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EDITED BY

Cristina Munari,
University of Ferrara, Italy

REVIEWED BY

Alan Deidun,
University of Malta, Malta
Alberto Felici,
University of Camerino, Italy

*CORRESPONDENCE

Federica Cacciatore
✉ federica.cacciatore@isprambiente.it

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Macrozoobenthos and environmental changing in the Venice Lagoon (Italy)

Federica Cacciatore^{1*}, Michele Cornello¹, Valentina Bernarello¹,
Federica Oselladore¹, Marta Novello², Alessandra Girolimetto²,
Massimo Zorzi², Daniele Bon², Fabio Strazzabosco²,
Andrea Bonometto¹ and Rossella Boscolo Brusà¹

¹Italian Institute for Environmental Protection and Research (ISPRA), Chioggia-Venice, Italy,

²Environmental Prevention and Protection Agency of Veneto Region (ARPAV), Padova, Italy

Macrozoobenthos are invertebrates playing a fundamental role in the ecosystem processes of several environments, such as lagoons. They contribute to nutrient cycles, metabolization of pollutants, sediment oxygenation, as well as filtering phytoplankton, and are a food source for other organisms at higher level of the food web. The distribution of macrozoobenthos depends on both abiotic and biotic factors, such as salinity, depth, hydrodynamics, sediment size and composition, as well as inter- and intraspecific competition and predation. Macrozoobenthos communities are commonly used as bioindicators to assess the quality of coastal and transitional marine ecosystems. In fact, they represent one of the biological quality elements for evaluating the ecological quality status of transitional and coastal waters under the Water Framework Directive. The aim of this study is to investigate changes in the macrozoobenthos community and their relationship with environmental parameters in the Venice Lagoon, one of the largest and most important transitional water bodies in the Mediterranean Sea. To this end, ecological indices were applied to 268 samples and 252 taxa, collected from 2011 to 2022, with macrozoobenthos sampled once every three years during the spring-summer period. Trends in environmental conditions of the water column (sampled seasonally each year) and sediments (sampled concurrently with macrozoobenthos) were also analyzed, highlighting a significant increase/decrease in some parameters, which were then related to dissimilarities in macrozoobenthos abundances. The results show that the macrozoobenthos community in the Venice lagoon has changed over time, with evidence of biodiversity loss and differences between polyhaline and euhaline areas, and between different hydrodynamic zones. The changes in macrozoobenthos are also significantly related to environmental parameters such as salinity, temperature, nutrients, organic carbon, silicate, and grain size.

KEYWORDS

biodiversity, climate change, Directive 2000/60/EC, salinity, nutrients, M-AMBI, sediments, transitional waters

Introduction

Soft bottom macrozoobenthos consists of benthic invertebrates generally defined as organisms retained by a 0.5 mm sieve size. Benthic assemblages play a fundamental role in the ecosystem processes of several environments, such as lagoons. Indeed, they contribute to nutrient cycles, metabolism of pollutants, sediment oxygenation, as well as the filtration of phytoplankton. Moreover, they are a food source for other organisms at higher level of the food web (Pearson and Rosenberg, 1978; Dauer et al., 2000).

Benthic assemblages are predominantly sedentary infaunal species, reflecting and responding to the environmental conditions in which they live (López-López and Sedeño-Díaz, 2015; Borja et al., 2000). The distribution of macrozoobenthos depends on both abiotic factors, such as salinity, depth, hydrodynamics, sediment size and composition, and biotic factors, such as inter- and intraspecific competition and predation (Pearson and Rosenberg, 1978; Dauer et al., 2000; Magni et al., 2009). Most species have long life spans and belong to a wide range of taxonomic, functional and trophic groups. Therefore, they can integrate disturbance events over time but also are sensitive to several different sources of disturbance, including groups with different tolerance levels (Pearson and Rosenberg, 1978; Dauer et al., 2000; Ponti et al., 2009). Therefore, macrozoobenthos is often used to predict imbalance in physical, chemical and biological conditions as well as the impact of anthropogenic activities and it is widely used worldwide as a bioindicator to assess the quality of marine, coastal and transitional ecosystems (see e.g.: Mistri et al., 2000; Mobashi et al., 2016; Li et al., 2017; Bangun et al., 2018; D'Alessandro et al., 2018; Dapeng et al., 2019). Indeed, benthic macroinvertebrates are among the biological quality elements to assess ecological quality in transitional and coastal waters according to the Water Framework Directive, in terms of their diversity, abundance and the presence of disturbance-sensitive *taxa* (European Parliament and Council, 2000).

Transitional aquatic environments are coastal areas where continental freshwater meets marine saltwater, characterized by a high variability in the chemical-physical parameters of the water, including temperature, salinity, and oxygen (Tagliapietra et al., 2009). As they are shallow surface waters, temperature and salinity are more variable compared to adjacent marine or freshwater systems. Additionally, they are zones of high biological production, as the nutrient enrichment that distinguishes them makes them optimal areas for reproduction, nesting, and wintering of various bird and fish species, some of which are of conservation and European community interest (Whitefield and Elliott, 2005). Sometimes, however, specific conditions of nutrient enrichment in the water column, as well as the reduction of water exchange with the open sea and the sedimentary nature of the seabed, can lead to common hypoxic and/or anoxic conditions (Cognetti et al., 2002; Knutsen et al., 2024).

All transitional environments are subject to natural formation and disappearance over the course of several millennia (Cognetti et al., 2002; Narayana and Priju, 2006). The formation and subsequent evolution of coastal lagoons and estuaries are due to

the interaction of multiple factors, including fluvial sediment deposits, marine currents, wave dynamics, wind forces, coastal soil subsidence, and sea level fluctuation (Narayana and Priju, 2006; Barausse et al., 2015; Molinaroli et al., 2009; Pérez-Ruzafa et al., 2011; Alademomi et al., 2020). However, various anthropogenic factors can accelerate the natural processes of morphological variation. These include seabed erosion caused by fishing gear, the creation of artificial canals or sandbars, wave action from boats, subsidence induced by extractive activities at sea, and abrupt sea level changes due to climate change (Molinaroli et al., 2009; Barausse et al., 2015). Nutrient enrichment, pollution, increased turbidity, fishing pressure, seabed erosion, and, in general, all sudden environmental parameter changes, caused by anthropogenic factors, impact biological communities, which may not have sufficient time to adapt and respond promptly to the environmental pressures they encounter, resulting in significant ecosystem-level consequences (Molinaroli et al., 2009; Newton et al., 2014; Barausse et al., 2015; Facca et al., 2020; European Environment Agency, 2021).

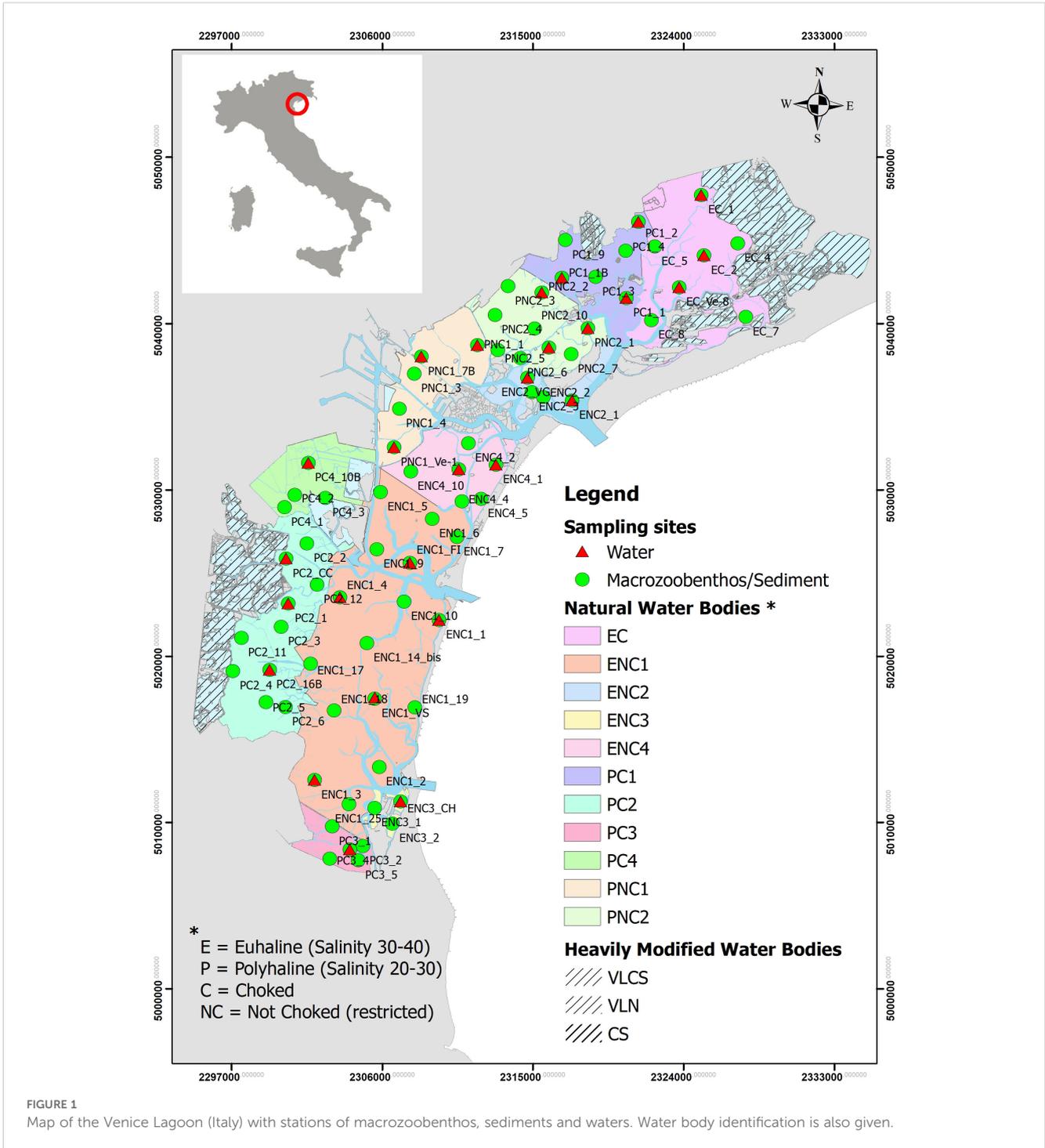
Since 2011, a monitoring program in accordance with the WFD has been active in the Venice Lagoon. This program includes macrozoobenthos and sediment surveys conducted at 77 stations once every three years, and water parameter measurements taken seasonally at 30 sites each year across both natural and heavily modified water bodies. After more than a decade, the accumulated dataset has enabled the investigation of spatial and temporal patterns and dynamics in the lagoon.

This study aims to examine changes in the macrozoobenthos community in the Venice Lagoon from 2011 to 2022 and to assess the relationship between biodiversity dynamics and environmental parameters within the context of climate change. While several studies have explored benthic responses to environmental and climatic pressures in other coastal lagoons (e.g., Anthony et al., 2009; Alademomi et al., 2020; Boutoumit et al., 2021), and others have addressed specific ecological aspects of macrozoobenthos in the Venice Lagoon (e.g., Sfriso et al., 2001; Oselladore et al., 2022), or the broader impacts of climate change on the lagoon's biodiversity (Lacoste et al., 2023), to the best of our knowledge, this study represents the first multi-station, long-term investigation specifically focused on macrozoobenthic biodiversity in the Venice Lagoon in relation to climate-driven environmental changes. By integrating biological and physico-chemical data over a 12-year period, this study provides a novel contribution to understanding the ecological dynamics of transitional ecosystems under increasing climate pressure.

