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RESEARCH ARTICLE

Mercury concentrations in the coastal marine food web along the Senegalese coast

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Abstract This paper presents the results of seasonal (wet and dry seasons) and spatial (five sites) variation of mercury concentration in seven marine organisms representative for shallow Senegalese coastal waters and including species of commercial importance. Total mercury levels were recorded in the green algae (*Ulva lactuca*); the brown mussel (*Perna perna*); the Caramote prawn (*Penaeus kerathurus*); and in the liver and muscles of the following fish: *Solea senegalensis*, *Mugil cephalus*, *Saratherondon melanotheron*, and *Sardinella aurita*. The total selenium (Se) contents were determined only in the edible part of *Perna perna, Penaeus kerathurus* and in the muscles of *Sardinella aurita* and *Solea senegalensis*. Hg concentration in fish species was higher in liver compared to the muscle. Between species differences in Hg, concentrations were recorded with the highest concentration found in fish and the lowest in algae. The spatiotemporal study showed that there was no clear seasonal pattern in Hg concentrations in biota, but spatial differences existed with highest concentrations in sites located near important anthropogenic pressure. For shrimp, mussel, and the muscles of sardine and sole, Hg concentrations were below the health safety limits for human consumption as defined by the European Union. The Se/Hg molar ratio was always higher than one whatever the species or location suggesting a protection of Se against Hg potential adverse effect.

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Introduction

Mercury (Hg) is a global threat for marine ecosystems. The most important anthropogenic sources of mercury pollution in the environment are urban discharges, agricultural materials, mining and combustion, and industrial discharges (Zhang and Wong 2007). Atmospheric depositions are the primary mechanisms of Hg introduction into aquatic ecosystems (U.S. EPA 2008). Mercury is usually found in the aquatic environment in the form of inorganic salts (iHg) and organomercurics (methylmercury). Methylmercury is considered to be the most toxic form and it is also the most abundant Hg species (75–100 % of total Hg) in fish meat (Burger and Gochfeld 2004). It is the main form of mercury that bioaccumulates in organisms (Henriques et al. 2013).

Consumption of fish and seafood products is the main source of Hg exposure for humans (Driscoll et al. 2013). Effects resulting in Hg consumption through fish include neurodevelopmental deficits (Crump et al. 1998; Crump and Trudeau 2009), postnatal development from problems of prenatal exposure cardiovascular diseases (Stringari et al. 2008) and locomotary deficits (Hightower and Moore 2003). The European limits for allowable levels of Hg in fish and seafood are 0.5 mg/kg for fish in general, but grow to 1.0 for some larger predatory species including shark, swordfish, marlin, tuna, and some bonyfish such as mullet, poor cod, and seabream (EC 1881/2006 and amendments 629/2008, 420/2011).

Unlike mercury, selenium (Se) is an essential trace element and represents a natural methylmercury and inorganic mercury antagonist, which potentially contracts or eliminates symptoms of toxicity that would otherwise accompany high mercury exposures (Squadrone et al. 2015). Many authors have suggested that the excess of Se protects again Hg toxicity and that Se/Hg molar ratio above one is protective for adverse effects due to mercury consumption (Peterson et al. 2009; Squadrone et al. 2015). In contrast, Se/Hg molar ratio below 1 is at a higher risk of mercury toxicity.

In Senegal, the main source of animal protein for the population comes from fishery products. Fishes, mollusks, and shellfish provide 75 % of the protein needs of the population (FAO 2006). The availability of these products is due to the fact that the Senegalese coast is among the richest fishing coastlines in the world resulting from the presence of the Canaries Current upwelling (Cropper et al. 2014). Every year, more than 400,000 tons of seafood landed in Senegal (FAO 2006). Part of it is exported to the African, American, Asian, and European markets and the rest is consumed locally. Despite this rather favorable situation, the Senegalese coast, like most of the world's coastal areas, is subject to serious environmental problems related to the densification of the population in coastal cities steadily growing and to the concentration along the coasts of all kinds of industries. Eighty percent of the industries are sited in Dakar, the capital city, which is home to more than 25 % of the total population.

In sub-Saharan African countries, environmental and health effects of Hg pollution have been reported from artisanal small-scale gold mining (Donkor et al. 2006; Ouédraogo and Amyot 2013). In Senegal, along the Gambia river impacted by the use of Hg in the gold amalgamation in small artisanal gold mining, total mercury (THg) concentrations in fish were below the European guideline of 0.5 mg kg^{-1} wet weight but 100 % of the mussels were above the safety limit (Niane et al. 2015). High THg concentrations (1.5 mg kg^{-1}) were found in the hair of the local population consuming fish and mussels from Gambia river, exceeding the concentration of Hg in hair (1 mg kg^{-1}). Previous studies have measured THg concentrations in marine species but have been focused on well-defined areas of the Senegalese coast (Dakar) and do not give an overview of the status of pollution along the coast (Birame et al. 2015; Net et al. 2015). These studies carried out only during one season (dry season) showed that THg contents in mussels and fish species were always lower than the European legislation limits for fish and seafood products apart from large predator fish such as swordfish and sharks (Gras and Mondain 1982). The Senegal climate is characterized by two major seasons: a rainy season from June/July to October and a long dry period between November and May. Because not only rain and runoff but also rivers seem to be important sources of Hg input to coastal marine waters, it was important to complete the investigation during the two seasons and at other sites along the Senegalese coast, particularly near the outlets of rivers.

The objective of this study was to evaluate the Hg contamination status of seven relevant marine species from different trophic levels of a food web, representative for shallow waters of the Senegalese coast: the green algae (*Ulva lactuca*); the brown mussel (*Perna perna*); shrimp (*Penaeus kerathurus*); and four fish species, namely the Senegalese sole (*Solea senegalensis*), the flathead mullet (*Mugil cephalus*), tilapia (*Saratherondon melanotheron*), and the round sardine (*Sardinella aurita*). The concentrations of total mercury were measured in samples taken from five sites in both dry and wet seasons to assess the possible health risk linked with their consumption. We also report selenium contents in the marine species and discuss its potential role in Hg detoxification.

