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1 Effects of a salmon fish farm on benthic habitats in a high-energy hydrodynamic system: the
2 case of the Rade de Cherbourg (English Channel)

3

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19

20 ABSTRACT

21

22 The Rade de Cherbourg (RdC), in the North Cotentin (Normandy, English Channel) is the
23 only French coastal zone where an offshore salmon farm has been in operation over the past
24 three decades. Our study leads to the identification of the Ecological Quality status of benthic
25 habitats based on a one-year survey (2013-2014) underneath and near the cages as well as in
26 non-impacted areas lying outside the influence of salmon farming. The semi-diurnal high tide
27 regime of the Rade de Cherbourg (5 to 8 m tidal range from neap to spring tide) should
28 prevent any significant accumulation of Organic Matter (OM) under the cages. Nevertheless,
29 higher Total Organic Carbon (TOC) and the presence of opportunistic species at sampling
30 stations under and near the cages indicate an impact of salmon farming on the benthic
31 habitats. Three benthic assemblages are identified, corresponding to three sediment types
32 with different levels of OM enrichment. The presence of several indicator species, such as the
33 polychaete worm *Capitella minima* belonging to the Capitellidae, reflects the local impact of
34 fish farming without long-term accumulation of OM in the shallow waters of the RdC.

35 Moreover, one of the main characteristics of the macrofauna of the RdC and neighbouring
36 zones is the current very high abundance and dominance of the tanaid *Apseudopsis latreillii*
37 in diverse sediment types. Benthic indices (AMBI, M-AMBI, and BO2A) were also able to
38 distinguish three main zones in relation to the distance to salmon cages.

39

40 *Keywords:* Macrobenthic communities; Sediment characteristics; Salmon fish farm; Benthic
41 indices; TOC enrichment

42

43 **1. Introduction**

44

45 The impact of aquaculture on benthic habitats had been highlighted since the end of the
46 1980s (Brown et al., 1987). More recently, Yokoyama (2002), Buschmann et al. (2006,
47 2009); Burridge et al. (2010), Wilding et al. (2012) and Lu et al. (2017) have described the
48 impact of aquaculture on sediment characteristics and macrofauna. The main impact leads to
49 the enrichment of Organic Matter (OM) in sediments that are initially oxygenated and the
50 accumulation of toxic compounds derived from aquaculture waste products (mainly H₂S and
51 NH₃). Under salmon cages sediment contains generally high levels of organic matter due to
52 waste products (feces, uneaten food, etc.), the driving force for most primary diagenetic
53 redox reactions (Kasten and Jørgensen, 2000). The high organic matter flux creates anoxic
54 conditions (oxygen consumption by aerobic respiration). The sulphate reduction process
55 becomes predominant because of the availability of high concentrations of sulphate in
56 seawater, which leads to the production of sulphides in sediment (Jørgensen, 1977; Bo
57 Barker, 1977). This phenomenon may induce changes in the benthic communities: i.e. an
58 increase in the abundance and biomass of species on a seabed enriched in OM (Brown et al.,
59 1987; Carroll et al., 2003; Hyland et al., 2005; Kalantzi and Karakassis, 2006).

60 Pearson and Black (2001) produced a review of the environmental impacts of marine fish
61 cage culture showing the effects of fish farming on coastal ecosystems, concerning the
62 influence of increased organic matter inputs on benthic habitats. Most of these previous
63 studies indicated that the impact of fish farming is local and depends greatly on factors such
64 as fish density, start date of activities, water depth, initial sea bottom site characteristics and
65 hydrodynamic regime (Frid and Mercer, 1989; Morrissey et al., 2000; Merceron et al., 2002;
66 Yokoyama, 2002; Tomassetti and Porrello, 2005; Kalantzi and Karakassis, 2006; Kutty et al.,
67 2007; Borja et al., 2009; Giles et al., 2009; Chang and Page, 2011; Wang et al., 2017).

68 Most of these studies reveal a change in sediment biogeochemistry and benthic ecology
69 around the cages extending to some metres distance away, in accord with the model of
70 Pearson and Rosenberg (1978) which describes the response of macrofauna to OM
71 enrichment in the sediment. The extreme accumulation of OM tends to create an anoxic/azoic
72 zone where both the oxygen demand and depletion are maximal (Brooks and Mahnken, 2003;
73 Brooks et al., 2004; Hargrave, 2010; Chang et al., 2013; Backman et al., 2009; Bannister et
74 al., 2014; Brooks et al., 2003; Wilding et al., 2012). Moreover, Fernandez-Gonzalez et al.
75 (2016) has highlighted the role of biofouling in fish farms appears to be an important vector
76 for colonization of the surrounding soft-bottom communities impacted by aquaculture.

77 The Rade de Cherbourg (RdC) is a protected semi-open area situated on the north coast of
78 the Cotentin Peninsula (central part of the English Channel), under a semi-diurnal high tide
79 regime (5 m to 8 m tidal range from neap to spring tide). It is sheltered from the swell by
80 breakwaters that enclose the outer harbour. In spite of 3.7 km of breakwaters interrupted by
81 two mains channels in the north of the RdC and a smaller channel in the east tidal currents
82 (up to 1 m/s) allow the mixing of water bodies and a significant concentration of suspended
83 particulate matter in the seawater (Merceron and Gaffet, 1994; Poizot et al., 2016). Due to
84 these conditions, the RdC has been recognized as a suitable place for the development of
85 aquaculture due to both the presence of highly mixed waters and presence of breakwaters
86 suppress swell impacts. Consequently, a trout farm has been established in the RdC since the
87 beginning of the 1990s, becoming a salmon farm (*Salmo trutta fario* then *Salmo salar*) during
88 the early years 2000. Today, this site hosts the only marine salmon farm in France, covering
89 an area of ~17 ha currently producing ~600 tons of salmon per year (data available in 1993,
90 1995, 2001, 2002, 2006, 2011, 2013, 2016 and 2017, with respective production volumes of
91 144, 290, 400, 800, 2300, 1200, 350, 250, 600 t) (Saumon de France, 2015).

92 The first study on the quality of the water column, sediments and benthic macrofauna
93 around the fish farm was carried in the early 1990s (Merceron and Gaffet, 1994; Bentley et
94 al., 1997; Kempf et al., 2002; Merceron et al., 2002). Nevertheless, in these studies, the
95 surveyed area was limited to the immediate vicinity of the aquaculture cages, and only the
96 dominant species of the macrobenthic fauna were identified.

97 The development of aquaculture in a high-energy hydrodynamic regime over the past 30
98 years has offered the opportunity to study the impact of human pressures on the benthic
99 habitats of the RdC. Moreover, Baux et al. (2017) have highlighted the great diversity of
100 benthic communities and habitats in the RdC and have identified three habitat types
101 corresponding to EUNIS codes giving in the classification of European benthic habitats

102 (EUNIS, 2012) as well as two types so far not attributed to any known benthic habitat, in
103 addition to one habitat characterized by the presence of *Zostera marina* beds. In this context
104 of rich diversity, it is also interesting to study in more detail the benthic communities as well
105 as the impact of the salmon farm.

106 The objective of this study is to assess the ecological quality status of benthic habitats and
107 to determine the impact of salmon farm on these benthic habitats, by considering the
108 sediment characteristics and macrofauna patterns in relation to distance from the salmon
109 cages. To study the impact of salmon farming on benthic communities, univariate,
110 multivariate analyses and benthic indices are used to assess the quality of benthic habitats.

111

112 **2. Materials and methods**

113

114 *2.1. Study site*

115

116 The RdC which construction ends in 1895 is the Europe's largest, extending over a
117 total area ~1,500 ha (Baux et al., 2017). The 'Grande Rade' (1,300 ha) is isolated from the
118 open sea by three breakwaters, with three channels allowing exchanges with open sea water
119 (West Channel, East Channel and Collignon Channel; Fig. 1). The oscillating water volume is
120 about 80,000 m³ at spring tide, with a tidal range of 5.3 m (Merceron et al., 2002). Several
121 small rivers and urbanized outfalls can give to minor fresh water inputs, into the RdC. The
122 maximum depth is ~20 m with a mean depth ~13 m (Gregoire et al., 2019). The mean winter
123 water temperature is 8-9 °C and reaches 17-18 °C at the end of the summer. The predominant
124 current is easterly during the flood tide and westerly during the ebb. The flood stream enters
125 by the 'West Channel' and flows out mainly by the 'East Channel' and to a lesser extent by
126 the 'Collignon Channel'. This is opposite to the situation at ebb tide. During flood and ebb
127 tide, depending on the interactions between bathymetry, coastline morphology and tidal
128 currents, gyres may form locally with a counterclockwise rotation (Merceron and Gaffet,
129 1994; Poizot et al., 2016).

130 The RdC sea bed is covered by four main sedimentary facies (Baux et al., 2017). The
131 western sector is generally made up of organic-rich mud with decaying marine algae and
132 coarse sand. The centre of the RdC consists of silty mud, while the east is covered by fine
133 sand. Gravel and coarse sand are found in the channels which connect the RdC with the open
134 sea.

