Check for updates

# Indicative value of benthic foraminifera for biomonitoring: Assignment to ecological groups of sensitivity to total organic carbon of species from European intertidal areas and transitional waters

Vincent M.P. Bouchet [a,*], Fabrizio Frontalini [b], Fabio Francescangeli [c], Pierre-Guy Sauriau [d], Emmanuelle Geslin [e], Maria Virginia Alves Martins [f,g], Ahuva Almogi-Labin [h], Simona Avnaim-Katav [i], Letizia Di Bella [j], Alejandro Cearreta [k], Rodolfo Coccioni [b], Ashleigh Costelloe [l], Margarita D. Dimiza [m], Luciana Ferraro [n], Kristin Haynert [o], Michael Martínez-Colón [p], Romana Melis [q], Magali Schweizer [e], Maria V. Triantaphyllou [m], Akira Tsujimoto [r], Brent Wilson [s], Eric Armynot du Châtelet [t]

[a] Univ. Lille, CNRS, Univ. Littoral Côte d'Opale, UMR 8187, LOG, Laboratoire d'Océanologie et de Géosciences, Station Marine de Wimereux, F 59000 Lille, France
[b] Univ. Urbino Dipartimento di Scienze Pure e Applicate (DiSPeA), Università degli Studi di Urbino "Carlo Bo", Campus Scientifico Enrico Mattei, Località Crocicchia, 61029 Urbino, Italy
[c] University of Hamburg, Institute for Geology, Centre for Earth System Research and Sustainability, Bundesstraße, 5520146 Hamburg, Germany
[d] La Rochelle Université, CNRS, Littoral Environnement et Sociétés, UMR 7266 LIENSs, 2 rue Olympe de Gouges, 17000 La Rochelle, France
[e] UMR 6112 LPG-BIAF, Univ. Angers, Univ. Nantes, CNRS, 2 Bd Lavoisier, F 49000 Angers, France
[f] Rio de Janeiro State University (UERJ), R. São Francisco Xavier, 524, Lab 1006, Maracanã, Rio de Janeiro 20550-900, Brazil
[g] Aveiro University, Department of Geosciences, GeoBioTec, Campus de Santiago, 3810-197 Aveiro, Portugal
[h] Geological Survey of Israel, Yesha'yahu Leibowitz 32, Jerusalem 9692100, Israel
[i] Israel Oceanographic and Limnological Research, Haifa 3108001, Israel
[j] Dipartimento di Scienze Della Terra, Sapienza Università di Roma, Italy
[k] Departamento de Geología, Universidad del País Vasco UPV/EHU, Apartado 644, 48080 Bilbao, Spain
[l] BioStratigraphic Associates (Trinidad) Limited, 113 Frederick Settlement, Old Southern Main Rd., Caroni, Trinidad and Tobago
[m] National and Kapodistrian University of Athens, Faculty of Geology and Geoenvironment, Panepistimioupolis, 15784 Athens, Greece
[n] CNR, Institute of Marine Sciences, National Research Council of Italy, Calata Porta di Massa, Naples, Italy
[o] University of Göttingen, J.F. Blumenbach Institute of Zoology and Anthropology, Göttingen, Germany
[p] Florida A&M University, School of the Environment, FSH Science Research Center, RM306B, 1515 South MLK Blvd, Tallahassee, FL 32307, USA
[q] Department of Mathematics and Geosciences, 34127 Trieste, Italy
[r] Faculty of Education, Shimane University, 1060 Nishikawatsucho, Matsue, Shimane 690-8504, Japan
[s] Cedar Lodge, Maenygroes, Cei Newydd, Ceredigion, Wales SA45 9RL, UK
[t] Univ. Lille, CNRS, Univ. Littoral Côte d'Opale, UMR 8187, LOG, Laboratoire d'Océanologie et de Géosciences, F 59000 Lille, France

ARTICLE INFO

ABSTRACT

This work contributes to the ongoing work aiming at confirming benthic foraminifera as a biological quality element. In this study, benthic foraminifera from intertidal and transitional waters from the English Channel/ European Atlantic coast and the Mediterranean Sea were assigned to five ecological groups using the weighted-averaging optimum with respect to TOC of each species. It was however not possible to assign typical salt marsh species due to the presence of labile and refractory organic matter that hampers TOC characterization. Tests of this study species' lists with Foram-AMBI on two independent datasets showed a significant correlation between Foram-AMBI and TOC, confirming the strong relation between foraminifera and TOC. For one of the validation datasets, associated macrofaunal data were available and a significant correlation was found between the foraminiferal Foram-AMBI and the macrofaunal AMBI. The here proposed lists should be further tested with sensitivity-based indices in different European regional settings.

* Corresponding author.
  *E-mail address:* vincent.bouchet@univ-lille.fr (V.M.P. Bouchet).

# 1. Introduction

Benthic foraminifera are increasingly recognized as indicators of human-induced stress (*e.g.*, Alve, 1995; Francescangeli et al., 2016, 2020; Polovodova Asteman et al., 2015), such as oil spills (*e.g.*, Morvan et al., 2004), drill cutting (*e.g.*, Mojtahid et al., 2006), heavy metals (*e.g.*, Martins et al., 2013), urban sewage (*e.g.*, Melis et al., 2019), and aquaculture (*e.g.*, Debenay et al., 2015). Recent developments in benthic foraminiferal biotic indices (Alve et al., 2016; Bouchet et al., 2012; Barras et al., 2014; Dimiza et al., 2016; Jorissen et al., 2018) have provided further opportunities for the application of this meiobenthic group as a biological quality element for ecological quality status (EcoQS) assessment in legislations concerning transitional waters (hereafter TWs; see definition in McLusky and Elliott, 2007) and marine environments (see review in Sousa et al., 2020). Foraminiferal indices based either on species diversity (Alve et al., 2009; Bouchet et al., 2012, 2013) or on the sensitivity of species to organic pollution (Alve et al., 2016; Barras et al., 2014; Dimiza et al., 2016; Jorissen et al., 2018), have been designed and successfully applied to assess EcoQS of benthic habitats (Alve et al., 2019; Bouchet et al., 2012, 2013, 2018a, 2020; Damak et al., 2020; Denoyelle et al., 2010; Dijkstra et al., 2017; El Kateb et al., 2020; Francescangeli et al., 2016; Jesus et al., 2020; Mojtahid et al., 2006, 2008; Melis et al., 2019).

In 2011, the informal FOraminiferal Bio-Monitoring (FOBIMO) international working group (WG) was established with the aims (i) to standardize methods for the use of benthic foraminifera in environmental biomonitoring (Schönfeld et al., 2012) and (ii) to unify the effort of "foraminiferologists" to establish a common biotic index to assess the EcoQS (Alve et al., 2016; Jorissen et al., 2018). The first aim of the FOBIMO WG was to agree to focus on and design an index based on the ecological response of benthic foraminiferal species to total organic carbon (TOC). Specifically, this implied assessing the level of sensitivity/tolerance of foraminiferal taxa to TOC by assigning them to ecological groups (EGs). In the pioneer work of Alve et al. (2016), the authors proposed to assign benthic foraminifera to five EGs following the terminology and definitions used in the macrofauna-based AZTI Marine Biotic Index (AMBI) (Borja et al., 2000) *i.e.*, sensitive (EGI), indifferent (EGII), tolerant (EGIII), second-order opportunistic (EGIV) and first-order (most) opportunistic (EGV) (see further details in the Material and methods section). Recently, Jorissen et al. (2018) suggested using a more explicit terminology and definitions for benthic foraminifera; describing species belonging to EGIII as "third-order opportunists".

In the species assignments used in macrofaunal AMBI, the peculiar natural features of intertidal, transitional and marine habitats or the various climate regime occurring in different geographical basins are not considered. This means that a species' indicative value is the same in an estuary and in open marine waters or in the Mediterranean Sea and in the Baltic Sea. In fact, the use of a single species classification list means that the indicative value of a species is a static concept; *i.e.*, a species is expected to have a similar sensitivity or tolerance to organic matter (OM) wherever it occurs and regardless its adaptation ability. However, some species are known to be plastic enough to adapt to their environment variability and could change their autecology requirements along environmental gradients (see review in Zettler et al., 2013 and references therein). Hence, the FOBIMO WG decided to establish four sub-WGs reflecting four main types of environments *i.e.,* (i) North-East Atlantic and Arctic fjords, continental shelves, and slopes (Alve et al., 2016), (ii) open marine waters in the Mediterranean Sea (Jorissen et al., 2018), (iii) intertidal areas and TWs (the present contribution), and (iv) tropical environments. Each sub-WG had the aim to define a list of the response to TOC of as many species as possible. Earlier, the NE Atlantic and Arctic Oceans and the Mediterranean Sea open environments sub-WGs have already published their respective species (see above). These lists of species can be used in the different sensitivity-based indices designed for benthic foraminifera that use the relative proportion of sensitive, tolerant and opportunistic species to assess EcoQS, either foraminifera-based AMBI (Foram-AMBI, Alve et al., 2016) or comparable methods (*e.g.*, Barras et al., 2014; Dimiza et al., 2016). These studies show a strong response of marine species to TOC, which is explained by the fact that TOC in such marine systems mainly consists of labile organic matter. However, it is questionable if this method to assign species according to their response to TOC gradients is also applicable in intertidal areas and TWs, where TOC is reflecting labile and refractory organic matter (Pusceddu et al., 2003). Noticeably, salt marsh sediments commonly exhibit very high TOC values, due to the halophile vegetation, responsible for the presence of large quantities of poorly reactive organic matter (Armynot du Châtelet et al., 2009a; Leorri et al., 2018; Middelburg et al., 1997).

This paper presents the first results of the sub-WG on intertidal areas and TWs along the European Atlantic coasts from the Belgian-French border down to Portugal and in the Mediterranean Sea.

The construction of ecological species lists is hampered by the fact that benthic foraminiferal taxonomy may vary considerably among studies, which complicated a reliable assignment to EGs. Specifically, foraminiferal species are traditionally defined on morphological criteria and are therefore mostly morphospecies. Molecular studies have shown that some of these morphospecies include cryptic or pseudocryptic species (Darling et al., 2016; Hayward et al., 2004; Richirt et al., 2019).

Another complication is that intertidal areas and TWs are characterized by strong environmental gradients and high natural variability of physico-chemical parameters (*e.g.*, salinity, temperature, grain-size, dissolved oxygen; Elliott and Quintino, 2007) coupled with natural organic matter enrichment (Pusceddu et al., 2003). Intertidal and TWs, therefore, often behave as naturally stressed environments (Dauvin, 2007; Elliott and Quintino, 2007), but also commonly experience high levels of anthropogenic stresses such as aquaculture (Bouchet and Sauriau, 2008), habitat destruction (*e.g.*, agricultural uses, coastal reinforcements), urban sewage and industrial discharges (Armynot du Châtelet et al., 2004; Morvan et al., 2004). Species distribution in these environments is the result of the complex interplay between natural and human-induced stressors. Therefore, it is challenging to achieve a reliable assignment of benthic foraminiferal species from these environments to EGs according to species response by considering only TOC.

In this context, the present study aimed at (i) developing an objective protocol for the species' assignment to EGs, (ii) investigating if it is possible to assign benthic foraminiferal species from intertidal areas and TWs from the considered geographical regions to the five EGs described in Alve et al. (2016) according to species responses to sediment TOC content, (iii) if applicable, validating the established lists by testing them using a sensitivity-based index on separate and independent datasets from the same geographic regions, and (iv) testing the hypothesis that species ecological requirements may vary between habitats/ecosystems and along latitudinal gradients by comparing species assignment lists from the present study. Because of the particular characteristics of foraminiferal habitats and communities, we decided to present the foraminiferal species assignments split in two lists: one for the English Channel/European Atlantic and one for the Mediterranean region. The recently developed Foram-AMBI (Alve et al., 2016), adapted from AMBI for benthic foraminifera, was used to test the reliability of these ecological species lists.

## 2. Material and methods

### 2.1. Ecological groups of sensitivity to TOC

Benthic macrofaunal species are traditionally assigned to five groups of sensitivity to OM (*e.g.*, Borja et al., 2000; Glémarec and Hily, 1981; Hily, 1983; Simboura and Zenetos, 2002) based on the seminal work of Pearson and Rosenberg (1978). Species are meant to be indicative of the prevailing environmental conditions; *i.e.*, the level of organic carbon enrichment where they are found. Taken from Grall and Glémarec

(1997) and Borja et al. (2000), the following characteristics were used by Alve et al. (2016) and Jorissen et al. (2018) to assign benthic foraminiferal species to the five EGs considering their response to TOC. These characteristics are used in the present study:

- Group I (EGI). "Sensitive species" are sensitive to TOC enrichment. Their relative abundance is highest at the lowest TOC values and drops to zero as organic carbon concentration increases.
- Group II (EGII). "Indifferent species" are indifferent to initial stages of organic carbon enrichment. They never dominate the assemblage. They occur in low relative abundance over a broad range of organic carbon concentrations, but are absent at very high concentrations.
- Group III (EGIII). "Tolerant species" are tolerant to excess organic carbon enrichment. They may occur at low TOC; their highest frequencies are stimulated by organic carbon enrichment but they are absent at very high organic carbon concentrations. This group has been termed "third-order opportunistic species" by Jorissen et al. (2018).
- Group IV (EGIV). "second-order opportunistic species" show a clear positive response to organic carbon enrichment with maximum abundances between the maxima of EGIII and EGV.
- Group V (EGV). "first-order opportunistic species" exhibit a clear positive response to excess organic carbon enrichment with maximum abundances at a higher stress level induced by organic load than species belonging to EGIV. At even higher TOC concentrations, foraminifera are not able to survive.

Based on Hily's model (Glémarec and Hily, 1981; Hily, 1984; Majeed, 1987), the theoretical succession of the relative abundance of each EG, was adapted to benthic foraminiferal species along a TOC gradient. According to Jorissen et al. (2018), the five categories are distributed as follows (Fig. 1).

### 2.2. Criteria to select datasets

Only previous studies in areas that strictly follow the definition of intertidal and TWs were selected. In the European Water Framework Directive (WFD, 2000/60/EC), TWs are defined as "*bodies of surface water in the vicinity of river mouths which are partially saline in character as a result of their proximity to coastal waters but which are substantially influenced by freshwater flows*" (European Communities, 2000, p. 6). In

the Mediterranean Sea, TWs also include mesohaline, poly-euhaline and hyperhaline lagoons (Reizopoulou et al., 2018). We decided to follow the definition of McLusky and Elliott (2007) who specified the different types of water bodies belonging to intertidal and TWs in the context of the implementation of the WFD and further marine legislations (see Table 1).

Three further criteria had to be met to retain the datasets used for the assignments:

- the study had to be based on living benthic foraminifera. Note that all datasets used in the present study are based on rose Bengal-stained fauna;
- the foraminiferal and TOC data had to be from the same station (less than 1 m from the sampling point); when the authors of the study only provide the OM content (studies 10, 12 and 18, Table 3), it was converted to TOC using the following formula: LOI = ~2 TOC (Barillé-Boyer et al., 2003; Frangipane et al., 2009);
- only samples containing >50 stained specimens were considered following Alve et al. (2016).

All studies from the English Channel/European Atlantic except one (see Appendix A) are based on the >63 μm fraction, whereas in the Mediterranean Sea studies are based on the fraction >63 or >125 μm (Appendix B). In total, 21 studies were selected from the English Channel/European Atlantic intertidal and TWs (Fig. 2, Appendix A) and 21 ones from the Mediterranean Sea (Fig. 2, Appendix B). The complete datasets are presented in Bouchet et al. (2021).

Due to lack of standardization, different methods were used in the different studies to measure TOC; from the classical loss-on-ignition (LOI) to the more sophisticated use of an elemental analyser (EA). While the latter directly quantifies TOC concentration, the LOI measures the OM content. It is still often used in large surveys because it allows for a quick and cheap measurement of sedimentary organic matter (Luczak et al., 1997). It is generally accepted that LOI may overestimate TOC content compared to EA (Barillé-Boyer et al., 2003). In the datasets from the English Channel/European Atlantic coast, the ranges of TOC obtained with LOI and EA are fairly similar. Apart from one study in the Ebro delta, all the studies in the Mediterranean Sea used an EA to measure TOC content. Therefore, TOC data from the different studies should be compared with caution.

