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Baseline

Metal(loid)s in superficial sediments from coral reefs of French Polynesia

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ABSTRACT

French Polynesia exhibits a wide diversity of islands and coral-reef habitats, from urbanized high islands to remote atolls. Here, we present a geographically extensive baseline survey that examine the concentrations of nine metals (Ag, Cd, Co, Cu, Fe, Mn, Ni, Pb and Zn) and one metalloid (As) in superficial sediments from 28 sites spread over three islands of French Polynesia. We used Principal Component Analysis, Pearson's correlation, hierarchical cluster analysis and generalized linear mixed-effect models on Pollution Load Index to investigate site contamination and metal(loid) associations. At most sites, metal(loid) concentrations were below commonly applied sediment quality guidelines. However, a few sites located near farming activities, river discharges and urbanized areas showed concentrations above these guidelines. This study provides critical baseline values for metal(loid) contaminants in this region and in coral-reef areas in general, and spur decreased discharge of metal(loid) contaminants in the anthropogenised areas of French Polynesia.

1.

Marine ecosystems have been experiencing increasingly frequent and severe environmental impacts due to growing anthropogenic activities (Halpern et al., 2008). Among these stressors, metal and metalloid – named hereafter metal(loid) - pollution has been recognized as an important threat to marine ecosystems for at least 40 years (Chapman et al., 2006; Stoeppler and Nürnberg, 1979). Global stressors (e.g. increasing seawater temperature and ocean acidification) can increase the toxicity of such chemical pollutant towards marine organisms (Noyes et al., 2009), and, in turn, such toxicants can reduce the resistance and resilience of marine organisms to global stressors (Negri et al., 2011; Negri and Hoogenboom, 2011). Metal(loid) pollution may therefore alter the ability of organisms to cope with climate change, and vice-versa. While global stressors are difficult to manage, efficient local management actions to reduce metal(loid) pollution may enhance the resistance of marine organisms to current and predicted environmental conditions. However, this requires baseline information on the metal(loid) concentrations in marine ecosystems. Sediments are good indicators of pollution history as they are major sinks of metal(loid)s following their discharge in the environment, whether the sources are natural or anthropogenic (Rodriguez-Barroso et al., 2010).

Coral reefs in tropical areas suffer increasing development of human activities that results in metal(loid) discharges in coastal areas (van Dam et al., 2011). Data related to metal(loid) concentrations in sediments from coral reef areas have focused on a few regions such as Australia (Haynes and Johnson, 2000; Reichelt and Jones, 1994), Caribbean and Central America (Gibbs and Guerra, 1997; Guzmán and Jiménez, 1992), Guam (Denton et al., 2005), Hawaii (Hédouin et al., 2009b, 2011a), New Caledonia (Hédouin et al., 2011b, 2009a; Metian et al., 2008), Fiji (Morrison et al., 2001), Samoa (Morrison et al., 2010) and Venezuela (Bastidas et al., 1999). However, such data is limited in French Polynesia, a region as vast as Europe in the South Pacific Ocean and composed of 118 islands with a wide diversity of island types from high islands (e.g. Tahiti and Mo'orea, Society archipelago) to atolls (e.g. Rangiroa, Tuamotu archipelago) (ORSTOM, 1993). Metal(loid) concentrations in the sediment were only investigated through two single cores performed at two sites in Tahiti, within the harbor of Papeete (Fichez et al., 2005). Moreover, while organic and metal(loid) concentrations have also been examined in coral reef organisms at Mo'orea (Fey et al., 2019; Roche et al., 2011), data related to the sediment are actually limited to the sedimentary organic matter at a single site (Fey et al., 2019). The current lack of information on the metal(loid) concentrations in the sediments of French Polynesia coral reefs represents significant hurdles to determine whether the increasing development of anthropogenic activities in this region (Thiault et al., 2018) is

