



HAL
open science

Metals and metalloids concentrations in three genotypes of pelagic Sargassum from the Atlantic Ocean Basin-scale

Océanne-Amaya Cipolloni, Julien Gigault, Émilie Pauline Dassié, Magalie Baudrimont, Pierre-Yves Gourves, Linda Amaral-Zettler, Pierre-Yves Pascal

► **To cite this version:**

Océanne-Amaya Cipolloni, Julien Gigault, Émilie Pauline Dassié, Magalie Baudrimont, Pierre-Yves Gourves, et al.. Metals and metalloids concentrations in three genotypes of pelagic Sargassum from the Atlantic Ocean Basin-scale. *Marine Pollution Bulletin*, 2022, 178, pp.113564. 10.1016/j.marpolbul.2022.113564 . hal-03720294

HAL Id: hal-03720294

<https://hal.science/hal-03720294>

Submitted on 12 Dec 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Title: Metals and Metalloids concentrations in three genotypes of**
2 **pelagic *Sargassum* at the Atlantic Ocean Basin scale**

3
4
5
6 **Authors list:** Océanne Cipolloni^{1*}, Julien Gigault², Émilie Pauline Dassié³, Magalie
7 Baudrimont³, Pierre-Yves Gourves³, Linda Amaral-Zettler^{4,5}, Pierre-Yves Pascal¹

8
9 **Affiliation :**

- 10 1. Université des Antilles, Équipe Biologie de la mangrove, Institut de Systématique,
11 Évolution, Biodiversité, ISYEB, UMR 7205, UFR SEN, 97100 Pointe-à-Pitre, France
12
13 2. Université de Laval, International Research Laboratory Takuvik (IRL), CNRS research
14 scientist, IRL 3376, G1V 0A6, Québec, Canada
15
16 3. Université de Bordeaux, CNRS, EPOC, EPHE, UMR 5805, F-33600 Pessac, France
17
18 4. NIOZ Royal Netherlands Institute for Sea Research, Den Burg, Netherlands
19
20
21 5. Institute for Biodiversity and Ecosystem Dynamics, The University of Amsterdam,
22 Amsterdam Netherlands
23
24
25

26 * Corresponding author: oceanne.cipolloni@gmail.com
27

28 **Running title (5 words):** Morphotypes, Arsenic, *S. natans*, *S. fluitans*, Caribbean Sea
29
30

31 **Abstract**
32

33 Since 2011 in Caribbean Islands have witnessed unprecedented massive strandings of a pelagic
34 brown algal *Sargassum* spp. that have damaged coastal ecosystems and disrupted the economy.

35 Brown algae have a high capacity to concentrate heavy metal contaminants. Through
36 accumulation of heavy metals during their journey, floating Sargassum can play a role in
37 contaminant transfer from off-shore to the coast. In July and August 2019, three genotypes of
38 *Sargassum* (*S. fluitans* III, *S. natans* I and *S. natans* VIII) were sampled in seven stations
39 regularly spaced along a 3400 km transect from the middle of the Atlantic Ocean to the
40 Guadeloupe islands (French West Indies). For each of the 72 samples of *Sargassum*,
41 concentrations of 15 heavy metal(loid)s elements were analyzed by Inductively Coupled
42 Plasma Optical Emission Spectrometer (ICP-OES). Mean metal concentrations in all
43 morphotypes and stations were ranked in the following descending order: As > Fe > Al > Mn
44 > Cd > Zn > Ni > V > Cu > Cr > Hg. The metalloids As was the most abundant contaminant in
45 all our samples with a mean concentration of As is $92.72 \mu\text{g}\cdot\text{g}^{-1}$ ppm and an maximum value
46 of $115 \mu\text{g}\cdot\text{g}^{-1}$ ppm which is accordance with concentrations previously observed in the
47 Caribbean area (80-150 ppm). Those value are above different maximum safety level and
48 strategies proposed for valorization of Sargassum should consider this content As
49 contamination levels to avoid environmental and health issues. At the scale of the Atlantic
50 Ocean, metallic element concentration do not present spatial longitudinal gradient. Genotypes
51 of *Sargassum* present different metal(oids) contamination distinct patterns observed with
52 distinction between *S. fluitans* III and the two genotypes of *S. natans* (I and VIII).

53

54 **I Introduction**

55

56 *Sargassum* is one of the most diverse genera of brown algae, with more than 350 species
57 described (Guiry and Guiry, 2022). Among this genus, only two historically-defined species
58 are strictly holopelagic (floating) during their entire life cycle, and forming rafts in the Atlantic
59 Ocean: *Sargassum fluitans* and *Sargassum natans* (Parr, 1939; Stoner, 1983). Recently
60 organellar genomic sequencing has differentiated morphotypes of *S. fluitans* III from *S. natans*
61 IV and VIII (Amaral-Zettler et al., 2017). The presence of Sargassum seaweed in the Atlantic
62 Ocean was reported in the 15th century by Christophe Columbus and in the middle of 19th
63 century by the German merchant marine (Gower and King, 2011). The distribution of
64 *Sargassum* was historically limited to the Sargasso Sea, the eastern edge of Gulf Mexico and
65 to the Azores islands (Lapointe, 1995). An increase in its distribution range was recently
66 detected though satellite imaging detection including the western Atlantic tropical region and
67 the South America from the northeastern Brazil to the Caribbean islands (Gower et al., 2013;
68 Guiry et al., 2014). The role played by oceans surface currents in controlling the distribution

69 and stranding of *Sargassum* algae on shorelines still remains unclear (Coston-Clements et al.,
70 1991). Pelagic *Sargassum* have begun blooming in the North Equatorial Recirculation Region
71 (NERR), and with the wind (driven Langmuir-circulation) (Rhyter, 1956) and ocean currents
72 (Loop current and Gulf Stream), are transported throughout the North the Atlantic Ocean, to
73 the Sargasso Sea, Gulf of Mexico and Caribbean Sea (Johnson et al., 2013; Wang et al., 2019).
74 *Sargassum* rafts provides an essential ecosystem habitat and refuge for different marine
75 organisms (Ross and Casazza, 2008; Witherington et al., 2012) and notably for marine species
76 of high economic importance (Hu et al., 2016; Lapointe et al., 2014).

77 For the first time in the summer 2011, for the first time unprecedented massive quantities of
78 *Sargassum* spp. stranded in the eastern Caribbean Islands and in the islands of the lesser Antilles
79 (Franks et al., 2011; Gower et al., 2013). Pelagic *Sargassum* were also reported in some places
80 where they were never previously spotted such as north eastern Brazil (Széchy et al., 2012). A
81 recurrent Great Atlantic *Sargassum* Belt in the NERR is now being reported annually by the
82 Moderate Resolution Imaging Spectro- radiometer (MODIS), this belt extend over Atlantic
83 Ocean to the Caribbean Sea (Wang et al., 2019). In 2018 it extended over 8850km and carried
84 more than and estimated 20 million metric tons of *Sargassum* wet biomass (Wang et al., 2019).

85 The stranding of *Sargassum* algae on the coast created important environmental impacts
86 threatening endangered species such as sea turtles (Casazza and Ross, 2008; Maurer et al.,
87 2015) and leading to the disappearance of seagrass ecosystems at large spatial scales
88 (Rodríguez-Martínez et al., 2019). *Sargassum* stranding also impact principal economic sources
89 of most coast through tourism, re-stricting harbors and fisheries (Langin, 2018). Stranded
90 *Sargassum* also presents important human health issues: respiratory disease, neurological
91 problems, and cardiovascular lesions (Resiere et al., 2018). In addition to those visible effects,
92 stranding of the brown algae could also present pernicious and invisible impacts as they present
93 the ability to concentrate heavy metals from their environment (Volesky and Holan, 1995) and
94 could consequently release those contaminants in stranding areas. Holopelagic *Sargassum* spp.
95 are indeed known to present high levels of inorganic arsenic (Dassié et al., 2021; Devault et al.,
96 2020). The high metal absorption capacity of *Sargassum* is due to alginate present in cells walls
97 with a high metallic affinity (Davis et al., 1999; Vieira and Volesky, 2000).

