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Level of contamination by metallic trace elements and organic molecules in the seagrass beds of Guadeloupe Island

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Abstract Seagrass bed ecosystems occupy the most important part of coastal shelf in the French West Indies. They also constitute nurseries for many invertebrates and fishes harvested by local fisheries. In Guadeloupe, coastal fish stocks are declining meanwhile several agroecosystems revealed to be heavily contaminated by pollutants (agricultural lands, rivers, mangroves, seagrass beds, and coral reefs). Considering these facts, a study of the contamination of seagrass beds (8000 ha) of the Grand Cul-de-Sac Marin (GCSM) bay was conducted on their sediments and marine phanerogams. The analyses concerned six metals (Cd, Cu, Hg, Pb, V, Zn), tributyltin, 18 polycyclic aromatic hydrocarbons (PAHs), eight polybrominated diphenyl ethers (PBDEs), 38 polychlorobiphenyls (PCBs), dithiocarbamates (CS2 residues), and 225 pesticide molecules.

Overall, the level of contamination of the seagrass beds was low for both sediments and phanerogams. Metallic trace elements were the main pollutants but with higher concentrations recorded in coastal sites, and their distribution can be explained by the proximity of river mouths and current patterns. The level of contamination was lower in plants than in sediments. However, the level of contamination between these two compartments was significantly correlated. The conclusion of this study is that, unlike other coastal ecosystems of Guadeloupe such as mangroves, the seagrass beds in the GCSM present a low degree of pollution. The observed level of contaminants does not seem to threaten the role of nursery played by the seagrass beds and does not likely present a risk for the reintroduction of manatees.

Keywords Seagrass beds · Antilles · Pollution · PAH · Metallic contaminants · Persistent organic pollutants

Introduction

The presence of pesticides in coastal marine ecosystems in the Caribbean has been reported since the early 1970s: McCloskey and Chesher (1971) measured 3–12 ppm of dichlorodiphenyltrichloroethane acid (DDT), 200 to 300 ppm dichlorodiphenyldichloroethylene (DDE) and 260–320 ppb of dieldrin in the coral *Acropora cervicornis* from Florida. They also observed significant amounts of DDT, dieldrin, and endrin in the barracuda (*Sphyraena barracuda*), still in Florida. Giam et al. (1973) also demonstrated the presence of organochlorines in grouper from the Gulf of Mexico and Florida, with doses increasing with the size of the fish. Glynn et al. (1995) found traces of chlordane, DDT, dieldrin, endrin, HCB, and chlordecone in virtually all major groups of marine reef in Florida—sponges (*Amphimedon compressa*), cnidarians (*Millepora alcicornis*, *Porites astreoides*), crustaceans (*Palinurus argus*), and fish (*Haemulon plumieri*).

Little is known about the level of contamination of marine food chains in the French West Indies, both in Guadeloupe and Martinique, and even less on the northern islands of St. Martin and St. Barthélemy.

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Approximately 9500 t of fish and 650 t of mollusks and crustaceans are harvested every year in Guadeloupe, and West Indians consume nearly 30 kg of fish per year (Anon 2003). Contaminants exported to the marine environment can have a direct impact on human health through the quality of the consumed products. Indirectly, they can have an impact on the ecosystem's functioning.

In Guadeloupe, pollution of banana field soils and aquatic environments by organochlorine insecticides (alpha-hexachlorocyclohexane (α-HCH), β-HCH, and chlordecone) already existed in 1977 (Snegaroff 1977; Cabidoche et al. 2009). The report of Kermarrec (1980) showed a significant biomagnification of perchlordecone in the tissues of aquatic animals at river mouths (i.e., 0.82 ppm in fish, 0.6 ppm in crabs, and up to 1.3 ppm in shrimps). More recently, Bonan and Prime (2001) demonstrated the existence of a pesticide contamination of river waters in Basse-Terre in Guadeloupe. The existence of a wide contamination of their food chains was also demonstrated (Monti 2001, 2005, 2006; Monti and Lemoine 2007; Coat et al. 2006, 2009, 2011). Bouchon and Lemoine (2003, 2007) studied the contamination of coastal marine ecosystems on the southeast coast of Basse-Terre, between Trois-Rivières and Goyave. That study revealed the presence of a few "old" molecules (DDT, HCH) but also chlordecone in the three coastal ecosystems (mangrove, seagrass beds, and coral reefs).

In Martinique, Pellerin-Massicote (1991) showed a significant contamination by organochlorine pesticides of mollusks, crustaceans, and fish from mangroves and seagrass beds in the Bay of Fort-de-France. Monti (2001) revealed the existence of a significant contamination of aquatic organisms in the pond of Salines related to vegetable agriculture. More recently, the existence of a pesticide pollution off the mouths of seven rivers of Martinique was also demonstrated (Bocquéné and Franco 2005; Coat et al. 2006). They also showed the existence of a correlation between heavy rains, which are likely to export carbamates to the coastal marine environment and a slower cholinesterase activity in surgeonfish (*Acanthurus bahianus*) and lobsters (*Palinurus argus*). Their work also revealed the presence of chlordecone in these two species, as well as in anchovies and tilapia. Others studies also dealt with the contamination of marine organisms (Bertrand et al. 2009, 2010, 2012, 2013; Bodiguel et al. 2011).

Among these studies, some have focused on the contamination of the sediments by polycyclic aromatic hydrocarbons (PAHs) and heavy metals, in Guadeloupe (Bernard 1995; Bernard et al. 1995; Ramdine et al. 2012) and in Martinique (Castaing et al. 1986; Pons et al. 1998; Mille et al. 2006; Robert 2012).

Despite their importance in the Lesser Antilles, there exists no study concerning the levels of contamination of marine phanerogams (*Thalassia testudinum* (Banks ex König) and *Syringodium filiforme* (Kützing)) in that region. Unfortunately, due to their proximity to the coast, they are directly threatened by pollution and contaminants coming from the land (see review by Rawlins et al. 1998; Ralph et al. 2007; Lewis and Devereux 2009). Moreover, the National Park of Guadeloupe is preparing the reintroduction in that bay of the manatee (*Trichechus manatus* (Linnaeus)) that disappeared from Guadeloupe at the beginning of the twentieth century. Manatees are mainly feeding on *Thalassia testudinum*. They swallow leaves, rhizomes, and roots, as well as sediments by inadvertence. An adult consumes about 30 to 35 kg of fresh seagrass per day. Their daily swimming range can encompass distances of 70 km (Hartman 1979). In the perspective of the reintroduction of that species, the contamination level of the seagrasses and their sediments is thus a major issue.