Materials and methods

Study area

The Venice lagoon (Figure 1) is a delicate and fragile transitional environment in the northwestern part of the Adriatic Sea (Italy). It is one of the largest (about 550 km²) and most important transitional waters in the Mediterranean Sea. It is a shallow body of water of approximately 1.3 m in depth, separated



from the sea by 3 wide inlets and with 14 freshwater inputs. It has been continually threatened by human activities, particularly over the last century, with significant man-made transformations (Sorokin et al., 2002; Guerzoni and Tagliapietra, 2006; Solidoro et al., 2010; Feola et al., 2024).

According to the WFD, the Venice Lagoon is a large coastal microtidal lagoon, divided into 11 natural water bodies (WBs), belonging to 4 different types according to salinity (P =Polyhaline with salinity range 20 - 30; E = Euhaline with salinity range 30-40) and by confinement degree (C= Choked; NC= Non-Choked) and 3

heavily modified WBs. For the present study, only natural WBs were considered.

Macrozoobenthos sampling and laboratory processing

Field surveys were conducted by boat in the spring (May/June) 2012, 2014, 2019 and 2022 in the Venice Lagoon at 75 stations (Figure 1). Sediment samples were collected using an Ekman-Birge

grab with a surface area of 15 x 15 cm (225 cm²), capable of penetrating the sediment vertically up to approximately 20 cm. At each station, three separate sediment samples were collected through independent deployments of the grab, resulting in a total sampling surface area of 0.0675 m². The sampling procedure adopted in this study strictly follows the official protocols established by ISPRA (2010), developed within the framework of the European Water Framework Directive (European Parliament and Council, 2000). These protocols are uniformly applied by all Regional Environmental Agencies in Italy to ensure consistency and comparability of benthic data across transitional water bodies.

The three sediment aliquots were separately sieved with a 1 mm mesh sieve. Although macrofauna is generally defined as organisms retained by a 0.5 mm sieve, a 1 mm mesh was used as it offers a practical balance between data representativeness and processing effort, without significantly affecting community parameters (APAT-SIBM-ICRAM, 2003).

The material retained by the sieve was transferred to an anesthetic solution to prevent the organisms from contracting, which would make the identification process difficult. The samples were then fixed in 70% ethyl alcohol for later sorting and identification of the fauna in the laboratories. Although the samples were processed individually, the results were later combined during the data analysis phase.

Macroinvertebrates were initially divided into major taxonomic groups (mollusks, crustaceans, polychaetes, etc.) and then subjected to refined classification. The data were ordered and conformed according to the taxonomic nomenclature considered in the Checklist of Italian Marine Fauna, published by the Italian Society of Marine Biology (Relini, 2008, 2010). In the case of species not included in the Italian checklist due to changes in taxonomic nomenclature, reference was made to the World Register of Marine Species (WORMS, 2025; <http://www.marinespecies.org/>).

Once the complete list of macrozoobenthos species was obtained, further comparison was made with the check list of macrozoobenthos species for the Adriatic and Mediterranean Seas edited and periodically updated by the Italian Society of Marine Biology (SIBM) to identify species not yet recorded.

All datasets are available at ARPAV Website as reported on Data Availability Section.

Environmental parameters

Water was sampled seasonally at 28 stations (Figure 1) each year from 2011 to 2022. Sediment samples were collected at the same time and stations as in the macrozoobenthos surveys (Figure 1).

All datasets are available on the ARPAV Website as reported in the Data Availability Section.

Data processing and statistical analyses

In the first monitoring cycle, 85 stations were sampled for macrozoobenthos assessment in natural water bodies, later optimized to 75, according to the approach by Cacciatore et al. (2019). Briefly, the

method presents a geostatistical approach to optimize the selection of monitoring stations for environmental studies. Although the article primarily addresses macrophytes, the same methodology was applied to macrozoobenthos in the Venice Lagoon. This approach ensures that the selected stations provide comprehensive and representative data while minimizing biases. This adjustment was made without compromising the comparability of data across cycles and remained consistent for all subsequent surveys.

The dataset obtained, based on data published by ARPAV (see Data Availability Section), was organized into a single abundance matrix of taxonomic units. The stations considered for each campaign were 68 out of the 75 sampled (85 in 2011). Indeed, some stations were relocated for logistical reasons (construction of new lagoon morphological structures, occupation of areas for fishing, clam cultivation etc.). Therefore, the 68 stations refer to those that have remained unchanged in terms of geographical location, and data for all 4 sampling campaigns are available. This abundance matrix consists of 272 samples and 363 *taxa*. The number of *taxa* was then reduced to 252 by deleting all those species and taxonomic groups whose sum of individuals was less than or equal to 2, across the 4 samplings campaigns.

For each station, the following descriptors and univariate indices were calculated: total abundance (N), richness (number of *taxa*), Margalef's richness index (Margalef, 1958), Shannon's diversity index (Shannon and Weaver, 1949), and Pielou's evenness index (Pielou, 1966).

Furthermore, the new reduced matrix was subjected to univariate analysis to calculate diversity indices (DIVERSE) after square root transformation (to reduce the influence of highly dominant *taxa* and to stabilize variance across samples) and calculation of the Bray-Curtis similarity index and multivariate analysis (Cluster Analysis (CLUSTER), Multidimensional Scaling (MDS), Analysis of Similarity (ANOSIM), Similarity Percentage (SIMPER), and Permutational Analysis of Variance (PERMANOVA)) using the software package Primer 6 & Permanova+ β 3. The reduced similarity matrix and the complete similarity matrix for each sampling year were tested using Primer RELATE analysis to test the hypothesis of no relationship between multivariate patterns. Matrices were found to be strongly correlated (Rho values between 0.999 and 1.000 with $p \leq 0.01$).

M-AMBI (Borja et al., 2004; Muxika et al., 2007) was applied at all the sampling stations (85 for the first survey, then 75) to assess the ecological quality status according to the requirements of the WFD. Boundaries and reference conditions to apply M-AMBI are water body type dependent, and those defined in the Italian regulations (see D.Lgs. 152/2006 ss. mm.ii.) intercalibrated by the Med-GIG (Mediterranean Geographical Intercalibration group) in European Member States. To compute the M-AMBI value for each WB, the arithmetic means of the EQR values of the stations belonging to the same WB was calculated. This mean was then referenced against the same reference conditions used for each station, as outlined in the aforementioned national normative guidelines (see D.Lgs. 152/2006 ss. mm.ii.).

The Seasonal Kendall test, implemented via the *kendall* package in R, was applied to detect monotonic trends in the quarterly time series of water parameters from 2011 to 2022. This test extends the Mann-Kendall approach by accounting for intra-annual (seasonal) variability,

evaluating trends within each season separately and then aggregating the results. Its use is particularly appropriate for datasets with regular seasonal sampling, as it improves the robustness and interpretability of trend detection in the presence of recurring seasonal patterns (Hirsch et al., 1982; Meals et al., 2011).

For the comparative analyses between macrozoobenthos abundances and water physico-chemical parameters, data from the 4 monitoring cycles of the 28 stations of physico-chemical quality elements were considered, as well as the corresponding stations of the EQB macrozoobenthos distributed in natural water bodies. To perform the appropriate comparisons, a three-year average value of the seasonal water samplings of each monitoring cycle was calculated for a total of 112 data points (28 stations for 4 cycles).

For comparative analyses between sediment parameters and macrozoobenthos, the 68 stations maintained over the years were considered. Because the set of sediment parameters analysed varied across the four sampling campaigns, and to ensure consistency in the statistical treatment of the data, comparisons between sediment characteristics and macrozoobenthic communities were conducted separately for each campaign.

Before performing the analyses, similarity matrices (Bray-Curtis's similarity) of the appropriately transformed macrozoobenthos data (square root transformation) were calculated, while the abiotic parameter data were normalized and logarithmically transformed when necessary. To minimize autocorrelation and multicollinearity among environmental variables, a variable selection procedure was applied: for granulometric data, only pelite (%) was retained as a representative fraction, while other highly correlated size classes were excluded; for chemical parameters, we retained individual elemental concentrations and excluded summed variables (e.g., TOC) to avoid redundancy. These steps ensured the robustness of the multivariate analyses and reduced the risk of overfitting due to interdependent variables.

The BEST function of BIOENV (Primer v.6) was then applied, which selects environmental variables by maximizing a rank correlation between the respective similarity matrices. Correlations were considered significant for $p < 0.01$. To better visualize the correlation results, biplot graphs from the Principal Component Analysis (PCA) of water and sediment parameters (R software) and MDS graphs (Primer v.6) of the macrozoobenthos similarity matrices were created.

Pearson's correlation coefficient was tested (after verifying the assumptions of linearity and normal distribution) for each monitoring cycle (2011, 2014, 2019 and 2022) among sediment parameters consistently analysed across all surveys (pelite, inorganic nitrogen and organic carbon) and the abundances and Shannon's diversity index values (R software).

Results

Biodiversity and ecological status of macrozoobenthos

The total abundance and richness decreased especially in the last year (2022), as well as Shannon's diversity and Margalef's

richness indices, whilst Pielou's evenness index increased over time (Figures 2a-e). The distribution of *taxa* abundances (Figure 2f) showed the disappearance of some *taxa* over time, such as Clitellata, Hexapoda, Bryozoa, Copepoda, Nematoda and Pycnogonida, although very few organisms were found to belong to these last four *taxa*. Other *taxa* were halved or nearly disappeared such as Crustacea, Polychaeta, Bivalvia, Cnidaria, Echinodermata, Tunicata, Nemertea. The only *taxon* which increased was Phoronida, whilst Gastropoda, Decapoda and Polyplacophora (except in 2014) remained fairly stable across the surveys.

The complete list of macrozoobenthic species recorded during the study is provided in Supplementary Table S1. Species highlighted in blue are those not listed in the current SIBM checklist of macrozoobenthic species of the Adriatic and Mediterranean seas. The CLUSTER analysis showed that, at a similarity level of 20%, eight significant groups with more than four elements can be identified. These groups were defined by the year of samplings and hydrological condition (choked/not choked) of water bodies (WB). In the first group, samples from 2011 predominated; in the second group, there were mainly choked (C) samples, especially from 2011 and 2014; in the third group, samples from 2014 and 2019 were predominant; in the fourth group, samples from non-choked (NC) stations prevailed; the fifth group consisted almost entirely of NC samples from 2011 and 2014; the sixth group also consisted of mainly NC samples, especially from 2022; the seventh group mostly included samples from 2019 and some from 2022; finally, the eighth group was entirely composed of samples from 2019 (mostly NC). Overall, it can be said that samples from 2019 and 2022 differed more from those of 2011 and 2014, which formed less homogeneous groups, and that many samples from 2022 tended to form small groups (with fewer than five elements), indicating a strong heterogeneity within the year.

The MDS graph (stress value of 0.28) depicts a differentiation both by confinement (Figure 3) and by salinity (Figure 4). ANOSIM results (Table 1) showed that "years" was among the factors that maximize intra-group similarity and minimize that from inter-group, followed by "salinity" and then "confinement". The pairwise test confirmed that all years were significantly different ($p = 0.01\%$) with lower R values between 2011 and 2014 and higher between 2011 and 2019. SIMPER analysis also confirmed lower similarity in each year (13-21%) and higher between years (mean dissimilarity values $>83\%$): the lowest dissimilarity was between 2011 vs 2014 (83%), whilst the highest dissimilarity was between 2019 vs 2022 (90%). These findings mostly depend on high heterogeneity of low frequency species among groups, as well as the variation on abundances of the same species with relative higher abundance and common at all groups. The most common species were the bivalve *Abra segmentum* (Récluz, 1843) and the amphipod *Gammarus insensibilis* (Stock, 1966).