98 A previous study provided an evaluation of metallic concentrations in an undifferentiated
99 mixture of three morphotypes of *Sargassum* spp. from a transect to the middle of Atlantic Ocean
100 to the lesser Antilles (Martinique) (Dassié et al., 2021). This approach can mask specific trends
101 in morphotype contamination as closely related species of the same genus can present different
102 abilities to absorb metal contaminants (Foster, 1976; Romera et al., 2007).

103 The present study measured the metallic contamination (14 different elements) in each of the
104 three recognized *Sargassum* genotypes: *S. natans* I, *S. natans* VIII, *S. fluitans* III, in seven
105 sampling stations, along a 3600 km transect extending from the middle of the Atlantic Ocean
106 (open sea) to the Guadeloupe islands (French West Indies).

107

108 **II Study Methodology**

109

110 **II.1 Study sites**

111 From July to August 2019, 72 samples of *Sargassum* were collected from seven different
112 stations during the RV *Pelagia* sargasso cruise PE-455 NIOZ (Royal Netherlands Institute for
113 Sea Research). The expedition stretched from the middle of Atlantic Ocean to the Guadeloupe
114 Islands (French West Indies) (Fig.1). In this region *Sargassum* spp. are frequently present from
115 the Eastern edge of the Gulf Stream as far as the Azores and to the Atlantic Ocean (Gower et
116 al., 2013).

117 **II.2 Fields collection**

118

119 During the cruise, the three genotypes of *Sargassum* algae were regularly sampled when algae
120 were available and the weather conditions were favorable. Fresh *Sargassum* were collected
121 manually from a small boat using a net from the surface to 5m depth using a net. After
122 collection, the samples were separated by genotypes: *S. fluitans* III, *S. natans* I and *S. natans*
123 VIII (Amaral-Zettler et al., 2017; Oyesiku and Egunyomi, 2014; Schell et al., 2015) and 40 to
124 80 g wet weight of each morphotype was washed with fresh water, placed in paper wraps and
125 introduced into a oven-dried for 48 h at 50°C. Back in the laboratory, samples were
126 homogenized using a vibro-grinder with metallic balls of 5mm (Retsch® MM 400).

127

128 **II.3 Heavy metals analyses**

129

130 The concentrations of 15 elements (Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Se, Sr V, Zn and
131 Hg), were analyzed using an Inductively Coupled Plasma Optical Emission Spectrometer
132 (Spectrometer ICP-OES 700®, Agilent Technologies). For each sample, a fixed amount of
133 algal powder (70-80mg) was placed in a plastic tube closed with 1 mL of nitric acid (HNO₃
134 67%) was added. The powder sample was then mineralized for 3 h at 100°C (Environmental –
135 EXPRESS HotBlock® - 54). After mineralization, 5 mL of deionized water was added to each

136 sample. With the same process, we analyzed the certified reference materials (DOLT-5, TORT-
137 3, IAEA-413). For Hg, approximately 15 mg of each sample was analyzed by using flameless
138 atomic absorption spectrometry (AMA 254, SYMALAB, France). With the same process, we
139 analyzed certified reference materials (IAEA-407). The results of metal concentrations in
140 *Sargassum* samples are expressed in $\mu\text{g}\cdot\text{g}^{-1}$ (ppm) dry weight. Hg concentrations were only
141 measured in stations 1, 5 and 6.

142

143 **II.4 Data analyses**

144

145 The variance and the homogeneity in each sample were verified by the Shapiro's and Level'
146 tests (with significance at the 95 % confidence level). Difference between means in elements
147 concentrations of each sample species and the difference in concentration of metals elements
148 between each species and genotype were tested using the non-parametric test Kruskal-Wallis
149 test.

150 Methods of multivariate statistics with Principal Component Analyses (PCA) were executed
151 on RStudio® and RCran, using following the packages: FactoMiner (Husson et al., 2020),
152 factoextra (Kassambara and Mundt, 2020), ggplot (Wickham et al., 2020) and corrplot (Wei
153 et al., 2021) in order to visualize the 15 elements (Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Se,
154 Sr V, Zn and Hg), and select metallic elements with higher influence in data structuration.
155 From PCA, temporal fluctuation of four principal elements (Al, As, Cu, Fe) were presented
156 whereas metallic elements (Co, Pb, Se, Sr and Hg) below the limit of detection (LOD) were
157 not presented.

158 **III Results**

159

160 Among the fourteen elements analyzed in *Sargassum* tissues, eight elements (Al, As, Cr, Fe,
161 Mn, Ni, V, and Zn) were the most frequent elements encountered and they were detected in
162 100% in the samples and above the limit of detection (LOD). Cd and Cu were detected in 87.7
163 % and 87.2% of samples respectively. The elements Co, Sr, and Pb were below the LOD.

164 Metal classed according to decreasing concentration in all samples including all stations and all
165 morphotypes were: As > Fe > Al > Mn > Cd > Zn > Ni > V > Cu > Cr > Hg. Among all non-
166 essential elements, As and Hg were the most and the least abundant elements respectively.

167 We used Principal Component Analysis (PCA) to determine the influence of metallic elemental
168 concentrations at the basin spatial scale and between the three *Sargassum* types (Figure 2). We
169 focused on the first two dimensions of PCA for the interpretation. The first principal component

170 (PC1) revealed 28.1% of the total variance and the second, 19.4% (PC2) of the total variance.
171 PC1 distinctly discriminated the variables Fe (30.7%), Al (17.1%) and the As (9.6%), and PC2
172 clearly discriminated the variables Mn (0.6%) and Ni (0.5%).

173 The PCA analysis showed the two genotypes *S. natans* I and *S. natans* VIII, were characterized
174 by high concentrations of As whereas *S. fluitans* III was more characterized by higher Al and
175 V (Figure 2.A) concentrations.

176 The PCA analysis of *Sargassum* by the station showed an absence of any tendency for spatial
177 preference, as stations are grouped together independently of their geographical origins. The
178 Station 6 is separated from the others stations and more influenced by Cd, Zn, Ni and Cr (Figure
179 2.B).

180 Five metallic elements stand out in our PCA analyses: Fe (86%), Al (48%), V (37%), and As
181 (27%).

182 There was significantly more As in *S. natans* VIII than in others two genotypes in all stations
183 (Kruskal-Wallis test p-value < 0.05). There was significantly less Fe and Al (Kruskal-Wallis
184 test p-value < 0.05) in the morphotype *S. natans* VIII than in two others genotypes in four of
185 the stations (Figure 2.A).

186

187 **IV Discussion**

188

189 The present study constitutes a first assessment of metallic and metalloid concentrations in *S.*
190 *natans* I, *S. natans* VIII and *S. fluitans* III along a transect at the Atlantic Ocean basin scale.

191 Analyses, revealed that contamination by metallic elements *i)* the metalloid As and the metallic
192 element Fe is the most abundant in the three genotypes of *Sargassum* *ii)* did not present a
193 longitudinal gradient, and *iii)* were significantly different between the three genotypes of
194 holopelagic *Sargassum*.

195

196 **Methodological considerations**

197 Holopelagic *Sargassum* spp. are naturally covered by calcareous epifauna: bryozoans, tube-
198 forming polychaetes, and crustose coralline algae (Weis, 1968). Calcareous material can
199 increase or decrease chemical elements absorption (Huffard et al., 2014). In our samples
200 epifauna was rare. Moreover, algae without visible epifauna were preferentially selected in
201 order to limit potential bias due to epifauna in collected samples.

202 The concentrations of metallic elements vary in leaves, stems, and air bladders of *Sargassum*
203 (Sadeghi et al., 2014). In our samples the entire algae biomass was dried and ground before

204 being analyzed without separating each tissue type. The respective abundances of each tissue
205 can change naturally according to seasons, water temperature and location (Critchley, 1983).
206 Observed variations in contamination can be due to variation of respective abundance of each
207 tissue more than to variation of environmental contamination. The sampling strategy was
208 chosen in order to have a general overview of metallic contamination of *Sargassum* but this
209 potential bias must be kept in mind when interpreting our result.

210

211 **Metal and Metalloid: As and Fe**

212 As, is a metal(loid) present naturally in the open and coastal marine environment, at a
213 concentration level of 15 and 25nM as hydrogen arsenate (Fattorini et al., 2006). Only certain
214 forms of As can be toxic, as inorganic forms presents higher toxicity than the organic forms
215 (trivalent state As III and the pentavalent state As V) (Yuan et al., 2007, Circuncisao et al.,
216 2018). In our study, the metalloid element As was the most present element in all samples.
217 Dissolved As is the most largely, rapidly and greatly absorbed dissolved metalloid compared
218 to other metalloids (Penrose, 1974; Neff et al., 1997). For *Sargassum*, most experimental
219 studies conclude that As is the most commonly present metal(loid) (Dassié et al., 2021; Devault
220 et al., 2021, 2020).