Species names were homogenized among studies following the World Register of Marine Species (WoRMS, Hayward et al., 2020a). Only accepted scientific names from WoRMS are used in this study, and the
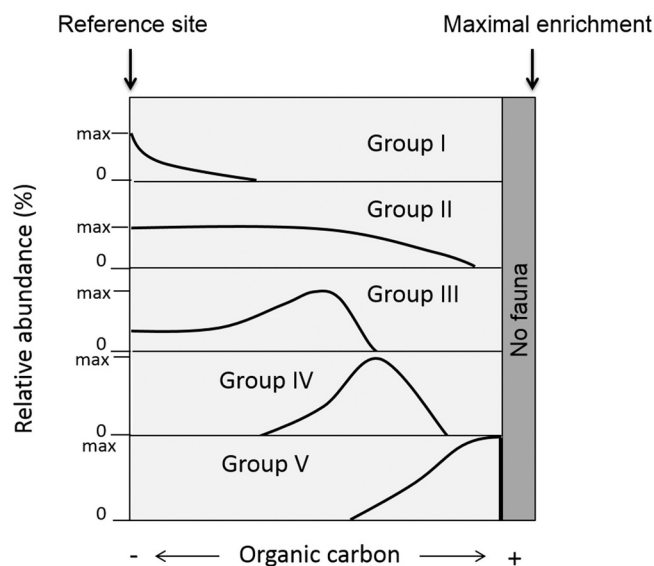


**Fig. 1.** Theoretical graph providing the succession of benthic foraminifera belonging to the five EGs according to their response to organic carbon enrichment. (From Jorissen et al. (2018))

**Table 1**
Water body types of intertidal areas and TWs according to McLusky and Elliott (2007); the "Artificial water body" type (European Communities, 2000, p. 6) was added to complete the original table.

| Water body types | Natural features |
| --- | --- |
| Classical estuary | Tidally dominated at the seaward part; salinity notably reduced by freshwater river inputs; riverine dominance landward |
| Lentic non-tidal lagoon | Limited exchange with the coastal area through a restricted mouth; separated from sea by sand or shingle banks, bars, coral, *etc.*, shallow area, tidal range <50 cm |
| Lentic micro-tidal lagoon | As above but with tidal range >50 cm |
| Ria | Drowned river valley, some freshwater inputs; limited exchanges with coastal waters |
| Delta | Low energy, characteristically shaped, sediment dominated, river mouth area; estuary outflow |
| Coastal freshwater/ brackish water plume | Outflow of estuary or lagoon, notably diluted salinity and hence differing biota than surrounding coast |
| Semi-enclosed bay/lagoon | Low energy, notably limited exchange with the open sea waters |
| Artificial water body | Harbors and docks, constructed dredging pools and coastal water bodies connected to the sea, created by human activities. |
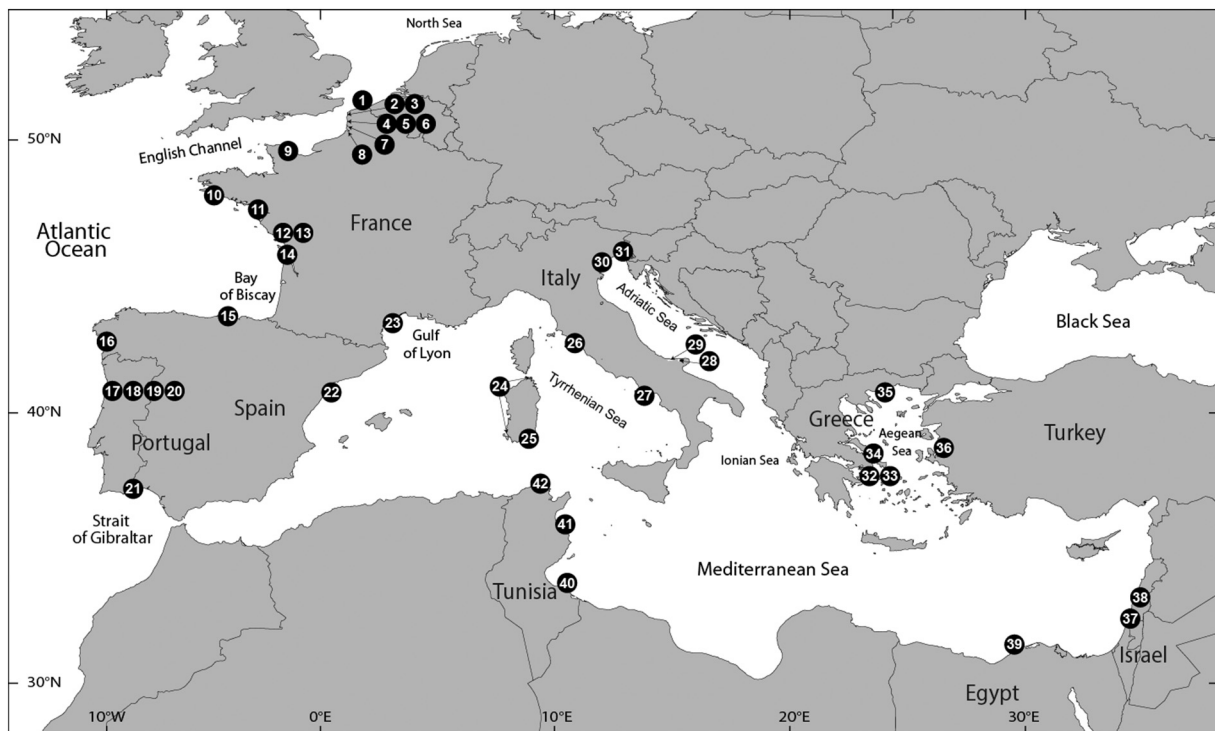
**Fig. 2.** Map showing the geographical distribution of the 42 studies used to assign the species from the English Channel/European Atlantic coast and the Mediterranean Sea intertidal and TWs. Numbers are the same in Appendices A and B.

unique AphiaID identifier is reported for each species. The Aphia platform is an infrastructure aiming at capturing taxonomic and related data and information (Vandepitte et al., 2015). Each taxon added to the Aphia database receives a unique and persistent identifier, the AphiaID. Once assigned to, the name and its corresponding ID cannot be physically deleted from the database, ensuring that the information is not lost.

### 2.3. Species assignment according to relation with TOC content

Indicator species are meant to provide information about environmental conditions. The knowledge of the environmental requirements of a species can be used to detect changes in abiotic conditions or to assess the environmental health of the study area. The assignment of foraminiferal species to the five EGs involves determining which species are more abundant at low, medium and high TOC concentrations.

This can be achieved in different ways. The macrofaunal AMBI list is based on a literature review allowing an inventory of the individual species responses to organic matter gradients, completed in some cases by experts' opinion (Borja et al., 2019). If the latter sounds rather subjective, the former should be reasonably objective. The Foram-AMBI lists for open marine environments of the NE Atlantic and Arctic Oceans (Alve et al., 2016) and the Mediterranean Sea (Jorissen et al., 2018) are both based on an objective review of available datasets, sometimes (in case of inconclusive data) with a small contribution of best expert judgment (Jorissen et al., 2018). These publications included a few plots

aim was to seek for an objective method for species assignments in order to avoid using "best expert judgment". The weighted-averaging (WA) optimum and tolerance approach was used (Birks et al., 1990; Ter Braak, 1987). The idea behind WA is that in a coastal lagoon with a certain TOC range, benthic foraminifera with their TOC optimum close to the coastal lagoon's TOC concentrations will most likely be the most abundant species. A simple and ecologically reasonable estimate of a benthic foraminiferal species' optimum is the average of all TOC values for intertidal areas and TWs in which the species occurs, weighted by the species relative abundance (WA regression). The estimated optimum allows to give an objective assessment of the species environmental requirements. To summarize, the WA optimum method is rapid, easy to implement, theoretically sound, robust (Birks et al., 1990) and leads to an objective assessment of species-specific indicative values.

### 2.4. Foram-AMBI

Foram-AMBI was used to test the species lists. It is adapted from the macrofauna-based AMBI (Borja et al., 2000), and was first introduced by Alve et al. (2016) for fjords, continental shelves and slopes in the North-East Atlantic and Arctic Oceans. Foram-AMBI uses the relative abundance of selected species to assess the EcoQS of marine systems and TWs.

Foram-AMBI was calculated using the AMBI formula (Borja et al., 2000):

$$\text{Foram} - \text{AMBI} = \{(0 \times \%\text{EGI}) + (1.5 \times \%\text{EGII}) + (3 \times \%\text{EGIII}) + (4.5 \times \%\text{EGIV}) + (6 \times \%\text{EGV})\}/100$$

exemplifying species-specific relative abundance patterns plotted against TOC, to better explain the followed methodology.

In the present study's effort to produce lists of foraminiferal species for the European Atlantic and Mediterranean intertidal and TWs, the

For the validation and test phase of the species lists using Foram-AMBI, awaiting a specific calibration for foraminifera, EcoQS were determined following the criteria established for the macrofauna-based AMBI (Table 2, Borja et al., 2000). In view of the first available results,

**Table 2**

Criteria for determining EcoQS according to Foram-AMBI (following criteria of macrofauna AMBI, Borja et al., 2000) and correspondence with sediment TOC (Bakke et al., 2010; Viaroli et al., 2004).

| EcoQS and associated color code | Bad | Poor | Moderate | Good | High |
|---|---|---|---|---|---|
| Foram-AMBI | >5.5 | 4.3–5.5 | 3.3–4.3 | 1.2–3.3 | <1.2 |
| Total organic carbon (%) | >4.1 | 3.4–4.1 | 2.5–3.4 | 2.0–2.5 | <2.0 |

the class limits must probably be redefined for foraminifera.

## 2.5. Testing the ecological assignment lists

In order to test our species assignment to EGs according to their response to TOC, Foram-AMBI was applied on two independent datasets from the English Channel/European Atlantic coast area and the Mediterranean Sea, which were not included in the master tables for calculation of the species assignment (to avoid circular arguments). Great attention was paid to find studies where a clear organic carbon gradient enrichment was observed.

In the English Channel/European Atlantic coast area, Foram-AMBI was applied on a study of the effects of oyster farming on living benthic foraminifera in SW France (Bouchet, 2007). Oyster farming leads to organic matter enrichment in the surrounding environment (Bouchet and Sauriau, 2008). The sampling stations were located in four different unvegetated intertidal mudflats harboring oyster parks actively used by shellfish operators: Rivedoux (R), Yves (Y), Charente (CH) and Daires (D) (Fig. 3; more details on the sampling sites in Bouchet and Sauriau, 2008). At all sampled stations, benthic foraminifera and macrofauna were sampled at the same time, allowing for a sound comparison between Foram-AMBI and AMBI, which is based on benthic macroinvertebrates (AMBI results were published in Bouchet and Sauriau,

2008).

In the Mediterranean Sea, Foram-AMBI was tested on data from the harbor of Cagliari in the South of Sardinia in Italy (Schintu et al., 2016) where a clear OM enrichment gradient was observed. This harbor includes the oil terminal of one of the largest oil refineries in the Mediterranean Sea. Sampling was carried out in four unvegetated zones of the harbor: (i) stations H1–H7: the historical port (HP), (ii) stations L1–L3: the Santa Gilla lagoon, (iii) stations G1–G10: the gulf facing the industrial areas, and (iv) stations B1–B3: control stations (Fig. 4).

## 2.6. Statistical analysis

The next two steps were followed to assign benthic foraminiferal species to the five EGs:

1. The WA optimum and tolerance were computed for each species to determine its preference with respect to TOC (%) using the optimos. prime R package (Sathicq et al., 2020).
2. Species assignment to EGs was done as follows: if a species had an optimum in the TOC range 0–2%, the species was assigned to EGI; in the range 2–2.5%, the species was assigned to EGII; in the range 2.5–3.4%, 3.4–4.1%, and above 4.1% to EGII, EGIII, EGIV and EGV. This is based on TOC-derived EcoQS (see Table 2; Bakke et al., 2010; Viaroli et al., 2004). One species' list per region was produced.

Typical example for each EG is shown for each region to visualize pattern of species response along the TOC gradient. A locally weighted scatterplot smooth line (LOESS) was fitted to each scatter plot. Marginal plots were added to each scatter plot to show the frequency of distribution of occurrences along the TOC gradient. The median of the distribution of the occurrences was also computed.

Two master tables (available in Bouchet et al., 2021) were used in the above-described procedure. These master tables included TOC percentages and species relative abundances data of the 21 studies from the
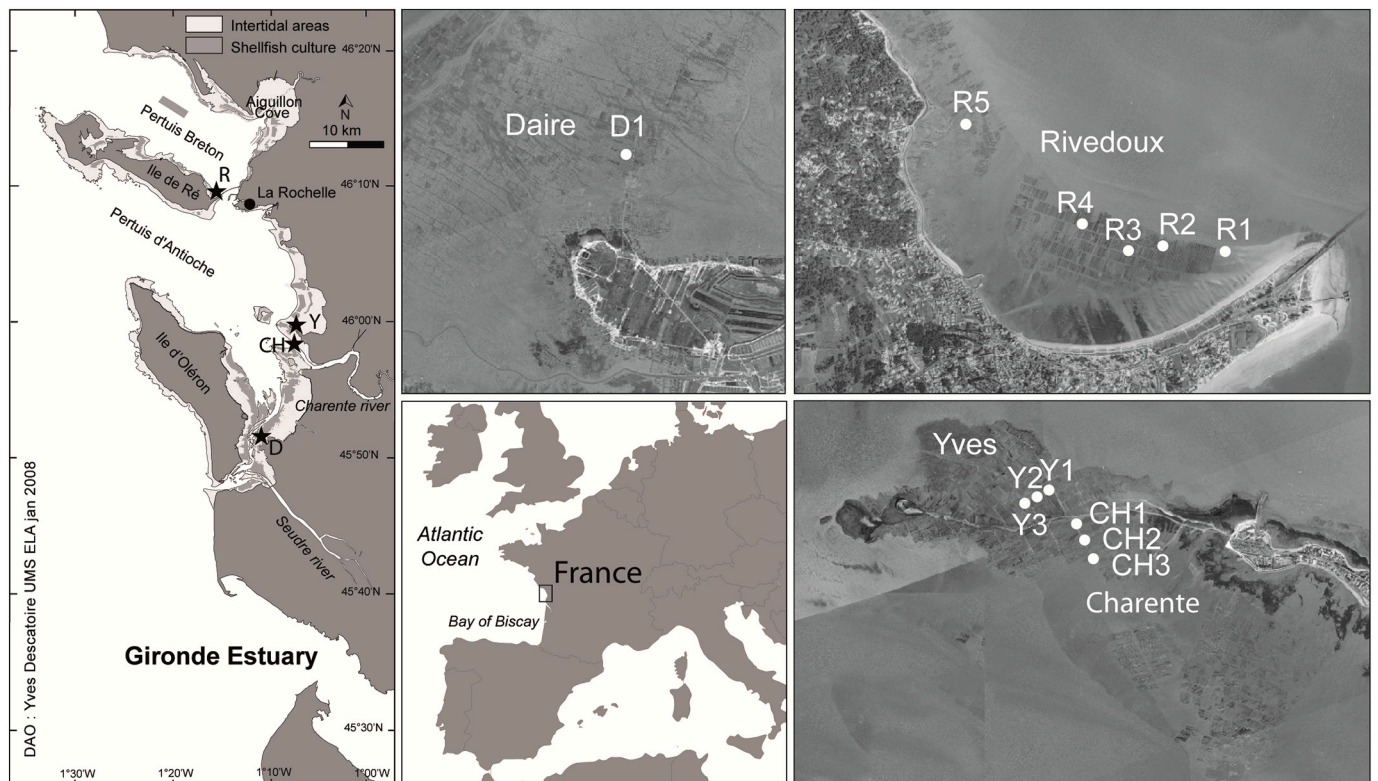


**Fig. 3.** Map of the sampling stations in the Pertuis Charentais (CH: Charente, D: Daires, R: Rivedoux and Y: Yves), SW France (from Bouchet and Sauriau, 2008).
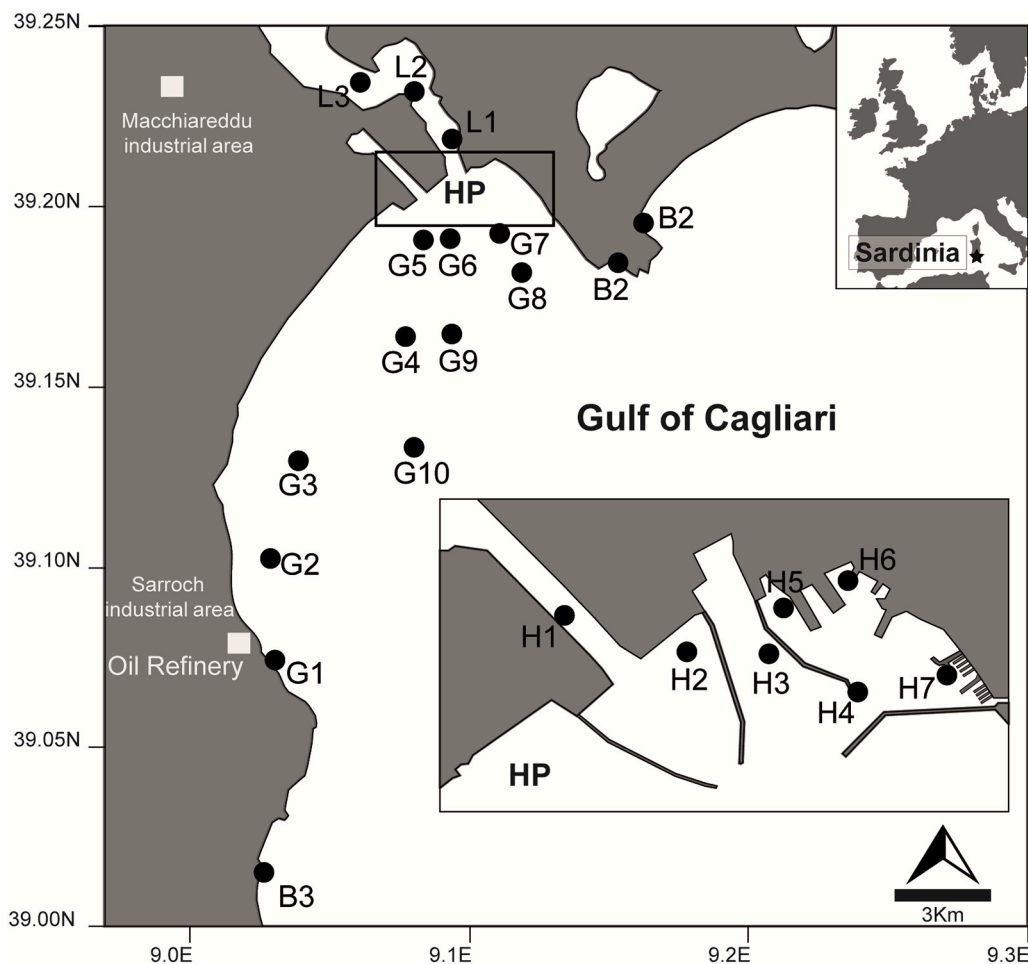
**Fig. 4.** Map of the sampling stations in the harbor of Cagliari in Sardinia (Italy). HP = historical port.
(Adapted from Schintu et al. (2016)).