Thus, the present study aims at assessing the level of contamination by metallic trace elements, PAHs, and organic molecules of the seagrass beds (plant and sediments) in the Bay of the Grand Cul-de-Sac Marin.

Study area

In terms of occupied surface of the continental shelf, seagrass beds represent the main coastal marine ecosystem in the French West Indies (Courboulès et al. 1992; Manière et al. 1993; Bouchon et al. 2002; Hily et al. 2010). In Guadeloupe Island, most of the seagrass beds are located in the Bay of the Grand Cul-de-Sac Marin (GCSM) where they cover 8000 ha (Chauvaud et al. 2001). They are mainly composed with *Thalassia testudinum* (Banks ex König) and *Syringodium filiforme* (Kützing) or with a mix of these two species. This habitat constitutes nurseries for many juveniles of fish species (Aliaume et al. 1990; Baelde 1990; Bouchon-Navaro et al. 1992, 2004; Bouchon et al. 1994; Kopp et al. 2007, 2010). This bay is closed by the largest barrier reef in the Lesser Antilles (30 km long) which shelters coastal mangrove formations and well-developed seagrass beds in the lagoon (Fig. 1). The ecosystems of the bay benefit from several types of protection: National Parc of Guadeloupe, Man and Biosphere Reserves (MAB), and the Ramsar Convention on Wetlands. Moreover, the ecosystems of the bay bear a significant artisanal fishing pressure and an economy based on "green" tourism in full development.

Sampling techniques and analyses of contaminants

Samplings of the phanerogam plants and of sediment were realized in 15 sites distributed in the seagrass beds of the bay (Table 1). In each station, *Thalassia testudinum* plants were collected including leaves, rhizomes, and roots (pooled for analysis). In situ, they were cleaned from sediment, rinsed in seawater, and preserved in iceboxes. Three replicate samples (referenced A, B, C) were collected by site. When

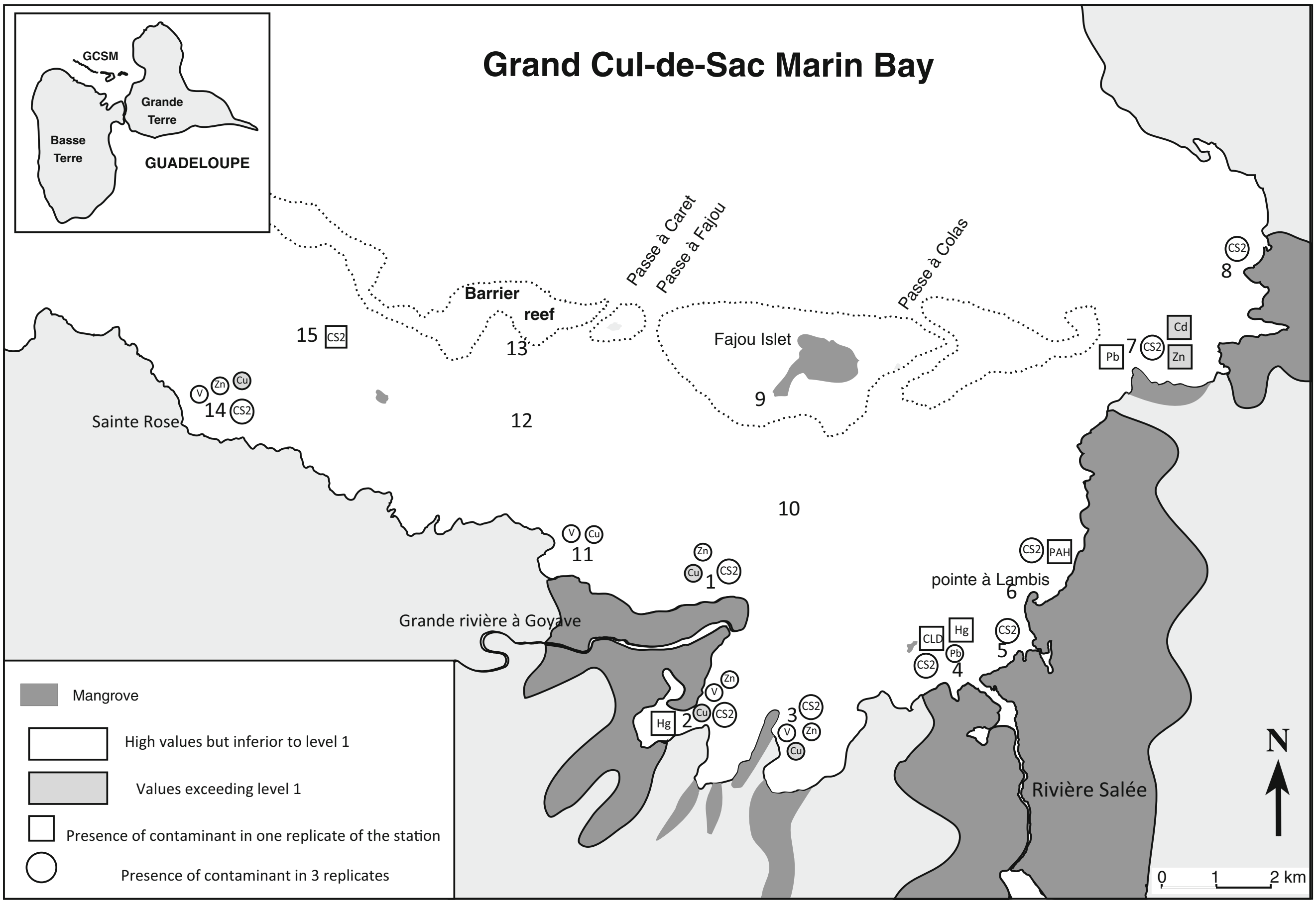

Fig. 1 Distribution of the main contaminants in the seagrass beds sediments in the GCSM Bay of Guadeloupe.

