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

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N. Baux[a,b,c], B. Chouquet[d], M. Martinez[a], J.P. Pezy[a], A. Raoux[a], P. Balay[d], C. Dancie[d], A. Baffreau[a,e] and J.C. Dauvin[a]

[a]*Normandie Univ., UNICAEN, UNIROUEN, CNRS UMR 6143 M2C, Laboratoire Morphodynamique Continentale et Côtière, 14000 Caen, France.*

[b]*Normandie univ., UNICAEN, Laboratoire des Sciences Appliquées de Cherbourg, EA 4253, 50100 Cherbourg, France*

[c]*Conservatoire National des Arts et Métiers, INTECHMER, 50100 Cherbourg, France*

[d]*Cellule de Suivi du Littoral Normand, CSLN, 76600 Le Havre, France.*

[e]*GEMEL-Normandie, Groupe d'Etude des Milieux Estuariens et Littoraux de Normandie, 14530 Luc-sur-mer, France.*

*Corresponding author: Conservatoire National des arts et Métiers, INTECHMER, 50100 Cherbourg, France, noemie.baux@lecnam.net (Noémie Baux).

ABSTRACT

At present, there are few operational indexes to assess the impact of a given human pressure taken alone. Nevertheless, the current challenge in the management of coastal marine environments in the framework of cumulative impacts and climatic change is to identify the relative contribution of each activity on ecosystem functioning. The objective of the present study is to propose an integrative approach to assess the environmental impacts of dumping operations, *via* the development of a new index, the Dredge Disposal Sediment Index (D²SI). From the selection of two types of station: impacted and unimpacted, D²SI integrates six sub-indices considering the biological and physical changes generated by dredge disposal on the seabed. A final score is proposed, according to the five classes of the European Water Framework Directive. The initial development of D²SI was conducted on the experimental dumping site of Machu (Bay of Seine), by applying a BACI (Before-After-Control-Impact) approach. An additional implementation (D²SI$_2$) is used in the case of absence of data on ichthyofaunal or biological traits of life of macrobenthic fauna, which yields a comparable assessment of dumping pressure.

35   In the future, the D²SI or D²SI$_2$ indexes should be tested on other dumping sites with a

36   view to comparing the assessment of this dumping activity.

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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**

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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

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

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

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

The objective of this study is to improve the index developed by Roberts et al. (1998) and modified by Dauvin et al. (2018), considering the biological and physical changes that are generated, to assess objectively the impact of dumping operations at sea and take into account the degradation or improvement of environment conditions. In the framework of the INDICLAP project ("INDicateurs de CLAPage") funded by the French Biodiversity Agency (FBA), a multicriteria approach was proposed, which includes benthic macrofauna (invertebrates >1mm) and ichthyofauna (benthodemersal fish), as well as morpho-sedimentary environment changes (bathymetry, sedimentary facies and deposit thickness). The new index proposed was named D²SI (Dredge Disposal Sediment Index). In the present study, we apply this index to a monitoring survey on an experimental dredge spoil disposal site (Machu site) located in the eastern part of the Bay of Seine (English Channel) using a BACI (Before-After-Control-Impact) approach (Pezy et al., 2017, 2018).

1. Materials and methods

1.1. Dredge Disposal Sediment Index (D²SI) concept

The multicriteria D²SI index is calculated considering the selection of two types of stations: impacted stations (under the direct influence of harbour sediment disposal) and unimpacted stations (without direct or indirect influence of harbour sediment disposal). Both impacted and unimpacted stations must be located on the same benthic community and sediment habitat at the beginning of dredge spoil operations. The D²SI is composed of six sub-indices taking into account the biological and physical changes generated by dredge disposal on the seabed. A score is calculated for each sub-index (Fig. 1). The addition of these scores yields a final score (D²SI) which allows us to classify the environment from "bad" to "excellent", according to the five classes of the European Water Framework Directive. Intervals are defined according to data from the Machu experimental dumping (eastern part of the Bay of Seine).

The six sub-indices are:
- D²SI-Benthos (D²SI$_B$), based on benthic macrofauna (invertebrates >1 mm), i.e. presence of the species and their abundances.

