

Industrial pressures and flooding events: shaping the benthic foraminiferal community in the Croton basin (Ionian Sea) over the last century

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ABSTRACT

Since coastal marine ecosystems have been increasingly affected by human activities over the past century, different marine legislations (e.g., Water Framework Directive) have been enacted to assess the environmental quality and its deviation from the background conditions. This study provides evidence of the historical environmental and Ecological Quality Status (EcoQS) changes along the 35-cm long sediment KR3 core, retrieved at the head of the Esaro submarine canyon in the Croton basin (Calabria, Ionian Sea, Italy). Croton is part of the Croton-Cassano-Cerchiara Site of National Interest, influenced by intense industrial activity (i.e., zinc purification, phosphorus production) between 1920s and 1990s. Geochemical, sedimentological, and benthic foraminiferal temporal changes along the core were investigated to reconstruct environmental and EcoQS variations. Trace metals concentrations (i.e., Cr, Pb, Zn) and Pollution Load Index values increase particularly during 1948–1968 period, reflecting the main industrial phase. The CONISS analysis based on benthic foraminiferal assemblages identifies three main phases: industrial settlement (1926–1959), industrialization peak and initial production decline (1962–1990), and industrial decline (1994–2016), that well correspond to the exploitation in the Croton coastal area. Exp(H_{bc}) and Foram-AMBI reflect moderate environmental conditions since 1926, and poor conditions between 1962 and 1968 corresponding to the main industrialization peak. Input of sandy fraction associated to historical documented flooding events corresponds to pronounced peaks of diversity (e.g., 1996 event) and the occurrence of shallower species along the core. This study highlights the necessity of an integrated (geochemical and biological) approach to separate the signals of anthropogenic pressure, extreme natural events, and shipping transport in the complex EcoQS assessment of submarine canyons.

1. Introduction

Coastal areas represent a priceless environmental heritage and provide ecological services for our human societies including habitat and food sources for migratory birds (Munari and Mistri, 2012), nursery

habitat for fish juveniles of high commercial value (Couturier et al., 2007) and blue carbon hotspots (Basconi et al., 2023). Concurrently, these ecosystems have been exploited and affected by urbanization and industrial settlements, pollution, and, more recently, by the effects of the climate change. Overall, human activities have led to the deterioration

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of water and sediments quality, particularly marine sediments that act as a final sink for heavy metals (e.g., Zn, Pb) and other anthropogenic (i.e., polycyclic aromatic hydrocarbons, polychlorobiphenyls) contaminants (Christophoridis et al., 2019). In Italy, areas of environmental value that are in need of remediation (art. 252–2, Legislative Decree n. 152/2006 of the Code of the Environment), where one or more matrices (i.e., water, soil, sediments) are affected by intense levels of contamination, are designed as Sites of National Interest (SINs). Many of these SINs are indeed coastal marine areas.

In response to concerns about ecological, environmental and human impacts on marine areas, the European Union (EU) members are committed to protect and preserve all waterbodies and their related ecological services and endorsed the Water Framework Directive (WFD 2000/60/EC), later implemented with the Marine Strategy Framework Directive (MSFD 2008/56/EC). These legislations represent among the main tools in Europe to monitor the Ecological Quality Status (EcoQS) of marine environments.

Bioindicators, as Biological Quality Elements (BQEs) *sensu* WFD, play a key role in assessing the EcoQS (Borja et al., 2009). These are defined as “organisms that can reveal the presence of pollutants by the occurrence of typical symptoms or measurable responses” (Mothersill and Seymour, 2016). Several studies have demonstrated that benthic foraminifera, unicellular eukaryotes, represent an efficient tool to evaluate the health of benthic habitats (Barras et al., 2014). To meet the objectives of the marine legislations, biotic indices have been developed to translate the ecological information provided by foraminiferal communities to EcoQS (O'Brien et al., 2021). Some of these indices are based on diversity, while others, such as Foram-AMBI (Jorissen et al., 2018), rely on the response of species (i.e., benthic foraminifera) along a pollution gradient, commonly ascribed to enrichment in total organic carbon (TOC).

Benthic foraminifera are widespread, minute and abundant organisms inhabiting the marine environments, also found in salt marshes (e.

g., Saffert and Thomas, 1998). They are easy to sample, highly diversified with specific ecological requirements, and most of them possess an agglutinated or calcitic test (i.e., shell). The preservation of their tests in the sedimentary records can be used to define the *in situ* reference conditions, or pristine (Dolven et al., 2013), meant as those that exist, or would exist, at high ecological status that is, with no, or very minor disturbance from anthropic influence (Wallin et al., 2003). Setting reference conditions is the anchor point of EQR (Ecological Quality Ratio) based classifications. EQR represents the ratio between the measured value and the expected value at reference conditions, for a given index and surface water body (Van de Bund and Solimini, 2007). EQR, therefore, reflects how much the measured value deviates from the reference condition and enables the assessment and reconstruction of EcoQS (e.g., S. Dos S. de Jesus et al., 2020). Additionally, analysis of foraminiferal assemblages enables the reconstruction of the historical environmental variations (e.g., Alve et al., 2009).

An integrated approach was applied by combining foraminiferal assemblages (e.g., abundance, diversity and biotic indices) together with geochemical and sedimentological analyses to determine the reference conditions, evaluate the EcoQS through time and reconstruct the paleo-environmental changes along the recent sedimentary record spanning the last ca 100 years in the heavily impacted Croton industrial site (Calabrian region, Ionian Sea, Italy).

2. Study area

Crotone is located in the Calabrian region (southern Italy, Fig. 1) on the northwestern part of the Ionian Sea. The investigated area falls within the Croton Basin, located between the slopes of the Sila Massif on the eastern side, and the Ionian Sea on the western side (Moretti and Guerra, 1997). The geological setting of the basin is linked to the SE-ward shifting of the Calabrian arc, followed by the subduction of the Ionian crust and the extension of the Tyrrhenian basin (Malinverno and

