different letters indicate significant differences between reference and CO_2 seeps site at each location.

consistent common patterns as in *P. oceanica* (Fig. 4). However, Cu was always much higher in roots than other plant parts and Hg was higher in both roots and leaves than in rhizomes.

Correlation between trace element content in sediments and those recorded in *P. oceanica* roots and rhizomes were significant and positive for Zn and Ni in rhizomes at Ischia and Panarea seeps respectively, whereas in roots Cd was observed with positive correlation only at Panarea seeps (Table 5). Correlations of trace element content in sediment and those observed in roots and rhizomes of *C. nodosa* were significant and negative for Pb in both roots and rhizomes and for Zn only in rhizomes at Vulcano seeps (Table 5).

The Bio-Sediment Accumulation Factor indicated that in *P. oceanica* there was high root accumulation of Cd at all three sites and of Cu at Panarea and Methana. In *C. nodosa*, there was high accumulation of Cu

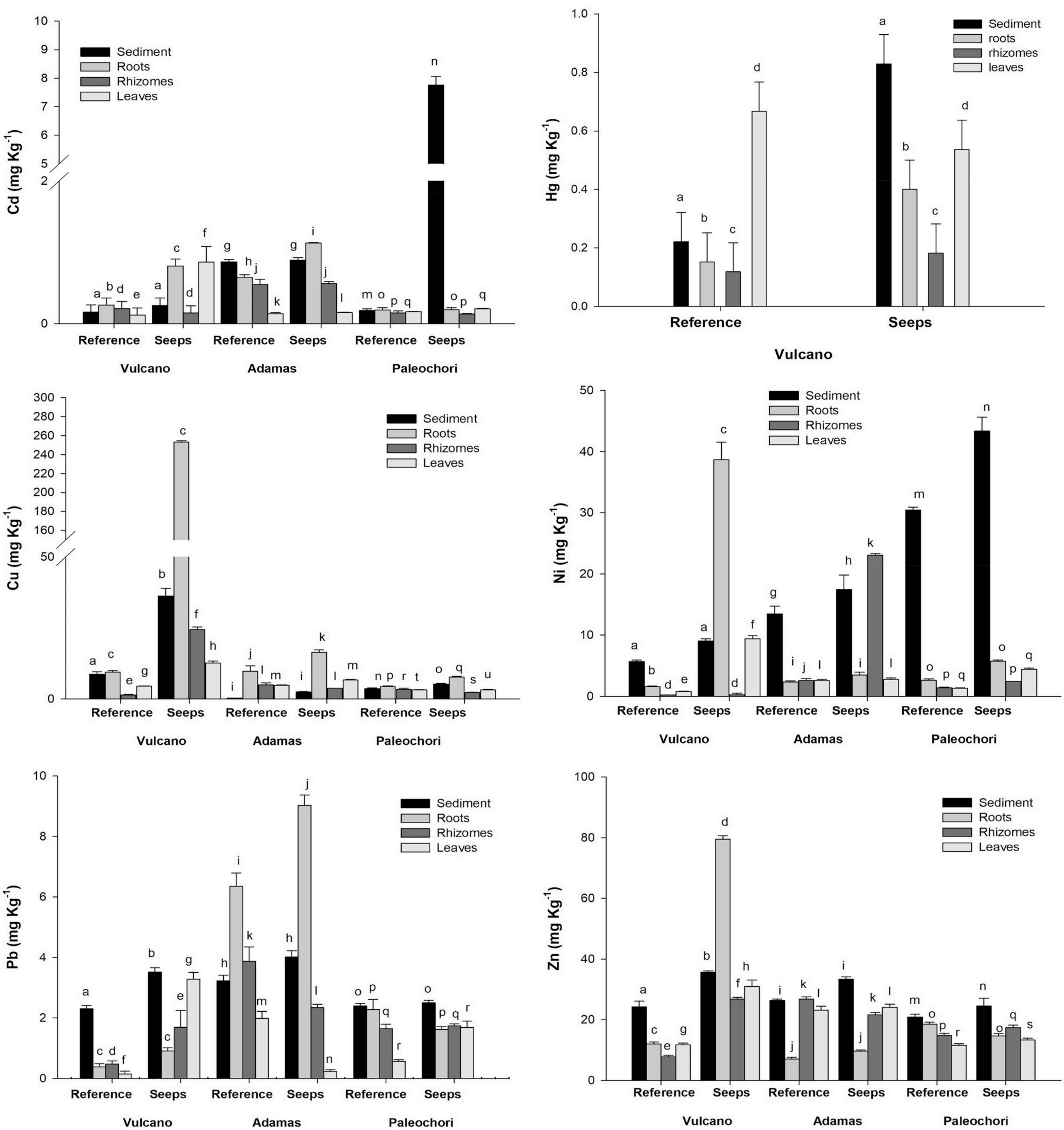

Fig. 4. Element concentrations (mean ± SE, n = 5) of Cd, Cu, Hg, Ni, Pb and Zn for *Cymodocea nodosa* in plant compartments and sediment at reference and CO_2 seeps off Italy and Greece. Different letters indicate significant differences between reference and CO_2 seep sites for each location.

in the roots at all three sites (Table 6).

Discussion

Shallow water CO_2 seeps have been used as natural analogues for future coastal ecosystems as they can have areas of seabed where entire communities of marine organisms are exposed to the shifts in carbonate chemistry that are expected due to continued anthropogenic CO_2 emissions (Hall-Spencer et al., 2008; Enochs et al., 2015; Connell et al., 2017). At such seeps, there are often elevated levels of trace elements and H_2S, so care is needed when using them to assess the effects of ocean acidification (Barry et al., 2010; Vizzini et al., 2010). This is done by mapping areas affected by volcanic fluid toxics and avoiding those areas when assessing the effects of increased pCO_2 in seawater (Boatta et al., 