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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 (D²SI): a new specific multicriteria index to**
3 **assess the impact of harbour sediment dumping**

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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 (D²SI).
27 From the selection of two types of station: impacted and unimpacted, D²SI 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 D²SI 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 (D²SI₂) 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 D²SI or D²SI₂ 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 (D²SI)] is developed.
- 45 - D²SI 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 D²SI (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 (D²SI) concept*

121

122 The multicriteria D²SI 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 D²SI 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 (D²SI) 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 - D²SI-Benthos (D²SI_B), based on benthic macrofauna (invertebrates >1 mm), i.e.
135 presence of the species and their abundances.

- 136 - D²SI-Ichthyofauna (D²SI_I), based on demersal fish i.e. presence of the species and their
137 abundances.
- 138 - D²SI-Sediment (D²SI_S), based on the percentage of sediment modification between the
139 natural sediment before disposal and the deposited sediment after the disposal.
- 140 - D²SI-Thickness (D²SI_T), 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 - D²SI-Resistance to dredge spoil sedimentation (D²SI_R), based on the ability of species
144 to resist deposition of dredge spoil during harbour sediment disposal.
- 145 - D²SI-Drifting (D²SI_D), 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 D²SI index applications are available in
149 additional online data.

150

151 1.2. Dredge Disposal Sediment Index (D²SI) computation

152

153 1.2.1. D²SI-Benthos (D²SI_B)

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 D²SI-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. D²SI-Ichtyofauna (D²SI_I)*

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. D²SI-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 D²SI_S 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. D²SI-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 D²SI-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 ≤ 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 D²SI 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 D²SI score
308 of 0-0.2 corresponds to an undisturbed environment. The degree of impact increase gradually
309 up to a D²SI 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 D²SI. 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), 1x10⁶ m³ 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 m³
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 m³ 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 m², for a total of 0.3 m²; 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 D²SI scores were calculated from sub-indices scores
398 (D²SI_B, D²SI_I, D²SI_S, D²SI_T; D²SI_D and D²SI_R) at each survey for MABIO and MASED sites
399 and presented on figures 3 and 4.

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

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

402

403 1.6. Benthic indicators comparisons

404

405 The D²SI results and environmental classification were compared with other biotic
406 indices: A) indices based on species classification in ecological groups: AMBI (AZTI Marine
407 Biotic Index; Borja et al., 2000; Muxika et al., 2005), M-AMBI (modified AMBI; Muxika et
408 al., 2007) and BO2A (Benthic Opportunistic Polychaete Amphipods index; Dauvin and
409 Ruellet, 2009); B) index based on diversity: H' (Shannon-Wiener index; Shannon, 1948); and
410 C) index based on trophic groups: ITI (Infaunal Trophic Index; Mearns and Word, 1982). To
411 compare the results, the environmental classification associated with the five EcoQs
412 (ECOLOGICAL Quality Status) classes recommended by the WFD (Water Framework Directive)
413 are used (“high”= unpolluted sites or normal; “good”= slightly polluted sites; “moderate”=
414 Moderately polluted sites; “poor”= heavily polluted sites and “bad” for extremely polluted
415 and azoic sites). The several ecological statuses considered for the selected benthic indicators
416 come from: Borja et al. (2004) and Muxika et al. (2007) for AMBI and M-AMBI; Dauvin
417 (2018) for BO2A (revisited from De-la-Ossa Carretero et al., 2010), Vincent et al. (2002) for
418 H', and Bellan (2008) for ITI.

419

420 **2. Results**

421

422 Values are calculated for the six sub-indices and a score is assigned to each station;
423 then, a final score is calculated for the index (D²SI). The scoring results are presented with the
424 volumes of spoil dumped on both sites (Fig. 3).

425 The D²SI-Benthos (D²SI_B) scoring (Fig. 3 A) reveals an immediate impact of dumping
426 on benthic communities, with an increase in score from 0 to 1 during dumping on MASED
427 and from 0.25 to 1 on MABIO. The scores increase on both sites during dumping operations,
428 thus reflecting an impact, and decrease during periods without dumping. At the end of the
429 experiment, both sites show a score equal to 0, highlighting a cessation of the impact of
430 dumping on the benthic communities. Nevertheless, on the MABIO site, the score increases
431 after the cessation of dumping and takes several months to return to 0. The correlation
432 coefficients between D²SI_B and dumped volumes (Table 5) are 0.60 and 0.54 for the MABIO
433 and MASED sites, respectively, which represent statistically significant values. D²SI_B scoring
434 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 (D²SI).