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136   -   D²SI-Ichtyofauna (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$_B$)*

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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):

168 1) 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

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

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

1.2.2. D²SI-Ichtyofauna (D²SI$_I$)

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

The D²SI-Ichtyofauna (D²SI$_I$) is calculated similarly to the D²SI$_B$ (Fig. 1), taking into account the species richness and abundances of the demersal fish species, it is scored from 0 to 1 in the same way of D²SI$_B$ (Table 2).

1.2.3. D²SI-Sediment

Dumping operations induce changes of bottom sediment at the dumping site and 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    $$D^2SI_S = \left| \frac{\% \; FP \; at \; impacted \; stations - \% \; FP \; at \; unimpacted \; stations}{\% \; FP \; at \; impacted \; stations + \% \; FP \; at \; unimpacted \; stations} \right| \quad (Eq. 1)$$

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

$$D^2SI_T = \left(TH^n_{Impacted} - TH^n_{Unimpacted}\right) + \left(e^{\left(Th^n_{Impacted} - Th^n_{Unimpacted}\right)} - 1\right) \quad (Eq.\ 2)$$

$$With\ TH^n = Initial\ bathymetry - bathymetry\ measured\ at\ time\ n$$

$$and\ Th^n = bathymetry\ measured\ at\ time\ n - bathymetry\ measured\ at\ n+1$$

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

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

1.2.5. D^2SI-Drifting and D^2SI-Resistance to landfill

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

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

(1) Resistance to landfill (resistance to sediment spoil deposition), which corresponds to the capacity of the macrofauna to resist increases in thickness of the sedimentary layer during sediment disposal. Indeed, benthic species that live in close contact with the seabed and have reduced mobility are highly exposed to the effects of dumping. In general, a large majority of the fauna disappear or are very strongly reduced just after the dumping (Witt et al., 2004; Bolam et al., 2006b). Some species are more resistant than others as the bivalves and polychaetes, partly owing to their ability to migrate vertically (Maurer and Aprill, 1979; 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
$$D^2SI_{R \, or \, D} = 1 - (\%G1 + \%G2) \quad (Eq.\ 3)$$

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. D²SI, 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), $1x10^6$ m^3 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^3

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^3 deposited per season: spring (16 April-14 May 2012), summer

327   (1-26 July 2012), autumn (10 0ctober-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 GMPR 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

11

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

401   *with x̄: 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 µm) 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 µm) 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

14

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 Kruskall-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

based on benthic abundances, sedimentary type and thickness of deposit, show an increase of scores according to the dumping periods. These three factors are determinant in calculating the final index score (D²SI), with significant correlations (respectively 0.69, 0.67 and 0.60 for MABIO and 0.80, 0.64 and 0.48 for MASED; Table 5). Moreover, they are significantly correlated with each other (D²SI$_B$-D²SI$_T$: 0.51 and D²SI$_S$-D²SI$_T$: 0.65 on MABIO; D²SI$_B$-D²SI$_T$: 0.60 on MASED; Table 5), reflecting conjoint response to dumping operations.

Conversely, the sub-index based on ichthyofauna (D²SI$_I$) shows large temporal fluctuations (Fig. 3B) which affect the calculation of the final index score (D²SI$_I$-D²SI correlations: 0.16 on MABIO, no data on MASED; Table 5). In fact, the mobility of the ichthyofauna and the sparse knowledge of the consequences of dumping impacts on this compartment makes it difficult to establish a reliable index. The previous study on the MABIO site (no ichthyofauna data on MASED site) shows an increase in abundances and biomass of demersal fish during the dumping period, reflecting an attraction of surrounding populations (Pezy et al., 2018). This phenomenon has also been documented, before and after deposition from a sewage effluent outfall into the ocean at Hawaii (Russo, 1982) and suggests that changes in fish abundance are related to variations in the distribution and abundance of benthic preys (Spies, 1984). On the Machu site, dumping operations caused a modification of invertebrate benthic communities with high abundances of some dominant species (Marmin, 2013), allowing a constant availability of prey. Moreover, the D²SI$_I$ results highlight the problem of selecting stations, which are rarely identical to those chosen for sampling of other compartments (invertebrate benthic macrofauna), which may introduce a bias into the study of a very local anthropogenic impact.