Material and methods

Study area and sampling

The study area is located along the Senegalese coast in the extreme west of the African continent (Fig. 1). Five sampling

Fig. 1 Map showing the sampling sites along the Senegalese coast

sites that differed in terms of anthropogenic pressure were selected to represent the Senegalese coast. Site 1 (Saint Louis) is located away from important human anthropogenic pressure but near the Senegal River which carries numerous pollutants (Diop et al. 2015). Three sites located near Dakar town are characterized by strong urban activity and high domestic waste and/or industrial discharge: Soumbedioune (Site 2), Hann (Site 3), and Rufisque (Site 4). Site 2 is dominated by discharges of domestic and hospital wastewaters and road runoff, being located only a few hundred meters from downtown Dakar and receiving all wastewater from surrounding neighborhoods. Site 3 is in the Hann Bay and is characterized by permanent discharges of a mixture of urban and food industry wastewaters, directly discharged to the sea without any treatment. Except for the presence of raw sewage outlets and a refuse site, site 4 was mainly selected because of the presence of an oil refinery and a cement factory. Site 5 (Joal) is located in the south of the country and at some distance from significant anthropogenic influences.

In this work, seven marine species were chosen to gain an overall picture of the mercury pollution along this coast and encompass macro algae, bivalves, crustaceans, and four fish species. The choice was based on the frequent consumption of these species by the population inhabiting the Senegalese coast, and it provided good coverage of several trophic levels and the opportunity to evaluate most elements' spatial distribution. Their main characteristics are as follows: (i) Macroalgae—*U. lactuca* provide qualitative information about the contamination level and environmental quality in an ecosystem due to their sedentary lifestyle and abundance in coastal seawater; (ii) Mussels—*Perna perna* is the only mussel of this genus in the Western coast of Africa and mussels are sedentary filtering organisms, which have been widely used as environmental sentinels for contamination studies; (iii) Crustaceans—*Penaeus kerathurus* is commercially one of the most important shrimp species in the Senegalese fishery and is also a target species for local fishermen using trammel nets; (iv) Four commercial coastal fish species widely distributed along the Senegalese coast and consumed by the local population were selected: a benthic fish species, the Senegalese sole *Solea senegalensis*; two benthopelagic fish species, flathead mullet *M. cephalus* and tilapia *Saratherondon melanotheron*, and one pelagic fish species, the round sardine *Sardinella aurita*. They are cosmopolitan fish species and occupy a wide variety of marine, estuarine, and freshwater environments in tropical, subtropical, and temperate coastal waters. *Solea senegalensis* with a practically sedentary life lives in sandy or muddy bottoms in coastal areas and feeds on benthic invertebrates such as larvae of polychaetes, bivalve mollusks, and small crustaceans. The benthopelagic fish species, strongly euryhaline, are omnivorous and their diet consists mainly of zooplankton, benthic organisms, and detritus. *Sardinella aurita* is a small pelagic fish feeding on plankton. This fat fish is the most often consumed species in Senegal.

At each site and for each season (dry season of January 2013 or wet season of August 2013), 500 mg of algae, ten samples of mussel (taken only at the Dakar sites), ten samples of shrimp, ten samples of sole, ten samples of mullet, ten samples of tilapia, and ten samples of sardinella were taken. Algae and mussels were collected in the subtidal zone at low tide and washed with water from their sampling location, while samples of crustaceans and fish were caught by local fishermen in the coastal areas. All the samples were immediately transported to the laboratory on ice. Each mussel, shrimp, and fish were measured for total length (nearest 1 mm) and weighed (nearest 0.1 g) in order to standardize samples' size among sites. Mussel and shrimp soft tissues, livers for all fish species and the left dorsolateral muscle of fish species were removed with stainless steel scalpel and Teflon forceps at a laminar flow bench (Class 100, US Federal Standard 209a) and then stored individually in polypropylene labeled bags at −20 °C until analysis.

Mercury analysis

About 250 mg of algae per site and per season, a total of 36 mussels, 45 shrimps, 50 sardinella, 45 mullet, 50 tilapia, and 45 sole were analyzed (Table 1). Samples were individually lyophilized for 48 h at −100 °C until constant weight and then manually ground to a powder with an agate mortar and pestle.

An AMA-254 Direct Analyzer (Altec) was employed to determine the concentration of total mercury (reported as mg of Hg on kg of dry weight, dw). A lyophilized sample (in the range of 0.010–0.050 g) was directly analyzed. The AMA-254 Direct Mercury Analyzer performs thermal

Table 1 Mean (± SD) length (cm) and weight (g) of the studied marine organisms

		P. perna	*P. kerathurus*	*S. senegalensis*	*M. cephalus*	*S. melanotheron*	*S. aurita*
Length (cm)	Range	5.1–8.5	11.3–18.9	23.6–35.1	24.9–43.4	11.4–26.3	20.6–33.2
	Mean ± SD	6.5 ± 1.1	14.3 ± 2.2	28.8 ± 3.5	30.5 ± 4.6	20.1 ± 5.2	30.6 ± 1.2
Weight (g)	Range	8.6–31.8	8.6–37.8	120–379	140–679	33.8–390	71.9–332
	Mean ± SD	20.9 ± 2.3	21.3 ± 2.3	220 ± 75	257 ± 12	163 ± 9	272 ± 35

decomposition, catalytic reduction, amalgamation, desorption, and atomic absorption spectroscopy to rapidly treat and analyze solid or liquid samples for mercury, with an output result for mercury content in about 5 min (per sample) with no pre-treatments required and no waste generation used. The limit of quantification (LOQ) for detection of Hg by means of this method was 0.001 mg kg^{-1} dw.

Selenium analysis

An aliquot of 100 mg from each material was digested in a concentrated solution of nitric acid (65 % Suprapur, Merck) at room temperature for 24 h and then at 100 °C for 4 h. Concentrations of Se were determined by an inductively coupled plasma with a mass spectrometer detector (ICP-MS, Varian 820-MS). A collision reaction interface (similar to a collision cell) and internal standards (indium (In), rhodium (Rh) ,and scandium (Sc)) were used to resolve the matrix effects for the determination of Se. Element concentrations are reported below in milligrams per kilogram dw, unless stated otherwise. The limit of quantification (LOQ) was 0.13 mg kg^{-1} for Se.