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 D²SI 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 (D²SI_B, D²SI_S and D²SI_T) 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_{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 D²SI 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 D²SI 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 D²SI 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 (D²SI), 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 D²SI 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 (D²SI₂) 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 D²SI 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 D²SI and D²SI₂ 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 D²SI or D²SI₂ 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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707

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942

943 **Figure captions**

944

945 Fig. 1: D²SI and D²SI₂ 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 D²SI MABIO and n=5 for D²SI
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 (m³; 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 D²SI and D²SI_{weighted} (calculated with different
959 degrees of weighting for each sub-index); C and D: comparison between D²SI and D²SI₂
960 (calculated without D²SI_I, D²SI_R and D²SI_D), for each survey with cumulated dumped
961 volumes (m³; Histograms), for MABIO and MASED sites. Standard deviation is illustrated by
962 error bars and calculated for each period with n=6 for D²SI and D²SI_{weighted} MABIO; n=5 for
963 D²SI and D²SI_{weighted} MASED; n=3 for D²SI₂ 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 D²SI-Benthos
969 and D²SI-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. D²SI-B and D²SI-I score and site disturbance classification.

973

974 Table 3. D²SI_S, D²SI_T, D²SI_R and D²SI_D scores associated with results of calculation
975 and site disturbance classification.

976

977 Table 4. D²SI 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 D²SI and dumped volumes, for MABIO and
981 MASED sites. D²SI_{weighted}: final index with weighting coefficient; D²SI₂: final index
982 calculation without scores integrating D²SI_I, D²SI_R and D²SI_D; 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.