2013; Agostini et al., 2018). The six CO_2 seeps that we surveyed showed sediments were enriched with Cd, Cu, Hg, Ni, Pb and Zn. This was expected since hydrothermal seep sediments often have high levels of metals (Aiuppa et al., 2000; Sternbeck and Östlund, 2001) due to continuous input from the subsea floor into the sediments (Dando et al., 1999). The calculated Sediment Quality Guidelines Quotient (Long and

Table 3
Three-way ANOVA differences in trace element levels between Locations: 3 levels (Methana (M), Panarea(P) and Ischia (V)), Sites:2 variables (CO_2 seeps, Reference)) and compartments:4 levels (Sediments (Sd), Rhizomes (Rh), Roots (R), Leaves (L)). Holm-Sidak significant test ($p < 0.05$) is presented for locations, sediment and *P. oceanica* compartments. Numbers in bold indicate differences that were not significant.

Element	Variation	p value	Holm-Sidak p values								
			Location			Sediment vs Compartment			Compartments		
			M vs P	M vs V	V vs P	Sd vs R	Sd vs Rh	Sd vs L	R vs Rh	Rh vs L	R vs L
Cd	Location	<0.001	<0.001	<0.001	<0.001						
	Station	<0.001									
	Compt.	<0.001				<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cu	Location	<0.001	<0.001	<0.001	<0.001						
	Station	<0.001									
	Compt.	<0.001				<0.001	<0.001	**0.314**	<0.001	<0.001	<0.001
Ni	Location	<0.001	<0.001	<0.001	<0.001						
	Station	<0.001									
	Compt.	<0.001				<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Pb	Location	<0.001	<0.001	<0.001	<0.001						
	Station	<0.001									
	Compt.	<0.001				<0.001	<0.001	<0.001	<0.001	<0.001	**0.652**
Zn	Location	<0.001	<0.001	<0.001	<0.001						
	Station	<0.001									
	Compt.	<0.001				**0.222**	<0.001	<0.001	<0.001	<0.001	<0.001

Table 4
Three-way ANOVA differences in trace element levels between Locations: 3 levels (Adamas (A), Paleochori (P) and Vulcano (V)), Sites:2 variables (CO_2 seeps, reference) and compartments: 4 levels (Sediments (Sd), Rhizomes (Rh), Roots (R), Leaves (L). Holm-Sidak significant test ($p < 0.05$) is presented for locations, sediment and *C. nodosa* compartments. Numbers (in bold) indicate differences that were not significant.