135 The salmon farm consists of cylindrical and cubic nets aligned along an East-West
136 axis, the concession area being located only 50 m south of the main breakwater, extending
137 over a distance of 1.5 km with a width of 100 m at a depth of ~12 m (Saumon de France,
138 2015) (Fig. 1). The average height of the nets ranges from 7 to 8 m below the sea surface, and
139 the distance above the seabed is ~ 3 to 7 m due to deformation of the fishnet cage under the
140 influence of the variable tidal currents and range. Inside the RdC, tidal currents are mainly
141 oriented East-West and reversely during the tide with current velocities up to 1 m/s. At the
142 fish farm site, a gyre (Merceron and Gaffet, 1994) is responsible of an asymmetric regime of
143 the currents velocities from flood to ebb. At neap tide, the flood currents are oriented west-
144 east 30% of the time and ebb currents are oriented east-west 70% of the time. During spring
145 tide, this asymmetric is reduced to respectively 40% (flood currents) and 60% (ebb currents).
146 This asymmetry is related to the establishment of a gyre within the concession area
147 (Merceron and Gaffet, 1994).

148

149 *2.2. Sampling and laboratory treatment*

150

151 Following an East-West axis parallel to the main breakwater where the cages are
152 located and according to the main tidal currents in this area in the RdC, six benthic stations (~
153 10-11 m depth) were sampled during five campaigns over an annual cycle in 2013-2014 (C1:
154 31 October 2013, C2: 19 February 2014, C3: 8 April 2014, C4: 13 June 2014 and C5: 18
155 September 2014) to identify the impact of this salmon farm. One station (CC8) was located
156 under a cage, two stations (OR and ER) outside the fish farm (> 600 m from the central
157 cages), and three others (OC8, EC8 and EC16) near the central cages (OC8: 50 m to the west;
158 EC8: 50 m to the east; EC16: 500 m to the east; Fig. 1). During the five sampling campaigns,
159 five replicates were collected using a 0.1 m² Van Veen grab covering a total sampling surface
160 area of 0.5 m² at each station for the macrofauna analysis plus one supplementary sample for
161 grain-size analysis. At station CC8, the Van Veen grab was manipulated by hand from the
162 cage structure between the salmon nets. The sampled faunal material was sieved onboard on
163 a 1-mm circular mesh. Fauna was preserved in 10% buffered formaldehyde prior to sorting,
164 identified to species as far as possible. Some species are grouped to the higher classification
165 rank when the morphological determination is doubtfully.

166 The taxonomic richness (TR) and abundance (A) are expressed in number of taxa and
167 number of individuals per 0.5 m², respectively. Species (or taxa) names were checked against
168 the World Register of Marine Species (<http://www.marinespecies.org>) on 1 September 2018.

169 The fine fraction (<50 μm) was measured by wet sieving and rinsed with fresh water
170 to remove the salt. Other sediment fractions were dried and sieved on a sieve shaker. Eight-
171 sieve column was used (8, 4, 2, 1, 0.5, 0.250, 0.125 and 0.050 mm). The sediment was
172 classified according to Wentworth's grain-size scale (Wentworth, 1922): <50 μm : silt clay;
173 50–125 μm : very fine sand; 125–250 μm : fine sand; 250–500 μm : medium sand; 500–1000
174 μm : coarse sand; 1000–2000 μm : very coarse sand; 2000–4000 μm : gravel; and >8000 μm :
175 pebbles). The results are expressed in percentage relative to the total dry weight of the
176 sample. Finally, we consider four grain-size classes for the definition of sediment types: fine
177 fraction (< 50 μm , denoted FF), fine sand (50-250 μm), medium and coarse sand (500–2000
178 μm) and gravels (> 2000 μm).

179 Sediments for Total Organic Carbon (TOC) analysis were freeze-dried and
180 homogenized. The coarse fraction was removed with a 2-mm sieve to keep only the fine
181 fraction. The weight of the sample was reduced to obtain 50 mg aliquots using a manual
182 quartering method (random separation of sample aliquots). Sediment samples were acidified
183 by H₃PO₄ (1 M), to remove carbonates, dried on a hot plate at 40° C and measured for TOC
184 content by combustion in a LECO CS 744 Carbon Sulfur analyzer. Two or three replicates
185 were analyzed per sample. The results of organic carbon measurements are expressed in
186 percent of dry sediment. The precision determined from replicate subsampling was $\pm 0.05\%$
187 organic carbon.

188

189 *2.3 Current measurements*

190

191 Two Acoustic Doppler Current Profilers (ADCPs: Teledyne RDI Sentinel S50 and
192 V50) were installed at a distance of 20 m (East) and 50 m (West) from the eastern cage (Fig.
193 1). Measurements were conducted between 6 and 24 October 2016, allowing the acquisition
194 of current velocity data during a tidal cycle (spring/neap tides). The two ADCPs measured
195 currents at the same height in the water column, running the same firmware, and were
196 configured for the same depth-cell size. Both ADCP's use 22 cells, with a depth-cell size of
197 0.5 m. Even if dates of velocities and directions measurements took place at a different
198 moment than the bottom sampling, they were considered as characteristics of flow conditions
199 at the studied site. The fish farm structures and shapes did not change between the two
200 sampling surveys.

201

202 *2.3. Data analysis*

203

204 2.3.1. Univariate analyses

205

206 Data were used to calculate the abundance A (0.5 ind.m^{-2}) and the most commonly
207 used biodiversity indices for each station, *i.e.* Taxonomic Richness (TR), Shannon-Weaver
208 diversity index (H') in \log_2 (Shannon and Weaver, 1963) and Pielou's evenness (J) (Pielou,
209 1966) for the six stations and five sampling dates. Data analysis was performed using the
210 PRIMER® version 6 software package (Plymouth Routines in Multivariate Ecological
211 Research) (Clarke & Gorley, 2006).

212 The Ecological Status indicating the quality of the station was estimated from H'
213 values according to the thresholds defined previously by Vincent et al. (2002) *i.e.*: bad 0-1;
214 poor 1-2; moderate 2-3; good 3-4 and high > 4 . Dauvin et al. (2017) proposed thresholds for
215 the taxonomic richness and J' , respectively *i.e.*: bad <10 , <0.20 ; poor 10-20, 0.20-0.40:
216 moderate 20-30, 0.40-0.60; good 30-40, 0.60-0.80 and high >40 , > 0.80 .

217 The biotic indices AMBI, M-AMBI and BO2A were also calculated to assess the
218 ecological status of the macrofauna (Borja et al., 2000; Dauvin et al., 2012, 2016). The five
219 ecological statuses of the European Water Framework Directive were used to assess the
220 benthic macrofauna according to the thresholds between these statuses proposed by Borja et
221 al., (2000) and Dauvin et al. (2012, 2016).

222 AMBI (AZTI Marine Biotic index) (Borja et al., 2000) is based on an *a priori*
223 classification of macrofauna species in five ecological groups (EG) according to their
224 sensitivity to OM. EG-I corresponds to taxa very sensitive to organic enrichment and
225 disturbance which are usually only present under unpolluted conditions, EG-II to taxa
226 indifferent to enrichment or disturbance, EG-III to taxa tolerant of excess OM enrichment,
227 which may occur under normal conditions, but which are stimulated by organic enrichment,
228 EG-IV, to second-order opportunistic species and EG-V, to first-order opportunistic species,
229 able to resist strong disturbance. The relative abundances of each EG serve to calculate
230 benthic indices following the formula given in Borja et al. (2000).

231

232
$$\text{AMBI} = 0 \text{ EG}_I + 1.5 \text{ EG}_{II} + 3 \text{ EG}_{III} + 4.5 \text{ EG}_{IV} + 6 \text{ EG}_V$$

233

234 The index is computed using the AZTI program (version 5.0) freely available online
235 at <http://www.aziti.es>. AMBI values lying between 0 and 6 can be converted into EcoQ using
236 the fixed scale provided by Borja et al. (2000).

237 M-AMBI is a multimetric index for assessing the ecological quality status of marine
238 and transitional waters (Bald et al., 2005; Muxika et al., 2007). It is based on benthic macro-
239 invertebrates and combines AMBI, which is a biotic index based on species
240 sensitivity/tolerance, with diversity and taxonomic richness. The M-AMBI algorithm
241 incorporates different metrics by means of factor analysis (FA). Reference values are
242 considered to represent an unperturbed environment, in which the Taxonomic Richness (TR)
243 and H' values are highest for the same type of benthic communities (respectively 50 for TR
244 and 3.5 for H'). We also assume that, in an unperturbed environment, first-order
245 opportunistic species (EG V of the AZTI list) would be absent or poorly represented with a
246 AMBI value of 2.5.