present, the same type of sampling was made for *Syringodium filiforme*. The nature of the sediments in the bay varies from terrestrial clay near the shore to coral calcareous sand near the barrier reef. Sediments were collected with a hand corer, and only the upper 5 cm of the core were kept for analysis. Three replicate samples were also collected in each site. Back to the

Table 1 Characteristics and location of the stations studied in the Bay of the Grand Cul-de-Sac Marin (*Thal Thalassia, Syr Syringodium*)

N°	Stations	Seagrass bed	Substrate	Latitude	Longitude
1	Grande Rivière à Goyave	*Thal+ Syr*	Mud	16° 18.304′	61° 36.271′
2	Pointe Pasquereau	*Thal*	Terrigenous red clay	16° 16.750′	61° 36.701′
3	Pointe à Nègre	*Thal+ Syr*	Mud	16° 16.878′	61° 35.956′
4	Mouth of Rivière-Salée	*Thal*	Mud+*Halimeda*	16° 17.108′	61° 33.748′
5	Belle Plaine	*Thal*	Mud+*Halimeda*	16° 17.695′	61° 32.704′
6	Pointe Lambis	*Thal+ Syr*	Muddy sand+*Halimeda*	16° 18.286′	61° 32.673′
7	Pointe J’ai Fouillé	*Thal*	Mud	16° 20.029′	61° 32.080′
8	Pointe à Retz	*Thal*	Muddy sand+*Halimeda*	16° 21.917′	61° 30.152′
9	East point of Fajou Islet	*Thal*	Muddy coral sand	16° 20.562′	61° 35.629′
10	Cay south of Fajou Islet	*Thal*	Muddy coral sand	16° 19.254′	61° 34.792′
11	Pointe Dupuis (Morne Rouge)	*Thal*	Mud+*Halimeda*	16° 18.400′	61° 38.080′
12	îlet La Biche	*Thal*	Muddy coral sand	16° 20.327′	61° 38.955′
13	West of îlet Caret	*Thal*	Coral sand	16° 21.535′	61° 38.324′
14	Rivière of Sainte-Rose	*Thal+ Syr*	Mud+*Halimeda*	16° 20.120′	61° 42.060′
15	Îlet Blanc du Carénage	*Thal+ Syr*	Muddy coral sand	16° 20.530′	61° 41.240′

laboratory, plants and sediment samples were weighted and dried at 48 °C (in order to avoid mercury sublimation) until mass stabilization. All samples were sent to La Drome laboratory for the analysis of six metals (Cd, Cu, Hg, Pb, V, Zn), tributyltin, 18 PAHs, eight polybrominated diphenyl ethers (PBDE), 38 polychlorobiphenyls (PCB), dithiocarbamates (CS2 residues), and 225 pesticide molecules. The complete list of analyzed molecules is available from the authors.

The Mantel test of matrix correlation was used to compare the level of contamination by metal trace elements of the sediments versus the contamination of phanerogams.

Results

Contamination of sediments

The contamination of sediment by metallic trace elements was examined in reference to the work of the group GÉODE [1] that defined two series of threshold values for metallic elements and PAHs considered as dangerous for the environment (Tables 2 and 3). Beyond level 1, the sediments are considered as "noncontaminated". Between levels 1 and 2, sediments are considered as "contaminated" and thorough studies must be undertaken before dredging and dumping. Above level 2, it is excluded to dump this type of sediment into the sea.

The results concerning the contamination of sediments are gathered in Table 4. The table presents only the contaminants for which significant results have been detected.

Contamination of sediments by metallic trace elements

The results concerning the contamination of sediments by metallic elements in the GCSM Bay are summarized in Fig. 2. Considering Table 2 as a reference, the levels of contamination observed were generally low. The values for cadmium (Fig. 1, Table 4) were below the level of quantification, except for station 7 where one of the three replicates presented a value of 1.8 mg kg^{-1}. For copper, stations 1, 2, 3, and 14 present replicates with values reaching level 1 from GÉODE recommendations (45 mg kg^{-1}). The concentrations of mercury were generally low, except for one replicate from station 2 (0.27 mg kg^{-1}) and one from station 4 (0.11 mg kg^{-1}). For lead, the values measured were low, with the exception of station 4 (replicates between 17 to 26.8 mg kg^{-1}) and station 7 where one replicate reached 20.8 mg kg^{-1}. Considering zinc, the most important values (still inferior to level 1) were found in stations 1, 2, 3, 4, and 14 (between 37.9 and 94.9 mg kg^{-1}). Station 7 presented a replicate with 447.6 mg kg^{-1}.

[1] GÉODE : *Groupe d'Étude et d'Observation sur les Dragages et l'Environnement (Group of study and Observations on dredging and on Environment).*

Table 2 Maximum levels L1 and L2, proposed by the group "GÉODE" concerning the contamination by metals of marine, estuarian, and salted sediments (mg kg^{-1} D. S.)

Metals	Level 1 (L1)	Level 2 (L2)	Ground noise
Cadmium (Cd)	1.2	2.4	0.5
Copper (Co)	45.0	90.0	35.0
Mercury (Hg)	0.4	0.8	0.2
Lead (Pb)	100.0	200.0	47.0
Zinc (Zn)	276.0	552.0	115.0

Vanadium constitutes the most important metallic contaminant of the seagrass bed sediment in the GCSM Bay. In stations 1, 2, 3, and 11, concentrations fluctuated between 103 and 353 mg kg^{-1}. At station 14 (mouth of the river of Sainte-Rose), values of vanadium fluctuated between 384 and 638 mg kg^{-1}.

Contamination of sediment by PAHs

Concerning the PAHs, a station (station 4, located near the mouth of the Rivière-Salée) presented a contamination of its sediments by several PAHs with values ranging from 12 to 24 µg kg^{-1} (benzo(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(ghi)perylene, and indeno(1,2,3-cd)pyrene). Moreover, at station 6, one sediment replicate contained 24 µg kg^{-1} of benzo(a)pyrene. With the exception of these two stations, seagrass sediments of the other sites studied in the GCSM Bay are free from traces of PAHs.

