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## The Dredge Disposal Sediment Index (D2SI): A new specific multicriteria index to assess the impact of harbour sediment dumping

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2           **The Dredge Disposal Sediment Index (D<sup>2</sup>SI): a new specific multicriteria index to**  
3           **assess the impact of harbour sediment dumping**

4  
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19  
20           **ABSTRACT**

21           At present, there are few operational indexes to assess the impact of a given human  
22           pressure taken alone. Nevertheless, the current challenge in the management of coastal marine  
23           environments in the framework of cumulative impacts and climatic change is to identify the  
24           relative contribution of each activity on ecosystem functioning. The objective of the present  
25           study is to propose an integrative approach to assess the environmental impacts of dumping  
26           operations, *via* the development of a new index, the Dredge Disposal Sediment Index (D<sup>2</sup>SI).  
27           From the selection of two types of station: impacted and unimpacted, D<sup>2</sup>SI integrates six sub-  
28           indices considering the biological and physical changes generated by dredge disposal on the  
29           seabed. A final score is proposed, according to the five classes of the European Water  
30           Framework Directive. The initial development of D<sup>2</sup>SI was conducted on the experimental  
31           dumping site of Machu (Bay of Seine), by applying a BACI (Before-After-Control-Impact)  
32           approach. An additional implementation (D<sup>2</sup>SI<sub>2</sub>) is used in the case of absence of data on  
33           ichthyofaunal or biological traits of life of macrobenthic fauna, which yields a comparable  
34           assessment of dumping pressure.

35 In the future, the D<sup>2</sup>SI or D<sup>2</sup>SI<sub>2</sub> indexes should be tested on other dumping sites with a  
36 view to comparing the assessment of this dumping activity.

37

38 *Keywords:* multicriteria indicator, integrative approach, dredge disposal impact,  
39 anthropogenic impact, benthic habitat, fine particles, morphological changes, Traits of Life,  
40 Bay of Seine.

41

## 42 **Highlights**

- 43 - Aim: Assessment of the impact of dumping on benthic ecosystems.
- 44 - A multicriteria index [Dredge Disposal Sediment Index (D<sup>2</sup>SI)] is developed.
- 45 - D<sup>2</sup>SI integrates six sub-indices based on biological and physical elements.
- 46 - Application on the experimental dumping site of Machu (Bay of Seine).

47

## 48 **Introduction**

49

50 The EEA (European Environment Agency, <https://www.eea.europa.eu/>) has  
51 implemented the DPSIR model [Drivers (driving forces, responsible for nuisance); Pressures  
52 (quantitative or qualitative); States (describing a component of the environment at a given  
53 moment); Impacts (on the studied biological/physical/chemical compartment) and Responses  
54 (reactions implemented for decision-making and management applied to minimize the  
55 impact)]. DPSIR is an approach that describes the interactions between society and  
56 environment and proposes recommendations for the development of an environmental  
57 assessment strategy (Kristensen, 2004). In this framework, indicators are developed to  
58 classify the degree of impact in relation to a pressure and to allow management to minimize  
59 its impact. In the future, the DPSIR (Drivers, Pressures, State, Impact and Response)  
60 approach should be extended to DAPSI(W)R(M) [Drivers-Activities-Pressures-State changes-  
61 Impacts (on Welfare)-Responses (as Measures)], according to the complexity of a given  
62 managed sea area in terms of multiple activities (Elliott et al., 2017). The aim of this approach  
63 is also to prevent confusion surrounding the terminology of the various elements, in particular  
64 between the definitions of Drivers and Pressures, between State and State changes as well as  
65 between these elements and Impact (Elliott et al., 2017).

66 Dredging is necessary to maintain sufficient water depth in harbour basins and provide  
67 access channels for the purpose of navigation and port activities. The dredged sediment, in

68 cases where they do not contain hazardous products, can be dumped at sea or in rivers (Engler  
69 et al., 1991; Marmin et al., 2014, 2016). Nevertheless, dumped sediment may have different  
70 physical and chemical characteristics compared to the native sediments, which produces  
71 multiple effects on the environment. A first and direct effect is the covering of sediment and  
72 benthos compartments (mechanical effect), which leads to the destruction of local habitats at  
73 least temporarily (Chauvin et al., 1986; Olenin, 1992; Boutin, 2000; Desprez, 2000; Smith  
74 and Rule, 2001; Bolam et al., 2006a, 2006b; Hermand, 2008; Marmin et al., 2014, 2016;  
75 Dauvin et al., 2017b; Méar et al., 2018). The environmental impact of dredging activities is  
76 one of the most important problems in coastal zone management (O'Connor, 1998).

77         Nevertheless, most scientific studies generally focus only on studying the structure of  
78 benthic invertebrates, in relation to their environment. The objectives of these studies are to  
79 assess the impacts generated and/or the recovery of the system (Van Dolah et al., 1984;  
80 Olenin, 1992; Harvey et al., 1998; Smith and Rule, 2001; Witt et al., 2004; Bolam et al.,  
81 2006a; Vivian et al., 2009; Marmin et al., 2016). There are a large number of indexes, based  
82 on benthic macrofauna, which generally classify taxa according to their membership in  
83 functional ecological groups. These indexes are frequently used in environmental studies, but  
84 few of them are related to specific pressures (Ware et al., 2009; Munari and Mistri, 2014).  
85 Indeed, most of the Benthic Indices were initially developed to assess the impact of Organic  
86 Matter (OM) enrichment or the impact of oil pollution on benthic organisms; this was the case  
87 for AMBI, BOPA, I2EC, BENTIX, BO2A, BQI etc. (Borja et al., 2000; Simboura and  
88 Zenetos, 2002; Dauvin, 2007, 2018; Pinto et al., 2009; Dauvin et al., 2016). However, these  
89 indices are not specific to the response of the benthos, to assess bottom perturbations and the  
90 impact of sediment disposal (Ware et al., 2009; Munari and Mistri, 2014). To our knowledge,  
91 only few indicators are specifically designed to identify the impact of dredge sediment  
92 disposal. Roberts et al. (1998) proposed a Macrofauna Monitoring Index based on the  
93 selection of species in response to spoil disposal, and calculating a ratio between the  
94 abundance of each species at impacted and unimpacted stations. Twenty years later, this  
95 approach was reconsidered by Dauvin et al. (2018a) who suggested to modify the Robert's  
96 index to a Dredge Spoil Disposal (DSD) index, which takes into account a more objective  
97 method for selecting and scoring species. Nevertheless, this index is also based on the benthic  
98 macrofauna response to a human pressure. In fact, the impact of dredging activities and  
99 disposal of dredge sediment produces multiple effects on the sedimentology, morphology and  
100 biological compartments of the environment (Van Dolah et al., 1984; Chauvin et al., 1986;  
101 Olenin, 1992; Boutin, 2000; Desprez, 2000; Smith and Rule, 2001; Bolam et al., 2006a, b;

102 Hermand, 2008; Vivan et al., 2009; Marmin et al., 2014, 2016; Méar et al., 2018; Pezy et al.,  
103 2018). Therefore, it appears essential to develop a multicriteria index, which includes both  
104 biological and physical changes generated by the impact of dredge sediment disposal.

105 The objective of this study is to improve the index developed by Roberts et al. (1998)  
106 and modified by Dauvin et al. (2018), considering the biological and physical changes that are  
107 generated, to assess objectively the impact of dumping operations at sea and take into account  
108 the degradation or improvement of environment conditions. In the framework of the  
109 INDICLAP project (“INDicateurs de CLAPage”) funded by the French Biodiversity Agency  
110 (FBA), a multicriteria approach was proposed, which includes benthic macrofauna  
111 (invertebrates >1mm) and ichthyofauna (benthodemersal fish), as well as morpho-  
112 sedimentary environment changes (bathymetry, sedimentary facies and deposit thickness).  
113 The new index proposed was named D<sup>2</sup>SI (Dredge Disposal Sediment Index). In the present  
114 study, we apply this index to a monitoring survey on an experimental dredge spoil disposal  
115 site (Machu site) located in the eastern part of the Bay of Seine (English Channel) using a  
116 BACI (Before-After-Control-Impact) approach (Pezy et al., 2017, 2018).

117

## 118 **1. Materials and methods**

119

### 120 *1.1. Dredge Disposal Sediment Index (D<sup>2</sup>SI) concept*

121

122 The multicriteria D<sup>2</sup>SI index is calculated considering the selection of two types of  
123 stations: impacted stations (under the direct influence of harbour sediment disposal) and  
124 unimpacted stations (without direct or indirect influence of harbour sediment disposal). Both  
125 impacted and unimpacted stations must be located on the same benthic community and  
126 sediment habitat at the beginning of dredge spoil operations. The D<sup>2</sup>SI is composed of six  
127 sub-indices taking into account the biological and physical changes generated by dredge  
128 disposal on the seabed. A score is calculated for each sub-index (Fig. 1). The addition of these  
129 scores yields a final score (D<sup>2</sup>SI) which allows us to classify the environment from “bad” to  
130 “excellent”, according to the five classes of the European Water Framework Directive.  
131 Intervals are defined according to data from the Machu experimental dumping (eastern part of  
132 the Bay of Seine).

133 The six sub-indices are:

- 134 - D<sup>2</sup>SI-Benthos (D<sup>2</sup>SI<sub>B</sub>), based on benthic macrofauna (invertebrates >1 mm), i.e.  
135 presence of the species and their abundances.

- 136 - D<sup>2</sup>SI-Ichthyofauna (D<sup>2</sup>SI<sub>I</sub>), based on demersal fish i.e. presence of the species and their  
137 abundances.
- 138 - D<sup>2</sup>SI-Sediment (D<sup>2</sup>SI<sub>S</sub>), based on the percentage of sediment modification between the  
139 natural sediment before disposal and the deposited sediment after the disposal.
- 140 - D<sup>2</sup>SI-Thickness (D<sup>2</sup>SI<sub>T</sub>), based on the thickness of the accumulated deposit each year  
141 (measured with bathymetric differentials) and considering the initial bathymetry  
142 before operations at the dumping site.
- 143 - D<sup>2</sup>SI-Resistance to dredge spoil sedimentation (D<sup>2</sup>SI<sub>R</sub>), based on the ability of species  
144 to resist deposition of dredge spoil during harbour sediment disposal.
- 145 - D<sup>2</sup>SI-Drifting (D<sup>2</sup>SI<sub>D</sub>), based on the ability of drifting individuals of a species to  
146 recolonize an area after disturbance near the sea bed.