English Channel/European Atlantic coast (587 samples) and the 21 studies from the Mediterranean Sea (301 samples).

As the distribution of OM, AMBI and Foram-AMBI was normally distributed (Kolmogorov-Smirnov test, p > 0.01), parametric statistics were used for the Cagliari and Pertuis parameters. The relation between Foram-AMBI, AMBI and organic matter (TOC values being not available for the Pertuis Charentais and Cagliari datasets) was quantified by mean of a Pearson's correlation coefficient $R^2$.

All these calculations were made using the statistical language R version 3.6.3 (R Core Team, 2020).

## 3. Results

### 3.1. Species assignments to EGs according to total organic carbon

#### 3.1.1. The English Channel/European Atlantic coast

In the English Channel/European Atlantic intertidal and TWs data-sets, TOC ranged between 0 and 16% (Appendix A). Fig. 5 presents a typical example of species-response curves for each of the five EGs. Most of the five figured species had a characteristic unimodal distribution pattern. However, the relative abundance distribution of *Cribroelphidium excavatum* and *C. williamsoni* was bimodal, with peaks at ~0–1% and ~7–12%, and at ~2–4% and ~7–9%, respectively. In total, 77 species from this geographic region were assigned: 22 in EGI, 13 in EGII, 23 in EGIII, 6 in EGIV and 13 in EGV (Appendix C). Despite their high opti-mum values, typical salt marsh species (*Balticammina pseudomacrescens*, *Entzia macrescens* and *Trochammina inflata*), which are dominant in en-vironments characterized by very high natural TOC values, were not

assigned. This is further explained in the discussion.

#### 3.1.2. The Mediterranean Sea

In the Mediterranean Sea intertidal and TWs datasets, TOC ranged between 0.07 and 17.8% (Appendix B). Fig. 6 presents typical examples of species-response curves for the five EGs. The relative abundance of most of the five figured species had unimodal distribution patterns. However, the relative abundance distribution of *Cribroelphidium gunteri* was bimodal, with peaks at ~2–3% and ~9–11%. In total, 79 species from this geographic region were assigned: 42 in EGI, 7 in EGII, 17 in EGIII, 4 in EGIV and 9 in EGV (Appendix D). Despite their high optimum values, typical salt marsh species (*Trochammina inflata*, *Entzia macres-cens* and *Haplophragmoides wilberti*), which are dominant in environ-ments characterized by very high natural TOC values, were not assigned. This point is further addressed in the discussion.

#### 3.1.3. Comparison of species assignments between the existing lists of benthic foraminifera

In total, the two lists established in this study for the English Channel and the European Atlantic and the Mediterranean Sea intertidal and TWs have 35 species in common (Table 3). Among these 35 species, ten species were assigned to the same EG in both regions, ten with a dif-ference in their assignment of only one category, whereas fifteen taxa showed an offset of two categories or more. Very surprisingly, the Elphidiidae *Cribroelphidium excavatum*, *C. gunteri* and *C. williamsoni*, *Bolivina* spp. and *Quinqueloculina* spp. exhibited an offset of three to four categories.
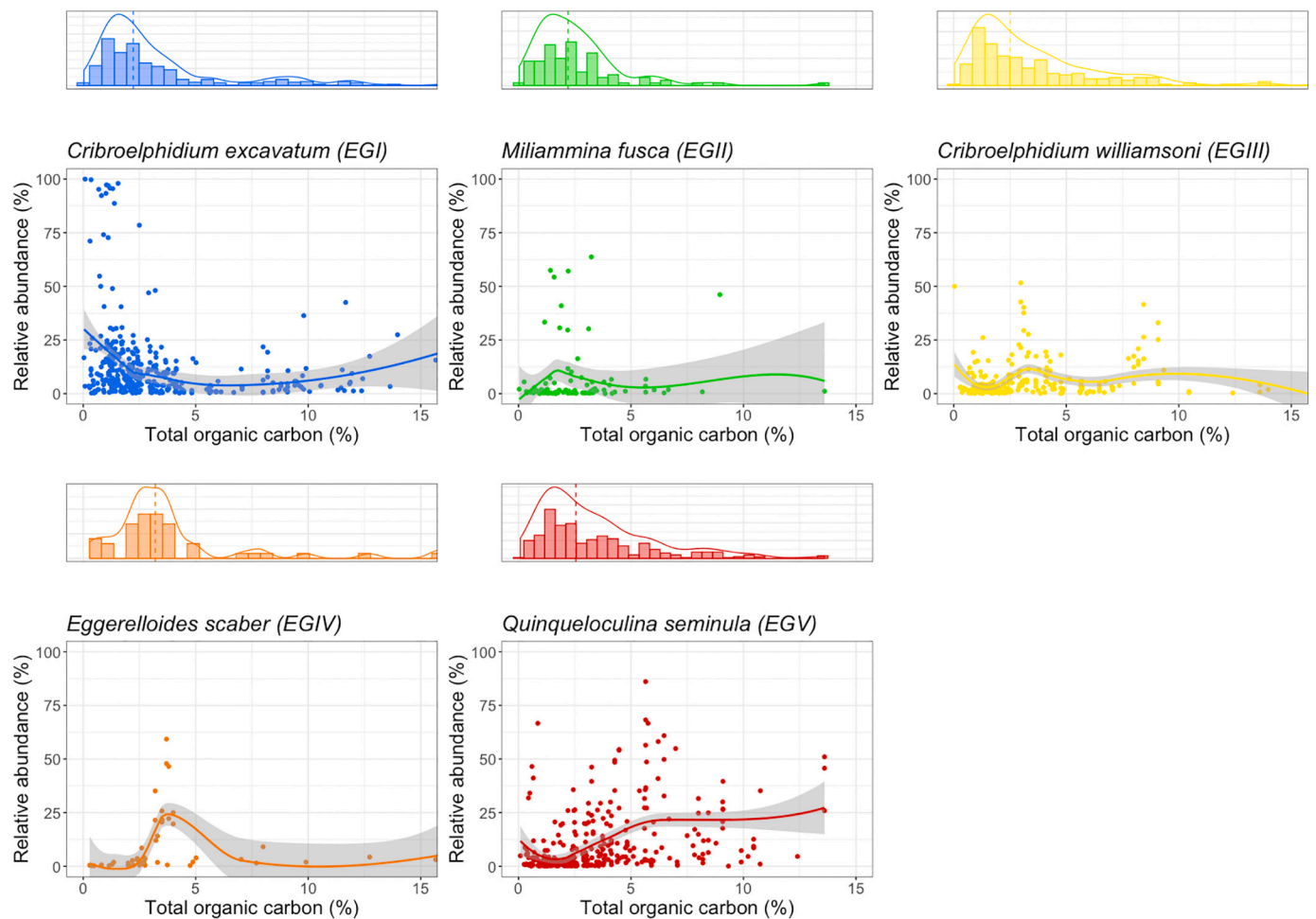
**Fig. 5.** Scatter plot fitted with a locally weighted scatterplot smooth line to visualize species response patterns along the total organic carbon (%) gradient. Typical examples are given for each of the five Foram-AMBI EGs from the English Channel/European Atlantic intertidal and TWs (one example per EG, shaded area is the 95% confidence interval): *Cribroelphidium excavatum* (EGI), *Miliammina fusca* (EGII), *Cribroelphidium williamsoni* (EGIII), *Eggerelloides scaber* (EGIV) and *Quinqueloculina seminula* (EGV). Marginal plots showed the frequency distribution of occurrences along the TOC gradient; and dashed line marked the median.

### 3.2. Test of the validity of the species' lists

#### 3.2.1. The English Channel/European Atlantic coast

In the Pertuis Charentais dataset, there was a significant positive correlation between Foram-AMBI and OM, and between AMBI and OM ($R^2 = 0.67$ p = 0.001 and $R^2 = 0.66$ p = 0.001; Fig. 7A and B; respectively). All foraminiferal species occurring at the sampling sites were assigned in EGs. Foram-AMBI ranged from 1.9 to 3.3 (Fig. 7A) and AMBI from 1.2 to 4 (Fig. 7B). They were significantly correlated ($R^2 = 0.56$, p < 0.01; Fig. 7C). Based on Foram-AMBI, EcoQS varied between good and moderate (Fig. 7). Both indices agreed that the best EcoQS was at the reference sampling station R1. Assessments of EcoQS derived from Foram-AMBI and AMBI partially match but were in some cases contradictory. There was 50% of full agreement between the two indices derived-EcoQS (Fig. 7A and B).

#### 3.2.2. The Mediterranean Sea

In the harbor of Cagliari, there was a significant positive correlation between Foram-AMBI and organic matter ($R^2 = 0.42$, p = 0.001; Fig. 7D). The relative abundance of species unassigned to EGs varied from 0.4 to 16.9%. Stations with the lowest organic matter (OM) values exhibited High EcoQS (Fig. 7D). With increasing OM content, Foram-AMBI-derived EcoQS changed to good i.e., slightly disturbed. There was a cluster of six samples with low TOC and low Foram-AMBI while all other samples had higher TOC and higher Foram-AMBI values.

## 4. Discussion

### 4.1. Natural variability of intertidal and TWs and reference conditions

The promising results of the present study do not, however, warrant an easy implementation of Foram-AMBI and comparable methods in intertidal areas and TWs. Biotic indices based on the indicator species concept, like AMBI, are not fully reliable to assess EcoQS in these water body types (*i.e.*, Borja et al., 2003; Blanchet et al., 2008; Bouchet and Sauriau, 2008; Salas et al., 2004). In fact, the natural features of these ecosystems hamper the disentanglement of natural- and human-induced changes. In particular, silt, clay and OM sedimentary contents are naturally high in intertidal areas and TWs, promoting tolerant and opportunistic species, while sensitive species naturally decline (Elliott and Quintino, 2007; Munari and Mistri, 2008). In intertidal areas and TWs, benthic communities could therefore be naturally similar to those found in anthropogenically-disturbed habitats (Blanchet et al., 2008; Munari and Mistri, 2008). Consequently, pristine, naturally disturbed intertidal areas and TWs could easily be misclassified in moderate to bad EcoQS (the so-called "estuarine quality paradox"; Dauvin, 2007; Dauvin and Ruellet, 2009; Elliott and Quintino, 2007), severely complicating the decision-making (Blanchet et al., 2008; Muniz et al., 2005; Quintino et al., 2006; Salas et al., 2004). The natural features of intertidal areas and TWs may also affect the outcome of sensitivity-based foraminiferal indices like Foram-AMBI and comparable methods. The definition of
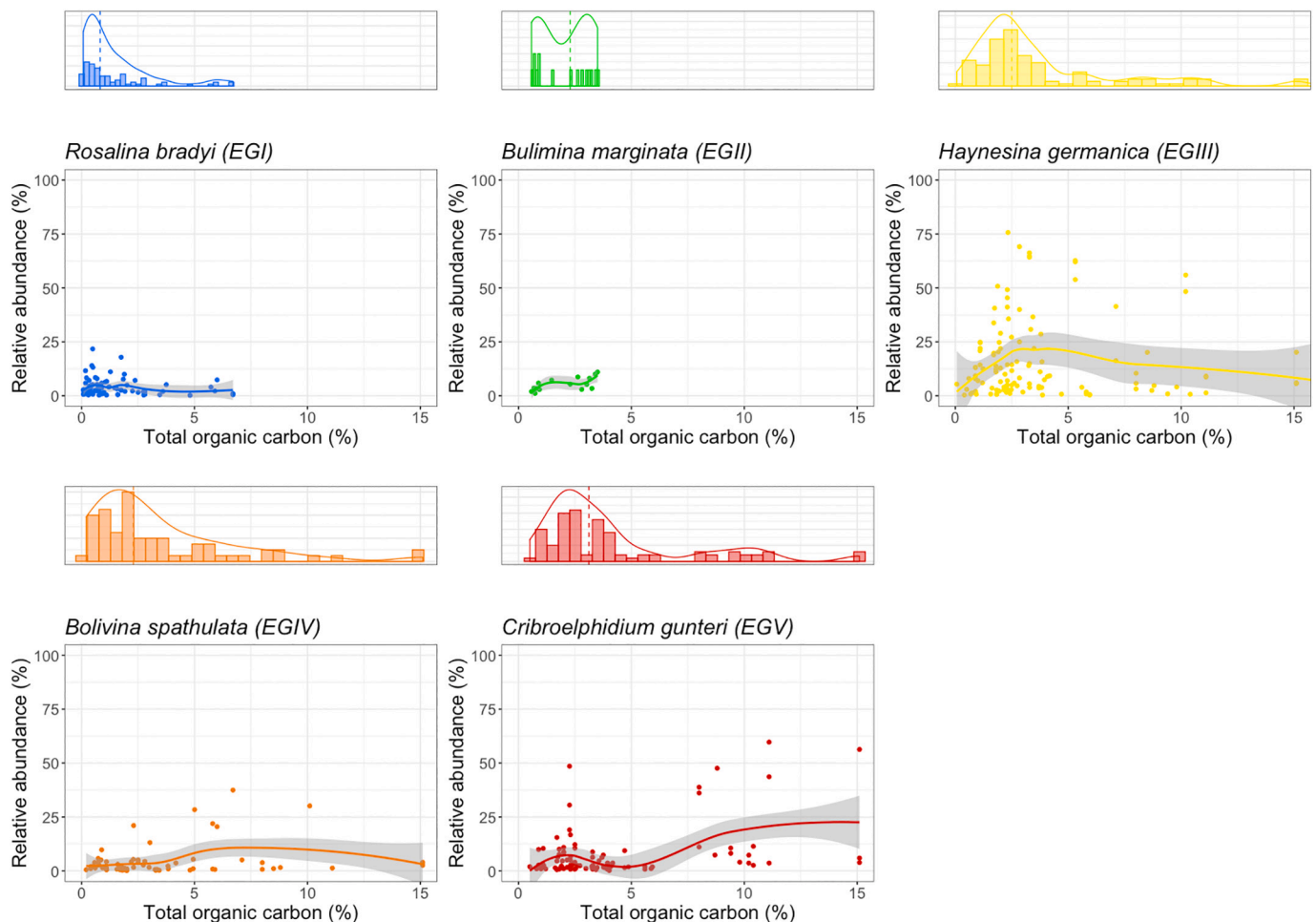
**Fig. 6.** Scatter plot fitted with locally weighted scatterplot smooth line to visualize species response patterns along the total organic carbon (%) gradient. Examples are given for each of the five Foram-AMBI EGs from the Mediterranean Sea intertidal and TWs (one example per EG, shaded area is the 95% confidence interval): *Rosalina bradyi* (EGI), *Bulimina marginata* (EGII), *Haynesina germanica* (EGIII), *Bolivina spathulata* (EGIV) and *Cribroelphidium gunteri* (EGV). Marginal plots showed the frequency distribution of occurrences along the TOC gradient; the dashed line marks the median.

water-body type-specific or local reference conditions is absolutely necessary to overcome such limitations. In fact, in order to assess the health of TWs and marine systems, it is mandatory to define reference conditions or to set targets according to marine legislations. For instance, a more robust assessment of EcoQS for TWs was obtained with benthic foraminifera using site-specific local reference conditions in the Oslofjord (Norway) (Dolven et al., 2013), in the Boulogne-sur-Mer harbor (France) (Francescangeli et al., 2016) and in the Santos estuary (Brazil) (Jesus et al., 2020). Furthermore, geochemical analyses of dated sediment cores can be used in combination with benthic foraminifera to determine ecological reference conditions in TWs (Klootwijk et al., 2021; Hess et al., 2020).

### 4.2. Assignment of benthic foraminifera from intertidal and TWs to EGs according to TOC response patterns

It is generally accepted that EcoQS obtained with AMBI (and Foram-AMBI) are valid only if species unassigned to EGs account for less than 20% (Borja and Muxika, 2005). In the two validation tests of the Foram-AMBI, there were virtually no unassigned species in the Pertuis Charentais dataset, and only 16.9% in the Harbor of Cagliari, warranting the validity of the EcoQS assessment. This suggests that enough species from intertidal and TWs have been assigned to test the lists over a large spatial scale in Europe.

For decades, increased supply of OM to coastal waters has been

considered to have a negative effect on ecosystems (Pearson and Rosenberg, 1978). As a consequence, TOC has become a typical indicator of environmental stress. Salt marshes are, per definition, vegetated by halophilic plants which are terrestrial in origin (Middelburg et al., 1997). Therefore, marsh habitats are expected to be characterized by high TOC (Armynot du Châtelet et al., 2018) whether or not they are impacted by human activities and discharge of organic carbon. Consequently, in salt marshes, TOC may be not a suitable indicator of human-induced stress. In the present study, TOC was the only ecological factor considered for species assignment to EGs. Commonly, in salt marshes, sediment contains a mix of refractory and labile OM (Armynot du Châtelet et al., 2009a; Leorri et al., 2018; Middelburg et al., 1997). Noticeably, the labile (food) directly stimulates growth and reproduction, while the refractory (terrestrial origin) TOC is not directly bioavailable (Pusceddu et al., 2009). Furthermore, environmental conditions encountered at low tide (*e.g.,* aerial exposure, low salinity, thermal stress) (Alve and Murray, 1999; Francescangeli et al., 2017) as well as seasonal changes (*e.g.,* desiccation or increased salinity during the dry season) further constrain foraminiferal species (Cearreta et al., 2002; De Rijk and Troelstra, 1997). Species distribution patterns in salt marshes are therefore mainly the outcome of a complex interplay between a number of natural stressors (see review in Murray, 2006).

