Benthic Foraminifera as Ecological Sentinels of Marine Systems Health

FORAM-ECO

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Prepared by co-chairs:

Michael Martínez-Colón
Florida A&M University, USA
Email: michael.martinez@famu.edu

Vincent Bouchet
Université de Lille, France
Email: vincent.bouchet@univ-lille.fr

Orit Hyams-Kaphzan
Geological Survey of Israel, Israel
Email: orithy@gsi.gov.il

1. Summary

The development and implementation of a cost effective and high-impact method for long-term marine monitoring is much needed. Benthic foraminifera are excellent candidates due to their high sensitivity to environmental changes and ability to provide an estimate of natural baseline conditions. Due to their tests (shells) good preservation in sediment archives and hence, unlike most macrofauna, it allows the evolutionary reconstruction of marine environment thus providing a snapshot to pre-industrial times and *in-situ* ground-reference conditions of environmental health changes over time (deterioration vs. restoration). Many studies link changes in foraminiferal density, diversity, and dominance to environmental stress and designed different biotic indices. However, there is still a knowledge gap in environmental constraints of benthic foraminiferal distribution patterns, and hence a robust biotic index suitable for different environments is missing. Furthermore, promising results obtained with the application of eDNA in biomonitoring studies advocate for a larger implementation of this technique in foraminiferal studies.

The aim of the international FORAM-ECO working group is to improve the understanding of the environmental constraints of benthic foraminiferal distribution patterns in order to develop a robust biotic index to be implemented and widely used by authorities in marine environments following these goals: (i) assessment and implementation of the best foraminiferal index; (ii) implementation of metabarcoding to complement morphologically-based indices; (iii) determination of pre-industrial baseline conditions; and (iv) knowledge transfer and capacity building among members and beyond.

2. Scientific Background and Rationale

2.1 Importance of foraminifera in bioindicator monitoring

In order to protect and restore marine ecosystems, many nations have enacted legislations such as, for instance, the Clean Water Act (CWA) or Oceans Act in USA, Australia or Canada, the Water Framework Directive (WFD, 2000/60/EC) and the Marine Strategic Framework Directive (MSFD, 2008/56/EC) in Europe. As a consequence, a plethora of methodologies, based on benthic macrofauna (Borja et al., 2000; Leshno et al., 2016), seagrasses (Krause-Jensen et al., 2005), fishes (Coates et al. 2007) and, more recently, benthic foraminifera (e.g., Bouchet et al., 2012; Barras et al., 2014; Alve et al., 2016 and references therein), have been suggested to assess the health of marine ecosystems. In particular, benthic macrofauna are currently the most widely used group to assess ecological quality status (EcoQS) in marine environments (Dauvin et al., 2012).

Lately, concerns arose about macrofaunal indices, pointing out drawbacks of these methods (see review in Spilmont, 2013). For example, macrofaunal benthic indicators suffer from expert judgment dependence (Texeira et al., 2010), methodological dependence (Karakassis et al., 2013), inconsistent methods to assign species to ecological groups (Zettler et al., 2013), inconsistency among indices (Bouchet & Sauriau, 2008), and temporal variability (Reiss & Kröncke, 2005). There is, hence, an urgency to develop an alternative method, which can be used to bridge an important knowledge gap concerning determination of recent pre-industrial reference conditions.