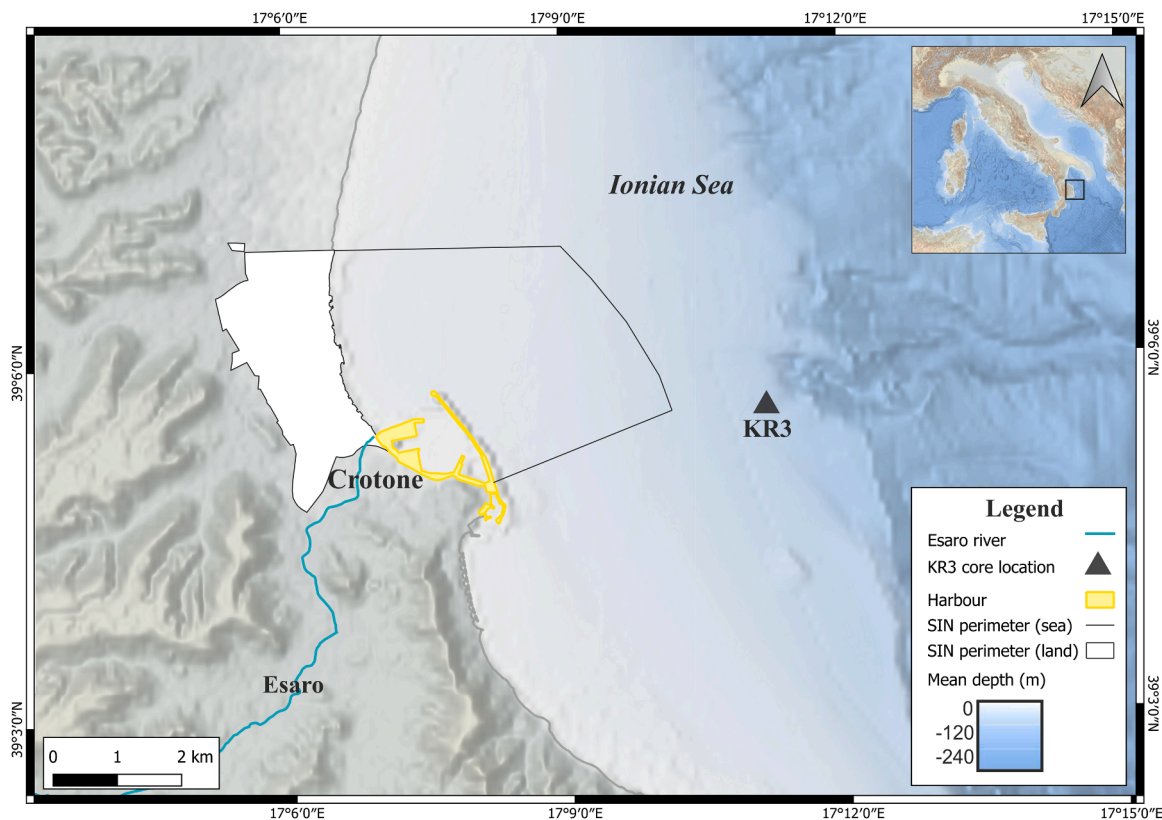


Fig. 1. Map of the study area (Crotone, Italy) displaying the Crotone–Cassano–Cerchiara SIN area (land perimeter in white, sea perimeter outlined), the harbour area (yellow), the Esaro river and the KR3 core location situated at the head of the Esaro submarine canyon. Seafloor bathymetry (mean depth) is also shown.

Ryan, 1986) and references therein. The Mio-Pleistocene Crotona basin is interpreted as part of the Ionian forearc basin, placed in the inner part of the Ionian accretionary wedge (Zecchin et al., 2004). In the basin Serravallian to Pleistocene marine pelitic sediments outcrop. The Calabrian slope is crossed by several gullies and canyons that act as a pathway between the shelf area and the offshore Ionian Basin. In the Crotona area, the most significant rivers are the Neto and Esaro (Perri et al., 2012), which transport sediments to the deep Ionian Basin through the Neto-Lipuda submarine canyon in the northern part of the basin and the Esaro submarine canyon in front of the Crotona town (Rebesco et al., 2009).

Crotona has a long history of contamination. Since the early 1920s and until the beginning of 1990, the area has been affected by intense industrialization. Indeed, the first plant of zinc production in Italy was built in the Crotona area, with the establishment of the Pertusola Sud industrial plant in 1928, which ceased production in 1999. Next to the Pertusola Sud, in 1926 the Montecatini industrial complex (former Fosfotec and Agricoltura) was established, producing phosphorites for phosphoric acid and nitrogenous and phosphatic fertilizers until 1992. Industrial residues (e.g., cubilot scoriae from zinc production, NORM and TENORM radionuclides from the Fosfotec plant) were stored in two large landfills adjacent to the coastal strip. Soils and groundwaters in the Crotona area were found to be affected by intense heavy metals contamination (e.g., Pb, Cd, and Zn), thus threatening environmental and human health (Martuzzi et al., 2002). For these reasons, 1,448 ha of land and 884 ha of sea were included in the Crotona-Cassano-Cerchiara SIN (D.M. 468/2001, D.M. 26 November 2002).

3. Materials and methods

3.1. Core sampling

The sampling survey was carried out during the CISAS_2 campaign (La Gattuta et al., 2018) offshore the Crotona basin. The core was retrieved at 6 km distance from the coast (beyond the SIN perimeter), at the head of the Esaro submarine canyon, at 70 m water depth. A 324 mm diameter cylindrical box-corer was used to extract the sample, out of which four cores of 60 mm diameter were collected. The present study focuses on the analysis of the KR3 offshore sediment core (39°05'31.91'' N, 17°11'00.29'' E), 35-cm long and sliced at 1 cm interval resolution. Research campaign was conducted in 2017 on board of the *R/V Minerva Uno* by the Institute of Anthropic impacts and Sustainability in the marine environment of the Italian Research Council (IAS-CNR).

3.2. Environmental and geochemical analysis

Granulometric and geochemical analyses were published in (Oliveri et al., 2022). The TERESA dating model (Abril-Hernández, 2024, 2026) was applied on KR3 sediment core, supposing that $^{210}\text{Pb}_{\text{ex}}$ concentration (A_0 , Bq kg^{-1}) at the sediment-water interface and Mass Accumulation Rate (MAR, $\text{g cm}^{-2} \text{y}^{-1}$) are normally distributed in time around their average values with amplitude s_{A_0} and s_{MAR} , respectively. Every dating is characterized by four parameters: A_0 , MAR, s_{A_0} , s_{MAR} . The TERESA depth-age model (Supplementary Material 1) is more accurate than the model published in (Oliveri et al., 2022), and even if the geochronologies do not significantly differ within their uncertainties, it allows us to estimate the different MARs occurred at each layer.

The present work provides new data on benthic foraminiferal assemblages to infer the EcoQS variations along the core. To determine the degree of sediment contamination due to heavy metals, the Pollution Load Index (PLI) (Tomlinson et al., 1980) was calculated. The PLI was obtained by taking n^{th} root product of the Contamination Factors (CFs), given by the ratio between the metal concentration observed in the sediments and the background value (e.g., the oldest value of the core, corresponding to 1902).

3.3. Benthic foraminifera

Bulk sediments were weighed on Kern EMB precision and then soaked in a solution of water and benzalkonium chloride for 24 h to facilitate sediments disaggregation (Duchamp-Alphonse et al., 2009). Sediments were then gently washed through a 63 μm nylon sieve to remove the finer fraction, and residues were dried at 50°C on a Cole-Parmer (model-4659) heating plate. Dried samples were weighed and stored in labelled plastic bags until examination. Benthic foraminifera were analysed from the > 125 μm sediment fraction in 29 samples, and, when possible, at least 300 specimens were picked. Sorting and identification were performed under a Discovery V8 Zeiss stereomicroscope. To obtain representative aliquots of sediment samples an Otto micro-splitter (Guptill et al., 1976) was used. Taxonomical identification largely followed the classifications of (Loeblich, Tappan, 1987) and other systematic studies from Adriatic and Mediterranean areas (Cimernan and Langer, 1991; Milker and Schmiedl, 2012).