In case we would have rigorously applied the method to use the WA optimum to classify species to EG's, the dominant species in salt marshes *Entzia macrescens*, *Trochammina inflata*, *Haplophragmoides wilberti* and

**Table 3**

Comparison of species assignments between the English Channel and European Atlantic intertidal and TWs (ECEA) and the Mediterranean Sea intertidal and TWs (MedS).

| | ECEA | MedS |
|---|---|---|
| *Ammobaculites balkwilli* | II | III |
| *Ammonia parkinsoniana* | II | I |
| *Ammonia tepida* | III | III |
| *Asterigerinata mamilla* | I | I |
| *Aubignyna perlucida* | V | V |
| *Bolivina dilatata* | III | II |
| *Bolivina ordinaria* | II | V |
| *Bolivina pseudoplicata* | II | V |
| *Bolivina striatula* | V | I |
| *Bolivina variabilis* | III | I |
| *Bolivina spathulata* | III | IV |
| *Bulimina elongata* | IV | III |
| *Bulimina marginata* | IV | II |
| *Buliminella elegantissima* | III | III |
| *Cibicidoides lobatulus* | I | I |
| *Cribroelphidium excavatum* | I | III |
| *Cribroelphidium gunteri* | III | V |
| *Cribroelphidium poeyanum* | I | III |
| *Cribroelphidium williamsoni* | III | I |
| *Elphidium advenum* | III | I |
| *Haynesina depressula* | I | I |
| *Haynesina germanica* | III | III |
| *Hopkinsina atlantica* | V | IV |
| *Hopkinsina pacifica* | V | V |
| *Miliammina fusca* | II | III |
| *Miliolinella subrotunda* | II | I |
| *Nonionoides turgidus* | III | III |
| *Planorbulina mediterranensis* | I | I |
| *Quinqueloculina carinatastriata* | V | I |
| *Quinqueloculina jugosa* | V | III |
| *Quinqueloculina lata* | V | II |
| *Quinqueloculina seminula* | V | I |
| *Quinqueloculina stelligera* | V | I |
| *Rosalina bradyi* | II | I |
| *Stainforthia fusiformis* | IV | V |

*Balticammina pseudomacrescens* would all have been assigned to EGIV/EGV, because of the consistently very high TOC values found in these environments. It implicitly means that we would interpret them as (strongly) opportunistic, and, additionally, that a high relative frequency of these taxa would indicate a polluted environment. The studied species distribution patterns are largely restricted to salt marshes where they naturally occur in high abundances (Alve and Murray, 1999; (Debenay et al., 2000); Cearreta et al., 2002; Fatela et al., 2009; Scott et al., 1996). The assignment of these typical salt marsh species to EGs IV and V would, in view of their systematically very high frequency in natural, apparently unpolluted, salt marshes, appear to be incorrect. For this reason, we did not assign typical salt marsh species to EGs.

### 4.3. Test of the species' assignments

In both validation datasets, Foram-AMBI yielded a positive significant correlation with organic matter content indicating that this sensitivity index calculated with the present study lists reflects the change in EcoQS along an OM gradient. In the Pertuis Charentais, the un-impacted station R1 had the lowest value, indicating a higher proportion of sensitive species. It was therefore possible to discriminate between this reference station and the impacted ones. Note that all stations are situated at the same level in the tidal zone and in similar habitats, so that differences in EcoQS are not due to the natural features of each of the sampling stations. In the harbor of Cagliari, Foram-AMBI adequately distinguished between high and good EcoQS.

In the Pertuis Charentais, a significant positive correlation between Foram-AMBI and AMBI values (based on macrofauna) confirmed previous correlations found between foraminiferal and macrofaunal communities and indices (Alve et al., 2019; Bouchet et al., 2018b). However,

only a 50% agreement in terms of EcoQS between Foram-AMBI and AMBI was reported. In this study, EcoQS boundaries established for AMBI (Borja et al., 2000) were used to infer EcoQS based on Foram-AMBI. Discrepancies in EcoQS assessment may suggest that specific Foram-AMBI-adapted criteria should be developed. For instance, intercalibration between the two indices may help improving the use of Foram-AMBI. This was successfully done in Norway when adapting the Norwegian Quality Index based on macrofauna ($NQI_m$) to the foraminiferal one ($NQI_f$) (Alve et al., 2019).

The results of the tests showed that the classification, obtained with the calculation of the WA optimum values for each species, probably adequately reflects differences in species tolerance to organic load-related stress. The outcome was a reliable assessment of EcoQS in the Pertuis Charentais and in the Harbor of Cagliari. The WA optimum method allowed for an objective assessment of the ecological requirement of each species along the TOC gradient. As for now in European intertidal and TWs, more tests on other independent data sets are, nevertheless, needed to further confirm the findings of this work, and most likely to improve the present study lists of species.

### 4.4. Potential problems due to benthic foraminiferal taxonomy

Different taxonomical schools co-exist in the foraminiferal community. Unfortunately, this sometimes leads to major inconsistencies with regards to species identification. Scientists working on other biological groups like macro-algae, phytoplankton or benthic macro-invertebrates organize workshops on a regular basis to compare and homogenize their taxonomy. After 20 years of workshops, scientists working on planktonic foraminifera have now agreed and published a global taxonomy of Cretaceous and Paleogene species and genera. In this way, they manage to minimize the remaining taxonomical inconsistency. This issue has also been raised by previous studies assigning benthic foraminifera to EGs (Alve et al., 2016; Jorissen et al., 2018). It appears relevant to keep organizing benthic foraminifera taxonomical workshops to intercalibrate the different taxonomical schools.

Since taxonomy is still mostly based on morphological criteria, taxonomical names used for the same foraminiferal species are rather inconsistent between researchers. For marine species, the WoRMS database provides an authoritative and comprehensive list of marine species including also information on synonymy. It is continuously revised, ensuring that it is kept up-to-date. Benthic foraminifera are included in the database (Hayward et al., 2020a), but foraminiferal studies rarely refer to it, unlike researchers working on benthic macro-invertebrates, for instance, for whom WoRMS is the database of reference for species names. It was therefore a true challenge to "homogenize" species names between studies to build up an accurate and reliable master table for this present work. To clearly and easily compare different foraminiferal studies, similar species concepts and consistent use of names are necessary. At the moment, WoRMS seems to be a relevant option to archive accepted scientific names (and associated synonyms) of benthic foraminiferal species. However, to ensure a high quality and to obtain the acceptance of the WoRMS database by a larger part of the community, the section concerning foraminiferal species needs the input of much more researchers working on foraminifera (Hayward et al., 2020b). Additionally, molecular analyses and a detailed morphological analysis based on SEM images of sequenced specimens have to be combined to confirm or refute the taxonomical identifications. The contribution of molecular studies has yet to be implemented in WoRMS.

### 4.5. Phylogeographic studies of (pseudo)cryptic species

In all studies considered for the species assignments, the taxonomy of benthic foraminifera was based on morphological criteria. However, cases such as cryptic species (different biological species with identical morphologies), morphological convergence (unrelated species showing
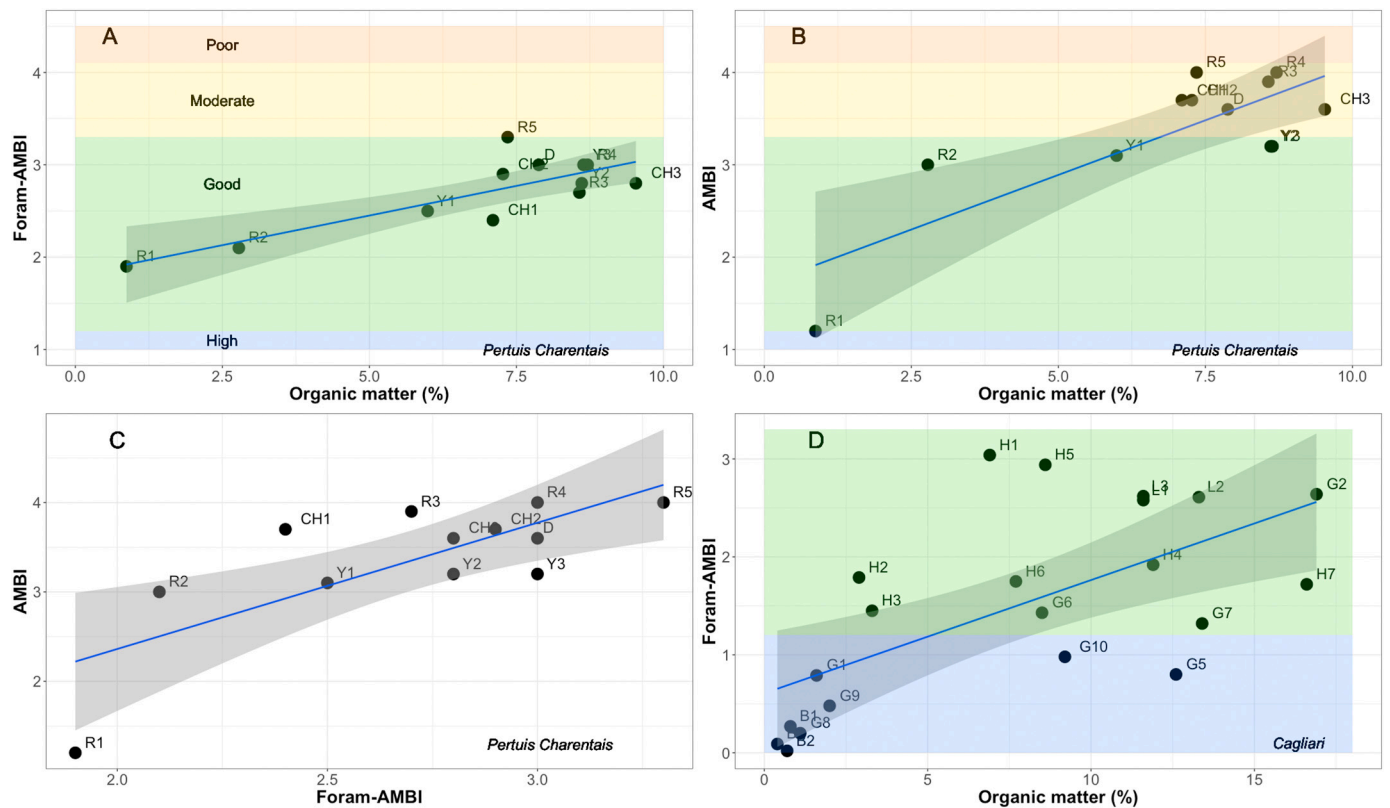
**Fig. 7.** Relationship between indices and OM in the Pertuis Charentais (A, B and C) and in the harbor of Cagliari (D). Linear regression models are in blue, grey shaded areas being the 95% confidence interval. In panel A, B and D, EcoQS are reported (for class boundaries see Table 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the same morphological characteristics) or ecophenotypic variations (same species looking different under different ecological conditions) are common, and make it virtually impossible to determine species by using morphology alone (Darling and Wade, 2008; Haynes, 1992; Pawlowski and Holzmann, 2008). The wide occurrence of cryptic species, which is starting to be visible through the increasing number of molecular studies, is a challenge for environmental biomonitoring (Feckler et al., 2014). In benthic foraminifera, the presence of cryptic species is now well documented in Elphidiidae (Darling et al., 2016; Pillet et al., 2013; Schweizer et al., 2011) and *Ammonia* (Bird et al., 2020; Hayward et al., 2004; Richirt et al., 2019). The present evidence suggests that different cryptic lineages in these taxa may have different ecological requirements, based on the observation of physiological (Jauffrais et al., 2018) or spatial distribution pattern differences (Bird et al., 2020; Richirt et al., 2019). Potentially, in the intertidal areas and TWs of the English Channel and the European Atlantic Ocean, one or several phylotypes of *C. excavatum* may be sensitive (*e.g.*, highest abundances at low TOC) while others may be more opportunistic (*e.g.*, highest abundances at high TOC). In such cases, it is important to combine morphological analyses and molecular identification (also called DNA barcoding or genetic characterization) (Hayward et al., 2004; Schweizer et al., 2005, 2009). Recently, a study on the genus *Ammonia* combined morphological and molecular taxonomies to determine morphological criteria for identifying the different phylotypes (Richirt et al., 2019). It is now possible to implement these morphological criteria in routine surveys to differentiate between the different pseudo-cryptic *Ammonia* species T1, T2 and T6. However, these morphological criteria for *Ammonia tepida* have only been available since 2019. In the studies used here, researchers pooled most *Ammonia* specimens under the name *A. tepida*.

Until data on the ecological requirements for each of the *Ammonia tepida* phylotypes are available, we decided to follow the taxonomy used

in the different studies even though we are fully aware that this is still an ongoing problem to be solved. This issue is however not specific to the work of our FOBIMO sub-WG on intertidal and TWs, as the other sub-WGs also had to cope with the same situation (Alve et al., 2016; Jorissen et al., 2018). Such improvements obtained by combining morphological and molecular analyses are important, considering that environmental biomonitoring uses the indicative value of species. However, their taxonomical identification needs to be cost effective, rapid and accurate.

Phylogeographic studies may help to better distinguish and identify possible cryptic species, and to describe the distribution pattern of the different phylotypes. Such studies, including large environmental surveys, allowing to understand the ecological requirements of each cryptic lineages, would complement morphological taxonomy. It will further help to assign species to the relevant EG. Therefore, ecological studies on cryptic species present a major topic for further scientific research projects.

### 4.6. Geographical variability of benthic foraminiferal EG assignments

The results of this study show that there can be an offset of up to four categories in species assignments to EGs depending on habitat type (different water-body types in TWs) or latitudinal gradient (from Northern Europe to the Mediterranean Sea). Noticeably, Elphidiidae, *Bolivina* spp. and *Quinqueloculina* spp., which are often the most abundant species, exhibited such large variations. Similar variations along latitudinal gradients and habitats types have been reported for macro-invertebrate species. For instance, the bivalve *Cerastoderma glaucum*, the polychaeta *Ampharete baltica* and *Hediste diversicolor* showed varying tolerance to OM content under different salinity regimes (Zettler et al., 2013).

In benthic foraminifera, these differences between areas and

environments may be explained by taxonomic discrepancies between the different regions (the same name given to different species or different names given to the same species) or plastic adaptation of the same species to different areas. For example, *Cribroelphidium gunteri* and *C. oceanense/C. oceanensis*, which share similar morphological features, are often mixed (Barbieri and Vaiani, 2018; Murray, 1979). It is therefore rather difficult to conclude if the assignment of *C. gunteri* in different EGs in the two studied regions (EGIII in the English Channel and Eastern Atlantic and EGV in the Mediterranean Sea) is due to local adaptation *i. e.*, plasticity or simply the result of taxonomical misidentification. The same may also apply to *Bolivina variabilis* (EGIII in the English Channel and Eastern Atlantic and EGI in the Mediterranean Sea), since the taxonomy is complex in bolivinids, leading to some confusions between morphological species. Furthermore, some of these morphospecies are known to shelter different cryptic or pseudocryptic species that are not separated when using the morphological concept, but could have different ecological requirements. For example, *C. excavatum* is assigned to EGI in the English Channel and Eastern Atlantic while it is assigned to EGIII in the Mediterranean Sea. The taxonomic situation of this morphospecies is rather confused because of its high intraspecific morphological variability, leading to the description of ecophenotypes, subspecies and species (Feyling-Hanssen, 1972). However, molecular studies showed that some of *C. excavatum* ecophenotypes can be raised to species (Darling et al., 2016). Similarly, *Quinqueloculina seminula* (Kaushik et al., 2019) contains cryptic species which might exhibit different ecological features explaining the assignment to EGV in the English Channel and Eastern Atlantic while it is assigned to the EGI in the Mediterranean Sea. This is however highly speculative; it may also be hypothesized that wrong taxonomical identification or plasticity in *C. excavatum* and *Q. seminula* may explain such differences.

Explaining the geographical variability of benthic foraminiferal EG assignments observed in this study remains quite uncertain. Describing and understanding the response of benthic foraminiferal species to TOC and to other natural and human-induces stressors in different habitats and along latitudinal gradients requires further work. This is in line with the increasing use of generalized linear mixed models (GLMMs) in biostatistics since non-normal data that involve random effects (*e.g.*, multimodal data based on different observers and/or environments) need to be carefully and appropriately handled (Bolker et al., 2009).

## 5. Conclusion

The present study shows that the classification probably adequately reflects differences in species tolerance to organic load-related stress. The tests of the species' lists on the two validation datasets can be considered a promising start which is worthy to pursue using other datasets. The assignment of typical salt marsh species was however not possible, since their classification in the opportunist EGs was not reflecting their natural ecological requirements. Furthermore, this study does not ensure that Foram-AMBI and comparable methods will perform well in all European waters. There is hence an urgent need to apply and

test sensitivity-based foraminiferal indices in different ecosystems and against different pollution sources. Otherwise, the community of foraminiferologists also suffers from severe taxonomical heterogeneity. A great effort must be devoted in the near future to encourage intercalibration exercises.