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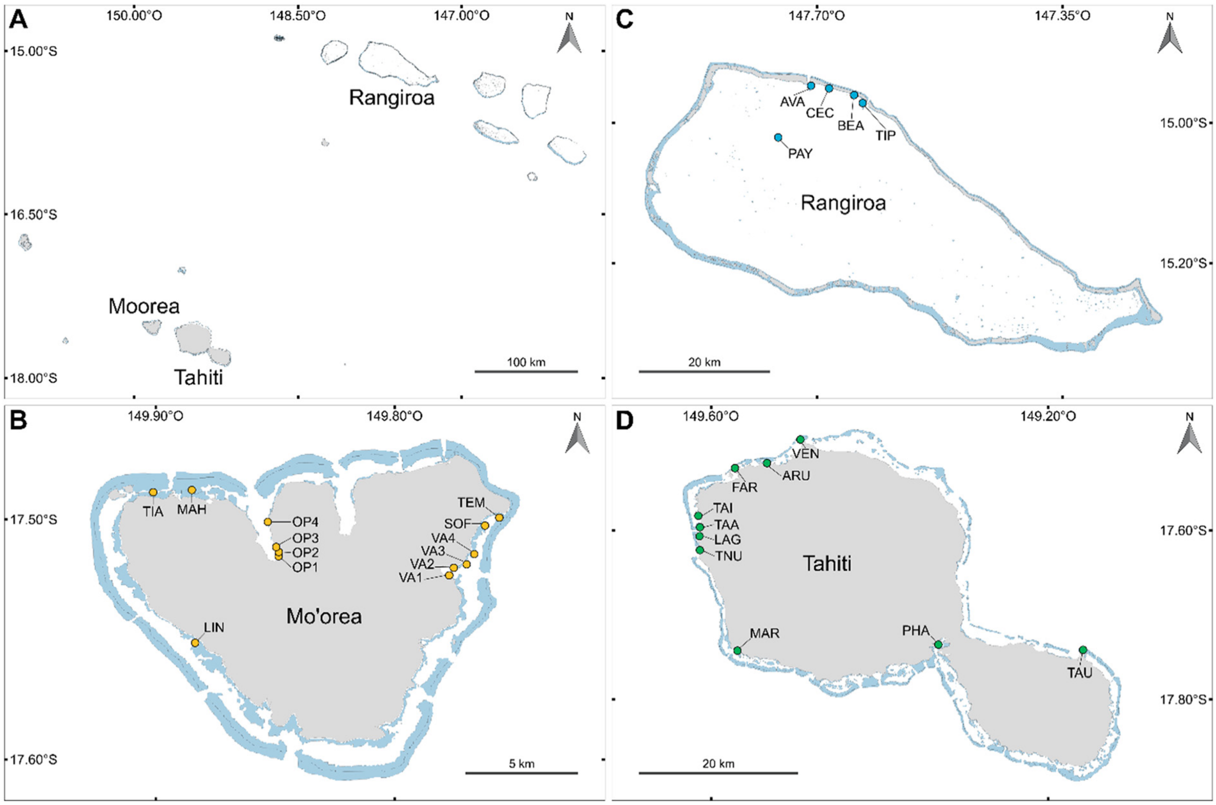

Fig. 1. Location of the sampling sites in Mo'orea, Rangiroa and Tahiti. A: Location of the three islands in French Polynesia. B–D: Location of the sampling sites in Mo'orea (yellow), Rangiroa (blue) and Tahiti (green), respectively. Gray zones indicate land areas and blue zones indicate coral reef areas. Site codes used in the other figures and tables of this manuscript correspond to the island initial followed by the site names presented in B–D.

associated with an increased contamination in metal(loid)s.

In this context, we measured the concentrations of ten metal(loid)s (Ag, As, Cd, Co, Cu, Fe, Mn, Ni, Pb, and Zn) in superficial sediments from 28 sites spread over the coral reefs of three contrasted islands of French Polynesia (Mo'orea, Rangiroa and Tahiti; Fig. 1). Tahiti is the most populated island of French Polynesia with 189,517 inhabitants (Insee/Ispf, 2017). It is located in the Society Archipelago and has two parts: a main island called Tahiti Nui and a peninsula called Tahiti Iti. Industrial activities are mainly located in the vicinity of the capital (Papeete) on Tahiti nui. Most of the population also inhabit Tahiti nui (89%, Insee/Ispf, 2017). Nonetheless, it has developed rapidly in the recent years, and predominantly associated with the construction of several goods and services establishments at Taravao (Tahiti Iti main city). Mo'orea is also located in the Society Archipelago, 17 km northwest of Tahiti. It is the second most urbanized island of French Polynesia, with 17,816 inhabitants (Insee/Ispf, 2017). Mo'orea is far less industrialized than Tahiti, restricted to some intensive agriculture activities (e.g. pineapple production), a fruit juice processing factory and most of the boat traffic related to ferries and daily transfers from Papeete to Vaiare harbor. Rangiroa is the largest atoll of French Polynesia, located in the Tuamotu Archipelago at approximately 430 km northeast of Papeete. There is no industry on the island and limited anthropogenic activities (i.e. pearl production, fishing, and tourism, all operating on a small scale) with 3657 inhabitants (Insee/Ispf, 2017).