The accuracy and precision of the analyses were assessed using procedural blanks, replicate analyses (1 for every 25 analysis) and analyses of two standard reference materials: DOLT-4 (dogfish liver, National Research Council, Canada) and DORM-3 (fish protein, National Research Council, Canada). Procedural blanks were below 2 % of the signal and the coefficient of deviation of three replicate measurements was consistently below 10 %. For both elements, 54 CRM samples of DOLT-4 and DORM-3 reference materials were analyzed and the recovery percentages resulted in ranges from 88 to 110 % and showed that the results were in good agreement with the certified values.

Data treatment and statistical analysis

The Se/Hg molar ratio was calculated from the total Se and the total Hg levels by dividing the concentration (in mg/kg) by the molecular weight (mean values 200.59 for Hg and 78.96 for Se).

Statistics were performed with "XLSTAT- Pro" 2014 (Addinsoft). Inter-species and spatial differences in Hg concentrations among samples from the five sites were analyzed with a one-way ANOVA, followed by post hoc Tukey tests. If the data did not comply with the parametric assumption of normality and homogeneity of variance, the non-parametric Kruskal-Wallis test and Mann-Whitney *U* test for post hoc, pairwise comparisons were used. A *t* test was used to observe the significant differences in Hg concentrations between the wet and dry seasons. In all tests, the significant level for differences in critical values was set at $p < 0.05$. Principal component analysis (PCA) was used to explore relationships between sites and Hg concentrations in the different species. The data were normalized by subtracting their mean and then dividing it by their standard deviation. The relative contributions of Hg to the overall differences between species and sites were examined in vector plots.

Results and discussion

Interspecific variability of Hg concentration

The mercury concentrations measured in algae, in the soft tissue of mussel and shrimp, and in the liver and muscle of fish species are presented for each species at each of the five sampling locations and for both studied seasons (Tables 2 and 3). Some species were not analyzed at all sites because they were absent. This is the case of mussel *Perna perna* which lives attached to the rock by its byssus and hence, was not found at muddy coastal sites such as Saint Louis and Joal. Species differences in Hg concentration were recorded with higher concentration found in fish liver (ranging from 0.006 to 0.681 mg kg^{-1} dw) and the lowest in algae (ranging from 0.005 to 0.014 mg kg^{-1} dw). *Perna perna* and *Penaeus kerathurus* also showed low Hg concentration ranging from 0.020 to 0.100 and from 0.012 to 0.122 mg kg^{-1} dw, respectively. In fish, the highest concentration was in the liver of the benthopelagic fish *M. cephalus* (0.242 ± 0.16 mg kg^{-1} dw). Such species-specific differences in Hg concentration highlight the complexity of Hg bioaccumulation in marine organisms, as well as the utility of employing a multi-species approach in the evaluation of mercury contamination. Hg concentration in fish is heavily dependent on their diet (Hall et al. 1997; Trudel and Rasmussen 2001; Staudinger 2011), trophic level of the organism (Amiard et al. 2006), and habitat (Staudinger 2011; Vieira et al. 2011; Cresson et al. 2014). In the present study, the Hg concentration in the pelagic fish muscle (Sardinella $= 0.075 \pm 0.048$ mg kg^{-1} dw) is in the same magnitude as the one in the benthic species (sole $= 0.074 \pm 0.050$ mg kg^{-1} dw). Sardinella is an omnivorous fish feeding on pelagic zooplankton containing copepods and euphausiids (Gushchin and Corten 2015) whereas sole is a carnivorous benthic species feeding on worms and small crustaceans that live in close association with sediment (Vinagre et al. 2006).

For fish species, differences in accumulation of Hg were recorded in liver and muscle (Fig. 2). Mercury was more concentrated in liver than in muscle tissue in all fish species but only *M. cephalus* presented significantly higher concentration in liver (*t* test, $p < 0.001$). The ratio of Hg between liver and muscle was 1.1, 1.2, 1.3, and 9.6 respectively for sole, sardinella, tilapia, and mullet. Our results are in contradiction with those of Hajeb et al. (2009), where muscles presented higher concentration of Hg than liver in different fish species but in agreement with many other studies (Joiris and Holsbeek 1999; Romeo et al. 1999; Agusa et al. 2005; Yamashita et al. 2005). Organs with higher metabolic activities, like the liver,

Table 2 Mean (± SD) mercury concentration (mg kg^{-1}) dry weight in the dry (S1) and wet (S2) season in liver and muscle of fish: *S. senegalensis; S. aurita; M. cephalus*, and *S. melanotheron*

Sites	S1		S2	
	Liver	Muscle	Liver	Muscle
S. senegalensis				
Saint Louis	0.046 ± 0.014	0.09 ± 0.024	NA	
Soumbédioune	0.167 ± 0.064	0.147 ± 0.057	0.091 ± 0.016	0.072 ± 0.021
Hann	0.013 ± 0.008[b,e]	0.019 ± 0.014	0.062 ± 0.034	0.046 ± 0.026
Rufisque	0.072 ± 0.051	0.068 ± 0.022	0.081 ± 0.012	0.063 ± 0.015
Joal	0.087 ± 0.036	0.071 ± 0.026	0.061 ± 0.031	0.044 ± 0.01
S. aurita				
Saint Louis	0.022 ± 0.008[b,d]	0.029 ± 0.006	0.183 ± 0.111	0.045 ± 0.027
Soumbédioune	0.128 ± 0.005	0.11 ± 0.000	0.053 ± 0.015	0.058 ± 0.045
Hann	0.059 ± 0.002[b]	0.097 ± 0.064	0.078 ± 0.01	0.054 ± 0.013
Rufisque	0.098 ± 0.045	0.044 ± 0.012	0.056 ± 0.014	0.046 ± 0.012
Joal	0.048 ± 0.003[b]	0.065 ± 0.018	0.076 ± 0.011	0.056 ± 0.008
M. cephalus				
Saint Louis	0.356 ± 0.282	0.036 ± 0.01	0.338 ± 0.017	0.022 ± 0.001
Soumbédioune	0.157 ± 0.041	0.029 ± 0.021	0.300 ± 0.237	0.052 ± 0.011
Hann	0.146 ± 0.057	0.016 ± 0.001	0.463 ± 0.113	0.036 ± 0.019
Rufisque	0.089 ± 0.014	0.015 ± 0.002	0.133 ± 0.06	0.011 ± 0.004
Joal	NA		0.290 ± 0.055	0.011 ± 0.002
S. melanotheron				
Saint Louis	0.080 ± 0.040	0.074 ± 0.031	0.345 ± 0.291	0.053 ± 0.015
Soumbédioune	0.128 ± 0.019	0.124 ± 0.033	0.111 ± 0.085	0.193 ± 0.121
Hann	0.047 ± 0.02[b]	0.018 ± 0.008	0.022 ± 0.006[a,d,e]	0.015 ± 0.005
Rufisque	0.078 ± 0.021	0.125 ± 0.034	0.102 ± 0.033	0.154 ± 0.041
Joal	0.057 ± 0.019[b]	0.064 ± 0.01	0.080 ± 0.016	0.031 ± 0.018