221 In the present study, the mean concentration of As was 92.72 $\mu\text{g}\cdot\text{g}^{-1}$ in all samples with a
222 maximum value of 115 $\mu\text{g}\cdot\text{g}^{-1}$. Those values are in the range of values previously observed in
223 the Caribbean area with As level fluctuating between 80 and 150 ppm in coastal waters
224 (Dawczynski et al., 2007; García-Sartal, 2012; Rodríguez-Martínez et al., 2020), and in the
225 open ocean between 0.1 and 382 $\mu\text{g}\cdot\text{g}^{-1}$ (Dassié et al., 2021). For all others elements, *Sargassum*
226 concentrations were below the French standard limit for the enrichment of organic soil product,
227 but higher than the fixed French norm of 18 $\mu\text{g}\cdot\text{g}^{-1}$ ppm for the As (NFU 44-051- ISSN 0335-
228 3931). As was also above the maximum level ($\sim 40 \mu\text{g}\cdot\text{g}^{-1}$ ppm) established in Europe for
229 seaweed derived food products and material derived from seaweed utilization (European
230 Commission, 2019), and above the limits recommended for agricultural soils in others countries
231 (Rodríguez-Martínez et al., 2020). In 2017, this elevated As led ANSES (France's Food Safety
232 Agency) to exclude the use of *Sargassum* spp. for food (humans and animals) in the Caribbean
233 area (ANSES 2017).

234 A general trend observed across all samples was the difference between concentrations of As
235 and Fe. This difference was not observed in *Sargassum* from the open-ocean Atlantic (Dassié
236 et al., 2021). The organic form of the iron (Fe) is an essential micronutrients in the marine
237 environment (Gledhiir and Buck, 2012). Fe is the fourth most abundant element on Earth and

238 but its concentration in sea water is very low (Johnson et al., 1997; Liu and Millero, 2002).
239 Experiments revealed that increasing the concentration in inorganic As would present a
240 negative influence in the variation of the Fe in *Sargassum patens* due to the action of phosphate
241 transporters (Mamun et al., 2019).

242 The concentration of As detected in this study was higher in *S. natans* VIII, than in the two
243 others forms. The composition of holopelagic *Sargassum* forms has changed over time since in
244 the 1930s, only *S. natans* I and *S. fluitans* III were the most abundant forms (Parr, 1939) but
245 since 2014, the rare form *S. natans* VIII became more abundant (Schell et al., 2015) and was
246 shown to also be genetically distinct from *S. natans* IV (Amaral-Zettler et al., 2017). The
247 dominance of this genotype presenting the highest concentration of As will hamper its
248 utilization and must be taken into consideration for a future valorization of *Sargassum* spp.,
249 which hamper their utilization. The metalloid As is present in coastal and open ocean, with
250 higher concentration in some location. Consequently, management strategies must consider this
251 constant As contamination.

252

253 **Spatial considerations**

254 Present results reveal an absence of a contamination trend associated with samples locations.
255 This absence of longitudinal gradient of metallic contamination could be linked with the pelagic
256 nature of *Sargassum*. At the scale of the Atlantic Ocean Basin, *Sargassum* are in perpetual
257 motion, and actually their precise movements and trajectories still remains unclear. Satellite
258 images proves high variability in the distribution of *Sargassum* according to the time and the
259 current (Gower et al., 2013; Gower and King, 2011). Undrogued Stokes drifters (USD) buoys
260 were shown to represent the drifting of *Sargassum* with respect to current shear (Haza et al.,
261 2008; Laxague et al., 2018) and wave-driven stokes (Fraser et al., 2018). In order to understand
262 the role of surface currents in *Sargassum* movements, stoke drifter were launched during our
263 sampling cruise and allowed determination of minimum, average and maximum speeds of
264 *Sargassum* in this area during this period (July-August 2019) representing respectively 0.081,
265 0.32 and 0.46 m.s⁻¹ (van Sebille et al., 2021). According to those measurements, minimum,
266 average and maximum time needed to travel between the two nearest stations (stations 3 and
267 4), would be respectively 11, 16 and 65 days respectively. An experimental study carried out
268 over on 40 days revealed that the absorption of metals elements by the benthic *Sargassum*
269 *thunbergii*, is clearly noticeable after ≥ 3 days (Wu et al., 2010).

270 The absence of spatial gradient could also be explained by a scenario of a rapid renewal of
271 *Sargassum* biomass. *Sargassum* clumps and rafts move rapidly, making the measurement of

272 their biomass and the evaluation of their production difficult (Wang and Hu, 2021). However,
273 the strong seasonality in aggregation of *Sargassum* slicks (Oviatt et al., 2019) and rapid blooms
274 implies that production could be important. In this context of rapid renewal, *Sargassum* would
275 not have time to accumulate metals during their transportation and would consequently present
276 a constant contamination. As a result, abundances of metal elements would not increase in
277 *Sargassum* along their journey in the Atlantic due to *i*) a relatively slow motion of algae at basin
278 scale *ii*) a short absorption time of metallic element *iii*) a relatively rapid renewal of *Sargassum*
279 biomass.

280 A similar transect in the open ocean Atlantic (from the center of the Atlantic Ocean to the coast
281 of Martinique) also revealed an absence of a longitudinal gradient of concentration in metallic
282 elements in *Sargassum* (Dassié et al., 2021). Similarly, a coastal study also highlighted an
283 absence of a longitudinal gradient of concentration in metallic elements during the journey of
284 *Sargassum* from the South to the North coast of Mexico (Rodríguez-Martínez et al., 2020).

285 Despite the absence of a longitudinal gradient of metallic concentration at Atlantic basin scale,
286 several of our stations periodically presented higher As concentration. In Stations 3, high As
287 levels might be explained by the close proximity with the mid-Atlantic ridge emitting metallic
288 elements (Mitra et al., 1994). Higher As concentrations in the stations closet to the coast, like
289 Station 7 was previously observed (Dassié et al., 2021) and could be linked with metallic
290 elements from anthropogenic activities (Breuer and Pichler, 2013) or coastal volcanic activities
291 (Fernandez et al., 2007). Similarly, *Sargassum* arriving close to the coast are known to integrate
292 components with terrestrial origin such as the Chlordecone pesticide (Devault et al., 2021).

293 This absence of a longitudinal gradient of metallic elements concentrations, highlights that the
294 *Sargassum* which runs aground along the coast of the Caribbean islands, doesn't have a
295 particular contamination specificity allowing a similar management and permitting a
296 standardized treatment in the Caribbean area in the future.

297

298 **Pelagic *Sargassum*: the three genotypes**

299 Metallic compositions differ between the three forms of *Sargassum* that also represent closely
300 related but distinct genotypes on the genomic level. The morphotype *S. natans* VIII presented
301 higher metalloid As concentrations and lower Fe concentration than *S. natans* I and *S. fluitans*
302 III. An opposite trend was previously observed with highest As content in *S. natans* I and lowest
303 in *S. natans* VIII (Davis et al., 2021). Observed As contents fluctuating from 20 to 231 $\mu\text{g}\cdot\text{g}^{-1}$
304 ppm, were in the range of value for those morphotypes (Milledge and Harvey, 2016; Milledge
305 et al., 2020).

306 The absorption of metal and metalloid elements can be influenced by the morphological fractal
307 structure of brown algae presenting a higher area-to-volume ratio increasing potentials
308 attachment and entrance of metals (Torresi et al., 2017; Woignier et al., 2011). The morphotype
309 *S. natans* VIII does not have thorns on its stem and presents a structure less complex with fewer
310 interstitial spaces and larger leaves (Schell et al., 2015). Despite this lower area-to-volume ratio
311 of *S. natans* VIII, the present study did not reveal lower concentrations of metals in this
312 morphotype than in the two others. If structural morphology was the only parameter influencing
313 metals concentration in *Sargassum*, the trend would be similar for all metals and they would all
314 present a lower abundance in *S. natans* VIII. That was not the case for the metalloid As,
315 therefore aspects other than morphological structure must consequently influence
316 concentrations of metallic elements.

