Assessment of the Ecological quality (EcoQ) of the Venice lagoon using the structure and biodiversity of the meiofaunal assemblages

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Abstract

Transitional Environments (TEs) have been deeply modified to meet human requirements, and for this reason are currently ranked among the most endangered aquatic ecosystems. The Adriatic basin hosts a large number of TEs of which the Lagoon of Venice is the largest one, but information on its meiofauna are very dated or focused to localized areas. The present study is the first to document the spatial distribution of meiofauna in the whole Venice lagoon. Furthermore, the health status of the TE of Venice has been assessed by means of several faunal parameters (richness, diversity indices, structure of the entire meiofaunal assemblage and only rare *taxa*). All the univariate meiofaunal parameters were consistent in highlighting the worst ecological quality of the Porto Marghera district. Instead, the structure of the entire meiofaunal assemblage as well as that of rare *taxa* seemed to detect variations not directly related to pollution. On the basis of our results, we have also critically discussed the usefulness of the various faunal parameters in the monitoring assessment of the TEs.

Key-words: Meiofauna, environmental monitoring, anthropogenic disturbance, Water Framework Directive, transitional environments, Venice.

1. INTRODUCTION

Meiofauna are the most diversified element of the marine biota: as many as 24 of the 35 animal *phyla* have representatives that live in meiofauna. They play an important role in benthic food webs, not only as consumers, but also because they feed on detritus, diatoms and algae, and prey on other small metazoans (see Zeppilli et al., 2015 and references therein). Meiofauna are the most abundant benthic group in the marine realm and their function seems to be much more complex than previously supposed, and requires further investigations to clarify their importance in the marine systems (see Balsamo et al., 2010 for review). Due to the short generation time, the high sensitivity to any environmental change and the lack of pelagic larval dispersion, meiofauna represent a promising tool for environmental monitoring assessment (Sandulli & de Nicola, 1990; Pusceddu et al., 2007; Semprucci and Balsamo, 2012). Furthermore, meiofaunal organisms may display a rapid response to natural environmental alterations or anthropogenic pressure and can integrate information based on the analysis of the macrobenthic compartment (Balsamo et al., 2012). The assessment of the ecological quality status (EQS) of aquatic ecosystems, since the Water Framework Directive (WFD, 2000/60/EC), is one of the major objectives of applied aquatic ecology in Europe. In line with this Directive, a variety of indices and approaches for assessing the EcoQ (Ecological Quality) has been discussed, but the majority of them are focused on macrofauna (e.g. Borja et al., 2000; Simboura & Zenetos, 2002) and, only in few cases, on meiofauna (Pusceddu et al., 2007; Moreno et al., 2011; Semprucci et al., 2014, 2015a,b).

The range of physical and biotic conditions has made transitional environments (TEs) interesting habitats for studies of the distribution, assemblage structure and habitat preferences of many meiofaunal organisms. The Adriatic basin hosts a large number of TEs of which the Lagoon of Venice is the largest one. TEs are been deeply modified to meet human requirements and are currently ranked among the most endangered aquatic ecosystems (Airoldi & Beck, 2007).

Venice lagoon is affected by a variety of inorganic and organic pollutants (Pusceddu et al., 2007). For instance, Venice and Mestre cities represent an important source of municipal wastewater discharges. Porto Marghera is one of the most disturbed industrial areas in Italy and Foraminifera revealed from moderate to strong impact of trace elements (see Coccioni et al., 2009 for details). Due to the shallowness of the water column, the low water exchange and high organic matter productivity, sediments of Venice represent the main sinks for many toxic substances. Here, dredging operations and fishing of clams often re-suspend and mix sediments leading to a redistribution of the pollutants along with both benthic and pelagic organisms (Fabbrocini et al., 2005). In addition, illegal dumping, agricultural drainage and even atmospheric deposition seem to influence the ecological quality of the area (Pusceddu et al. 2007; Coccioni et al., 2009).

Many studies on meiofauna have been carried out in Italian TEs (Colangelo & Ceccherelli 1994; Villano & Warwick, 1995; Fiordelmondo et al., 2003; Fabbrocini et al., 2005; Pusceddu et al., 2007; Cibic et al., 2012; Frontalini et al., 2014; Semprucci et al., 2014). In particular, in the northern Italian sector, some information are available from the Po Delta lagoon (Sacca di Goro) (Colangelo & Ceccherelli 1994), the 'Valli di Comacchio' complex (Guerrini et al., 1998), the Palude Della Rosa at Lagoon of Venice (Villano & Warwick, 1995) and the Marano lagoon (Cibic et al., 2012). However, they are generally dated and focused on circumscribed areas. Thus, the present study may offer a notable advance in the knowledge on the meiofauna inhabiting the TE systems because it documents for the first time their spatial distribution in the whole Venice lagoon. Furthermore, the health status of the TE of Venice is assessed and all the meiofaunal parameters used are critically discussed for the evaluation of their usefulness in the monitoring of the TEs.