## CRediT authorship contribution statement

**Vincent M.P. Bouchet:** Conceptualization, Supervision, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft. **Fabrizio Frontalini:** Investigation, Writing – original draft. **Fabio Francescangeli:** Investigation, Visualization, Writing – original draft. **Pierre-Guy Sauriau:** Formal analysis, Visualization, Writing – review & editing. **Emmanuelle Geslin:** Supervision, Writing – review & editing. **Maria Virginia Alves Martins:** Investigation, Writing – review & editing. **Ahuva Almogi-Labin:** Writing – review & editing. **Simona Avnaim-Katav:** Investigation, Writing – review & editing. **Letizia Di Bella:** Writing – review & editing. **Alejandro Cearreta:** Investigation, Writing – review & editing. **Rodolfo Coccioni:** Writing – review & editing. **Ashleigh Costelloe:** Writing – review & editing. **Margarita D. Dimiza:** Writing – review & editing. **Luciana Ferraro:** Investigation, Writing – review & editing. **Kristin Haynert:** Writing – review & editing. **Michael Martínez-Colón:** Writing – review & editing. **Romana Melis:** Investigation, Writing – review & editing. **Magali Schweizer:** Writing – review & editing. **Maria V. Triantaphyllou:** Investigation, Writing – review & editing. **Akira Tsujimoto:** Writing – review & editing. **Brent Wilson:** Writing – review & editing. **Eric Armynot du Châtelet:** Supervision, Investigation, Writing – original draft.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

## Appendix A. Datasets from the English Channel/European Atlantic coast used for species assignments

| Dataset | Region | Country | Local study area | Water body type | Reference | Number of samples | Foram size fraction | TOC method | % TOC range |
|---|---|---|---|---|---|---|---|---|---|
| 1 | English Channel | France | Grand-Fort Philippe | Classical estuary | (Francescangeli, 2017) | 12 | >63 μm | CHN Elemental analyser | 0.4–2.7 |
| 2 | English Channel | France | Liane estuary | Classical estuary | Armynot du Châtelet et al. (2011) | 53 | >63 μm | CHN Elemental analyser | 0.3–5.9 |
| 3 | English Channel | France | Boulogne sur Mer Harbour | Artificial water body | (Francescangeli, 2017) | 12 | >63 μm | CHN Elemental analyser | 0.03–3.9 |
| 4 | English Channel | France | Canche estuary | Classical estuary | Francescangeli et al. (2017) | 103 | >63 μm | CHN Elemental analyser | 0.03–13.6 |

(*continued*)

| Dataset | Region | Country | Local study area | Water body type | Reference | Number of samples | Foram size fraction | TOC method | % TOC range |
|---|---|---|---|---|---|---|---|---|---|
| 5 | English Channel | France | Canche estuary | Classical estuary | Armynot du Châtelet et al. (2018) | 63 | >63 µm | CHN Elemental analyser | 0.03–13.6 |
| 6 | English Channel | France | Canche estuary | Classical estuary | (Francescangeli, 2017) | 12 | >63 µm | CHN Elemental analyser | 1.2–3.8 |
| 7 | English Channel | France | Authie estuary | Classical estuary | (Francescangeli, 2017) | 12 | >63 µm | CHN Elemental analyser | 0.7–1.8 |
| 8 | English Channel | France | Somme estuary | Classical estuary | (Francescangeli, 2017) | 16 | >63 µm | CHN Elemental analyser | 0.3–2.2 |
| 9 | English Channel | France | Bay of Veys | Coastal freshwater/ brackish water plume | Bouchet (unpublished) | 6 | >63 µm | LOI | 0.8–1.55 |
| 10 | Atlantic | France | Crouesty harbor | Artificial water body | Armynot du Châtelet (2003) | 14 | >63 µm | LOI | 0.1–16 |
| 11 | Atlantic | France | Loire estuary | Classical estuary | Mojtahid et al. (2016) | 32 | >150 µm | LECO-CS200® analyser | 0.1–2.6 |
| 12 | Atlantic | France | Aiguillon bay | Coastal freshwater/ brackish water plume | Armynot du Châtelet et al. (2009b) | 41 | >63 µm | LOI | 6.1–13.6 |
| 13 | Atlantic | France | Aiguillon Bay/ Ré Island | Coastal freshwater/ brackish water plume | Bouchet et al. (2009) | 3 | >63 µm | LOI | 9.1–9.9 |
| 14 | Atlantic | France | Ronce Perquis | Coastal freshwater/ brackish water plume | Bouchet et al. (2007) | 5 | >63 µm | LOI | 3.6–5.9 |
| 15 | Atlantic | Spain | Plentzia estuary | Classical estuary | Cearreta et al. (2002) | 5 | >63 µm | Walkey method | 3.6–9.3 |
| 16 | Atlantic | Spain | Ria de Vigo | Ria | Diz et al. (2006) | 28 | >63 µm | LECO-CS200® analyser | 2–4 |
| 17 | Atlantic | Portugal | Ria de Aveiro | Ria | Martins et al. (2015) | 53 | >63 µm | LOI | 0.1–7.4 |
| 18 | Atlantic | Portugal | Ria de Aveiro | Ria | Martins et al. (2013) | 29 | >63 µm | LOI | 1–10.7 |
| 19 | Atlantic | Portugal | Ria de Aveiro | Ria | Martins et al. (2010) | 15 | >63 µm | LOI | 0.6–10.7 |
| 20 | Atlantic | Portugal | Ria de Aveiro | Ria | Martins et al. (2016) | 31 | >63 µm | LOI | 1.4–3.8 |
| 21 | Atlantic | Portugal | Guadiana estuary | Classical estuary | Camacho et al. (2014) | 42 | >63 µm | CHN Elemental analyser | 0.2–8.9 |

Location of the different areas is shown in Fig. 2. TOC: total organic carbon, LOI: loss of ignition.

## Appendix B. Datasets from the Mediterranean Sea coast used for species assignments

| Dataset | Region | Country | Local study area | Water body type | Reference | Number of samples | Foram size fraction | TOC method | % TOC range |
|---|---|---|---|---|---|---|---|---|---|
| 22 | Mediterranean Sea | Spain | Ebro delta | Delta | Benito et al. (2016) | 36 | >63 µm | LOI | 0.89–17.8 |
| 23 | Mediterranean Sea | France | Bagès-Sigean lagoon | Lentic non-tidal lagoon | Foster et al. (2012) | 11 | >125 µm | CHN Elemental analyser | 0.5–3 |
| 24 | Mediterranean Sea | Italy | Sardinia island | Semi-enclosed bay/Lagoon | Schintu et al. (2015) | 18 | >63 µm | LOI | 0.5–10.1 |
| 25 | Mediterranean Sea | Italy | Santa Gilla | Lentic tidal lagoon | Frontalini et al. (2009) | 17 | >63 µm | CHN Elemental analyser | 1.7–2.5 |
| 26 | Mediterranean Sea | Italy | Orbetello | Lentic non tidal lagoon | Frontalini et al. (2010) | 7 | >63 µm | CHN Elemental analyser | 2.84–7.11 |
| 27 | Mediterranean Sea | Italy | Naples harbor | Artificial water body | Ferraro et al. (2006) | 54 | >125 µm | CHN Elemental analyser | 0.12–5.73 |
| 28 | Mediterranean Sea | Italy | Varano lake | Lentic non tidal lagoon | Frontalini et al. (2013) | 24 | >125 µm | CHN Elemental analyser | 1.1–4.2 |
| 29 | Mediterranean Sea | Italy | Lesina lagoon | Lentic tidal lagoon | Frontalini et al. (2010) | 11 | >63 µm | CHN Elemental analyser | 4.7–10.4 |
| 30 | Mediterranean Sea | Italy | Venice lagoon | Lentic tidal lagoon | Coccioni et al. (2009) | 12 | >63 µm | CHN Elemental analyser | 8–15.1 |
| 31 | Mediterranean Sea | Italy | Marano and Grado lagoon | Lentic tidal lagoon | Melis (unpublished data) | 11 | >63 µm | CHN Elemental analyser | 0.1–4.5 |
| 32 | Mediterranean Sea | Greece | Saronikos gulf | Semi-enclosed bay/lagoon | Portela (2017) | 11 | >125 µm | CHN Elemental analyser | 0.4–3.2 |
| 33 | Mediterranean Sea | Greece | Saronikos gulf | Semi-enclosed bay/lagoon | Dimiza et al. (2016) | 10 | >125 µm | CHN Elemental analyser | 0.6–3.1 |
| 34 | Mediterranean Sea | Greece | Evoikos gulf | Semi-enclosed bay/lagoon | Goreija (2013) | 8 | >125 µm | CHN Elemental analyser | 0.3–0.9 |
| 35 | Mediterranean Sea | Greece | Kavala bay | Semi-enclosed bay/lagoon | Delliou (2013) | 6 | >125 µm | CHN Elemental analyser | 0.1–0.8 |
| 36 | Mediterranean Sea | Turkey | Gulf of Izmir | Semi-enclosed bay/lagoon | Bergin et al. (2006) | 9 | >250 µm | Hach method | 2.4–6.7 |
| 37 | Mediterranean Sea | Israel | Timsah pond | Lentic non-tidal lagoon | Flako-Zaritsky et al. (2011) | 2 | >63 µm | CHN Elemental analyser | 10.6–12.6 |
| 38 | Mediterranean Sea | Israel | Betzet, Naaman, Poleg, Lachish estuaries | Classical estuary | Avnaim-Katav et al. (2016) | 7 | >63 µm | CHN Elemental analyser | 0.1–2.5 |
| 39 | Mediterranean Sea | Egypt | Abu-Qir bay | Semi-enclosed bay/lagoon | Elshanawany et al. (2011) | 18 | >63 µm | LECO-CS200® analyser | 0.1–6.7 |

(*continued*)

| Dataset | Region | Country | Local study area | Water body type | Reference | Number of samples | Foram size fraction | TOC method | % TOC range |
|---|---|---|---|---|---|---|---|---|---|
| 40 | Mediterranean Sea | Tunisia | Djerba lagoon | Lentic non-tidal lagoon | El Kateb et al. (2018) | 9 | >63 µm | CHN Elemental analyser | 0.07–0.9 |
| 41 | Mediterranean Sea | Tunisia | Monastir bay | Semi-enclosed bay/lagoon | Damak et al. (2019) | 10 | >125 µm | Walker and Black method | 0.5–5.25 |
| 42 | Mediterranean Sea | Tunisia | Bizerte lagoon | Lentic non-tidal lagoon | Alves Martins et al. (2015) | 10 | >63 µm | CHN Elemental analyser | 3.2–5.9 |

Location of the different areas is shown in Fig. 2. TOC: total organic carbon, LOI: loss of ignition.

## Appendix C. Assigned species from the English Channel/European Atlantic intertidal and TWs per ecological group (EG)

| Accepted scientific name | Accepted AphiaID | Optimum | Tolerance − | Tolerance + | EG |
|---|---|---|---|---|---|
| *Cribroelphidium poeyanum* | 113244 | 0.6 | 0.2 | 1.9 | I |
| *Subanomalina pauperata* | 847845 | 0.9 | 0.5 | 1.9 | I |
| *Asterigerinata mamilla* | 112933 | 1.1 | 0.6 | 2.0 | I |
| *Neocorbina nitida* | N.D. | 1.3 | 0.7 | 2.3 | I |
| *Haynesina depressula* | 113293 | 1.3 | 0.8 | 2.2 | I |
| *Lepidodeuterammina eddystonensis* | 817119 | 1.4 | 0.8 | 2.5 | I |
| *Elphidium pereirum* | N.D. | 1.5 | 1.3 | 1.7 | I |
| *Cribroelphidium excavatum* | 254680 | 1.6 | 0.6 | 4.0 | I |
| *Gavelinopsis praegiri* | 113159 | 1.6 | 0.9 | 2.7 | I |
| *Elphidium margaritaceum* | 113279 | 1.6 | 0.8 | 3.1 | I |
| *Planorbulina mediterranensis* | 113634 | 1.6 | 1.1 | 2.4 | I |
| *Polysaccammina hyperhalina* | 867465 | 1.6 | 0.6 | 4.5 | I |
| *Lepidodeuterammina ochracea* | 114306 | 1.7 | 1.1 | 2.5 | I |
| *Cibicidoides lobatulus* | 988323 | 1.7 | 0.7 | 3.8 | I |
| *Bolivina robusta* | 466349 | 1.7 | 1.0 | 2.8 | I |
| *Arenoparrella mexicana* | 417609 | 1.7 | 0.8 | 3.5 | I |
| *Paratrochammina (Lepidoparatrochammina) haynesi* | 736766 | 1.8 | 1.2 | 2.5 | I |
| *Elphidium cuvillieri* | 113263 | 1.8 | 0.8 | 3.8 | I |
| *Reophax nana* | 114011 | 1.8 | 1.3 | 2.5 | I |
| *Elphidium pulvereum* | 528472 | 1.8 | 1.0 | 3.3 | I |
| *Discorbis vilardeboanus* | 113154 | 1.8 | 1.0 | 3.4 | I |
| *Leptohalysis scottii* | 578704 | 1.9 | 1.5 | 2.4 | I |
| *Spirillina vivipara* | 113737 | 2.0 | 1.1 | 3.7 | II |
| *Rosalina bradyi* | 113167 | 2.0 | 1.3 | 3.0 | II |
| *Cribroelphidium magellanicum* | 113242 | 2.0 | 1.4 | 2.9 | II |
| *Ammobaculites balkwilli* | 163639 | 2.0 | 1.4 | 3.1 | II |
| *Ammotium morenoi* | 736481 | 2.1 | 1.2 | 3.7 | II |
| *Cibicidoides ungerianus* | 112889 | 2.1 | 1.3 | 3.4 | II |
| *Haplophragmoides manilaensis* | 417577 | 2.1 | 1.6 | 2.7 | II |
| *Miliolinella subrotunda* | 112564 | 2.1 | 0.8 | 5.4 | II |
| *Bolivina pseudoplicata* | 112982 | 2.2 | 1.1 | 4.5 | II |
| *Miliammina fusca* | 114064 | 2.3 | 1.2 | 4.3 | II |
| *Bolivina ordinaria* | 112978 | 2.3 | 0.7 | 7.2 | II |
| *Ammoscalaria pseudospiralis* | 113918 | 2.4 | 1.5 | 3.7 | II |
| *Ammonia parkinsoniana* | 418095 | 2.4 | 2.1 | 2.7 | II |
| *Bolivina dilatata* | 112973 | 2.5 | 1.7 | 3.6 | III |
| *Haynesina germanica* | 113294 | 2.5 | 1.0 | 6.1 | III |
| *Bolivina variabilis* | 112998 | 2.5 | 1.0 | 6.4 | III |
| *Buliminella elegantissima* | 113747 | 2.5 | 1.3 | 4.9 | III |
| *Ammotium cassis* | 114029 | 2.6 | 2.2 | 3.1 | III |
| *Eilohedra vitrea* | 466420 | 2.7 | 2.3 | 3.1 | III |
| *Miliammina obliqua* | 465995 | 2.7 | 1.6 | 4.6 | III |
| *Cribroelphidium williamsoni* | 1026169 | 2.7 | 0.9 | 8.2 | III |
| *Bolivinellina translucens* | 526512 | 2.7 | 2.3 | 3.2 | III |
| *Ammonia tepida* | 112857 | 2.8 | 1.1 | 7.1 | III |
| *Tiphotrocha comprimata* | 114331 | 2.8 | 1.3 | 5.9 | III |
| *Nonionella stella* | 113604 | 2.8 | 2.0 | 4.0 | III |
| *Bolivina spathulata* | 112988 | 2.9 | 2.4 | 3.5 | III |
| *Fursenkoina complanata* | 466392 | 2.9 | 2.5 | 3.5 | III |
| *Bolivinellina pseudopunctata* | 112999 | 3.0 | 2.3 | 3.9 | III |
| *Bulimina gibba* | 113040 | 3.1 | 2.5 | 3.7 | III |
| *Nonionoides turgidus* | 466471 | 3.2 | 2.5 | 4.0 | III |
| *Siphotrochammina lobata* | 522046 | 3.2 | 1.1 | 9.0 | III |
| *Cribroelphidium gunteri* | 1026170 | 3.2 | 1.2 | 8.7 | III |
| *Textularia earlandi* | 114273 | 3.2 | 1.3 | 7.9 | III |
| *Bulimina elegans* | 901990 | 3.2 | 1.2 | 8.6 | III |
| *Elphidium advenum* | 113254 | 3.3 | 2.9 | 3.6 | III |
| *Cribroelphidium gerthi* | 1026171 | 3.3 | 1.7 | 6.5 | III |
| *Stainforthia fusiformis* | 113070 | 3.4 | 1.8 | 6.5 | IV |
| *Balticammina pseudomacrescens* | 556254 | 3.4 | 2.8 | 4.2 | NA |
| *Bulimina marginata* | 113042 | 3.5 | 3.2 | 3.8 | IV |

(*continued*)

| Accepted scientific name | Accepted AphiaID | Optimum | Tolerance − | Tolerance + | EG |
|---|---|---|---|---|---|
| *Cornuspira involvens* | 112488 | 3.6 | 1.5 | 8.5 | IV |
| *Cribrostomoides jeffreysii* | 114035 | 3.6 | 3.6 | 3.6 | IV |
| *Eggerelloides scaber* | 113938 | 3.7 | 2.6 | 5.2 | IV |
| *Bulimina elongata* | 933974 | 3.9 | 2.5 | 5.9 | IV |
| *Hopkinsina atlantica* | 582285 | 4.1 | 2.0 | 8.7 | V |
| *Trochammina inflata* | 114348 | 4.1 | 1.9 | 9.1 | NA |
| *Quinqueloculina seminula* | 112674 | 4.3 | 1.9 | 9.7 | V |
| *Rotaliammina concava* | 850049 | 4.3 | 2.3 | 8.0 | V |
| *Entzia macrescens* | 742429 | 4.7 | 2.4 | 9.0 | NA |
| *Aubignyna hamblensis* | 146404 | 5.1 | 3.6 | 7.1 | V |
| *Quinqueloculina carinatastriata* | 466057 | 5.2 | 4.2 | 6.3 | V |
| *Elphidium articulatum* | 113257 | 5.3 | 2.9 | 9.6 | V |
| *Quinqueloculina lata* | 112644 | 5.4 | 2.3 | 12.7 | V |
| *Bolivina striatula* | 112989 | 6.2 | 3.4 | 11.6 | V |
| *Quinqueloculina stelligera* | 920885 | 7.1 | 3.2 | 15.8 | V |
| *Hopkinsina pacifica* | 113728 | 7.4 | 4.8 | 11.6 | V |
| *Fusulina lucida* | 909789 | 7.6 | 4.2 | 13.7 | V |
| *Quinqueloculina jugosa* | 112641 | 7.6 | 4.8 | 12.1 | V |
| *Aubignyna perlucida* | 466408 | 11.2 | 10.0 | 12.5 | V |

For each species, accepted scientific name and AphiaID (source: WoRMS), optimum and tolerance range to TOC are also reported. *Balticammina pseudomacrescens*, *Trochammina inflata* and *Enztia macrescens* are not assigned (NA).