Contamination of sediment by pesticides and their residues

Among the 226 molecules of pesticides and other organic contaminants tested, only chlordecone and dithiocarbamates residues (CS2) appeared in the seagrass bed sediment in the GCSM Bay. Chlordecone appeared in one replicate of station 4 (mouth of the Rivière-Salée) with a value of 11 µg kg^{-1} of dry sediment. Pollution by dithiocarbamates estimated by

Table 3 Maximum levels L1 and L2, proposed by the group "GÉODE" concerning the contamination by PAHs of marine, estuarian, and salted sediments (mg kg^{-1} D. S.)

PAHs	Level 1 (L1)	Level 2 (L2)
Fluoranthene	0.4	5
Benzo(b)fluoranthene	0.3	3
Benzo(k)fluoranthene	0.2	1
Benzo(a)pyrene	0.2	1
Benzo(g,h,i)perylene	0.2	1
Indeno(1,2,3-c,d)pyrene	0.2	1

Table 4 Results of the analyses of sediments concerning metal trace elements (mg kg^{-1}of dry weight), PAHs (μg kg^{-1} DW), and pesticides (μg kg^{-1} DW)

Stations		Heavy metals						PAHs					Pesticides	
		Cadmium	Copper	Mercury	Lead	Zinc	Vanadium	B1	B2	B3	B4	I	CH	D
	1 A	<0.2	37.5	0.06	8.0	58.5	121.7							
1	1 B	<0.2	48.5	0.06	9.1	61.9	143.3							53
	1 C	<0.2	45.5	0.07	9.7	65.0	138.0							53
	2 A	<0.2	59.9	0.08	8.5	94.9	353.4							81
2	2 B	<0.2	79.2	0.27	9.4	70.1	376.4							83
	2 C	<0.2	45.0	0.04	8.6	57.2	294.1							76
	3 A	<0.2	37.7	0.09	12.7	52.8	103							124
3	3 B	<0.2	46.1	0.09	16.0	68.1	135.7							88
	3 C	<0.2	42.5	0.09	15.2	61.9	126.1							121
	4 A	<0.2	16.0	0.10	22.1	50.7	25.1		12	16			11	92
4	4 B	<0.2	12.2	0.09	17.0	37.9	22.3						< LD	86
	4 C	<0.2	18.2	0.11	26.8	60.7	27.7	13	12	14	22	10		94
	5 A	<0.2	13.6	0.07	9.9	32.4	30.7							73
5	5 B	<0.2	15.6	0.05	11.9	37.2	35.9							84
	5 C	<0.2	19.5	0.04	11.9	39.8	37.0							100
	6 A	<0.2	6.4	0.03	3.2	13.9	22.2							53
6	6 B	<0.2	9.5	0.03	3.6	25.8	45.3							74
	6 C	<0.2	10.9	0.06	7.9	30.8	52.4		24					61
	7 A	<0.2	8.9	0.05	4.6	20.6	39.9							67
7	7 B	1.8	9.3	0.05	20.8	447.6	37.2							50
	7 C	<0.2	8.8	0.04	4.3	18.7	40.0							59
	8 A	<0.2	8.1	0.06	8.5	21.7	34.5							97
8	8 B	<0.2	9.4	0.05	7.9	19.5	29.2							66
	8 C	<0.2	7.1	0.05	7.6	19.0	30.6							78
	9 A	<0.2	2.0	<0.02	0.7	3.9	1.4							
9	9 B	<0.2	1.5	<0.02	0.4	3.4	0.4							
	9 C	<0.2	1.9	<0.02	0.8	3.3	2.6							
	10 A	<0.2	1.1	<0.02	0.3	2.6	0.4							
10	10 B	<0.2	0.9	<0.02	0.4	2.5	0.4							
	10 C	<0.2	0.9	0.02	0.3	3.0	0.3							
	11 A	<0.2	39.0	0.06	7.2	46	104.4							
11	11 B	<0.2	30.3	0.06	8.0	49.5	110.2							
	11 C	<0.2	32.5	0.06	8.8	51.8	117.9							
	12 A	<0.2	1.1	<0.02	0.3	2.9	1.0							
12	12 B	<0.2	1.2	<0.02	0.4	3.0	0.6							
	12 C	<0.2	0.9	<0.02	0.2	3.1	0.3							
	13 A	<0.2	1.4	<SQ(1)	0.3	2.9	0.6							
13	13 B	<0.2	1.1	<0.02	0.4	3.0	1.1							
	13 C	<0.2	1.5	<0.02	0.3	2.1	0.6							
	14 A	<0.2	48.4	0.07	9.1	77.3	384.1							
14	14 B	<0.2	50.3	0.04	8.3	91.1	637.5							63
	14 C	<0.2	40.0	0.06	9.2	70.3	377.4							55
	15 A	<0.2	5.3	<0.02	1.3	7.2	10.4							
15	15 B	<0.2	5.3	<0.02	1.3	7.2	10.1							
	15 C	<0.2	5.8	<0.02	1.5	7.5	13.1							62

B1 benzo(a)anthracene, *B2* benzo(a)pyrene, *B3* benzo(b)fluoranthene, *B4* benzo(ghi)perylene, *I* indeno(1,2,3-cd)pyrene, *CH* chlordecone, *D* dithiocarbamates (CS2)