2. MATERIAL AND METHODS

2.1. Study area

The lagoon of Venice is the largest wetland in the Mediterranean Basin, located along the north-eastern Adriatic coast, with a surface area of ~550 km^2 and an average depth of 1.5 m (Fig. 1). The entire lagoon area is represented by land (8%), including Venice itself and many smaller islands, water (67%), and sandbanks (25%). The lagoon is connected to the Adriatic Sea by three inlets: Lido, Malamocco and Chioggia. The semidiurnal tidal cycle exchanges about 50% of the lagoon water with the sea during spring tides, and this is further reduced to 25% during neap tides (Silvestri et al., 2000). Salinity varies between

34.4–34.9‰ at high tide and 32.8–33.6‰ at low tide (Marcello, 1967; Albani & Serandrei Barbero, 1982). The water dynamics have relevant effects at the inlets and within the main channels and poorly close to the mainland. Natural and artificial channels of varying depths, salt marshes, mud flats and small estuaries determine the complex morphology and hydrodynamics of the lagoon (Coccioni et al., 2009). The sediments of the lagoon are primarily composed of clayey silts in the tidal flats, and sands to silty sands in the main channels, and close to the entrances of the inlets (Albani et al., 1991; Basu & Molinari, 1994). Albani et al. (1995) also suggested a very limited mobility of bottom sediment within the lagoon. The contamination of the lagoon waters and sediments began in about 1920 when the first industrial district of Porto Marghera was built that was one of the most important industrial areas in Italy until the 1970s (Apitz et al., 2007). Despite the closure of many factories, the overall pollution impact from Porto Marghera is considerable and from moderate to strong levels of heavy metals (Hg, Zn, Pb and Cu) were still detectable (see Coccioni et al., 2009 for review).

2.2. Sampling routine

Meiofaunal assemblages were studied at the lagoon of Venice during summer 2004 (from 20 July to 9 September 2004). Sediment samples were taken at 21 sites. They were sub-divided in five main zones for their different level of anthropogenic impact: Zone 1 (Sts. 1, 2, 3, 4, 5 and 50), Zone 2 (Sts. 9, 10, 11 and 13), Zone 3 (Sts. 23, 26, 27, 32 and 92), Zone 4 (Sts. 52 and 54), and Zone 5 (Sts. 25, 25B, 72 and 78) (Fig. 1). In detail, Zone 1: Unpolluted, but with a Poor Water Exchange (UPWE); Zone 2: Polluted, Airport surrounding (PA); Zone 3: Polluted, industrial district Marghera (PM); Zones 4 and 5: Unpolluted and with a Good Water Exchange (UGWE).

At each site, sediments were collected by means of a box-corer (40 × 40 cm width and 20 cm in height), sub-sampled with Plexiglas corers (diameter: 26 mm; height: 50 mm), and preserved in 10% buffered (Borax) formalin (4% formaldehyde) in filtered tap water.

2.3. Meiofaunal analyses

For meiofaunal extraction, sediment samples were sieved through a 500 µm mesh, and a 45 µm mesh was used to retain the smallest organisms. The fraction remaining on the latter sieve was re-suspended in water, followed by settlement in Ludox AM (McIntyre & Warwick, 1984). Meiofauna were counted and classified to higher *taxon* under stereomicroscope, after staining with Rose Bengal (0.5 gl^{-1}). The density (n. of individuals 10 cm^{-2}), taxon richness, Shannon-diversity (Shannon & Weaver, 1949) and Pielou-evenness (Pielou, 1969) (both log_2) of the assemblages were then calculated. The rare *taxa* were defined as the *taxa* that represented <1% of the total abundance of all investigated samples (Bianchelli et al., 2010). As suggested by Bianchelli et al. (2010), the general dominance of nematodes and copepods in the meiobenthic assemblages may mask changes in the relative contributions of other *taxa*. When statistical analysis is restricted to rare meiofaunal *taxa*, the differences tested between the habitats may be more evident. EQS was assessed using the number (richness) of meiofaunal *taxa* as a determinant (Danovaro et al., 2004, modified according to WFD classes). In order to evaluate the possible effects of the human impact on the meiofaunal assemblage, the total number of nematode and copepod individuals were computed in the ratio Ne:Co that was also analysed according to Raffaelli & Mason (1981). The hypothesis was that the divergent auto-ecological characteristics of the two groups (the extreme tolerance of nematodes and the high sensitivity of copepods) might detect the occurrence of pollution.