3.4. Ecological quality status reconstruction

To evaluate the EcoQS variations based on benthic foraminifera, different ecological and diversity indices were considered. The diversity-based index $\text{Exp}(H'_{\text{bc}})$ (Bouchet et al., 2012), was computed with the package “entropy” (Hausser and Strimmer, 2025) in RStudio (version 4.5.2). The Foramin Stress Index (FSI) (Dimiza et al., 2016), based on the proportions of sensitive and stress-tolerant taxa, was also calculated. FSI ranges from 1 to 10, a value of 1 indicates degraded environments while a value of 10 indicates optimal environmental conditions. In addition, the Foramin-AMBI (Jorissen et al., 2018) was derived by following the species assignments of the Mediterranean region for open marine environments (Jorissen et al., 2018). To reconstruct the EcoQS as required by Annex V, 1.4.1 of WFD, values of EQR were calculated for both $\text{Exp}(H'_{\text{bc}})$ and FSI indices. The EQR ranges as a numerical value between 0 and 1, with high ecological status represented by values close to one and bad ecological status by values close to zero.

While 35 samples were processed for geochemistry and dating to establish a robust chronological framework, foraminiferal analysis was restricted to a subset of 29 samples due to the limited availability of aliquots within the core sections. Examining the foraminiferal assemblage record, it was possible to determine type-specific reference conditions in the Crotona basin. The oldest values of diversity and FSI in 1926 were defined as the reference values, as the oldest values of the core (i.e., KR3 34–35, 1902) were not available. Furthermore, as the industrial activities were established since 1926, foraminiferal communities in 1926 are assumed to constitute a reliable mirror of the early anthropic pressures in the Crotona coastal area. The EQR boundaries to define EcoQS were determined using the “Reference Conditions Working Group” recommendations (Wallin et al., 2003).

3.5. Statistical analysis

Relative abundances of benthic foraminiferal species along the core depth (i.e., years) that exceeded 5% in at least 1 sample were considered dominant and retained to identify main clusters (i.e., temporal phases) by performing a Constrained Incremental Sum of Squares (CONISS) cluster analysis (Grimm, 1987).

Redundancy Analysis (RDA) was performed to investigate possible relationships between benthic foraminiferal species (i.e., response matrix) and environmental variables (i.e., explanatory matrix). Before running the analysis, we applied “*decostand*” function to standardize environmental variables and Hellinger’s transformation to standardize abundance data, obtained by computing square root of relative abundance (Legendre and Gallagher, 2001). A Detrended Correspondence Analysis (DCA) was conducted and then the RDA model was created. A forward selection on the global model (Blanchet et al., 2008) was performed with “*ordiR2step*” function, which computes forward model

solely on adjusted R^2 and p -value (e.g., adding one variable at the time and keeping it only if it significantly increases the model's adjusted R^2) and allows to obtain a more parsimonious model. Multicollinearity among the retained variables was verified with the “vif.cca” function ($VIF < 5$). Lastly, species with relative abundance $> 5\%$ in at least one sample were plotted in the triplot. Additionally, a subset of rare species was added to the triplot, given that their occurrence was solely found in sandy layers (e.g., 1997). Statistical significance of the model was assessed by “anova.cca” function applied Monte Carlo permutation test ($n = 999$). To assess the relationship between benthic foraminiferal indices and geochemical variables, a Spearman matrix correlation was performed. Statistical significance was evaluated at $p < 0.05$, $p < 0.01$, and $p < 0.001$ levels.

The analyses were computed in RStudio (version 4.3.2) using the community ecology package “vegan” (Oksanen et al., 2025) to compute RDA, “tidypaleo” (Dunnington et al., 2022) to perform the CONISS dendrogram and “corrplot” (Wei and Simko, 2024) to perform Spearman matrix correlation.

4. Results

4.1. Geochronology and environmental parameters

The analysed part of the core (i.e., 0–29 cm) spanned from 1926 to 2016 with an average sedimentation rate of 0.32 cm/year (see Supplementary Material 1).

Silt and clay fractions were merged to obtain the muddy fraction ($< 63 \mu\text{m}$). Grain size distribution was mainly dominated by the muddy fraction (72–99%), except for layers 12–15 cm (1973–1979) and 7–8 cm (1997) that showed a sharp increase in the sandy fraction up to 28% and 12%, respectively (Fig. 2). Heavy metals concentrations (i.e., Cr, Pb, Zn) showed a wide variation along the KR3 core. Particularly, Cr ranging from 54.61 to 101.37 mg kg^{-1} slightly increased from the base of the core until 1951, whereas Zn varied from 84.86 to 148.32 mg kg^{-1} and Pb between 23.61 and 84.43 mg kg^{-1} , both exhibited an increasing trend in the period spanning 1948–1968. The PLI varied between 0.79 and 1.37 (1.06 on mean), with the greatest values between 1948 and

1965 (Fig. 2).

4.2. Benthic foraminifera and EcoQS

A total of 164 benthic foraminiferal taxa were identified along the KR3 core, of which 72 could be classified with certainty only to the genus level. To investigate changes in the community over time, benthic foraminiferal species with $> 5\%$ abundance in at least one sample were plotted against the age-depth model (Fig. 3). *Valvulineria bradyana* (20.7% on mean, range 7.4–37.8%), *Globocassidulina subglobosa* (5.9% on mean, range 0–11.7%), *Bulimina aculeata* (5.2% on mean, range 0–13.3%) and *Cassidulina laevigata* (5.1% on mean) were dominant along the entire core, except for a sharp decrease in *C. laevigata*, *G. subglobosa* and *Melonis affinis* relative abundance in 1979 (Fig. 3). *Ammonia batava* (5.6% on mean, range 0.7–15%) showed the highest values of relative abundance from the base of the core up to 1959, decreasing in correspondence of the increase in abundance of *Ammonia aberdoveyensis* (3.7% on mean, range 0–11.2%), almost absent until 1950's. *Melonis pompilioides* (4.5% on mean, range 0–16.6%) exhibited higher values in relative abundance in the lower part of the core (i.e., 1926–1959); similarly, *M. affinis* (2.9% on mean) showed higher relative abundances in the lower part of the core with a peak in 1968. *Bulimina marginata* (7.3% on mean, range 1.4–19.2%) exhibited high values from 1948 with a peak in 1990 followed by a drop in abundance (Fig. 3), whereas *Cibicides pseudoungerianus* (3.5% on mean, range 0–17.1%) and *Uvigerina mediterranea* (2.5% on mean) were almost absent until 1968 and increased in abundance towards recent years (i.e., 1994–2009) (Fig. 3).