[a] Significant decrease (Kruskal-Wallis and Mann-Whitney *U* test for post hoc pairwise comparisons; $p < 0.05$) compared to Saint Louis

[b] Significant decrease (Kruskal-Wallis and Mann-Whitney *U* test for post hoc pairwise comparisons; $p < 0.05$) compared toSoumbédioum

[c] Significant decrease (Kruskal-Wallis and Mann-Whitney *U* test for post hoc pairwise comparisons; $p < 0.05$) compared to Hann

[d] Significant decrease (Kruskal-Wallis and Mann-Whitney *U* test for post hoc pairwise comparisons; $p < 0.05$) compared to Rufisque

[e] Significant decrease (Kruskal-Wallis and Mann-Whitney *U* test for post hoc pairwise comparisons; $p < 0.05$) compared to Joal

accumulate more metals than organs with lower metabolic activities, such as muscle (Kalay et al. 1999). Liver stores metals for detoxification by producing metallothioneins (Hogstrand and Haux 1991). Thus, liver and gill are more often recommended as environmental indicator organs of water pollution than other fish organs.

Marine organisms used in this study are all species widely used to evaluate chemical contamination in many parts in the world since measures of element concentrations in water and sediment do not fully reflect the levels of contaminants in biota (Wang et al. 2010; Ali et al. 2013; Diop et al. 2014). In order to assess the level of contamination of the Senegalese coastal waters, the levels of Hg found in the biota were compared with results from the same species in studies performed in similar coastal waters knowing that species Hg levels vary according to individuals' size. Hg levels measured in fish were in the same order of magnitude or lower than those previously reported for the same species. Hg levels measured in *Sardinella aurita* were in the same order of magnitude as the concentration values reported for the same species collected along the coast of Mauritania (0.090 ± 0.080 mg kg^{-1} dw, Romeo et al. 1999) but six times lower than those reported in *Sardinella aurita* (mean Hg concentration = 0.50 mg kg^{-1} dw) from Tunisia (Joiris and Holsbeek 1999). Positive relationships have often been reported in the literature regarding mercury levels and fish size and age (Joiris and Holsbeek 1999; Vieira et al. 2011; Squadrone et al. 2015). We also found weak positive relationships in Hg concentrations with fish size but only *Solea senegalensis* presented a significant relationship ($Hg = 0.0098 \times TL - 0.212$; $R^2 = 0.33$; $p = 0.002$). The absence of significant relationships in the other

Table 3 Mean (± SD) mercury concentration (mg kg^{-1}) dry weight in the dry (S1) and wet (S2) season in the mussel *P. perna*. the shrimp *P. kerathurus*, and the green algae *U. lactuca*

Sites	S1	S2
P. perna		
Soumbédioune	0.094 ± 0.009	0.052 ± 0.005
Hann	0.029 ± 0.006^{b,d}	0.024 ± 0.003^{b,d}
Rufisque	0.052 ± 0.013	0.054 ± 0.007
P. kerathurus		
Saint Louis	0.038 ± 0.004	0.035 ± 0.003^{c,d,e}
Soumbédioune	0.028 ± 0.009	0.036 ± 0.005^{c,d,e}
Hann	0.012 ± 0.001^{a}	0.092 ± 0.011
Rufisque	NA	0.089 ± 0.01
Joal	0.024 ± 0.006	0.102 ± 0.017
U. lactuca		
Soumbédioune	0.010 ± 0.001	0.008 ± 0.001^{c}
Hann	0.006 ± 0.001^{b,d}	0.014 ± 0.001
Rufisque	0.011 ± 0.003	0.005 ± 0.001^{c,e}
Joal	0.007 ± 0.001	0.011 ± 0.002

[a] Significant decrease (Kruskal-Wallis and Mann-Whitney *U* test for post hoc pairwise comparisons; $p < 0.05$) compared to Saint Louis

[b] Significant decrease (Kruskal-Wallis and Mann-Whitney *U* test for post hoc pairwise comparisons; $p < 0.05$) compared toSoumbédioum

[c] Significant decrease (Kruskal-Wallis and Mann-Whitney *U* test for post hoc pairwise comparisons; $p < 0.05$) compared to Hann

[d] Significant decrease (Kruskal-Wallis and Mann-Whitney *U* test for post hoc pairwise comparisons; $p < 0.05$) compared to Rufisque

[e] Significant decrease (Kruskal-Wallis and Mann-Whitney *U* test for post hoc pairwise comparisons; $p < 0.05$) compared to Joal

fish species may result from the narrow size range of the fish analyzed in the present study. Indeed, as we explored inter sites contamination, our sampling strategy was to analyze fish of the same size range from the different sites.

It is generally considered that Hg bioaccumulation occurs all along the fish life because Hg uptake in fish tissue is higher than their rate of excretion, thus larger and older fish display higher Hg concentrations. The individuals of sardinella used in the present study were larger (20.6 to 33.2 cm) and hence older than those analyzed in Tunisia (17.3 to 20.1 cm) by

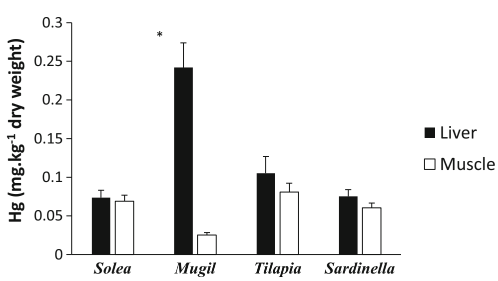

Fig. 2 Variation in mercury contents (mg kg^{-1} dry weight) in liver and muscle of different fish species. *Asterisk* denote significant difference ($p < 0.05$)

Joiris and Holsbeek (1999). This suggests that Tunisian coastal waters are more contaminated by Hg than our study area when considering only sardinella.

