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Editorial

The Ecological Quality Status Assessment of Marine and Transitional Ecosystems: New Methods and Perspectives for the Future

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Abstract: Worldwide legislation emphasizes the need to monitor the health of aquatic ecosystems based on the response of biological quality elements to environmental conditions. A plethora of methodologies have been suggested in this sense. Lately, substantial efforts have led to the exploration of new biological quality elements from the meiobenthic compartment and the implementation of new methodologies based on environmental DNA. Due to their short life-cycles, meiofaunal organisms respond quickly to environmental variability. Changes in population dynamics and species composition are indicative of changes in environmental conditions. Recent pioneer studies have shown that biotic indices based on benthic foraminifera and nematodes can efficiently assess the health of transitional and marine ecosystems. The use of environmental DNA, as well as other fingerprinting techniques, is increasing in biomonitoring studies, and further calibrations are still needed to implement this method. The published papers in this Special Issue represent well the wide applicability of meiobenthic groups, i.e., benthic foraminifera and nematodes, allowing us to address a key ecological knowledge gap in order to convince decision makers and stakeholders about the advantage of introducing new biological quality elements in environmental biomonitoring.

Keywords: pollution; biomonitoring; nematode; foraminifera; meiofauna

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1. Introduction

Since the end of the 19th century, human activities have greatly altered the ecological quality of coastal areas. In response to concerns about environmental degradation, many nations have enacted legislation to counteract anthropogenic pollution, such as the Clean Water Act (CWA) or Oceans Act in the USA, Australia, and Canada, and the Water Framework Directive (WFD, 2000/60/EC) and Marine Strategic Framework Directive (MSFD, 2008/56/EC) in Europe. The WFD established a basis for the protection of ground, continental, transitional, and coastal waters, emphasizing the need to monitor and assess the ecological quality status (EcoQS) of these ecosystems. According to the WFD, European countries had to restore the environment to a "good" EcoQS by 2015. Since 2008, the MSFD has aimed to "*achieve good environmental status of the EU's marine waters by 2020 and to protect the resource base upon which marine-related economic and social activities depend*" (www.ec.europa.eu/environment/water/marine.htm, accessed on 3 August 2023). The MSFD highlights the necessity for the scientific community to increase its scientific knowledge of the elements that define the state of marine environments.

The implementation of this marine legislation has generated fruitful debate amongst marine scientists about how to define and implement efficient and reliable bio-assessment tools. As a consequence, a plethora of methodologies and tools, based on benthic macrofauna [1,2], seagrasses [3], fishes [4] and, more recently, on benthic foraminifera [5,6] and nematodes [7,8], have been suggested for assessing the health of marine systems. In this context, benthic macrofauna are the most widely used biological quality element to assess the so-called ecological quality status (EcoQS) in marine and transitional environments [9]. Lately, concerns have arisen about these macrofaunal indices, pointing out drawbacks of these methods [10]. Hence, there is an urgent need to develop alternative methods.

This Special Issue provided a unique forum to attract high-quality papers on the use of meiofaunal organisms to monitor the diversity and health of transitional and marine waters. Specifically, this Special Issue highlighted the need for an improvement in the marine legislation implementation process, particularly focusing on new groups such as meiofauna and new techniques, either numerical or with the use of geochemistry.

2. Overview of This Special Issue

2.1. The Estuarine Quality Paradox

Biotic indices based on the indicator species concept, such as AMBI, are currently facing issues in reliably assessing the EcoQS in these environments [11,12]. In fact, their natural features hamper disentangling natural- from human-induced changes, the so-called "estuarine quality paradox" [13]. Specifically, silt, clay, and organic matter sedimentary contents are naturally high in intertidal and TWs, promoting tolerant and opportunistic species, while sensitive species decline [13]. Benthic communities are, hence, similar to those found in anthropogenically disturbed areas [12]. This leads to the misclassification of a moderate to bad EcoQS in pristine intertidal areas in TWs, impairing decision making [12].

The paper by Jorissen et al. [14] proposed the marine influence index (MII) to provide an integrated, quantitative description of the highly variable environmental features controlling the foraminiferal communities in estuarine mudflats. The MII contains three components, as follows: (1) the relative distance along the salinity gradient, (2) the emergence time relative to a reference tidal cycle, and (3) the relative importance of the river outflow in the 30 days before sampling the foraminiferal fauna. The MII was designed to serve as a tool for predicting the composition of foraminiferal assemblages in intertidal estuarine mudflats, in particular, the relative frequencies (at different sites) of marine, estuarine, and freshwater species, and of stress-tolerant taxa.

The ability of the MII to correctly predict foraminiferal communities was tested in the companion paper by Fouet at al. [15]. This study focused on the distribution of foraminiferal species on the intertidal mudflats of two contrasted estuaries (Auray and Vie) along the French Atlantic coast. In these two estuaries, *Haynesina germanica* and the *Ammonia tepida* morphogroup dominated these foraminiferal communities. The work by Fouet et al. [15] showed that the MII was significantly correlated with the controlling environmental parameters (distance to the sea, percentage grains of <63 μm), as well as with the foraminiferal distribution patterns (PCA axis 1, species richness, and percentages of *Elphidium* spp. and *Quinqueloculina* spp.). Their results suggested that the MII explains a substantial part of the foraminiferal distribution patterns in estuarine intertidal mudflats, and can be used to detect deviations from the natural distribution in response to anthropogenic pollution.