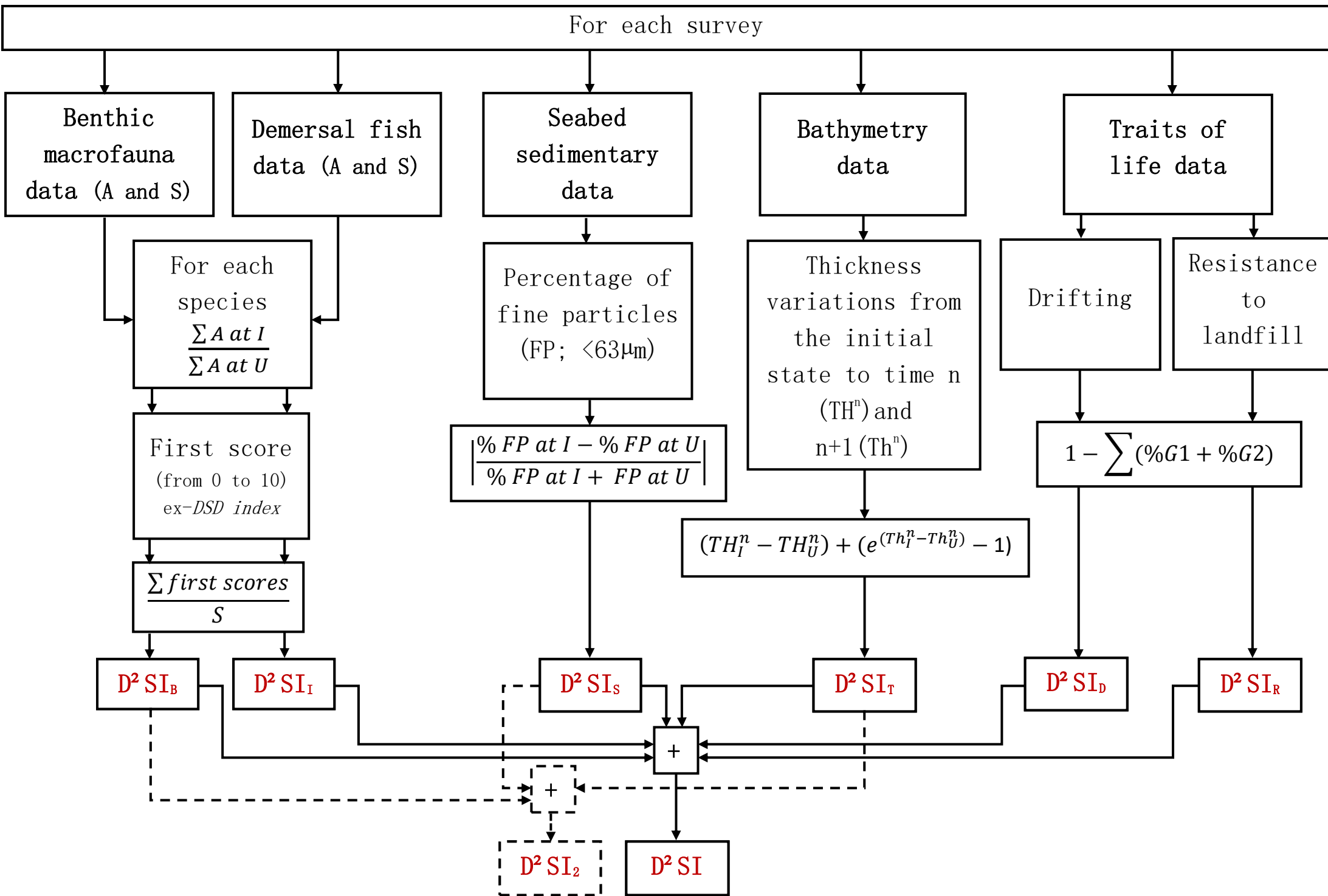


Fig. 1: D²SI and D²SI₂ workflow. A: abundances; S: specific richness; I: impacted station; U: unimpacted station; G: group; +: addition (see text for other explanations).