147

148 Calculation methods for each sub-indices and D<sup>2</sup>SI index applications are available in  
149 additional online data.

150

## 151 1.2. Dredge Disposal Sediment Index (D<sup>2</sup>SI) computation

152

### 153 1.2.1. D<sup>2</sup>SI-Benthos (D<sup>2</sup>SI<sub>B</sub>)

154

155 The benthic macrofauna of soft-bottom habitats is known to be a good indicator of  
156 environmental quality because the constituent species live on and within the substrate. Since  
157 the benthic macrofauna is specific to a particular habitat if the sediment is normally  
158 unperturbed, any perturbations of the substrate induces a modification of the benthic  
159 communities (Dauvin, 1993; Borja et al., 2000). Numerous studies have highlighted the  
160 negative impacts on this compartment caused by physical and chemical modifications induced  
161 by dredge spoil deposition (Van Dolah et al., 1984; Olenin, 1992; Desprez, 2000; Bolam et  
162 al., 2006a; b; Hermand, 2008; Vivan et al., 2009; Marmin et al., 2014, 2016; Pezy et al., 2017,  
163 2018).

164 The D<sup>2</sup>SI-Benthos is constructed following the DSD index (Dauvin et al., 2018), and the  
165 resulting values are scored from 0 to 1.

166 Calculations are based on successive steps (Robert *et al.*, 1998; Dauvin et al., 2018)  
167 which are performed separately for each campaign (Fig. 1):

1681) The first step is similar to that carried out for the DSD index (Dauvin et al., 2018). The sum of  
169 the macrofauna abundances is calculated for each species for impacted and unimpacted

170 stations; the ratio of the sum of the impacted stations and unimpacted stations is then  
171 calculated for each species. A first score from 1 to 10 is attributed based on each species ratio,  
172 reflecting the impact of dumping operations on the macrofauna abundances (Table 1). A score  
173 of 10 indicates a species present only at the unimpacted stations, while a score of 1 indicates a  
174 species tolerant of dumping operations with high abundances at impacted stations (abundance  
175 at unimpacted samples ten times higher than those at impacted samples). A score of 0  
176 indicates the species is present only at impacted stations (ratio not predictable; Table 1). In  
177 this case, the ratio is not calculable. Then, a mean score is computed which corresponds to the  
178 sum of the species scores (Table 1) divided by the number of species present in the sample.  
179 This mean score varies between 0 and 10.

180 In a second step, the mean score is divided in five classes corresponding to a scale varying  
181 from 0 to 1 in order to give more weight to the middle classes, thus taking account of natural  
182 variations in the macrofauna abundances (Table 2). For a mean score between 4 and 6  
183 corresponding to an undisturbed environment, a  $D^2SI_B$  score of 0 is attributed; then, with an  
184 increase in perturbation of the environment, scores of 0.25, 0.50, 0.75 and 1 are attributed  
185 following the threshold defined in Table 2.

186

### 187 *1.2.2. D<sup>2</sup>SI-Ichtyofauna (D<sup>2</sup>SI<sub>I</sub>)*

188

189 Pelagic fish species living in the water column are mobile and are thus less impacted by  
190 dumping operations (Wilber et al., 2007). Demersal fishes, which feed mainly on benthic  
191 organisms, can be heavily impacted by the destruction and alteration of benthic environments  
192 (Alzieu, 1999). Moreover, fish eggs and larvae are sensitive to turbid plumes and the release  
193 of nutrients or chemical contaminants into the water column when the sediments are  
194 deposited.

195 The  $D^2SI$ -Ichtyofauna ( $D^2SI_I$ ) is calculated similarly to the  $D^2SI_B$  (Fig. 1), taking into  
196 account the species richness and abundances of the demersal fish species, it is scored from 0  
197 to 1 in the same way of  $D^2SI_B$  (Table 2).

198

### 199 *1.2.3. D<sup>2</sup>SI-Sediment*

200

201 Dumping operations induce changes of bottom sediment at the dumping site and  
202 surrounding areas, locally causing the release of fine particles and increasing the turbidity

203 near the seafloor (Chauvin et al., 1986; Boutin, 2000; Smith and Rule, 2001; Marmin et al.,  
204 2016; Baux et al., 2019).

205 This sub-index reflects the difference between deposited sediment and native  
206 sediment, regardless of any differences in their grain-size characteristics. The working  
207 hypothesis adopted here is that large differences between native sediment and deposited  
208 sediment lead to higher impacts than when the sediments are similar. In the Bay of Seine, the  
209 enhanced impact is related to the massive inputs of fine particles (<63 µm) from harbour  
210 basins and the Seine estuary (Lesourd et al., 2016; Méar et al., 2018; Baux et al., 2019).

211 The D<sup>2</sup>SI<sub>S</sub> is based on the difference of fine particles (<63 µm; noted “FP” in Eq. 1)  
212 content (in percentage) between impacted and unimpacted stations (Eq. 1).

213

$$214 \quad D^2SI_S = \left| \frac{\% FP \text{ at impacted stations} - \% FP \text{ at unimpacted stations}}{\% FP \text{ at impacted stations} + \% FP \text{ at unimpacted stations}} \right| \quad (Eq. 1)$$

215

216 As with other sub-indices, calculations are performed separately for each campaign  
217 and a score from 0 to 1 is attributed based on the results (Eq. 1) to allow classification of the  
218 disturbance (Table 3). The score interval limits (interval of 0.2, except for the first scale and  
219 last scale) are defined according to results from the Machu site. A score of 0 corresponds to  
220 an undisturbed environment, in contrast to a score of 1, which corresponds to the maximal  
221 degree of defined disturbance (Table 3).

222

#### 223 1.2.4. D<sup>2</sup>SI-Thickness

224

225 A large amount of research has highlighted the changes in bathymetry (formation of  
226 underwater relief) induced by dumping operations (Desprez, 2000; Fredette and French,  
227 2004), generating a modification of physical conditions (modification of local marine currents  
228 near the seabed and sedimentary types).

229 To calculate D<sup>2</sup>SI-Thickness, the *in-situ* thickness is obtained by bathymetric  
230 measurements, integrating initial bathymetry (before operations at the dumping site) and the  
231 accumulation of deposits over time between each survey included in the study (Eq. 2). It is  
232 preferable to keep the same method of measuring bathymetry for all surveys, in order to  
233 eliminate measurement bias. Multibeam measurements are recommended.

234



235 
$$D^2SI_T = (TH_{Impacted}^n - TH_{Unimpacted}^n) + (e^{(Th_{Impacted}^n - Th_{Unimpacted}^n)} - 1) \quad (Eq. 2)$$

236

237 *With  $TH^n$  = Initial bathymetry – bathymetry measured at time n*

238 *and  $Th^n$  = bathymetry measured at time n – bathymetry measured at n + 1*

239

240  $TH^n$  corresponds to the thickness variation (bathymetric differential) measured from  
241 the initial state to time n.  $Th^n$  corresponds to the variation in thickness (bathymetric  
242 differential) between time n and n+1 (Eq. 2).

243 As with the other sub-indices, a score from 0 to 1 is attributed based on the calculation  
244 results (Eq. 2) to allow classification of the disturbance (Table 3). A calculated value of  $\leq 0$   
245 corresponds to no change in thickness or sediment loss by erosion. Also, a  $D^2SI_T$  value of 0  
246 leads to classification as an undisturbed environment. In contrast,  $D^2SI_T$  1 (calculated value  
247  $>6$ ) corresponds to a significant and gradual increase of thickness compared to the state before  
248 dumping (Table 3).

249

#### 250 *1.2.5. $D^2SI$ -Drifting and $D^2SI$ -Resistance to landfill*

251

252 The use of biological and ecological traits of life in the assessment of the quality of  
253 marine habitats is relatively recent and offers some interesting perspectives (Dauvin et al.,  
254 2017b). Several authors have hypothesized that specific modifications of the combination of  
255 community life-history traits in disturbed ecosystems depend on the nature and intensity of  
256 the disturbance (Usseglio-Polatera et al., 2000; Bremner et al., 2003, 2006; Bolam et al.,  
257 2006a; Janson, 2007; Dauvin et al., 2017a,b)

258 Two Biological Traits of Life are selected here and integrated into the calculation of  
259 the  $D^2SI$  index:

260 (1) Resistance to landfill (resistance to sediment spoil deposition), which corresponds  
261 to the capacity of the macrofauna to resist increases in thickness of the sedimentary layer  
262 during sediment disposal. Indeed, benthic species that live in close contact with the seabed  
263 and have reduced mobility are highly exposed to the effects of dumping. In general, a large  
264 majority of the fauna disappear or are very strongly reduced just after the dumping (Witt et  
265 al., 2004; Bolam et al., 2006b). Some species are more resistant than others as the bivalves  
266 and polychaetes, partly owing to their ability to migrate vertically (Maurer and Aprill, 1979;  
267 Maurer et al., 1981a, 1981b, 1982; Miller et al., 2002; Janson, 2007). Very little information

268 on this biological trait of life exists in the literature and the behaviour of species is often based  
269 on laboratory experiments or studies in the wild, and concern only a small number of species  
270 (Trevor, 1978; EPA, 1989; Chandrasekara and Frid, 1998; Essink, 1999; Bolam et al., 2004;  
271 Powilleit et al., 2006; Janson, 2007; Powilleit et al., 2009).

272 (2) Drifting corresponds to the ability of macrofauna juveniles and adults to colonize  
273 following a disturbance, by their active or passive movements mainly due to currents near the  
274 seabed. Drifting is an important part of recolonization phenomena in the eastern part of the  
275 Bay of Seine (Olivier et al., 1996; Desroy and Retière, 2001; Janson, 2007; Marmin, 2013).

276 For calculation of the  $D^2SI_R$  and  $D^2SI_D$  sub-indices, the data are grouped into five  
277 categories identifying the ability of macrofauna to resist sediment spoil deposition: G1 =  
278 <1cm; G2 = 3 to 10 cm; G3 = 10 to 30 cm; G4 = 30 to 50 cm; G5 = >50 cm] and into three  
279 categories quantifying the ability to recolonize by drifting (drifting and associated categories:  
280 G3 = high; G2 = low or possible; and G1 = absent). The calculations of both sub-indices are  
281 based on the assumption that the most sensitive species will disappear first after dumping  
282 operations [low capacity to resist to increase in thickness of the sedimentary layer (G1 and  
283 G2) or absence/low capacity of recolonization by drifting (G1 and G2)], and the proportion of  
284 species that show a high resistance to sediment spoil deposition (G3- G5) or high ability to  
285 recolonize by drifting (G3) will increase. The calculation takes into account the percentage of  
286 G1 and G2 taxa (Eq. 3) that will be the most sensitive during sediment disposal. The  
287 respective percentages of G1 and G2 (% G1 and % G2; Eq. 3) are calculated on all taxa that  
288 can be included into a category. Taxa that are not categorized as belonging to any of the  
289 groups are excluded from the calculation (taxa that have no group may be sensitive or  
290 resistant).