Element	Variation	p value	Holm-Sidak p values								
			Location			Sediment vs Compartment			Compartments		
			A vs P	A vs V	V vs P	Sd vs R	Sd vs Rh	Sd vs L	R vs Rh	Rh vs L	R vs L
Cd	Location	<0.001	<0.001	<0.001	<0.001						
	Station	<0.001									
	Compt.	<0.001				<0.001	<0.001	<0.001	<0.001	**0.787**	<0.001
Cu	Location	<0.001	**0.626**	<0.001	<0.001						
	Station	<0.001									
	Compt.	<0.001				<0.001	**0.621**	<0.001	<0.001	<0.001	<0.001
Ni	Location	<0.001	<0.001	**0.853**	<0.001						
	Station	<0.001									
	Compt.	<0.001				<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Pb	Location	<0.001	<0.001	<0.001	**0.286**						
	Station	<0.001									
	Compt.	<0.001				<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Zn	Location	<0.001	<0.001	<0.001	<0.001						
	Station	<0.001									
	Compt.	<0.001				<0.001	<0.001	<0.001	<0.001	**0.910**	<0.001

Table 5
Results of correlation analysis between trace element content in sediment and seagrass (*P. oceanica* and *C. nodosa*) roots and rhizomes at high CO_2 seeps off Italy and Greek coast. The correlation co-efficient (r) and significance level ($p < 0.050$) are presented. Bold letters indicate significant correlation, only trace elements with significant correlations are shown.

Seagrass	Location	Element	Sediment-roots		Sediment-rhizomes	
			r	p value	r	p value
P. oceanica	Ischia	Zn	−0.234	0.704	0.870	**0.048**
	Panarea	Cd	0.841	0.014	−0.910	**0.032**
		Ni	−0.358	0.554	0.884	**0.046**
C. nodosa	Vulcano	Pb	−0.881	0.048	−0.889	**0.037**
		Zn	−0.795	0.108	−0.966	**0.007**

MacDonald, 1998; MacDonald et al., 2000) suggests Hg (at Vulcano), Cu (at Ischia) plus Cd and Ni (at Paleochori) were at high enough levels to have adverse impacts on marine biota. So, careful selection of study sites is needed to avoid the combined effects of trace metals and toxic gases while conducting ocean acidification research.

The trace element levels observed within CO_2 seep sediments were higher for Cd (from Methana & Panarea) and Cu (from Vulcano & Ischia), were similar for Hg (from Ischia, Panarea & Methana) and lower for Ni, Pb and Zn than mean element levels observed around the Mediterranean coast of Italy (Table 7). The sediments we studied were sandy

Table 6
Bio-Sediment Accumulation Factor (BSAF) of trace metals in *P. oceanica* and *C. nodosa* roots at CO_2 seeps (seeps) and Reference (Ref.) stations off Italy and Greek coast. Sediment (Sd), Roots (Ro). Bold numbers indicate BSAF>1 value.

Seagrass	Location	Ischia		Panarea		Methana	
	Elements	BSAF(Ro/Sd)		BSAF(Ro/Sd)		BSAF(Ro/Sd)	
		Ref.	Seeps.	Ref.	Seeps	Ref.	Seeps
P. oceanica	Cd	**1.9**	**3.0**	0.08	**2.71**	**2.12**	**1.28**
	Cu	0.17	0.29	**5.15**	**3.10**	**8.21**	**4.49**
	Hg	0.47	0.43	**1.95**	0.13	–	–
	Ni	**1.12**	**1.11**	0.22	**1.10**	**3.63**	**3.42**
	Pb	**1.42**	**1.21**	0.75	0.74	0.61	0.75
	Zn	0.81	0.56	**1.12**	0.52	**1.70**	**1.87**
		Vulcano		**Adamas**		**Paleochori**	
C. nodosa	Cd	**1.71**	**2.23**	0.45	0.52	**1.03**	0.03
	Cu	**1.14**	**4.32**	**36.65**	**6.50**	**1.23**	**1.49**
	Hg	**1.97**	0.51	**-**	**-**	–	–
	Ni	0.28	**3.17**	**2.05**	**1.69**	0.09	0.13
	Pb	0.07	0.11	0.76	**1.28**	0.97	0.65
	Zn	0.50	**1.13**	**1.62**	**2.27**	0.90	0.62