The application of two-way crossed PERMANOVA (Table 2) among groups determined by the factors "water bodies" (fixed, 11 levels) and "years" (fixed, 4 levels) allowed for the verification of whether these groups were significantly different from each other and if there was an interaction between the two factors. Both factors

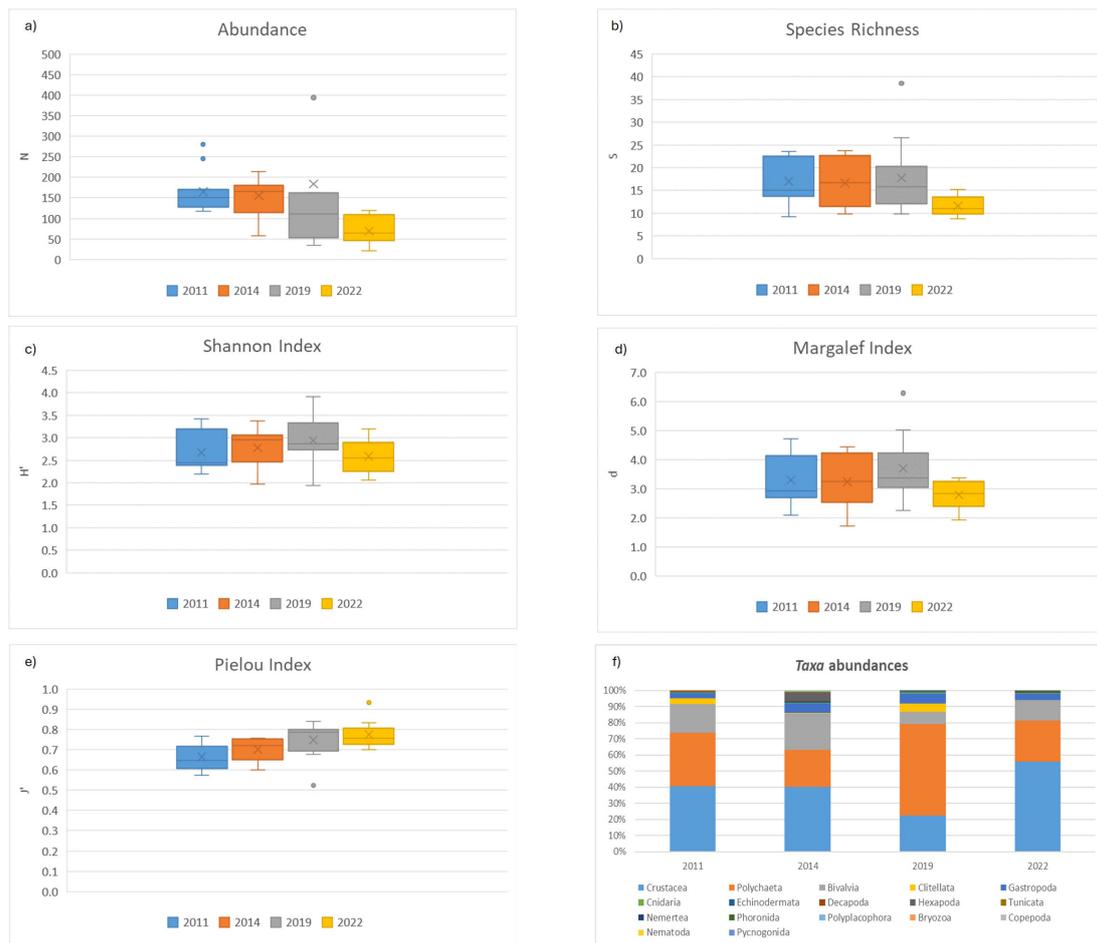


FIGURE 2

Box and whiskers of (a) abundance, (b) species richness (c) Shannon's diversity index, (d) Margalef's richness index, (e) Pielou's evenness index and (f) taxa abundances, in macrozoobenthos sampled from 2011 to 2022 in the Venice Lagoon. (x = mean, - = median, box limits are 25° and 75° percentiles, whiskers are max and min).

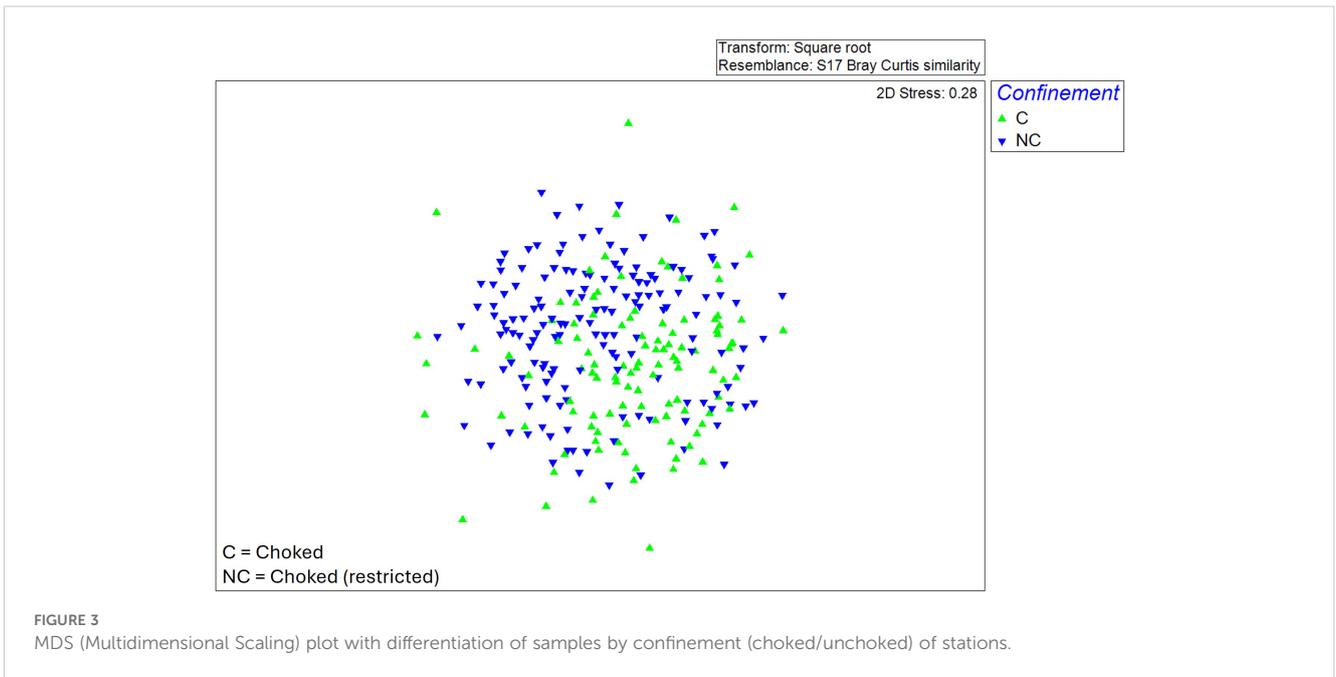
were found to be significant, as it was the interaction. Higher pseudo-F also indicated that the temporal factor is the most determining factor.

Figure 5 depicts a decrease of ANOSIM's R values in salinity-based differentiation, relatively stable values for water body differentiation after 2014, and an alternation of significance and non-significance results when seeing the confinement-related differentiation.

Ecological quality status of macrozoobenthos assessed by M-AMBI is reported in Figure 6. Ecological quality ratio (EQR) values ranged between 0.29 to 0.97 and covered all quality status from Bad to High. In the first monitoring cycle (2011), the water bodies' EQR scores ranged between 0.54 and 0.74, with 2 WBs in Good ecological status, 1 in Poor, and the others in Moderate status. In the second cycle (2014), scores ranged between 0.57 and 0.81; only one WB was recorded in Good status, 1 in Poor, and the remaining 9 in Moderate condition. In the third cycle (2019), all WB were in Moderate condition except for 3, which were in Good condition; EQR values ranged between 0.57 and 0.82. Finally, in the fourth monitoring cycle (2022), no water bodies were in Good status, 4

were in Poor, and the remaining 7 were in Moderate status, with EQR values ranging between 0.54 and 0.70. Compared to 2011, in 2022 there was a deterioration in 5 water bodies: ENC1 and PC2, which were in Good status in 2011, were in Moderate status in 2022; ENC2, ENC4, and PC4, which were in Moderate status in 2011, were in Poor status in 2022. Compared to 2014, in 2022 the water bodies EC, ENC2, and PC4 shifted from Moderate to Poor status, and only one water body (PC3) shifted from Good to Moderate status; the other water bodies remained unchanged. Finally, compared to 2019, in 2022 the ecological quality deterioration affected 6 water bodies: EC, ENC4, and PC4 shifted from Moderate to Poor status; PC2 and PNC2 shifted from Good to Moderate status, while ENC2 shifted from Good to Poor status.

Figure 7 shows that, in the latest monitoring cycle, the average M-AMBI values for all natural water bodies in the Venice Lagoon reflect the lowest levels of species richness and diversity, indicating a general decline in macrozoobenthic biodiversity. Conversely, the first three monitoring cycles generally show better quality, with higher diversity values in the second and third cycles, and higher richness in the first cycle,



Water and sediment parameters

Table 3 reports the results of the application of the Seasonal Kendall's test in the trend analysis of water parameters sampled seasonally each year from 2011 to 2022. Figure 8 depicts trends of those parameters that were found to be significant in the Seasonal Kendall's test at the lagoon scale. Nitrogen compounds showed that throughout the lagoon there was a general decreasing trend in concentrations over the years, significant for all analyzed forms except for nitrates. The trend analysis of phosphorus compounds was limited to total dissolved phosphorus (TDP), as

orthophosphate (P-PO₄) was often present in concentrations below the limit of quantification (LOQ) of analytical instruments. Like nitrogen compounds, there was a significant decrease in TDP concentration throughout the lagoon over the years. Considering the carbon compounds, i.e. total organic carbon (TOC), particulate organic carbon (POC), and dissolved organic carbon (DOC), the Seasonal Kendall's test yielded significant results only for the latter parameter, despite all three compounds showing a general decreasing trend over the years. Both chlorophyll *a* and dissolved oxygen (O₂) values showed a decreasing trend over the analyzed period, with significance observed only for dissolved oxygen.

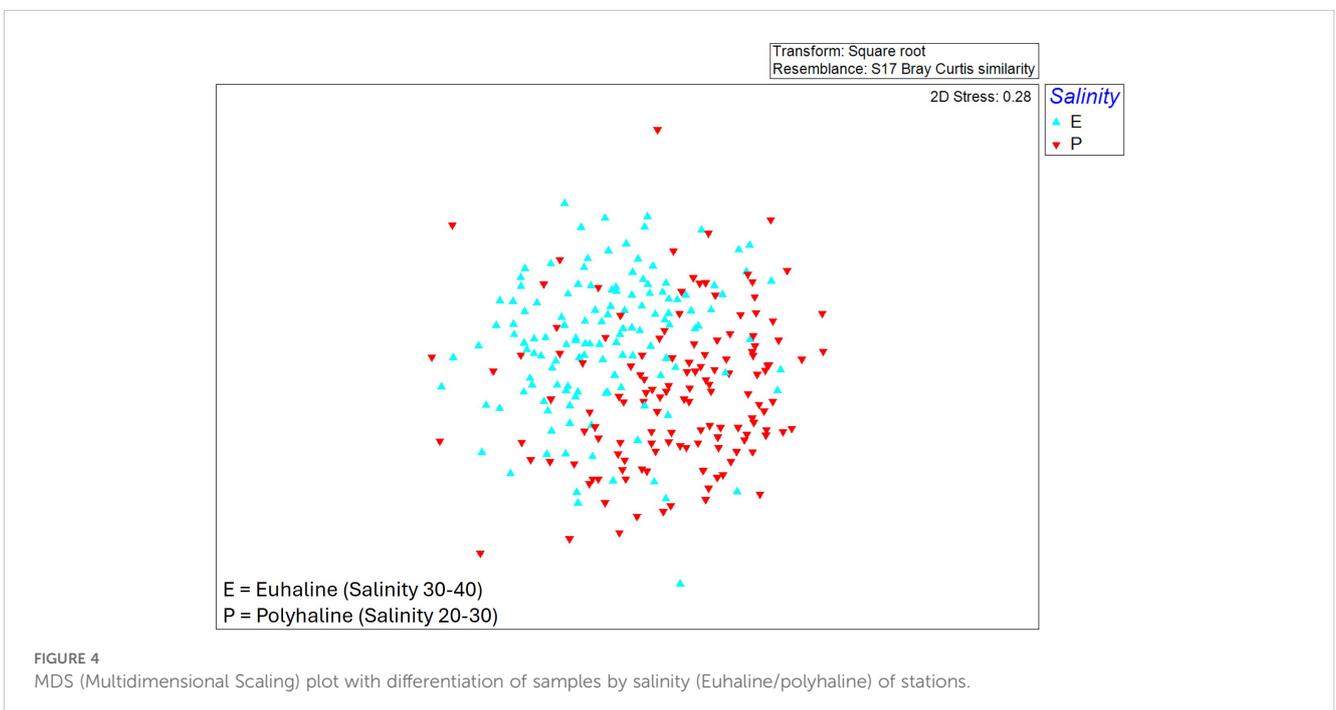


TABLE 1 Results of the analysis of similarity (ANOSIM) between groups identified by each factor: years (4 groups), water bodies (11 groups), salinity (2 groups), confinement (2 groups).