247 The BO2A (Benthic Opportunistic Annelids Amphipods Ratio) (Dauvin and Ruellet,
248 2009; Dauvin, 2018) is calculated following the formula:

249

$$250 \quad \text{BO2A} = \log_{10} [f_{\text{oa}} / (f_{\text{sa}} + 1) + 1]$$

251

252 where f_{oa} is the frequency of opportunistic annelids (Clitellata and Polychaeta) (i.e.,
253 number of opportunistic polychaetes corresponding to Ecological Groups IV and V of Grall
254 and Glémarec (1997) and used for calculating AMBI (Borja et al., 2000), plus the
255 Oligochaeta and Hirudinea, divided by the total number of individuals in a sample), and f_{sa} is
256 the sensitive amphipod frequency (i.e., number of amphipods, excluding the opportunistic
257 *Jassa* amphipods, divided by the total number of individuals in a sample), and $f_{\text{oa}} + f_{\text{sa}} \leq 1$.

258 A two-way ANOVA is used to test spatio-temporal changes (stations and campaigns
259 factors) for TS, A, H', J, AMBI, M-AMBI and BO2A. A Shapiro-Wilk normality test and a
260 Bartlett test for homogeneity of variances are performed prior to each ANOVA. The Tukey
261 Honestly Significant Difference test is applied when ANOVA shows significant differences.

262

263 2.3.2. *Multivariate analysis*

264

265 The spatial structure of the sediment characteristics and the benthic community are
266 analysed using a multivariate analysis following Clarke and Gorley (2006) with the PRIMER
267 software package (Plymouth Routines In Multivariate Ecological Research). Data analysis is
268 performed using non-metric multidimensional scaling ordination (MDS), and a Hierarchical
269 Ascendant Classification (HAC) is created by group average linking using the Bray-Curtis
270 similarity measure (Beals, 1984). In comparison with other similarity measures, the Bray-

271 Curtis is known to be one of the more efficient indexes to highlight the similarity between
272 samples (Bloom, 1981).

273 Sorensen's coefficient for Presence/Absence of taxa, and $\text{Log}_{10}+1$ -transformed
274 abundances (0.5 ind.m^2) are used to down-weight the effect of very abundant species. To
275 identify the species within different groups which principally account for the observed
276 assemblage differences, SIMPER (SIMilarity PERcentage) routines are performed using a
277 decomposition of Bray-Curtis similarity on log-transformed abundance data (Clarke and
278 Warwick, 1994).

279

280 **3. Results**

281

282 *3.1. Hydrological conditions*

283

284 Table 1 summarizes the main characteristics of the water column during the year
285 2013-2014. While the temperatures show considerable seasonal variations, with a maximum
286 at the end of summer in September-October ($17.9 \text{ }^\circ\text{C}$) and a minimum in winter in February
287 ($8.2 \text{ }^\circ\text{C}$), the salinity remains stable throughout the year with values included between 34.4
288 and 34.7. The diurnal oxygen saturation reaches a maximum in September 2014 (123%),
289 probably in relation with a high primary production at that time; the turbidity is low, with
290 very low values (1.2 NTU) at both of the early sampling dates and low values during the rest
291 of the year ($< 14 \text{ NTU}$).

292

293 *3.2. Currents near the cages*

294

295 Ebb currents flow westward at almost 270° , while flood currents flow eastward at
296 almost 90° . Ebb currents start to flow a few hours before high tide, and flood currents start
297 after low tide during spring tides and before low tide during neap tides. During neap tides, the
298 ebb current runs for 60% of the time, and the flood current for 40% (Table 2). During spring
299 tides, flood currents run for 30% of the time, and ebb currents make up the remaining 70%.
300 At West ADCP location, mean velocities and directions highlight a more erratic behaviour
301 during ebb currents (270°) than at East ADCP location. This is the reverse for flow currents
302 (90°) in a lesser extent. At both ADCPs, the maximum velocity increases twofold between
303 neap tide and spring tide. The maximum velocity is three times higher during spring tide
304 compared with neap tide.

305

306 3.3. Sediment characteristics

307

308 Using HAC and MDS to analyse the grain-size characteristics of the sediments from
309 the five stations at the five sampling dates, we can distinguish three main groups (Fig. 2).

310 The first group is made up of five observations, four from CC8 and one from OC8.
311 For this group, the mean percentage of Fine fraction (FF)= 11.4, fine sand= 51.3, coarse sand
312 and gravel= 37.3. The sediment type corresponds to sand and gravel with a low percentage of
313 FF, mainly restricted to station CC8 located under the cage.

314 The second group comprises 10 observations, 4 from EC8, 4 from EC16 and those
315 from OR in October 2013 and OC8 in June 2014. For this group, the mean % FF= 16.2, fine
316 sand= 76.2, coarse sand and gravel= 7.6, corresponding to fine sand sediment mainly
317 represented at EC8 and EC16 (two stations in the eastern part of the salmon cages).

318 The third group comprises 14 observations, including the five sampling dates at ER,
319 four at OR (except at OR in October), the observation from EC16 in June 2014, three
320 observations from OC8 (February, April and September 2014), one from CC8 in September,
321 and one from EC8 in June 2014. For this group, the mean % FF= 14.9, fine sand= 60.1,
322 coarse sand and gravel= 25.0, corresponding to heterogeneous muddy sediment, according to
323 the Wentworth classification (Wentworth, 1922). This group comprises both reference
324 stations OR and ER plus station OC8 in the western sector of the salmon cages.

325 The TOC levels remain relatively stable throughout the year (Table 3) with a global
326 mean of 0.55 +/- 0.04%. While seasonal changes are very slight, there are nevertheless some
327 differences in TOC between the stations, with a minimum at station EC8 in the eastern part of
328 the salmon cages (0.35+/-0.06%) ranging up to a maximum at station CC8 under the cages
329 (0.82 +/- 0.05%).

330 Figure 3 shows the mean annual values of TOC for the five stations as a function of
331 FP (fine particles < 50 µm). The mean values of TOC at four stations (OR, EC8, EC16 and
332 ER) follow a linear trend from 0.3% TOC and 5% FP to 0.6% TOC and 16% FP. The
333 reference stations OR and ER also yield the highest TOC, with the latter being the richest in
334 FP content. The stations (EC8 and EC16) located in the eastern sector of the salmon cages are
335 characterized by lower fine fraction percentage (6-8%) and TOC (0.3-0.4%). For these four
336 stations, there is no organic matter enrichment. Station CC8 under the cages and OC8 in the
337 western sector of the cages show different patterns, with a low percentage of FP and, on the
338 contrary, relative high percentages of TOC (>0.6%) in comparison with other stations.

339 The similarity between the stations is high (80 %), but three groups can be identified
340 with granulometric data combined with those of FP and TOC (Figs. 2 and 3; Table 3). Firstly,
341 stations CC8 and OC8 under and near the western sector of the cages are characterized by
342 mixed sediment with high TOC%. Secondly, stations EC8 and EC16 in the eastern sector of
343 the cages are located on fine sand with low TOC%. Lastly, the reference stations OR and ER
344 are distant from the cages, showing high percentages of fine particles correlated with high
345 percentages of TOC on heterogeneous mixed sediment.

346

347 3.4. General characteristics of the fauna

348

349 A total of 182 taxa are identified during the study, the polychaetes dominate in terms
350 of diversity with 71 taxa representing 38% of the TR (Taxonomic Richness), the molluscs
351 with 36 taxa (20% of TR) and the amphipods with 32 taxa (17% of TR). These three
352 dominant zoological groups comprise a total of 139 taxa (75% of the fauna recorded). A total
353 of 119,296 individuals are sampled, with 98 taxa being represented only by a few number of
354 individuals (<10), making up only 0.27% of the collected fauna. The tanaids account for 61%
355 of the recorded individuals, followed by the polychaetes (25%), amphipods (6%) and
356 molluscs (1.5%). The TR varies from 22 to 78 and the abundances from 455 to 11,355
357 individuals. 0.5m⁻² without any clear seasonal pattern or differences between the six stations
358 (Table 3).

359 Moreover, the ten most abundant species account for 106,921 individuals making up
360 89.6% of the macrofauna. The tanaid *Apseudopsis latreillii* represents 60.3% of the total
361 number of collected individuals, then the polychaetes *Notomastus latericeus* (9.4%) and
362 *Dipolydora giardi* (9.0%), the Maldanidae, mainly represented by *Euclymene oerstedii*
363 (4.3%), the amphipod *Ampelisca tenuicornis* 1.7%, the polychaetes *Phyllodoce mucosa*
364 (1.3%) and *Capitella minima* (1.3%), the amphipod *Phtisica marina* (1%), the polychaete
365 *Chaetozone gibber* (0.7%) and the bivalve *Thyasira flexuosa* (0.7%).

366 To summarize, although the fauna is diversified, it is dominated numerically by a
367 small number of species, especially by the tanaid *Apseudopsis latreillii* (species identified in
368 December 2017 by specialist P. Pesquete, Aveiro University, personal communication).