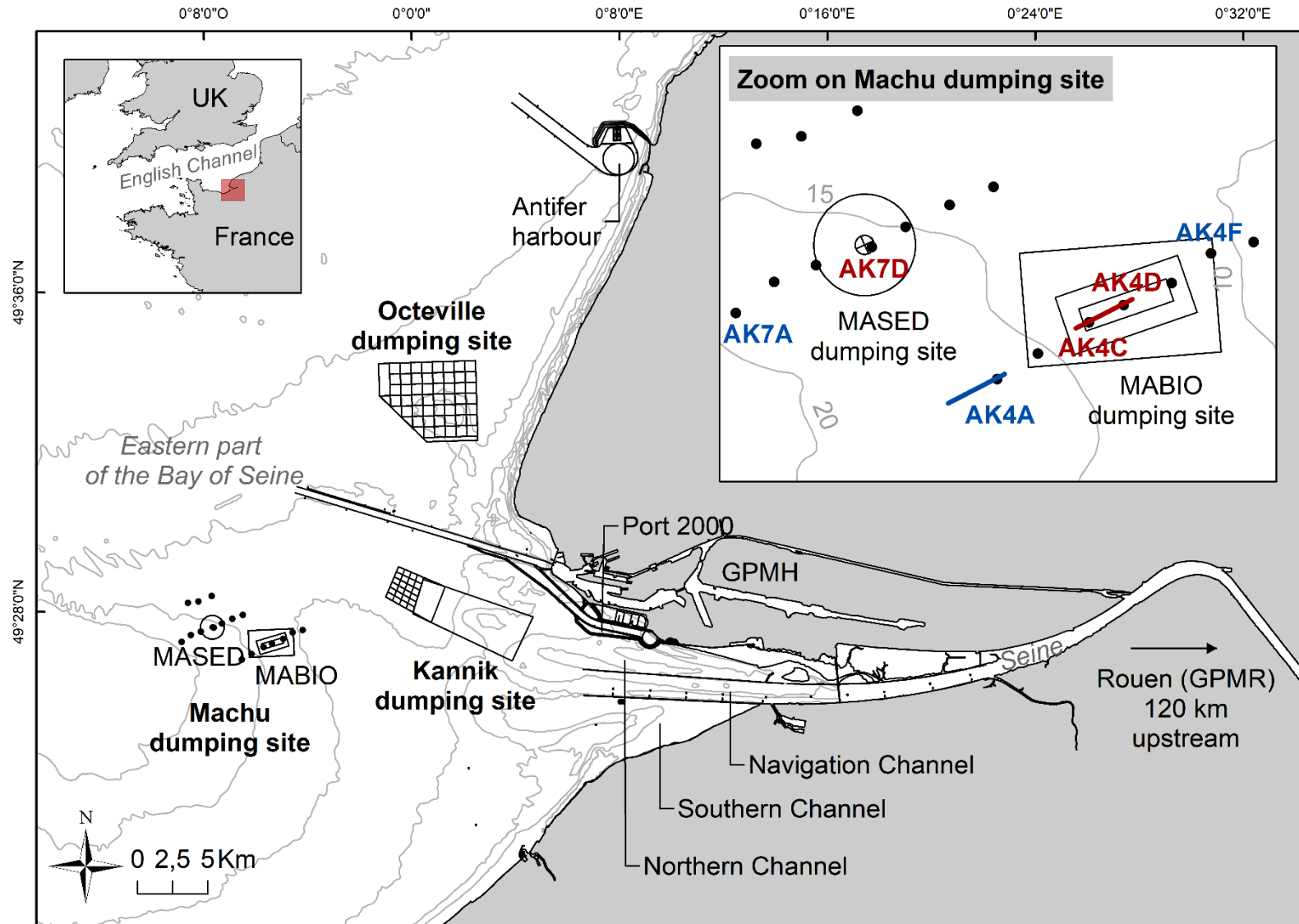


Fig. 2. Map of the eastern part of the Bay of Seine showing location of the Machu experimental dredge spoil disposal zone. Distribution of sampling stations (point: benthic macrofauna and sediment; line: ichthyofauna) over the two dumping sites (MACHED and MABIO). In red: impacted stations; in blue: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