Sampling sites were selected along the coasts of Tahiti (10 sites), Mo'orea (13 sites) and Rangiroa (5 sites) (Fig. 1), by choosing sites with various anthropogenic inputs, i.e. potentially contaminated sites near the river mouth in the vicinity of cities, industries, harbors and marinas, and suitable reference sites close to remote beaches and reefs supposedly less contaminated (Table S1). Sediment samples were collected from September to November 2012. At each site, three superficial sediment samples (i.e. triplicates), each of 50 to 75 g wet weight (ww), were collected in acid-washed plastic bags by scuba diving. Following collection, samples were stored in a freezer at −20 °C until being processed for contaminant analyses. Before analysis, each sample was screened through a 1 mm sieve to remove large particles (this < 1 mm fraction constitutes 80–90% of the total sediment of each sample, and preliminary observations showed that the < 63 mm fraction represented < 0.2% of the total sediment). Aliquots of 150–250 mg were microwave digested in a mixture of 3 ml of suprapure nitric acid (VWR/Merck) and 1 ml of suprapure hydrochloric acid (VWR/Merck), and then diluted to 25 ml with MilliQ-quality water. Metal(oid)s were then analyzed by Inductively Coupled Plasma Atomic Emission Spectrometry (Varian Vista-Pro ICP-OES) and Mass Spectrometry (Thermo-FisherScientific XSeries II ICP-MS). Certified Reference Materials (CRM) provided by the National Research Council Canada were treated and analyzed in a similar way as the samples. The CRM were dogfish liver DOLT-4, lobster hepatopancreas TORT-2 and marine sediment MESS-3 and the results from their analysis indicated a recovery ranging from 80 to 107% (Table S2).

The concentrations of metal(loid)s measured in superficial sediments from 28 sites in French Polynesia coral reefs ranged from 0.01 to 1.18 µg g^{-1} dw (dry weight) for Ag, 0.21 to 27.3 µg g^{-1} dw for As, 0.01 to 0.20 µg g^{-1} dw for Cd, 0.46 to 42.2 µg g^{-1} dw for Co, 0.14 to 35.1 µg g^{-1} dw for Cu, 10.4 to 32,513 µg g^{-1} dw for Fe, 0.11 to 549 µg g^{-1} dw for Mn, 0.04 to 325 µg g^{-1} dw for Ni, 0.02 to 21.5 µg g^{-1} dw for Pb and 3.03 to 194 µg g^{-1} dw for Zn (Table 1).

Metal(loid) concentrations were then compared to three sediment quality guidelines: the Threshold Effect Level (TEL), the Effect Range Low (ERL), and the Effect Range Median (ERM) (Buchman, 2008; Long et al., 1995), which define concentrations that have adverse effects on biological organisms (Supplementary Text 1). Concentrations were below these sediment quality guidelines for all sites in Rangiroa and most sites in Mo'orea and Tahiti (Fig. S1). In Mo'orea, the sites with

Table 1
Metal(loid) concentrations in superficial sediments from coral reefs of French Polynesia. Data are expressed in μg g^{-1} dw (dry weight), and correspond to the mean (sd) of $n = 3$ samples for each site (i.e. triplicates). § indicates sd < 0.005. Sites are indicated by the initial of the island, followed by the site name as in Fig. 1.