Factors	Global R	p-value (%)
Years	0.277	0.01
Water bodies	0.231	0.01
Salinity	0.212	0.01
Confinement	0.109	0.01

Table 4 reported the results of all sediment parameters analyzed in the Venice Lagoon from 2011 to 2022. Figure 9 depicts the results of the three sediment parameters analyzed across the four monitoring cycles (*i.e.*: pelite, total nitrogen and total organic carbon).

Environmental parameters and macrozoobenthos relations

The results of the comparison between the chemical-physical parameters of water and the macrozoobenthos are reported in Figure 10. The PCA score plot (Figure 10a) allows for the characterization of water samples according to the first and second components, which together explain 61.5% of the total variance. The first component includes the variables salinity, TDN, TDP, TSS, POC, and Chl *a*, while pH, dissolved oxygen, and temperature belong to the second component. DOC and silicates are in an intermediate position.

By comparing the PCA results with the MDS plot (Figure 10b), two groups of cases can be identified, corresponding, respectively, to the first and last monitoring cycles. The BIOENV analysis (Figure 10c) showed that DOC, POC, silicates, salinity, and TDP are the environmental variables most significantly correlated ($Rho=0.345$, $p=0.01\%$) between the two similarity matrices.

The results of the comparison between the sediment parameters and the macrozoobenthos for each monitoring cycle are reported in Figures 11–14. The PCA results of the abiotic parameters (Figures 11a–14a) are mostly similar, despite modifications to the analytical panel over the years, consistent with the largely conservative environmental matrix. The factor weight plots for all four cycles show that sediment samples mainly differed in grain size and organic content.

In the first cycle, 2011 (Figure 11a), the first component (explaining 49.8% of the total variance) includes total nitrogen, total organic carbon and phosphorus, Eh and pH, while pelite,

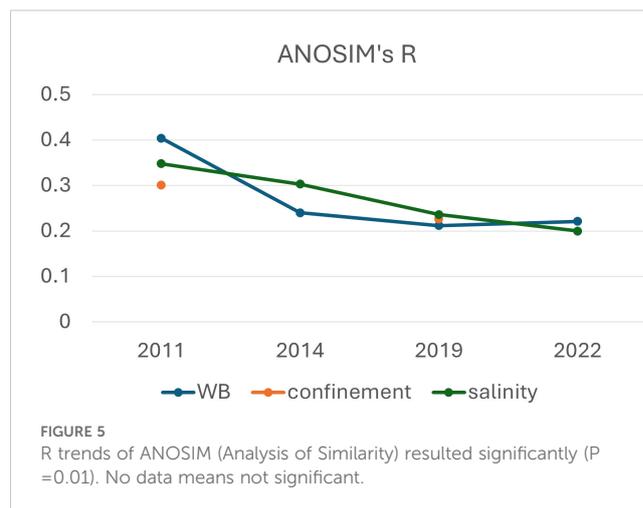


FIGURE 5 R trends of ANOSIM (Analysis of Similarity) resulted significantly ($P=0.01$). No data means not significant.

inorganic carbon and phosphorus are positioned between the two main components. In the second cycle, 2014 (Figure 12a), only three parameters were usable for PCA, after removing autocorrelations, with total carbon and nitrogen belonging to the first component (73.5% of the total variance), and pelite to the second (25.4% of the total variance). In the third cycle, 2019 (Figure 13a) the first component (50.4% of the total variance) includes inorganic phosphorus and carbon, while pelite belongs to the second component (30.9% of the total variance). Finally, in the fourth cycle, 2022 (Figure 14a) the PCA plot is very similar to that of the first cycle, with the first component (59.1% of the total variance) characterized by organic carbon, total nitrogen and phosphorus, while pelite belongs to the second component (24.1%).

Comparing the PCA and MDS plots for each cycle (Figures 11b–14b), similar groupings are evident over the years, with choked samples on one side and non-choked on the other. Notably, most samples from choked polyhaline WBs form a distinct group. In the first cycle, three groups are identified: the group of choked polyhaline WB samples, the group of samples from the only choked euhaline WB in the lagoon, and the group of non-choked euhaline samples. In the second cycle, the groups are again formed by choked polyhaline, non-choked euhaline samples, and a heterogeneous group of non-choked polyhaline and euhaline samples. In the third cycle, besides the choked polyhaline group, a group mainly represented by ENC1 and ENC2 samples is identified. Finally, in the last cycle, the only recognizable group in both data distributions is represented by choked polyhaline samples. BIOENV results of each cycle are reported in Figures 11c–14c.

TABLE 2 Results of the Permutational Analysis of Variance (PERMANOVA) between groups identified by each factor: water bodies (11 groups) and years (4 groups).

Factors	df	SS	MS	Pseudo-F	P(perm)	perms
Water bodies	10	1.1746e ⁵	11746	3.8448	0.001	996
years	3	84053	28108	9.1713	0.001	997
Water bodies x years	30	1.1282e ⁵	3760.8	1.2310	0.001	995
Results	228	6.9653e ⁵	3054.9			

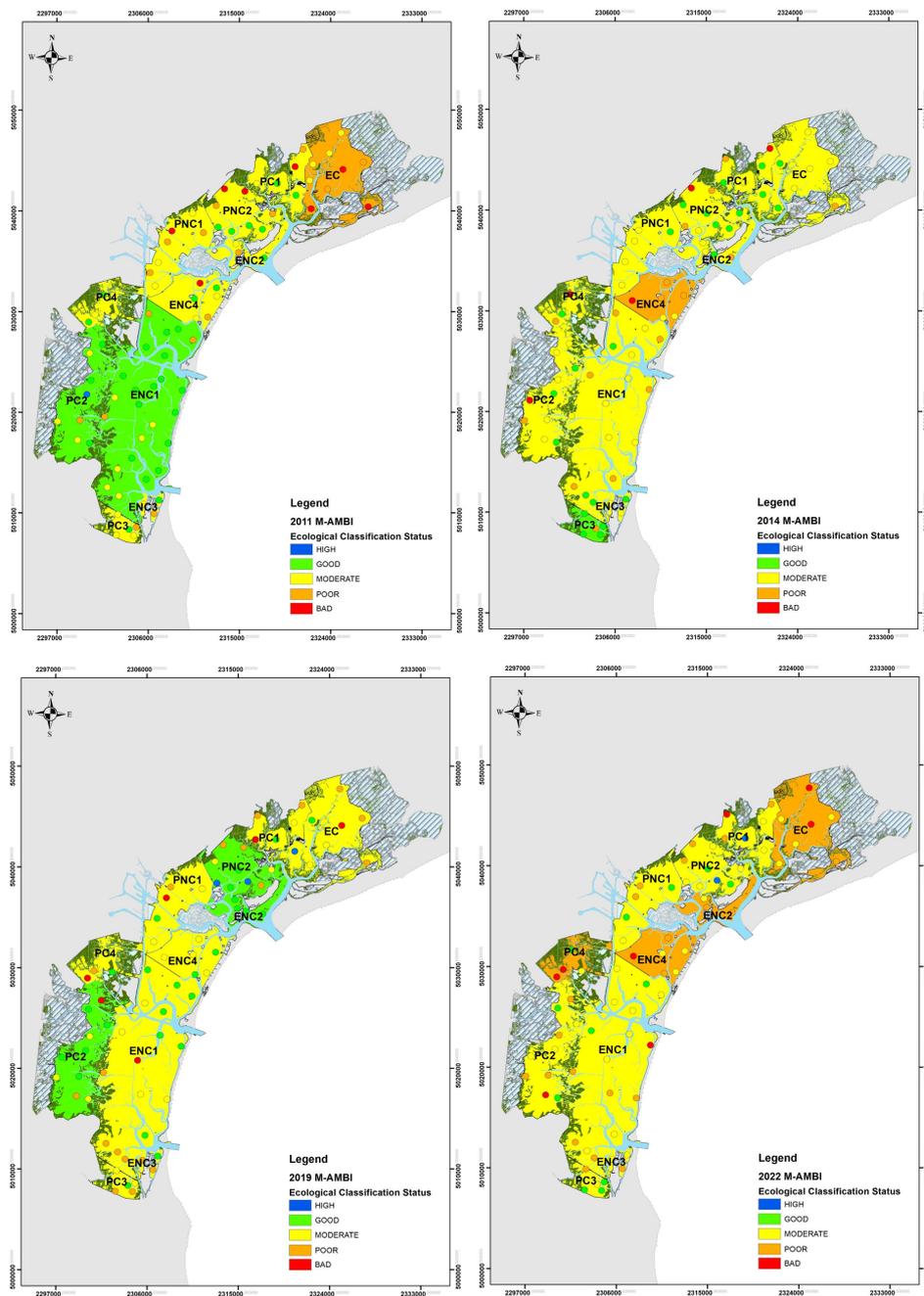


FIGURE 6 Maps of the ecological quality status of macrozoobenthos assessed by M-AMBI in stations and water bodies of the Venice Lagoon from 2011 to 2022.

Pearson’s correlation analyses among sediments parameters and macrozoobenthos characteristics revealed significant inverse correlation between Shannon’s index and organic carbon contents in 2014 ($R = -0.6, p < 0.05$), 2019 ($R = -0.53, p < 0.05$) and 2022 ($R = -0.70, p < 0.05$).