317 The chemical composition of morphotypes can influence metal concentrations. Cell walls of
318 brown algae are characterized by the presence of phycollid elements (Khotimchenko et al.,
319 2001). These phycollid compounds are involved in several chemical mechanisms like ion
320 entrapment in polysaccharide networks increasing the absorption capacity of metal elements
321 (Volesky and Holan, 1995; Zeraatkar et al., 2016). According to brown seaweed species,
322 abundance of phycollids can change and can influence the ability to absorb metallic elements
323 (Davis et al., 1999; Fourest and Volesky, 1997; Haug et al., 1966). The morphotype *S. natans*
324 VIII contains higher abundance of phycollids components than the others (Davis et al., 2021).
325 These singular chemical compositions could explain the better absorption of metalloid As by
326 *S. natans* VIII than by *S. natans* I and *S. fluitans* III.

327 Genotype encompasses phenotypic characteristics such as morphology and physiology.
328 Morphotypes of holopelagic *Sargassum* are genetically distinct but closely related (Amaral-
329 Zettler et al., 2017). In the present study, each species was characterized by a particular metallic
330 composition pattern. Morphotypes of *S. natans* (I and VIII) metallic compositions were more
331 similar to each other than to *S. fluitans* consistent with their genetic relatedness. The ability to
332 absorb metal is a reduced aspect of all phenotype characteristics, however our conclusions
333 about resemblances between morphotypes are in accordance with genetic differentiation
334 actually admitted.

335

336 **Conclusion**

337

338 Different green strategies and solutions are proposed to exploit stranded *Sargassum* and to
339 reduce their pressure on impacted the coastal areas. Our study confirmed the high As content

340 of *Sargassum* at a large spatial scale. In this context some strategies of *Sargassum* valorization
341 such as construction materials and bioenergy (Chávez et al., 2021; López Miranda et al., 2021)
342 should be favored over others such as fertilizer production that should be considered with
343 caution to avoid environmental and health issues. *Sargassum* could also cause environmental
344 and health problems through the discharge of contaminants into the coastal marine
345 environment. *Sargassum* genotypes present different contamination patterns and the abundance
346 of each morphotypes have been changing during recent years. In this context of abundance
347 changes, the global metal contamination of floating *Sargassum* spp. will likely also change in
348 the future.

349
350
351
352

353 **Author Contributions**

354

355 OC conceived the research, collected the samples, identified *Sargassum* species, carried out
356 sample preparation, acquired the data, performed data analyses, , conducted the analytical
357 research and interpretation, and wrote the first draft of the paper. JG funded the analysis
358 research. EPD carried out some sample preparation, analyses and data acquisition. MB
359 proofreaded the manuscript. PYG contributed to the data analysis. LA-Z led the NIOZ PE455
360 oceanographic expedition, helped to collect samples and edited/proofread the manuscript. PYP
361 contribute to editing and proofreaded the manuscript. All co-author edited and revised the
362 manuscript.

363

364 **Acknowledgments**

365

366 We thank the NIOZ *R/V Pelagia* crew members and scientists aboard the cruise 64PE455. The
367 marine station of Arcachon from the University of Bordeaux and the machines allowed to
368 realize the analyzes of metallic elements. OC was partly supported financially by the institution
369 of Guadeloupe Region.

370

371

372

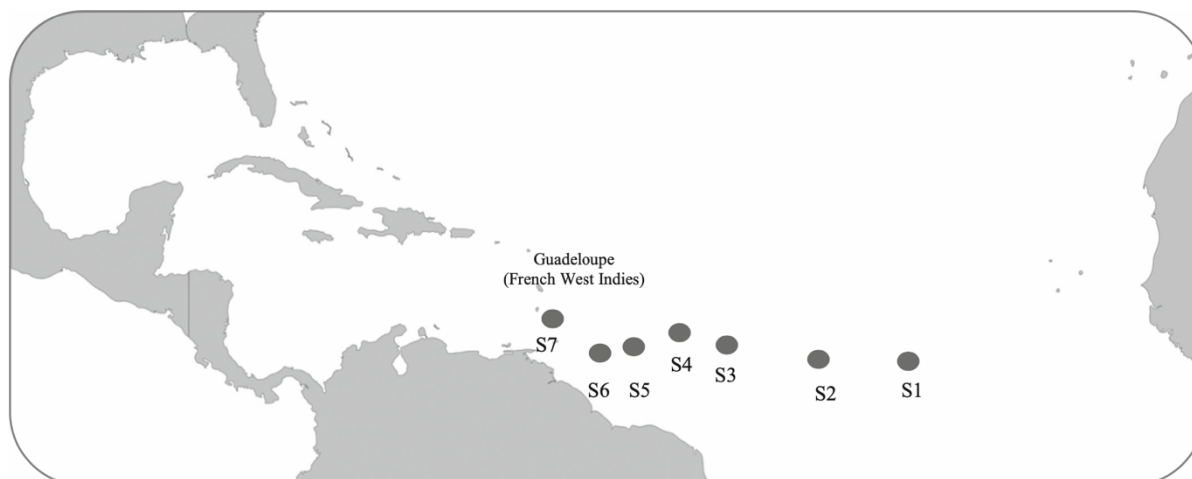
373

374 **Table and figures**

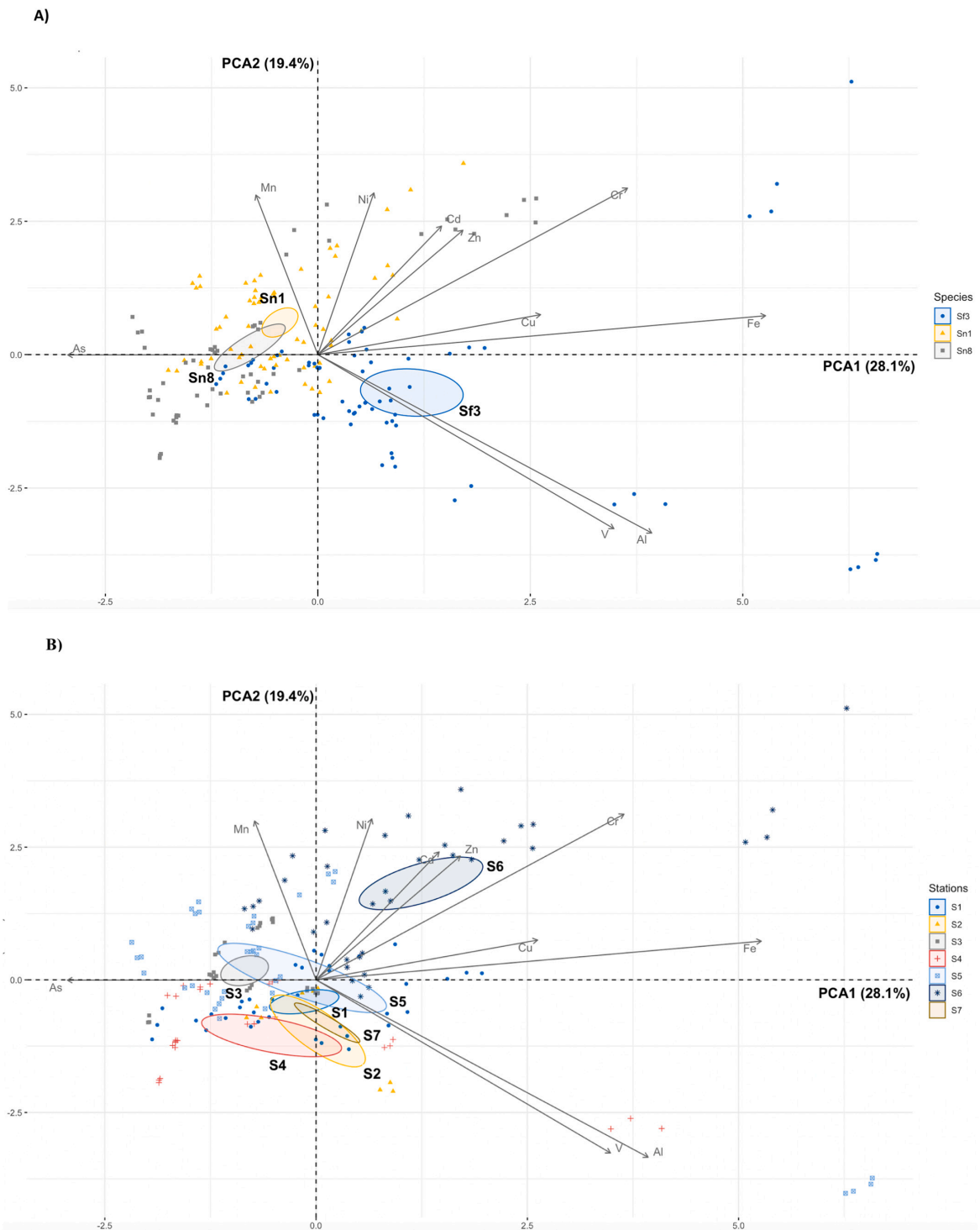
375 **Table 1** – Elements concentration (ppm = $\mu\text{g}\cdot\text{g}$) of pelagic *Sargassum* spp. collected from 7 different stations
 376 along a transect to the middle Atlantic Ocean to the Lesser Antilles (Guadeloupe – French West Indies) with their
 377 respective standard error (standard deviation divided by the squared root of the number of data), and the average
 378 in bold. Below the table there are recovery rates obtained from the analyses of certified reference material (TORT-
 379 3, DOLT-5, IAEA 413, and IAEA 407