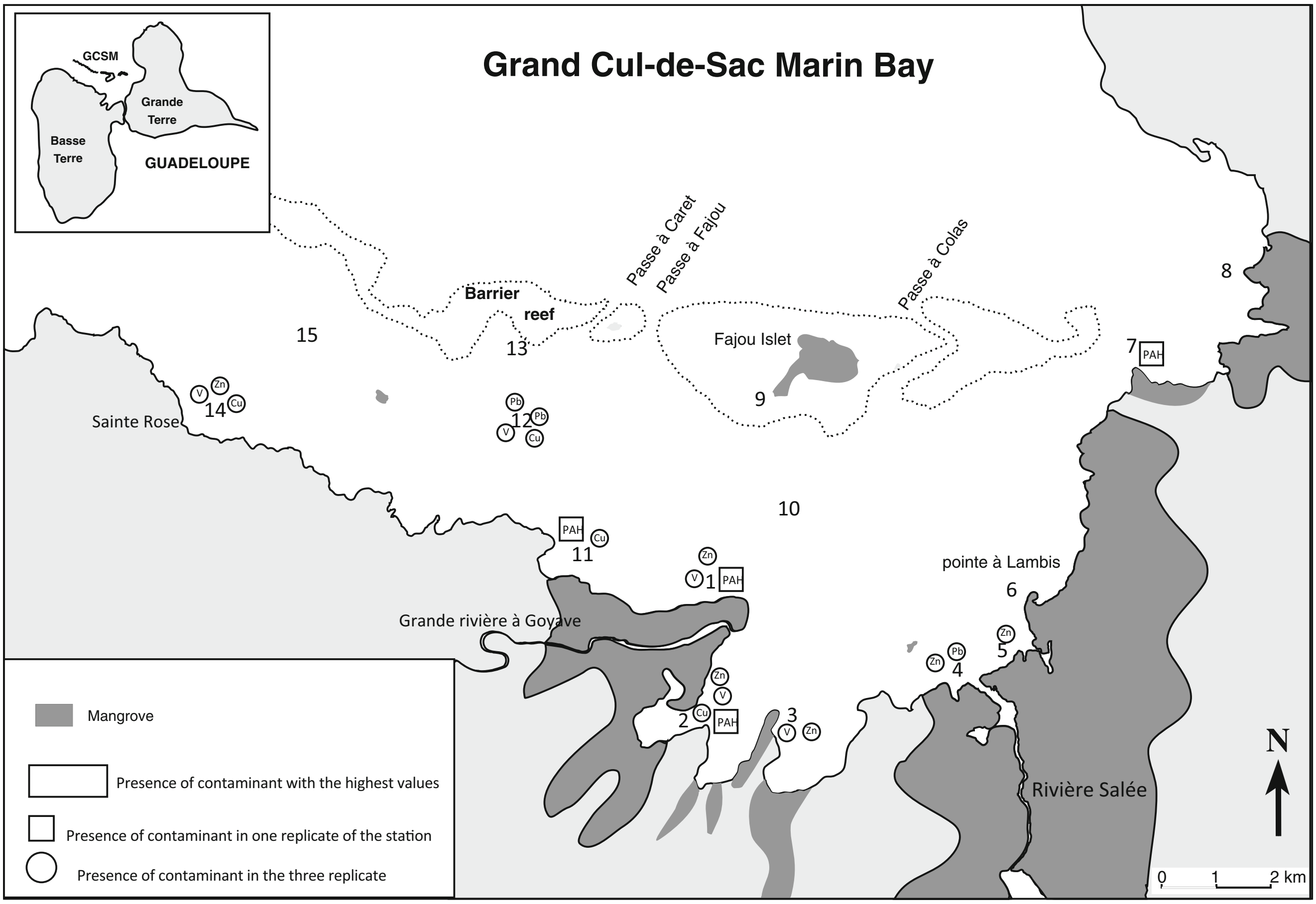

Fig. 2 Distribution of the main contaminants in the seagrass plants in the GCSM Bay of Guadeloupe.

carbon disulfide residues (CS2) was found in the sediments of all the coastal seagrass beds of the bay located east of the Grande Rivière à Goyave. (stations 1 to 8) (Fig. 2). CS2 residues were also found at station 14 (mouth of the river of Sainte-Rose) and at station 15 (ilet Blanc du Carénage). The most contaminated site was located in station 3 (Pointe-à-Nègre) with a maximum value of 124 μg kg^{-1} in one of the three replicates. Sediments from the other stations presented values ranging from 50 to 100 μg kg^{-1} of dry sediment.

Contamination of seagrass plants

The analytical results for the contamination by metallic elements and PAHs of *Thalassia testudinum* plants at 15 sites are presented in Table 5 and Fig. 2. The same type of analyses was made for *Syringodium filiforme* at stations 1, 6, 14, and 15.

Contamination of seagrass plants by metallic trace elements

Cadmium was present in small quantities in *Thalassia* plants at station 2 (Pointe Pasquereau) with values of 0.4 mg kg^{-1} of dry extract for each of the three replicates. In station 12, one replicate presented a value of 8.2 mg kg^{-1} (islet La Rose). For the other stations, the values were below or equal to the quantification analytic threshold (0.2 mg kg^{-1}).

The mean levels for copper contamination of *Thalassia* plants were generally low. The maximum values of 10.4 to 12.7 mg kg^{-1} were observed at station 2 (Pointe Pasquereau). One replicate in station 12 (islet La Biche) contained 11.4 mg kg^{-1} of copper. Finally, the *Thalassia* plants at station 14 (mouth of the river of Sainte-Rose) contained 5.4 to 7.7 mg kg^{-1} of copper by dry extract. The maximum value observed was in *Syringodium* from this same station.

The values of contamination by mercury were low in all the stations and remained below 0.04 mg kg^{-1} of dry extract of *Thalassia* plants. The same was also true for *Syringodium*. This element is the most toxic among trace metals, especially in the form of alkylated compounds that are readily biomagnified in food chains.

Lead levels found in phanerogams were also low for all the stations. The maximum level was reached at station 4 (mouth of the Rivière-Salée) with values ranging from 2 to 2.9 mg kg^{-1} according to replicates. At station 12 (islet La Biche), one of the replicates contained 10.9 mg kg^{-1} of lead.

Table 5 Results of the analyses of seagrasses concerning metal trace elements (mg kg^{-1}of dry weight) and PAHs (μg kg^{-1} DW)