369

370 3.4. Spatio-temporal patterns of the macrofauna

371

372 Using the abundance data and applying a Bray-Curtis similarity level of 50%, the
373 HAC and MDS analyses allow us to identify three groups (Fig. 4). Group 1 includes the 10
374 observations from stations OC8 and CC8. Group 2 corresponds to the observations from
375 reference sites OR and ER, plus two sampling dates for EC16 (June and September) and June
376 for EC8. Group 3 includes seven observations from EC8 (four dates) and EC16 (three dates).
377 Table 4 show significant differences in abundances, H' and J' between stations, while only
378 differences of TR are observed between ER and EC8.

379 Finally, analyses of sediment characteristics and macrofauna abundance lead to the
380 identification of a spatial pattern with three groups of stations: two stations (CC8 and OC8)
381 located under the cages and in the western sector of the cages, two stations (EC8 and EC16)
382 in the eastern sector of the cages, and, finally, the reference stations OR and ER. A weak
383 pattern is observed at the scale of the observations during the 2013-2014 sampling year
384 (Tables 3 and 4). Table 4 shows significant differences of Taxonomic Richness between C1
385 and C5, while significant differences in abundances are observed between C4 and C5, and for
386 both diversity indices H' and J' between C2 and C4.

387 The tanaid *Apseudopsis latreillii* dominates the macrofauna in the three groups of
388 stations, with an abundance $\geq 2,000$ ind.0.5m²; similarly, the polychaete *Notomastus*
389 *latericeus* shows noteworthy abundance in all three groups, but decreases in abundance from
390 stations under and in the western sector of the cages towards the reference stations (Table 5).
391 Opportunistic species (GIV and GV) are only abundant in the first group of stations (CC8 and
392 OC8); conversely, sensitive species are present and abundant at both references stations (OR
393 and ER) (Table 5).

394

395 3.5. Ecological quality status

396

397 The values of the three benthic indices (AMBI, M-AMBI and BO2A) and their
398 corresponding Ecological Quality Status (EcoQS) allow us to identify three groups of stations
399 without seasonal changes: references stations ER and OR plus EC16 and OC8 show a good to
400 high EcoQS, station EC8 shows moderate to high EcoQS depending on the sampling
401 campaign or the biotic index, and station CC8 shows a moderate EcoQS. The diagnosis based
402 on H' and J' yields a poor to moderate EcoQS, but both of these indices are clearly
403 influenced by high *Apseudopsis latreillii* abundances which lower their values.

404

405 4. Discussion

406

407 The Rade de Cherbourg has hosted a salmon farm since the beginning of the 1990s
408 (Kempf et al., 2002; Merceron et al., 2002). Our recent study (2013-2014) offered the
409 opportunity to assess the ecological quality status of benthic habitats in the RdC three
410 decades after the initial establishment of aquaculture in this zone (firstly a trout farm and then
411 a salmon farm). Bachelet (2014) highlighted the effects of anaerobic degradation due to
412 sulphate-reducing processes at the water-sediment interface in areas east of the salmon cages,
413 as well as high ammonium concentrations resulting from faeces and non-consumption of feed
414 for farmed fishes at the station located under the cages (Bachelet, 2014). Both the high-
415 energy hydrodynamic regime in the RdC and the acceleration of currents under the cages
416 (Poizot et al., 2016), has led to the dispersal of excess organic waste. The increase of current
417 velocity under the fishnets is also responsible of erosion, which has resulted in modifications
418 of the bottom morphology. As measured during this study, the maximum current velocity
419 reaches $0.7 \text{ m}\cdot\text{s}^{-1}$, which is two times higher during Spring tide compared with Neap tide.
420 Nevertheless, this maximum velocity is very slow in comparison with values recorded off the
421 North Cotentin coast especially in the Raz Blanchard, a zone where the maximum velocity
422 can reach $5.0 \text{ m}\cdot\text{s}^{-1}$ during Spring tide (Salomon and Breton, 1991, 1993). Velocity
423 measurements near the cages show that the fish farm is always under the influence of tidal
424 currents, including during neap tides. The water within the farm is regularly replenished and
425 homogenized (Poizot et al., 2016). The strong asymmetry of the tidal currents (as regards
426 both duration and intensity of flow) leads us to consider that ebb current is dominant on the
427 farm (Poizot et al., 2016). These conditions correspond to the coastal farming classification of
428 Holmer (2010), preventing the accumulation of OM under the cages due to dispersal of the
429 residual organic matter derived from the waste-feed and faeces, in contrast to enclosed
430 salmon farms such as in Norwegian fjords (Kutti et al., 2007; Holmer, 2010). Moreover, the
431 moderate fish production over the past 25 years (mean ~ 700 tonnes of salmon per year) has
432 caused a negligible supplementary input of organic matter in the RdC (Murat et al., 2012).

433 The six stations chosen in this study are located in two main EUNIS benthic habitats
434 (Baux et al., 2017): A5.334 *Melinna palmata* in mixed muddy fine sand (OC8, CC8, and
435 EC8) and a new habitat with *Spio decorata* and *Apseudopsis latreilli* in very fine sand and
436 fine sand (OR, ER and EC16). Analyses of the six stations sampled during the five
437 campaigns show that the macrofauna can be separated at a similarity of 50 % in three benthic
438 assemblages (Fig. 4; Table 5).

439 The first group corresponds to reference stations OR and ER at some distance from
440 the cages, with high percentages of fine particles ($\cong 14\%$) higher than at other studied stations
441 ($\cong 7\%$) and relatively high mean TOC ($\cong 0.56\%$) on heterogeneous mixed sediment. The
442 relationship between TOC and fine particles suggests that both stations are in dynamic
443 equilibrium outside the influence of the cages (Fig. 3).

444 The second group of stations EC8 and EC16 is located in the eastern sector of the
445 cages on fine sand ($\cong 7.2\%$ of FP) with low TOC content (0.37%). These lower values (FP
446 and TOC) are consistent with higher energy hydrodynamic conditions (stronger currents and
447 enhanced turbulence) linked to an acceleration of currents under the cages (Poizot et al.,
448 2016). These hydrodynamic conditions result in a winnowing of fine particles and organic
449 matter.

450 The third group corresponds to stations CC8 and OC8 (under and near the cages in their
451 western sector), which are characterized by mixed sediment with the highest TOC% (\cong
452 0.73%) and the lowest FP% ($\cong 6.5\%$). Low FP percentage of the sediment is linked to the
453 impact of cages on water flow (higher turbulence and current intensity) (Poizot et al., 2016).
454 In contrast to the stations in the second group, stations CC8 and OC8 do not appear to have a
455 faunal community consistent with fish farm (high OM content) due to the presence of faeces
456 and feed-waste. Despite the high-energy hydrodynamic conditions, the input of organic
457 matter is sufficient to enrich the underlying sediment.

458 During the present study, very high densities of the tanaid *Apseudopsis latreillii* are
459 observed under salmon cages, as well as in other muddy sand habitats of the RdC. This
460 species is known to have an affinity with clean fine sands (Bakalem et al., 2009). The three
461 benthic assemblages for each of the three communities identified are dominated by *A.*
462 *latreillii* with very high abundances both in terms of time (year scale) and space. High
463 abundances of this species are observed in most of the benthic habitats of the RdC except the
464 mud habitat (Baux et al., 2017). This species is widely distributed all along the North
465 Cotentin coastline, and a very high abundance is found outside the fish farm and the RdC in
466 its eastern part (Martinez, 2017) as well as in some sand and gravel habitats in the western
467 sector of the RdC (personal observations). Such high abundances have been observed in other
468 marine areas (Table 6), but the present study represents the first report of such high
469 abundances of this species associated with a fish farm. The abundances observed in the RdC
470 and in its eastern part (20,000-23,000 ind.m⁻²) are among the highest recorded values. Only
471 the abundance observed in the Persian Gulf (Dubai creek) reaches higher values, with 43,000

472 ind.m⁻², but this site is subject to the impact of organic pollution (Saunders et al., 2007). The
473 relationship between fish farm and its increasing of Organic Matter and abundance of *A.*
474 *latreillii* need to be clarified in the future.

475 Except for the Aber Wrach in the western part of the English Channel along the
476 Brittany coast where the abundance exceeds 3,000 ind.m⁻² (Dauvin and Gentil, 1990; Hily
477 and Bouteille, 1999), *A. latreillii* is a rare species in the benthic communities of the English
478 Channel. It is mostly associated with the *Melinna palmata* muddy sand community as in the
479 Rivière de Morlaix station in the Bay of Morlaix, in an area naturally enriched in OM
480 (Dauvin, 2000), and is very rarely recorded in the eastern part of the English Channel.
481 Moreover, *A. latreillii* never occurs as dense populations or as a dominant species such as
482 observed in the North Cotentin. Abundant populations occur elsewhere principally on fine
483 sand and muddy fine, in *Zostera marina* meadows (Hily and Bouteille, 1999; Esquete et al.,
484 2011; Gamito et al., 2011), and rarely on coarse sand (Lourido et al., 2008).