and lacked the clay particles (<63 μm) which bind more trace elements. Trace element levels observed at seep sediments off Vulcano, Italy were in the same range for Cd, 5-fold higher for Hg and lower for Cu (1.7-fold), Pb (6-fold) and Zn (2-fold) from previous measurements by Vizzini et al. (2013). Levels of Hg and Pb measured at Panarea CO_2 seeps were 5-fold and 4-fold lower from those reported by Renzi et al. (2011), probably because Renzi et al. (2011) sampled just after a massive outgassing event with increased input of elements. Trace element levels in seep sediments of the Greek coast were 3-fold (Cu), 2-fold (Pb) and 1.2-fold (Zn) lower than previously reported by Hodkinson et al. (1994), whereas Cd and Ni are reported for the first time for this coast (Table 7). These higher levels of elements could be in part due to weathering and land run-off on-land which makes their way to these shallow volcanic seeps along with hydrothermal inputs (Hodkinson et al., 1994). However, the influence of land run-off (from agricultural inputs and waste water) and tourism can lead to input of various trace metals like Cu and increase their availability in non-seep areas (Bonanno and Orlando-Bonaca, 2017). This explains why certain reference sites had similar or higher levels of trace metals than seep sites. The difference in element levels within the CO_2 seep sediments of Italy and Greece coasts indicates, variation in influx of elements from CO_2 seeps. These variations of trace element levels in sediment between CO_2 seeps and pristine sites off Greek and Italian coast were also reflected in the plant accumulation of trace elements in roots, rhizomes and leaves (Table 7).

Element levels were higher in seagrass compartments at the seep sites compared to reference sites. Seagrass element accumulation is more element and seagrass tissue-specific rather than species-specific (Bonanno and Orlando-Bonaca, 2017) resulting in seagrass compartments acting as metal accumulators (Govers et al., 2014). In our analyses most elements in both seagrasses were more concentrated in roots than rhizomes than the leaves, which is typical for *P. oceanica* and *C. nodosa* (Bonanno and Orlando-Bonaca, 2017). Root accumulation is common in both terrestrial and aquatic plants where they store and sequester certain elements to avoid damage to photosynthetic apparatus. Seagrasses have different tolerance mechanisms for dealing with trace elements that either accumulate in the roots or are moved out through the leaves which are then shed, as observed in *P. oceanica* (Di Leo et al., 2013; Richir and Gobert, 2016) and in *C. nodosa* (Malea and Haritinoids, 1999; Bonanno and Di Martino, 2016). This transfer of trace elements from roots to leaves promotes the release of these elements into the food webs of coastal ecosystems or the water column (Richir et al., 2015). On the other hand, storage and sequestration of metals below ground tissues reduces metal release (Windham et al., 2001). Seagrasses accumulate some elements, such as Cd and Ni, that are essential micronutrients (Sanz-Lazáro et al., 2012) rather than Hg or Pb that are toxic (Kabata-Pendias and Mukherjee, 2007), similar preferences has been observed for accumulation of Zn over Pb in both *P. oceanica* (Sanchiz et al., 2001) and *C. nodosa* (Malea and Haritonidis, 1999; Llagostera et al., 2011). However, seagrasses also tend to store toxic elements like Hg and Pb in the vacuoles of cortical tissue of roots outside the endodermis or in cell walls, thereby preventing the uptake of these elements into rhizomes and leaves (Windham et al., 2001).

Significant positive correlation of trace elements between seagrass tissues and sediment suggest the bioindication potential of seagrass tissues for that trace element (Bonanno and Raccuia, 2018). For instance a positive correlation was found in *P. oceanica* for Cd through the sediment-root pathway and for Zn and Ni through sediment to rhizome, which indicates that roots of *P. oceanica* are potential bioindicators of Cd and rhizomes of Zn and Ni at CO_2 seeps off Italy. In *C. nodosa* no positive correlation was found for any of the elements analysed, which indicates their low potential for being bioindicators of trace metals and this also suggests why *P. oceanica* is used as a bioindicator in most of trace metal accumulation studies in the Mediterranean Sea (Bonanno et al., 2017). In *P. oceanica* significant negative correlation was found for Cd in sediment-rhizomes and in *C. nodosa* a negative correlation was found for Pb between sediment-roots and Zn between sediment-rhizomes. Negative correlation suggests that the preferable route for Cd transfer in *P. oceanica* (Lafabrie et al., 2008; Di Leo et al., 2013) and Zn in *C. nodosa* (Malea and Haritonidis, 1999) is through water column rather than the sediment-root pathways. Similarly, elements such as Pb with negative correlation in *C. nodosa*, suggests Pb being toxic is not stored within the seagrass compartments (Sanchiz et al., 2001).