	Al	As	Cd	Cr	Cu	Fe	Mn	Ni	V	Zn
S1	25,01 $\pm 5,32$	87,92 $\pm 13,87$	0,70 $\pm 0,09$	4,16 $\pm 1,11$	1,53 $\pm 0,49$	60,87 $\pm 15,85$	19,42 $\pm 5,69$	3,07 $\pm 0,26$	1,33 $\pm 0,08$	6,68 $\pm 0,83$
S2	35,67 $\pm 12,66$	85,43 $\pm 10,43$	0,86 $\pm 0,05$	0,52 $\pm 0,16$	1,67 $\pm 0,13$	48,83 $\pm 16,75$	19,89 $\pm 7,15$	3,30 $\pm 0,67$	8,17 $\pm 0,69$	8,17 $\pm 1,36$
S3	15,93 $\pm 4,02$	95,93 $\pm 13,17$	1,01 $\pm 0,11$	0,735 $\pm 0,37$	<LOD	31,24 $\pm 8,92$	23,71 $\pm 7,21$	3,93 $\pm 0,58$	1,43 $\pm 0,03$	8,30 $\pm 1,33$
S4	28,54 $\pm 16,88$	88,60 $\pm 8,78$	1,05 $\pm 0,81$	0,72 $\pm 0,12$	2,15 $\pm 0,81$	38,94 $\pm 22,11$	22,82 $\pm 6,48$	3,95 $\pm 0,25$	2,24 $\pm 0,64$	5,30 $\pm 1,30$
S5	24,53 $\pm 19,56$	99,53 $\pm 9,06$	1,04 $\pm 0,01$	2,30 $\pm 0,82$	3,51 $\pm 0,80$	47,34 $\pm 21,14$	24,76 $\pm 13,17$	5,08 $\pm 1,28$	1,90 $\pm 0,96$	6,07 $\pm 0,91$
S6	16,05 $\pm 1,81$	88,23 $\pm 8,78$	82,88 $\pm 120,15$	4,66 $\pm 1,60$	3,87 $\pm 0,69$	52,69 $\pm 13,56$	24,27 $\pm 8,29$	5,86 $\pm 2,25$	1,38 $\pm 0,26$	7,11 $\pm 0,86$
S7	29,69 $\pm 2,88$	103,44 $\pm 9,53$	0,48 $\pm 0,024$	2,39 $\pm 1,01$	4,24 $\pm 0,33$	49,87 $\pm 10,69$	22,44 $\pm 9,62$	4,16 $\pm 0,001$	2,42 $\pm 1,28$	4,65 $\pm 0,39$
Mean	25,06	92,72	12,57	2,21	2,68	47,11	22,47	4,18	2,6	6,61
IAEA413 recovery rate (%SD)		101,55 $\pm 3,92$	97,96 $\pm 12,88$	100,70 $\pm 10,39$		94,55 $\pm 51,23$	97,01 $\pm 7,12$	97,57 $\pm 8,$ 34		98,70 $\pm 7,99$
DOLT-5 recovery rate (%SD)		100,21 $\pm 0,018$	95,28 $\pm 0,19$		93,85 $\pm 0,38$	91,20 $\pm 14,60$				98,75 $\pm 1,65$
TORT-3 recovery rate (%SD)		115,59 $\pm 0,77$	92,93 $\pm 0,69$		93,47 $\pm 5,32$	82,27 $\pm 3,28$	85,76 $\pm 0,37$	87,97 $\pm 0,08$	89,90 $\pm 0,10$	98,71 $\pm 1,73$

380
381



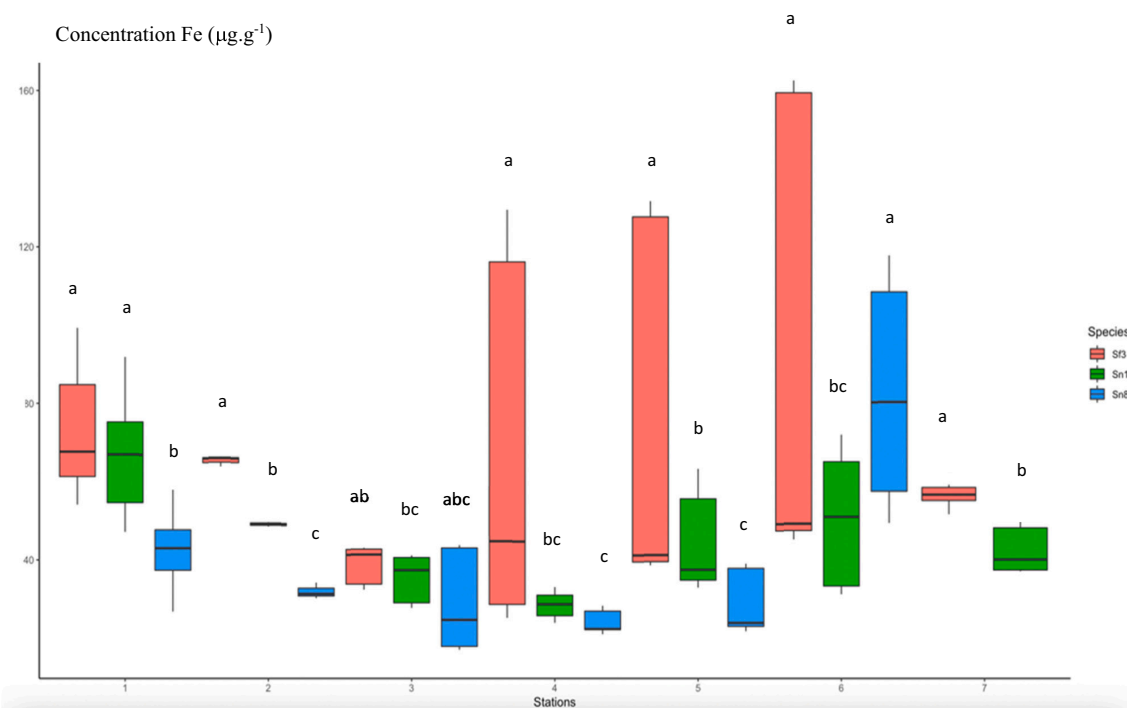
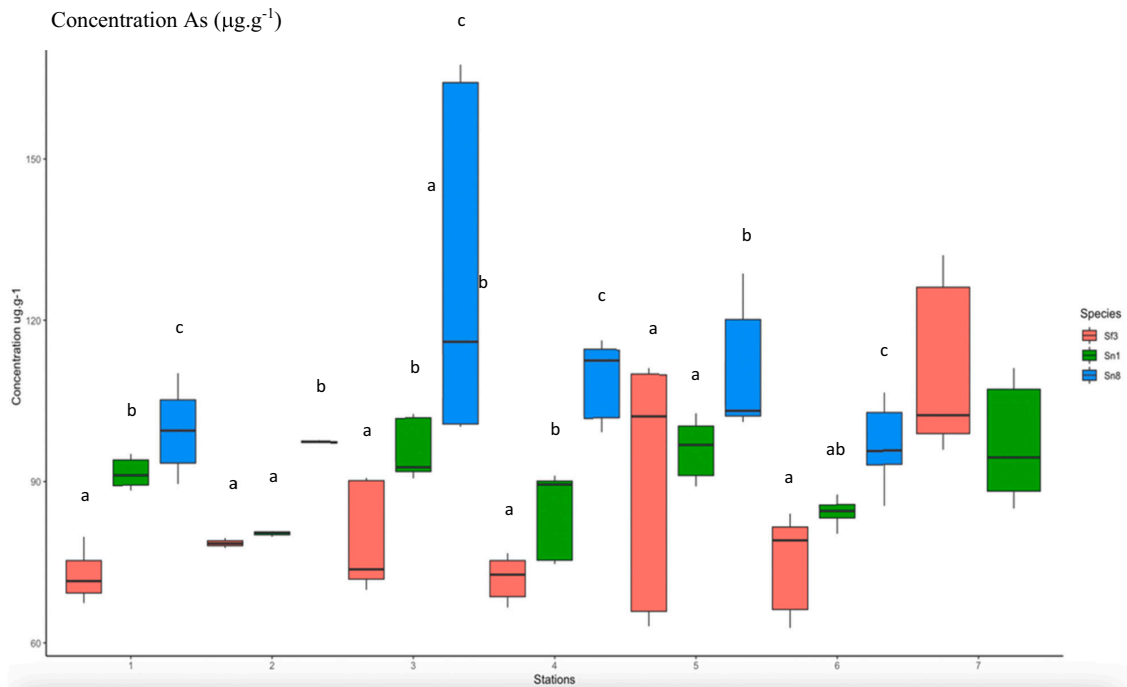
382
 383 **Figure 1** Sampling sites. Location of the sampling sites : S1 (6°98'N; -31°80'W), S2 (6°87'N;-34°42'W), S3
 384 (8°02'N;-47°07'W), S4 (8°45'N;-47°07'W), S5 (8°42'N; -49°73'W), S6 (12°39'N; -56°78'W), S7 (16°13'N; -
 385 61°37'W) of *Sargassum* sp. along the transect from Middle Atlantic Ocean to Guadeloupe (French West Indies),
 386 during the cruise expedition RV-Pelagia PE-455 (NIOZ) between July and August 2019.