The Hg levels found in *M. cephalus* in our study are higher than those found in the same species in South Africa (Net et al. 2015) but fish size differences of individuals analyzed in the two studies make the comparison difficult. The green algae *U. lactuca* is fast growing and can withstand a wide range of ecophysiological conditions and high pollution levels. A relationship between concentrations of several heavy metals in water and algae was shown in many studies (Costa et al. 2011; Henriques et al. 2015). Henriques et al. (2015) have shown that *U. lactuca* is efficient at taking up mercury in ambient water. For these reasons, the species is frequently chosen as a sentinel of pollution (Costa et al. 2011; Turner and Furniss 2012). However, we found that this species had the lowest Hg concentration compared with the other species studied. The concentrations measured in *U. lactuca* are in the same range as those recorded in Spain (Schuhmacher et al. 1993) and ten times lower than those found in South Africa (Misheer et al. 2006).

It was shown that Hg content in the mussel *Perna perna* is correlated with their concentration in the surface sediment (Belabed et al. 2013). Hg levels measured in *Perna perna* in this study are in the same range as those found in the North African coast (Belabed et al. 2013) but lower than those found in Ghana (values range from 0.11 to 0.76 mg kg^{-1} dw) (Joiris et al. 2000).

Few studies have analyzed element concentrations in *Penaeus kerathurus*, particularly in the West African coast, but the Hg concentrations found in this study are in the range of those observed in other areas (Turkmen 2012).

Seasonal and spatial variation of mercury content

Variation of Hg content in marine organisms between the dry (S1) and wet (S2) seasons is shown in Fig. 3. Values represented correspond to the mean Hg in all individuals of the same species sampled in the five locations at each season. In all species studied, except for *Perna perna* and *Solea senegalensis* which concentrated more Hg in the dry season, highest Hg concentrations were recorded in the wet season. There were only significant seasonal differences (*t* test, $p < 0.05$) for *Penaeus kerathurus*, *M. cephalus,* and *Saratherondon melanotheron*. Seasonal variation in Hg concentrations may be affected by seasonal species differences in physiology (feeding and reproduction) (Belabed et al. 2013; Staudinger 2011). As water temperature increases, so do organisms' metabolic rate and feeding activity, resulting in an increase in metal uptake and accumulation in tissues (Obasohan and Eguavoen 2008). Behavior differences (spatial migration) can expose species to different Hg concentrations. *M. cephalus* and *Saratherondon melanotheron* are two fish

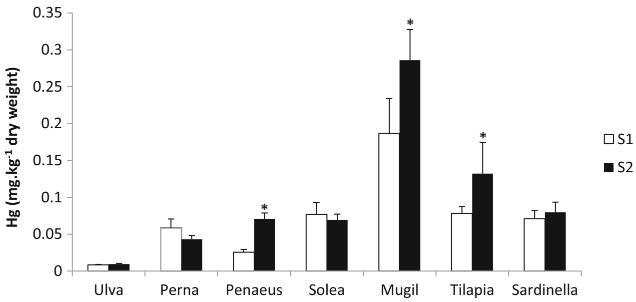

Fig. 3 Variation of mercury content in marine organisms between the dry (S1) and wet (S2) seasons. *Asterisk* denote significant difference ($p < 0.05$)

species that migrate to fresh and brackish water. Seasonal variations of Hg may also be related to environmental changes such as rainfall leading to varying runoff from land and rivers, upwelling intensity, and the water circulation along the coast. In the West African area, upwelling intensity is greater during the dry season and lower during the wet season (Braham et al. 2014).

Hg levels are known to increase according to individuals' size (Branco et al. 2007; Vieira et al. 2011; Squadrone et al. 2015). To prevent any size influence on the concentration of Hg, for each species, same-sized individuals were selected from the different sites in order to evaluate the spatial variation of Hg pollution. The results of the principal component analyses (PCA) indicated that Hg concentrations in the species analyzed explained 54 % of the spatial variations (Fig. 4). Saint Louis (site 1) is characterized by significantly higher levels of Hg in the liver of *M. cephalus*. Since this species migrates in estuaries, specimens analyzed from Saint Louis have probably been exposed to the pollution of this estuary. Soumbédioune (site 2) was characterized by species such as sole, tilapia, mussels, and algae with highest Hg concentrations compared with the other sites. Rufisque (site 4) is characterized by high Hg concentration in sardinella. These two latter sites, located near Dakar city and harbor, are affected by directly discharged mixed urban and industrial wastewaters. Hann (site 3) and Joal (site 5) are less contaminated by Hg. Joal is located in the south of the Senegal coast far from significant anthropogenic activity.

Risk for human health

Because of the presence of higher Hg content in marine organisms during the wet season (S2), possible health risk associated with their consumption was assessed during this season. Analyses concerned only mussels, shrimp, sardinella, and sole. If some of these species are highly consumed by the local population, others such as shrimp and sole are among the most exported species to the European Union.