Bio-Sediment Accumulation Factor analysis shows that the pathway of uptake/storage is not always the sediment-root pathways, even though high element concentrations were observed in sediments at CO_2 seeps. Even though, in *P. oceanica* Cd and Ni were found with BSAF>1 in roots at all three seep stations, which suggests that accumulation of elements like Cd and Ni are made through the sediment-root pathway for elements like Cu, Hg, Pb and Zn, a mixed response (higher at reference and lower at seep sites or vice versa) of BSAF>1 was found, which indicates that for these trace elements both sediment-root and water-root pathways may be used. BSAF>1 value observed for trace elements in *P. oceanica* at the CO_2 seeps of Italy and Greek coast are within the range of BSAF values observed for *P. oceanica* in the Mediterranean Sea (Bravo et al., 2016). In *C. nodosa,* Cu was the only element with BSAF>1 in roots at all three seep stations, whereas other elements showed mixed responses. Cu being an essential element is preferred for root accumulation through sediment-root pathway, whereas other elements can use a mixed accumulation from sediment-roots or water roots or water -leaves pathway (Bonanno and Di Martino, 2016). However, in both *P. oceanica* at Ischia and Panarea and *C. nodosa* at Vulcano seeps, that Hg accumulation from sediment-roots pathway (BSAF>1) was not higher than reference sites, which suggests Hg being toxic to the plant roots is not preferred for accumulation in seagrass (Bonanno and Di Martino, 2016).

At CO_2 seeps the low pH can alter the metal speciation and favour the release of metals form sediment (Simpson et al., 2004; Atkinson et al., 2007). The chemical form in which metals are present (e.g. whether they are bound to organic or inorganic compounds) is a key issue determining their bioavailability. Low pH of seawater tends to release metals that are less strongly associated with sediments, increasing their potential bioavailability (Riba et al., 2004). Thus, low pH can increase the concentration of certain dissolved metals, which would affect the sediment-seagrass associated biota e.g., by increasing Cu, Cd and Zn bio-availability, their accumulation and possible toxic effects (Basallote et al., 2014).

In our research, all the CO_2 seeps had low pH (7.4–7.9) conditions, which are known to increase the availability of Cd, Cu, Ni, Pb and Zn in their free ion forms (Roberts et al., 2013). Low pH combined with increased availability can influence and increase seagrass uptake of trace elements (Yang and Ye, 2009) that can lead to higher accumulation and storage of trace elements in seagrass roots and leaves (Bonanno and

Table 7
Mean range of trace element (mg/Kg) levels measured in surface sediments and in *P. oceanica* and *C. nodosa* tissues off the coast of Italy and Greece arranged from low to high concentrations. Data collected from literature only included pristine sites containing seagrass meadows around Greece and Italy and seagrass meadows within contaminated sites and sediments taken from ship-based cores were excluded. Samples of CO_2 seeps off Italy and Greek coast are indicated in bold. Sediment (Sd), Leaves (L), Rhizomes (Rh), Roots (Ro).