291

$$292 \quad D^2SI_{R \text{ or } D} = 1 - (\%G1 + \%G2) \quad (Eq. 3)$$

293

294 As with the other sub-indices,  $D^2SI_R$  and  $D^2SI_D$  are determined separately for each  
295 campaign and a score from 0 to 1 is attributed to allow classification of the disturbance (Table  
296 3). Low calculated values indicate the presence of sensitive species, poorly resistant to spoil  
297 deposition or with very little ability to recolonize by drifting, and which thus reflect an  
298 undisturbed environment (score of  $D^2SI_R$  and  $D^2SI_D$  = 0). A high calculated value highlights  
299 the disappearance of sensitive species impacted by dumping operations.

300

301 *1.2.6.  $D^2SI$ , final calculation*

302

303 The D<sup>2</sup>SI is calculated by adding respective scores of each sub-index (Fig. 1; Eq. 4).

304 
$$D^2SI = D^2SI_B + D^2SI_I + D^2SI_S + D^2SI_T + D^2SI_R + D^2SI_D \quad (Eq. 4)$$

305

306 As with the other sub-indices which are calculated separately for each campaign, a  
307 score of 0 to 1 is attributed to allow classification of the disturbance (Table 4). A D<sup>2</sup>SI score  
308 of 0-0.2 corresponds to an undisturbed environment. The degree of impact increase gradually  
309 up to a D<sup>2</sup>SI score of 0.8-1, classifying the disturbance at the highest level (extremely  
310 disturbed; Table 4).

311

### 312 1.3. Study site

313

314 The experimental dumping site of Machu (eastern part of the Bay of Seine) was used  
315 to develop and test the application of D<sup>2</sup>SI. A dumping experiment was carried out in 2012-  
316 2013, according to a BACI (Before-After-Control-Impact) approach (covering the 2010-2015  
317 period; Fig. 2). Dredged material was deposited at two experimental sites with two distinct  
318 approaches to study two dumped sediment methods. At the first site (MASED), 1x10<sup>6</sup> m<sup>3</sup> of  
319 sediment was deposited on a single point at 16 m water depth, with the dredger remaining  
320 stationary from 13 May 2012 to 15 December 2012, with two interruptions in dumping (1-26  
321 July and 9 October-22 November 2012). At the MASED site, the dumping generated a  
322 conical deposit 5 m in height (Marmin et al., 2016). At the second site (MABIO), 999,800 m<sup>3</sup>  
323 was deposited and spread out over a rectangular area of about 100 ha (1400 m x 700 m) at 13  
324 m depth. On this site, a wider area was covered, leading to the formation of a smaller deposit  
325 2 m in height (Marmin et al., 2016). At the MABIO site, the dumping took place during four  
326 periods with about 250,000 m<sup>3</sup> deposited per season: spring (16 April-14 May 2012), summer  
327 (1-26 July 2012), autumn (10 October-7 November 2012) and winter (24 January-21 February  
328 2013). Both zones correspond to a fine to medium clean sand *Ophelia borealis-Nephtys*  
329 *cirrosa* community (Marmin, 2013). The dumped sediment consisted of muddy fine sand, and  
330 the spoil material accumulated on or near the two dumping sites, with a maximum mud  
331 content (i.e. particles < 63 µm) of 50% compared to < 5% in the natural sediment in place  
332 before dumping operations. Due to hydrodynamic forcing (wave climate and tidal currents),  
333 about 50% (MABIO) and 75% (MASED) of the volume of dredged material remained at the  
334 end of the dumping periods (Marmin et al., 2016).

335 Following the experimental dumping operations, the Rouen harbour authority (*Grand Port*  
336 *Maritime de Rouen*, GPMR) has used the Machu dumping site since 2016, replacing the  
337 saturated Kannik dumping site, historically used since 1977 (Fig. 2; Marmin et al., 2014).

338

#### 339 1.4. Data used in the study

340

341 All of the benthic macrofauna data (invertebrates >1mm) come from Marmin (2013),  
342 while the bathymetry and sedimentological data are due to Marmin et al. (2016) and the  
343 ichthyofauna (demersal fishes) observations of the GPMR were acquired by the technical  
344 studies office “Cellule du Suivi du Littoral Normand (CSLN)”.

345

##### 346 1.4.1. *Macrofauna, sediment and ichthyofauna data*

347

348 Two WSW – ENE transects (named AK4 for MASED and AK7 for MABIO, Fig. 2)  
349 were defined to study the sediment characteristics and macrofauna (Marmin et al., 2016).  
350 Seven stations spaced at intervals of 500 m were defined for each transect. To develop and  
351 test the new index, four stations were selected within the MABIO site: AK4 C and AK4 D as  
352 impacted stations, AK4 A and AK4 F as unimpacted stations; and two stations were selected  
353 within the MASED site (due to the presence of conical deposit which reduce the impacted  
354 area surface): AK7 D as an impacted station and AK7 A as an unimpacted station (Fig. 2).

355 Sediments and macrobenthos were sampled using a Van Veen grab. Three replicates  
356 were sampled (unit sampling surface area: 0.1 m<sup>2</sup>, for a total of 0.3 m<sup>2</sup>; Marmin, 2013). Grab  
357 sampling was carried out 14 times from 2010 to 2015: twice before dumping (April 2010 and  
358 November 2011), seven times during the overall dumping period (May, June, July, October  
359 and November 2012 and January and March 2013) and five times after dumping (May,  
360 August and November 2013, March 2014 and March 2015). The sampled macrofauna  
361 material was sieved on a 1-mm circular mesh. Only species with an occurrence >4 and/or with  
362 a total abundance >20 individuals were selected (61 species for MABIO and 41 for MASED;  
363 see Dauvin et al., 2018). Fine granulometric fractions (<63 µm) were obtained by wet sieving  
364 (Marmin et al., 2016).

365 Ichthyofauna data were collected from 19 bottom trawl surveys (headline rope: 9 m; mesh  
366 size cod end: 10 mm knot-to-knot; trawling at night for 15 min at a speed of approximately  
367 2.5 knots) on the MABIO site, comparable to the benthos sampling (Fig. 2): before the  
368 dumping operations (April, July, October 2010 and January 2011); during the dumping

369 operations (May, June, July, October and November 2012 and January and February 2013)  
370 and after dumping (April, July and October 2013, January 2014, July, November 2014 and  
371 February, May 2015). There are no fish data from the MASED site.

372

#### 373 *1.4.2. Bathymetric data*

374

375 Bathymetric data were acquired by multibeam echo-sounder by Rouen harbour staff.  
376 A first campaign was conducted in April 2010, before experimental dumping, on the MABIO  
377 and MASED sites. These data represent the initial bathymetry of the two dumping sites. On  
378 MABIO site, ten campaigns were conducted: one campaign before dumping (November  
379 2011), three campaigns during dumping operations (May, August and October 2012) and six  
380 campaigns after dumping operations (May, July and September 2013, April and September  
381 2014 and December 2015). Seven campaigns were conducted on the MASED site one  
382 campaign before dumping (November 2011), two campaigns during dumping operations (July  
383 and December 2012) and four campaigns after dumping operations (September 2013,  
384 September 2014, March 2015 and December 2016).

385

#### 386 *1.4.3. Biological traits of life*

387

388 A literature search allowed us to create a database of biological traits characterizing  
389 ‘Resistance to landfill’ and ‘Drifting’ for taxa whose abundances represent 95% of the total  
390 abundance (40 taxa on MABIO and 35 taxa on MASED).

391

### 392 1.5. Statistical analysis

393

394 To validate the index, Spearman’s correlation coefficients were calculated, and the  
395 non-parametric Kruskal-Wallis test and multiple comparison tests were performed with the R  
396 3.4.1 software, after testing normality of data with the Shapiro test.

397 Standard deviation (Eq. 5) for D<sup>2</sup>SI scores were calculated from sub-indices scores  
398 (D<sup>2</sup>SI<sub>B</sub>, D<sup>2</sup>SI<sub>I</sub>, D<sup>2</sup>SI<sub>S</sub>, D<sup>2</sup>SI<sub>T</sub>; D<sup>2</sup>SI<sub>D</sub> and D<sup>2</sup>SI<sub>R</sub>) at each survey for MABIO and MASED sites  
399 and presented on figures 3 and 4.

$$400 \quad s_x^2 = \sqrt{\sum \frac{(x_i - \bar{x})^2}{(n - 1)}} \quad (Eq. 5)$$

with  $\bar{x}$ : mean of sample and  $n$ : size of sample.

## 1.6. Benthic indicators comparisons

The D<sup>2</sup>SI results and environmental classification were compared with other biotic indices: A) indices based on species classification in ecological groups: AMBI (AZTI Marine Biotic Index; Borja et al., 2000; Muxika et al., 2005), M-AMBI (modified AMBI; Muxika et al., 2007) and BO2A (Benthic Opportunistic Polychaete Amphipods index; Dauvin and Ruellet, 2009); B) index based on diversity: H' (Shannon-Wiener index; Shannon, 1948); and C) index based on trophic groups: ITI (Infaunal Trophic Index; Mearns and Word, 1982). To compare the results, the environmental classification associated with the five EcoQs (ECOLOGICAL Quality Status) classes recommended by the WFD (Water Framework Directive) are used (“high”= unpolluted sites or normal; “good”= slightly polluted sites; “moderate”= Moderately polluted sites; “poor”= heavily polluted sites and “bad” for extremely polluted and azoic sites). The several ecological statuses considered for the selected benthic indicators come from: Borja et al. (2004) and Muxika et al. (2007) for AMBI and M-AMBI; Dauvin (2018) for BO2A (revisited from De-la-Ossa Carretero et al., 2010), Vincent et al. (2002) for H', and Bellan (2008) for ITI.

## 2. Results

Values are calculated for the six sub-indices and a score is assigned to each station; then, a final score is calculated for the index (D<sup>2</sup>SI). The scoring results are presented with the volumes of spoil dumped on both sites (Fig. 3).