Site	Ag	As	Cd	Co	Cu	Fe	Mn	Ni	Pb	Zn
M-LIN	0.03	1.43	0.02	3.91	0.40	550	8.81	0.81	0.18	4.43
	(§)	(0.11)	(§)	(0.12)	(0.02)	(19.8)	(0.90)	(0.12)	(0.01)	(0.11)
M-MAH	0.11	0.22	0.02	18.4	0.39	109	5.35	0.04	0.03	4.52
	(§)	(0.01)	(§)	(0.66)	(0.03)	(3.19)	(0.79)	(0.01)	(0.01)	(0.06)
M-OPU1	1.18	16.2	0.20	14.6	31.7	28,585	512	62.6	2.01	60.6
	(0.10)	(0.12)	(0.02)	(0.74)	(17.4)	(1157)	(23.8)	(3.57)	(0.09)	(5.64)
M-OPU2	0.48	7.87	0.08	5.95	14.2	32,513	549	68.9	0.91	77.3
	(0.04)	(1.42)	(0.01)	(0.86)	(0.24)	(765)	(13.8)	(2.35)	(0.15)	(4.91)
M-OPU3	0.15	2.48	0.04	14.7	0.92	2,163	28.0	2.30	0.45	5.79
	(§)	(0.15)	(0.02)	(0.25)	(0.12)	(171)	(2.84)	(0.63)	(0.08)	(1.15)
M-OPU4	0.12	2.95	0.02	12.3	0.56	2,007	49.9	2.50	0.92	4.61
	(0.01)	(0.36)	(§)	(0.73)	(0.01)	(145)	(2.67)	(0.60)	(0.10)	(0.53)
M-SOF	0.03	0.81	0.02	3.81	0.23	236	2.65	0.17	1.17	4.42
	(§)	(0.02)	(0.01)	(0.05)	(0.01)	(20.2)	(0.18)	(0.14)	(1.04)	(0.13)
M-TEM	0.02	0.56	0.04	3.97	0.25	55.1	2.09	0.06	0.17	4.23
	(§)	(0.03)	(0.02)	(0.05)	(§)	(5.29)	(0.19)	(0.03)	(0.01)	(0.21)
M-TIA	0.01	7.58	0.01	0.47	0.76	197	4.55	1.51	3.03	3.03
	(0.01)	(0.34)	(0.01)	(0.02)	(0.03)	(13.1)	(0.38)	(0.07)	(0.14)	(0.14)
M-VAI1	0.21	17.8	0.07	4.48	1.89	6,727	97.8	6.98	0.89	14.7
	(0.02)	(2.03)	(0.01)	(0.13)	(0.41)	(531)	(5.09)	(0.72)	(0.10)	(1.43)
M-VAI2	0.09	12.3	0.03	2.34	4.80	5,688	83.7	8.24	3.28	18.6
	(0.02)	(0.66)	(0.01)	(0.52)	(0.54)	(756)	(2.84)	(1.37)	(0.04)	(2.73)
M-VAI3	0.02	8.00	0.02	0.53	0.80	1,233	31.1	2.21	3.20	3.20
	(§)	(0.17)	(§)	(§)	(0.02)	(70.1)	(1.52)	(0.28)	(0.07)	(0.07)
M-VAI4	0.02	7.88	0.02	0.50	0.79	518	8.06	1.67	3.15	3.15
	(0.01)	(0.45)	(0.01)	(0.01)	(0.04)	(153)	(1.72)	(0.08)	(0.18)	(0.18)
R-AVA	0.03	0.38	0.02	5.39	0.28	82.2	0.82	0.04	0.45	4.19
	(§)	(0.10)	(§)	(0.10)	(0.01)	(36.7)	(0.09)	(0.01)	(0.07)	(0.16)
R-BEA	0.03	0.59	0.04	5.24	0.25	12.8	0.54	0.07	0.14	5.00
	(§)	(0.13)	(0.02)	(0.08)	(0.01)	(4.86)	(0.09)	(0.04)	(0.01)	(1.58)
R-CEC	0.02	0.68	0.02	4.01	0.21	90.3	1.30	0.04	0.13	4.32
	(§)	(0.08)	(§)	(0.05)	(§)	(24.5)	(0.20)	(§)	(0.01)	(0.07)
R-PAY	0.03	0.21	0.02	5.31	0.17	31.8	0.30	0.04	0.02	4.17
	(§)	(0.02)	(§)	(0.05)	(0.02)	(48.0)	(0.29)	(§)	(§)	(0.41)
R-TIP	0.03	0.23	0.02	5.05	0.14	10.4	0.11	0.05	0.03	4.51
	(§)	(0.01)	(§)	(0.14)	(0.01)	(0.29)	(§)	(0.01)	(0.01)	(0.03)
T-ARU	0.03	8.30	0.02	3.35	1.62	4,648	57.9	12.4	3.29	8.53
	(0.01)	(0.08)	(§)	(0.25)	(0.25)	(342)	(0.46)	(1.02)	(0.08)	(0.66)
T-FAR	0.06	8.07	0.06	20.8	35.1	20,191	286	118	21.5	194
	(0.01)	(0.55)	(0.04)	(1.40)	(8.60)	(1,141)	(19.4)	(10.5)	(11.8)	(112)
T-LAG	0.05	8.45	0.02	20.8	11.4	18,820	227	107	3.31	40.7
	(0.01)	(0.99)	(0.01)	(3.60)	(1.24)	(1,782)	(30.9)	(24.8)	(0.18)	(7.98)
T-MAR	0.02	8.02	0.02	1.26	0.80	1,797	18.5	4.70	3.21	3.21
	(§)	(0.37)	(§)	(0.30)	(0.04)	(145)	(3.46)	(1.57)	(0.15)	(0.15)
T-PHA	0.03	27.3	0.02	5.69	1.88	7,352	130	11.4	3.21	6.81
	(0.01)	(1.10)	(§)	(0.58)	(0.43)	(324)	(21.8)	(1.96)	(0.04)	(0.77)
T-TAA	0.07	8.08	0.03	18.5	22.1	16,991	252	118	3.23	28.1
	(0.01)	(0.08)	(0.01)	(4.05)	(3.46)	(1,770)	(35.7)	(34.1)	(0.03)	(3.60)
T-TAI	0.02	8.21	0.02	0.46	0.82	955	18.2	1.97	3.28	3.28
	(§)	(0.07)	(§)	(0.11)	(0.01)	(411)	(8.64)	(0.28)	(0.03)	(0.03)
T-TAU	0.02	8.13	0.02	1.76	0.95	2,427	29.1	8.47	3.25	4.58
	(§)	(0.11)	(§)	(1.35)	(0.25)	(1,305)	(15.9)	(6.22)	(0.05)	(1.99)
T-TNO	0.04	7.98	0.02	42.2	6.62	25,287	454	325	5.85	50.0
	(§)	(0.13)	(§)	(4.00)	(1.06)	(1,107)	(26.6)	(38.3)	(0.03)	(0.86)
T-VEN	0.04	8.25	0.02	27.5	8.12	21,142	308	185	3.30	35.5
	(§)	(0.28)	(§)	(1.83)	(0.65)	(651)	(16.7)	(23.6)	(0.11)	(1.01)