## Appendix D. Assigned species from the Mediterranean Sea intertidal and TWs per ecological group (EG)

| Accepted scientific name | Accepted AphiaID | Optimum | Tolerance − | Tolerance + | EG |
|---|---|---|---|---|---|
| *Cribroelphidium incertum* | 113240 | 0.1 | 0.1 | 0.2 | I |
| *Sigmavirgulina tortuosa* | 113392 | 0.2 | 0.1 | 0.5 | I |
| *Cibicides refulgens* | 112877 | 0.2 | 0.1 | 0.7 | I |
| *Sigmoilina costata* | 112693 | 0.2 | 0.1 | 0.5 | I |
| *Astrononion stelligerum* | 113552 | 0.2 | 0.1 | 0.7 | I |
| *Asterigerinata mamilla* | 112933 | 0.4 | 0.2 | 1.1 | I |
| *Haynesina depressula* | 113293 | 0.5 | 0.2 | 1.2 | I |
| *Elphidium complanatum* | 113261 | 0.5 | 0.2 | 1.2 | I |
| *Rosalina macropora* | 113173 | 0.7 | 0.2 | 3.1 | I |
| *Cibicidoides lobatulus* | 988323 | 0.7 | 0.3 | 1.9 | I |
| *Rosalina bradyi* | 113167 | 0.8 | 0.3 | 2.1 | I |
| *Triloculina trigonula* | 112772 | 0.8 | 0.2 | 2.4 | I |
| *Textularia agglutinans* | 114264 | 0.8 | 0.5 | 1.3 | I |
| *Elphidium crispum* | 113262 | 0.8 | 0.3 | 2.4 | I |
| *Cassidulina carinata* | 183041 | 0.9 | 0.7 | 1.0 | I |
| *Rosalina globularis* | 113171 | 0.9 | 0.2 | 4.2 | I |
| *Planorbulina mediterranensis* | 113634 | 0.9 | 0.3 | 2.7 | I |
| *Elphidium advenum* | 113254 | 0.9 | 0.2 | 4.0 | I |
| *Peneroplis pertusus* | 112815 | 0.9 | 0.3 | 2.8 | I |
| *Quinqueloculina laevigata* | 112642 | 1.0 | 0.2 | 4.2 | I |
| *Ammonia beccarii* | 112849 | 1.1 | 0.3 | 3.4 | I |
| *Porosononion granosum* | 954808 | 1.1 | 0.5 | 2.2 | I |
| *Massilina secans* | 163641 | 1.1 | 0.3 | 4.7 | I |
| *Quinqueloculina stelligera* | 920885 | 1.1 | 0.3 | 4.5 | I |
| *Nonionoides grateloupii* | 418051 | 1.2 | 0.7 | 2.1 | I |
| *Ammonia parkinsoniana* | 418095 | 1.2 | 0.2 | 6.1 | I |
| *Quinqueloculina berthelotiana* | 112816 | 1.2 | 0.7 | 2.2 | I |
| *Bolivina variabilis* | 112998 | 1.3 | 0.4 | 4.1 | I |
| *Peneroplis planatus* | 112817 | 1.4 | 0.6 | 3.3 | I |
| *Adelosina mediterranensis* | 112536 | 1.4 | 0.5 | 4.2 | I |
| *Miliolinella subrotunda* | 112564 | 1.5 | 0.5 | 4.4 | I |
| *Discorinopsis aguayoi* | 417645 | 1.5 | 0.4 | 6.1 | I |
| *Quinqueloculina carinatastriata* | 466057 | 1.6 | 0.8 | 3.0 | I |
| *Quinqueloculina bicostata* | 417701 | 1.6 | 0.8 | 3.1 | I |
| *Cribroelphidium williamsoni* | 1026169 | 1.6 | 0.9 | 2.7 | I |
| *Siphonaperta aspera* | 593433 | 1.6 | 2.9 | 0.8 | I |
| *Spirillina vivipara* | 113737 | 1.6 | 0.3 | 8.8 | I |
| *Bolivina striatula* | 112989 | 1.7 | 0.4 | 7.9 | I |
| *Quinqueloculina seminula* | 112674 | 1.8 | 0.7 | 4.7 | I |
| *Cycloforina contorta* | 112516 | 1.8 | 0.8 | 3.9 | I |
| *Adelosina longirostra* | 112535 | 1.8 | 1.0 | 3.5 | I |
| *Adelosina milletti* | 522161 | 1.9 | 1.1 | 3.3 | I |
| *Adelosina cliarensis* | 112529 | 2.0 | 0.9 | 4.1 | II |
| *Bulimina marginata* | 113042 | 2.1 | 1.2 | 3.8 | II |
| *Quinqueloculina lata* | 112644 | 2.2 | 0.6 | 8.5 | II |
| *Valvulineria bradyana* | 112960 | 2.2 | 1.2 | 3.9 | II |
| *Bolivina dilatata* | 112973 | 2.2 | 0.9 | 5.7 | II |
| *Rectuvigerina phlegeri* | 113755 | 2.3 | 1.3 | 4.0 | II |

(*continued*)

| Accepted scientific name | Accepted AphiaID | Optimum | Tolerance − | Tolerance + | EG |
|---|---|---|---|---|---|
| *Ammobaculites exiguus* | 417589 | 2.3 | 2.0 | 2.7 | II |
| *Quinqueloculina jugosa* | 112641 | 2.4 | 1.1 | 5.0 | III |
| *Vertebralina striata* | 112785 | 2.4 | 1.0 | 5.5 | III |
| *Ammonia tepida* | 112857 | 2.4 | 0.9 | 6.1 | III |
| *Ammobaculites balkwilli* | 163639 | 2.4 | 1.4 | 4.2 | III |
| *Ammoscalaria runiana* | 113919 | 2.4 | 2.0 | 3.0 | III |
| *Bulimina elongata* | 933974 | 2.5 | 1.3 | 4.9 | III |
| *Cribroelphidium excavatum* | 254680 | 2.5 | 2.0 | 3.3 | III |
| *Triloculina marioni* | 112763 | 2.6 | 1.3 | 5.0 | III |
| *Cribroelphidium selseyense* | 754247 | 2.6 | 1.7 | 4.1 | III |
| *Buliminella elegantissima* | 113747 | 2.7 | 0.4 | 16.2 | III |
| *Haynesina germanica* | 113294 | 3.0 | 1.5 | 5.8 | III |
| *Nonionoides turgidus* | 466471 | 3.0 | 2.3 | 4.0 | III |
| *Cribroelphidium poeyanum* | 113244 | 3.2 | 2.5 | 4.1 | III |
| *Textularia bocki* | 114267 | 3.2 | 2.7 | 3.7 | III |
| *Miliammina fusca* | 114064 | 3.2 | 2.4 | 4.3 | III |
| *Discorbinella bertheloti* | 113143 | 3.3 | 2.5 | 4.3 | III |
| *Adelosina pulchella* | 112538 | 3.3 | 1.8 | 6.1 | III |
| *Ammonia batava* subsp. *compacta* | 1381806 | 3.4 | 2.6 | 4.5 | IV |
| *Bolivina spathulata* | 112988 | 3.6 | 1.5 | 8.5 | IV |
| *Porosononion subgranosus* | 556679 | 3.8 | 2.7 | 5.2 | IV |
| *Hopkinsina atlantica* | 582285 | 3.9 | 3.1 | 4.8 | IV |
| *Bolivina ordinaria* | 112978 | 4.2 | 3.4 | 5.1 | V |
| *Bolivina pseudoplicata* | 112982 | 4.3 | 3.3 | 5.5 | V |
| *Cribroelphidium gunteri* | 1026170 | 4.7 | 2.1 | 10.7 | V |
| *Rosalina irregularis* | 113172 | 4.8 | 4.1 | 5.6 | V |
| *Aubignyna perlucida* | 466408 | 5.2 | 1.8 | 15.3 | V |
| *Quinqueloculina oblonga* | 912989 | 5.2 | 3.5 | 7.8 | V |
| *Quinqueloculina costata* | 523480 | 5.9 | 3.2 | 11.0 | V |
| *Trochammina inflata* | 114348 | 8.2 | 3.9 | 17.3 | NA |
| *Entzia macrescens* | 742429 | 8.4 | 3.9 | 17.9 | NA |
| *Hopkinsina pacifica* | 113728 | 10.2 | 7.7 | 13.7 | V |
| *Stainforthia fusiformis* | 113070 | 10.4 | 8.5 | 12.8 | V |
| *Haplophragmoides wilberti* | 113955 | 11.1 | 8.4 | 14.8 | NA |

For each species, accepted scientific name and AphiaID (source: WoRMS), optimum and tolerance range to TOC are also reported. *Trochammina inflata*, *Enztia macrescens* and *Haplophragmoides wilberti* are not assigned (NA).

# References

Alve, E., 1995. Benthic foraminiferal distribution and recolonization of formerly anoxic environments in Drammensfjord, southern Norway. Mar. Micropaleontol. 25, 169–186. https://doi.org/10.1016/0377-8398(95)00007-N.

Alve, E., Murray, J.W., 1999. Marginal marine environments of the Skagerrak and Kattegat: a baseline study of living (stained) benthic foraminiferal ecology. Palaeogeogr. Palaeoclimatol. Palaeoecol. 146, 171–193. https://doi.org/10.1016/S0031-0182(98)00131-X.

Alve, E., Lepland, A., Magnusson, J., Backer-Owe, K., 2009. Monitoring strategies for re-establishment of ecological reference conditions: possibilities and limitations. Mar. Pollut. Bull. 59, 297–310. https://doi.org/10.1016/j.marpolbul.2009.08.011.

Alve, E., Korsun, S., Schönfeld, J., Dijkstra, N., Golikova, E., Hess, C., Husum, K., Panieri, G., 2016. Foram-AMBI: a sensitivity index based on benthic foraminiferal faunas from North-East Atlantic and Arctic fjords, continental shelves and slopes. Mar. Micropaleontol. 122, 1–12. https://doi.org/10.1016/j.marmicro.2015.11.001.

Alve, E., Hess, S., Bouchet, V.M.P., Dolven, J.K., Rygg, B., 2019. Intercalibration of benthic foraminiferal and macrofaunal biotic indices: an example from the Norwegian Skagerrak coast (NE North Sea). Ecol. Indic. 96, 107–115. https://doi.org/10.1016/j.ecolind.2018.08.037.

Alves Martins, M.V., Zaaboub, N., Aleya, L., Frontalini, F., Pereira, E., Miranda, P., Mane, M., Rocha, F., Laut, L., El Bour, M., 2015. Environmental quality assessment of Bizerte Lagoon (Tunisia) using living foraminifera assemblages and a multiproxy approach. PLoS One 10 (9), e0137250. https://doi.org/10.1371/journal.pone.0137250.

Armynot du Châtelet, E., 2003. Évaluation des possibilités d'utilisation des foraminifères comme bio-indicateurs de pollution dans les environnements paraliques (Thèse de doctorat). University of Angers.

Armynot du Châtelet, E., Debenay, J.-P., Soulard, R., 2004. Foraminiferal proxies for pollution monitoring in moderately polluted harbors. Environ. Pollut. 127, 27–40. https://doi.org/10.1016/S0269-7491(03)00256-2.

Armynot du Châtelet, E., Bout-Roumazeilles, V., Riboulleau, A., Trentesaux, A., 2009a. Sediment (grain size and clay mineralogy) and organic matter quality control on living benthic foraminifera. Rev. Micropaleontol. 52, 75–84. https://doi.org/10.1016/j.revmic.2008.10.002.

Armynot du Châtelet, E., Degré, D., Sauriau, P.-G., Debenay, J.-P., 2009b. Distribution of living benthic foraminifera in relation with environmental variables within the Aiguillon cove (Atlantic coast, France): improving knowledge for paleoecological interpretation. Bull. Soc. Géol. Fr. 180, 131–144. doi:https://doi.org/10.2113/gssgfbull.180.2.131.

Armynot du Châtelet, E., Francescangeli, F., Bouchet, V.M.P., Frontalini, F., 2018. Benthic foraminifera in transitional environments in the English Channel and the southern North Sea: a proxy for regional-scale environmental and paleo-environmental characterisations. Mar. Environ. Res. 137, 37–48. https://doi.org/10.1016/j.marenvres.2018.02.021.

Avnaim-Katav, S., Agnon, A., Sivan, D., Almogi-Labin, A., 2016. Calcareous assemblages of the southeastern Mediterranean low-tide estuaries - seasonal dynamics and paleo-environmental implications. J. Sea Res. 108, 30–49. https://doi.org/10.1016/j.seares.2015.12.002.

Bakke, T., Källqvist, T., Ruus, A., Breedveld, G.D., Hylland, K., 2010. Development of sediment quality criteria in Norway. J. Soils Sediments 10, 172–178. https://doi.org/10.1007/s11368-009-0173-y.

Barbieri, G., Vaiani, S.C., 2018. Benthic foraminifera or Ostracoda? Comparing the accuracy of paleoenvironmental indicators from a Pleistocene lagoon of the Romagna coastal plain (Italy). J. Micropalaeontol. 37, 203–230. https://doi.org/10.5194/jm-37-203-2018.

Barillé-Boyer, A.-L., Barillé, L., Massé, H., Razet, D., Héral, M., 2003. Correction for particulate organic matter as estimated by loss on ignition in estuarine ecosystems. Estuar. Coast. Shelf Sci. 58, 147–153. https://doi.org/10.1016/S0272-7714(03)00069-6.

Barras, C., Jorissen, F.J., Labrune, C., Andral, B., Boissery, P., 2014. Live benthic foraminiferal faunas from the French Mediterranean coast: towards a new biotic index of environmental quality. Ecol. Indic. 36, 719–743. https://doi.org/10.1016/j.ecolind.2013.09.028.

Benito, X., Trobajo, R., Cearreta, A., Ibáñez, C., 2016. Benthic foraminifera as indicators of habitat in a Mediterranean delta: implications for ecological and palaeoenvironmental studies. Estuar. Coast. Shelf Sci. 180, 97–113. https://doi.org/10.1016/j.ecss.2016.06.001.

Bergin, F., Kucuksezgin, F., Uluturhan, E., Barut, I.F., Meric, E., Avşar, N., Nazik, A., 2006. The response of benthic foraminifera and ostracoda to heavy metal pollution in Gulf of Izmir (Eastern Aegean Sea). Estuar. Coast. Shelf Sci. 66, 368–386. https://doi.org/10.1016/j.ecss.2005.09.013.

Bird, C., Schweizer, M., Roberts, A., Austin, W.E., Knudsen, K.L., Evans, K.M., Filipsson, H.L., Sayer, M.D., Geslin, E., Darling, K.F., 2020. The genetic diversity, morphology, biogeography, and taxonomic designations of Ammonia (Foraminifera) in the Northeast Atlantic. Mar. Micropal. 155, 101726 https://doi.org/10.1016/j.marmicro.2019.02.001.

Birks, H.J.B., Line, J.M., Juggins, S., Stevenson, A.C., Ter Braak, C.J.F., 1990. Diatoms and pH reconstruction. Phil. Trans. R. Soc. Lond. B 327, 263–278. https://doi.org/10.1098/rstb.1990.0062.

Blanchet, H., Lavesque, N., Ruellet, T., Dauvin, J.-C., Sauriau, P.-G., Desroy, N., Desclaux, C., Leconte, M., Bachelet, G., Janson, A.-L., Bessineton, C., Duhamel, S., Jourde, J., Mayot, S., Simon, S., de Montaudouin, X., 2008. Use of biotic indices in semi-enclosed coastal ecosystems and transitional waters habitats - implications for the implementation of the European Water Framework Directive. Ecol. Indic. 8, 360–372. https://doi.org/10.1016/j.ecolind.2007.04.003.