485 The response of *A. latreillii* to pollution continues to be debated, and the sensitivity of
486 this species to pollution is unclear since it is reported as being both tolerant and sensitive (de-
487 la-Ossa-Carretero et al., 2010). It is classified in the list of tolerant species (GIII in AMBI,
488 Borja et al., 2000; Table 5). Along the Castellon coast (W. Mediterranean) de-la-Ossa-
489 Carretero et al. (2010) has shown that the species responds negatively to sewage pollution,
490 displaying reduced abundances near outfalls with a higher input of suspended solids,
491 nutrients and a possible trend to hypoxia at stations near the discharge channels. As *A.*
492 *latreillii* is a GIII species largely dominant in the three benthic assemblages recorded under
493 and near the cages, the AMBI and M-AMBI benthic indices lead mainly to the attribution of
494 a good EcoQS at the stations except for station CC8 under the cages where a moderate
495 EcoQS is obtained (Table 3). The use of BO2A yields the same EcoQS for the six stations
496 (Table 3). Nevertheless, both diversity indices (H' and J; Table 3) assign degraded poor and
497 moderate EcoQS for these stations in relation to high abundances of the dominant species *A.*
498 *latreillii* and the poorly structured distribution of abundances between species.

499 Apart from the top dominant species, the other dominant taxa show different patterns
500 of abundances in the three assemblages (Table 5). Opportunistic species such as the
501 polychaetes *Dipolydora giardi*, *Capitella minima*, *Chaetozone gibber*, *Caulleriella alata* and
502 *Cirriiformia tentaculata* and the amphipod *Jassa herdmani* (EG IV and V) are abundant at
503 stations under and near the cages (OC8 and CC8) or in the eastern sector of the cages, and
504 rare at the reference stations. EG III species such as the polychaetes *Phyllodoce mucosa* and
505 *Neanthes acuminata*, the amphipod *Gammarella fucicola* and the tanaid *Zeuxo holdichi* show

506 similar patterns with decreasing abundance from the stations under the cages to the reference
507 stations. Conversely, the polychaetes Maldanidae (mainly *Euclymene oerstedii*), *Melinna*
508 *palmata*, *Hilbigneris gracilis* and *Acromegalomma vesiculosum*, the bivalve *Thyasira*
509 *flexuosa* and the tanaid *Apseudes talpa* are abundant only at the reference stations (Table 5).
510 The amphipods sensitive to organic pollution (*Ampelisca tenuicornis* and *Phtisica marina*)
511 and the polychaete *Lanice conchilega* show similar abundances at both eastern stations and at
512 the reference stations (Table 5).

513 In summary, there is a decrease in abundance of opportunistic species away from
514 stations OC8 and CC8 near the cages and, conversely, an increase in abundance of sensitive
515 species from stations under and near the cages towards the reference stations (OR and ER).
516 The abundances of both opportunistic and sensitive species show intermediate abundances at
517 stations in the influence zone (EC16 and EC8).

518 All the results (sediment type, fine particles, TOC percentages, macrofauna
519 abundances and biotic indices), show that the fish farm impact remained relatively low in this
520 tidal regime: but three benthic habitats can be distinguished:

- 521 i) an impacted zone (under the cages and in the western sector of the cages; stations
522 CC8 and OC8), exhibits moderate accumulation of OM and an enhanced
523 hydrodynamic regime;
- 524 ii) an influenced zone (stations EC8 and EC16 in the eastern sector of the cages) with a
525 single impact (enhanced hydrodynamics);
- 526 iii) A non-impacted zone corresponding to both reference stations (ER and OR) (Tables
527 3, 5 and Figs. 2, 4).

528 Our results highlight a local impact of the salmon fish farm, with a relative lower number
529 of species under cages and the reduction in the rate of degradation of benthic OM inputs
530 since the establishment of fish farming in the 1990s. In addition, these observations appear to
531 support the Intermediate Disturbance Hypothesis, which proposes that the diversity and
532 abundance of organisms increases when the disturbance is intermediate in frequency and
533 intensity (Huston, 1979; Wilson, 1994; Dial and Roughgarden, 1998; De Backer et al., 2014;
534 Pezy et al., 2018).

535 Although tidal currents prevent the accumulation of OM in the RdC, Bachelet (2014)
536 observed the presence of local anaerobic degradation by sulphate-reducing processes at the
537 water-sediment interface to the east of the salmon cages, as well as high ammonium flux
538 under the cages, resulting from faeces and waste-feed derived from the salmon farm at the
539 station under the cages. Again, the impact in the RdC appears very limited.

540 Moreover, many studies have shown that certain parameters play a major role in
541 determining the impact of farms, such as high fish density, age of the concession, water
542 depth, previous sediment types located at the site and hydrodynamic regime (Frid and
543 Mercer, 1989; Morrisey et al., 2000; Merceron et al., 2002; Borja et al., 2009; Giles et al.,
544 2009; Chang and Page, 2011). The current velocity appears to be one of the most important
545 parameters because it favours the dispersal of waste and ensures the absence of anoxic
546 conditions under the fish cages (Black et al., 1996; Keeley et al., 2013). Facing with the large
547 increase of OM in sediments under the cages and in surrounding habitats in coastal ecosystem
548 with weak currents, fish farmers have chosen to develop aquaculture in deeper waters, mainly
549 in Norwegian fjords and in higher energy hydrodynamic regimes (Holmer, 2010; Falconer et
550 al., 2013; Bannister et al., 2014).

551 In the case of the RdC, the abundances of opportunistic and sensitive species are clearly
552 linked to the impact of salmon cages; opportunistic species are more abundant in the
553 assemblages impacted by the farm and, in the contrary, sensitive species are more abundant
554 in the reference non-impacted assemblages (Table 5). Moreover, in this particular megatidal
555 environment, the benthic habitats are impacted by two main factors: the input of OM in
556 relation to the fish farm and the increase in currents near and under the fish cages. The RdC is
557 particularly suitable for aquaculture, with an increase of current velocities under the cages in
558 shallow waters due to the reduction of the open water column under the cages. This
559 phenomenon prevents a large accumulation of OM under the cages and favours the dispersal
560 of OM outside the fish farm, which is reinforced by tidal currents.

561 In their prospect, the 'GMG Saumon de France' company envisaged the transfer of cages
562 to the neighbouring eastern part of the RdC, which exhibits a higher energy hydrodynamic
563 regime than in the RdC. Our results do not justify this repositioning of the fish farm outside
564 the RdC, the existing salmon cages showing a relative low and local impact. Some studies
565 had shown that after the cessation of fish production or after fallowing (i.e. period during
566 which there is a pause in production), the opportunistic taxa undergo a decline in only two
567 months (Zhulay et al., 2015), or six months (Brooks et al., 2013a), whereas the impact could
568 have a duration of several years (Brooks et al., 2004; Pereira et al., 2004; Keeley et al.,
569 2012a,b, 2015). In the case of the cessation of activity in the RdC salmon farm, it will be
570 interesting to survey the resilience of benthic habitats in this area.

571

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573

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582

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800

801 Figure 1. Location of the six sampling stations near the salmon farm in the Rade de
802 Cherbourg and benthic habitats identified by Baux et al. (2017). * Location of the two sites
803 used for ADCP current measurements.

804

805 Fig. 2. HAC and MDS analyses of sediment characteristics for the five stations at the five
806 sampling dates. **A.** Dendrogram using group average linking of Bray-Curtis similarities on
807 square root transformed sediment data. **B.** MDS ordination based on standardized and square
808 root sediment data and Bray-Curtis similarities (see Fig. 1 for location of stations; oct13:
809 October 2013; feb: February 2014; apr14: April 2014; jun14: June 2014; sept14: September
810 2014).

811

812 Fig. 3. Relationship between percentage of TOC and fine particles ($< 50 \mu\text{m}$), showing
813 evidence of the enrichment of TOC at stations CC8 and OC8 (see Fig. 1 for location of
814 stations).

815

816 Fig. 4. **A:** Dendrogram showing hierarchical clustering of data from 30 sites in the Rade de
817 Cherbourg, using group average linking of Bray-Curtis similarities on $\text{Log}(x+1)$ abundance
818 of the taxa. The three groups of samples are separated at 50% similarity. **B:** MDS ordination
819 of the 30 sites sampled in the Rade de Cherbourg, based on standardized and $\text{Log}(x+1)$
820 transformation of abundances and Bray-Curtis similarities. (see Fig. 1 for location of the
821 stations; oct13: October 2013; feb: February 2014; apr14: April 2014; jun14: June 2014;
822 sept14: September 2014).