Benthic foraminifera are protozoans that have increasingly been acknowledged as indicators of human-induced environmental stresses (e.g., Schwing et al., 2017), such as oil spills (Morvan et al., 2004;), heavy metals (Martínez-Colón et al., 2018), urban sewage (Hyams-Kaphzan et al. 2009), and aquaculture (Oron et al., 2014). Due to their short life cycles (3 months to 2 years; Murray, 1991), they respond quickly to environmental changes and adapt their population density and species composition accordingly (e.g., Kenigsberg et al., 2020). An important advantage compared to soft-body macrofauna is that foraminiferal tests (shells) composed of calcium carbonate or agglutinated grains, are preserved in the sediments. The high fossilization and preservation potential make them reliable paleoecological indicators of marine environments, thus providing a historical aspect to ecosystem deterioration or remediation, which have taken place during the last centuries (Dolven et al., 2013; Polovodova Asteman et al., 2015; Francescangeli et al., 2016; Hess et al., 2020). Such records are essential to assess pre-industrial conditions. Foraminifera occur in almost all marine environments and have much higher abundances than macrofauna. Thus, quantitative and statistically valid data are obtained from a small sediment sample volume (i.e., 50 cm^3). Recently proposed benthic foraminiferal biotic indices (Bouchet et al., 2012; Alve et al., 2016; Dimiza et al., 2016) provide opportunities for the further development and implementation of foraminifera as an acknowledged biological quality element considered by legislations for marine EcoQS assessment. Foraminiferal indices are based either on species diversity (Alve et al., 2009; Bouchet et al., 2012) or their sensitivity to environmental stressors (Barras et al., 2014; Jorissen et al., 2018; Prazeres et al., 2019). Foraminiferal indices have been particularly designed and applied to assess EcoQS of environmentally impacted marine habitats (e.g., Bouchet et al., 2018; Alve et al., 2019; El Kateb et al., 2020). Furthermore, eDNA studies (i.e., metabarcoding) were successfully applied to assess the impact of pollution e.g. from mercury, oil drilling and gas platform and aquaculture (Laroche et al., 2016; Cordier et al., 2019; Frontalini et al., 2018; He et al., 2018). However, benthic foraminifera are not yet acknowledged as a biological quality element by marine legislations, and, hence, foraminiferal indices are occasionally considered by legislations only in few countries (France, Israel, Norway, Australia).

2.2 The Challenge and Relevance to SCOR

Since 2011, the international FOraminiferal BIo-MOnitoring initiative (FOBIMO) has standardised methods for the use of benthic foraminifera in environmental monitoring. They unified the effort of foraminiferologists based worldwide to establish a common biotic index to assess the EcoQS. Amongst numerous protocols to assess the EcoQS (Birk et al., 2012), the AMBI index based on benthic macrofauna (Borja et al., 2000) is the most successful (Borja et al., 2019). Inspired by this work the, Foram-AMBI was introduced by Alve et al. (2016) for the North-East Atlantic and Arctic, including their fjords, continental shelves and slopes. Specifically, benthic foraminiferal species were assigned to ecological groups according to their response (e.g., tolerance, sensitivity, etc.) to organic matter enrichment in soft sediments (following Pearson & Rosenberg, 1978; Glémarec & Hily, 1981). Following the guideline of the FOBIMO working group, much emphasis was given on further development and testing of the Foram-AMBI index.

Other critical foraminiferal biotic indices were developed and successfully tested. Based on diversity indices H' (Alve et al., 2009) and Exp(H'_{bc}) (Bouchet et al., 2012), EcoQS were accurately assessed against different pollution sources (Bouchet et al., 2012, 2018; Dolven et al., 2013; Melis et al., 2016; Francescangeli et al., 2016; Dijkstra et al., 2017; El Kateb et al., 2020). In addition, sensitivity-based indices were designed like the Tolerant Species Index for the Mediterranean (TSI-med) (Barras et al. 2014) and the Foram Stress Index (FSI) (Dimiza et al., 2016) to assess the current health of marine environments. Few applications of these evolving indices highlighted their good performance in assessing EcoQS (Damak et al. 2020, El Kateb et al., 2020, Minhat et al., 2020). Finally, a multi-metric foraminiferal index has been adapted from the Norwegian macrofaunal index NQI (NQIf; Alve et al., 2019). Promising work using metabarcoding have not yet been formalized into a molecular-based index like the gAMBI (see review in Borja et al. 2019). Our community is hence putting a huge effort into the development of a robust benthic foraminiferal index to be used in environmental assessment and monitoring. The biggest challenge is now to thoroughly test these indices to determine how relevant they are in assessing EcoQS in different types of marine and climatic regimes and against different sources of pollution. The ultimate aim of the FORAM-ECO SCOR working group will be to work on the integration of benthic foraminifera in environmental monitoring guidelines as well as in governmental monitoring efforts.