The D<sup>2</sup>SI-Benthos (D<sup>2</sup>SI<sub>B</sub>) scoring (Fig. 3 A) reveals an immediate impact of dumping on benthic communities, with an increase in score from 0 to 1 during dumping on MASED and from 0.25 to 1 on MABIO. The scores increase on both sites during dumping operations, thus reflecting an impact, and decrease during periods without dumping. At the end of the experiment, both sites show a score equal to 0, highlighting a cessation of the impact of dumping on the benthic communities. Nevertheless, on the MABIO site, the score increases after the cessation of dumping and takes several months to return to 0. The correlation coefficients between D<sup>2</sup>SI<sub>B</sub> and dumped volumes (Table 5) are 0.60 and 0.54 for the MABIO and MASED sites, respectively, which represent statistically significant values. D<sup>2</sup>SI<sub>B</sub> scoring variations are in agreement with the results of Marmin (2013) and Pezy et al. (2017, 2018),

435 who have highlighted the impact of dumping on benthic communities of Machu site, finding a  
436 higher taxonomic richness and abundances before and after dumping in comparison to the  
437 dumping period, which is associated with lower values. The dumping impact is correctly  
438 identified by the higher  $D^2SI_B$  values

439 The  $D^2SI$ -Sediment ( $D^2SI_S$ ) scoring for MABIO and MASED (Fig. 3C) shows a  
440 modification in sediments characterized by an increase of score during the dumping period.  
441 The score is 0 before dumping for both sites but increases rapidly after the first dumping  
442 operation (score= 1). Although variations in this sub-index are observed, the scores remain  
443 relatively high throughout the dumping period. The scores observed after cessation of  
444 experimental dumping are high, reflecting a persistent impact. These scores are in agreement  
445 with variations in observed fine particle percentages. On the MABIO site, the average  
446 percentage of fine particles measured ( $< 63 \mu\text{m}$ ) before, during and after dumping operations  
447 are, respectively, 0.4%, 21.2% and 10.5% on impacted stations and only 0.9%, 3.2% and  
448 1.8% on unimpacted stations. On the MASED site, the average percentage of fine particles ( $<$   
449  $63 \mu\text{m}$ ) measured before, during and after dumping operations are, respectively, 4.3%; 20.7%  
450 and 11.7% on impacted station, and only 0.7%, 2.4% and 0.6% on unimpacted station. The  
451 increase of the percentage of fine particles is clearly observed on the impacted zone of the  
452 MABIO and MASED sites during dumping operations (21.2% and 20.7%), and remains high  
453 after cessation of dumping (10.5% and 11.7%). The  $D^2SI_S$  score correctly reflects the  
454 sedimentary modification caused by the inputs of fine particles during dumping operations  
455 and the persistent impact after dumping operations. However, there is no direct correlation  
456 between the  $D^2SI_S$  and dumped volumes (-0.098 on MABIO and 0.25 on MASED; Table 5),  
457 since this sub-index is not linked to the deposited volumes but rather the difference between  
458 original and deposit types of sediment surface.

459 The  $D^2SI$ -Thickness ( $D^2SI_T$ ) score highlights a gradual increase of sedimentary  
460 thickness, characterized by a gradual increase of values, especially for the MASED site (Fig.3  
461 D), which shows a stronger increase in the score (0 before dumping and 1 from the third  
462 operation, on the MASED site), in comparison to the MABIO site (0 before dumping, 0.5  
463 from the second operation). At the end of the experiment, the score for the MASED site is  
464 higher than for the MABIO site (respectively, 0.50 and 0.25). In addition, the  $D^2SI_T$  allows us  
465 to differentiate both dumping methods and reflects the two different impacts produced. These  
466 high scores observed on MASED site are linked to the experimental dumping method, which  
467 consists of creating a conical deposit on the impacted zone (initial bathymetry: 16.4 m;  
468 bathymetry on the last survey: 12.2 m). This contrasts with the MABIO site, where the

469 sediment was spread out over a rectangular area on the impacted zone (initial bathymetry:  
470 14.3 m; bathymetry on the last survey: 12.2 m). In the same way as described for the previous  
471 sub-index,  $D^2SI_T$  is not directly correlated with dumped volumes (0.14 on MABIO and 0.12  
472 on MASED; Table 5), but reflects the dumping method used.

473 The scores obtained for the other sub-indices,  $D^2SI_I$ ,  $D^2SI_R$  and  $D^2SI_D$ , show few  
474 distinct trends (Fig. 3 B, E and F). The  $D^2SI_I$  scores are low during the main dumping periods  
475 (0-0.25) and high after dumping operations (0.50-1), with large fluctuations (Fig. 3B) but no  
476 apparent link with dumping operations or dumped volumes (Table 5). In the same way, the  
477  $D^2SI_R$  and  $D^2SI_D$  scores are difficult to understand, with very high values for  $D^2SI_R$ , for both  
478 sites, before and after the dumping operations (Fig.3 E) and no significant correlations with  
479 dumped volumes (-0.083 for MABIO and -0.21 for MASED; Table 5).  $D^2SI_D$  shows clearer  
480 trends (Fig. 3F), with increased scores during dumping operations for both sites, but with  
481 many fluctuations during and after dumping operations and no significant correlations with  
482 dumped volumes (0.27 for MABIO and 0.35 for MASED; Table 5).

483 Finally, the final score ( $D^2SI$ ) on MABIO and MASED sites (Fig. 3G, H) shows low  
484 values before dumping operations (respectively, 0.25 and 0.20; site classified as Slightly  
485 disturbed) in comparison with values during deposition of spoil (max 0.85 in July, 2012 and  
486 January 2013 and min 0.60 in November 2012 on the MABIO site; max 0.80 in January 2013  
487 and min 0.65 in June 2012), which yields classification of site as Heavily disturbed to  
488 Extremely disturbed. After, several months without dumping operations, the scores return to  
489 relatively low values (0.35 for MABIO and 0.45 for MASED), the sites being classified as  
490 Slightly disturbed on MABIO and Moderately disturbed on MASED. These results highlight  
491 the persistence of the impact following spoil deposition, with a higher impact on the conical  
492 site (MASED). A non-parametric Kruskal-Wallis test and multiple comparison tests were  
493 carried out on the MABIO and MASED data to study score differences between the three  
494 periods. These tests reveal significant differences between  $D^2SI$  before-during dumping and  
495 before-after dumping (KW test = 8.964; df = 2, p-value = 0.011). However, many fluctuations  
496 are observed, with poor correlations between the final index and the dumped volumes (0.13  
497 on MABIO and 0.39 on MASED; Table 5).

498

#### 499 **4. Discussion**

500

501 The BACI method conducted on the experimental Machu site allows to identify the  
502 link between the pressures induced by sediment deposal at sea and various physical and



503 biological parameters of the environment (Marmin, 2013; Marmin et al., 2016; Pezy et al.,  
504 2017, 2018). The data collected on this site are favourable to the development and the test of  
505 new indicators as a textbook case. Based on the data collected from this site, we propose an  
506 integrative approach, coupling biological and physical data, to assess the impact of dumping  
507 operations, *via* a new multicriteria index: The Dredge Disposal Sediment Index (D<sup>2</sup>SI).

508

#### 509 4.1. Dumping impact on Machu site

510

511 Previous studies have highlighted the impact caused by dumping operations on benthic  
512 macrofauna and the trophic web, as well as on physical and chemical conditions (Bolam et al.,  
513 2006; Ware et al., 2010; Marmin, 2013; Marmin et al., 2016; Pezy et al., 2017, 2018).

514 On the Machu site, on the one hand, taxonomic richness and abundances in the  
515 impacted zone are significantly lower than values obtained in the unimpacted zone (Marmin,  
516 2013; Marmin et al., 2016; Pezy et al., 2018). Changes in the species composition and  
517 abundances of the benthic community are observed during and after dumping operations.  
518 Before the dumping operation, there was a typical *Nephtys cirrosa* community in medium  
519 sand characterized by the polychaetes (*Magelona filiformis/johnstoni*, *Nephtys cirrosa*) and  
520 amphipods (*Megaluropus agilis*, *Urothoe elegans*,) as found in the eastern part of the Bay of  
521 Seine (Marmin, 2013). After dumping, the Machu site corresponds to a mixture of the  
522 *Nephtys cirrosa* and *Abra alba* communities in medium and muddy fine sand (with the  
523 bivalves *Phaxas pellucidus*, *Spisula subtruncata*, and the polychaete *Owenia fusiformis*;  
524 Marmin, 2013; Marmin et al., 2016; Pezy et al., 2018).

525 On the other hand, the study of food web modelling and the ENA (Ecological Network  
526 Analysis; Ulanowicz, 2004) carried out by Pezy et al. (2017, 2018) reveals changes in the  
527 food-web structure and functioning induced by dumping operations as well as the high  
528 resilience of the affected zones after a short dumping phase.

529 Regarding these results, the D<sup>2</sup>SI proposed here yields consistent results, with  
530 increased values during dumping and a persistent impact after dumping, highlighted by the  
531 maintenance of higher values than before the dumping experiment.

532

#### 533 4.2. Determining sub-indices

534

535 Among the six sub-indices proposed, three of them (D<sup>2</sup>SI<sub>B</sub>, D<sup>2</sup>SI<sub>S</sub> and D<sup>2</sup>SI<sub>T</sub>) allow to  
536 correctly highlight the impact caused by dumping at sea. These three sub-indices, which are

537 based on benthic abundances, sedimentary type and thickness of deposit, show an increase of  
538 scores according to the dumping periods. These three factors are determinant in calculating  
539 the final index score ( $D^2SI$ ), with significant correlations (respectively 0.69, 0.67 and 0.60 for  
540 MABIO and 0.80, 0.64 and 0.48 for MASED; Table 5). Moreover, they are significantly  
541 correlated with each other ( $D^2SI_B$ - $D^2SI_T$ : 0.51 and  $D^2SI_S$ - $D^2SI_T$ : 0.65 on MABIO;  $D^2SI_B$ -  
542  $D^2SI_T$ : 0.60 on MASED; Table 5), reflecting conjoint response to dumping operations.