The Hg and Se concentrations obtained in dry weight (mg kg^{-1} dw) in these species were converted into mg kg^{-1}

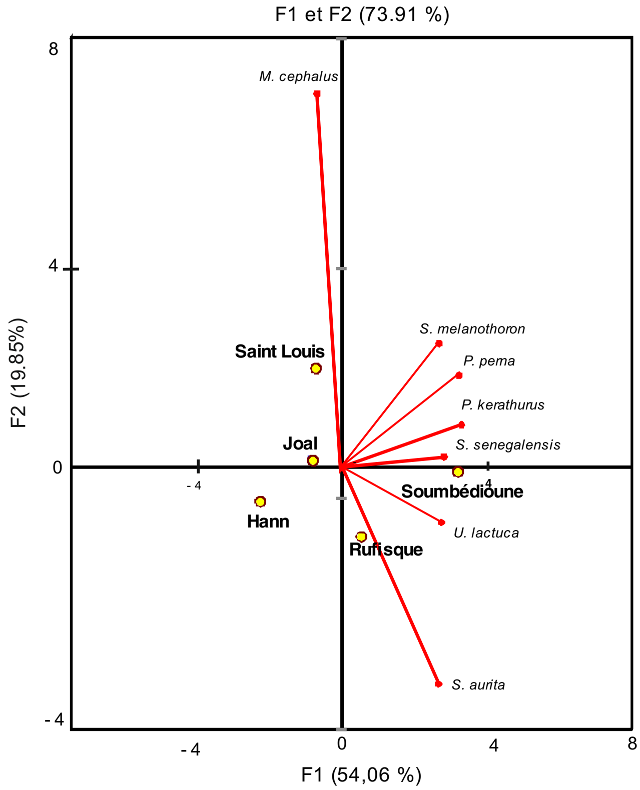

Fig. 4 PCA showing relationships between sites and the highest Hg concentrations recorded in the different species

wet weight (ww) in order to compare them with published guideline values for seafood destined for human consumption and to compare them with other studies. According to the weighed mass before and after drying, the following factors were applied to obtain the concentrations in wet weight: 0.22 for *P. perna* and *S. senegalensis*, 0.26 for *P. kerathurus* and 0.30 for *S. aurita*.

The levels of Hg in mussels (0.011 ± 0.005 mg kg^{-1} ww), shrimp (0.014 ± 0.008 mg kg^{-1} ww), sole (0.016 ± 0.009 mg kg^{-1} ww), and sardinella (0.018 ± 0.009 mg kg^{-1} ww) (Table 4) were well below the legal limit of 0.5 mg kg^{-1} ww fixed by the European Union for fish and seafood (EC 1881/2006 and amendments 629/2008, 420/2011). The World Health Organization (WHO) assumes that foods with mercury concentrations of 0.5 mg kg^{-1} ww or higher are improper for human consumption (WHO 1996).

No significant differences were observed in Hg concentrations in edible parts of the marine organisms analyzed. Total Hg content in this study was low or in the same amount of magnitude when compared to other areas in West Africa (e.g., Biney and Ameyibor 1992; Romeo et al. 1999; see also the review of Bosch et al. 2016)

The Se contents in mussels (0.163 ± 0.073 mg kg^{-1} ww), shrimp (0.211 ± 0.085 mg kg^{-1} ww), sole (0.549 ± 0.188 mg kg^{-1} ww), and sardinella (0.839 ± 0.187 mg kg^{-1} ww) (Table 4) were quite low but no limits were

Table 4 Total mercury and total selenium (mean ± SD; mg kg^{-1} wet weight) and the Se/Hg molar ratio (mean ± SD and range values) in the edible part of *P. perna, P. kerathurus,* and in the muscle of *S. senegalensis* and *S. aurita*

Species	Hg (mean ± SD)	Se (mean ± SD)	Hg µmol g	Se µmol g	Se/Hg molar ratio (mean ± SD)	Se/Hg molar ratio (min; max)
P. perna	0.011 ± 0.005	0.163 ± 0.073	0.056	2.06	37 ± 12	26–55
P. kerathurus	0.014 ± 0.009	0.211 ± 0.085	0.071	2.67	37 ± 18	14–69
S. senegalensis	0.016 ± 0.009	0.549 ± 0.188	0.079	6.95	88 ± 22	58–165
S. aurita	0.018 ± 0.010	0.839 ± 0.197	0.090	10.6	118 ± 32	65–125

fixed for this element, and there are fewer data for comparison on Se content in marine organisms from Africa. There were no differences (ANOVA, $p < 0.05$) in Se content in the muscles of the fish species analyzed but they were significantly higher than in mussels and shrimp. In all species, the Se levels are higher than Hg levels (Table 4).

The concentrations of Hg and Se in marine organisms have been the subject of intense study in recent years due to their antagonistic effect. As recently suggested by many authors, the Se/Hg molar ratio above one can protect fish against mercury toxicity, although the actual ratio that provides protection is unclear, because of the variability in toxicokinetics (Watanabe 2002; Squadrone et al. 2015). The molar ratio explains the number of Se atoms versus Hg atoms present or consumed. The Se/Hg molar ratios in this study are high and differed significantly among the species examined (Table 4). Mean Se/Hg values were 37, 37, 88, and 117, respectively, for *Perna perna, Penaeus kerathurus, Solea senegalensis,* and *Sardinella aurita*. Ralston and Raymond (2010) demonstrated that selenium lowers the toxicity of methylmercury when the Se/Hg molar ratio is higher than 1:1. Due to the high affinity of Se to Hg, Se is thought to sequester methylmercury, and reduce its bioavailability in organisms (Sormo et al. 2011). The Se/Hg molar ratio largely greater to one in all species analyzed suggest that the potential effect of Se excess protects humans consuming these marine organisms by reducing Hg toxicity.

Conclusion

Our results confirm the low concentrations of Hg found in marine species of the Senegalese coast (Gras and Mondain 1982; Birame et al. 2015; Net et al. 2015). In this area, high Hg concentration has been reported only in large predator fish such as swordfish and sharks (Gras and Mondain 1982). Results indicate that Hg concentrations in fish and other marine organisms (algae, mussels, and shrimps) from the Senegalese coast are lower or in the same order as observed in the other African countries and more generally in marine coastal areas. These low concentrations of not only Hg but also other pollutants (Net et al. 2015; Diop et al. 2016a, b) may be due to the very high marine dynamics off the coast of Senegal favoring the dispersion of pollutants seaward and their low accumulation in the study area.

Strong differences of Hg concentrations by biota were demonstrated, revealing the utility of employing a suite of organism bioindicators to monitor contamination in coastal areas. There was no clear seasonal pattern in Hg concentrations in biota but spatial differences exist with highest concentrations in sites located near important anthropogenic pressure.