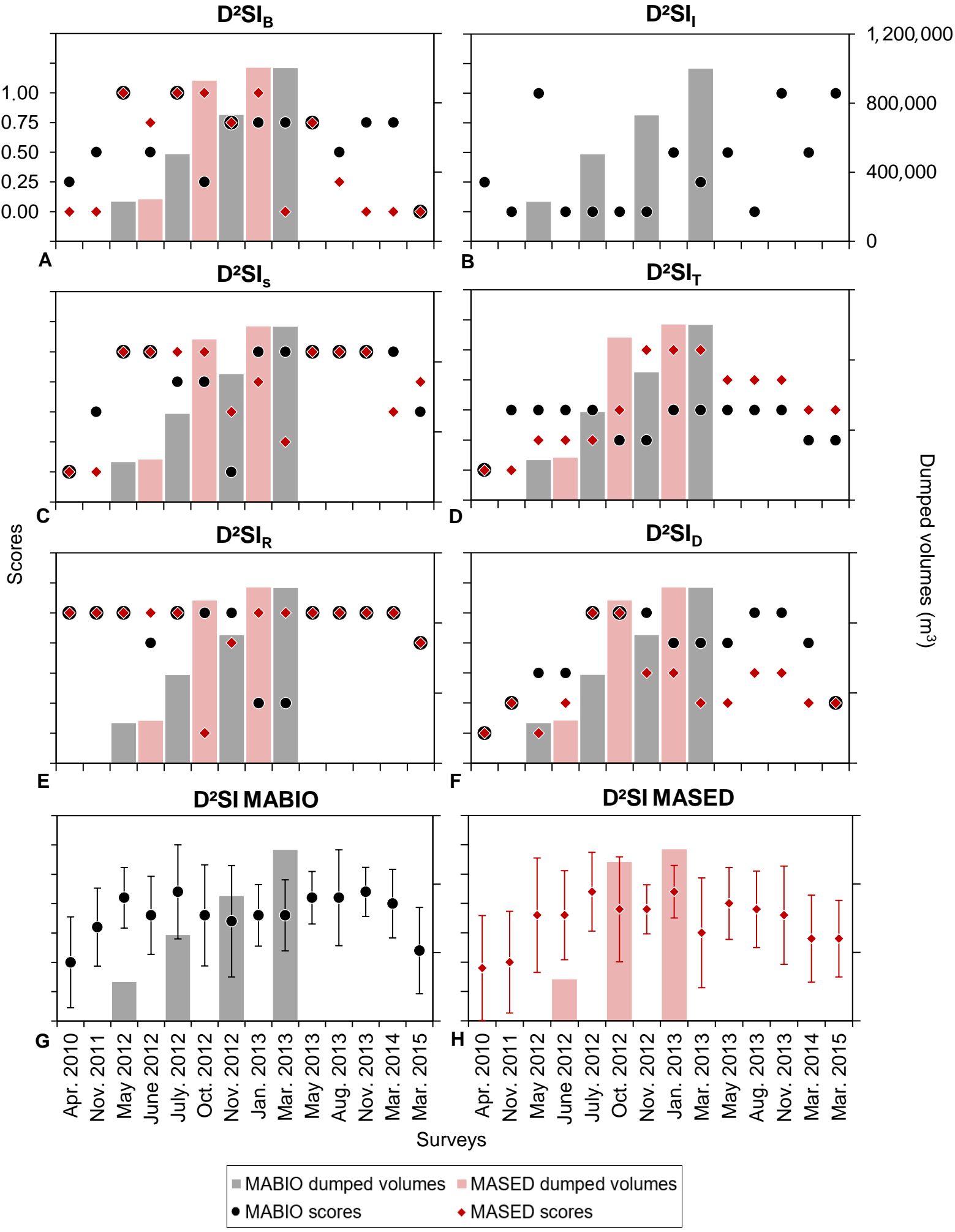


Fig. 3. Sub-indices and final index scores (black and red points) with standard deviation (error bars on G and H, calculated with $n=6$ for D^2SI MABIO and $n=5$ for D^2SI MASED, for each period. No error bars in graphs A to F because $n=1$ for each period) for each survey and cumulated dumped volumes (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.