The CONISS cluster analysis performed on the relative abundance of the main benthic foraminiferal species (Fig. 3) identified three main clusters: cluster A (spanning 1926–1959) and cluster B (1962–2016) that can be further divided in subcluster B1 (1962–1990) and subcluster B2 (1994–2016). Subcluster A was mainly dominated by *V. bradyana* (21.4% on mean), *A. batava* (9.3% on mean) and *M. pompilioides* (8% on mean), followed by *B. marginata* (5.1% on mean) *B. aculeata* (5.2% on mean) and *G. subglobosa* (4.9% on mean). The lowest abundances of *A. aberdoveyensis*, *U. mediterranea*, *C. laevigata* and *C. pseudoungerianus*

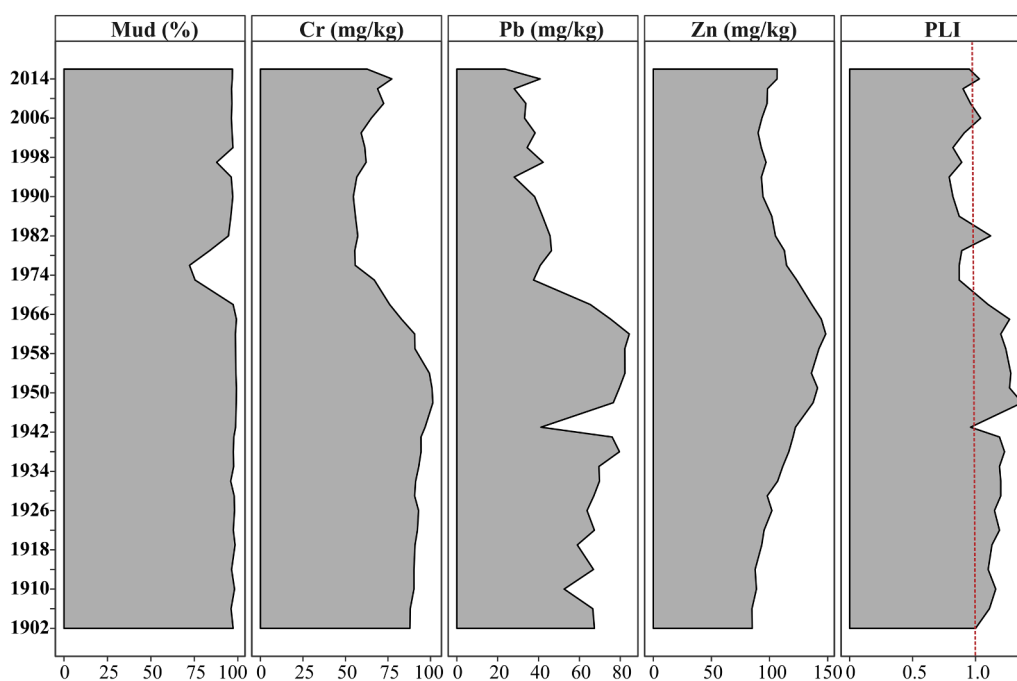


Fig. 2. Stratigraphic profiles of mud content (%), trace metal concentrations in mg kg^{-1} (i.e., Cr, Pb, and Zn) and Pollution Load Index (PLI) values plotted along the KR3 core. Shaded areas represent downcore variations of each parameter. The dashed vertical line in the PLI panel indicates the threshold value ($\text{PLI} = 1$) above which the index suggests polluted conditions.

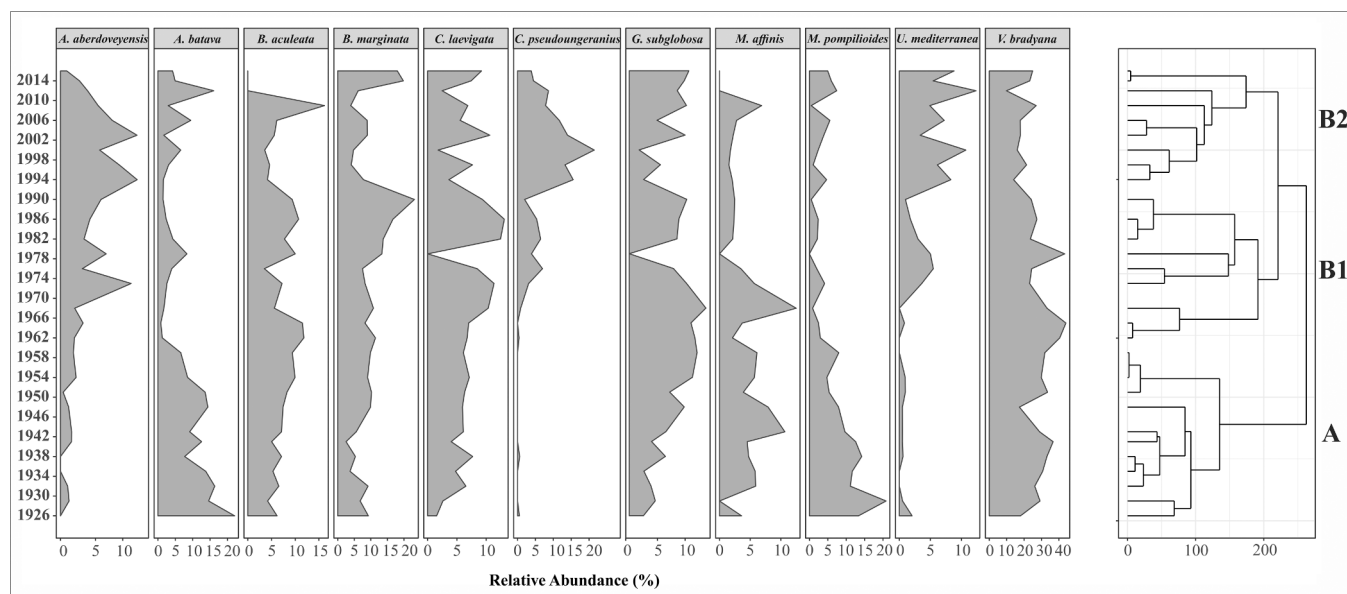


Fig. 3. Relative abundance of benthic foraminiferal taxa (relative abundance >5% in at least one sample) as a function of time (depth) along the KR3 sediment core and CONISS dendrogram.

were observed in this cluster (less than 5%). The assemblage of sub-cluster B1 was characterized by an increase of *V. bradyana* (25.9% on mean), *Bulimina marginata* (10.2% on mean), *G. subglobosa* (7.5% on mean), *C. laevigata* and *B. aculeata*, that increased up to 7.1% and 7% on mean, respectively. *Ammonia aberdoveyensis* also increased up to 4.6% on mean. The subcluster B2 was mostly represented by *V. bradyana* (14.3% on mean), *C. pseudoungerianus* (8.5% on mean), *B. marginata* (6.6% on mean), *A. aberdoveyensis* (6% on mean), *U. mediterranea* (45.6% on mean) and *G. subglobosa* (5.3% on mean).