2.2. Ecological Quality Status Monitoring with Benthic Foraminifera

In their seminal review, O'Brien et al. [16] investigated the use of foraminiferal biotic indices in transitional waters, and further suggested future research perspectives. In transitional waters, foraminifera can be used as environmental sentinels, providing ecological data such as diversity and sensitivity, which might serve as indices for EcoQS assessments. Foraminifera-based indices have been shown to correlate not only with various environmental stressors, but also with the most common macrofaunal-based indices. In this review, they presented, in detail, the existing foraminifera-based indices. Further, they illustrated the use of foraminiferal indices with some case studies to exemplify the key issues and discuss their potential solutions. Lastly, they evaluated the current status and future potential of an emerging field, genetic biomonitoring, focusing on how these new techniques can be used to increase the accuracy of EcoQS assessments in transitional systems by supplementing more established morphology-based methods.

Good taxonomy is a crucial aspect in any sampling survey. Pavard et al. [17] developed a fast and accurate method for identifying with a stereomicroscope the three phylotypes of *Ammonia* found in Europe. Among benthic foraminifera, the genus *Ammonia* is characterized by a high morphological variability that makes it particularly challenging to recognize using traditional morphology-based taxonomy. In this study, they assessed the possibility of implementing the two following criteria using a stereomicroscope, i.e., the average pore diameter and the elevation of sutures on the spiral side, initially developed for SEM images. Though the stereomicroscopic identification of *Ammonia* phylotypes based on these two morphological parameters needs to be cross-validated using molecular tools, this approach noticeably allows for the identification of an individual three to seven times faster than that using SEM. Finally, in the context of *Ammonia* phylotype T6 potentially being a non-indigenous species in Europe, this method will help to quickly identify *Ammonia* phylotypes; hence, this will contribute to monitoring the presence of T6 in different regions, providing new insights into its invasion in Europe.

The use of benthic foraminifera as biological quality elements for the implementation of marine legislation was highlighted in the papers by Carvalho et al. [18] in Brazil and Fajemila et al. [19] on the Lagos lagoon in Nigeria. In the latter, foraminiferal distribution patterns were driven by salinity and a multitude of stressors related to increasing anthropogenic influences. The three main foraminiferal assemblages identified along the continental slope of the Potiguar Basin (Brazil) represented the upper, middle, and lower slope. The distribution of foraminiferal species was driven by bathymetry, sediment (grain size, organic matter, chlorophyll, and phytodetritus content), and the water masses' properties (oxygen, temperature, and nutrients), together with bottom geomorphology and currents.

Three contributions specifically focused on monitoring the health of benthic habitats. In detail, Dubois et al. [20] considered the effects of fish farming in Corsica (France) in the Mediterranean Sea, Parent et al. [21] tested different biotic indices in a large survey along the French coast of the Mediterranean Sea, and Filippos et al. [22] assessed the effects of a sewage outfall in front of the nearshore beach of Cigarras in Brazil. All these studies highlighted the accuracy of foraminiferal biotic indices in evaluating EcoQS. However, the $\mathrm{Exp}(H'_{bc})$ was less efficient in the oligotrophic ecosystems of the Mediterranean Sea, where indices based on the response of species to organic pollution, i.e., Foram-AMBI and TSI-Med, showed better results. Furthermore, Parent et al. [21] proposed boundaries between the EcoQS adapted to benthic foraminifera for the Foram-AMBI index.

2.3. Innovative Approaches for the Future of Biomonitoring

The work from McGann [23] quantified the temporal association between two foraminiferal species, *Bulimina denudata* and *Eggereloides advenus*, with macrofaunal toxicity measures, i.e., fertilization in the purple sea urchin *Stronglyocentrotus purpuratus*, survival in the amphipod *Grandidierella japonica*, and sediment analyses. The abundance of *B. denudata* was positively correlated with amphipod survival and negatively correlated with arsenic, cadmium, unionized ammonia, and TOC. In the case of *E. advenus*, this was negatively correlated with sea urchin fertilization success, as well as beryllium, cadmium, and total PCBs. As both these foraminiferal species are tolerant to polluted sediments and their relative abundances appear to mirror those of macrofaunal toxicity tests, their use as cost- and time-effective marine sediment toxicity tests should be further investigated.

The study from Hoober et al. [24] introduced a method for defining element trace metal assessment in coastal sediments using benthic foraminiferal shells. Specifically, analyses of individual foraminifera shell chambers using the single-chamber Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICPMS) may provide documentation for short-term pollution events. The baseline assessment level (BAL) method presented in this work can be defined as the minima background concentrations for each element trace metal within a particular area, expressed as metal/Ca. The results demonstrated that the use of foraminiferal whole-shell ICPMS analyses could be implemented as a potential practical tool for routine monitoring once BAL values have been established.

Finally, Semprucci et al. [25] developed a new approach to detecting changes in the nematode community structure. Noticeably, they suggested a combination of morpho-functional traits (i.e., amphid, cuticle, buccal cavity, and tail shape) as an alternative to the taxonomic identification of nematodes. The results clearly demonstrated that the defined biological traits perfectly mirror the changes of the nematode community at the genus level. This method would greatly shorten the analyses of nematode fauna in biomonitoring programs, avoiding the need for experienced taxonomists to detect environmental changes in these nematode communities. This method can be also adapted to other meiobenthic groups, opening up new perspectives for the ecological assessment of meiofaunal communities.

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