Research on heavy metal concentrations in commonly consumed fish species and seafood is still needed, especially in Africa, where the average contribution of fish protein to the total animal protein supply is about 20 % (FAO, http://www.fao.org/fishery/sofia/en). Fish and shellfish consumption remain the major sources of protein for Senegalese people, particularly in the coastal areas. Hg contents in the edible parts of species analyzed were well below the EU's recommended maximum level of Hg for human consumption. Moreover, the Se/Hg molar ratio were always higher than one whatever the species or location suggesting a protection of Se against Hg potential adverse effect.

Due to the ever increasing environmental pressure on the Senegal coast ecosystem, a regular monitoring of element levels in marine fish, particularly in large predator fish such as swordfish and sharks, is necessary to assess any further environmental deterioration. Such monitoring will be of major importance to resource managers and public health officials.

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References

Agusa T, Kunito T, Iwata H et al (2005) Mercury contamination in human hair and fish from Cambodia: levels, specific accumulation and risk assessment. Environ Pollut 134(1):79–86

Ali H, Khan E, Sajad MA (2013) Phytoremediation of heavy metals concepts and applications. Chemosphere 91(7):869–881

Amiard JC, Amiard-Triquet C, Barka S et al (2006) Metallothioneins in aquatic invertebrates: their role in metal detoxification and their use as biomarkers. Aquat Toxicol 76:160–202

Belabed BE, Laffray X, Dhib A et al (2013) Factors contributing to heavy metal accumulation in sediments and in the intertidal mussel *Perna perna* in the Gulf of Annaba (Algeria). Mar Pollut Bull 74(1):477–489

Biney CA, Ameyibor E (1992) Trace metal concentrations in the pink shrimp Penaeus notialis from the coast of Ghana. Water Air Soil Pollut 63(3–4):273–279

Birame N, Momar N, Abdoulaye D et al (2015) Determination of methyl mercury in biological samples from Dakar coast using CV-AAS and a simple ultrasound method. Res J Chem Env 19:1–7

Bosch AC, O'Neill B, Sigge GO et al (2016) Heavy metals in marine fish meat and consumer health: a review. J Sci Food Agric 96(1):32–48

Braham CB, Fréon P, Laurec A et al (2014) New insights in the spatial dynamics of sardinella stocks off Mauritania (North-West Africa) based on logbook data analysis. Fish Res 154:195–204

Branco V, Vale C, Canário J et al (2007) Mercury and selenium in blue shark (*Prionace glauca*, L. 1758) and swordfish (*Xiphias gladius*, L. 1758) from two areas of the Atlantic Ocean. Environ Pollut 150(3): 373–380

Burger J, Gochfeld M (2004) Mercury in canned tuna: white versus light and temporal variation. Environ Res 96(3):239–249

Costa S, Crespo D, Henriques BMG (2011) Kinetics of mercury accumulation and its effects on *Ulva lactuca* growth rate at two salinities and exposure conditions. Water Air Soil Pollut 217:689–699

Cresson P, Fabri MC, Bouchoucha M et al (2014) Mercury in organisms from the Northwestern Mediterranean slope: importance of food sources. Sci Total Environ 497:229–238

Cropper TE, Hanna E, Bigg GR (2014) Spatial and temporal seasonal trends in coastal upwelling off Northwest Africa, 1981–2012. Deep Sea Rese Pt I 86:94–111

Crump KL, Trudeau VL (2009) Mercury-induced reproductive impairment in fish. Environ Toxicol Chem 28(5):895–907

Crump KS, Kjellström T, Shipp AM et al (1998) Influence of prenatal mercury exposure upon scholastic and psychological test performance: benchmark analysis of a New Zealand cohort. Risk Anal 18(6):701–713

Diop C, Dewaelé D, Diop M et al (2014) Assessment of contamination, distribution and chemical speciation of trace metals in water column in the Dakar coast and the Saint Louis estuary from Senegal, west Africa. Mar Pollut Bull 86:539–546

Diop C, Dewaelé D, Cazier F et al (2015) Assessment of trace metals contamination level, bioavailability and toxicity in sediments from Dakar coast and Saint Louis estuary in Senegal, West Africa. Chemosphere 138:980–987

Diop M, Howsam M, Diop C et al (2016a) Spatial and seasonal variations of trace elements concentrations in liver and muscle of round sardinelle (*Sardinella Aurita*) and senegalese sole (*Solea Senegalensis*) along the Senegalese coast. Chemosphere 144:758–766

Diop M, Howsam M, Diop C et al (2016b) Assessment of trace element contamination and bioaccumulation in algae (*Ulva lactuca*), mussels (*Perna perna*), shrimp (*Penaeus kerathurus*), and fish (*Mugil cephalus, Saratherondon melanotheron*) along the Senegalese coast. Mar Pollut Bull

Donkor AK, Bonzongo JC, Nartey VK et al (2006) Mercury in different environmental compartments of the Pra River Basin, Ghana. Sci Total Environ 368(1):164–176

Driscoll CT, Mason RP, Chan HM et al (2013) Mercury as a global pollutant: sources, pathways, and effects. Environ Sci Technol 47(10):4967–4983

EC (2006) No 1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuffs. Official J European 364:5–24

EC (2008) No 629/2008 of 2 July 2008 amending Regulation (EC) No 1881/2006 setting maximum levels for certain contaminants in foodstuffs. Official J European 173(6), 4 pages

U.S. EPA (2008) Model-based analysis and tracking of airborne mercury emissions to assist in watershed planning

FAO (2006) Report of the FAO Working Group on the assessment of small pelagic fish off Northwest Africa. Banjul, Gambia, 2–11 May 2006. FAO Fish. Report 811, 192 pages

Gras G, Mondain J (1982) Rapport methylmercure/mercure total dans difgferentes espèces de poissons péchés sur les côtes de l'Afrique de l'Ouest. Toxicol Eur Res 4:191–195

Gushchin A, Corten A (2015) Feeding of pelagic fish in waters of Mauritania: 1. European anchovy *Engraulis encrasicolus*, European sardine *Sardina pilchardus*, round sardinella *Sardinella aurita*, and flat sardinella *S. maderensis*. J Ichthyol 55:77–85

Hajeb P, Jinap S, Ismail A et al (2009) Assessment of mercury level in commonly consumed marine fishes in Malaysia. Food Control 20(1):79–84