2.3 Rationale and Timeliness of FORAM-ECO SCOR working group

As above-mentioned, there has been an increasing number of publications assessing EcoQS using benthic foraminifera over the last few years. These contributions highlighted (i) the urgency to revise and extend the existing species lists of sensitivity-based indices, (ii) the need to provide a suitable method for intertidal, estuarine and transitional environments, in which it is particularly challenging to decipher between natural and human-induced stressors, (iii) to solve taxonomical issues, also by molecular methods, and (iv) establishment of pre-industrial environmental conditions that will assess the validity of current restoration practices. Moreover, benthic foraminifera may be used for establishing the reference (pre-impacted) conditions for the sake of marine conservation assessments by utilizing the fossilization potential of foraminiferal tests in sediments. The establishment of a SCOR working group would allow to formalize what has been started by the informal FOBIMO working group. More important, our community is at a key moment of the development of an environmental health index based on benthic foraminifera. In order to achieve the establishment of an EcoQS assessment method based on benthic foraminifera, a SCOR working group is the best format to achieve this goal.

3. Terms of Reference

ToR #1: Assess state-of-the-art methodologies for organic matter characterizations in marine sediments. This will address the issue of identifying the origin of organic matter to disentangle between natural and anthropogenic sources. Identifying the type(s) of organic matter (i.e., lipids) via multiple methods (i.e., molecular) will delineate which type of organic matter is the most appropriate assessment measure for biomonitoring of environmental quality status.

ToR #2: Expand the benthic foraminiferal species assignment to distinct ecological categories as a function of organic matter gradients. This will be done regionally to consider the species local ecological requirements. This would help establishing region-specific reference conditions.

ToR #3: Assess the applicability of existing foraminiferal diversity indices [H' and $Exp(H'_{bc})$], sensitivity indices (TSI-med, FSI and Foram-AMBI) and the multi-metric index NQI_f against different types of pressures. This would require defining appropriate reference conditions for each of the indices. By doing inter-calibrations, priority will be given to the best practice when using benthic foraminifera as a biomonitoring tool for environmental health assessments.

ToR #4: Apply the suitability and effectiveness of benthic foraminifera as a tool to assess pre-industrial conditions recorded in sediment archives in order to understand if current environmental settings have potentially degraded or recovered.

ToR #5: Evaluate the correspondence of taxonomic inventories between morphology- and molecular-based analysis. The unassigned molecular sequences will also be screened for ecological signature along organic matter and other impact gradients to expand the range of molecular-based bioindicators. This will contribute to design a molecular-based foraminiferal biotic index.

4. Working Plan

FORAM-ECO will timely accomplish all ToRs over a window of four years (2021-2024). Although they may appear ambitious, the preliminary studies of the FOBIMO initiative and from other researchers provide a solid base for our research. The FORAM-ECO encompasses a number of synergistic activities including networking, data collection, data analysis through collaboration amongst all members and stakeholders, placing data in a global context, dissemination and publication. FORAM-ECO meetings will coincide with relevant international meetings (e.g., Living Forams 2021) to expand the network and engage other researchers (including early-career) and stakeholders (e.g., resource managers, policy makers) in knowledge transfer. Stakeholder engagement and close collaboration is essential to ensure that the FORAM-ECO outcomes are in alignment with management/policy applications.

The ToR#1 will compile studies from multiple sources to review the methodologies used in environmental studies (including molecular techniques) related to sediment characteristics. From this assessment the best protocol, considered the most scientifically sound and cost-effective, will be used. The expertise of all members will help to disentangle these protocols to assess their reliability, reproducibility and timeliness in order to “ground-truth” the best method when coupled with benthic foraminiferal ecological studies (ToR#2). This will require the acquisition of marine sediments from different climate zones (e.g., tropical, temperate) to be tested. Given the present-day geographical coverage of all the members this is a realistic task. Ongoing funded projects by FORAM-ECO members (PREVENT in Sweden, FORESTAT and Foram-INDIC in France, Foraminiferal Barcoding in Brazil, Gulf of Mexico Foram-AMBI in USA) will serve as synergistic platforms to test this method.

The ToR#2 will identify the ecological characteristics of benthic foraminifera, a pre-requirement to test existing and newly developed indices based on these protozoans. A key factor for the success of this ToR is to revise, update, and complement the current species assignments to be used in all the proposed indices (ToR#3) with the ultimate goal of applying its results to determine the categorization of a foraminiferal species as sensitive or tolerant to a type of organic matter. The outcome will be a new, more reliable data set to be tested with current indices (ToR#3), and its translation into EcoQS in marine environments. We will rely on ongoing projects from several FORAM-ECO members to provide supporting ecological data.