The choice of both biological traits (resistance to dumping of spoil and drifting) is based on a knowledge of the study site and the fact that several authors have hypothesized a specific modification of the combination of community life-history traits in disturbed ecosystems, depending on the nature and intensity of the disturbance (Stearns, 1976, 1977; Usseglio-Polatera et al., 2000; Bremner et al., 2003; Bolam et al., 2006a,b; Janson, 2007; Dauvin et al., 2017a,b). The capacity of invertebrate benthic species to resist the deposition of spoil sediment does not seem to be a determining factor to assess the impact of dumping on the studied site (low correlations with dumped volumes: -0.083 on MABIO and -0.21 on MASED and with D²SI: 0.31 on MABIO and -0.064 on MASED). In fact, the benthic communities of the eastern part of the Bay of Seine are characterized by very resistant and resilient species, particularly well adapted to the particular oceanographic and anthropogenic 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-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, D²SI is calculated using only the scores of
609 D²SI$_B$, D²SI$_S$ and D²SI$_T$ (considering unweighted scores for these three sub-indices), without
610 including the scores of D²SI$_I$, D²SI$_R$ and D²SI$_D$ (Fig. 4 C, D). The resulting index is named
611 D²SI$_2$ (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 D²SI and D²SI$_2$ (KW= 20.69; df = 10; p-value = 0.02). Correlations between D²SI$_2$ 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 (D²SI) or between dumped volumes and weighted index (D²SI$_{weighted}$; Table 5). As with
618 the previous index, the statistical tests on D²SI$_2$ for each dumping period only show
619 differences between before-during dumping operations (KW test= 10.679; df= 2; p-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 D²SI 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 D²SI and D²SI$_2$ 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 D²SI values, during dumping: from Moderately to Extremely disturbed; after
636 dumping: Slightly to Extremely disturbed; Fig. 3). Also, D²SI and D²I$_2$ 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 2-2.5x10^6 m³.y^{-1} on the Octeville site and 3.5-4x10^6 m³.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 (D²SI$_2$) 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 D²SI$_2$ 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 D²SI$_2$ 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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Figure captions

944

945   Fig. 1: D²SI and D²SI$_2$ 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 (m^3; 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 D²SI$_2$

960   (calculated without D²SI$_I$, D²SI$_R$ and D²SI$_D$), for each survey with cumulated dumped

961   volumes (m^3; 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 D²SI$_2$ MABIO and MASED. The y-axis and x-axis are

964   the same for each graph.

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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. D^2SI_S, D^2SI_T, D^2SI_R and D^2SI_D scores associated with results of calculation
975   and site disturbance classification.

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977   Table 4. D^2SI results of calculation and site disturbance classification.

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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^2SI and dumped volumes, for MABIO and
981   MASED sites. $D^2SI_{weighted}$: final index with weighting coefficient; D^2SI_2: final index
982   calculation without scores integrating D^2SI_I, D^2SI_R and D^2SI_D; Volumes: *in situ* dumped
983   volumes. Numbers in bold: significant values. In red: p-value.