Discussion

The analysis of the biodiversity of the macrozoobenthic community in the Venice Lagoon, based on data collected from

2011 to 2022, during ecological classification monitoring according to WFD, revealed a temporal decrease in *taxa* and number of organisms. Spatially, polyhaline water bodies consistently exhibited lower richness than euhaline ones, while choked water bodies had fewer species compared to those non-choked. This spatial heterogeneity is quite common in benthic assemblage in relation to different abiotic environmental characteristics, such as hydrology and sediment texture (Kneib, 1984; Pearson and Rosenberg, 1978; Dauer et al., 2000). However, 2022 generally recorded the lowest number of species, while the species richness of previous years

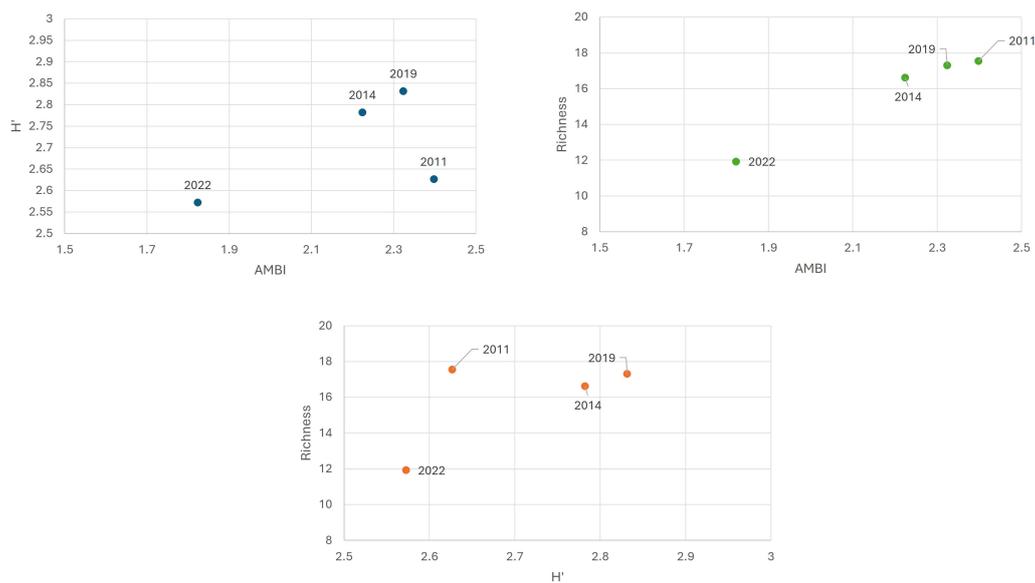


FIGURE 7

Relationship between the parameters of the M-AMBI index: Shannon Diversity Index (H'), number of taxa (Richness), AMBI for the Venice Lagoon for each monitoring cycle (2011, 2014, 2019, 2022).

remained relatively similar; in terms of abundance, there was a continuous year-on-year decline from 2011 to 2022. Moreover, the analysis of similarity (ANOSIM's R) of inter- and intra-groups confirmed a consistent decrease in salinity-based differentiation, while there was a stabilization in the differentiation between water bodies, and an alternation between significance and non-significance in confinement-related differentiation. These findings indicate a trend towards homogenization, particularly concerning confinement. This is consistent with numerical simulations that predicted, in a global warming perspective, a general reduction in variability of physical characteristics in the Mediterranean lagoons, with a tendency towards marinization (Ferrarin et al., 2014). The sharp decline in species richness and abundance observed in 2022 coincides with an extreme climatic event. According to ARPAV (2023), 2022 was the warmest year on record in the Veneto region, with an average air temperature anomaly of +1.2 °C compared to the 1993–2021 reference period. The year was also characterized by recurrent heatwaves and exceptionally low precipitation, leading to widespread drought. As reported by ISPRA (2023), these conditions resulted in the highest annual average salinity values recorded in the Venice Lagoon over the past decade. Such combined thermal and hydrological stressors likely contributed to the observed ecological shifts in benthic communities.

The macrozoobenthic community in Venice Lagoon presented a faunal composition that is characteristic of lagoon environments with the dominance of Crustacea, Polychaeta and Bivalvia. Similar results were obtained for other lagoons in the Northern and Southern Adriatic Sea and Sardinia Island (Sfriso et al., 2001; Marzano et al., 2003; Munari et al., 2010; Oselladore et al., 2022). However relative abundances changed over time, as well as some taxa declined sharply or nearly disappeared.

A general decline in species richness was observed when comparing the earlier sampling years (2011 and 2014) with the more recent ones (2019 and 2022), with 2022 showing the lowest overall diversity. This trend was consistent across the most represented taxonomic groups, including polychaetes, amphipods, and bivalves. Polychaetes showed a partial recovery in 2019, mainly due to the proliferation of spionids, particularly *Streblospio shrubsolii*. This species is known for its opportunistic behaviour, short lifespan, and rapid growth, and is often considered an indicator of environmental stress (Borja et al., 2000). Chironomids were scarcely present in 2011 and 2019 and completely absent in 2022, with a notable peak only in 2014. Decapods maintained relatively stable numbers across the years, except for a marked increase in 2014, although their overall abundance remained low. Malacostracan crustaceans showed a decline from a peak in 2011 to a minimum in 2019, followed by a slight recovery in 2022. This pattern was largely driven by amphipods, with the 2022 increase attributed to a high number of tanaidaceans. Echinoderms were most abundant in 2014, with abundances three times higher than in 2011 and 2019, and sharply declined in 2022. Their distribution is typically associated with areas under strong marine influence. Bivalves were abundant in 2011 and 2014 but their numbers halved in 2019 and 2022. Gastropods increased in 2014 and 2019 but dropped significantly in 2022. Polychaetes declined in 2014 and collapsed in 2022, with sedentary species being the most represented throughout the study period.

Ferrarin et al. (2012), considering a long period with several hydromorphological changes and related variations in Venice Lagoon, hypothesized a scenario for the benthic community predicting a progressive decrease in the number of species. This

scenario included a general increase in polychaetes and a reduction in bivalves, attributed to the hydrological impacts of human interventions, which were expected to result in conditions more similar to the inner areas of the lagoon. Our findings, although covering a shorter period and fewer changes than those simulated by Ferrarin et al. (2012), confirm the reduction in Bivalvia, as well as in Crustacea and Polychaeta.

In the last two sampling campaigns, eight species were recorded that were not listed in the checklist of macrozoobenthic species of the Adriatic and Mediterranean Seas of the Italian Society of Marine Biology (SIBM). Of these, six belong to the Crustacea group and are relatively small and morphologically similar, which increases the likelihood of misidentification (Del Pasqua et al., 2022). For some of the recently detected *taxa*, such as certain Tanaid species, taxonomic uncertainty remains due to their cryptogenic nature, and ongoing studies are focusing on their genetic characterization and distribution (Faasse, 2013; Del Pasqua et al., 2022).

It is important to note that the Venice Lagoon is widely recognized as a hotspot for non-indigenous species (NIS) introductions in the Mediterranean Sea, primarily due to intense anthropogenic pressures such as maritime traffic, aquaculture, and canalization (Occhipinti-Ambrogi, 2000; Occhipinti-Ambrogi and Savini, 2003; Marchini et al., 2015a, b). This context underscores the

importance of continuous monitoring and taxonomic refinement to detect and track emerging NIS and assess their potential ecological impacts.

Biological invasions are among the greatest threats to native biodiversity, and recently, Venice Lagoon has been identified as an ideal habitat for the spread of *Mnemiopsis leidyi* A. Agassiz, 1865 (Piccardi et al., 2025). This species is an invasive zooplanktivorous ctenophore that preys on various organisms, affecting the biodiversity of zooplankton (Schroeder et al., 2023) and impacting fishing activities (Piccardi et al., 2025). The abundance of the comb jelly has significantly increased since 2014 (Piccardi et al., 2025), making it plausible that the explosion of this species has also had direct consequences on the biodiversity of the macrozoobenthos in Venice Lagoon. Indeed, most of the *taxa* that disappeared in our findings after 2014, mostly crustaceans, gastropods, and bivalves, have zooplanktonic larval stages.

Regarding another well-known alien species recently invading the Northern Adriatic lagoons, *Callinectes sapidus*, its proliferation began in 2023 and primarily impacted the Po Delta River lagoons, where clam farming is the predominant activity (Chiesa et al., 2025). The present study reports data up to 2022. However, it is crucial to remain vigilant for potential consequences of this voracious species, which has caused severe impacts on native ecological communities (Onofri et al., 2008; Marchessaux et al., 2023). Indeed, it prefers benthic infauna, particularly bivalve mollusks, but it also consumes polychaetes, amphipods, and other benthic prey (Mansour and Lipcius, 1991; Mansour, 1992).

The ecological quality of the macrozoobenthos in the Venice Lagoon, as indicated by the M-AMBI index, showed variable classifications across space and time, predominantly reflecting a Moderate status according to the WFD definition. Across the entire lagoon, considering the average values of all natural water bodies, the ratio of the M-AMBI index parameters (Shannon's diversity index, number of species and AMBI) indicated that, in the last monitoring cycle, species richness and diversity reached their lowest values, confirming a general decline in the biodiversity of the macrozoobenthos in Venice Lagoon. The M-AMBI seems to behave predictably in the presence or absence of pressure, in both coastal and transitional water bodies, such as different hydro-morphological pressures, including dredging or canalization, with high AMBI values and low diversity and richness levels especially in presence of organic matter, nutrient and pollutant discharges, which can result ultimately in oxygen depletion, eutrophication, etc (Borja et al., 2008). Venice lagoon is a dynamic and unique ecosystem, experiencing several anthropogenic activities which are modifying its hydrodynamic regimes (Ferrarin et al., 2012), as well as causing hypoxia or anoxia events (Brigolin et al., 2021), or pollutant and nutrient discharges (Bellucci et al., 2002; Maggi et al., 2012; Guolo et al., 2025). However, unlike other studies that analysed M-AMBI or AMBI responses to adverse impacts (Muxika et al., 2005; Borja et al., 2008), in Venice Lagoon diversity and richness declined, whilst AMBI improved with values dropping from 2.2-2.4 in the first surveys to 1.8 in 2022. These ranges of AMBI values are reported to indicate a slightly disturbed benthic community in Good status (Muxika et al., 2005; Borja et al., 2008).

TABLE 3 Seasonal Kendall test's results of water parameters sampled seasonally from 2011 to 2022.

Parameter	Trend	Tau	p
pH	↘	-0.103	ns
Temperature	↘	-0.078	ns
Salinity	↗	0.422	***
Dissolved oxygen	↘	-0.267	*
TSS	↘	-0.067	ns
Chlorophyll a	↘	-0.023	ns
Phaeopigments	↗	0.028	ns
DOC	↘	-0.231	*
POC	↘	-0.082	ns
TOC	↘	-0.198	ns
SiO ₂	↗	0.051	ns
DIN	↘	-0.323	**
N-NH ₄	↘	-0.391	***
N-NO ₃	↘	-0.162	ns
N-NO ₂	↘	-0.277	*
TDN	↘	-0.257	*
TDP	↘	-0.331	**

ns (not significant) = $p > 0.05$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. TSS, Total Suspended Solids; DOC, dissolved organic carbon; POC, particulate organic carbon; TOC, total organic carbon; SiO₂, Dissolved silicates; DIN, Dissolved Inorganic Nitrogen; N-NH₄, Ammonia; N-NO₃, Nitrate; N-NO₂, Nitrites; TDN, Total Dissolved Nitrogen; TDP, total dissolved phosphorus.