Stations		Phanerogams	Heavy metals						PAHs			
			Cadmium	Copper	Mercury	Lead	Zinc	Vanadium	B	Py.	A	Ph.
	1 A	*Thalassia*	<0.2	4.6	0.03	0.6	25.6	15.1				
1	1 B	*Thalassia*	<0.2	6.1	0.03	0.9	26.9	17.1	0.01			
	1 C	*Thalassia*	<0.2	4.8	0.02	0.7	24.5	14.4				
	1	*Syringodium*	<0.2	3.6	<0.02	0.5	16.4	4.5				
	2 A	*Thalassia*	0.4	12.7	0.03	0.8	32.9	35.6				
2	2 B	*Thalassia*	0.4	10.4	0.04	0.7	30.8	27.5				
	2 C	*Thalassia*	0.4	11.4	0.02	0.8	31	33.3		0.07		
	3 A	*Thalassia*	0.2	5.4	0.03	0.7	21.4	10.5				
3	3 B	*Thalassia*	0.2	4.8	< SQ(1)	0.6	23.5	10.4				
	3 C	*Thalassia*	0.2	4.6	< SQ(1)	0.7	26.1	9.2				
	4 A	*Thalassia*	<0.2	5.4	0.03	2.9	30.6	8.3				
4	4 B	*Thalassia*	<0.2	5	0.02	2.8	32	8.2				
	4 C	*Thalassia*	<0.2	4.3	0.02	2	25.9	6.1				
	5 A	*Thalassia*	<0.2	3.6	0.02	0.7	23.5	5.7				
5	5 B	*Thalassia*	<0.2	4	<0.02	0.9	23.2	7.1				
	5 C	*Thalassia*	<0.2	4	<0.02	1.1	20.6	8.4				
	6 A	*Thalassia*	<0.2	2.3	<0.02	0.8	18.1	7.1				
6	6 B	*Thalassia*	<0.2	2.1	<0.02	0.7	17	5.4				
	6 C	*Thalassia*	<0.2	1.8	<0.02	0.6	16	5.2				
	6	*Syringodium*	<0.2	2.2	<0.02	0.5	11.9	2.3				
	7 A	*Thalassia*	<0.2	2	0.02	0.9	21.6	7.3				
7	7 B	*Thalassia*	<0.2	2.3	<0.02	0.6	24	8.3			0.04	
	7 C	*Thalassia*	<0.2	1.9	0.02	0.6	22.8	7.1				
	8 A	*Thalassia*	<0.2	2	0.02	0.7	19.2	5.2				
8	8 B	*Thalassia*	<0.2	2.4	<0.02	1	21.5	7.8				
	8 C	*Thalassia*	<0.2	8.3	0.03	0.7	20.4	6.7				
	9 A	*Thalassia*	<0.2	0.9	<0.02	<0.2	18.5	2.7				
9	9 B	*Thalassia*	<0.2	0.9	0.04	<0.2	20	2.4				
	9 C	*Thalassia*	<0.2	0.9	<0.02	<0.2	22.6	2.3				
	10 A	*Thalassia*	<0.2	1.6	<0.02	0.3	19.7	5.3				
10	10 B	*Thalassia*	<0.2	1.7	0.02	0.4	20.9	4.7				
	10 C	*Thalassia*	<0.2	1.5	0.02	0.3	20.8	5.3				
	11 A	*Thalassia*	<0.2	4.6	0.02	0.5	16.7	7.4				
11	11 B	*Thalassia*	<0.2	7.9	0.02	0.5	14.3	10.9				
	11 C	*Thalassia*	<0.2	4.6	0.02	0.4	15.5	10.6				0.06
	12 A	*Thalassia*	<0.2	1.8	<0.02	0.4	16.9	4.4				
12	12 B	*Thalassia*	8.2	11.4	0.03	10.9	26.4	18.9				
	12 C	*Thalassia*	<0.2	2	<0.02	0.3	15.8	5.6				
	13 A	*Thalassia*	<0.2	1.9	<0.02	0.3	16.1	6.5				
13	13 B	*Thalassia*	<0.2	2.3	<0.02	0.2	15.7	3.9				
	13 C	*Thalassia*	<0.2	2.4	<0.02	0.8	20.5	4.7				
	14 A	*Thalassia*	<0.2	6.9	<0.02	1	28.4	26.2				
14	14 B	*Thalassia*	<0.2	6.3	<0.02	0.7	29.3	19.3				
	14 C	*Thalassia*	<0.2	5.4	<0.02	0.8	32	15.2				
	14	*Syringodium*	<0.2	7.7	<0.02	0.7	18.6	9.5				
	15 A	*Thalassia*	<0.2	1.5	<0.02	0.4	12.7	2				
15	15 B	*Thalassia*	<0.2	1.9	<0.02	<0.2	12	2.5				
	15 C	*Thalassia*	<0.2	1.9	<0.02	<0.2	12.7	1.7				
	15	*Syringodium*	<0.2	1.9	<0.02	<0.2	14.1	1.3				

B benzo(a)anthracene, *Py.* pyrene, *A* anthracene, *Ph.* phenanthrene

The highest values for zinc were observed at stations 1 to 5, located east of the mouth of the Grande Rivière à Goyave, where zinc levels in *Thalassia* plants varied from 20.6 to 32.9 mg kg^{-1} of dry extract. The *Syringodium* present at station 3 contained 16.4 mg kg^{-1} of zinc. Another peak of this metal was observed at station 14 (mouth of the river of Sainte-Rose) with *Thalassia* contents varying between 28.4 to 32 mg kg^{-1} of dry extract. *Syringodium* plants in this station had a content of 18.6 mg kg^{-1} of zinc. In the other stations observed, values fluctuated between 12 to 23 mg kg^{-1}.

The highest values for vanadium were found in *Thalassia* plants from stations 1, 2, and 3 located at the east of the Grande Rivière à Goyave. Values of vanadium varied between 9 and 36 mg kg^{-1} of dry extract. The *Syringodium* present at station 1 contained only 4.5 mg kg^{-1} of vanadium. Station 14 (mouth of the river of Sainte-Rose) had replicates with values ranging from 15 to 26 mg kg^{-1}. In this station, *Syringodium* presented a lower contamination level (9.5 mg kg^{-1}). Finally, one of the replicates of station 12 (islet La Biche) contained 18.9 mg kg^{-1} of vanadium.

Contamination of phanerogams by PAHs

In the GCSM Bay, marine phanerogams were not significantly contaminated with PAHs. Traces of contaminants were detected in only one replicate at each station: benzo(b)fluoranthene (0.01 mg kg^{-1}) at station 1, pyrene (0.07 mg kg^{-1}) at station 2, anthracene (0.04 mg kg^{-1}) at station 7, and phenanthrene (0.06 mg kg^{-1}) at station 11.

Contamination of phanerogams by pesticides and their residues

No trace of contamination by the 225 molecules of pesticides and other organic contaminants was found in the plants of marine phanerogams.

Elements of comparison

It seemed interesting to investigate the existence of a correlation between the contamination level of sediment and that of phanerogams plants growing above. This calculation was done using a Mantel test. The test was performed using only the matrices of contamination by metal elements; contamination values by PAHs and other organic pollutants were too weak. The results of the test showed that there was a statistically significant correlation between the sediment contamination matrix and that of seagrass phanerogams (r=0.359, p=0.0001).