387

388 **Figure 2** Principal Component Analyzes (PCA) in Dim1 (28.1%) and Dim2 (19.4%) A) represented the
 389 relationship between Sargassum sp. metallic elements and the species for the three morphotypes: Sn1 (Sargassum
 390 natans I), Sn8 (Sargassum natans VIII), Sf3 (Sargassum fluitans III). B) represented the relationship between
 391 Sargassum sp. metallic elements and the sampling sites: S1 (Station 1), S2 (Station 2), S3 (Station 3), S4 (Station
 392 4), S5 (Station 5), S6 (Station 6), S7 (Station 7).

393



394

395 **Figure 3** Elements metals concentration for the spatial variability Concentrations of five most frequent
 396 elements ($\mu\text{g}\cdot\text{g}^{-1}$) in the sargasso algae collected from 7 different stations (S1, S2, S3, S4, S5, S6, S7) along
 397 the transect from Middle Atlantic Ocean to Guadeloupe (French West Indies), between July and August
 398 2019. The horizontal axis represented the stations and the each morphotypes. The color of the boxplot
 399 represents the sargasso morphotypes. The horizontal black lines represent the median for each station.

400 The letters represent the difference significantly between the three morphotypes for each station (S. natans I,
 401 S. natans VIII and S. fluitans III), using a non-parametric test ANOVAs based on the Kruskal-Wallis (test p-
 402 value < 0.05).

403

404

405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438

Bibliography

- Amaral-Zettler, L.A., Dragone, N.B., Schell, J., Slikas, B., Murphy, L.G., Morrall, C.E., Zettler, E.R., 2017. Comparative mitochondrial and chloroplast genomics of a genetically distinct form of *Sargassum* contributing to recent “Golden Tides” in the Western Atlantic. *Ecol. Evol.* 7, 516–525. <https://doi.org/10.1002/ece3.2630>
- Breuer, C., Pichler, T., 2013. Arsenic in marine hydrothermal fluids. *Chem. Geol.* 348, 2–14. <https://doi.org/10.1016/j.chemgeo.2012.10.044>
- Casazza, T.L., Ross, S.W., 2008. Fishes associated with pelagic *Sargassum* and open water lacking *Sargassum* in the Gulf Stream off North Carolina. *Fish. Bull.* 106, 348–363.
- Chávez, V., Lithgow, D., Losada, M., Silva-Casarin, R., 2021. Coastal green infrastructure to mitigate coastal squeeze. *J. Infrastruct. Preserv. Resil.* 2, 1–12. <https://doi.org/10.1186/s43065-021-00026-1>
- Coston-Clements, L., Settle, L.R., Hoss, D.E., Cross, F.A., 1991. Utilization of the *Sargassum* Habitat by Marine Invertebrates and Vertebrates., *Memo NOAA Tech 2*, v–413.
- Critchley, A.T., 1983. Experimental observations on variability of leaf and air vesicle shape of *Sargassum muticum*. *J. Mar. Biol. Assoc. United Kingdom* 63, 825–831. <https://doi.org/10.1017/S0025315400071241>
- Dassié, E.P., Gourves, P.-Y., Cipolloni, O., Pascal, P.-Y., Baudrimont, M., 2021. First

439 assessment of Atlantic open ocean Sargassum spp. metal and metalloid concentrations.
440 Environ. Sci. Pollut. Res. <https://doi.org/10.1007/s11356-021-17047-8>

441 Davis, D., Simister, R., Campbell, S., Marston, M., Bose, S., McQueen-Mason, S.J., Gomez,
442 L.D., Gallimore, W.A., Tonon, T., 2021. Biomass composition of the golden tide pelagic
443 seaweeds Sargassum fluitans and S. natans (morphotypes I and VIII) to inform
444 valorisation pathways. Sci. Total Environ. 762, 143134.
445 <https://doi.org/10.1016/j.scitotenv.2020.143134>

446 Davis, T.A., Volesky, B., Vieira, R.H.S.F., 1999. Sargassum seaweed as biosorbent for heavy
447 metals. Elsevier Sci. 34, 4270–4278.

448 Dawczynski, C., Schäfer, U., Leiterer, M., Jahreis, G., 2007. Nutritional and toxicological
449 importance of macro, trace, and ultra-trace elements in algae food products. J. Agric.
450 Food Chem. 55, 10470–10475. <https://doi.org/10.1021/jf0721500>

451 Devault, D.A., Massat, F., Baylet, A., Dolique, F., Lopez, P.J., 2021. Arsenic and chlordecone
452 contamination and decontamination toxicokinetics in Sargassum sp. Environ. Sci. Pollut.
453 Res. <https://doi.org/10.1007/s11356-020-12127-7>

454 Devault, D.A., Pierre, R., Marfaing, H., Dolique, F., Lopez, P.J., 2020. Sargassum
455 contamination and consequences for downstream uses: a review. J. Appl. Phycol. 33,
456 567–602. <https://doi.org/10.1007/s10811-020-02250-w>

457 European Commission, 2019. Official Journal of the European Union, Commission regulation
458 (EU) 2019/1869 of 7 November 2019 amending and correcting annex I to directive
459 2002/32/EC of the European Parliament and of the council as regards maximum levels
460 for certain unde- sirable.

461 Fattorini, D., Notti, A., Regoli, F., 2006. Characterization of arsenic content in marine
462 organisms from temperate, tropical, and polar environments. Chem. Ecol. 22, 405–414.
463 <https://doi.org/10.1080/02757540600917328>

464 Fernandez, A., Singh, A., Jaffé, R., 2007. A literature review on trace metals and organic
465 compounds of anthropogenic origin in the Wider Caribbean Region. Mar. Pollut. Bull.
466 54, 1681–1691. <https://doi.org/10.1016/j.marpolbul.2007.08.007>

467 Foster, P., 1976. Concentrations and concentration factors of heavy metals in brown algae.
468 Environ. Pollut. 10, 45–53. [https://doi.org/https://doi.org/10.1016/0013-9327\(76\)90094-](https://doi.org/https://doi.org/10.1016/0013-9327(76)90094-)
469 X

470 Fourest, E., Volesky, B., 1997. Alginate Properties and Heavy Metal Biosorption by Marine
471 Algae. Appl. Biochem. Biotechnol. 67, 215–226.