Sediment	Sample	Cd	Cu	Hg	Ni	Pb	Zn	References*
	Sd	0.06[a]	–	–	–	1.77[h]	–	a, h
	Sd	0.15[b] (0.12–0.17)	0.20[k]	–	–	2.2[k]	–	b, k
	Sd	0.15[c]	1.6[h]	–	–	**2.53[d] (2.27–2.74)**	7.5[h]	c, h, **d**
	Sd	**0.18[d] (0.14–0.28)**	2.03[a]	–	–	**3.23[n] (2.76–3.72)**	10.5[k]	**d**, a, **n**, k
	Sd	0.22[e] (0.19–0.25)	**2.52[n] (2.3–2.7)**	–	–	**3.52[i] (3.2–3.97)**	11.4[c]	e, **n, i, c**
	Sd	**0.22[f] (0.11–0.32)**	3.04[c]	–	–	4.57[a]	**13.43[m] (11.9–15.7)**	**f,** c, a, **m**
	Sd	0.23[g] (0.15–0.30)	**3.53[l] (3.05–3.75)**	–	**1.39[m] (0.99–1.39)**	5.66[g] (4.31–7)	**15.67[l] (11.5–18.7)**	g, **l, m**
	Sd	0.24[h]	**5.23d (4.8–5.6)**	**0.11[f] (0.01–0.20)**	**1.84[j] (0.85–2.20)**	6.22[c]	**24.54[d] (14.7–28)**	h, **d, f, j,** c
	Sd	**0.26[i] (0.23–0.31)**	6.24[e] (5.23–7.25)	0.14[e] (0.1–0.17)	3.23[k]	**9.41[l] (9–10)**	**27.35[j] (24.3–30.7)**	**i,** e, k, **l, j**
	Sd	**0.26[j] (0.23–0.29)**	**6.68[0] (6.01–6.91)**	0.39[g] (0.18–0.60)	5.4[c]	**11.52[m] (11.1–14.8)**	31.75[a]	**j, o,** g, c, **m**, a
	Sd	0.3[k]	15.15[b] (8.0–22.3)	**0.59[m] (0.38–0.95)**	**6.91[l] (5.6–8.9)**	**14.25[j] (12.05–15.3)**	**35.74[n] (31.2–35.8)**	k, b, **m, l, j, n**
	Sd	**0.35[l] (0.30–0.38)**	18[p]	**0.60 [j] (0.55–0.67)**	**9.01[i] (8–9.87)**	**15.40[f] (5.8–25.0)**	43[h]	**l,** p, **j, i, f,** h
	Sd	**0.67[m] (0.18–0.98)**	**36.15[i] (29.41–44.80)**	**0.83 [i] (0.74–1.09)**	**13.47[n] (10–17)**	20[p]	43.05[b] (35–68)	**m, i, n,** p, b
	Sd	**0.89[n] (0.76–0.97)**	**51.25f (26.4–76.1)**	0.95[b] (0.1–1.79)	**43.37[d] (35.2–48.1)**	21.65[b] (14.2–29.1)	**46[f] (13.8–78.2)**	**n, f,** b, **d**
	Sd	**1[0]**	**114[j] (113–116)**	**4.5[°]**	46.1[e] (39.8–52.4)	**60[°]**	51.5[e] (31.4–54.7)	**o, j,** e
P. oceanica	L	**0.23[l] (0.10–0.29)**	1.90[q] (1.01–2.79	0.025[r] (0.01–0.04)	**1.03[m] (0.82–1.47)**	0.33[q] (0.15–0.52)	**23.9[l] (21.07–26.99)**	**l,** q, r, **m,**
	L	0.30[q] (0.22–0.38)	**6.89[j] (5.47–8.72)**	0.095[w] (0.01–0.18)	**1.95[j] (1.81–2.81)**	1.18[r] (0.4–1.96)	55.7[k]	q, **j,** w, r, k
	L	**0.62[j] (0.49–0.77)**	**7.39[l] (6.2–8.6)**	**0.33[m] (0.23–0.41)**	3.32[q] (1.44–5.21)	**1.53[m] (1.51–1.89)**	86.25[u] (16.5–156)	**j, l, m,** q, u
	L	**0.64[m] (0.48–0.84)**	10.41[u] (3.12–17.7)	**0.42[j] (0.15–0.62)**	9.5[k]	**1.69[j] (1.32–1.87)**	**115.5[j] (110.5–119.8)**	**m**, u, **j**, k
	L	1.08[r] (0.4–1.76)	10.5[k]	–	**12.34[l] (10.81–17.74)**	2.1[k]	201[v] (142–260)	r, k, **l**, v
	L	1.30[s] (0.60–2.0)	11.51[s] (6–17.02)	–	21.2[t]	**2.86[l] (0.33–8.29)**	**390.3[m] (342.5–424.1)**	s, t, **l, m**
	L	1.45[k]	36.50[v] (19.8–53.2)	–	41[x] (21.1–60.9)	3.05[v] (1.1–5)	–	k, v, x, v
	L	1.99[t]	**41.26[m] (35.93–47.80)**	–	–	7.19[u] (0.59–13.8)	–	t, **m**, u
	L	3.22[u] (0.95–5.49)	–	–	–	8.2[s] (5.2–11.2)	–	u, s
	L	5.55[v] (3.6–7.5)	–	–	–	–	–	v
	Rh	**0.24[l] (0.22–0.27)**	**6.3[l] (4.92–6.88)**	**0.1[m] (0.08–0.17)**	2.34[k]	**0.48[m] (0.18–1.11)**	**8.67[m] (8.87–9.65)**	l, m, k
	Rh	0.89[k]	**8.67[m] (7.9–9.82)**	**0.16[j] (0.12–0.19)**	3.34[x]	1.6[s] (0.8–2.4)	32.5[k]	k, **m, j,** x, s
		1.15[v] (0.6–1.7)	10.35[s] (5.4–15.3)	–	**3.6[m] (3.1–3.97)**	**4.45[l] (2.78–7.29)**	**32.99[j] (29.44–34.57)**	v, s, **m, l, j**
	Rh	1.6[s] (0.8–2.4)	11.85[v] (9.4–14.3)	–	**5.78[j] (5.21–6.26)**	**4.92[j] (3.82–5.64)**	**46.97[l] (43.61–48.55)**	s, v, **j, l**
	Rh	**2.48[m] (2.26–2.69)**	**14.29[j] (13.25–15.25)**	-	**15.68[l] (10.98–19.93)**	14.02[v] (0.03–28)	58[u]	**m, j, l,** v, u
	Rh	**4.76[j] (4.43–5.58)**	29.51[x] (0.41–58.6)	-	-	-	-	**j**, x
	Ro	1.8[k]	14.6[k]	**0.38[m] (0.18–0.53)**	5.12[k]	2.56[k]	44.3[k]	k, **m**
	Ro	**0.45[l] (0.29–0.67)**	**15.78[l] (14.96–16.55)**	**0.73[j] (0.6–0.94)**	**4.35[j] (3.79–4.95)**	**1.65[m] (1.52–1.7)**	**15.66[m] (14.23–18.85)**	**l, j, m**
	Ro	**0.55[m] (0.36–0.74)**	18.18[x] (0.25–36.1)	–	**7.36[m] (6.96–7.96)**	**6.01[j] (5.23–7)**	**17.85[j] (15.11–19.32)**	**m**, x, **j**
	Ro	**0.76[j] (0.53–0.89)**	**33.65[j] (33.77–35.67)**	–	**22.88[l] (21.6–24.79)**	**7.03[l] (6.22–7.77)**	**27.41[l] (23.38–26.83)**	**j, l**
	Ro	-		-		-	-	**m**, x