To address ToR#3 the FORAM-ECO project will incorporate other stressors that are directly related to organic matter (e.g., bottom water oxygenation, methane) affecting foraminiferal ecology in different climatic regimes. Thus, we will study the proper implementation of critical and promising foraminiferal biotic indices such as the FSI. The FORAM-ECO will develop an extended data set to quantitatively describe the degree of natural vs anthropogenic stressors (e.g., pollutants, temperature, sediment composition). This multi-proxy approach will require the expertise of all members and stakeholders to produce independent recommendations of the parameters to be routinely used in environmental assessments.

This ToR#4 addresses the need of using fossil foraminifera to establish reference conditions that will help stakeholders assess pre-industrial conditions and will help them understand if current risk-management practices are effective. To attain this, the distribution of historical foraminiferal records from sediment archives will be used to trace their natural faunal variability and establish baselines for a direct comparison with modern (impacted) environments. Assemblage changes will then be scrutinized to assess if they are a result from anthropogenic stressors or natural climate variability or a combination of the two. To validate this approach, several foraminiferal biotic indices (ToR#1, #3) will be implemented to distinguish foraminiferal response in areas known to have been historically impacted by human activities and those less affected, also considering that truly pristine sites no longer exist.

To address ToR#5, the FORAM-ECO will engage in cutting-edge science by implementing the use of benthic foraminiferal molecular barcoding next to a traditional morphospecies approach to identify bioindicator species. Recently, much emphasis has been given to the development of molecular based biotic indices, for instance using benthic macrofauna (Aylagas et al., 2014) or bacteria (Aylagas et al., 2017). Environmental DNA studies in benthic foraminifera highlighted that the molecular “signature” of all the species has not yet been determined (e.g., Pawlowski et al., 2016). On the basis of these very promising works, this ToR#5 will focus on (i) complementing existing barcoding of the benthic foraminiferal species that will help bridging the gap between morphological and molecular taxonomy (ongoing projects FORESTAT and Foram-INDIC will serve as data provider platforms) and (ii) design a molecular-based foraminiferal biotic index that will be highly complementary to eDNA.

Timeline summary:

Month 1-12 (2021): Goals to achieve include: (i) kick-off meeting at the Living Forams 2021 (June) workshop in Germany breakdown of the ToR into tasks; (ii) sub-groups to engage in ToR#1-#2; (iii) compilation of published studies; (iv) review of critical protocols and a manuscript draft; (v) initial engagement of stakeholders; (vi) assign working sub-groups based on regional marine environments; (vii) assign a working group for web development and advertising; (viii) discuss leverage funding sources.

Months 12-24 (2022): Goals to achieve include: (i) sub-groups to engage in ToR#3-#5; (ii) second meeting at the FORAMS 2022 International Symposium on Foraminifera (July) in Italy; (iii) discuss data-set generated from ToR#1-#2 and provide feedback and revisions before publication; (iv) continued stakeholder engagement; (v) host a workshop at the FORAMS 2022 meeting.

Months 24-36 (2023): Goals to achieve include: (i) sub-groups to continue work on ToR#3-#5; (ii) third meeting in Eilat, Israel (to be confirmed for June); (iii) host a bioindicator training session the SCOR Visiting Scholar program in Brazil; (iv) sub-groups to discuss data-set generated and all members and stakeholders provide feedback and revisions for ToR#3-#4 to be published; (v) updates on molecular data from ToR#5.

Months 36-48 (2024): Goals to achieve include: (i) sub-groups to continue work on ToR#3-#5; (ii) fourth and final meeting (June) (location to be decided); (iii) host a workshop at meeting; (iv) all members and stakeholders to discuss data-set generated and provide feedback and revisions for ToR#5 to be published; (v) all members and stakeholders to discuss final protocol article (Ocean Best Practices).

5. Deliverables

A. Development of a website to disseminate/publicize FORAM-ECO: [1] selected methods (ToR#1, #3, #5); [2] meetings and workshops; [3] data base for foraminiferal species assignments and molecular data; and [4] training videos about field sampling, laboratory sample processing, and index calculations/interpretations to benefit the early-career scientists and colleagues from developing countries and countries with economies in transition and help in the implementation of the Foram-ECO SCOR WG outcomes.