metal(loid) concentrations higher than these thresholds were M-OP1 (Ni concentration above ERM, Ag, As and Cu concentrations above ERL), M-OP2 (Ni concentration above ERM and As concentration above ERL), M-TIA (As concentration above TEL) and M-VA1, M-VA2, M-VA3 and M-VA4 (As concentration above ERL) (Fig. S1). In Tahiti, all sites showed As concentrations above ERL and T-FAR, T-LAG, T-TAA, T-TNO and T-VEN exhibited Ni levels above ERM. Also, at T-FAR, Cu and Zn concentrations exceeded ERL and Pb concentration exceeded TEL (Fig. S1).

Based on the Kaiser criterion (i.e. eigenvalue ≥1, Kaiser, 1960), three principal components (PCs) on metal(loid) concentrations in sediments were retained, accounted for 86% of the total variance (Table S3). The Principal Component Analysis (PCA) revealed a largely unidimensional variation in sediment contamination across sites, with PC1 accounting for 55.6% of the total variance, while PC2 and PC3 accounted for 19.4% and 12.0%, respectively, of the total variance (Table S3 and loading factors are available in Table S4). PC1 is a good indicator of the overall level of contamination, with a group of almost non-contaminated sediments on the left, and two groups of more contaminated sediments on the right (Fig. 2A). Further cluster analyses confirmed these major groups of sites, with a first group that includes M-OP1, M-OP2, T-FAR, T-LAG, T-TAA, T-TNO and T-VEN, and a second group that includes all the other sites, and in particular all the sites from Rangiroa (Fig. 2B). PC2 and PC3 reflect the differences between Mo'orea and Tahiti in terms of contamination by clustering metal(loid)s in three groups (Figs. 2A and S2A−B). The first group comprises Ag, As