(*continued on next page*)

Table 7 (*continued*)

Sediment	Sample	Cd	Cu	Hg	Ni	Pb	Zn	References*
	Sd	0.06[a]	–	–	–	1.77[h]	–	a, h
			37.21[m] (35.21–38.21)		24.77[x] (3.44–46.2)			
C. nodosa	L	**0.15[n] (0.14–0.18)**	2.1[x]	0.53[g] (0.36–0.70)	2.33[z]	**0.23[n] (0.09–0.39)**	**13.30[d] (11.89–15.33)**	**n**, x, g, z, **d**
	L	**0.21[d] (0.18–0.23)**	**3.21[d] (2.77–3.88)**	**0.54[i]**	**2.76[n] (2.33–3.65)**	**1.69[d] (1.12–2.29)**	**24.12[n] (21.47–26.49)**	**d**, i, **n**
	L	0.55[c]	3.9[c]	-	2.80[x]	1.85[c]	**30.94[i] (26.48–38.65)**	c, x, **i**
	L	**0.86[i] (0.37–1.74)**	**6.63[n] (6.07–7.28)**	-	**4.44[d] (4.12–4.89)**	**3.29[i] (2.58–3.80)**	43.4[c]	**i, n,** d
	L	**1.03[f] (0.45–1.61)**	9.6[y]	–	5.57[c]	**5.56[f] (2.86–8.26)**	57.5[y]	**f**, y, c
	L	1.2[y]	**12.67[i] (10.52–14.74)**	–	7.6[y]	18.37[g] (3.32–33.42)	–	y, **i**, g
	L	2.10[g] (0.39–3.82)	–	–	**9.41[i] (7.13–10.71)**	–	–	g, **i**
	Rh	**0.14[d] (0.12–0.16)**	2.06[c]	**0.18[i] (0.17–0.19)**	1.15[c]	0.38[c]	24.2[c]	**d**, c, **i**
	Rh	**0.15[i] (0.12–0.20)**	**2.29[d] (2.03–2.66)**	–	0.85[z]	**1.69[i] (0.53–3.26)**	**17.36[d] (14.65–19.54)**	**d**, z, **i**
	Rh	**0.56[n] (0.52–0.67)**	**3.76[n] (3.74–3.79)**	-	1.2[y]	**1.74[d] (1.61–1.94)**	**21.66[n] (19.97–23.60)**	**n**, y, **d**
	Rh	2.1[y]	5.64[x] (0.19–11.10)	–	**2.42[d] (2.39–2.57)**	**2.34[n] (2.01–2.67)**	23[y]	y, x, **d, n**
	Rh	–	7.7[y]	–	**2.61[n] (2.11–3.58)**	–	**26.78[i] (25.08–28.47)**	y, **n**, **i**
	Rh	–	**24.41[i] (21.57–26.86)**	–	**2.88[i] (2.49–3.71)**	–	–	**i**
	Rh	-	-	-	5.17[x] (1.4–8.95)	-	-	x
	Ro	0.21[c]	3.35[c]	**0.4[i]**	3.45[c]	4.56[c]	35.3[c]	c, **i**
	Ro	**0.19[d] (0.14–0.27)**	**7.71[d] (6.76–8.21)**	–	0.34[z] (0.34–5.04)	**0.91[i] (0.81–1.05)**	**9.72[n] (8.90–10.79)**	**d**, z, **i**, **n**
	Ro	**0.81[i] (0.78–0.80)**	12.8[y]	–	**2.33[n] (1.64–3.01)**	**1.62[d] (1.42–1.85)**	**14.64[d] (12.82–17.44)**	**i**, y, **n**, **d**
	Ro	**1.13[n] (1.10–1.14)**	**16.39[n] (14.04–18.96)**	–	3.4[x] (3.4–50)	**9.02[n] (8.04–9.81)**	22.92[y]	**n**, x, y
	Ro	2.1[y]	38.26[x] (1.11–75.4)	-	5.2[y]	-	**79.52[i] (76.11–82.84)**	y, x, **i**
	Ro	–	**253[i] (248.4–258.40)**	–	**5.75[d] (5.19–6.37)**	–	–	**i, d**
	Ro	–		–	**38.67[i] (32–48)**	–	–	i