Hall B, Bodaly R, Fudge R et al (1997) Food as the dominant pathway of methylmercury uptake by fish. Water Air Soil Pollut 100(1–2):13–24

Henriques B, Rodrigues S, Coelho C et al (2013) Risks associated with the transfer of toxic organo-metallic mercury from soils into the terrestrial feed chain. Environ Int 59:408–417

Henriques B, Rocha LS, Lopes CB (2015) Study on bioaccumulation and biosorption of mercury by living marine macroalgae: prospecting for a new remediation biotechnology applied to saline waters. Chem Eng J 281:759–770

Hightower JM, Moore D (2003) Mercury levels in high-end consumers of fish. Environ Health Perspect 111(4):604

Hogstrand C, Haux C (1991) Binding and detoxification of heavy metals in lower vertebrates with reference to metallothionein. Comp Biochem Physiol C 100(1):137–141

Joiris CR, Holsbeek L (1999) Total and methylmercury in sardines *Sardinella aurita* and *Sardina pilchardus* from Tunisia. Mar Pollut Bull 38(3):188–192

Joiris CR, Holsbeek L, Otchere FA (2000) Mercury in the bivalves Crassostrea tulipa and Perna perna from Ghana. Mar Pollut Bull 40:457–460

Kalay M, Ay Ö, Canli M (1999) Heavy metal concentrations in fish tissues from the Northeast Mediterranean Sea. Bull Environ Contam Toxicol 63(5):673–681

Misheer N, Kindness A, Jonnalagadda S (2006) Seaweeds along KwaZulu-Natal coast of South Africa—3: elemental uptake by *Ulva lactuca* (sea lettuce). J Environ Sci Health C 41(6):1249–1259

Net S, Henry F, Rabodonirina S et al (2015) Accumulation of PAHs, Me-PAHs, PCBs and total mercury in sediments and marine species in coastal areas of Dakar, Senegal: contamination level and impact. Int J Environ Res 9(2):419–432

Niane B, Guédron S, Moritz R, Cosio C et al (2015) Human exposure to mercury in artisanal small-scale gold mining areas of Kedougou region, Senegal, as a function of occupational activity and fish consumption. Environ Sci Pollut Res 22(9):7101–7111

Obasohan E, Eguavoen O (2008) Seasonal variations of bioaccumulation of heavy metals in a freshwater fish *(Erpetoichthys calabaricus)* from Ogba River, Benin City, Nigeria. Afr J General Agr 4(3): 153–163

Ouédraogo O, Amyot M (2013) Mercury, arsenic and selenium concentrations in water and fish from sub-Saharan semi-arid freshwater reservoirs (Burkina Faso). Sci Total Environ 444:243–254

Peterson SA, Ralston NV, Peck DV et al (2009) How might selenium moderate the toxic effects of mercury in stream fish of the western US? Envir Sci Tech Lib 43(10):3919–3925

Ralston NVC, Raymond LJ (2010) Dietary selenium's protective effects against methylmercury toxicity. Toxicology 278:112–123

Romeo M, Siau Y, Sidoumou Z, Gnassia-Barelli M (1999) Heavy metal distribution in different fish species from the Mauritania coast. Sci Total Environ 232:169–175

Schuhmacher M, Domingo J, Llobet J et al (1993) Chromium, copper, and zinc concentrations in edible vegetables grown in Tarragona Province, Spain. Bull Environ Contam Toxicol 50(4):514–521

Sormo EG, Tomasz MC, Ida BØ et al (2011) Selenium moderates mercury toxicity in free-ranging freshwater fish. Environ Sci Technol 45(15):6561–6566

Squadrone S, Benedetto A, Brizio P et al (2015) Mercury and selenium in European catfish (*Silurus glanis*) from northern Italian rivers: can molar ratio be a predictive factor for mercury toxicity in a top predator? Chemosphere 119:24–30

Staudinger MD (2011) Species-and size-specific variability of mercury concentrations in four commercially important finfish and their prey from the northwest Atlantic. Mar Pollut Bull 62(4):734–740

Stringari J, Nunes AK, Franco JL et al (2008) Prenatal methylmercury exposure hampers glutathione antioxidant system ontogenesis and causes long-lasting oxidative stress in the mouse brain. Toxicol Appl Pharmacol 227(1):147–154

Trudel M, Rasmussen JB (2001) Predicting mercury concentration in fish using mass balance models. Ecol Appl 11(2):517–529

Turkmen G (2012) Seasonal variation of heavy metals in shrimp *Penaeus kerathurus* (forskal, 1775) from Izmir bay, Turkey. J Anim Vet Adv 11:2839–2844

Turner A, Furniss O (2012) An evaluation of the toxicity and bioaccumulation of thallium in the coastal marine environment using the macroalga, *Ulva lactuca*. Mar Pollut Bull 64(12):2720–2724

Vieira C, Morais S, Ramos S et al (2011) Mercury, cadmium, lead and arsenic levels in three pelagic fish species from the Atlantic Ocean: intra-and inter-specific variability and human health risks for consumption. Food Chem Toxicol 49(4):923–932

Vinagre C, Fonseca V, Cabral H et al (2006) Habitat suitability index models for the juvenile soles, *Solea solea* and *Solea senegalensis*, in the Tagus estuary: defining variables for species management. Fish Res 82(1):140–149

Wang Y, Chen P, Cui R et al (2010) Heavy metal concentrations in water, sediment, and tissues of two fish species (*Triplohysa pappenheimi, Gobio hwanghensis)* from the Lanzhou section of the Yellow River, China. Environ Monit Assess 165(1–4):97–102

Watanabe C (2002) Modification of mercury toxicity by selenium: practical importance? Tohoku J Exp Med 196(2):71–77

WHO (World Health Organization) (1996) Health criteria other supporting information. In: Guidelines for drinking water quality, vol 2, 3rd edn. Geneva, pp 31–388

Yamashita Y, Omura Y, Okazaki E (2005) Total mercury and methylmercury levels in commercially important fishes in Japan. Fish Sci 71(5):1029–1035

Zhang L, Wong M (2007) Environmental mercury contamination in China: sources and impacts. Environ Int 33(1):108–121