1°42'0"W

1°39'0"W

1°36'0"W

Stations	LatDD	LongDD
OR	49.6729	-1.6324
OC8	49.6730	-1.6314
CC8	49.6729	-1.6305
EC8	49.6733	-1.6252
EC16	49.6733	-1.6222
ER	49.6731	-1.6403

Digue Centrale

OR

OC8

EC8

EC16

ER

CC8

Salmon farm

0 0,1 0,2Km

Digue de
Querqueville

Digue Centrale

English Channel

Digue de
Coillignon

Grande Rade

Petite Rade

CHERBOURG-EN-COTENTIN

Legend

- Sampling
- * ADCP measurement

Benthic habitat

- A5.431. - *C. fornicata* shoal in coarse mixed sediment (a)
- A5.433. - *A. squamata* and *A. latreilli* in mixed sediment (b)
- A5.334. - *M. palmata* in muddy sand (c)
- A5.334. - *M. palmata* in mixed muddy fine sand (d)
- S. decoratus* in fine sand (e1)
- S. decoratus* and *A. latreilli* in very fine and fine sand (e2)
- A5.5331. - *Z. marina/angustifolia* beds



0 1 2Km



1°42'0"W

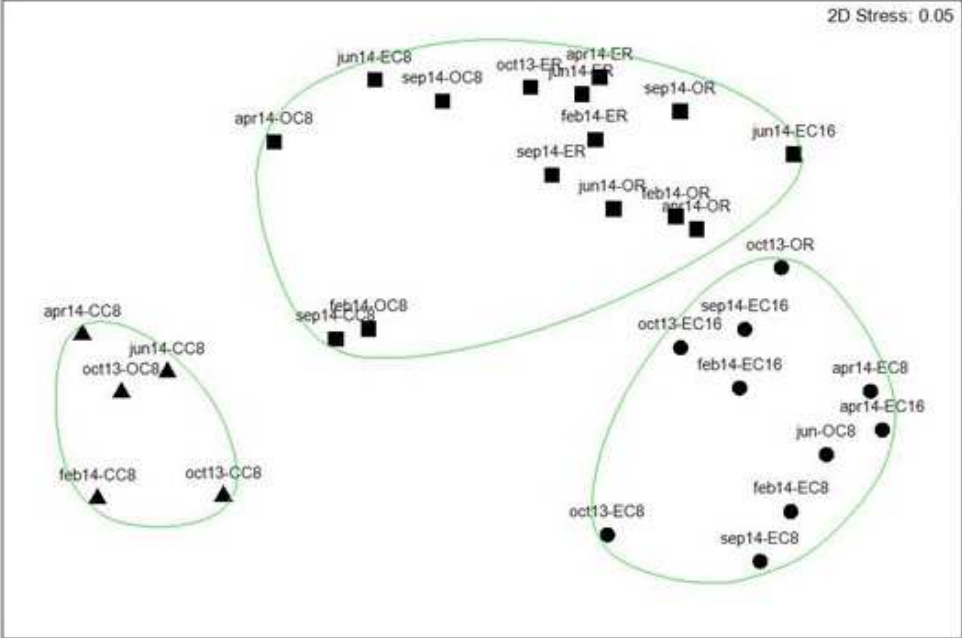
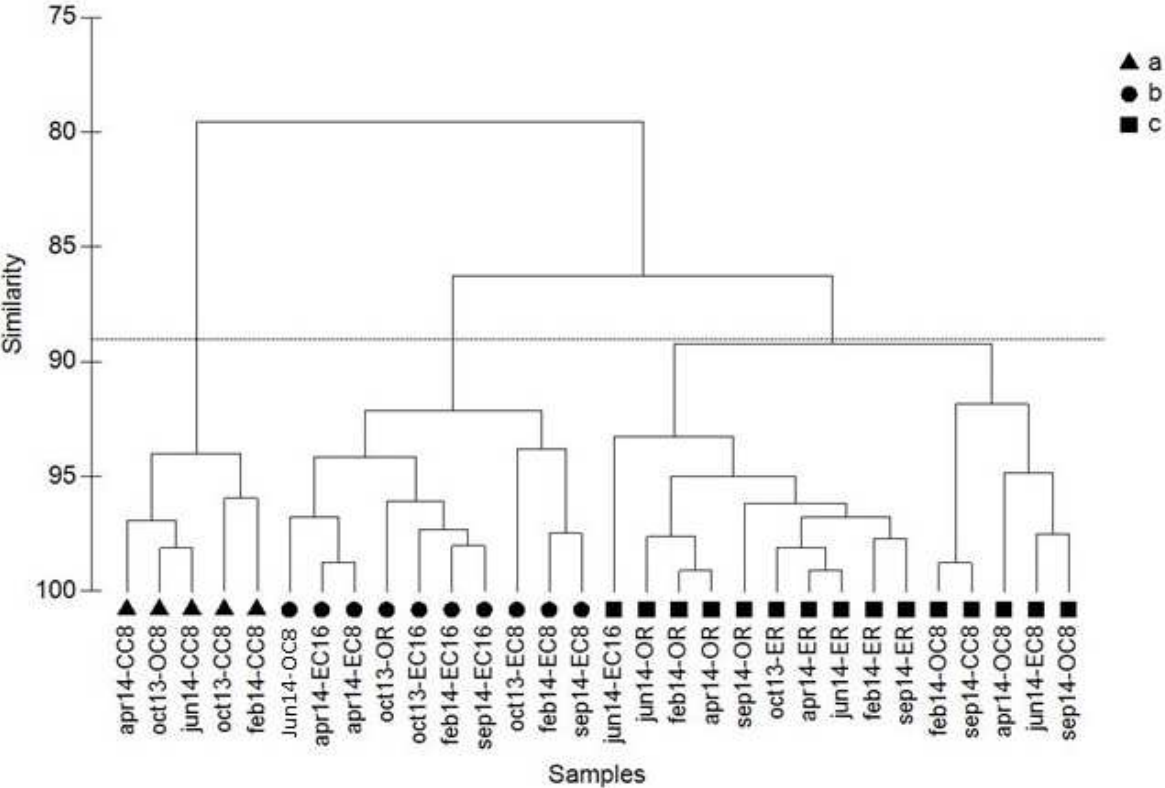
1°39'0"W