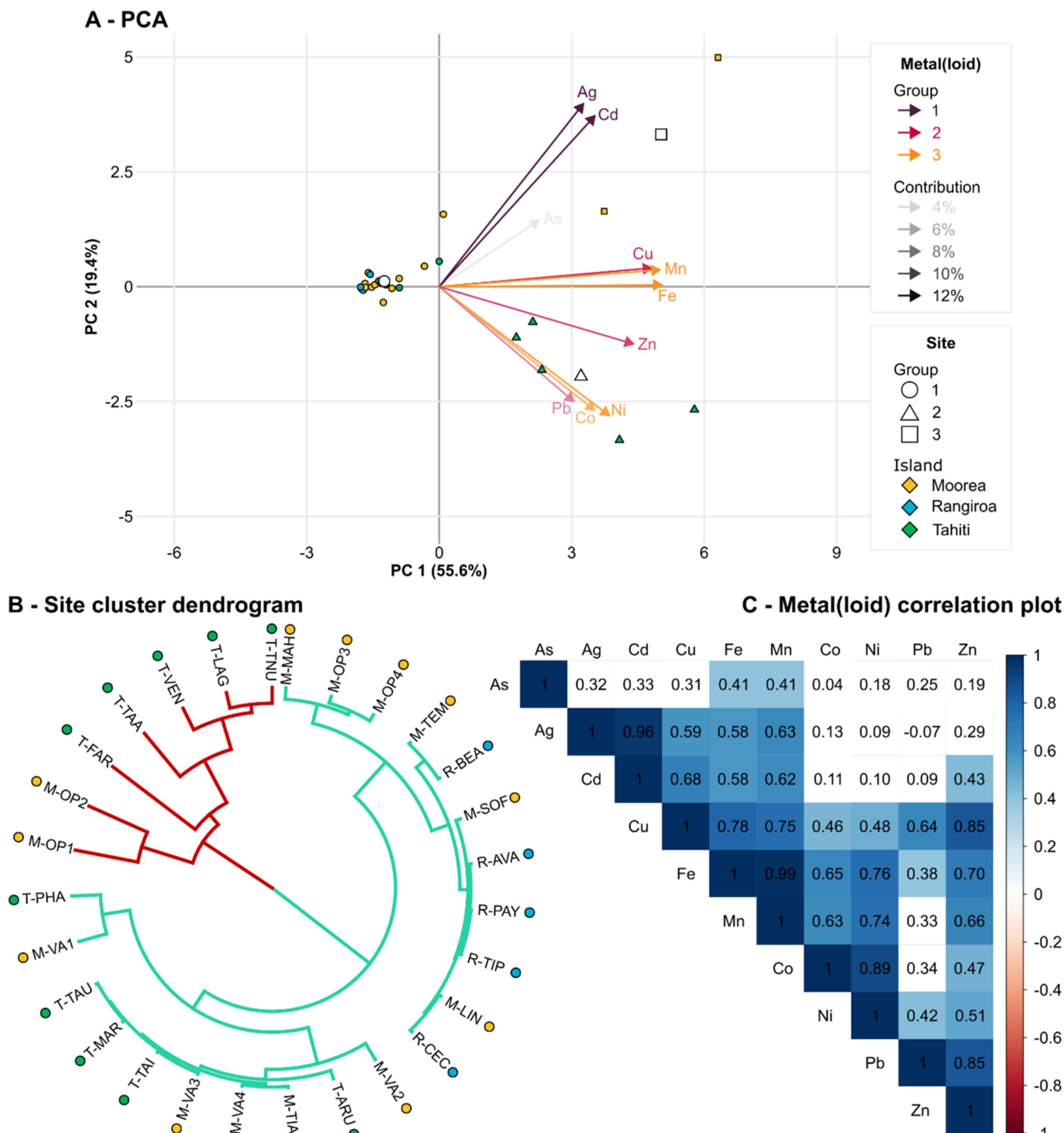

Fig. 2. Site and metal(loid) grouping based on the concentrations measured in the sediment. A: Principal Component Analysis (PCA) of sites (as individuals) and metal(loid)s (as variables) according to metal(loid) concentrations in the 28 sites from Mo'orea, Rangiroa and Tahiti. The three main groups of metal(loid)s and sites have been added. B: Cluster classification of sites based on metal(loid) concentrations. The number of clusters was measured using the gap statistic. Sites are indicated by the initial of the island, followed by the site name as in Fig. 1. C: Correlation plot of metal(loid)s based on their concentrations across sites. Data indicate the Spearman r correlation coefficients.

and Cd and drives the contamination in Mo'orea (Fig. 2A). The second group comprises Cu, Pb and Zn, and the third group comprises Co, Fe, Mn and Ni, and these groups differ on PC3 (Fig. S2A–B) and drive the contamination in Tahiti, in particular at T-FAR for the second group. Strong positive ($r > 0.63$, Fig. 2C) and significant ($P < .001$, Table S5) correlations were indeed observed between Ag and Cd, between Cu, Pb and Zn, and between Co, Fe, Mn and Ni (Fig. 2C, Table S5).