543 Conversely, the sub-index based on ichthyofauna ( $D^2SI_I$ ) shows large temporal  
544 fluctuations (Fig. 3B) which affect the calculation of the final index score ( $D^2SI_I$ - $D^2SI$   
545 correlations: 0.16 on MABIO, no data on MASED; Table 5). In fact, the mobility of the  
546 ichthyofauna and the sparse knowledge of the consequences of dumping impacts on this  
547 compartment makes it difficult to establish a reliable index. The previous study on the  
548 MABIO site (no ichthyofauna data on MASED site) shows an increase in abundances and  
549 biomass of demersal fish during the dumping period, reflecting an attraction of surrounding  
550 populations (Pezy et al., 2018). This phenomenon has also been documented, before and after  
551 deposition from a sewage effluent outfall into the ocean at Hawaii (Russo, 1982) and suggests  
552 that changes in fish abundance are related to variations in the distribution and abundance of  
553 benthic preys (Spies, 1984). On the Machu site, dumping operations caused a modification of  
554 invertebrate benthic communities with high abundances of some dominant species (Marmin,  
555 2013), allowing a constant availability of prey. Moreover, the  $D^2SI_I$  results highlight the  
556 problem of selecting stations, which are rarely identical to those chosen for sampling of other  
557 compartments (invertebrate benthic macrofauna), which may introduce a bias into the study of  
558 a very local anthropogenic impact.

559 The choice of both biological traits (resistance to dumping of spoil and drifting) is  
560 based on a knowledge of the study site and the fact that several authors have hypothesized a  
561 specific modification of the combination of community life-history traits in disturbed  
562 ecosystems, depending on the nature and intensity of the disturbance (Stearns, 1976, 1977;  
563 Usseglio-Polatera et al., 2000; Bremner et al., 2003; Bolam et al., 2006a,b; Janson, 2007;  
564 Dauvin et al., 2017a,b). The capacity of invertebrate benthic species to resist the deposition of  
565 spoil sediment does not seem to be a determining factor to assess the impact of dumping on  
566 the studied site (low correlations with dumped volumes: -0.083 on MABIO and -0.21 on  
567 MASED and with  $D^2SI$ : 0.31 on MABIO and -0.064 on MASED). In fact, the benthic  
568 communities of the eastern part of the Bay of Seine are characterized by very resistant and  
569 resilient species, particularly well adapted to the particular oceanographic and anthropogenic  
570 conditions in this shallow coastal area (high-energy hydrodynamic regime, many anthropic

571 activities, frequent silt input, etc.; Marmin, 2013).  $D^2SI_R$  does not allow us to account for the  
572 impact caused by the increase in thickness of the sediment layer (negative correlations  
573 between  $D^2SI_T$  and  $D^2SI_R$ : -0.20 on MABIO and -0.18 on MASED; Table 5). Conversely, the  
574 sub-index based on capacity of drifting shows better correlations with  $D^2SI$  (0.62 on MABIO  
575 and 0.70 on MASED; Table 5), but the poor correlations with dumped volumes (Table 5) and  
576 with  $D^2SI_B$  (0.37 on MABIO and 0.42 on MASED; Table 5) suggest that this biological trait  
577 characterizes only a small number of species with high abundances on the studied site. On the  
578 Machu site, the ability of drifting has been observed in the bivalve *Abra alba* (Olivier et al.,  
579 1996), which has shown an immediate recolonization of the site, with high abundances of  
580 adults on the MABIO site in June 2012, just one month after the end of the first dumping  
581 phase (Marmin, 2013). The displacement of juveniles but also some adults drifting near the  
582 seabed can lead to a rapid colonization of defaunated and impacted zones in this eastern part  
583 of the Bay of Seine (Olivier et al., 1996). As the biological traits are variable from one site to  
584 another and from area to another in relation to local and general current conditions near the  
585 seabed, this sub-index appears inappropriate to assess the impact of dumping on the  $D^2SI$   
586 score.

587

#### 588 4.3. Additional approaches

589

590 In this study, we use a calculation test by adding different weighting coefficients for  
591 each sub-index according to the consistency of the data (x3 for  $D^2SI_B$ , x2 for  $D^2SI_S$  and  $D^2SI_T$ ,  
592 x1 for  $D^2SI_I$ ,  $D^2SI_D$  and  $D^2SI_R$ ). There is no statistical difference between the unweighted  
593 ( $D^2SI$ ) and the weighted ( $D^2SI_{weighted}$ ) indices for the MABIO and MASED sites (KW test=  
594 25.462; df= 16; p-value= 0.062) and both indices are significantly correlated (0.95 for  
595 MABIO and 0.95 for MASED; Table 5 and Fig. 4 A, B). Nevertheless,  $D^2SI$  is less strongly  
596 correlated with dumped volumes (0.13 on MABIO and 0.39 on MASED; Table 5) than  
597  $D^2SI_{weighted}$ . The weighted index shows higher correlations with dumped volumes, especially  
598 on the MASED site (0.25 on MABIO and 0.51 on MASED). By giving a greater weight to the  
599 scores of sub-indices based on benthic compartment, sedimentary and thickness modification  
600 included in the final index calculation, we can achieve a better assessment of the impact of  
601 dumping according to the dumped volumes (Fig. 4 A, B). However, in comparison with the  
602 results of statistical tests carried out on  $D^2SI$  for each dumping period (before, during and  
603 after dumping, presented in the Results section), the statistical tests on  $D^2SI_{weighted}$  for each  
604 dumping period only show differences between before-during dumping operations (KW test=

605 10.08;  $df= 2$ ;  $p\text{-value}= 0.007$ ). Therefore, the weighting of scores of sub-indexes yields a  
606 better correlation with the dumped volumes, but reduces the differences between scores after  
607 dumping periods, indicating a persistent impact.

608 In the light of the above observations,  $D^2SI$  is calculated using only the scores of  
609  $D^2SI_B$ ,  $D^2SI_S$  and  $D^2SI_T$  (considering unweighted scores for these three sub-indices), without  
610 including the scores of  $D^2SI_I$ ,  $D^2SI_R$  and  $D^2SI_D$  (Fig. 4 C, D). The resulting index is named  
611  $D^2SI_2$  (Fig. 1). Graphically, the absence of these three latter sub-indices changes the  
612 ecological classification status for MABIO (Fig. 4C) and MASED (Fig. 4D), with generally  
613 lower scores. The Kruskal-Wallis test highlights significant differences between the scores of  
614  $D^2SI$  and  $D^2SI_2$  ( $KW= 20.69$ ;  $df = 10$ ;  $p\text{-value} = 0.02$ ). Correlations between  $D^2SI_2$  and  
615 dumped volumes are stronger, especially on the MASED site (0.31 on MABIO and 0.54 on  
616 MASED; Table 5), in comparison with correlations between dumped volumes and original  
617 index ( $D^2SI$ ) or between dumped volumes and weighted index ( $D^2SI_{\text{weighted}}$ ; Table 5). As with  
618 the previous index, the statistical tests on  $D^2SI_2$  for each dumping period only show  
619 differences between before-during dumping operations ( $KW\text{ test}= 10.679$ ;  $df= 2$ ;  $p\text{-value}=$   
620  $0.005$ ), indicating a persistent impact. Therefore, the index calculated without considering  
621 ichthyofauna and biological traits of the macrofauna allows a better assessment of the  
622 environmental impact caused by dumping operations.

623

#### 624 4.4. Biotic indices comparison

625

626 In comparison with other biotic indices based on species classification in ecological  
627 group (AMBI, M-AMBI, BO2A), on diversity ( $H'$ ) and on trophic groups (ITI), the  $D^2SI$  is  
628 specific to dumping impact and allows a better categorization of this impact (Table 6). In fact,  
629 all index mean values obtained for the Machu site correspond to “very good” and “good”  
630 ecological status, before, during and after dumping (except for ITI value before dumping on  
631 MASED site). These results characterize the Machu site as being unpolluted (or normal, with  
632 ITI classification) to slightly stressed, whatever the period studied (Table 6). Conversely,  
633  $D^2SI$  and  $D^2SI_2$  mean values classifies the impact as ranging from Undisturbed to Moderately  
634 disturbed before dumping, Heavily disturbed during and after dumping operations (on non-  
635 average  $D^2SI$  values, during dumping: from Moderately to Extremely disturbed; after  
636 dumping: Slightly to Extremely disturbed; Fig. 3). Also,  $D^2SI$  and  $D^2I_2$  differentiates periods  
637 before dumping from other periods and reflecting the impact caused by physical and  
638 biological modifications.

639

#### 640 4.5. Further work

641

642 After developing D<sup>2</sup>SI on the Machu experimental site in full compliance with the  
643 BACI approach, this index is being tested on two other dumping sites in eastern part of the  
644 Bay of Seine: Octeville (used by Le Havre harbour) and Kannik (used by Rouen harbour; Fig.  
645 2). These sites differ from the Machu site because they have been used historically (from  
646 1947 for Octeville and from 1977 to 2015 for Kannik), with higher accumulated dumped  
647 volumes (mean of  $2\text{-}2.5 \times 10^6 \text{ m}^3 \cdot \text{y}^{-1}$  on the Octeville site and  $3.5\text{-}4 \times 10^6 \text{ m}^3 \cdot \text{y}^{-1}$  on the Kannik  
648 site). The application of D<sup>2</sup>SI to these two dumping sites leads to more complicated  
649 understanding in comparison with the textbook case of the experimental Machu site,  
650 especially due to: (1) a lack of initial data conditions, before the beginning of spoil deposition  
651 (especially on the Octeville site); (2) a lack of accurate and regularly sampled bathymetric  
652 data (or data only available from stations without initial conditions) and (3) spatial and  
653 temporal gaps between samplings. These elements are quite often lacking in surveys of  
654 French dumping sites, thus preventing a precise study of the impact caused by harbour  
655 dumping activities and the use of the D<sup>2</sup>SI multicriteria index. To use this index for other  
656 dumping sites, it would be necessary to acquire regular data on impacted and unimpacted  
657 zones, and to have at least some information on macrofauna, bathymetry and sediment  
658 composition as a function of time.

659

#### 660 5. Conclusion

661

662 An integrative approach is proposed, using a new multicriteria approach, the Dredge  
663 Disposal Sediment Index (D<sup>2</sup>SI), to assess the impact of dumping and attribute a degree of  
664 impact according to the pressure undergone by the system. This index is developed on the  
665 experimental Machu site in the eastern part of the Bay of Seine. The appropriate assessment  
666 of the impacts of dumping on this experimental site and application of the BACI approach  
667 allow to differentiate three distinct periods (before, during and after dumping; Marmin et al.  
668 2016; Pezy et al, 2017, 2018). The assessment of the impact of dumping at the Machu site  
669 offers a textbook example that appears very favourable for the development of a new index  
670 designed to measure the response of the benthic environment to the pressure of dumping  
671 dredge spoil.