1°36'0"W

49°30'0"N

49°30'0"N

Figure 2



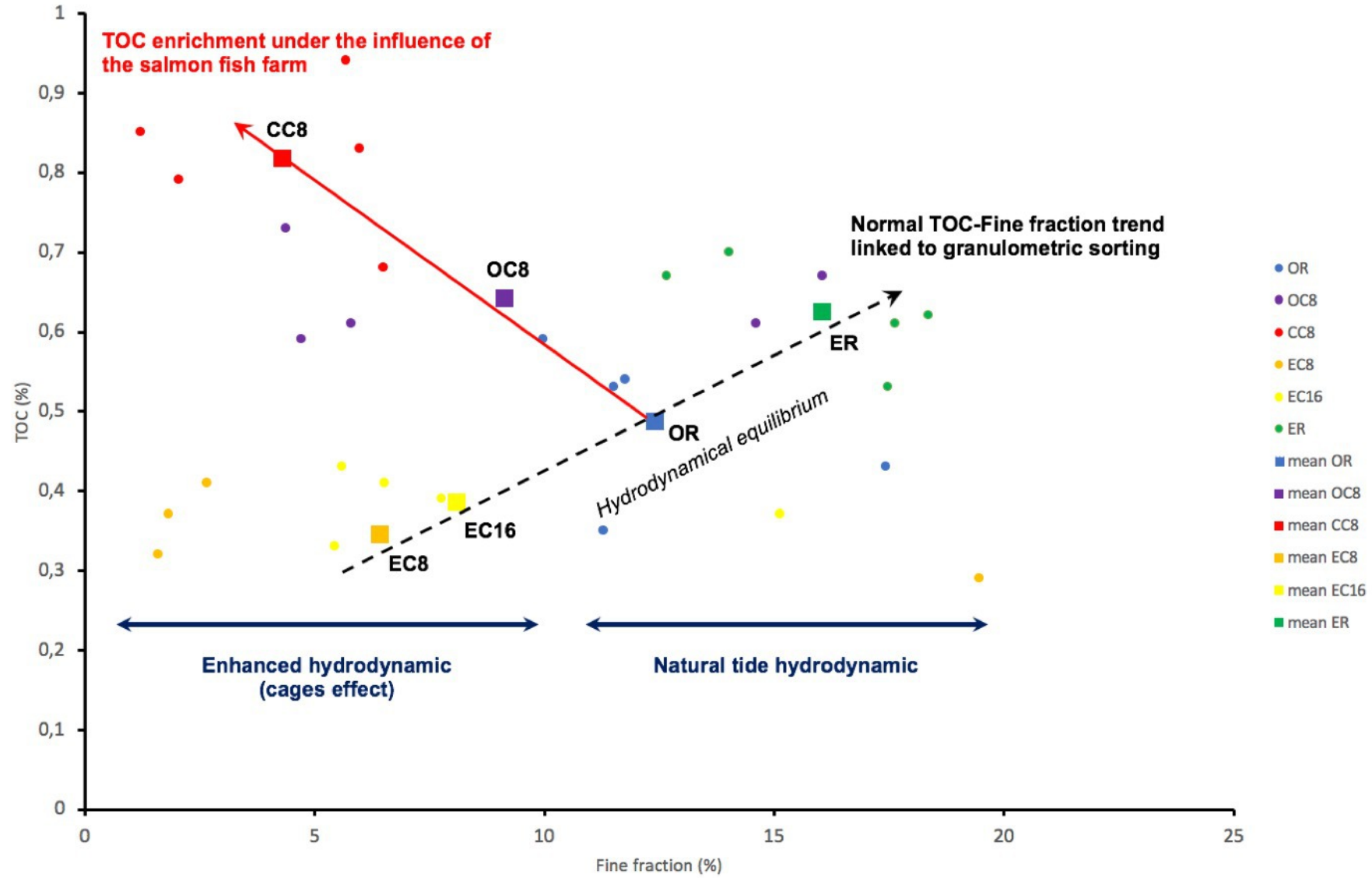


Figure 4

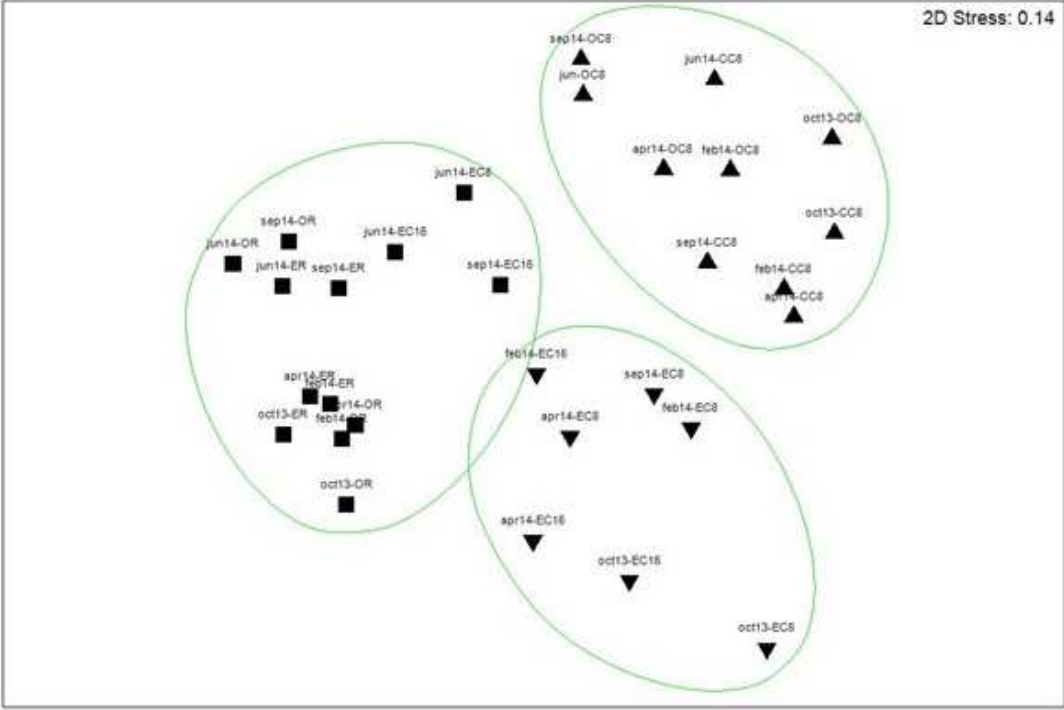
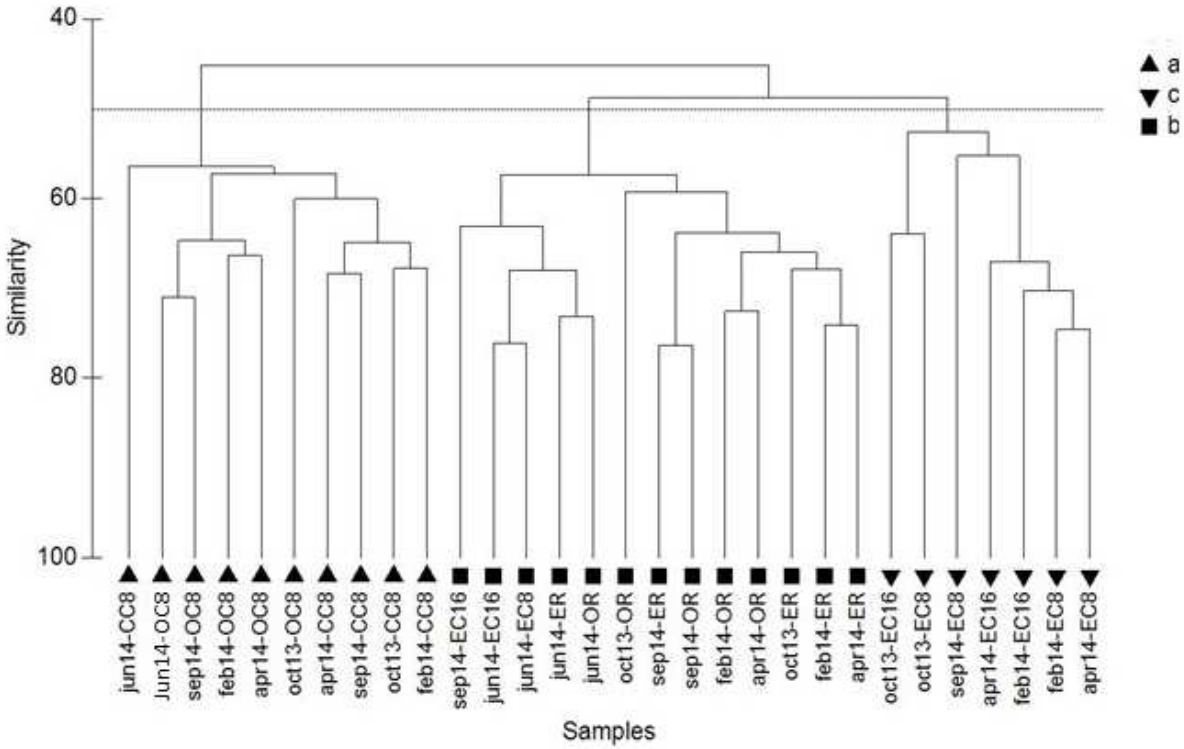


Table 1. Mean seawater characteristics during the five sampling campaigns. C1: 31 October 2013, C2: 19 February 2014, C3: 8 April 2014, C4: 13 June 2014 and C5: 18 September 2014.

	C1	C2	C3	C4	C5
Salinity (psu)	34.5	34.4	34.6	34.7	34.6
Temperature (°C)	17.7	8.2	11.1	14.7	17.9
Oxygen saturation (%)	102	101	103	107	123
Turbidity (NTU)	1.2	2.1	14.0	11.0	8.0

Table 2. Main characteristics of tidal currents measured by the eastern ADCP.

Main characteristics	Neap tide	Spring tide
Tidal range (m)	2.0	6.5
Maximum flood current velocity (m.s ⁻¹)	0.10	0.20
Maximum ebb current velocity (m.s ⁻¹)	0.30	0.70
Flood current (% of time)	40%	33%
Ebb current (% of time)	60%	66%

Table 3. Characteristics of sediments and macrofauna collected from sampling stations. TOC (%): Total Organic Carbon; FP (%): Fine Particles < 50 µm in dry sediment. TR: Total taxonomic richness per 0.5 m²; A: Total abundance (ind.0.5m²); H': Shannon-Weaver diversity index in log₂; J': Pielou's evenness index. Mean values of the Benthic Indices (AMBI, M-AMBI, and BO2A) calculated with the five replicates for each station. C1: 31 October 2013, C2: 19 February 2014, C3: 8 April 2014, C4: 13 June 2014 and C5: 18 September 2014. Ecological Quality Status (EcoQS), red: bad; poor: orange; moderate: yellow; good: green; high: blue.