B. Intercalibrated foraminiferal index which can be applied in marine environments and in different climate zones.

C. Peer-reviewed publications: [1] a review on recommendations on organic matter analysis (ToR#1);[2] a manuscript on the proof of concept [1] when using foraminifera as biotic indices following trends in organic matter composition (ToR#2-3); [3] a manuscript building on the findings of [1-2], will produce a comprehensive list of benthic foraminiferal species assignments (data base) that will be pivotal in the refinement and implementation of foraminiferal index applications (ToR#2-#4); and [4] a manuscript related to benthic foraminifera in molecular work in order to improve foraminiferal species assignments and bioindicators (ToR#5).

D. Dissemination of the FORAM-ECO: [1] attending international meetings to advertise the international efforts of the group; [2] share the website; FORAM-ECO meetings; and [3] attention to colleagues from developing nations to share knowledge/implementation of foraminifera as bioindicators.

E. A final report to be submitted to Ocean Best Practices (www.oceanbestpractices.net) in strong collaboration with stakeholders to finalize the standard use(s) of benthic foraminifera in biomonitoring studies.

6. Capacity Building

The overarching goal of FORAM-ECO is to provide accessibility of the methods available to the international community of environmental scientists, with specific emphasis on early-career scientists and including scientists from developing countries (e.g., Nigeria, Brazil). The worldwide scientific cooperation of this FORAM-ECO project will shape and solidify a gender-balanced, refreshed FORAM-ECO community that will enhance the expertise, know-how, outreach and dissemination, of marine environmental studies. The first initiative is to structure the FORAM-ECO community, which started in 2011 with the FOBIMO have created the platform and the conditions required to generate a substantial project, that will promote foraminiferal biomonitoring across the world, beyond Europe. A sufficient number of leading senior scientists as well as early-career investigators, spread across leading European Institutions, seconded by partners from the wide international community, can presently provide the necessary state-of-the-art knowledge, skills and facilities to educate a much larger generation of young scientists.

Capacity building objectives of FORAM-ECO will include:

1) Promote knowledge exchange among scientists representing a wide spectrum of disciplines (e.g., biology, sedimentology, chemistry, etc.) including stakeholders (e.g., policy, resource management) outside the academia.

2) Stimulating experience and sharing the facilities among academia and other stakeholders (e.g., resource managers); many of the shared facilities are usually very difficult to access from outside a formalized network.
3) Facilitate exchange of expertise between early-career and scientists from developed countries with those from countries with economies in transition and developing nations by organizing meetings and workshops. Young researchers will be strongly encouraged to take active roles in these research initiatives.
4) Generation of international archives of various foraminiferal species including a contribution to current molecular banks and their ecological categories based on organic matter gradients.
5) Participation in the SCOR Visiting Scholar program in a developing nation (Brazil) will expand the reach of FORAM-ECO training and communication efforts. The goal is two-fold: (1) to train scientists; and (2) stakeholder engagement (e.g., policy makers, environmental government agencies) in the applicability of FORAM-ECO.

Through these objectives, FORAM-ECO will obtain a fundamental improvement of capacity building, expertise and facilities at a global level – resulting in a recognized international leadership in the field of foraminiferal biomonitoring. These proposed activities are to be held as training events (2 days) during each FORAM-ECO meeting and as a one-week long workshop for the SCOR Visiting Scholar program. In addition, to ensure the longevity of the FORAM-ECO beyond the SCOR, we will partner with the and the International Symposium on Foraminifera (FORAMS) and to hold special workshops to leverage training sessions for young and early-career scientists from academia, government and industry. These leveraging events will bring together not only the Full and Associated members but will also allow the scientific community at large to attend, receive training, learn about foraminiferal biomonitoring and become part of the goals of the FORAM-ECO.

7. Working Group Composition

The FORAM-ECO is composed of researchers from 16 nations including three from the emerging/developing nations of Nigeria, Brazil, and India. In addition, one early-career fellow (Tristan Cordier- Switzerland) is a Full Member and a second one is an Associated Member (Patrick Schwing- USA) in which both will benefit the most as part of their career development. The transdisciplinary expertise of the members of the FORAM-ECO members will add-value to the fulfillment of the proposed ToRs. This FORAM-ECO provides the opportunity for each member to engage in the knowledge transfer of state-of-the-art research fields such as earth science, marine science, sediment and water geochemistry, biotic indices, marine macro- and microfaunal ecology, trace metal chemistry, chemical oceanography, foraminiferal biology and ecology, molecular biotic indices, and experimental culture work among others. The co-chairs, Michael Martínez-Colón (USA), Vincent Bouchet (France), and Orit Hyams-Kaphzan (Israel) will ensure the progression towards the completion of all the deliverables associated to the ToRs.