672 The D<sup>2</sup>SI is calculated by considering impacted (under the direct influence of harbour  
673 sediment disposal) and unimpacted stations (without direct or indirect influence of the  
674 harbour sediment disposal) and is composed of six sub-indices that take into account the  
675 biological and physical impacts generated by dredge disposal at sea (integrating data on  
676 benthic macrofauna, demersal fish, sedimentary types, bathymetry, resistance to dredge  
677 sediment deposition and drifting capacity). A final score is calculated using each sub-index,  
678 allowing us to classify the disturbance. In the absence of data on ichthyofauna and biological  
679 traits of life of macrobenthic fauna, an additional approach (D<sup>2</sup>SI<sub>2</sub>) shows that results based  
680 on only three sub-indices, including at least benthic macrofauna, sedimentary types and  
681 thickness, appear sufficient surrogate to provide a similar assessment of dumping pressure.

682 The first application of the D<sup>2</sup>SI to the Machu site yields a good estimation of the  
683 dumping impact, in comparison with other biotic indices (AMBI, M-AMBI, etc.; Pezy et al.,  
684 2018). The D<sup>2</sup>SI and D<sup>2</sup>SI<sub>2</sub> indexes highlight the disturbance induced by dumping at the  
685 beginning of sediment deposition, with an increase in their values as well as the degree of  
686 associated impact. The multicriteria index also allows to highlight the persistence of the  
687 impact after cessation of deposition, while comparing the different methods of dumping  
688 (spread out or concentrated deposit) and shows a return to the values before dumping two  
689 years after the end of the pressure.

690 In the future, depending on the availability of data, the D<sup>2</sup>SI or D<sup>2</sup>SI<sub>2</sub> indexes should  
691 be tested on other dumping sites to estimate its robustness and with a view to comparing the  
692 assessment of the impact of this human activity. The present study opens up prospects for the  
693 development of multicriteria indices as well as indices that are specific of dumping impact.

694

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696

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942

943 **Figure captions**

944

945 Fig. 1: D<sup>2</sup>SI and D<sup>2</sup>SI<sub>2</sub> workflow. A: abundances; S: specific richness; I: impacted  
946 station; U: unimpacted station; G: group; +: addition (see text for other explanations).

947 Fig. 2. Map of the eastern part of the Bay of Seine showing location of the Machu  
948 experimental dredge spoil disposal zone. Distribution of sampling stations (point: benthic  
949 macrofauna and sediment; line: ichthyofauna) over the two dumping sites (MASED and  
950 MABIO). In red: impacted stations; in blue: unimpacted stations.

951 Fig. 3. Sub-indices and final index scores (black and red points) with standard  
952 deviation (error bars on G and H, calculated with n=6 for D<sup>2</sup>SI MABIO and n=5 for D<sup>2</sup>SI  
953 MASED, for each period. No error bars in graphs A to F because n=1 for each period) for  
954 each survey and cumulated dumped volumes (m<sup>3</sup>; histograms), for MABIO and MASED  
955 sites. MABIO and MASED points can be superimposed. The y-axis and x-axis are the same  
956 for each graph.

957

958 Fig. 4. A and B: comparison between D<sup>2</sup>SI and D<sup>2</sup>SI<sub>weighted</sub> (calculated with different  
959 degrees of weighting for each sub-index); C and D: comparison between D<sup>2</sup>SI and D<sup>2</sup>SI<sub>2</sub>  
960 (calculated without D<sup>2</sup>SI<sub>I</sub>, D<sup>2</sup>SI<sub>R</sub> and D<sup>2</sup>SI<sub>D</sub>), for each survey with cumulated dumped  
961 volumes (m<sup>3</sup>; Histograms), for MABIO and MASED sites. Standard deviation is illustrated by  
962 error bars and calculated for each period with n=6 for D<sup>2</sup>SI and D<sup>2</sup>SI<sub>weighted</sub> MABIO; n=5 for  
963 D<sup>2</sup>SI and D<sup>2</sup>SI<sub>weighted</sub> MASED; n=3 for D<sup>2</sup>SI<sub>2</sub> MABIO and MASED. The y-axis and x-axis are  
964 the same for each graph.

965

966 **Table captions**

967

968 Table 1: Ratio, threshold and scores for species used in calculation of D<sup>2</sup>SI-Benthos  
969 and D<sup>2</sup>SI-Ichthyofauna [from DSD index (Dauvin *et al.*, 2018)]. Example for reading  
970 assistance: a score of 1 indicates high abundances at impacted stations (abundance at  
971 unimpacted samples is ten times higher than those at impacted samples).

972 Table 2. D<sup>2</sup>SI-B and D<sup>2</sup>SI-I score and site disturbance classification.

973

974 Table 3. D<sup>2</sup>SI<sub>S</sub>, D<sup>2</sup>SI<sub>T</sub>, D<sup>2</sup>SI<sub>R</sub> and D<sup>2</sup>SI<sub>D</sub> scores associated with results of calculation  
975 and site disturbance classification.

976

977 Table 4. D<sup>2</sup>SI results of calculation and site disturbance classification.

978

979 Table 5: Spearman's correlation coefficients and significance tests (p-value 0: \*\*\*; 0.001:  
980 \*\*: 0.05: \*; 0.1: ' ) between each sub-index, final D<sup>2</sup>SI and dumped volumes, for MABIO and  
981 MASED sites. D<sup>2</sup>SI<sub>weighted</sub>: final index with weighting coefficient; D<sup>2</sup>SI<sub>2</sub>: final index  
982 calculation without scores integrating D<sup>2</sup>SI<sub>I</sub>, D<sup>2</sup>SI<sub>R</sub> and D<sup>2</sup>SI<sub>D</sub>; Volumes: *in situ* dumped  
983 volumes. Numbers in bold: significant values. In red: p-value.

984

985 Table 6: Ecological indicators mean values and environmental classification (EcoQS) for  
986 MABIO and MASED sites according to dumping periods (before, during and after dumping)  
987 and considered stations (AK4 A, C, D, F and AK7 A, D). The several ecological statuses  
988 considered for the selected benthic indicators come from: Borja et al. (2004) and Muxika et al.  
989 (2007) for AMBI and M-AMBI; Dauvin (2018) for BO2A (revisited from De-la-ossa  
990 Carretero et al., 2010), Vincent et al. (2002) for H'and Bellan (2008) for ITI. Colours  
991 correspond to the WFD classification.

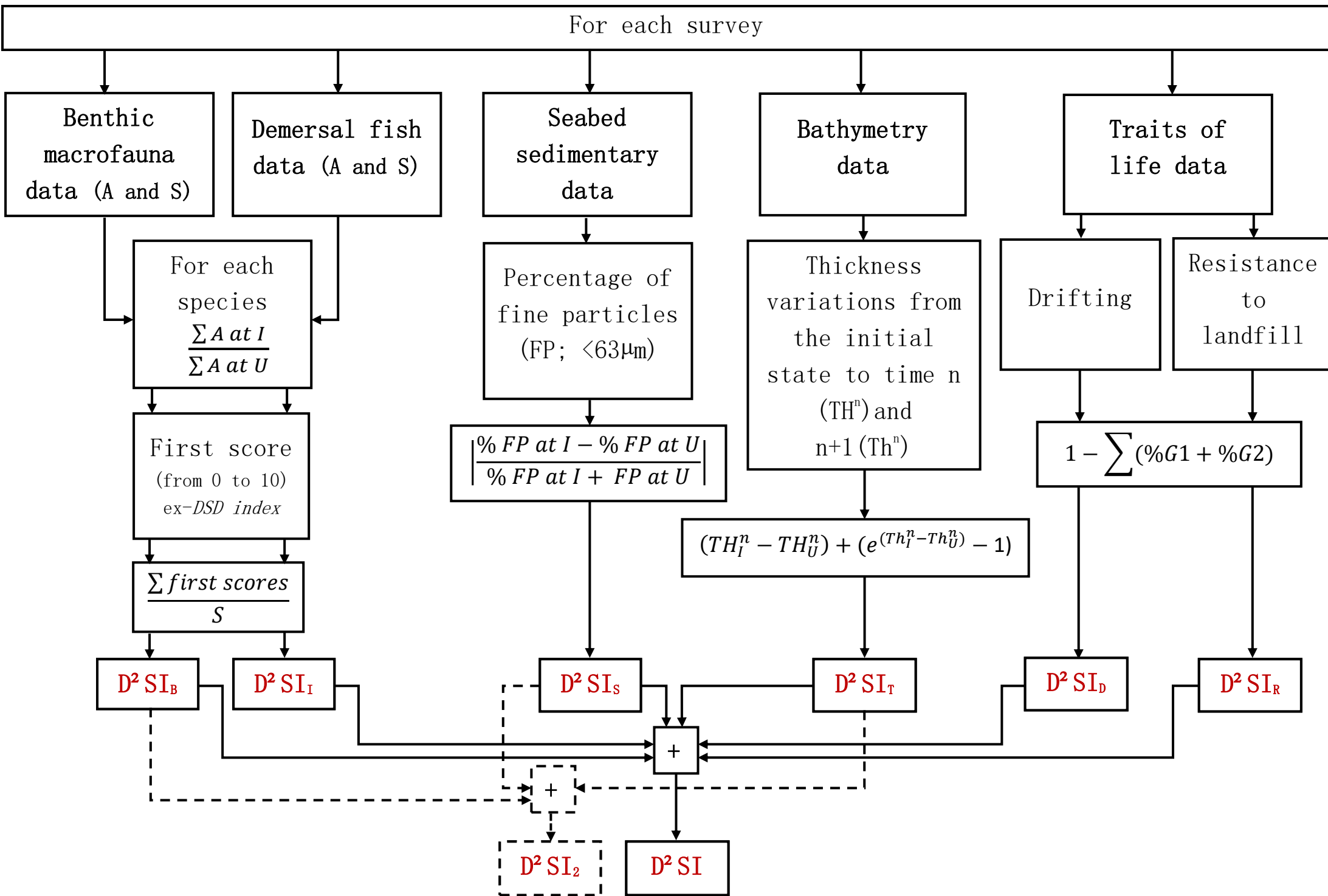


Fig. 1: D<sup>2</sup>SI and D<sup>2</sup>SI<sub>2</sub> workflow. A: abundances; S: specific richness; I: impacted station; U: unimpacted station; G: group; +: addition (see text for other explanations).