*a)Cozza et al., 2013 (Ionian Sea, Italy), b) Di Leo et al., (2013) (Taranto Gulf, Italy), c) Di Leo et al., (2013) (Vendicari Sicily, Italy), **d) This Study (Paleochori, Greece),** e) Bonanno and Raccuia (2018) (Sicily, Italy), **f)** Vizzini et al. (2013) **(Vulcano, Italy),** g) Vizzini et al., (2013) (Sicily), h) Campanella et al., (2001) (Sicily), **i) This study (Vulcano), j) This study (Ischia),** k)Bonanno and Di Martino, 2017 (Vendicari, Sicily), **l)This study (Methana, Greece), m) This study (Panarea, Italy), n) This study (Adamas, Greece),** o) Renzi et al., (2011) (Panarea, Italy), p) Hodkinson et al., (1994) (Hellenic Volcanic Arc, Greece), q)Bravo et al., (2016) (Tyrrhenian Sea, Italy), r) Constantini et al., 1991 (Italy), s)Baroli et al., (2001) (North Sardinia, Italy), t) Catsiki and Bei (1992) (Aegean Sea, Greece), u) Conti et al., (2010) (Linosa island, Italy), v)Conti et al., (2007) (Ustica island, Italy), w) Pergent and Pergent-Martini (1999) (Ischia, Italy), x) Catsiki& Panayotidis, 1993 (Aegean Sea, Greece), y) Nicolaidou and Nott (1998) (North Evvoikos Gulf, Greece), z) Malea and Kevrekidis (2013) (Thessaloniki Gulf, Greece).

Orlando-Bonaca, 2017). Higher accumulation can lead to metal stress once threshold levels are reached and affect the seagrass physiological processes (Olivé et al., 2017). However, it is difficult to measure toxic effects of metals on seagrass in *in-situ* conditions due to variable environmental settings, but few *ex-situ* studies on metal toxicity have been conducted on *Cymodocea serrulata* (Prange and Dennison, 2000), *Halophila ovalis* and *H. spinulosa* (Prange and Dennison, 2000; Ambo-Rappe et al., 2011). Considering the observed results from these ex-situ metal toxicity studies, there is a possibility that elements such as Cu and Pb at the CO_2 seeps may affect *P. oceanica* and *C. nodosa* photosynthesis as well as root and leaf structures (Prange and Dennison, 2000; Ambo-Rappe et al., 2011). This may be why seagrasses are abundant at some seeps but not at others.

Conclusion

We observed that Greek and Italian marine CO_2 seeps had elevated levels of trace elements in sediments compared to reference sites, and that this can be used to investigate interactions between seawater pH, element bioavailability and element accumulation within marine organisms. Care is needed when using volcanic CO_2 seeps as analogues for the effects of ocean acidification as increased levels of trace elements can be harmful to marine biota. In some cases, such as Ischia, high levels of Cu in the sediment were not accumulated in seagrass. At other sites low pH increased the accumulation of trace metals in seagrass, such as with Zn off Vulcano, Panarea and Ischia. Our research shows that ocean acidification can affect the bioaccumulation of some trace elements, which is relevant to agencies responsible for monitoring the effects of contamination in the marine environment.

Declaration of competing interest

The authors AK Mishra, Rui Santos and Jason Hall Spencer declare there is no conflict of interest between any organization or individuals regarding the manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2019.104810.

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