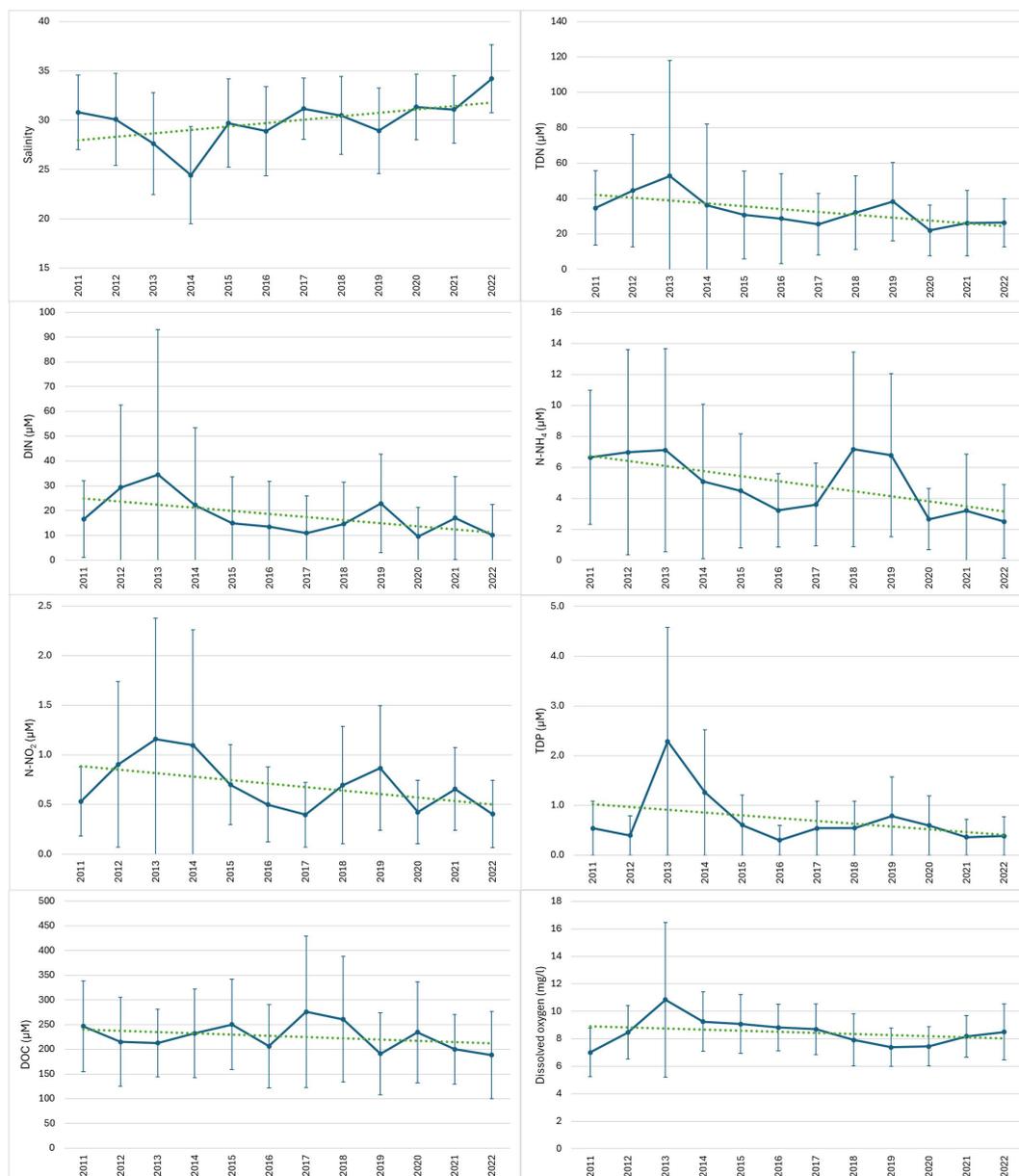


FIGURE 8

Trends of concentrations of parameters (salinity, TDN, DIN, N-NH₄, N-NO₂, TDP, DOC, dissolved Oxygen) from 2011 to 2022, found to be significant in the Seasonal Kendall's test at the lagoon scale. Bars indicate standard deviations.

To evaluate changes in environmental conditions in Venice Lagoon, trends in water parameters and assessments of sediment characteristics were performed. The results indicated significant decreasing temporal trends from 2011 to 2022 for dissolved oxygen, dissolved organic carbon (DOC), ammonium (NH₄), nitrite (NO₂), total dissolved nitrogen (TDN), and total dissolved phosphorus (TDP). Conversely, a significant increasing trend was observed for salinity. The nutrient reduction is consistent with [Acri et al. \(2020\)](#) who observed similar trends from 1998 to 2017 in Venice Lagoon. Nutrient inputs in Venice Lagoon are typically associated with riverine inflows ([Zirino et al., 2016](#)) and the trophic conditions of this environment have been generally improving in the recent years

([Acri et al., 2020](#); [Ponis et al., 2024](#)). Therefore, higher salinity can be linked to greater marine influence, as evidenced by the rising average sea level in the Venice Lagoon ([Crosato, 2024](#)), one of the impacts of climate change. Indeed, some predictive studies for 2050 indicated that the decrease in river runoff, coupled with increased evaporation, will lead to higher salinity and temperature in the Adriatic basin, even though site-specific phenomena may cause deviations from this trend ([Verri et al., 2024](#); [da Costa et al., 2024](#)).

Rising temperature is one of the primary indicators of global warming, and in the Venice Lagoon, an increase in water temperature was reported from 1998 to 2017 due to climate trends ([Acri et al., 2020](#)). The trend test of the present study did

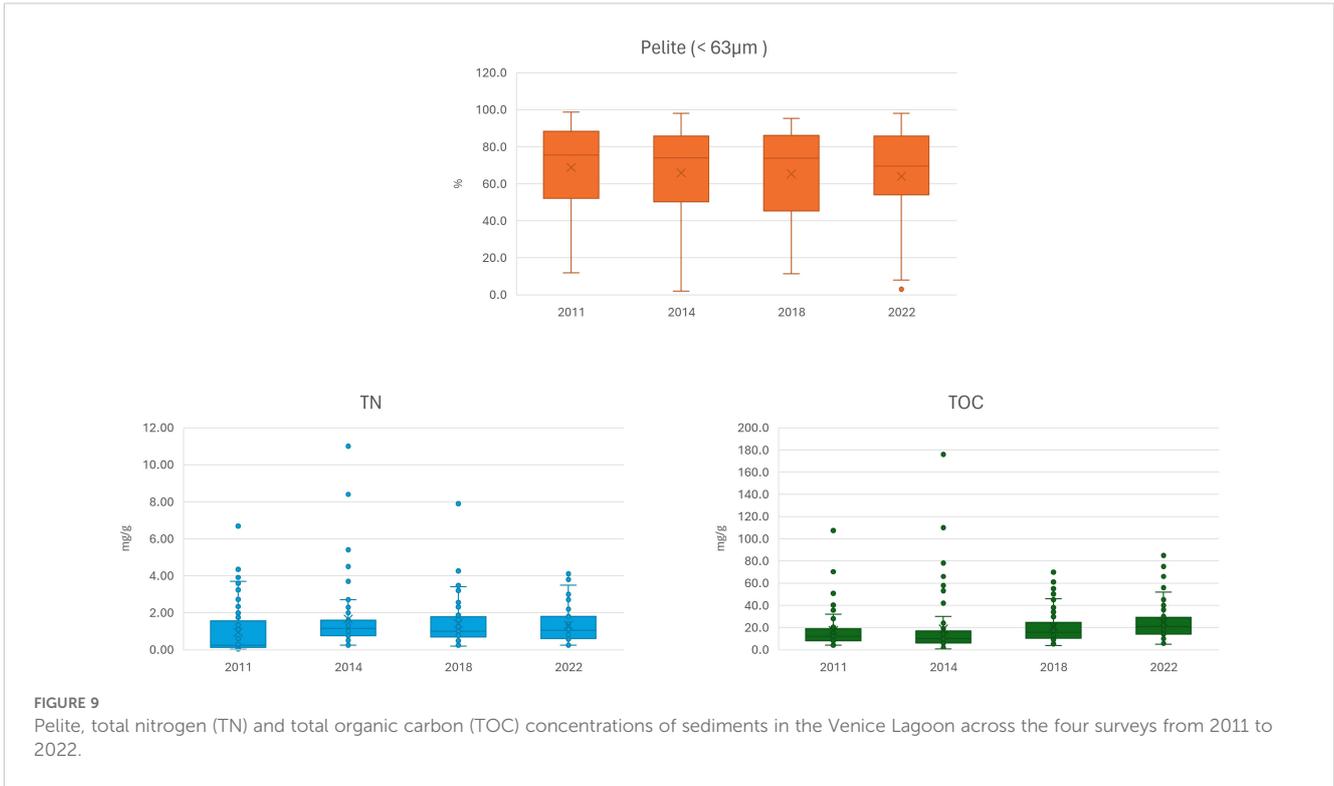
TABLE 4 Sediment parameters resulted in the Venice Lagoon from 2011 to 2022.

Parameters	Year	Mean	Median	Min	Max	St. Dev.
pH (mv)	2011	7.41	7.42	6.85	7.87	0.20
Eh (mv)	2011	-82	-83	-217	166	82
Gravel (%)	2011	6.0	4.4	0.0	19.5	5.0
	2014	5.6	4.0	0.0	23.0	5.3
	2022	8.1	18.0	0.0	49.0	7.9
Sand (%)	2011	25.2	15.0	0.8	83.4	22.9
	2014	27.4	19.0	1.0	98.0	24.1
	2022	27.1	18.0	1.0	96.0	24.4
Pelite < 63µm (%)	2011	68.8	75.5	11.8	98.8	23.1
	2014	67.0	74.0	2.0	99.0	24.3
	2019	64.5	73.9	11.4	96.2	23.9
	2022	64.8	69.0	3.0	99.0	24.5
Total Phosphorous (µg/g)	2011	409	386	199	684	116
	2022	373	360	150	810	157
Inorganic Phosphorous (µg/g)	2011	325	315	179	636	89
	2019	400	372	180	716	112
Organic Phosphorous (µg/g)	2011	84	67	4	260	57
	2019	324	297	164	649	90
Total Nitrogen (mg/g)	2011	0.95	0.24	0.03	6.68	1.30
	2014	1.79	1.30	0.50	11.00	1.76
	2019	1.16	0.86	0.19	4.26	0.82
	2022	1.36	1.10	0.25	4.10	0.99
Total Carbon (mg/g)	2011	70.6	73.8	23.7	146.8	17.3
	2019	68.6	73.8	17.8	98.6	15.2
	2022	67.3	73.0	16.0	107.0	17.4
Inorganic Carbon (mg/g)	2011	53.4	54.3	17.6	82.6	16.0
	2019	52.6	56.4	12.0	80.2	15.7
	2022	42.2	43.0	7.6	91.0	17.8
Organic Carbon (mg/g)	2011	17.2	12.2	4.0	107.5	15.9
	2014	19.0	11.0	0.8	176.0	26.2
	2019	16.0	13.6	3.8	69.8	10.5
	2022	25.1	21.0	5.0	85.0	15.5

St. Dev., standard deviation.