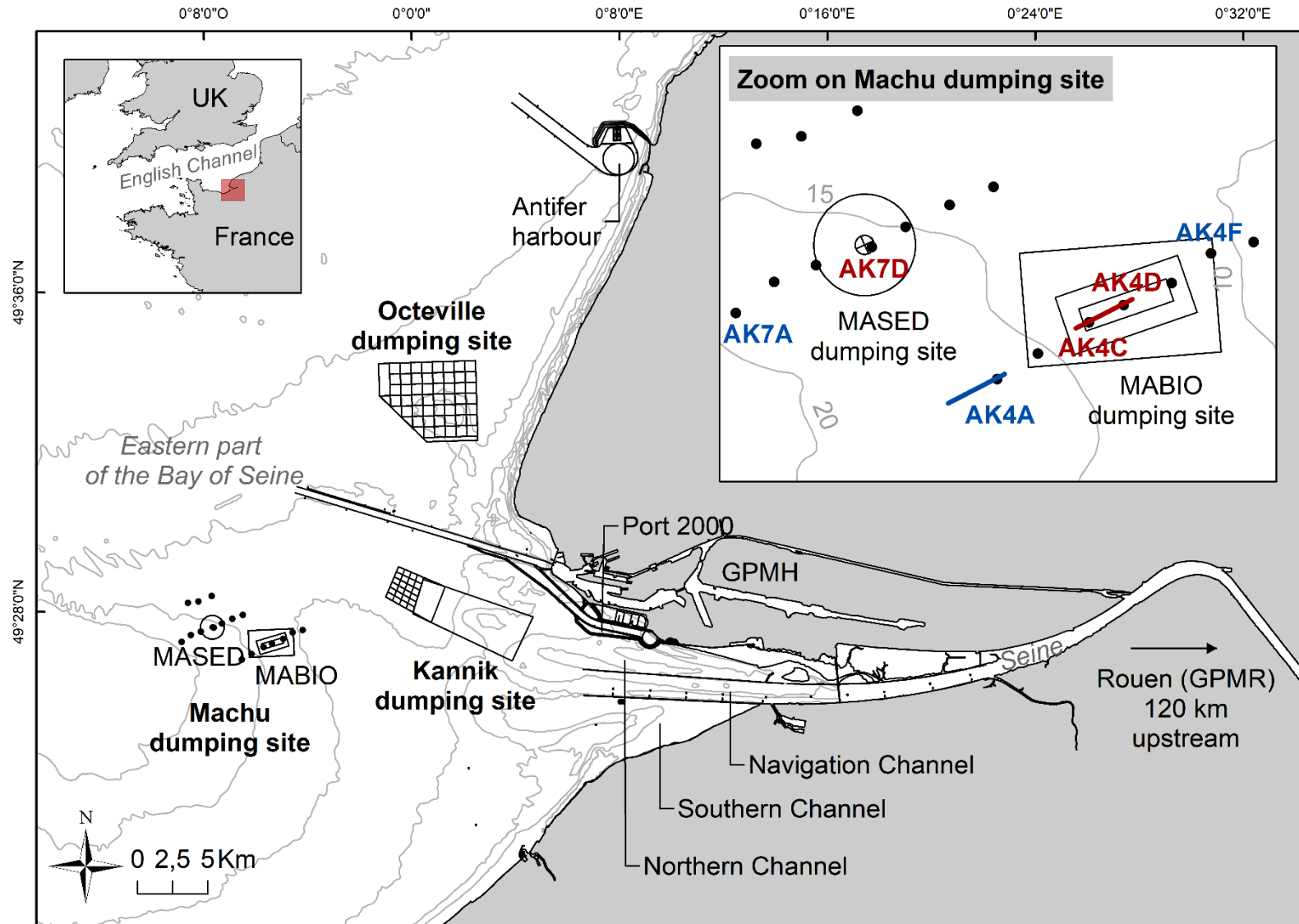


Fig. 2. Map of the eastern part of the Bay of Seine showing location of the Machu experimental dredge spoil disposal zone. Distribution of sampling stations (point: benthic macrofauna and sediment; line: ichthyofauna) over the two dumping sites (MACHED and MABIO). In red: impacted stations; in blue: unimpacted stations.

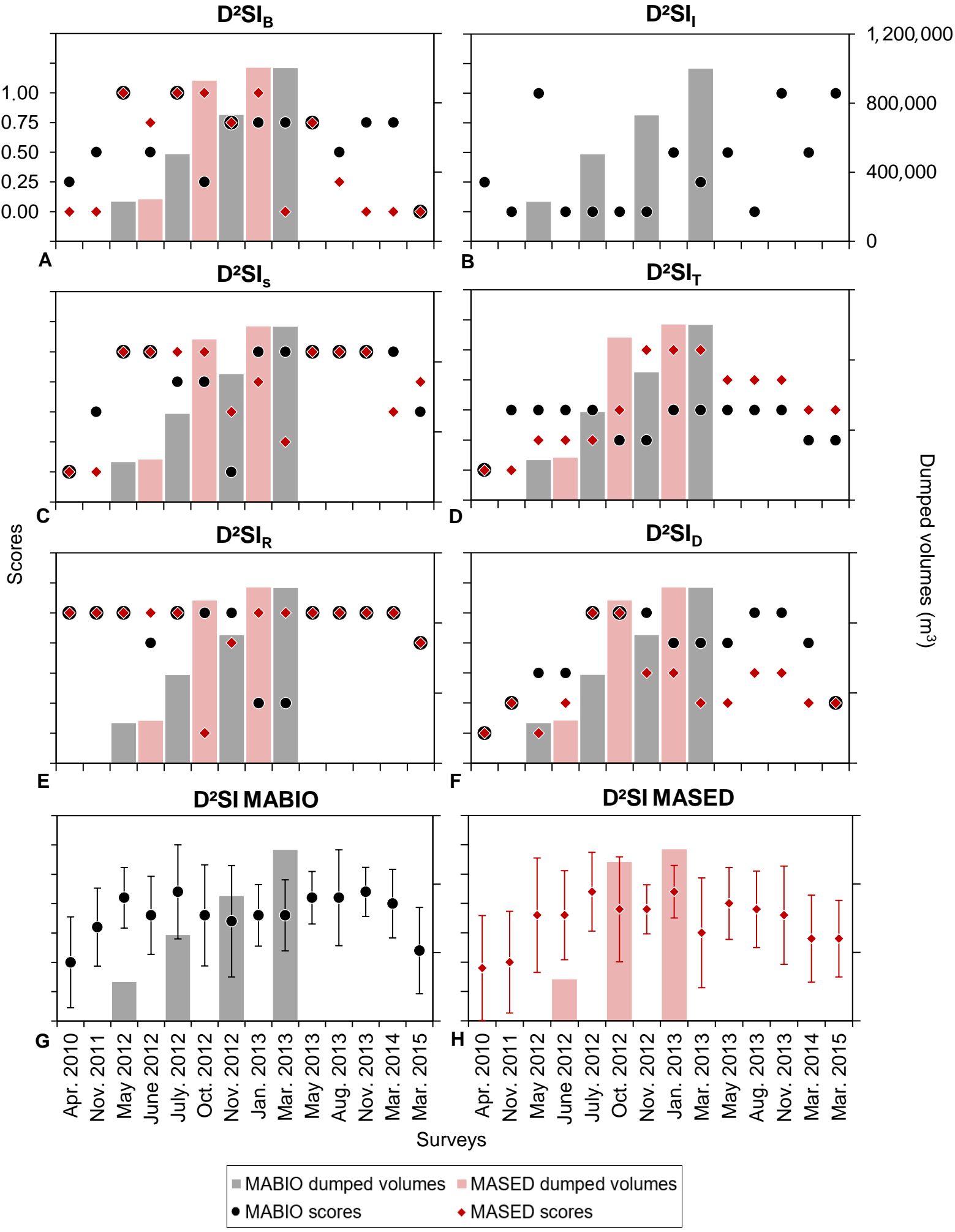


Fig. 3. Sub-indices and final index scores (black and red points) with standard deviation (error bars on G and H, calculated with  $n=6$  for  $D^2SI$  MABIO and  $n=5$  for  $D^2SI$  MASED, for each period. No error bars in graphs A to F because  $n=1$  for each period) for each survey and cumulated dumped volumes ( $m^3$ ; histograms), for MABIO and MASED sites. MABIO and MASED points can be superimposed. The y-axis and x-axis are the same for each graph.