Discussion

Contaminants were mainly observed in the seagrass beds located near the shore, and their pattern of dispersion could be explained by the direction of surface currents. In the GCSM Bay, the main currents are driven by the eastern trade winds and are directed towards the west of the bay along the shore (Assor 1988). Several sources of contamination were identified: the mouth of the Grande Rivière à Goyave and that of the rivers of Lamentin and Sainte-Rose. The Rivière-Salée, which collects the runoffs of the airfield of the Guadeloupe airport, constitutes the source of pollution of the bay by PAHs.

Metallic trace elements were mainly present in sediments. For cadmium, the telluric noise can be important. Lewis et al. (2007) reported values for this metal fluctuating from 0.2 to 0.35 mg kg^{-1} in sediments from Florida seagrass beds. Levels for cadmium observed in this study never exceeded 1.8 mg kg^{-1} in one sediment sample, which is rather low when compared to values reported by Fernandez et al. (2007)) in the Caribbean area (between 0.03 to 67.9 mg kg^{-1}). One phanerogam sample also contained cadmium at 8 mg kg^{-1}, a high value in regard of those reported by Solis et al. (2008) in *Thalassia* from Mexico (<1 mg kg^{-1}). Alvarez-Legorreta et al. (2008) have shown that cadmium was directly absorbed by the leaves from seawater and not by their root system. Still according to these authors, cadmium generates the elaboration of thiol compounds as antioxidant in the plant. Malea (1994) showed that cadmium was toxic for *Halophila* leave cells at concentrations superior to 51 mg kg^{-1}. Considering its low occurrence in the samples and its moderate level of contamination, this metal does not seem to be an environmental threat for the seagrass beds of the bay.

Maximal values observed for copper were 45 mg kg^{-1} in one sample of sediment and 12.7 mg kg^{-1} in *Thalassia* plants. For Florida seagrass bed sediments, Lewis et al. (2007) found concentrations of copper between 0.08 and 70.8 mg kg^{-1}, and, in Texas (Gulf of Mexico), Whelan et al. (2005) published values of 11.5 mg kg^{-1} of copper for the sediment of a coastal lagoon. In Mexico, copper concentrations in *Thalassia* fluctuate between 4 and 27 mg kg^{-1} (Solis et al. 2008). At low concentrations, copper is an essential element to virtually all plants and animals. Elevated levels of copper are toxic in aquatic environments and may affect plants, invertebrates, and fish (Nor 1987). Prange and Dennisson (2000) have shown that this metal affects the photosynthetic process of seagrasses at a level of 1 mg l^{-1} in seawater. However, they also demonstrated that the threshold of copper sensitivity is widely variable between phanerogam species and even inside a same species. There is no threshold value for the concentration of copper enacted by the European Union.

The concentrations in mercury were globally low, with a maximum value of 0.27 mg kg^{-1} for one sediment sample and none in *Thalassia*. In Florida, Lewis et al. (2007) also found low values of mercury in seagrass bed sediments (0.004 to 0.057 mg kg^{-1}). In the present study, possible sources of contamination might respectively be the Grande Rivière à Goyave and the river of Lamentin for station 2 and the Rivière-Salée for station 4. Absent from the marine phanerogams, mercury does not seem to present a threat for the seagrass community of the bay.

For lead, maximum values were 26.8 mg kg^{-1} in one replicate of sediment and 10.9 mg kg^{-1} in one replicate of plants. From Lewis et al. (2007), concentrations of lead in sediments varied between 0.2 and 28.5 mg kg^{-1} in Florida seagrass beds. The concentrations observed in the GCSM Bay of Guadeloupe are low, except in one station. Purnama et al. (2015)) showed that the concentration of lead of 1.8 mg kg^{-1} in *Thalassia hemprichii* leaves depressed chlorophylle concentration and root growth. This metal deserves further monitoring.

Considering zinc, the most important value found in sediments was 447 mg kg^{-1} and 32.9 mg kg^{-1} in one sample of *Thalassia*. Lewis et al. (2007) found lower values in the sediment of Florida seagrass beds (2.2 to 10 mg kg^{-1}), as well as Whelan et al. (2005) in a lagoon from Texas (32.7 mg kg^{-1}). In *Thalassia* plants, values of 13 to 35 mg kg^{-1} were observed in Mexico by Solis et al. (2008). Zinc is not considered as a highly toxic metal. Generally, zinc is an essential element which acts as a plant nutrient, but at higher concentrations, it becomes toxic (Rout and Das 2003). Malea et al. (1995) revealed the existence of a positive correlation between cell mortality and zinc concentration in *Halophila stipulacea* (tropical marine phanerogam).Vanadium constitutes the most important metallic contaminant of the GCSM seagrass beds with a maximal value of 638 mg kg^{-1} in one sediment sample and 36 mg kg^{-1} for one sample of *Thalassia*. In volcanic islands like Guadeloupe, its origin is probably largely telluric. Miramand and Fowler (1998) estimated that the natural concentration of this metal in marine sediments ranged from 20 to 200 mg kg^{-1} of dry extract, the highest values being found near the coasts. Solis et al. (2008) found values of vanadium ranging from 1 to 7 mg kg^{-1} of dry extract in *Thalassia* plants from Mexico. In Venezuela, Alfonso et al. (2008)) found values for *Thalassia testudinum* ranging from 1.09 to 15.14 mg kg^{-1}. Vanadium is not considered as a very toxic element and was not taken into consideration in the work of the group GÉODE. However, according to Imtiaz et al. (2015), if low concentration of vanadium in sediment (<2 mg kg^{-1}) may enhance chlorophyll synthesis, high values are harmful for plants. The toxicity of this metal depends on its level of oxidation as well as on the nature of the organic compound it forms.

Many studies have focused on the accumulation of metallic trace element in seagrasses (Sanchiz et al. 2001). Heavy metals, at high concentrations, generally disrupt the photosynthetic function. However, the impact can be reversed when removing these contaminants (Prasad and Strzalka 1999). Moreover, a same species can present wide tolerance variations to metal impacts. It is not clear whether this is due to phenotypic or genotypic variations between the populations (Ralph et al. 2007).