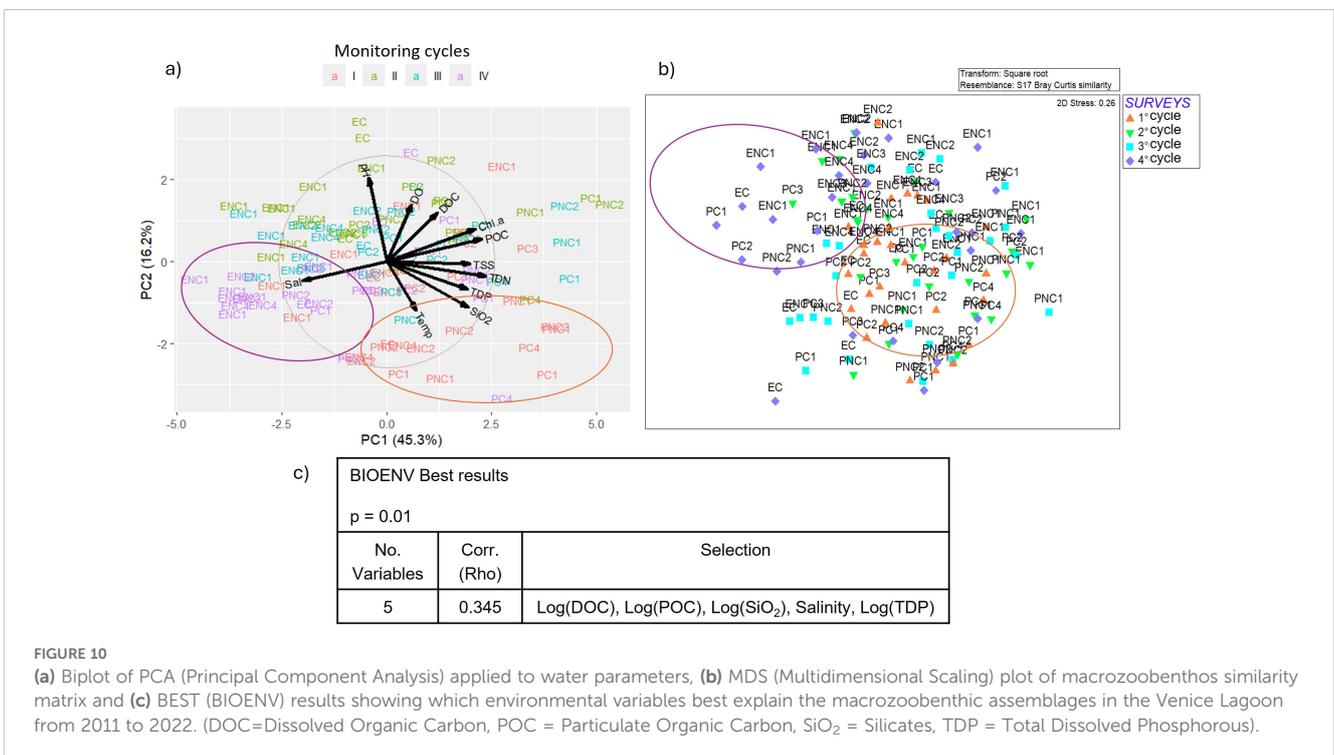
not yield significant results, but data were obtained from quarterly campaigns from 2011 to 2022. Although the sampling frequency of water parameters is designed to provide the necessary information for water quality management according to the WFD, an analysis of data from continuous monitoring and longer time series could corroborate the results of the trend test of the present study, as well as better meet climate change assessment objectives.

In addition, recent studies and institutional reports have highlighted the occurrence of extreme climatic events that may have influenced the ecological dynamics of the lagoon. For instance, data from the National Climate Change Adaptation Platform (ISPRA, 2023) indicates that all lagoons in the Northern Adriatic Sea, including the Venice Lagoon, have experienced a general increase in both temperature and salinity over the past



decade. Specifically, during the period 2011–2023, polyhaline and euhaline water bodies in the Venice Lagoon exhibited a positive trend in temperature, albeit not statistically significant, and a statistically significant increase in salinity. These findings are consistent with broader regional climate trends. As reported above, according to

ARPAV (2023), the year 2022 was the warmest on record in the Veneto region, with an average air temperature anomaly of +1.2 °C compared to the 1993–2021 reference period. Notably, the average of daily maximum and minimum temperatures reached +1.2 °C and +3.2 °C, respectively. In addition to recurrent heatwaves, 2022 was



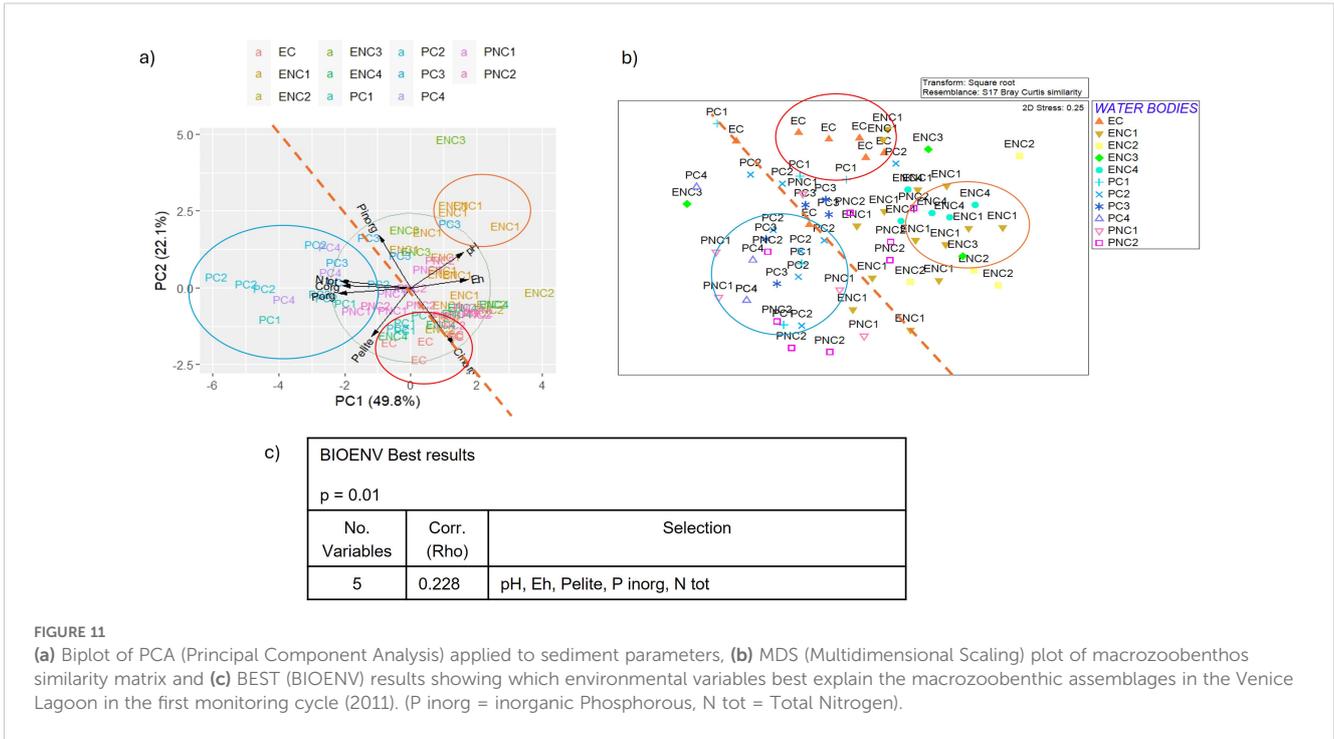


FIGURE 11

(a) Biplot of PCA (Principal Component Analysis) applied to sediment parameters, (b) MDS (Multidimensional Scaling) plot of macrozoobenthos similarity matrix and (c) BEST (BIOENV) results showing which environmental variables best explain the macrozoobenthic assemblages in the Venice Lagoon in the first monitoring cycle (2011). (P inorg = inorganic Phosphorous, N tot = Total Nitrogen).

characterized by exceptionally low precipitation, leading to widespread and prolonged drought conditions. This extreme event prompted the declaration of a national state of emergency by the Italian government. As reported by ISPR (2023), the resulting hydrological stress contributed to the highest annual average salinity values recorded in the Venice Lagoon over the past decade.

These anomalies, although not directly captured by the quarterly sampling design of this study, represent important indirect signals of climate change. The limited temporal

resolution of biological and physico-chemical data may hinder the detection of short-term ecological responses to such events, including shifts in species composition or community structure. Therefore, integrating high-frequency environmental monitoring with biological observations could enhance the capacity to detect and attribute climate-driven changes in transitional ecosystems such as the Venice Lagoon.

Concerning sediments, the analytical panels varied over time, hindering a comprehensive temporal analysis.

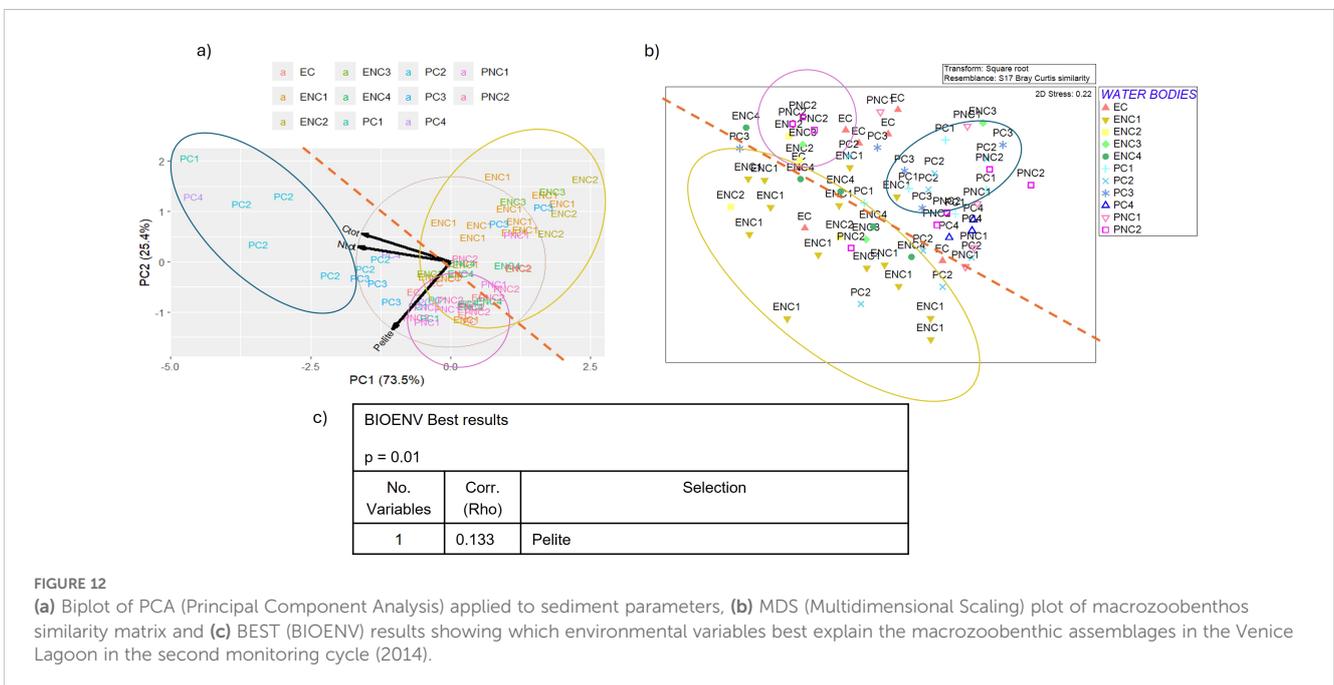


FIGURE 12

(a) Biplot of PCA (Principal Component Analysis) applied to sediment parameters, (b) MDS (Multidimensional Scaling) plot of macrozoobenthos similarity matrix and (c) BEST (BIOENV) results showing which environmental variables best explain the macrozoobenthic assemblages in the Venice Lagoon in the second monitoring cycle (2014).