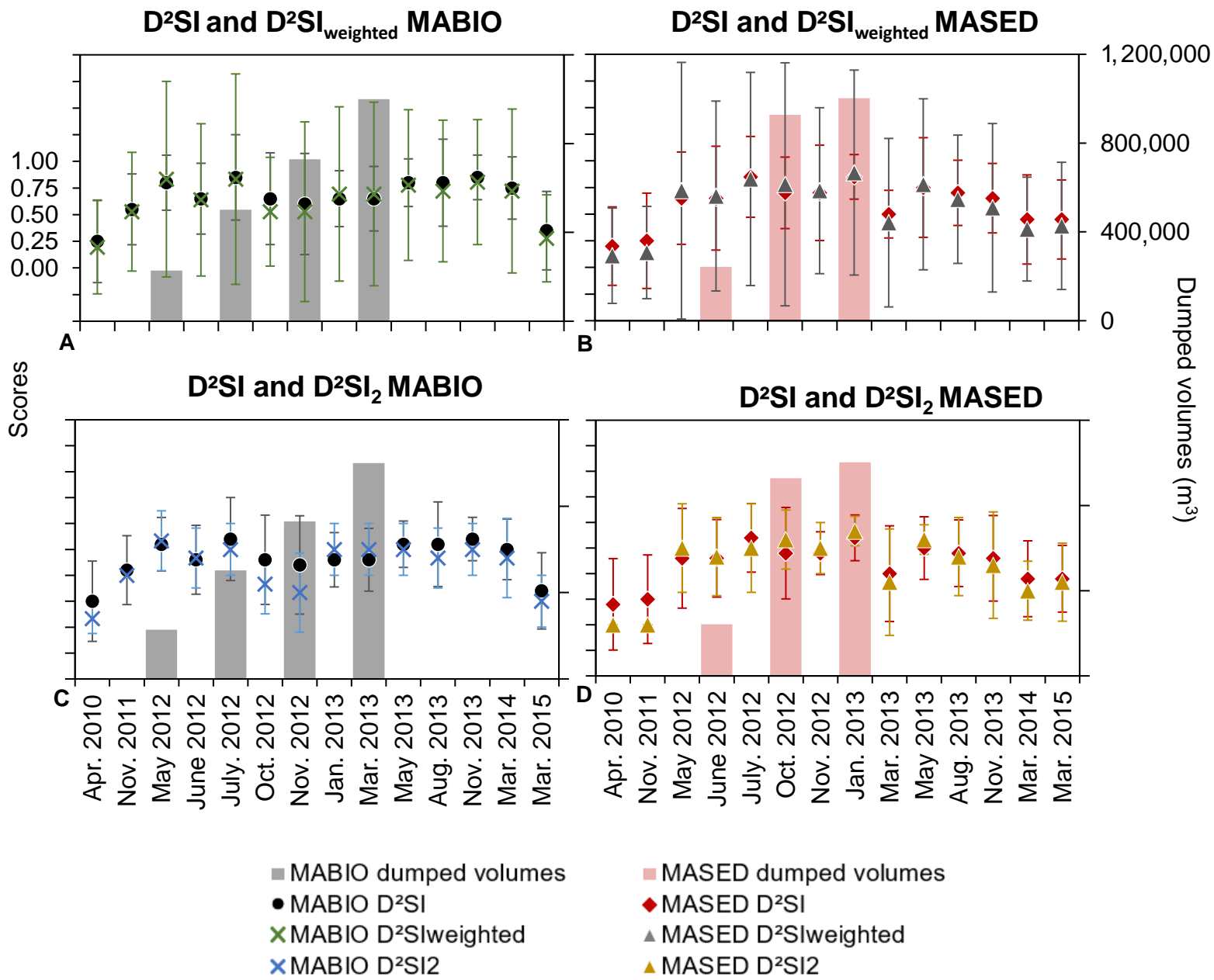


Fig. 4. A and B: comparison between  $D^2SI$  and  $D^2SI_{weighted}$  (calculated with different degrees of weighting for each sub-index); C and D: comparison between  $D^2SI$  and  $D^2SI_2$  (calculated without  $D^2SI_I$ ,  $D^2SI_R$  and  $D^2SI_D$ ), for each survey with cumulated dumped volumes ( $m^3$ ; Histograms), for MABIO and MASED sites. Standard deviation is illustrated by error bars and calculated for each period with  $n=6$  for  $D^2SI$  and  $D^2SI_{weighted}$  MABIO;  $n=5$  for  $D^2SI$  and  $D^2SI_{weighted}$  MASED;  $n=3$  for  $D^2SI_2$  MABIO and MASED. The y-axis and x-axis are the same for each graph.

Table 1: Ratio, threshold and scores for species used in calculation of D<sup>2</sup>SI-Benthos and D<sup>2</sup>SI-Ichthyofauna [from DSD index (Dauvin *et al.*, 2018)]. Example for reading assistance: a score of 1 indicates high abundances at impacted stations (abundance at unimpacted samples is ten times higher than those at impacted samples).

<b>Ratio</b> <b>Impacted/unimpacted</b>	<b>Group</b>	<b>Score for species</b>
Ratio = 0	Species found only at the unimpacted stations	10
0.2 ≥ Ratio	>5 times higher	9
0.2 < Ratio ≤ 0.4	>2.5–5 times higher	8
0.4 < Ratio ≤ 0.6	>1.75–2.5 times higher	7
0.6 < Ratio ≤ 0.8	>1.25–1.75 times higher	6
0.8 < Ratio ≤ 1	>1–1.25 times higher	5
1 < Ratio ≤ 2	>1–2 times lower	4
2 < Ratio ≤ 4	>2–4 times lower	3
4 < Ratio ≤ 10	>4–10 times lower	2
10 < Ratio	>10 times lower	1
Ratio not calculable	Species absent from unimpacted stations and present only at impacted stations	0

Table 2:  $D^2SI_B$  and  $D^2SI_I$  score and site disturbance classification.

<b>Score for species / taxonomic richness</b>	<b><math>D^2SI_B</math> and <math>D^2SI_I</math> Score</b>	<b>Site disturbance classification</b>
[10 - 8]	1	Extremely disturbed
]8 - 7]	0.75	Heavily disturbed
]7 - 6.5]	0.5	Moderately disturbed
]6.5 - 6]	0.25	Slightly disturbed
]6 - 4]	0	Undisturbed
]4 - 3.5]	0.25	Slightly disturbed
]3.5 - 3]	0.50	Moderately disturbed
]3 - 2]	0.75	Heavily disturbed
]2 - 0]	1	Extremely disturbed

Table 3: D<sup>2</sup>SI<sub>S</sub>, D<sup>2</sup>SI<sub>T</sub>, D<sup>2</sup>SI<sub>R</sub> and D<sup>2</sup>SI<sub>D</sub> scores associated with results of calculation and site disturbance classification.

<b>Index</b>	<b>Results of calculation</b>	<b>Score</b>	<b>Site disturbance classification</b>
D <sup>2</sup> SI <sub>S</sub>	[0 - 0.1[	0	Undisturbed
	[0.1 - 0.3[	0.25	Slightly disturbed
	[0.3 - 0.5[	0.50	Moderately disturbed
	[0.5 - 0.7[	0.75	Heavily disturbed
	> 0.7	1	Extremely disturbed
D <sup>2</sup> SI <sub>T</sub>	≤ 0	0	Undisturbed
	[0 - 2[	0.25	Slightly disturbed
	[2 - 4[	0.50	Moderately disturbed
	[4 - 6[	0.75	Heavily disturbed
	> 6	1	Extremely disturbed
D <sup>2</sup> SI <sub>R</sub> and D <sup>2</sup> SI <sub>D</sub>	[0- 0.1[	0	Undisturbed
	[0.1 – 0.3[	0.25	Slightly disturbed
	[0.3 – 0.5[	0.50	Moderately disturbed
	[0.5 – 0.7[	0.75	Heavily disturbed
	[0.7 – 1]	1	Extremely disturbed

Table 4: Results of D<sup>2</sup>SI calculation and associated site disturbance classification.

<b>D<sup>2</sup>SI</b>	<b>Site disturbance classification</b>
[0 – 0.2[	Undisturbed
[0.2 – 0.4[	Slightly disturbed
[0.4 – 0.6[	Moderately disturbed
[0.6 – 0.8[	Heavily disturbed
[0.8 – 1]	Extremely disturbed

Table 5: Spearman's correlation coefficients and significance tests (p-value 0: \*\*\*; 0.001: \*\*; 0.05: \*; 0.1: ‘) between each sub-index, final D<sup>2</sup>SI and dumped volumes, for MABIO and MASED sites. D<sup>2</sup>SI<sub>weighted</sub>: final index with weighting coefficient; D<sup>2</sup>SI<sub>2</sub>: final index calculation without scores integrating D<sup>2</sup>SI<sub>I</sub>, D<sup>2</sup>SI<sub>R</sub> and D<sup>2</sup>SI<sub>D</sub>; Volumes: *in situ* dumped volumes. Numbers in bold: significant values. In red: p-value.

MASED	<b>D<sup>2</sup>SI<sub>B</sub></b>	0.20	0.44	<b>0.51</b>	0.13	0.37	<b>0.69</b>	<b>0.83</b>	<b>0.82</b>	<b>0.60</b>	MABIO
	NA	<b>D<sup>2</sup>SI<sub>I</sub></b>	0.34	0.00	-0.17	-0.28	0.16	0.27	0.35	-0.15	
	<b>0.60</b>	NA	<b>D<sup>2</sup>SI<sub>S</sub></b>	<b>0.65</b>	-0.26	0.22	<b>0.67</b>	<b>0.69</b>	<b>0.78</b>	-0.098	
	0.074	NA	0.072	<b>D<sup>2</sup>SI<sub>T</sub></b>	-0.20	0.18	<b>0.60</b>	<b>0.66</b>	<b>0.80</b>	0.14	
	-0.15	NA	-0.013	-0.18	<b>D<sup>2</sup>SI<sub>R</sub></b>	0.28	0.31	0.23	-0.11	-0.083	
	0.42	NA	0.40	0.41	-0.35	<b>D<sup>2</sup>SI<sub>D</sub></b>	<b>0.62</b>	0.45	0.27	0.27	
	<b>0.80</b>	NA	<b>0.64</b>	<b>0.48</b>	-0.064	<b>0.70</b>	<b>D<sup>2</sup>SI</b>	<b>0.95</b>	<b>0.79</b>	0.13	
	<b>0.91</b>	NA	<b>0.65</b>	0.38	-0.14	<b>0.59</b>	<b>0.95</b>	<b>D<sup>2</sup>SI<sub>weighted</sub></b>	<b>0.89</b>	0.25	
	<b>0.89</b>	NA	<b>0.64</b>	0.44	-0.23	<b>0.52</b>	<b>0.92</b>	<b>0.97</b>	<b>D<sup>2</sup>SI<sub>2</sub></b>	0.31	
	<b>0.54</b>	NA	0.25	0.12	-0.21	0.35	0.39	<b>0.51</b>	<b>0.54</b>	<b>Volumes</b>	

Table 6: Ecological indicators mean values and environmental classification (EcoQS) for MABIO and MASED sites according to dumping periods (before, during and after dumping) and considered stations (AK4 A, C, D, F and AK7 A, D). The several ecological statuses considered for the selected benthic indicators come from: Borja et al. (2004) and Muxika et al. (2007) for AMBI and M-AMBI; Dauvin (2018) for BO2A (revisited from De-la-ossa Carretero et al., 2010), Vincent et al. (2002) for H' and Bellan (2008) for ITI. Colours correspond to the WFD classification.

	AMBI		M-AMBI		BO2A		H'		ITI		D <sup>2</sup> SIF		D <sup>2</sup> SIF <sub>2</sub>		
	Values	EcoQS	Values	EcoQS	Values	EcoQS	Values	EcoQS	Values	EcoQS	Values	EcoQS	Values	EcoQS	
<b>MASED</b>	<b>Before</b>	1.10	Undisturbed	0.75	Slightly	0.0035	Undisturbed	4.81	Undisturbed	59	Perturbed	0.4	Moderately	0.0	Undisturbed
	<b>During</b>	1.10	Undisturbed	0.81	Undisturbed	0.0080	Undisturbed	4.78	Undisturbed	68	Normal	0.7	Heavily	0.7	Heavily
	<b>After</b>	1.23	Slightly	0.81	Undisturbed	0.0042	Undisturbed	4.83	Undisturbed	74	Normal	0.7	Heavily	0.6	Heavily
<b>MABIO</b>	<b>Before</b>	1.21	Slightly	0.71	Slightly	0.0088	Undisturbed	4.39	Undisturbed	62	Normal	0.2	Slightly	0.3	Slightly
	<b>During</b>	1.85	Slightly	0.74	Slightly	0.0289	Slightly	4.35	Undisturbed	70	Normal	0.7	Heavily	0.6	Heavily
	<b>After</b>	0.67	Undisturbed	0.76	Slightly	0.0078	Undisturbed	3.70	Slightly	84	Normal	0.6	Heavily	0.6	Heavily