The degree of contamination of the different sites was examined using the Pollution Load Index (PLI) described by Tomlinson et al. (1980). PLI was determined as the nth root of the product of the n Contamination Factor (CF) of the n elements: PLI = $\left(\prod_i^n CF_i\right)^{1/n}$, and $CF_i = \frac{C_i}{C_b}$, where C_i is the concentration of the metal(loid) i, and C_b is the background concentration of this metal(loid). Since the concentrations measured in sediments from Rangiroa are lower than those generally used as background values (Bowen, 1979), the means of these concentrations for each metal(loid) were used as background values in the PLI calculations performed in this study. Pollution Load Index (PLI) varied across sites ($\chi_{27}{}^2 = 15{,}617$, $P < .001$; Gamma Generalized

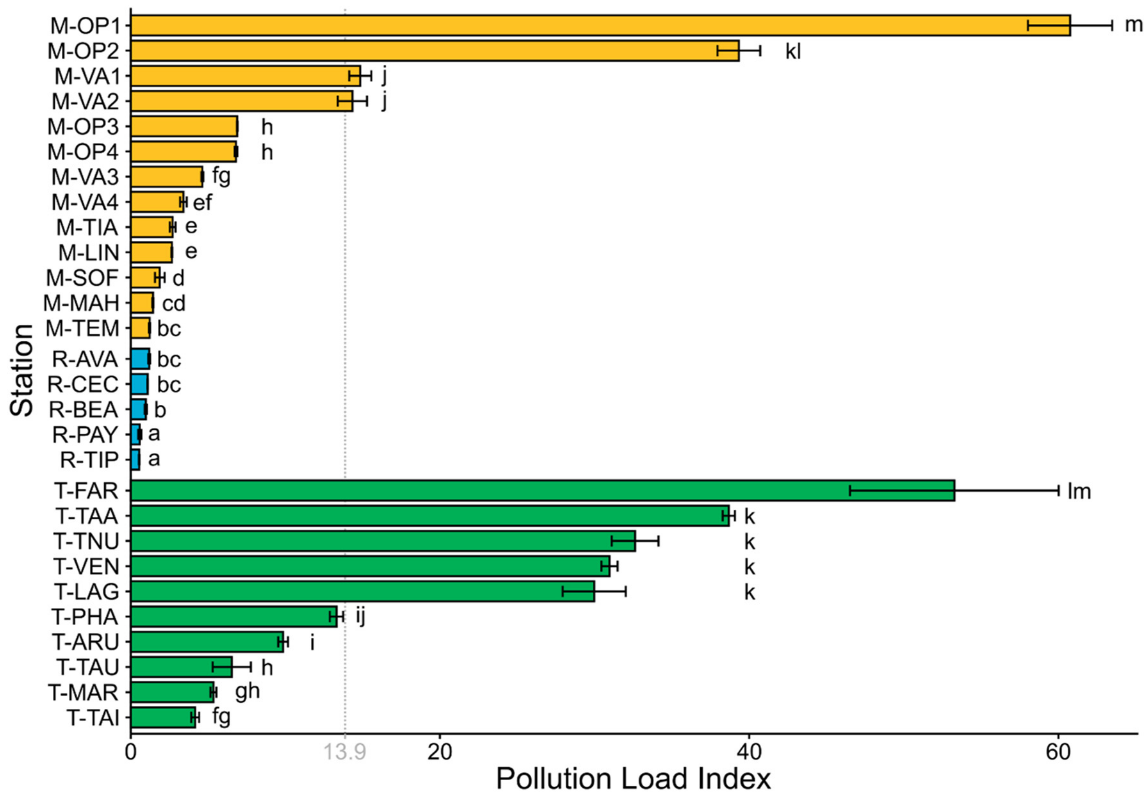

Fig. 3. Pollution Load Index (PLI) of reef superficial sediments 28 sites across French Polynesia. Sites from Mo'orea, Rangiroa and Tahiti are indicated by orange, blue and green bars, respectively. Sites are indicated by the initial of the island, followed by the site name as in Fig. 1. Bars and error bars indicate mean ± se ($n = 3$). The dashed line indicates the mean PLI value of all sites. Letters on the right of each bar indicate statistically different groups according to Tukey posthoc-test following Gamma Generalized Linear Mixed-Effect Model.

Linear Mixed-Effects Model, Supplementary Text 2, Bolker et al., 2009), with the same trends and clusters as in Figs. 2 and S1. M-OP1, M-OP2 and T-FAR exhibited the highest PLI, followed by T-TAA, T-TNU, T-VEN and T-LAG, and then by M-VA1 and M-VA2 (Fig. 3). Other sites showed a PLI under the average PLI (when combining all sites), and the lowest PLI were observed for sites at Rangiroa (Fig. 3).