7.1 Full Members (*: co-chairs; ^: early-career) (50% female)

Name	Gender	Place of work	Expertise
1. Michael Martínez-Colón*	Male	Florida A&M University, **USA**	Geochemistry, Earth-/Marine Sciences, foraminiferal ecology-/ paleoecology
2. Vincent Bouchet*	Male	University of Lille, **France**	Biology, ecology, biotic indices, foraminifera, and macrofauna
3. Orit Hyams-Kaphzan*	Female	Geological Survey of Israel, **Israel**	Marine ecology and paleoecology, Environmental Sciences, foraminifera
4. Silvia Spezzaferri	Female	University of Fribourgh, **Switzerland**	Taxonomy, ecology, bioindicators, benthic foraminifera
5. Guillem Mateu-Vicens	Male	University of the Balearic Islands, **Spain**	Biology, foraminiferal ecology/paleoecology, carbonate sedimentology, isotope geochemistry
6. Magali Schweizer	Female	University of Angers, **France**	DNA barcoding, phylogeography, trophic strategies, exotic species, foraminifera
7. Akira Tsujimoto	Male	Shimane University, **Japan**	Earth-/Marine Sciences, radiochemistry, sediment chronology
8. Virginia Martins	Female	Universidade de Aveiro, **Portugal**	Pollution, ecological bioindicators, Earth Science, transitional environments
9. Tristan Cordier^	Male	University of Geneva, **Switzerland**	Metabarcoding, molecular biotic indices, geneticist, foraminifera
10. Irina Polovodova Asteman	Female	University of Gothenburg, **Sweden**	Earth-/Marine Sciences, marine pollution, paleoecology/ ecology

7.2 Associated Members (^: early-career) (50 % female)

Name	Gender	Place of work	Expertise
1. Joachim Schönfeld	Male	Helmholtz Centre for Ocean Research, **Germany**	Marine Science, bioindicator ecology, protocol development
2. Maria Triantaphyllou	Female	National and Kapodistrian	Foraminiferal ecology and paleoecology,

		University of Athens, **Greece**	Environmental Micropaleontology
3. Silvia Sousa	Female	University of São Paulo, **Brazil**	Environmental-/Marine Sciences, Foraminiferal paleoecology/ ecology
4. Sigal Abramovich	Female	Ben-Gurion University of the Negev, **Israel**	Marine biomonitoring and pollution, ocean warming, foraminiferal geochemistry, molecular Phylogeny
5. Rajeev Saraswat	Male	National Institute of Oceanography, **India**	Environmental-/Marine Sciences, ecology and geochemistry of foraminifera
6. Luciana Ferraro	Female	Italian National Research Council, **Italy**	Environmental-/Marine Sciences, foraminiferal ecology/paleoecology
7. Patrick Schwing**^**	Male	University of South Florida, **USA**	Paleoecology/ecology, foraminiferal geochemistry, radiochemistry, Earth-/Marine Sciences
8. Olugbenga T. Fajemila	Male	Osun State University, **Nigeria**	Foraminiferal paleoecology/ ecology, Environmental-/ Marine Sciences
9. Sergei Korsun	Male	Shirshov Institute of Oceanology, **Russian Federation**	Environmental-/Marine Biology, ecology, bioindicators
10. Silvia Hess	Female	University of Oslo, **Norway**	Environmental impact assessment, marine biomonitoring, marine ecology/paleoecology, Environmental Geology

8. Working Group Contributions

1) Michael Martínez-Colón (co-chair) is a marine biogeochemist who studies the effects of organic matter and heavy metals on the benthic foraminifera in tropical and subtropical climate regions. He combines ecology, ocean chemistry and geology to reconstruct the natural and/or anthropogenic evolution of marine environments. Also has extensive experience in informal teaching (e.g., school teacher workshops).