472 Franks, J.S., Johnson, D.R., Ko, D.S., Rubio, G.S., Hendon, J.R., Lay, M., 2011.

473 Unprecedented Influx of Pelagic Sargassum along Caribbean Island Coastlines during
474 Summer 2011. *Gulf Caribb. Fish. Inst.* 6–8.

475 Fraser, C.I., Morrison, A.K., Hogg, A.M.C., Macaya, E.C., van Sebille, E., Ryan, P.G.,
476 Padovan, A., Jack, C., Valdivia, N., Waters, J.M., 2018. Antarctica’s ecological isolation
477 will be broken by storm-driven dispersal and warming. *Nat. Clim. Chang.* 8, 704–708.
478 <https://doi.org/10.1038/s41558-018-0209-7>

479 García-Sartal, C., 2012. Bioavailability and speciation of arsenic in edible seaweed. Ph.D.
480 thesis. University of Santiago de Compostella, Spain.

481 Gledhiir, M., Buck, K.N., 2012. The organic complexation of iron in the marine environment:
482 A review. *Front. Microbiol.* 3, 1–17. <https://doi.org/10.3389/fmicb.2012.00069>

483 Gower, J., Young, E., King, S., 2013. Satellite images suggest a new Sargassum source region
484 in 2011. *Remote Sens. Lett.* 4, 764–773. <https://doi.org/10.1080/2150704X.2013.796433>

485 Gower, J.F.R., King, S.A., 2011. Distribution of floating Sargassum in the Gulf of Mexico
486 and the Atlantic ocean mapped using MERIS. *Int. J. Remote Sens.* 32, 1917–1929.
487 <https://doi.org/10.1080/01431161003639660>

488 Guiry, M.D., Guiry, G.M., 2022. World-Wide electronic publication. *Natl. Univ. Ireland.*
489 *Algaebase 2022.*

490 Guiry, M.D., Guiry, G.M., Morrison, L., Rindi, F., Miranda, S.V., Mathieson, A.C., Parker,
491 B.C., Langanen, A., John, D.M., Bárbara, I., Carter, C.F., Kuipers, P., Garbary, D.J.,
492 2014. *AlgaeBase: An on-line resource for algae.* *Cryptogam. Algal.* 35, 105–115.
493 <https://doi.org/10.7872/crya.v35.iss2.2014.105>

494 Haug, A., Larsen, B., Smidsrød, O., 1966. A study of the constitution of Alginic Acid by
495 Partial Acid Hydrolysis. *Acta Chem. Scand.* 20, 183–190.

496 Haza, A.C., Poje, A.C., Özgökmen, T.M., Martin, P., 2008. Relative dispersion from a high-
497 resolution coastal model of the Adriatic Sea. *Ocean Model.* 22, 48–65.
498 <https://doi.org/10.1016/j.ocemod.2008.01.006>

499 Hu, C., Murch, B., Barnes, B.B., Wang, M., Maréchal, J.-P., Franks, J., Johnson, D.,
500 Lapointe, B., Goodwin, D.S., Schell, J.M., Siuda, A.N.S., 2016. Sargassum Watch
501 Warns of Incoming Seaweed. *Eos Trans. Am. Geophys. Union* 97.
502 <https://doi.org/10.1117/1.OE.53.5.051402.Laffoley>

503 Huffard, C.L., von Thun, S., Sherman, A.D., Sealey, K., Smith, K.L., 2014. Pelagic
504 Sargassum community change over a 40-year period: temporal and spatial variability.
505 *Mar. Biol.* 161, 2735–2751. <https://doi.org/10.1007/s00227-014-2539-y>

506 Husson, F., Josse, J., Le, S., Mazet, J., 2020. *Multivariate Exploratory Data Analysis and Data*

507 Mining (FactoMineR) [WWW Document]. URL [https://cran.r-](https://cran.r-project.org/web/packages/FactoMineR/index.html)
508 [project.org/web/packages/FactoMineR/index.html](https://cran.r-project.org/web/packages/FactoMineR/index.html)

509 Johnson, D.R., Ko, D.S., Franks, J.S., Moreno, P., Sanchez-Rubio, G., 2013. The Sargassum
510 Invasion of the Eastern Caribbean and Dynamics of the Equatorial North Atlantic. *Proc.*
511 *65th Gulf Caribb. Fish. Inst.* 65, 2012–2013.

512 Johnson, K.S., Michael Gordon, R., Coale, K.H., 1997. What controls dissolved iron
513 concentrations in the world ocean? *Mar. Chem.* 57, 137–161.
514 [https://doi.org/10.1016/S0304-4203\(97\)00043-1](https://doi.org/10.1016/S0304-4203(97)00043-1)

515 Kassambara, A., Mundt, F., 2020. Extract and Visualize the Results of Multivariate Data
516 Analyses (factoextra) [WWW Document]. URL [https://cran.r-](https://cran.r-project.org/web/packages/factoextra/index.html)
517 [project.org/web/packages/factoextra/index.html](https://cran.r-project.org/web/packages/factoextra/index.html)

518 Khotimchenko, Y.S., Kovalev, V. V., Savchenko, O. V., Ziganshina, O.A., 2001. Physical-
519 Chemical Properties, Physiological Activity, and Usage of Alginates, the
520 Polysaccharides of Brown Algae. *Russ. J. Mar. Biol.* 27.
521 <https://doi.org/10.1023/A:1013851022276>

522 Langin, K., 2018. Seaweed masses assault Caribbean islands. *Science* (80-.). 360, 1157–
523 1158. <https://doi.org/10.1126/science.360.6394.1157>

524 Lapointe, B., 1995. A comparison of nutrient-limited productivity in *Sargassum natans* from
525 neritic vs. oceanic waters of the western North Atlantic Ocean. *Limnol. Oceanogr.*
526 <https://doi.org/10.2307/2838178>

527 Lapointe, B.E., West, L.E., Sutton, T.T., Hu, C., 2014. Ryther revisited: Nutrient excretions
528 by fishes enhance productivity of pelagic *Sargassum* in the western North Atlantic
529 Ocean. *J. Exp. Mar. Bio. Ecol.* 458, 46–56. <https://doi.org/10.1016/j.jembe.2014.05.002>

530 Laxague, N.J.M., Özgökmen, T.M., Haus, B.K., Novelli, G., Shcherbina, A., Sutherland, P.,
531 Guigand, C.M., Lund, B., Mehta, S., Alday, M., Molemaker, J., 2018. Observations of
532 Near-Surface Current Shear Help Describe Oceanic Oil and Plastic Transport. *Geophys.*
533 *Res. Lett.* 45, 245–249. <https://doi.org/10.1002/2017GL075891>

534 Liu, X., Millero, F.J., 2002. The solubility of iron in seawater. *Mar. Chem.* 77, 43–54.
535 [https://doi.org/10.1016/S0304-4203\(01\)00074-3](https://doi.org/10.1016/S0304-4203(01)00074-3)

536 López Miranda, J.L., Celis, L.B., Estévez, M., Chávez, V., van Tussenbroek, B.I., Uribe-
537 Martínez, A., Cuevas, E., Rosillo Pantoja, I., Masia, L., Cauich-Kantun, C., Silva, R.,
538 2021. Commercial Potential of Pelagic *Sargassum* spp. in Mexico. *Front. Mar. Sci.* 8.
539 <https://doi.org/10.3389/fmars.2021.768470>

540 Mamun, M.A. Al, Omori, Y., Papry, R.I., Kosugi, C., Miki, O., 2019. Bioaccumulation and

541 biotransformation of arsenic by the brown macroalga *Sargassum patens* C. Agardh in
542 seawater : effects of phosphate and iron ions 2669–2685.

543 Maurer, A.S., Neef, E. De, Stapleton, S., 2015. Sargassum accumulation may spell trouble for
544 nesting sea turtles. *Front. Ecol. Environ.* 13, 394–395.

545 Milledge, J., Harvey, P., 2016. Golden Tides: Problem or Golden Opportunity? The
546 Valorisation of Sargassum from Beach Inundations. *J. Mar. Sci. Eng. Rev.* 4, 60.
547 <https://doi.org/10.3390/jmse4030060>

548 Milledge, J.J., Maneein, S., Arribas-López, E., Bartlett, D., 2020. Sargassum Inundations in
549 Turks and Caicos : Methane. *Energies* 13, 1–27.