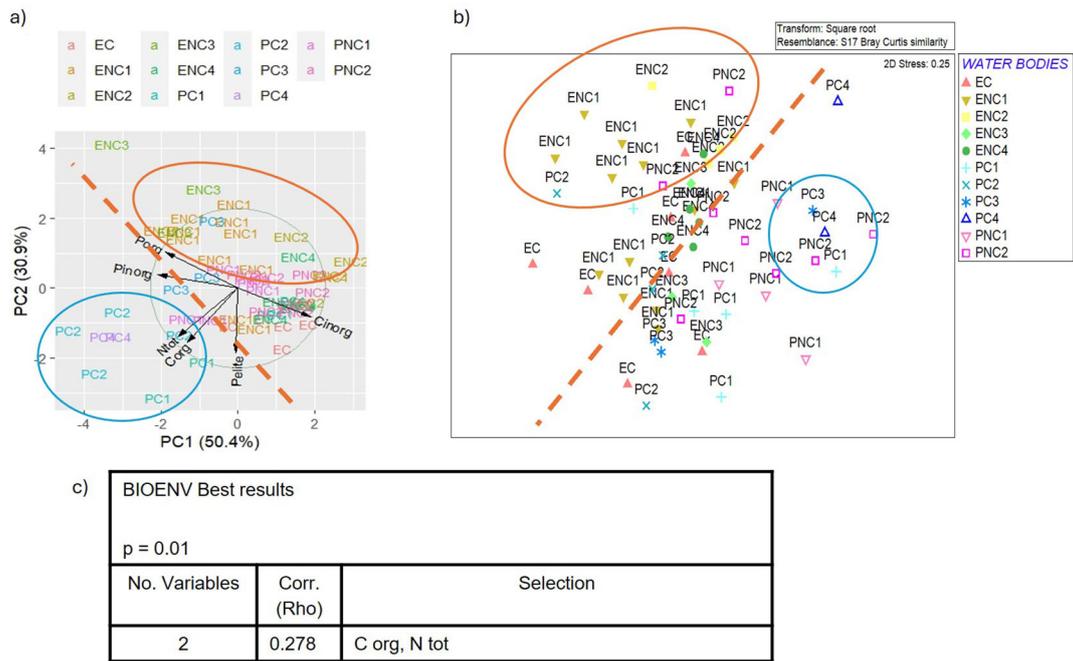


FIGURE 13

(a) Biplot of PCA (Principal Component Analysis) applied to sediment parameters, (b) MDS (Multidimensional Scaling) plot of macrozoobenthos similarity matrix and (c) BEST (BIOENV) results showing which environmental variables best explain the macrozoobenthic assemblages in the Venice Lagoon in the third monitoring cycle (2019). (C org = total organic Carbon, P inorg = inorganic Phosphorous, N tot = total Nitrogen).

Nevertheless, it can be observed that the sediment matrix remained largely conservative over time, apart from organic carbon, which nearly doubled from 2011 to 2022, and organic phosphorus, which increased almost fourfold from 2011 to 2019.

However, PCA results confirmed that choked areas were characterized by higher values of pelite and organic carbon compared to areas more influenced by marine waters and stronger hydrodynamics.

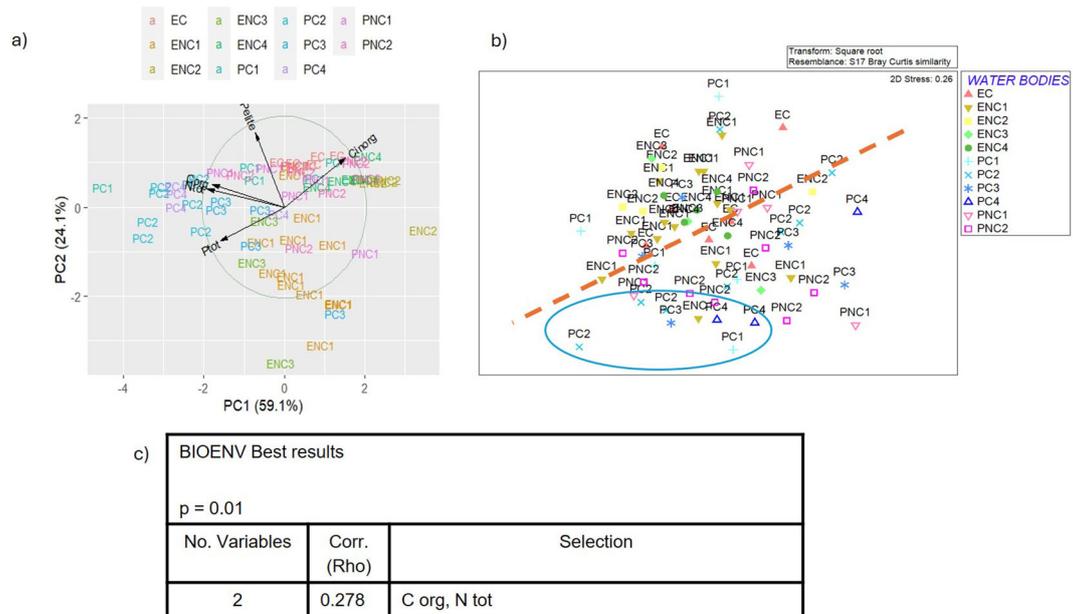


FIGURE 14

(a) Biplot of PCA (Principal Component Analysis) applied to sediment parameters, (b) MDS (Multidimensional Scaling) plot of macrozoobenthos similarity matrix and (c) BEST (BIOENV) results showing which environmental variables best explain the macrozoobenthic assemblages in the Venice Lagoon in the fourth monitoring cycle (2022). (C org = total organic Carbon, N tot = total Nitrogen).

Analysing the biodiversity of the macrozoobenthos in relation to water parameters, revealed a significant correlation with salinity, silicates, organic carbon (DOC and POC), and total dissolved phosphorus (TDP). Salinity emerged as a key factor influencing the structure of the benthic assemblage in the studied lagoon. The observed variations in community composition and organism performance are consistent with previous findings that highlight the sensitivity of benthic *taxa* to salinity fluctuations, particularly in transitional waters (Gibson, 1982; Muresan et al., 2019; Semprucci et al., 2019; Boutoumit et al., 2021). In our case, increased salinity levels were associated with reduced species richness and shifts in dominant *taxa*, suggesting a stress response likely linked to osmotic regulation challenges. These results align with documented impacts of salinity on survival, growth, and metabolic activity in aquatic organisms (Folt and Chen, 1999; Velasco et al., 2019), supporting the interpretation that salinity acts as a structuring environmental variable in this ecosystem.

Spatial and temporal changes in food sources can also affect the biodiversity of macrozoobenthos, as the animals within this community exhibit diverse feeding habits (Doi et al., 2005; Park et al., 2017). These variations could explain the significant relationships between macrozoobenthos and both organic carbon and total dissolved phosphorus (TDP) highlighted in this study. Additionally, silicates are equally important, as their concentrations can reflect environmental variations that may impact the distribution of macrozoobenthos (Ittekkot et al., 2000; Faresi et al., 2012).

Regarding sediments, the parameters found significant in statistical analyses (granulometry, organic content and nutrients) are among those that typically influence the distribution of *taxa* in the macrozoobenthic community (Pearson and Rosenberg, 1978; Dauer et al., 2000; Sharani et al., 2018). Moreover, lower levels of diversity were significantly associated with higher organic carbon contents, especially in the last three surveys. The richness of benthic communities in transitional waters typically declines as the organic content in the sediments increases (Magni et al., 2009). The accumulation of organic carbon in sediments is typical of eutrophicated systems, which are likely to support a limited number of *taxa* (Pusceddu et al., 2007). Although trophic trends have improved recently, eutrophic conditions persist in the inner parts of the Venice Lagoon (Ponis et al., 2024). Therefore, it can still be considered as one of the causes of the lower macrozoobenthos biodiversity as observed in the present study, but particularly in the choked water bodies influenced by freshwater.

Lastly, it is well known that the Venice Lagoon has various point and diffuse sources of pollutants and contaminants, including industrial discharges from Porto Marghera, sewage outfalls from the cities of Venice and Chioggia, harbor activities, agricultural and urban runoff, and atmospheric deposition (Bellucci et al., 2002; Frignani et al., 2003; Maggi et al., 2012; Feltracco et al., 2022; Pizzini et al., 2024; Guolo et al., 2025). These activities contribute to a mixture of contaminants that can directly affect the macrozoobenthos community by exposing organisms to contaminated sediments. However, continuous and spatially extended monitoring of emerging and re-emerging contaminants

could help to better assess the spatial and temporal dynamics of macrozoobenthos revealed in the present study.

Conclusions

The analysis of the macrozoobenthic community in the Venice Lagoon from 2011 to 2022 indicates a significant temporal decline in both *taxa* richness and abundance, with 2022 marking the lowest biodiversity levels recorded across the entire lagoon. This decline is consistent across different lagoonal typologies, with polyhaline and choked water bodies showing lower species richness compared to euhaline and non-choked areas.

Significant correlations were found between macrozoobenthic biodiversity and environmental variables such as salinity, organic carbon, silicates, and total dissolved phosphorus. Most of these parameters, except salinity, showed a decreasing trend from 2011 to 2022. The sediment matrix remains largely conservative, with granulometry, organic content, and nutrients acting as key factors influencing *taxa* distribution especially in spatial rather than temporal dimensions.

These ecological patterns coincide with broader environmental changes observed in the region. Recent institutional reports (ISPRA, 2023; ARPAV, 2023) highlight a decade-long trend of increasing temperature and salinity in the Northern Adriatic lagoons, including Venice. The year 2022 was characterized by extreme climatic conditions—record-breaking temperatures, recurrent heatwaves, and severe drought—which led to unprecedented salinity levels in the lagoon. These combined thermal and hydrological stressors likely contributed to the sharp ecological shifts observed in benthic communities.

Although the quarterly sampling design of water parameters limits the detection of short-term ecological responses, these anomalies represent important indirect signals of climate change. Integrating high-frequency environmental monitoring with biological observations could significantly enhance the capacity to detect and attribute climate-driven changes in transitional ecosystems such as the Venice Lagoon.

Finally, although the current monitoring strategy was not specifically designed to detect non-indigenous species, a comparison with the most recent national checklist of macrozoobenthic species for the Adriatic Sea revealed the presence of some *taxa* not previously recorded in the area. Most of these were small crustaceans, often difficult to identify morphologically, and are currently considered cryptogenic species whose origin remains uncertain due to insufficient taxonomic or biogeographic information. Their detection underscores the importance of integrating traditional morphological approaches with molecular tools to improve the resolution of biodiversity assessments, particularly in regions like the Venice Lagoon, which is recognized as a hotspot for species introductions.

The results of this study carry important implications for environmental policy and management. The ecological shifts observed, especially those recorded in 2022, underscore the vulnerability of transitional ecosystems to extreme climatic events.

These findings suggest the need for adaptive management strategies that incorporate climate resilience into lagoon governance.

The study also revealed the need to complement routine monitoring programs, primarily designed for ecological status assessment under the Water Framework Directive, with targeted strategies aimed at early detection and tracking of non-indigenous species. This is especially relevant in the context of accelerating environmental change, where shifts in species composition may occur rapidly and involve cryptic or newly introduced *taxa*. The long-term and spatially extensive dataset collected in this study represents a valuable resource for environmental policy. Its integration of biological and physico-chemical data over more than a decade provides a solid basis for evaluating water quality trends and anticipating climate-driven ecological changes, supporting more informed and adaptive management strategies.

In summary this study reveals a concerning decline in biodiversity and underscores the importance of continuous monitoring and targeted management strategies to mitigate further ecological degradation in the Venice Lagoon.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: <https://www.arpa.veneto.it/dati-ambientali/open-data/idrosfera/acque-di-transizione/acque-di-transizione-laguna-di-veneziah-monitoraggio-ecologico>.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

FC: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MC: Conceptualization, Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – review & editing. VB: Data curation, Formal analysis, Investigation, Software, Visualization, Writing – review & editing. FO: Data curation, Formal analysis, Visualization, Writing – review & editing. MN: Data curation, Project administration, Validation, Writing – review & editing. AG: Data curation, Investigation, Resources, Writing – review & editing. MZ: Data curation, Investigation, Writing – review & editing. DB: Data curation, Investigation, Validation, Writing – review & editing. FS: Funding acquisition, Project administration, Supervision, Writing – review & editing. AB: Funding acquisition, Investigation, Project administration, Validation, Writing – review & editing. RBB: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. To improve and check academic english language of the text.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2025.1603523/full#supplementary-material>

SUPPLEMENTARY TABLE 1

Faunal lists of macrozoobenthic species recorded during each sampling campaign (2011, 2014, 2019 and 2022). Species names highlighted in blue indicate *taxa* not included in the most recent Checklist of Macrozoobenthic Species of the Adriatic and Mediterranean Seas published by the Italian Society of Marine Biology (SIBM).

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