Bolker, B.M., Brooks, M.E., Clark, C.J., Geange, S.W., Poulsen, J.R., Stevens, M.H.H., White, J.-S.S., 2009. Generalized linear mixed models: a practical guide for ecology and evolution. Trends in Ecol. & Evol. 24, 127–135. https://doi.org/10.1016/j.tree.2008.10.008.

Borja, A., Muxika, I., 2005. Guidelines for the use of AMBI (AZTI's Marine Biotic Index) in the assessment of the benthic ecological quality. Mar. Pollut. Bull. 50, 787–789. https://doi.org/10.1016/j.marpolbul.2005.04.040.

Borja, A., Franco, J., Pérez, V., 2000. A marine biotic index to establish the ecological quality of soft-bottom benthos within European estuarine and coastal environments. Mar. Pollut. Bull. 40, 1100–1114. https://doi.org/10.1016/S0025-326X(00)00061-8.

Borja, A., Muxika, I., Franco, J., 2003. The application of a Marine Biotic Index to different impact sources affecting soft-bottom benthic communities along European coasts. Mar. Pollut. Bull. 46, 835–845. https://doi.org/10.1016/S0025-326X(03)00090-0.

Borja, A., Chust, G., Muxika, I., 2019. Chapter three - forever young: the successful story of a marine biotic index. Adv. Mar. Biol. 82, 93–127. https://doi.org/10.1016/bs.amb.2019.05.001.

Bouchet, V.M.P., 2007. Dynamique et réponse fonctionnelle des foraminifères et de la macrofaune benthiques en zone ostréicole dans les pertuis charentais (Thèse de doctorat). University of Angers.

Bouchet, V.M.P., Sauriau, P.-G., 2008. Influence of oyster culture practices and environmental conditions on the ecological quality of intertidal mudflats in the Pertuis Charentais (SW France): a multi-index approach. Mar. Pollut. Bull. 56, 1898–1912. https://doi.org/10.1016/j.marpolbul.2008.07.010.

Bouchet, V.M.P., Debenay, J.-P., Sauriau, P.-G., Radford-Knoery, J., Soletchnik, P., 2007. Effects of short-term environmental disturbances on living benthic foraminifera during the Pacific oyster summer mortality in the Marennes-Oléron Bay (France). Mar. Environ. Res. 64, 358–383. https://doi.org/10.1016/j.marenvres.2007.02.007.

Bouchet, V.M.P., Sauriau, P.G., Debenay, J.-P., Mermillod-Blondin, F., Schmidt, S., Amiard, J.-C., Dupas, B., 2009. Influence of the mode of macrofauna-mediated bioturbation on the vertical distribution of living benthic foraminifera: first insight from axial tomodensitometry. J. Exp. Mar. Biol. Ecol. 371, 20–33. https://doi.org/10.1016/j.jembe.2008.12.012.

Bouchet, V.M.P., Alve, E., Rygg, B., Telford, R.J., 2012. Benthic foraminifera provide a promising tool for ecological quality assessment of marine waters. Ecol. Indic. 23, 66–75. https://doi.org/10.1016/j.ecolind.2012.03.011.

Bouchet, V.M.P., Alve, E., Rygg, B., Telford, R.J., 2013. Erratum to 'Benthic foraminifera provide a promising tool for ecological quality assessment of marine waters.' Ecol. Indic. 26, 183. doi:https://doi.org/10.1016/j.ecolind.2012.10.002.

Bouchet, V.M.P., Goberville, E., Frontalini, F., 2018a. Benthic foraminifera to assess Ecological Quality Statuses in Italian transitional waters. Ecol. Indic. 84, 130–139. https://doi.org/10.1016/j.ecolind.2017.07.055.

Bouchet, V.M.P., Telford, R.J., Rygg, B., Oug, E., Alve, E., 2018b. Can benthic foraminifera serve as proxies for changes in benthic macrofaunal community structure? Implications for the definition of reference conditions. Mar. Environ. Res. 137, 24–36. https://doi.org/10.1016/j.marenvres.2018.02.023.

Bouchet, V.M.P., Deldicq, N., Baux, N., Dauvin, J.-C., Pezy, J.-P., Seuront, L., Méar, Y., 2020. Benthic foraminifera to assess ecological quality statuses: the case of salmon fish farming. Ecol. Indic. 117, 106607. https://doi.org/10.1016/j.ecolind.2020.106607.

Bouchet, V.M.P., Frontalini, F., Francescangeli, F., Sauriau, P.G., Geslin, E., Martins, M.V.A., Almogi-Labin, A., Avnaim-Katav, S., Di Bella, L., Cearreta, A., Coccioni, R., Costelloe, A., Dimiza, M.D., Ferraro, L., Haynert, K., Martínez-Colón, M., Melis, R., Schweizer, M., Triantaphyllou, M.V., Tsujimoto, A., Wilson, B., Armynot du Châtelet, E., 2021. Relative abundances of benthic foraminifera in response to total organic carbon in sediments: data from European intertidal areas and transitional waters. Data in Brief (submitted).

Camacho, S., Moura, D., Connor, S., Scott, D., Boski, T., 2014. Ecological zonation of benthic foraminifera in the lower Guadiana Estuary (southeastern Portugal). Mar. Micropaleontol. 114, 1–18. https://doi.org/10.1016/j.marmicro.2014.10.004.

Cearreta, A., Irabien, M.J., Ulibarri, I., Yusta, I., Croudace, I.W., Cundy, A.B., 2002. Recent salt marsh development and natural regeneration of reclaimed areas in the Plentzia Estuary. N. Spain. Estuar. Coast. Shelf Sci. 54, 863–886. https://doi.org/10.1006/ecss.2001.0862.

du Châtelet, Armynot, Gebhardt, K., Langer, M.R., 2011. Coastal pollution monitoring: foraminifera as tracers of environmental perturbation in the port of Boulogne-sur-Mer (Northern France). Neues Jahrb. Für Geol. Paläontol. 262, 91–116. https://doi.org/10.1127/0077-7749/2011/0187.

Coccioni, R., Frontalini, F., Marsili, A., Mana, D., 2009. Benthic foraminifera and trace element distribution: a case-study from the heavily polluted lagoon of Venice (Italy). Mar. Pollut. Bull. 59, 257–267. https://doi.org/10.1016/j.marpolbul.2009.08.009.

Damak, M., Frontalini, F., Elleuch, B., Kallel, M., 2019. Benthic foraminiferal assemblages as pollution proxies along the coastal fringe of the Monastir Bay (Tunisia). J. Afr. Earth Sci. 150, 379–388. https://doi.org/10.1016/j.jafrearsci.2018.11.013.

Damak, M., Fourati, R., Elleuch, B., Kallel, M., 2020. Environmental quality assessment of the fish farms' impact in the Monastir Bay (eastern of Tunisia, Central Mediterranean): a benthic foraminiferal perspective. Environ. Sci. Pollut. Res. 27, 9059–9074. https://doi.org/10.1007/s11356-019-07523-7.

Darling, K.F., Wade, C.M., 2008. The genetic diversity of planktic foraminifera and the global distribution of ribosomal RNA genotypes. Mar. Micropaleontol. 67, 216–238. https://doi.org/10.1016/j.marmicro.2008.01.009.

Darling, K.F., Schweizer, M., Knudsen, K.L., Evans, K.M., Bird, C., Roberts, A., Filipsson, H.L., Kim, J.H., Gudmundsson, G., Wade, C.M., Sayer, M.D.J., Austin, W.E.N., 2016. The genetic diversity, phylogeography and morphology of Elphidiidae (Foraminifera) in the Northeast Atlantic. Mar. Micropaleontol. 129, 123. https://doi.org/10.1016/j.marmicro.2016.09.001.

Dauvin, J.-C., 2007. Paradox of estuarine quality: benthic indicators and indices, consensus or debate for the future. Mar. Pollut. Bull. 55, 271–281. https://doi.org/10.1016/j.marpolbul.2006.08.017.

Dauvin, J.-C., Ruellet, T., 2009. The estuarine quality paradox: is it possible to define an ecological quality status for specific modified and naturally stressed estuarine ecosystems? Mar. Pollut. Bull. 59, 38–47. https://doi.org/10.1016/j.marpolbul.2008.11.008.

De Rijk, S., Troelstra, S.R., 1997. Salt marsh foraminifera from the Great Marshes, Massahusetts: environmental controls. Palaeogeogr. Palaeoclimatol. Palaeoecol. 130, 81–112.

Debenay, Jean-Pierre, Guillou, Jean-Jacques, Redois, Fabrice, Geslin, Emmanuelle, 2000. Distribution trends of foraminiferal assemblages in paralic environments. Environmental Micropaleontology, The application of microfossils to environmental geology. Kluwer Academic/Plenum Publishers, New York, pp. 39–67.

Debenay, J.-P., Marchand, C., Molnar, N., Aschenbroich, A., Meziane, T., 2015. Foraminiferal assemblages as bioindicators to assess potential pollution in mangroves used as a natural biofilter for shrimp farm effluents (New Caledonia). Mar. Pollut. Bull. 93, 103–120. https://doi.org/10.1016/j.marpolbul.2015.02.009.

Delliou, A., 2013. Benthic Foraminifera as a Bio-monitoring Tool for Marine Ecosystem of North Aegean (MSc thesis). Aristotle University of Thessaloniki.

Denoyelle, M., Jorissen, F.J., Martin, D., Galgani, F., Miné, J., 2010. Comparison of benthic foraminifera and macrofaunal indicators of the impact of oil-based drill mud disposal. Mar. Pollut. Bull. 60, 2007–2021. https://doi.org/10.1016/j.marpolbul.2010.07.024.

Dijkstra, N., Junttila, J., Skirbekk, K., Carroll, J., Husum, K., Hald, M., 2017. Benthic foraminifera as bio-indicators of chemical and physical stressors in Hammerfest harbor (Northern Norway). Mar. Pollut. Bull. 114, 384–396. https://doi.org/10.1016/j.marpolbul.2016.09.053.

Dimiza, M.D., Triantaphyllou, M.V., Koukousioura, O., Hallock, P., Simboura, N., Karageorgis, A.P., Papathanassiou, E., 2016. The Foram Stress Index: a new tool for environmental assessment of soft-bottom environments using benthic foraminifera. A case study from the Saronikos Gulf, Greece, Eastern Mediterranean. Ecol. Indic. 60, 611–621.

Diz, P., Francés, G., Rosòn, G., 2006. Effects of contrasting upwelling-downwelling on benthic foraminiferal distribution in the Ría de Vigo (NW Spain). J. Mar. Syst. 60, 1–18.

Dolven, J.K., Alve, E., Rygg, B., 2013. Defining past ecological status and *in situ* reference conditions using benthic foraminifera: a case study from the Oslofjord. Norway. Ecol. Indic. 29, 219–233. https://doi.org/10.1016/j.ecolind.2012.12.031.

El Kateb, A., Stalder, C., Neururer, C., Fentimen, R., Spangenberg, J.E., Spezzaferri, S., 2018. Distribution of benthic foraminiferal assemblages in the transitional environment of the Djerba lagoon (Tunisia). Swiss J. Geosci. 111, 561–578.

El Kateb, A., Stalder, C., Martinez-Colón, M., Mateu-Vicens, G., Francescangeli, F., Coletti, G., StainbanK, S., Spezzaferri, S., 2020. Foraminiferal-based biotic indices to assess the ecological quality status of the Gulf of Gabes (Tunisia): present limitations and future perspectives. Ecol. Indic. 111, 105962. https://doi.org/10.1016/j.ecolind.2019.105962.

Elliott, M., Quintino, V., 2007. The Estuarine Quality Paradox, environmental homeostasis and the difficulty of detecting anthropogenic stress in naturally stressed areas. Mar. Pollut. Bull. 54, 640–645. https://doi.org/10.1016/j.marpolbul.2007.02.003.

Elshanawany, R., Ibrahim, M.I., Milker, Y., Schmiedl, G., Badr, N., Kholeif, S.E.A., Zonneveld, K.A.F., 2011. Anthropogenic impact on benthic Foraminifera, Abu-Qir Bay, Alexandria. Egypt. J. Foraminifer. Res. 41, 326–348. https://doi.org/10.2113/gsjfr.41.4.326.

European Communities, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. Off. J. Eur. Communities 43 (L327) (75 pp.).

Fatela, F., Moreno, J., Moreno, F., Araújo, M.F., Valente, T., Antunes, C., Taborda, R., Andrade, C., Drago, T., 2009. Environmental constraints of foraminiferal assemblages distribution across a brackish tidal marsh (Caminha, NW Portugal). Mar. Micropaleontol. 70, 70–88.

Feckler, A., Zubrod, J.P., Thielsch, A., Schwenk, K., Schulz, R., Bundschuh, M., 2014. Cryptic species diversity: an overlooked factor in environmental management? J. Appl. Ecol. 51, 958–967.

Ferraro, L., Sprovieri, M., Alberico, I., Lirer, F., Prevedello, L., Marsella, E., 2006. Benthic foraminifera and heavy metals distribution: a case study from the Naples Harbour (Tyrrhenian Sea, Southern Italy). Environ. Pollut. 142, 274–287.

Feyling-Hanssen, R.W., 1972. The foraminifer *Elphidium excavatum* (Terquem) and its variant forms. Micropaleontology 18, 337–354.

Flako-Zaritsky, S., Almogi-Labin, A., Schilman, B., Rosenfeld, A., Benjamini, C., 2011. The environmental setting and microfauna of the oligohaline Timsah pond, Israel: the last remnant of the Kabara swamps. Mar. Micropaleontol. 80, 74–88. https://doi.org/10.1016/j.marmicro.2011.06.002.

Foster, W.J., Armynot du Châtelet, E., Rogerson, M., 2012. Testing benthic foraminiferal distributions as a contemporary quantitative approach to biomonitoring estuarine heavy metal pollution. Mar. Pollut. Bull. 64, 1039–1048. https://doi.org/10.1016/j.marpolbul.2012.01.021.

Francescangeli, F., 2017. Spatio-temporal Distribution of Benthic Foraminifera in Intertidal Areas of Hauts de France: Environmental Applications and Implications. University of Lille (PhD thesis).

Francescangeli, F., Armynot du Chatelet, E., Billon, G., Trentesaux, A., Bouchet, V.M.P., 2016. Palaeo-ecological quality status based on foraminifera of Boulogne-sur-Mer harbour (Pas-de-Calais, Northeastern France) over the last 200 years. Mar. Environ. Res. 117, 32–43.

Francescangeli, F., Bouchet, V.M.P., Trentesaux, A., Armynot du Châtelet, E., 2017. Does elevation matter? Living foraminiferal distribution in a hyper tidal salt marsh (Canche Estuary, Northern France). Estuar. Coast. Shelf Sci. 194, 192–204. https://doi.org/10.1016/j.ecss.2017.06.023.

Francescangeli, F., Quijada, M., Armynot du Châtelet, E., Frontalini, F., Trentesaux, A., Billon, G., Bouchet, V.M.P., 2020. Multidisciplinary study to monitor consequences of pollution on intertidal benthic ecosystems (Hauts de France, English Channel, France): comparison with natural areas. Mar. Environ. Res. 160, 105034. https://doi.org/10.1016/j.marenvres.2020.105034.

Frangipane, G., Pistolato, M., Molinaroli, E., Guerzoni, S., Tagliapietra, D., 2009. Comparison of loss on ignition and thermal analysis stepwise method for determination of sedimentary organic matter. Aquatic Conserv: Mar. Fresh. Ecosyst. 19, 24–33.

Frontalini, F., Buosi, C., Da Pelo, S., Coccioni, R., Cherchi, A., Bucci, C., 2009. Benthic foraminifera as bio-indicators of trace element pollution in the heavily contaminated Santa Gilla lagoon (Cagliari, Italy). Mar. Pollut. Bull. 58, 858–877. https://doi.org/10.1016/0025-326X(87)90360-2.

Frontalini, F., Buosi, C., Coccioni, R., 2010. Benthic foraminiferal assemblages and trace element contents from the lagoons of Orbetello and Lesina. Environ. Monit. Assess. 170, 245–260.

Frontalini, F., Margaritelli, G., Francescangeli, F., Rettori, R., Armynot du Chatelet, E., Coccioni, R., 2013. Benthic foraminiferal assemblages and biotopes in a coastal lake: the case study of lake Varano (Southern Italy). Acta Protozool. 52, 147–160.

Glémarec, M., Hily, C., 1981. Perturbations apportées à la macrofaune benthique de la baie de Concarneau par les effluents urbains et portuaires. Acta Oecologica Oecologia Appl. 2, 139–150.

Goreija, A., 2013. Study of the Geoenvironmental Conditions of the Surface Sediments of South Evoikos Gulf (MSc thesis). National and Kapodistrian University of Athens.

Grall, J., Glémarec, M., 1997. Using biotic indices to estimate macrobenthic community perturbations in the Bay of Brest. Estuar. Coast. Shelf Sci. 44 (S1), 43–53. https://doi.org/10.1016/S0272-7714(97)80006-6.

Haynes, J.R., 1992. Supposed pronounced ecophenotypy in foraminifera. J. Micropalaeontol. 11, 59–63.

Hayward, B.W., Holzmann, M., Grenfell, H.R., Pawlowski, J., Triggs, C.M., 2004. Morphological distinction of molecular types in *Ammonia* - towards a taxonomic revision of the world's most commonly misidentified foraminifera. Mar. Micropaleontol. 50, 237–271. https://doi.org/10.1016/S0377-8398(03)00074-4.