Results of diversity index $\text{Exp}(H'_{bc})$ and ecological index FSI and their relative EQR, along with Foram-AMBI investigation are plotted in Fig. 4. $\text{Exp}(H'_{bc})$ values ranged between 22.19 and 110.04, with four

major peaks in 1973, 1982, 2003 and 2016. The EcoQS based on EQR of the oldest value of $\text{Exp}(H'_{bc})$ (i.e., 78.3 in 1926) highlighted moderate conditions from 1929 to 1962, whereas poor conditions were observed between 1965 and 1968. Improved EcoQS (e.g., good to high) was inferred in the period spanning 1973–2016, except a drop to moderate conditions in layers corresponding to 1979 and 2012. The values of FSI varied between 1.76 and 4.14. The EQR calculated on the oldest FSI value (i.e., 3.02 in 1926 was assumed as reference condition), suggested high EcoQS conditions throughout the core, with mainly good conditions during the period spanning 1954–1990 (only moderate conditions were registered in 1965) with values ranging between 0.58 and 0.75, eventually returning to high conditions from 1994 onwards. (Fig. 4).

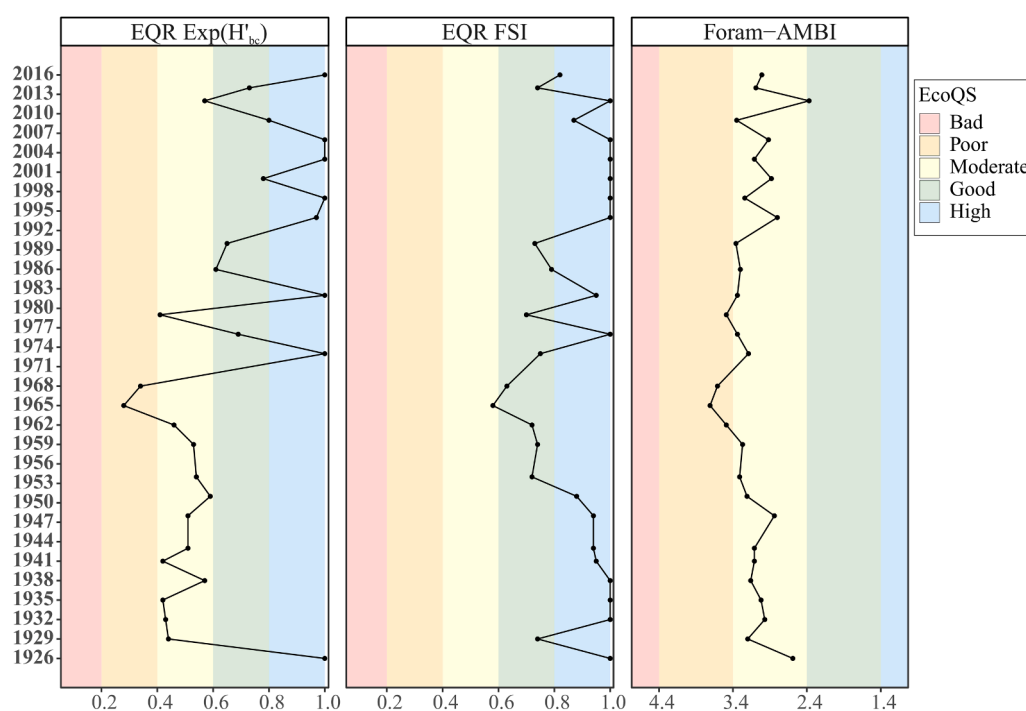


Fig. 4. Ecological and diversity indices and relative Ecological Quality Ratio (EQR) reconstructed along the KR3 core: Ecological Quality Ratio (EQR) based on $\text{Exp}(H'_{bc})$ oldest value, Ecological Quality Ratio (EQR) based on Foram Stress Index (FSI) oldest value, Foram-AMBI.

Lastly, Foram-AMBI values ranged between 2.59 and 3.31 from the base of the core up to 1959 (i.e., moderate conditions), revealing poor conditions (values between 3.49 and 3.61) during 1962–1968 interval and in 1979, finally returning to moderate conditions from 1982 until the top of the core and to good conditions only in 2012 (Fig. 4).

The RDA (Fig. 5) was statistically significant (p -value = 0.001, permutation test with 999 iterations), explaining 41.5% of the constrained proportion of the model. The first two axes explained 35.76% of the variance of the response matrix (i.e., foraminiferal assemblages), with an adjusted R^2 of 0.31. The first axis (RDA1: 27.7%) was positively driven by heavy metals (i.e., Mn, Cr), strongly negatively related with sand content, and positively related to the presence of *C. decipiens* in fine metal enriched sediments during 1948–1951 interval. *Ammonia falsobeccarii* occurrence was mostly related to Cr and Mn in the samples encompassing 1932–1941. The second axis (RDA2: 8.06%) was primarily associated with Zn concentrations (Fig. 5). The latter was linked to the occurrences of *B. aculeata*, *G. subglobosa*, *M. affinis* and *V. bradyana* in the samples encompassing the 1954–1968 interval, while occurrences of *B. marginata* and *C. laevigata* were related to the 1970s and in the 1980s, respectively. Sand fraction was associated in 1997 with the occurrence of epiphytic and shallow water species (e.g., *Haynesina germanica*, *Rosalina macropora*). The occurrences of *A. batava* and *M. pompilioides* were related to the lowest part of the core (1926–1929 interval), whereas occurrences of *U. mediterranea* and *C. pseudoungerianus* were mostly related with sandy sediments in the upperpart of the core (i.e., since 1994). *Ammonia aberdoveyensis* showed negative relation with metal enriched sediments and mostly occurred since the 1970s.

5. Discussion

The CONISS analysis based on benthic foraminiferal assemblages identifies three main phases that well correspond with the development and historical exploitation of the Crotona area: (i) “Initial industrial settlement”, (ii) “Industrialization peak and initial production decline”, (iii) “Industrial decline”.

5.1. Industrial settlement

Benthic foraminiferal assemblage of cluster A, spanning the interval 1913–1943, reflects the early industrialization settlement. The PLI trend along the KR3 sediment core indicated yet degraded conditions since the early 20 s (i.e., values greater than 1 since 1926), reflecting high Cr concentrations (92.9 mg kg^{-1}) observed during the same time interval. PLI reached its greatest value in 1948 (i.e., 1.37), mirroring the heavy metal enrichment (i.e., $\text{Zn} = 137.4 \text{ mg kg}^{-1}$ and $\text{Cr} = 101.3 \text{ mg kg}^{-1}$). A drop in benthic foraminiferal diversity since 1929 was also accompanied by a general increasing trend in heavy metal (e.g., Cr, Pb, and Zn) concentrations in the sediments that revealed the highest values from the base of the core until 1959 (i.e., top of cluster A). This can be ascribed to the intense industrial production started in the Crotona area since the early 1920s with the establishment of the chemical plants former Fosfotec and Agricoltura (Eni Rewind), and the zinc plant production former Pertusola Sud. PLI decreases in 1943 (PLI value = 0.96), likely related to the fall of Pb concentrations (41.1 mg kg^{-1}) in the same layer.