In the present study, a significant correlation was found between the concentration of metallic trace elements in the sediments and in *Thalassia* plants. Contamination of sediments presented an average value about five times higher than the contamination of *Thalassia*. These results suggest that sediment contamination is probably inducing that of the seagrasses growing above them. Seagrasses are bioaccumulators of metals (Ward 1989). Contamination of the plants can follow two pathways: from surrounding waters to leaves and (or) from interstitial sediment water to the roots. Metals are then translocated to the other parts of the plant (Ralph et al. 2007). Considering this fact, several authors have proposed to use seagrass as bioindicators for pollution by metal trace elements (Lafabrie et al. 2009; Govers et al. 2014).

PAHs were found in one sample of sediment near the mouth of the Rivière-Salée. The seagrasses only presented low traces of PAHs. This contamination probably originates from the airfield of Guadeloupe, which is close to this site. As for heavy metals, the GÉODE group defined baseline levels for PAHs in sediments (Table 4). Compared to these threshold values, the contents of PAHs in the seagrass bed sediment appeared to be low in the GCSM. Long et al. (1995) considered whether a variety of chemical contaminants in sediments affected the biology of organisms (fishes and invertebrates). Among the 13 PAHs tested in that study, two (benzo(a)anthracene and benzo(a)pyrene) were found in the sediments of Guadeloupe. These authors defined two "guideline values": concentrations below the effects range-low (ERL) value were those for which effects would "rarely" be observed, whereas concentrations at the effects range-median (ERM) value were considered those that produced "frequent" effects. For the two PAHs found in sediment of the present study, the ERLs for benzo(a)pyrene and benzo(a)anthracene were 430 μg kg^{-1} (dry weight) and 261 μg kg^{-1} (dry weight), respectively. It should be noted that in the sediment sample contaminated by PAHs in Guadeloupe, the values determined for these two chemicals were 13 μg kg^{-1} for benzo(a)anthracene and 12 μg kg^{-1} for benz(a)pyrene, well below the ERL levels suggested by Long et al. (1995) but still with a capacity to elicit biological effects. From Ralph et al. (2007), PAHs are largely more toxic for seagrass than other hydrocarbons generally found in oil spills. They are lipophilic and so are able to pass through lipid membranes and tend to accumulate in the thylakoid membrane of the chloroplast, perturbing the photosynthesis process (Ren et al. 1994). Nevertheless, considering that only one station is contaminated at a low level by PAHs, these contaminants do not seem to constitute a threat for the seagrass beds of the investigated bay.

Among the 225 pesticides and other organochloride contaminants tested in the GCSM, only chlordecone and dithiocarbamates residues (CS2) appeared in the seagrass bed sediment and none in the seagrass plants. That absence of contamination of the *Thalassia* plants is probably due to the low contamination of the sediment by pesticides. Chlordecone appeared in one sample of sediment (0.11 μg kg^{-1}). Nevertheless, Bouchon and Lemoine (2007) found in crustaceans (*Penaeus schmitti* and three species of *Callinectes* crabs) and fish (*Centropomus undecimalis*), from the shores of the GCSM Bay, concentrations of chlordecone ranging from 10 to 100 μg kg^{-1}. All the contamination was localized at the mouth of the Grande Rivière à Goyave, the water of which is collecting the runoffs of some banana crops. Chlordecone is able to present a high bioamplification in the food web as observed in Martinique (Bodiguel et al. 2011) and Guadeloupe (Dromard et al. (2015)). In a particularly contaminated zone of Guadeloupe by chlordecone (Goyave), we recently found values of chlordecone in *Thalassia* leaves fluctuating around 3 μg kg^{-1}. In some species of the associated fauna of these seagrass beds, chlordecone level exceeded 1600 μg kg^{-1}. In Guadeloupe, the maximum residue limit (MRL) for chlordecone is fixed at 20 μg kg^{-1} of fresh extract. Connolly and Tonelli (1985) developed a mathematical model to attempt to clarify the relationship between kepone (a commercial name for chlordecone) levels in striped bass and other teleosts and those measured in the water column and sediments. The model indicated that for kepone concentrations to remain at or below 0.3 μg g^{-1} in fish tissues, the concentrations in the water column and sediments would fluctuate between 3–9 ng l^{-1} and 13–39 ng g^{-1}, respectively.

The dithiocarbamates are organosulfur compounds that can form polymers with transition metals. The presence of a heavy metal ion in the molecule increases the potential toxicity of that molecule. In Guadeloupe, dithiocarbamates are mainly used as fungicides. Pollution by dithiocarbamates, estimated by carbon disulfide residues (CS2), contaminated the sediments of 10 (out of 15) stations studied in the GCSM Bay, with values ranging from 50 to 124 μg kg^{-1} in 25 of the 29 replicates sediment samples. Bouchon and Lemoine (2007) showed that dithiocarbamate residues represented the main contaminant in the food chain of mangroves in the GCSM Bay, with CS2 values ranging from 20 to 970 μg kg^{-1} of dry extract. Values from the present study are lower. However, these values should be considered with caution, because the contamination by dithiocarbamates was evaluated by analyzing the carbon disulfide residues (CS2). It has been shown that these radicals exist naturally in confined coastal habitats, such as estuaries and mangroves (Ki-Hyun and Andreae 1992; Sciare et al. 2002). These radicals can be naturally produced by the decomposition of organic matter in anaerobic conditions. This natural background can lead to an overestimation of pollution by dithiocarbamates. The levels of dithiocarbamate residues found in the sediments of the bay were low (maximum 124 μg kg^{-1}). However, the fact that they were found so ubiquitously in the samples of sediment suggests that dithiocarbamates should form the subject of further monitoring.

Conclusions

At the end of the study, it is possible to conclude that, unlike other ecosystems of Guadeloupe (see Dromard et al. 2015), the seagrass beds of the GCSM Bay present a low degree of pollution. The observed levels of contaminants do not seem to threaten the role of nursery played by the seagrass beds and do not likely present a risk for the project of reintroduction of manatees led by the National Park of Guadeloupe. Moreover, there is a project of construction of an incinerator for all the garbage of Guadeloupe windward of the GCSM Bay. The present work shall constitute a baseline study for future monitoring of an eventual pollution from this incinerator.

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