Hayward, B.W., Le Coze, F., Vachard, D., Gross, O., 2020a. World Foraminifera Database. Accessed at. http://www.marinespecies.org/foraminifera. on 2020-08-11. doi: 10.14284/305.

Hayward, B.W., Le Coze, F., Vandepitte, L., Vanhoorne, B., 2020b. Foraminifera in the World Register of Marine Species (WoRMS) taxonomic database. J. Foram. Res. 50, 291–300.

Hess, S., Alve, E., Andersen, T.J., Joranger, T., 2020. Defining ecological reference conditions in naturally stressed environments – how difficult is it? Mar. Environ. Res. 156, 104885.

Hily, C., 1983. Dynamique de la recolonisation par la macrofaune d'un substrat dragué à proximité du port de Brest. Oceanol. Acta 15, 113–120.

Hily, C., 1984. Variabilité de la macrofaune benthique dans les milieux hypertrophiques de la Rade de Brest (Thèse de Doctorat d'État). Université de Bretagne Occidentale.

Jauffrais, T., LeKieffre, C., Koho, K.A., Tsuchiya, M., Schweizer, M., Bernhard, J.M., Meibom, A., Geslin, E., 2018. Ultrastructure and distribution of kleptoplasts in benthic foraminifera from shallow-water (photic) habitats. Mar. Micropaleontol. 138, 46–62.

Jesus, M.S.D.S., Frontalini, F., Bouchet, V.M.P., Yamashita, C., Sartoretto, J.R., Figueira, R.C.L., Sousa, S.H.D.M., 2020. Reconstruction of the palaeo-ecological quality statuses in an anthropogenised estuary using benthic foraminifera: the Santos estuary (Sao Paulo state, SE Brazil). Mar. Env. Res. 162, 105121. https://doi.org/10.1016/j.marenvres.2020.105121.

Jorissen, F.J., Nardelli, M.P., Almogi-Labin, A., Barras, C., Bergamin, L., Bicchi, E., El Kateb, A., Ferraro, L., McGann, M., Morigi, C., Romano, E., Sabbatini, A., Schweizer, M., Spezzaferri, S., 2018. Developing Foram-AMBI for biomonitoring in the Mediterranean: species assignments to ecological categories. Mar. Micropaleontol. 140, 33–45. https://doi.org/10.1016/j.marmicro.2017.12.006.

Kaushik, T., Murugan, T., Dagar, S.S., 2019. Morphological variation in the porcelaneous benthic foraminifer *Quinqueloculina seminula* (Linnaeus, 1758): genotypes or morphotypes? A detailed morphotaxonomic, molecular and ecological investigation. Mar. Micropaleontol. 150, 101748. https://doi.org/10.1016/j.marmicro.2019.101748.

Klootwijk, A.T., Alve, E., Hess, S., Renaud, P.E., Sorlie, C., Dolven, J.K., 2021. Monitoring environmental impacts of fish farms: comparing reference conditions of sediment geochemistry and benthic foraminifera with the present. Ecol. Indic. 120, 106818 https://doi.org/10.1016/j.ecolind.2020.106818.

Leorri, E., Zimmerman, A.R., Mitra, S., Christian, R.R., Fatela, F., Mallinson, D., 2018. Refractory organic matter in salt marshes-effect on C sequestration calculations. Sci. Total Environ. 633, 391–398. https://doi.org/10.1016/j.scitotenv.2018.03.120.

Luczak, C., Janquin, M.-A., Kupka, A., 1997. Simple standard procedure for the routine determination of organic matter in marine sediment. Hydrobiologia 345, 87–94.

Majeed, S.A., 1987. Organic matter and biotic indices on the beaches of north Brittany. Mar. Pollut. Bull. 18, 490–495. https://doi.org/10.1016/0025-326X(87)90360-2.

Martins, V., Ferreira da Silva, E., Sequeira, C., Rocha, F., Duarte, A.C., 2010. Evaluation of the ecological effects of heavy metals on the assemblages of benthic foraminifera of the canals of Aveiro (Portugal). Estuar. Coast. Shelf Sci. 87, 293–304. https://doi.org/10.1016/j.ecss.2010.01.011.

Martins, V.A., Frontalini, F., Tramonte, K.M., Figueira, R.C.L., Miranda, P., Sequeira, C., Fernández-Fernández, S., Dias, J.A., Yamashita, C., Renó, R., Laut, L.L.M., Silva, F.S., Rodrigues, M.A.D.C., Bernardes, C., Nagai, R., Sousa, S.H.M., Mahiques, M., Rubio, B., Bernabeu, A., Rey, D., Rocha, F., 2013. Assessment of the health quality of Ria de Aveiro (Portugal): heavy metals and benthic foraminifera. Mar. Pollut. Bull. 70, 18–33. https://doi.org/10.1016/j.marpolbul.2013.02.003.

Martins, M.V.A., Silva, F., Laut, L.L.M., Frontalini, F., Clemente, I.M.M.M., Miranda, P., Figueira, R., Sousa, S.H.M., Dias, J.M.A., 2015. Response of benthic foraminifera to organic matter quantity and quality and bioavailable concentrations of metals in Aveiro Lagoon (Portugal). PLoS One 10, e0118077. https://doi.org/10.1371/journal.pone.0118077.

Martins, M.V.A., Pinto, A.F.S., Frontalini, F., da Fonseca, M.C.M., Terroso, D.L., Laut, L.L. M., Zaaboub, N., da Conceição Rodrigues, M.A., Rocha, F., 2016. Can benthic foraminifera be used as bio-indicators of pollution in areas with a wide range of physicochemical variability? Estuar. Coast. Shelf Sci. 182, 211–225. https://doi.org/10.1016/j.ecss.2016.10.011.

McLusky, D.S., Elliott, M., 2007. Transitional waters: a new approach, semantics or just muddying the waters? Estuar. Coast. Shelf Sci. 71, 359–363. https://doi.org/10.1016/j.ecss.2006.08.025.

Melis, R., Celio, M., Bouchet, V.M.P., Varagona, G., Bazzaro, M., Crosera, M., Pugliese, N., 2019. Seasonal response of benthic foraminifera to anthropogenic pressure in two stations of the Gulf of Trieste (northern Adriatic Sea): the marine protected area of Miramare versus the Servola water sewage outfall. Mediterr. Mar. Sci. 20, 120–141. https://doi.org/10.12681/mms.16154.

Middelburg, J.J., Nieuwenhuize, J., Lubberts, R.K., van de Plassche, O., 1997. Organic carbon isotope systematics of coastal marshes. Est. Coast. Shelf Sci. 45, 681–687. https://doi.org/10.1006/ecss.1997.0247.

Mojtahid, M., Jorissen, F., Durrieu, J., Galgani, F., Howa, H., Redois, F., Camps, R., 2006. Benthic foraminifera as bio-indicators of drill cutting disposal in tropical east Atlantic outer shelf environments. Mar. Micropaleontol. 61, 58–75.

Mojtahid, M., Jorissen, F., Pearson, T.H., 2008. Comparison of benthic foraminiferal and macrofaunal responses to organic pollution in the Firth of Clyde (Scotland). Mar. Pollut. Bull. 56, 42–76.

Mojtahid, M., Geslin, E., Coynel, A., Gorse, L., Vella, C., Davranche, A., Zozzolo, L., Blanchet, L., Bénéteau, E., Maillet, G., 2016. Spatial distribution of living (Rose Bengal stained) benthic foraminifera in the Loire estuary (western France). J. Sea Res. 118, 1–16. https://doi.org/10.1016/j.seares.2016.02.003.

Morvan, J., Le Cadre, V., Jorissen, F., Debenay, J.-P., 2004. Foraminifera as potential bio-indicators of the "Erika" oil spill in the Bay of Bourgneuf: field and experimental studies. Aquat. Living Resour. 17, 317–322. https://doi.org/10.1051/alr:2004034.

Munari, C., Mistri, M., 2008. The performance of benthic indicators of ecological change in Adriatic coastal lagoons: throwing the baby out with the water? Mar. Pollut. Bull. 56, 95–105. https://doi.org/10.1016/j.marpolbul.2007.09.037.

Muniz, P., Venturini, N., Pires-Vanin, A.M.S., Tommasi, L.R., Borja, A., 2005. Testing the applicability of a Marine Biotic Index (AMBI) to assessing the ecological quality of soft-bottom benthic communities, in the South America Atlantic region. Mar. Pollut. Bull. 50, 624–637. https://doi.org/10.1016/j.marpolbul.2005.01.006.

Murray, J.W., 1979. In: Kermack, D.M., Barnes, R.S.K. (Eds.), British Nearshore Foraminiferids. Synopses of the British Fauna (New Series). Academic Press, London, New York, p. 16 (68 pp.).

Murray, J.W., 2006. Ecology and Applications of Benthic Foraminifera. Cambridge University Press, Cambridge (426 pp.).

Pawlowski, J., Holzmann, M., 2008. Diversity and geographic distribution of benthic foraminifera: a molecular perspective. Biodivers. Conserv. 17, 317–328.

Pearson, T., Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanogr. Mar. Biol. Annu. Rev. 16, 229–311.

Pillet, L., Voltski, I., Korsun, S., Pawlowski, J., 2013. Molecular phylogeny of *Elphidiidae* (foraminifera): Mar. Micropal. 103, 1–14.

Polovodova Asteman, I., Hanslik, D., Nordberg, K., 2015. An almost completed pollution-recovery cycle reflected by sediment geochemistry and benthic foraminiferal assemblages in a Swedish–Norwegian Skagerrak fjord. Mar. Pollut. Bull. 95, 126–140. https://doi.org/10.1016/j.marpolbul.2015.04.031.

Portela, M., 2017. Benthic Foraminifera as a Tool for Assessment of Soft-bottom Environments and Projection to the Recent Past: Saronikos Gulf (Aegean Sea) Case Study (MSc thesis). University of Lille.

Pusceddu, A., Dell'Anno, A., Danovaro, R., Manini, E., Sara, G., Fabiano, M., 2003. Enzymatically hydrolyzable protein and carbohydrate sedimentary pools as indicators of the trophic state of detritus sink systems: a case study in a Mediterranean coastal lagoon. Estuaries 26, 641–650.

Pusceddu, A., Dell'Anno, A., Fabiano, M., Danovaro, R., 2009. Quantity and bioavailability of sediment organic matter as signatures of benthic trophic status. Mar. Ecol. Prog. Ser. 375, 41–52. https://doi.org/10.3354/meps07735.

Quintino, V., Elliott, M., Rodrigues, A.M., 2006. The derivation, performance and role of univariate and multivariate indicators of benthic change: case studies at differing spatial scales. J. Exp. Mar. Biol. Ecol. 330, 368–382. https://doi.org/10.1016/j.jembe.2005.12.040.

R Core Team, 2020. R: A Language and Environment for Statistical Computing. In: R Foundation for Statistical Computing. Austria. URL, Vienna. https://www.R-project.org/.

Reizopoulou, S., Penna, M., Boix, D., Buchet, R., Costas, N., Derolez, V., Gascon, S., Gifre, J., Artinoy, M., Pardo, I., Quintana, X., Trabucco, B., Sala, J., Salas Herrero, F., 2018. Transitional Waters Mediterranean Geographic Intercalibration Group. Benthic Invertebrates Ecological Assessment Methods; EU 29561. Pulbication office of the European Union, Luxembourg (JRC114720, 39 pp.).

Richirt, J., Schweizer, M., Bouchet, V.M.P., Mouret, A., Quinchard, S., Jorissen, F.J., 2019. Morphological distinctions of three *Ammonia* phylotypes occurring along European coasts. J. Foraminifer. Res. 49, 76–93. https://doi.org/10.2113/gsjfr.49.1.76.

Salas, F., Neto, J.M., Borja, A., Marques, J.C., 2004. Evaluation of the applicability of a marine biotic index to characterize the status of estuarine ecosystems: the case of Mondego estuary (Portugal). Ecol. Indic. 4, 215–225. https://doi.org/10.1016/j.ecolind.2004.04.003.

Sathicq, M.B., Nicolosi Gelis, M.M., Cochero, J., 2020. Calculating autoecological data (optima and tolerance range) for multiple species with the 'optimos.prime' R package. Austral Ecology 45, 845–850. https://doi.org/10.1111/aec.12868.

Schintu, M., Buosi, C., Galgani, F., Marrucci, A., Marras, B., Ibba, A., Cherchi, A., 2015. Interpretation of coastal sediment quality based on trace metal and PAH analysis, benthic foraminifera, and toxicity tests (Sardinia, Western Mediterranean). Mar. Poll. Bull. 94, 72–83. https://doi.org/10.1016/j.marpolbul.2015.03.007.

Schintu, M., Marrucci, A., Marras, B., Galgani, F., Buosi, C., Ibba, A., Cherchi, A., 2016. Heavy metal accumulation in surface sediments at the port of Cagliari (Sardinia, western Mediterranean): environmental assessment using sequential extractions and benthic foraminifera. Mar. Poll. Bull. 11, 45–56. https://doi.org/10.1016/j.marpolbul.2016.07.029.

Schönfeld, J., Alve, E., Geslin, E., Jorissen, F., Korsun, S., Spezzaferri, S., Abramovich, S., Almogi-Labin, A., Armynot du Chatelet, E., Barras, C., Bergamin, L., Bicchi, E., Bouchet, V.M.P., Cearreta, A., Di Bella, L., Dijkstra, N., Trevisan Disaro, S., Ferraro, L., Frontalini, F., Gennari, G., Golikova, E., Haynert, K., Hess, S., Husum, K., Martins, V., McGann, M., Oron, S., Romano, E., Mello Sousa, S., Tsujimoto, A., 2012. The FOBIMO (FOraminiferal BIo-MOnitoring) initiativeö—towards a standardised protocol for soft-bottom benthic foraminiferal monitoring studies. Mar. Micropaleontol. 94-95, 1–13.

Schweizer, M., Pawlowski, J., Duijnstee, I.A.P., Kouwenhoven, T.J., van der Zwaan, G.J., 2005. Molecular phylogeny of the foraminiferal genus *Uvigerina* based on ribosomal DNA sequences. Mar. Micropaleontol. 57, 51–67. https://doi.org/10.1016/j.marmicro.2005.07.001.

Schweizer, M., Pawlowski, J., Kouwenhoven, T., van der Zwaan, B., 2009. Molecular phylogeny of common Cibicidids and related Rotaliida (Foraminifera) based on small subunit rDNA sequences. J. Foraminifer. Res. 39, 300–315. https://doi.org/10.2113/gsjfr.39.4.300.

Schweizer, M., Polovodova, I., Nikulina, A., Schönfeld, J., 2011. Molecular identification of *Ammonia* and *Elphidium* species (foraminifera, Rotaliida) from the Kiel Fjord (SW Baltic Sea) with rDNA sequences. Helgol. Mar. Res. 65, 1–10. https://doi.org/10.1007/s10152-010-0194-3.

Scott, D.B., Collins, E.S., Duggan, J., Asioli, A., Saito, T., Hasegawa, S., 1996. Pacific Rim marsh foraminiferal distributions: implications for sea-level studies. J. Coast. Res. 12, 850–861.

Simboura, N., Zenetos, A., 2002. Benthic indicators to use in ecological quality classification of Mediterranean soft bottom marine ecosystems, including a new biotic index. Mediterr. Mar. Sci. 3, 77–111. https://doi.org/10.12681/mms.249.

Sousa, S.H.M., Yamashita, C., Semensatto Jr., D.L., Santarosa, A.C.A., Iwai, F.S., Omachi, C.Y., Disaró, S.T., Martins, M.V.A., Barbosa, C.F., Bonetti, C.H.C., Vilela, C. G., Laut, L., Turra, T., Alve, E., Armynot du Châtelet, E., Bouchet, V.M.P., Burone, L., Carmo, A., Figueira, R., Figueiredo, M., Frontalini, F., Geslin, E., Lamparelli, C., Licari, L., Lorini, M., Lourenço, R., Mahiques, M., Martin, T., Mello, R., Millo, C., Moreira, D., Pawlowski, J., Rodrigues, A., Siegle, Eduardo, 2020. Opportunities and challenges in incorporating benthic foraminifera in marine and coastal environmental biomonitoring of soft sediments: from science to regulation and practice. J. Sediment. Environ. 5, 257–265. https://doi.org/10.1007/s43217-020-00011-w.

Ter Braak, C.J.F., 1987. Unimodal Models to Relate Species to Environment (Doctoral thesis). University of Wageningen.

Vandepitte, L., Vanhoorne, B., Decock, W., Dekeyzer, S., Verbeeck, A.T., Bovit, L., Hernandez, F., Mees, J., 2015. How Aphia—the platform behind several online and taxonomically oriented databases—can serve both the taxonomic community and the field of biodiversity informatics. J. Mar. Sci. Eng. 3, 1448–1473. https://doi.org/10.3390/jmse3041448.

Viaroli, P., Bartoli, M., Giordani, G., Magni, P., Welsh, D.T., 2004. Biogeochemical indicators as tools for assessing sediment quality/vulnerability in transitional aquatic ecosystems. Aquatic Conserv: Mar. Freshw. Ecosyst. 14, S19–S29. https://doi.org/10.1002/aqc.647.

Zettler, M.L., Proffitt, C.E., Darr, A., Degraer, S., Devriese, L., Greathead, C., Kotta, J., Magni, P., Martin, G., Reiss, H., Speybroeck, J., Tagliapietra, D., Van Hoey, G., Ysebaert, T., 2013. On the myths of indicator species: issues and further consideration in the use of static concepts for ecological applications. PLoS One 8, e78219. https://doi.org/10.1371/journal.pone.0078219.