The first axis of RDA reveals a granulometric-geochemical gradient, driven by heavy metals (e.g., Cr and Mn) that have a stronger affinity for

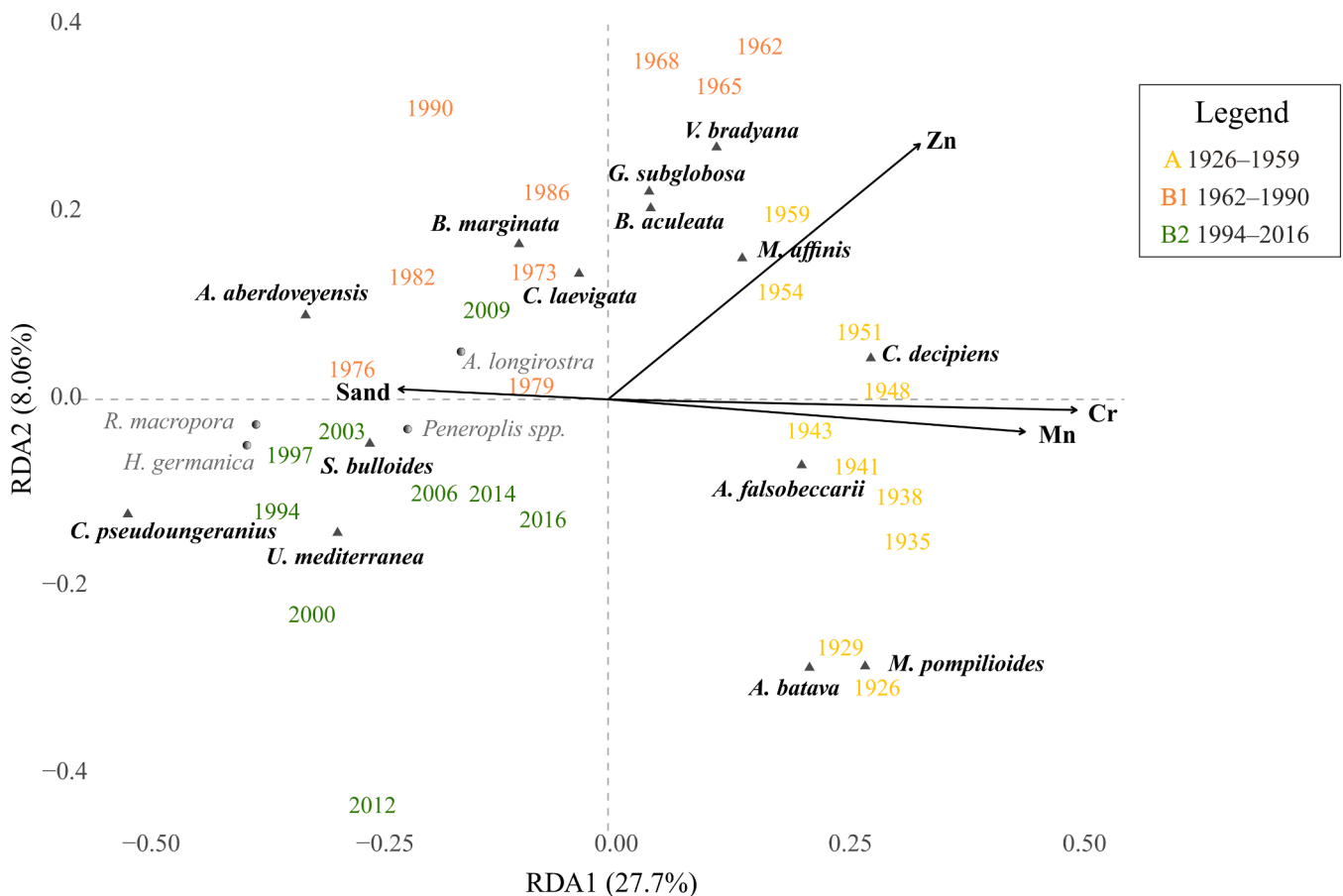


Fig. 5. Redundancy analysis (RDA) biplot showing years (i.e., following CONISS clusters A, B1, B2), environmental variables (indicated by arrows), benthic foraminifera taxa and benthic rare species indicated by triangles and dots, respectively.

finer (i.e., mud, % of silt and clay) fraction than coarser one (i.e., sand) in the period spanning 1920–1943. Due to their high surface area and negative charged surface, clayey sediments play a key role in the adsorption of heavy metals (Rybicka et al., 1995), this is well reflected by the enrichment in metals in mud dominated samples. *Ammonia falsobeccarii*, *Elphidium macellum* and *C. decipiens* showed positive correlation for both Cr and Mn. *Ammonia falsobeccarii* is a deep infaunal species in anoxic sediments, also in surface sediments; its secondary dorsal apertures have been linked to the possibility to cope with severe environmental conditions, whereas *C. decipiens* is commonly found in infralittoral areas (Bellotti et al., 1994) with coarse sediments. The lower part of the core (1926–1929) is associated with *A. batava* and *M. pompilioides* occurrences, reflecting the early industrialization stages. *Melonis pompilioides* is commonly found in circalittoral assemblages (Bergamin et al., 1997), well adapted to nutrient-rich environments but cannot tolerate strong ecological stress due to long periods of very low oxygen levels (Sjoerdsma and Van der Zwaan, 1992). *Ammonia batava* is a subtidal species reported to tolerate heavy metal enrichments in water and is able to uptake metals (e.g., Pb) in its calcite test from culturing experiments (e.g., Schmidt et al., 2022).

The assemblage of the interval A is constituted by “second-order opportunist” *V. bradyana* and “third order opportunists” (e.g., *B. marginata*, *B. aculeata*) species (Jorissen et al., 2018). Other species included in this cluster are *A. batava*, and stress tolerant taxa such as *G. subglobosa*. *Valvulinaria bradyana* is an opportunistic species that tolerates dysoxic conditions (Fontanier et al., 2002) and is recorded in areas under river discharge, high organic matter and low oxygen concentration (Jorissen, 1987). *Globocassidulina subglobosa* is a widespread infaunal species characterized by an opportunistic behaviour (Gooday, 1988).