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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.
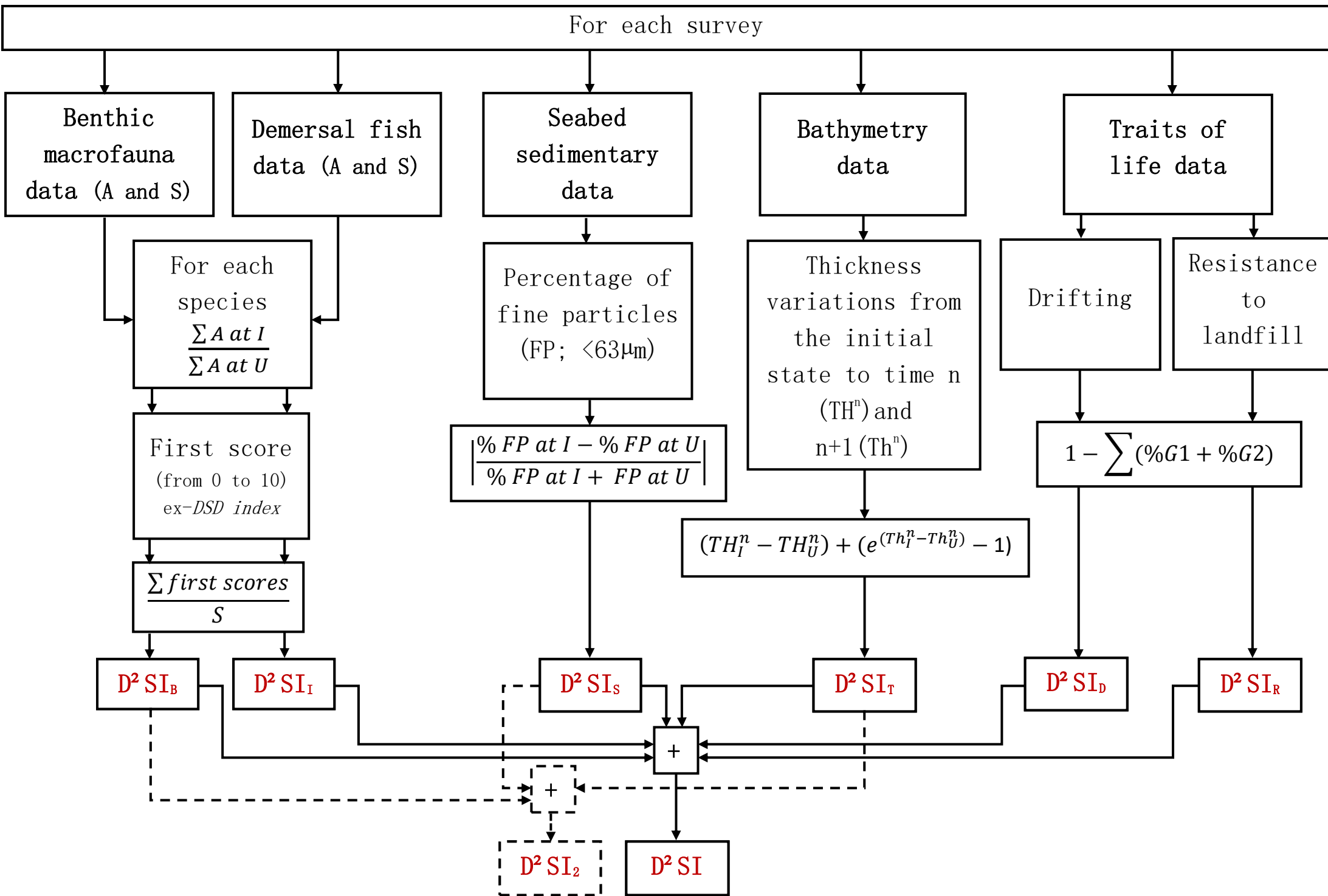
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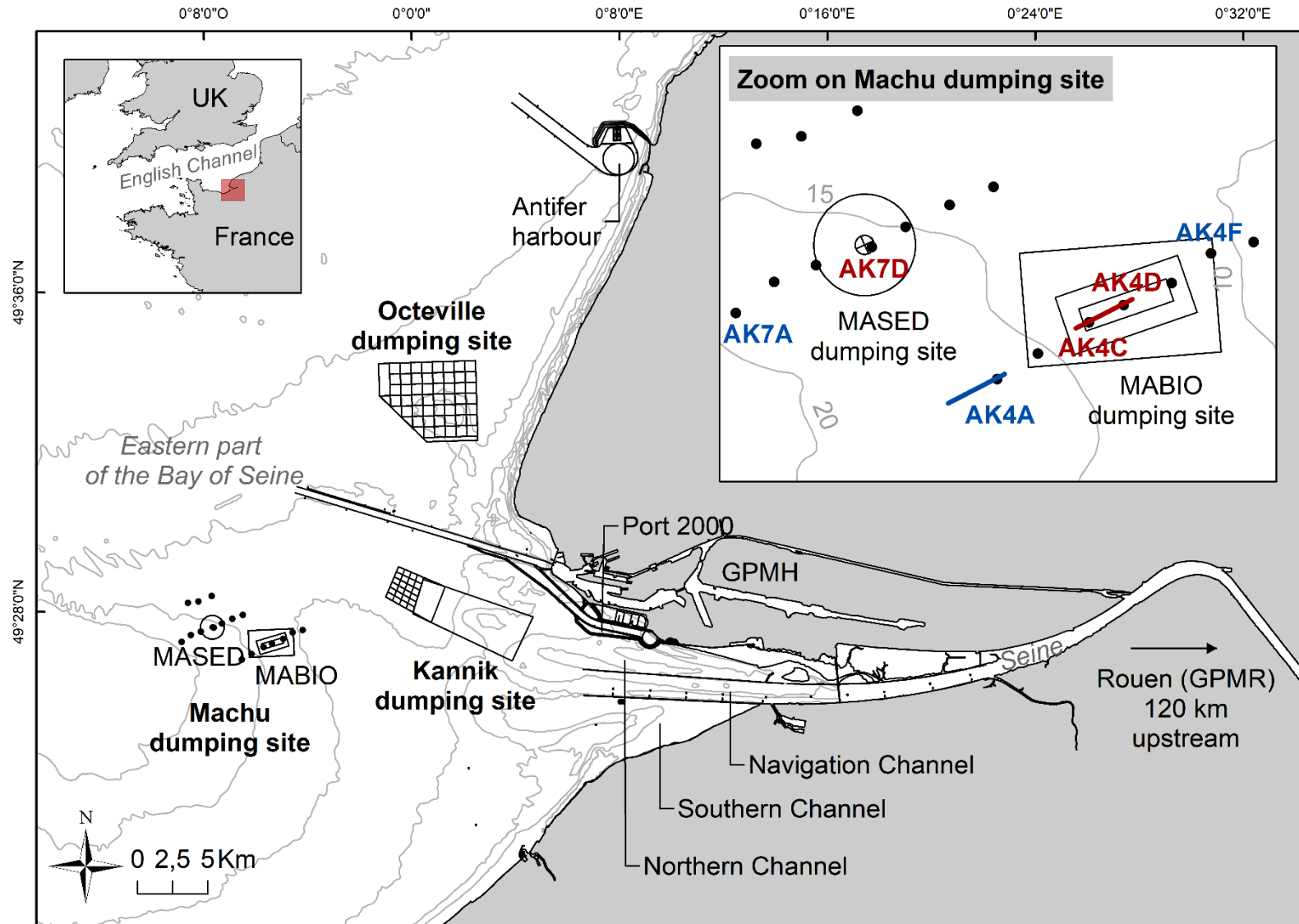
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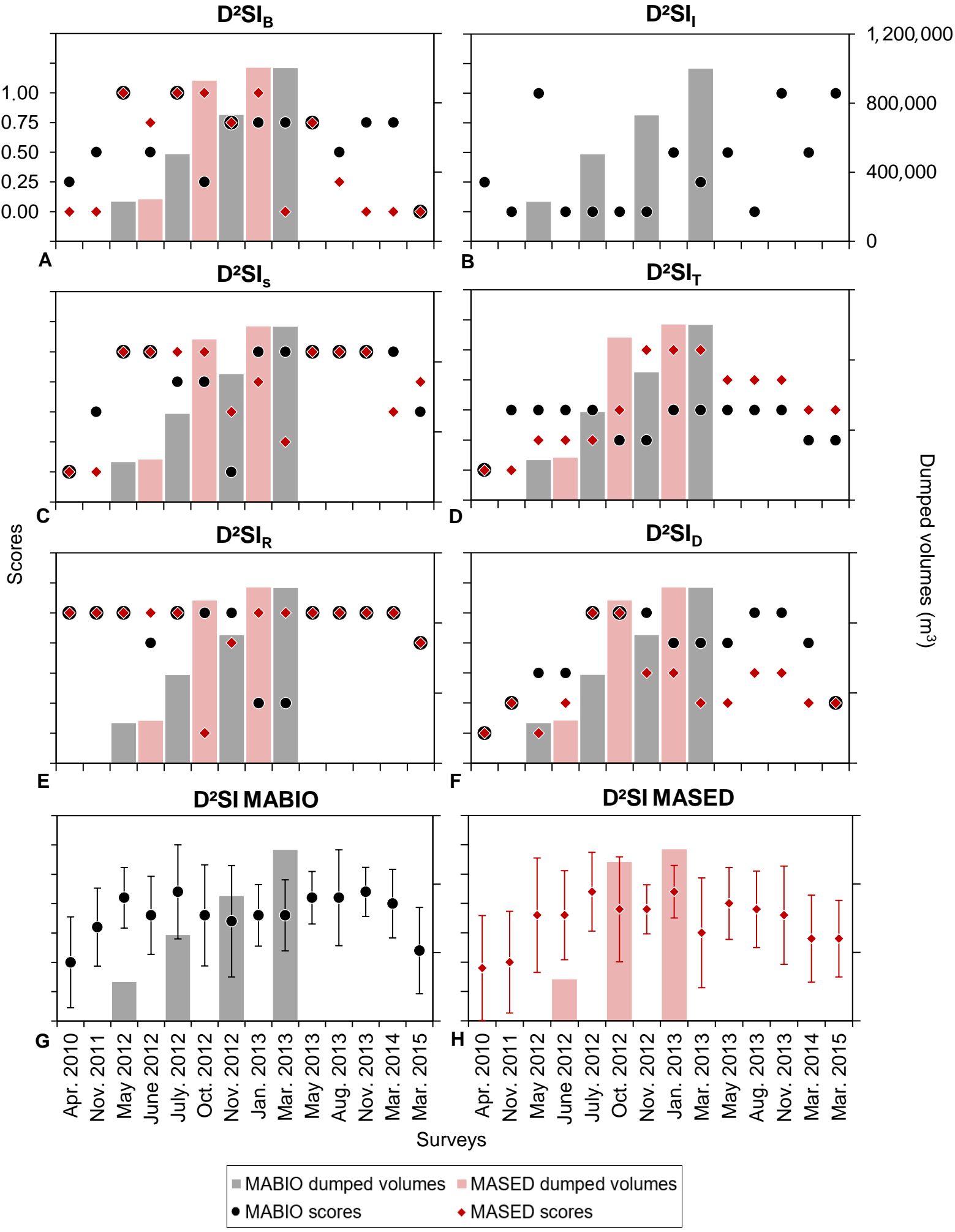