2) Vincent Bouchet (co-chair) is involved in what drives general benthic foraminiferal diversity and community patterns to assess present and past anthropogenic impacts on foraminifera to answer the following question: Can benthic foraminifera serve as reliable indicators in the context of the implementation of marine legislations? This includes the development of indices based on benthic foraminifera and direct comparison with benthic macrofauna.

3) Orit Hyams-Kaphzan (co-chair) is involved in many aspects of marine biomonitoring. She uses live and dead benthic foraminifera of the Israeli Mediterranean shallow shelf and deep sea as sensitive indicators for anthropogenic pollution or introduction of alien species. She also uses these as an assessment tool for marine national reserve conservation.

4) Silvia Spezzaferri applies benthic foraminifera as biomonitoring tools since 1992 (AVICENNE EU Project) and is one of the founding members of the FOBIMO initiative and members of the steering committee. She participated in the establishment of the standardize method for the studies of benthic foraminifera in soft-bottom sediments (FOBIMO protocol).

5) Guillem Mateu-Vicens has developed foraminiferal biotic indices for seagrass-dominated ecosystems and is engaged in trophic relationships based on isotopic analysis.

6) Magali Schweizer combines DNA barcoding and morphological criteria to identify benthic foraminiferal species more accurately. She also studies the phylogeography of this group to identify endemic, cosmopolitan and human introduced species and the trophic strategies of foraminifera to better characterize their ecology.

7) Akira Tsujimoto is a benthic foraminiferal specialist in Japan and will provide Asian examples on the relationship between benthic foraminifera and organic matter.

8) Virginia Martins uses meiofauna to establish ecological indicators given special attention to the response of living benthic foraminifera, to various types of pollution such as eutrophication and heavy metal pollution among others. She also engages in establishing ecological descriptors for paleoenvironmental (baseline) reconstructions.

9) Tristan Cordier is a benthic foraminiferal molecular biologist that combines environmental genomics and machine learning to develop a new framework for the monitoring of marine ecosystems health under anthropogenic pressures.

10) Irina Polovodova Asteman studies several aspects of environmental change in coastal regions such as climate change, coastal hypoxia, ocean acidification, pollution and introduction of alien species. In particular, using foraminifera as proxies for establishment of alien species, marine pollution and temporal changes within marine protection areas such as national parks are directly related to marine conservation topic.

9. Relationship to Other International Programs and SCOR Working Groups

9.1 No association with current/past SCOR WG

The initiative proposed by our FORAM-ECO is unique in terms of using benthic foraminifera as the taxonomic group for bioindicator monitoring. Previously, only planktic foraminifera was proposed to be used as a proxy for ocean chemistry by WG-138. FORAM-ECO will for the first time incorporate the application of benthic foraminifera within SCOR WG.

9.2 COST Action 15219- Developing new genetic tools for bioassessment of aquatic ecosystems in Europe (www.dnaqua.net)

This international working group is engaged in the development and application of modern molecular techniques to be used in environmental health assessments of marine environments to determine its ecological status. Networking and collaborating with their WG2 titled "Biotic Indices and Metrics" will benefit our ToR#5 activities and deliverables since both aim towards the development of new genetic tools for bioassessment. We anticipate having them co-host our final meeting in 2024.

9.3 foramBARCODING working group (www.forambarcoding.unige.ch)

This working group will be valuable in providing an independent source of foraminiferal barcoding results of our ToR#5.

9.4 International School of Foraminifera (ISF) (www.isf.tmsoc.org)

The ISF offers a summer course every year to train researchers from academia and industry (oil) in the fundamentals of foraminiferal biology and ecology. This will be a great opportunity collaborate with ISF to implement in their program the uses and applications of the indices developed by FORAM-ECO in their training session (Capacity Building) on foraminiferal bioindicator ecology.

9.5 Water Framework Directive (Marine Directive) (www.ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm)

Data and studies generated by FORAM-ECO related to organic matter pollution, bioindicator ecology, and inorganic contaminant (e.g., heavy metals) will supplement the data base of the Marine Directive. In addition, this will provide an avenue to share our finding in alignment with the Marine Directive which can help in reaching local stakeholders based in individual countries.

10. Key References

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11. Appendix (5 peer reviewed articles/Full Member)

1) Michael Martínez-Colón

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