In agreement with the foraminiferal association, mainly composed of opportunistic species, the Foram-AMBI index indicates moderate EcoQS conditions from the base of the core, supported by the EcoQS based on $\text{Exp}(H'_{bc})$ that reveals that the area experienced “Moderate” conditions from 1926 until the early 1960s. On the contrary, the FSI suggests “High” EcoQS conditions up to 1943. While the Foram-AMBI takes more into account the proportion of opportunistic species, the FSI is largely determined by the proportion of stress-sensitive species. Furthermore, the reference list for FSI (Dimiza et al., 2016) does not include a full list for species assignment. For these reasons, discrepancies between the indices might lead to different EcoQS assignments.

5.2. Industrialization peak and initial production decline

The assemblage of subcluster B1, embracing 1962–1990 interval, is mainly characterized by opportunistic species abundances variations, and is interpreted as a transition phase, where industrialization after reaching its peak production started to decrease. Concurrently, the Crotona area was affected by natural flood events that affected the benthic foraminiferal community record. Final peak of the industrial phase is well reflected by the PLI values remaining constantly > 1 until 1968. Subsequently, industrial production started to slightly decrease, taking PLI values < 1 (i.e., unpolluted conditions) from 1973 onwards. Foraminiferal assemblage of this subcluster is characterized by an increase in “second-order opportunists” (e.g., *C. laevigata*, *V. bradyana*), “third-order opportunists” (e.g., *B. marginata*, *B. aculeata*) and stress tolerant taxa abundance (*G. subglobosa*), particularly until the early 1960s. *Bulimina marginata* is a shallow infaunal species commonly associated with environmental stressed conditions (e.g., Jorissen et al., 1992) and can tolerate anoxic conditions. *Cassidulina laevigata* is a cosmopolitan species that prefers well-oxygenated waters but is able to stand hypoxic conditions (Nardelli et al., 2014). *Globocassidulina subglobosa* is a species that responds opportunistically to the input of organic matter (e.g., Gooday, 1988). Conversely, increased abundance of *C. pseudoungerianus* and *A. aberdoveyensis* is recorded in the upperpart of subcluster B1, reflecting the slightly improved environmental

conditions. Benthic foraminiferal assemblage reflects the metal contamination (i.e., Pb, Zn) and the industrial production in the samples encompassing the 1962–1968 interval (98.4% mud content, on mean), with the occurrence of opportunistic (i.e., *V. bradyana*) and infaunal buliminids (e.g., indicator of dysoxic conditions) (Kaiho, 1994) species (i.e., *B. aculeata*), as highlighted by the RDA. During this interval, “Poor” EcoQS conditions were found between 1965 and 1968 based on EQR of $\text{Exp}(H'_{bc})$ and Foram-AMBI (“Poor” conditions registered again in 1979), while FSI suggested “Moderate” conditions in 1965. The Spearman’s rank correlation matrix (Fig. S1) performed between benthic foraminiferal indices and industrial contamination revealed a significant and negative correlation between foraminiferal diversity (i.e., $\text{Exp}(H'_{bc})$) and heavy metal concentrations, particularly for Pb and Zn ($p < 0.001$), as well as for Cd and Cu ($p < 0.01$), validating the existing relationship among these factors. In addition, FSI showed a strong statistical relation with the same pollutants, reaching the highest significance level with Zn ($p < 0.001$). The Foram-AMBI index was not included in the Spearman’s rank correlation matrix because it showed no significant relationship with any of the investigated heavy metals (Cd, Cu, Pb, and Zn). This lack of significance may be attributed to the limited assignment of taxa to ecological groups, with only 94 of the 164 identified taxa classified. Such a limitation may have reduced the sensitivity of the index and potentially obscured underlying relationships between the Foram-AMBI index and certain heavy metals, particularly Cd and Pb. Furthermore, it is worth noting that the Foram-AMBI was originally developed to assess ecological responses to organic matter enrichment rather than to characterize heavy-metal contamination gradients.

5.3. Industrial decline

The third interval identified by the CONISS dendrogram (i.e., subcluster B2), spanning 1984–2016, highlights a further improvement of the environmental conditions, compared to cluster A. After 1980, an industrial crisis linked to a reduction in zinc demand led to industrial production decline, which turned into worker protests during the early 1990s. The decline of the industrialization in the Crotona area is reflected by the PLI values < 1 (except in 2006 and 2014), indicating prevailing unpolluted environmental conditions throughout this interval. Similarly, the initial recovery is supported by the increase in relative abundance of sensitive species occurring in oxygenated sediments (e.g., *C. pseudoungerianus*) during the 2000s (i.e., negatively related with metal enrichment), as revealed by the RDA output (left side, Fig. 5).

The assemblage of subcluster B2 is still composed of opportunistic species (e.g., *V. bradyana*, *B. marginata*, *U. mediterranea*), although a concurrent increase in relative abundance of epifaunal oxic species *C. pseudoungerianus* and *Sphaeroidina bulloides* is recorded, supporting a shift towards better environmental conditions. *Cibicides pseudoungerianus* is an epifaunal taxa which thrives in well-oxygenated sediments, whereas *S. bulloides* indicates high oxygenation conditions (e.g., Barmawidjaja et al., 1992; Kaiho, 1994).

Since 1990 onwards, improved ecological conditions (“Good” to “High”) are highlighted by the EcoQS based on EQR of $\text{Exp}(H'_{bc})$ values, except in 2012 (EQR $\text{Exp}(H'_{bc}) = 0.57$). This is also confirmed by the EcoQS based on EQR of FSI values during 1994–2016 interval (i.e., “High” conditions) and confirmed by the Foram-AMBI values, which showed “Moderate” conditions since 1982 onwards and reaching “Good” conditions only in 2012.

5.4. Natural flooding events may bias EcoQS assessment

Although grain size throughout the entire core is mainly composed of muddy fraction (95% on average), consistent with the depositional environment of the Crotona basin, two major inputs of coarse-grained (i.e., highest values of sandy content) sediments are observed along the KR3 sediment core during 1976–1979 interval (24.6% and 16.2%,