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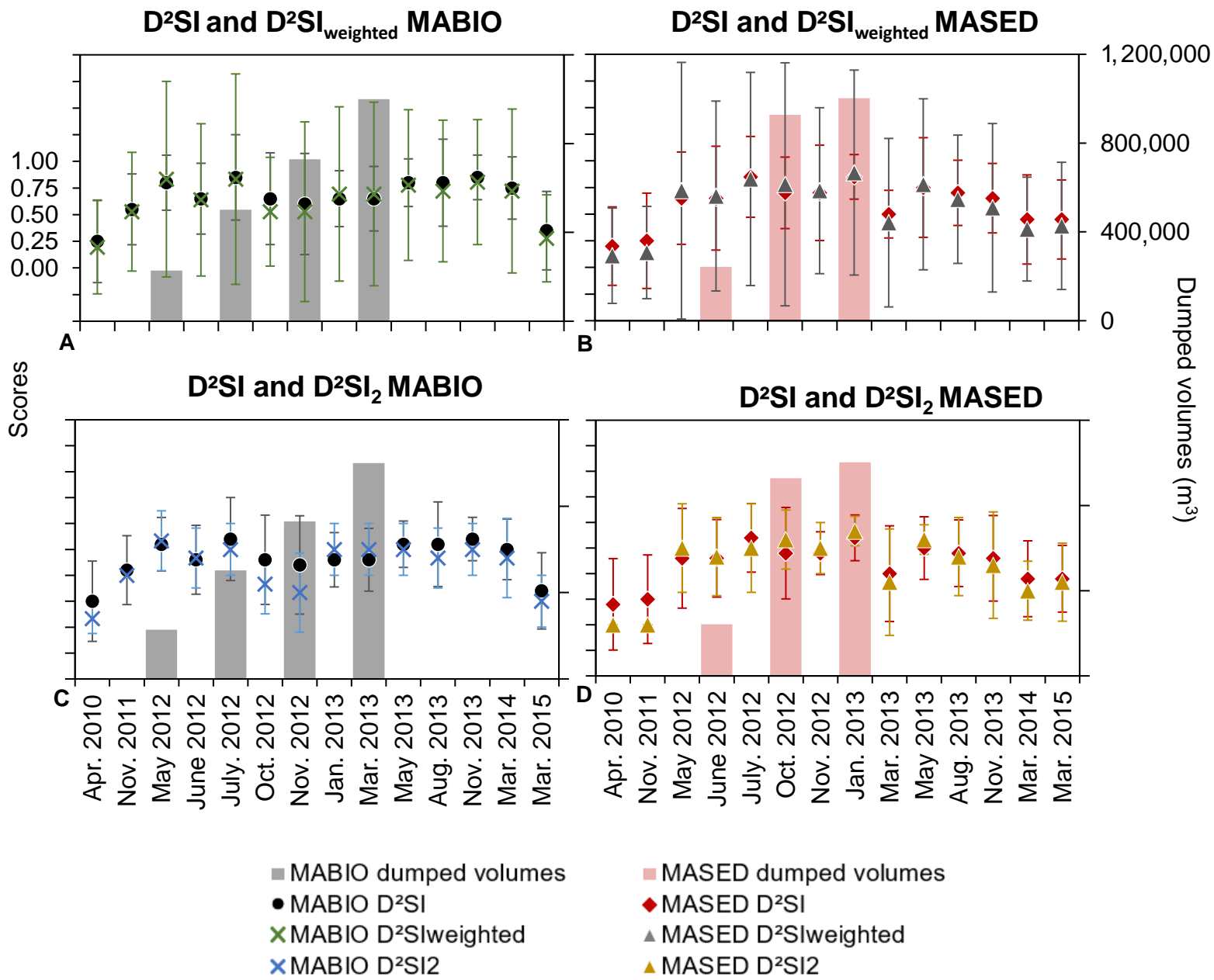
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Table 1: Ratio, threshold and scores for species used in calculation of D²SI-Benthos and D²SI-Ichthyofauna [from DSD index (Dauvin *et al.,* 2018)]. Example for reading assistance: a score of 1 indicates high abundances at impacted stations (abundance 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	than at impacted samples	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: D²SI$_B$ and D²SI$_I$ score and site disturbance classification.