This study provides the first large-scale baseline of metal(loid) concentrations in superficial sediments from coral reefs of three islands of French Polynesia, highlighting various degrees of contamination across and within islands. Our results highlight a clear gradient of contamination in metal(loid)s in superficial sediments of French Polynesia, from pristine coral reef sites (e.g. Rangiroa) to sites with higher river discharge and anthropogenic influence (e.g. Mo'orea and Tahiti). In Rangiroa, none of the metal(loid) concentrations exceeded any of the sediment quality guidelines. These concentrations were lower than those reported in most other tropical areas (Denton et al., 2005; Morrison et al., 2010), in particular at similar remote and non-polluted sites (Denton et al., 2006, 2005; Denton and Morrison, 2009). Further, they are lower than the classically used background values (Bowen, 1979), and therefore represent important baseline values of metal(loid) concentrations for sediments of French Polynesia but also for coral reef areas in general. Evaluating the metal(loid) concentrations in reef sediments from such remote environments is topical when one wants to assess the environmental effects of anthropogenic activities in more urbanized areas (Kadhum et al., 2015). In Mo'orea, a few sites also exhibited low concentrations of metal(loid) contamination and similar PLI as Rangiroa sites, while two other sites (M-OP1 and M-OP2, where no coral cover was present) showed the highest PLI of this study. In particular, Ni concentrations at M-OP1 and M-OP2 exceeded ERM and concentrations of Ag and As exceeded the records from sediments of other coral reef regions (Bastidas et al., 1999; Denton et al., 2005; Guzmán and Jiménez, 1992; Haynes and Johnson, 2000; Hédouin et al., 2011b, 2009b; Metian et al., 2008; Morrison et al., 2010). Sediment contamination rapidly dropped further away in Opunohu Bay, as evidenced by the low metal(loid) concentrations recorded at M-OP3 and M-OP4, and the same decreasing contamination gradient was observed in Vaiare Bay (M-VA1 to M-VA4). These gradients are therefore probably linked to the discharge of sediments from the Opunohu and Vaiare streams but also to salinity shifts in Opunohu and Vaiare bays, which are known to affect metal(loid) solubilization, speciation, precipitation, diffusion and advection (Barletta et al., 2019; Coynel et al., 2016; de Souza Machado et al., 2016). In Tahiti, the highest contamination levels were observed in the sediments collected in Papeete (T-FAR, Table S1), the capital of French Polynesia. This site was the only one monitored in a previous study (Fichez et al., 2005), and we observed moderate increases in the concentrations of all the elements that examined in both this previous study and the current study. High concentrations of Co, Cu, Fe, Mn, Ni, and Zn were observed at 5 sites in Tahiti, with Ni concentrations exceeding the ERM and constituting a potential threat to marine organisms if bioavailable (Gissi et al., 2016).

PCA and correlation analyses can highlight which elements may originate from the same source (Yongming et al., 2006), but identifying those sources would require further research and additional data on sediment grain size, total organic carbon content, total nitrogen content, mineralogy, and origin (e.g. terrestrial vs. marine). Indeed, metal(loid) concentrations can be influenced by the structure and composition of the sediment itself, as well as by the geological characteristics of the island (Hédouin et al., 2009b). For instance, and in contrast with Rangiroa (Chevalier, 1973), high concentrations of Fe and Mn are expected in basaltic-rich volcanic islands with high terrestrial inputs such as Mo'orea and Tahiti (Fichez et al., 2005). The overall higher metal(loid) concentrations in the sediments from Tahiti and Mo'orea vs. Rangiroa could therefore be related to their river network and higher land surface areas (ORSTOM, 1993). Metal(loid) concentrations can also be associated with anthropogenic inputs, and our results are consistent with the fact that high concentrations of Co, Cu, Ni, and Zn are often associated with domestic discharges and industrial activities such as the presence of harbors and marinas (Fichez et al., 2005; Harris et al., 2001).

While highlighting the opportunity for further research regarding the sources of contamination, our study provides critical baseline values for the vast region of French Polynesia, and for coral reef areas in general. Our results emphasize the necessity to minimize the levels of metal(loid)s discharged in the marine environment of the most populated Islands in French Polynesia, where concentrations of certain metal(loid)s already exceed sediment quality guidelines, potentially threatening the health of coral reef organisms. This need is critical, especially as local stressors such as metal(loid) pollution may reduce the capacity of coral reefs to face the unprecedented changes associated with global warming and ocean acidification.

CRediT authorship contribution statement

Marc Besson: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing - original draft. **Marc Metian:** Conceptualization, Data curation, Methodology, Project administration, Resources, Supervision, Validation, Writing - review & editing. **Paco Bustamante:** Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Resources, Validation, Writing - review & editing. **Laetitia Hédouin:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Project administration, Resources, Validation, Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2020.111175.

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