respectively) and in 1997 (12.2%). The Crotona area faced several historical flash flood events, such as in 1976 and 1996 (Mendicino, 2006). Particularly, the 1996 flash flood event affected the Esaro and Passovectchio rivers with over 120 mm of rainfall in three hours (Macchione et al., 2019); this event is consistent with the input of large amounts of coarse-grained sediments from the coastal area to the offshore registered in 1997 (i.e., 12.2% of sandy fraction). These two intervals (i.e., 1976–1979 and 1996) are also punctuated by a significant increase of MAR (0.33–0.53 and 0.57 g cm⁻² y⁻¹, respectively) providing evidence of a higher accumulation of sediment. Studies on extreme flooding events showed that large sediments input can physically transport benthic organisms and induce alteration in the benthic community structure and diversity (e.g., Mistri et al., 2019). We reported the appearance in the 1997 sample of shallow-water species (i.e. *H. germanica*) and epiphytic specimens (i.e., *R. macropora*) commonly associated with sandy sediments and seagrass meadows. Particularly, the genus *Rosalina* is a shallow marine species commonly found in vegetated bottoms (e.g., Sgarrella and Moncharmont Zei, 1993), whereas *H. germanica* is commonly found in shallow-water and intertidal habitats. Furthermore, the first and only occurrence of *Adelosina longirostra* was reported in the mid-1970s, matching the flooding event and the sandy peak (i.e., 27.8%). This species is commonly found in infralittoral (e.g., depths shallower than 30 m) environments (Sgarrella and Moncharmont Zei, 1993). The increase in diversity is most likely attributable to long-range transport of sediments and benthic foraminiferal assemblages. Therefore, the peaks in diversity associated with flooding events are here interpreted as an apparent, rather than genuine, increase and are consistent with higher sandy content. Similarly, another peak in diversity is observed in the 2003 layer and coincides with the occurrence of *Peneroplis* spp. Species from the genus *Peneroplis* are epiphytic (depth range 0–70 m), commonly associated with marine phanerogams endemic to the Mediterranean Sea, such as *Posidonia* or *Cymodocea* substrates (Langer, 1993), therefore the occurrence of this species may be explained by a displacement process linked to sedimentary dynamics influencing the Esaro canyon. *Ammonia aberdoveyensis* is nearly absent before 1950's, while *A. batava* shows the highest values of relative abundance (i.e., 9.5% on mean) until 1953. *Ammonia aberdoveyensis* occurrence is normally limited to intertidal environments (Bird et al., 2020) but it has been reported also in subtidal ones (Pavard et al., 2023). This species thrives in mud and muddy sand substrates and is abundant in estuaries. *Ammonia batava*, on the other hand, is primarily a subtidal species that can also occur in intertidal environments (Bird et al., 2020) and has been also recorded at water depth up to 120 m (Hayward et al., 2021). Additional flooding events that took place in the early 50 s (e.g., in 1954, 1957, 1959) in the Crotona area may have transported *A. aberdoveyensis* specimens from shallow areas to coastal settings, where they survived and, over time, possibly replaced *A. batava*. Indeed, *A. aberdoveyensis* increases in abundance from sub-cluster B1, while *A. batava* abundance decreases. Furthermore, slightly improved environmental conditions emphasized by the decrease in the PLI values after 1973 may have favoured the proliferation of more specialist species *A. aberdoveyensis*, which is capable of tolerate hypoxic and anoxic sediments, and adapt to a wide range of salinities (Bird et al., 2020), potentially outcompeting *A. batava*.

The influence of the complex processes shaping the continental slope and the Esaro Canyon and, consequently, the sedimentary record cannot be excluded. The Crotona continental margin, in particular, is characterized by the presence of submarine landslides (e.g., Bianchini et al., 2025; Zecchin et al., 2018). On the other hand, maritime traffic within the Crotona harbour and coastal area must also be considered as a potential driver of sediment and biological transport. Particularly, the discharge of ballast waters may facilitate the displacement of shallow-water benthic foraminiferal species (e.g., Gollasch, 2006) toward deeper canyon settings, further affecting the interpretation of the local ecological record.

Although the EcoQS based on EQR of Exp(H'_{bc}) suggests a shift in

EcoQS from “Poor” (1968) to “High” and “Good” (1973 and 1976) following the 1976 flood occurred in the Crotona area, this assessment might represent an artefact and likely suffers from methodological bias. Therefore, we contend that these indices do not provide a reliable representation of the area's ecological health during that period.

6. Conclusions

In the present study, benthic foraminifera have been used as ecological proxies along the KR3 sediment core to infer the environmental and historical EcoQS changes in the Crotona basin (Ionian Sea, Italy) during the last 100 years. The geochemical record highlights high concentrations of heavy metals (e.g., Cr, Pb, Zn) and PLI values from the base of the core, and particularly in the interval spanning 1948–1968, reflecting the main stages and peak of the industrial complex. The intense industrialization in the Crotona area is well reflected in the variation of benthic foraminiferal assemblage composition as well as in the EcoQS. In details, the record indicates mainly “Moderate” conditions from 1926, mirroring the early industrialization phase, shifting to “Poor” conditions during 1965–1968 (i.e., industrialization peak). “Good” to “High” conditions are inferred for the 1982–2016 interval. Nonetheless, the benthic foraminiferal community and sedimentological record in the Esaro canyon appear to be influenced by an interplay of multiple factors. Accordingly, sharp increases in diversity and in sand fractions reflect the flooding events in 1996 (i.e., occurrence of shallow-water species *R. macropora* and *H. germanica*), 1976 (occurrence of infralittoral species *A. longirostra*), and 2003 (i.e., occurrence of epiphytic species *Peneroplis* spp.). Extreme flooding events appear to alter the natural composition of the foraminiferal communities with the addition of allochthonous species, which might increase or modify diversity, leading to an improved but biased EcoQS assessment. These observations emphasise the need for a comprehensive understanding of the historical, physical and hydrodynamical features of the investigated site to avoid any inaccurate and biased assessment of the EcoQS. In the specific context of the Crotona coastal area, this complexity is further amplified by both natural and anthropogenic transport mechanisms. On one hand, the presence of submarine landslides and gravity-driven processes, characteristic of the Crotona slope, may physically mix displaced shallow-water assemblages with relatively deeper communities. On the other hand, the intense maritime traffic and associated ballast water discharge in the Crotona coastal area may facilitate long-range transport and introduction of non-indigenous or shallow-water species into deeper settings, further overprinting the natural faunal signal. Consequently, variations in community diversity linked to these phenomena may induce a misinterpretation in the EcoQS assessment. This study also highlights the need for improved ecological knowledge of benthic foraminiferal species to ensure reliable interpretation of the benthic foraminiferal record.

These findings underscore the significant role of integrating geochemical and sedimentological analysis with benthic foraminiferal community variations to create a solid framework to assess EcoQS over time. Furthermore, this approach allowed to discriminate between human impacts, extreme natural events, and maritime transport of sediments and organisms within the marine ecosystem.

CRedit authorship contribution statement

Antonio Schirone: Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Julien Richirt:** Writing – original draft, Methodology, Formal analysis. **Vincent M.P. Bouchet:** Writing – original draft, Supervision, Methodology, Formal analysis, Data curation. **Elvira Oliveri:** Project administration, Methodology, Funding acquisition, Data curation. **Fabio Francescangeli:** Writing – original draft. **Ivana Delbono:** Project administration, Methodology, Funding acquisition, Data curation. **Carla Buosi:** Supervision, Investigation. **Carla Cristallo:** Writing – original draft, Visualization,

Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fabrizio Frontalini**: Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mario Sprovieri**: Project administration, Funding acquisition.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.rsma.2026.105133](https://doi.org/10.1016/j.rsma.2026.105133).

Data availability

Data are available in supplementary materials.

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