Score for species / taxonomic richness	D²SI$_B$ and D²SI$_I$ 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
D²SI$_S$	[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
D²SI$_T$	≤ 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
D²SI$_R$ and D²SI$_D$	[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. $D^2SI_{weighted}$: final index with weighting coefficient; D^2SI_2: final index calculation without scores integrating D^2SI_I, D^2SI_R and D^2SI_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**	**D²SI_2**	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		D²SIF		D²SIF₂	
		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

For each survey

| Benthic macrofauna data (A and S) | Demersal fish data (A and S) | Seabed sedimentary data | Bathymetry data | Traits of life data |

For each species $\dfrac{\sum A\ at\ I}{\sum A\ at\ U}$

Percentage of fine particles (FP; <63μm)

Thickness variations from the initial state to time n (TH^n) and n+1 (Th^n)

Drifting

Resistance to landfill

First score (from 0 to 10) ex-$DSD\ index$

$\left|\dfrac{\%\ FP\ at\ I - \%\ FP\ at\ U}{\%\ FP\ at\ I + FP\ at\ U}\right|$

$1-\sum(\%G1+\%G2)$

$\dfrac{\sum first\ scores}{S}$

$(TH_I^n - TH_U^n) + (e^{(Th_I^n - Th_U^n)} - 1)$

$D^2\,SI_B$ $D^2\,SI_I$ $D^2\,SI_S$ $D^2\,SI_T$ $D^2\,SI_D$ $D^2\,SI_R$

+

+

$D^2\,SI_2$ $D^2\,SI$