Stations/campaigns	TOC (%)	% FF	TR	A	H'	J'	AMBI	M-AMBI	BO2A	
OR	C1	0.59	10.0	55	3,920	1.53	0.26	2.72	0.69	0.002
	C2	0.53	11.5	59	3,381	1.70	0.29	2.64	0.73	0.005
	C3	0.35	11.3	51	3,340	1.64	0.29	2.63	0.69	0.005
	C4	0.54	11.8	44	2,935	2.30	0.42	2.32	0.76	0.008
	C5	0.43	17.4	78	7,022	2.11	0.34	2.37	0.88	0.005
ER	C1	0.53	17.5	70	3,250	3.14	0.51	2.42	0.95	0.024
	C2	0.70	14.0	58	3,089	2.63	0.45	2.28	0.86	0.012
	C3	0.62	18.4	55	3,190	2.51	0.43	2.27	0.83	0.010
	C4	0.61	17.6	45	3,065	2.56	0.47	2.51	0.77	0.031
	C5	0.67	12.7	57	7,792	2.21	0.38	2.39	0.80	0.010
EC16	C1	0.41	6.5	38	1,248	1.74	0.33	3.03	0.61	0.046
	C2	0.43	5.6	49	3,007	2.59	0.46	3.01	0.75	0.072
	C3	0.33	5.5	33	2,164	2.08	0.41	2.21	0.70	0.008
	C4	0.37	15.1	47	8,451	2.06	0.37	2.71	0.71	0.024
	C5	0.39	7.8	53	3,889	2.28	0.40	3.02	0.73	0.065
EC8	C1	0.32	1.6	22	445	2.65	0.59	3.13	0.63	0.123
	C2	0.41	2.7	32	1,973	2.91	0.58	3.66	0.65	0.142
	C3	0.34	6.5	34	3,119	1.97	0.39	2.81	0.64	0.024
	C4	0.29	19.5	39	7,324	1.70	0.32	3.21	0.60	0.077
	C5	0.37	1.8	45	2,054	2.23	0.41	3.50	0.65	0.147
OC8	C1	0.59	4.7	37	1,502	2.17	0.42	2.75	0.68	0.022
	C2	0.61	5.8	57	3,648	2.36	0.40	3.04	0.76	0.052
	C3	0.61	14.6	55	6,913	1.78	0.31	2.99	0.69	0.015
	C4	0.73	4.4	59	11,355	1.76	0.30	3.19	0.69	0.039
	C5	0.67	16.1	65	7,964	2.36	0.39	3.25	0.77	0.082
CC8	C1	0.79	2.1	48	3,177	3.07	0.55	3.79	0.72	0.162
	C2	0.85	1.2	35	2,113	2.80	0.55	3.88	0.63	0.157
	C3	0.68	6.5	43	1,693	2.34	0.43	2.97	0.70	0.031
	C4	0.94	5.7	34	3,284	2.04	0.40	3.52	0.58	0.065
	C5	0.83	6.0	48	2,989	2.35	0.42	3.60	0.66	0.164

Table 4. Results of two-way ANOVA statistical tests. C1: 31 October 2013, C2: 19 February 2014, C3: 8 April 2014, C4: 13 June 2014 and C5: 18 September 2014.

			F	p-value	Tukey test
Taxonomic richness	Dates	4	2.82	<0.05	C1≠C5
	Stations	6	2.31	<0.05	ER≠EC8
Abundance	Dates	4	14.43	<0.001	C2≠C4, C5 C1≠C4, C5 C3≠C4, C5
	Stations	6	6.57	<0.001	OC8≠EC16, CC8, EC8, ER, OR
H'	Dates	4	3.87	<0.01	C2≠C3, C4
	Stations	6	4.41	<0.001	OR≠ER, CC8 OC8≠ER, CC8 CC8≠EC16
J'	Dates	4	4.42	<0.01	C4≠C1, C2
	Stations	6	11.67	<0.001	OR≠EC16, ER, EC8, CC8 CC8≠EC16 OC8≠ER, EC8, CC8
AMBI	Dates	4	2.45	<0.05	C5≠C3
	Stations	6	24.75	<0.001	ER≠EC16, OC8, EC8, CC8 OR≠OC8, EC8, CC8 EC16≠OC8, CC8 CC8≠OC8
M-AMBI	Dates	4	1.14	0.34	-
	Stations	6	4.73	<0.001	ER≠EC16, EC8, OC8, CC8
BO2A	Dates	4	6.37	<0.001	C3≠C1, C2, C5 C5≠C2
	Stations	6	23.3	<0.001	OR≠OC8, CC8, EC8 ER≠EC8, CC8 EC16≠EC8, CC8 OC8≠EC8, CC8 CC8≠EC16
Σ			143		

Table 5. Mean abundances per 0.5 m² for dominant taxa in the three zones identified around the salmon cages in the Rade de Cherbourg. EG: Ecological Group from AZTI consulted on 15th February 2018 (see Fig. 1 for location of the six stations).

Taxa	EG	CC8/OC8	EC16/EC8	OR/ER
<i>Apseudopsis latreillii</i>	III	2538.9	1980.8	2669.5
<i>Notomastus latericeus</i>	III	574.3	375.0	169.4
<i>Dipolydora giardi</i>	IV	554.9	452.1	68.0
<i>Capitella minima</i>	V	115.2	34.0	1.8
<i>Phyllodoce mucosa</i>	III	66.3	70.7	15.5
<i>Gammarella fucicola</i>	III	65.9	-	1.1
<i>Chaetozone gibber</i>	IV	60.8	12.7	11.8
<i>Jassa herdmani</i>	V	60.2	0.3	0.2
<i>Caulleriella alata</i>	IV	50.0	10.3	7.6
<i>Cirriformia tentaculata</i>	IV	44.6	16.7	2.6
<i>Cheirocratus intermedius</i>	I	41.8	3.9	8.2
<i>Zeuxo holdichi</i>	III	39.1	6.5	5.5
<i>Abludomelita obtusata</i>	II	38.5	1.4	9.7
<i>Steromphala umbilicalis</i>	I	19.6	-	0.5
<i>Neanthes acuminata</i>	III	15.8	7.7	0.1
<i>Ampelisca tenuicornis</i>	I	4.0	99.9	99.5
<i>Phtisica marina</i>	I	0.3	60.0	62.0
Maldanidae	I	1.1	59.4	450.1
<i>Lanice conchilega</i>	II	1.1	34.7	31.9
<i>Tritia reticulata</i>	II	15.1	12.7	9.0
<i>Hilbigneris gracilis</i>	III	5.0	9.3	34.6
<i>Melinna palmata</i>	III	-	0.9	80.7
<i>Thyasira flexuosa</i>	III	0.1	6.4	77.6
<i>Acromegalomma vesiculosum</i>	I	2.9	1.0	38.7
<i>Apseudes talpa</i>	II	-	0.1	25.8
<i>Abra alba</i>	III	3.9	7.4	12.0

Table 6. Sites and habitats showing high abundance (mean abundance and maximum abundance ind.m²) of the tanaid *Apseudopsis latreilli* in the World Ocean. OM: % Organic Matter in dry sediment.

Sites	Benthic habitat	Abundance		OM (%)	Reference	
		mean	max			
English Channel	Rade de Cherbourg, Normandy, France	Mixed, coarse sand and gravel	5,078	20,700	3.5	This study
		Muddy fine sand	4,339	10,320	3.0	This study
		Fine sand	3,962	14,640	2.5	This study
		<i>A. squamata</i> and <i>A. latreilli</i> mixed sediment	3,151	4,777	3.7	Baux, 2015
		<i>M. palmata</i> muddy sand	2	3	6.5	Baux, 2015
		<i>M. palmata</i> mixed muddy fine sand	2,690	4,720	3.2	Baux, 2015
		<i>S. decorata</i> fine sand	453	2,130	1.2	Baux, 2015
		<i>A. latreilli</i> and <i>S. decorata</i> in very fine sand	2,250	6,280	3.5	Baux, 2015
Baie du Becquet, Normandy, France	<i>A. squamata</i> and <i>A. latreilli</i> mixed sediment	8,900	22,787	1.6	Martinez, 2017	
		<i>C. coarse</i> mixed sediment	2,563	5,150	2.0	Martinez, 2017
		Amphipods and polychaetes in muddy sand	6,822	13,770	1.7	Martinez, 2017
Aber Wrach, Brittany, France	Intertidal <i>S. decorata</i> fine sand	740	-	-	Hily and Bouteille, 1999	
		Intertidal <i>Z. marina</i> meadows	3,086	-	-	Hily and Bouteille, 1999
		Fine sand <i>A. alba</i> - <i>H. bilineata</i> community	2,535	3,608	-	Dauvin and Gentil, 1990
Atlantic	Galicia, Ria de Grove, Spain	Subtidal <i>Z. marina</i> meadows	5,940	9,640	-	Esquete et al., 2011
		Fine sand community	398	2,161	1.8	Lourido et al., 2008
		Coarse sand community	348	2,289	1.5	Lourido et al., 2008
		Muddy fine sand community	1,778	5,321	3.1	Lourido et al., 2008
Ria de Formosa, Portugal	Subtidal <i>Z. marina</i> meadows	1,528	-	2.8	Gamito et al., 2012	
Mediterranean Sea	South-eastern Spain	Sandy soft-bottom in Portman Bay	1,432	-	-	Marin-Guirao et al., 2005
		Marine caves of Granada's coast	2,106	-	-	Navarro-Barranco et al., 2013
	Castellon coast Spain	Well-sorted fine sand community	-	1,033	-	De-la-Ossa-Carretero et al., 2010
western Italian coast	Well-sorted fine sand community, Pisa	4,335	-	-	Tataranni and Lardicci, 2010	
Marmara Sea, Turkey	Well-sorted fine sand community	80	166	2.85	Ates et al., 2014	
Persian Gulf, Dubai creek	Muddy sediment under organic pollution	17,650	43,000	-	Sauders et al., 2007	