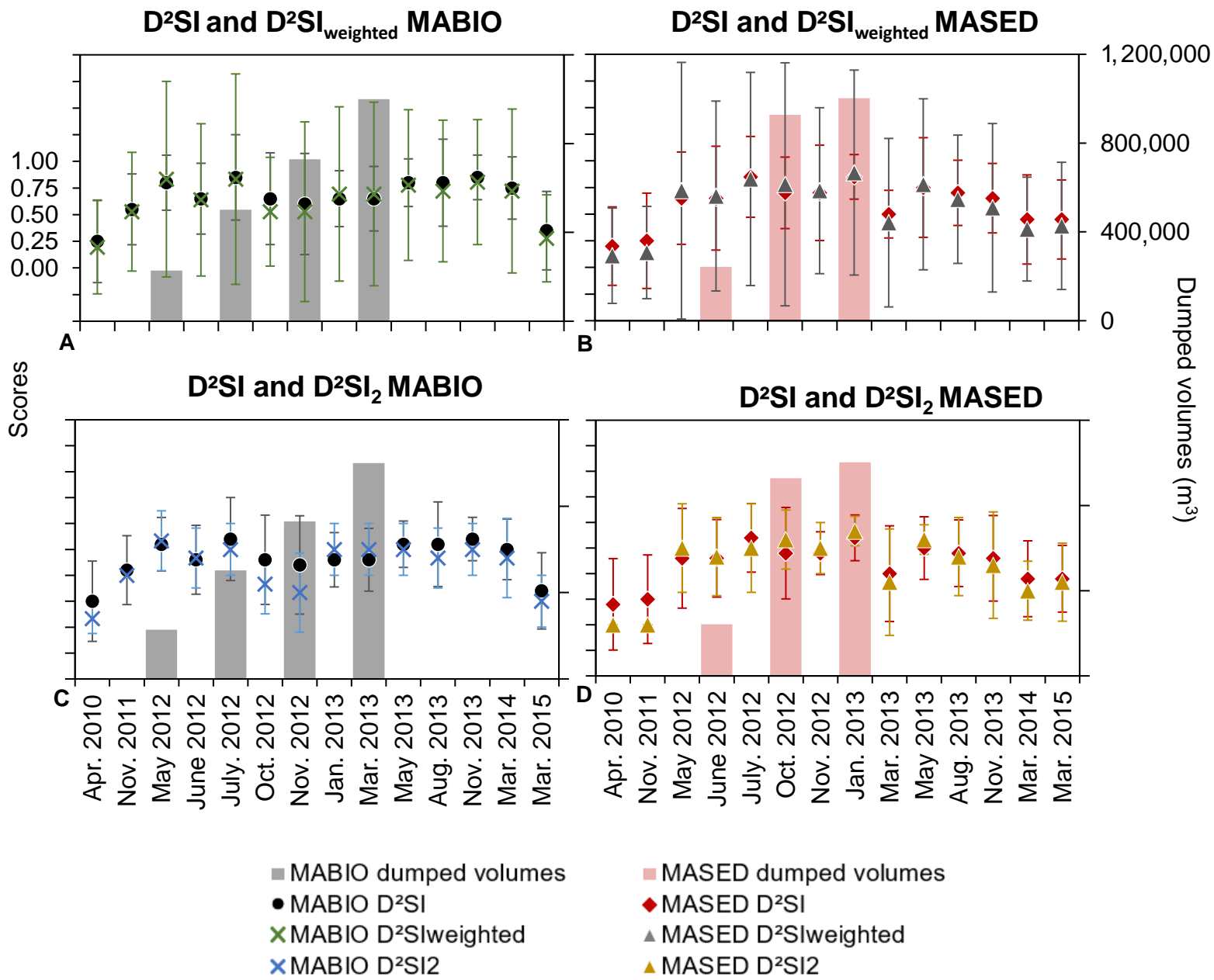


Fig. 4. A and B: comparison between D^2SI and $D^2SI_{weighted}$ (calculated with different degrees of weighting for each sub-index); C and D: comparison between D^2SI and D^2SI_2 (calculated without D^2SI_I , D^2SI_R and D^2SI_D), for each survey with cumulated dumped volumes (m^3 ; Histograms), for 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 D²SI-Benthos and D²SI-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).

Ratio Impacted/unimpacted		Group	Score for species
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	Abundance at unimpacted samples	>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.

Score for species / taxonomic richness	D^2SI_B and D^2SI_I Score	Site disturbance classification
[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: D²SI_S, D²SI_T, D²SI_R and D²SI_D scores associated with results of calculation and site disturbance classification.

Index	Results of calculation	Score	Site disturbance classification
D ² SI _S	[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 ² SI _T	≤ 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 ² SI _R and D ² SI _D	[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 D²SI calculation and associated site disturbance classification.

D²SI	Site disturbance classification
[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 D²SI and dumped volumes, for MABIO and MASED sites. D²SI_{weighted}: final index with weighting coefficient; D²SI₂: final index calculation without scores integrating D²SI_I, D²SI_R and D²SI_D; Volumes: *in situ* dumped volumes. Numbers in bold: significant values. In red: p-value.

MASED	D²SI_B	0.20	0.44	0.51	0.13	0.37	0.69	0.83	0.82	0.60	MABIO
	NA	D²SI_I	0.34	0.00	-0.17	-0.28	0.16	0.27	0.35	-0.15	
	0.60	NA	D²SI_S	0.65	-0.26	0.22	0.67	0.69	0.78	-0.098	
	0.074	NA	0.072	D²SI_T	-0.20	0.18	0.60	0.66	0.80	0.14	
	-0.15	NA	-0.013	-0.18	D²SI_R	0.28	0.31	0.23	-0.11	-0.083	
	0.42	NA	0.40	0.41	-0.35	D²SI_D	0.62	0.45	0.27	0.27	
	0.80	NA	0.64	0.48	-0.064	0.70	D²SI	0.95	0.79	0.13	
	0.91	NA	0.65	0.38	-0.14	0.59	0.95	D²SI_{weighted}	0.89	0.25	
	0.89	NA	0.64	0.44	-0.23	0.52	0.92	0.97	D²SI₂	0.31	
	0.54	NA	0.25	0.12	-0.21	0.35	0.39	0.51	0.54	Volumes	

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 ² SIF		D ² SIF ₂		
	Values	EcoQS	Values	EcoQS	Values	EcoQS	Values	EcoQS	Values	EcoQS	Values	EcoQS	Values	EcoQS	
MASED	Before	1.10	Undisturbed	0.75	Slightly	0.0035	Undisturbed	4.81	Undisturbed	59	Perturbed	0.4	Moderately	0.0	Undisturbed
	During	1.10	Undisturbed	0.81	Undisturbed	0.0080	Undisturbed	4.78	Undisturbed	68	Normal	0.7	Heavily	0.7	Heavily
	After	1.23	Slightly	0.81	Undisturbed	0.0042	Undisturbed	4.83	Undisturbed	74	Normal	0.7	Heavily	0.6	Heavily
MABIO	Before	1.21	Slightly	0.71	Slightly	0.0088	Undisturbed	4.39	Undisturbed	62	Normal	0.2	Slightly	0.3	Slightly
	During	1.85	Slightly	0.74	Slightly	0.0289	Slightly	4.35	Undisturbed	70	Normal	0.7	Heavily	0.6	Heavily
	After	0.67	Undisturbed	0.76	Slightly	0.0078	Undisturbed	3.70	Slightly	84	Normal	0.6	Heavily	0.6	Heavily