550 Mitra, A., Elderfield, H., Greaves, M.J., 1994. Rare earth elements in submarine hydrothermal
551 fluids and plumes from the Mid-Atlantic Ridge. *Mar. Chem.* 46, 217–235.
552 [https://doi.org/10.1016/0304-4203\(94\)90079-5](https://doi.org/10.1016/0304-4203(94)90079-5)

553 Oviatt, C.A., Huizenga, K., Rogers, C.S., Miller, W.J., 2019. What nutrient sources support
554 anomalous growth and the recent sargassum mass stranding on Caribbean beaches? A
555 review. *Mar. Pollut. Bull.* 145, 517–525.
556 <https://doi.org/10.1016/j.marpolbul.2019.06.049>

557 Oyesiku, O.O., Egunyomi, A., 2014. Identification and chemical studies of pelagic masses of
558 *Sargassum natans* (Linnaeus) Gaillon and *S. fluitans* (Borgesen) Borgesen (brown
559 algae), found offshore in Ondo State, Nigeria. *African J. Biotechnol.* 13, 1188–1193.
560 <https://doi.org/10.5897/ajb2013.12335>

561 Parr, A.E., 1939. Quantitative observations on the pelagic sargassum vegetation of the
562 western north Atlantic. *Bull. Bingham Oceanogr. Collect.* 6, 1–94.

563 Resiere, D., Valentino, R., Nevière, R., Banydeen, R., Gueye, P., Florentin, J., Cabié, A.,
564 Lebrun, T., Mégarbane, B., Guerrier, G., Mehdaoui, H., 2018. Sargassum seaweed on
565 Caribbean islands: an international public health concern. *Lancet* 392, 2691.
566 [https://doi.org/10.1016/S0140-6736\(18\)32777-6](https://doi.org/10.1016/S0140-6736(18)32777-6)

567 Rodríguez-Martínez, R.E., Medina-Valmaseda, A.E., Blanchon, P., Monroy-Velázquez, L.
568 V., Almazán-Becerril, A., Delgado-Pech, B., Vásquez-Yeomans, L., Francisco, V.,
569 García-Rivas, M.C., 2019. Faunal mortality associated with massive beaching and
570 decomposition of pelagic Sargassum. *Mar. Pollut. Bull.* 146, 201–205.
571 <https://doi.org/10.1016/j.marpolbul.2019.06.015>

572 Rodríguez-Martínez, R.E., Roy, P.D., Torrescano-Valle, N., Cabanillas-Terán, N., Carrillo-
573 Domínguez, S., Collado-Vides, L., García-Sánchez, M., Tussenbroek, B.I. van, 2020.
574 Element concentrations in pelagic Sargassum along the Mexican Caribbean coast in

2018-2019. Peer J 10, 14.

Romera, E., González, F., Ballester, A., Blázquez, M.L., Muñoz, J.A., 2007. Comparative study of biosorption of heavy metals using different types of algae. *Bioresour. Technol.* 98, 3344–3353. <https://doi.org/10.1016/j.biortech.2006.09.026>

Ross, S.W., Casazza, T.L., 2008. Fishes associated with pelagic Sargassum and open water lacking Sargassum in the Gulf Stream off North Carolina. *Fish. Bull.* 106, 348–363.

Sadeghi, S.A.T., Kamali, A.A., Kabirifard, A.M., 2014. Determination of Heavy Metals in *Sargassum angustifolium* Marine Alga of South West Coasts of Iran for Using in Animal Nutrition. *Env. Pharmacol. Life Sci* 3, 261–265.

Schell, J.M., Goodwin, D.S., Siuda, A.N.S., 2015. Recent Sargassum inundation events in the Caribbean: shipboard observations reveal dominance of a previously rare form. *Oceanography* 28, 102–104.

Stoner, A.W., 1983. Pelagic Sargassum : Evidence for a major decrease in biomass. *Deep Sea Res. Part I Oceanogr. Res. Pap.* 30, 469–474.

Széchy, M.T.M., Guedes, P.M., Baeta-Neves, M.H., Oliveira, E.N., 2012. Verification of *Sargassum natans* (Linnaeus) Gaillon (Heterokontophyta: Phaeophyceae) from the Sargasso Sea off the coast of Brazil, western Atlantic Ocean. *Check List* 8, 638–641. <https://doi.org/10.15560/8.4.638>

Torresi, E., Polesel, F., Bester, K., Christensson, M., Smets, B.F., Trapp, S., Andersen, H.R., Plósz, B.G., 2017. Diffusion and sorption of organic micropollutants in biofilms with varying thicknesses. *Water Res.* 123, 388–400. <https://doi.org/10.1016/j.watres.2017.06.027>

van Sebille, E., Zettler, E., Wienders, N., Amaral-Zettler, L., Elipot, S., Lumpkin, R., 2021. Dispersion of Surface Drifters in the Tropical Atlantic. *Front. Mar. Sci.* 7, 1–10. <https://doi.org/10.3389/fmars.2020.607426>

Vieira, R.H.S.F., Volesky, B., 2000. Biosorption: a solution to pollution? *Int. Microbiol.* 3, 17–24. <https://doi.org/10.2436/im.v3i1.9237>

Volesky, B., Holan, Z.R., 1995. Biosorption of Heavy Metals. *Biotechnol. Prog.* 11, 235–250. <https://doi.org/10.1021/bp00033a001>

Wang, M., Hu, C., 2021. Satellite remote sensing of pelagic Sargassum macroalgae: The power of high resolution and deep learning. *Remote Sens. Environ.* 264, 112631. <https://doi.org/10.1016/j.rse.2021.112631>

Wang, M., Hu, C., Barnes, B.B., Mitchum, G., Lapointe, B., Montoya, J.P., 2019. The great Atlantic Sargassum belt. *Science* (80-.). 364, 83–87.

609 <https://doi.org/10.1126/science.aaw7912>

610 Wei, T., Simko, V., Levy, M., Xie, Y., Jin, Y., Zemla, J., Freidank, M., Cai, J., Protivinsky,
611 T., 2021. Visualization of a Correlation Matrix (corrplot) [WWW Document]. URL
612 <https://cran.r-project.org/web/packages/corrplot/index.html>

613 Weis, J.S., 1968. Fauna associated with pelagic Sargassum in the Gulf Stream. *he Am. Midl.*
614 *Nat. J.* 80, 554–558.

615 Wickham, H., Chang, W., Henry, L., Pedersen, T.L., Takahashi, K., Wilke, C., Woo, K.,
616 Yutani, H., Dunnington, D., 2020. Create Elegant Data Visualisations Using the
617 Grammar of Graphics (ggplot2) [WWW Document]. URL [https://cran.r-](https://cran.r-project.org/web/packages/ggplot2/index.html)
618 [project.org/web/packages/ggplot2/index.html](https://cran.r-project.org/web/packages/ggplot2/index.html)

619 Witherington, B., Hirama, S., Hardy, R., 2012. Young sea turtles of the pelagic Sargassum-
620 dominated drift community: Habitat use, population density, and threats. *Mar. Ecol.*
621 *Prog. Ser.* 463, 1–22. <https://doi.org/10.3354/meps09970>

622 Woignier, T., Morell, M., Morell, O., Duffours, L., Soler, A., 2011. Low water transport in
623 fractal microstructure of tropical soils: Application to chlordecone pesticide trapping.
624 *Ecohydrol. Hydrobiol.* 11, 121–127. <https://doi.org/10.2478/v10104-011-0035-2>

625 Wu, H., Zhan, D., Liu, H., Ding, G., Liu, W., LiMei-zhen, M., 2010. Study on accumulation
626 and degradation of heavy metals by the Brown alga *Sargassum thunbergii*. *Mar. Sci.* 34,
627 69–74.

628 Zeraatkar, A.K., Ahmadzadeh, H., Talebi, A.F., Moheimani, N.R., McHenry, M.P., 2016.
629 Potential use of algae for heavy metal bioremediation, a critical review. *J. Environ.*
630 *Manage.* 181, 817–831. <https://doi.org/10.1016/j.jenvman.2016.06.059>

631

632

633

634

635

636

637