2.4. Statistical analysis

Statistical analyses were performed using SPSS Statistics v. 21 and PRIMER v. 5 programs. Difference in mean values of the univariate measures was tested by one-way ANOVA with Tukey's comparison test ($p<0.05$). Prior to analysis, the normality and homoscedasticity assumptions were checked using the Kolmogorov-Smirnov and Levene's tests, respectively. When required, the data were log (1+x) transformed.

The multivariate relationships between the entire meiofaunal assemblages and rare *taxa* were analysed by non-metric multidimensional scaling (nMDS) using the Bray–Curtis similarity measure (fourth root-transformed data). A SIMPER test (cut-off of 90%) was used to determine the contribution of each *taxon* to the total dissimilarity (Clarke & Warwick, 2001; Clarke & Gorley, 2001).

3. RESULTS

All examined samples were composed of silty muddy sediment, on average 40% of clay and 60% of silt.

Total meiofaunal abundance ranged from 77.4 ind. 10 cm^{-2} (Zone 3 at St. 92) to 2685.5 ind. 10 cm^{-2} (Zone 2 at St. 10). The Zones 2 and 1 displayed the highest abundance values, while the Zone 5 the lowest ones (Table 1).

Meiofaunal assemblages appeared well represented, with a total of 12 *taxa*: platyhelminthes, nematodes, kinorhynchs, rotifers, annelids, copepods (adults and juveniles), ostracods, cumaceans, amphipods, isopods, cladocerans and halacaridans (Table 1). The highest value of richness (8 *taxa*) was detected at St. 13 (Zone 2), while the lowest (2) at St. 92 (Zone 3) (Table 2). The most abundant and widest distributed *taxa* were: nematodes, copepods, annelids, kinorhynchs and ostracods, while rare ones (< 1%

in all the Sts.) were platyhelminthes, rotifers, cumaceans, amphipods, isopods, cladocerans and halacaridans. Rare *taxa* were completely absent at the Sts.: 2, 10, 23, 25, 25B, 26, 27 and 92 and above all in the Zone 3 (Table 1 and 2).

Margalef index revealed the highest values (1.1) at Sts. 1 and 13 (Zones 1 and Zone 2), while the lowest (0.3) at Sts. 25 and 25B (Zone 5). Shannon index was highest (1.9) at Sts. 1 and 2 (Zone 1), and lowest (0.2) at St. 23 (Zone 3). Pielou showed the highest value (0.9) at St. 92 and the lowest at St. 23 (both in the Zone 3). The lowest Ne:Co ratio was at St. 2, Zone 1 (0.8), while the highest at St. 23, Zone 3 (28.7) (Table 2). However, no significant differences of the univariate measures were detected in the comparisons (ANOVA, $p > 0.05$).

Non-metric multidimensional scaling (nMDS) performed on the structure of the entire meiofaunal assemblage showed a main subdivision in two groups: group 1 represented by Zone 1-2 and group 2 represented by Zone 3-5 (Fig. 2). This is in line with the results of the SIMPER routine that showed a prevalence of copepod (adults and *nauplii*), nematodes, kinorhynchs, amphipods, halacaridans in the group 1 and of annelids, amphipods and cladocerans in the group 2 (Appendix A, Supplementary Material).

Multivariate analyses on rare *taxa* did not reveal a real grouping among the five zones (Fig. 3) because of the higher dissimilarity levels detected, also confirmed by SIMPER test (cut-off 90%)(Appendix B, Supplementary Material). In particular, the lowest dissimilarities were between Zone 4 *vs.* 5 (Av. Dis. = 36%) followed by Zone 1 *vs.* 2 (Av. Dis. = 40%)(SIMPER, 90%). SIMPER test revealed a higher abundance of amphipods and cladocerans at the Zones 4 and 5, while platyhelminthes, halacaridans, rotifers and cumaceans at Zones 1 and 2 (Appendix B, Supplementary Material).

According to Danovaro et al. (2004), modified in agreement with the EcoQ classes of the WFD, the area revealed from bad to moderate EcoQ (Ecological Quality): the EcoQs more frequently represented were bad (in a total of 11 Sts.) and poor (in 9 Sts.). In detail, the lowest EcoQ was revealed in the Zones 3, 4 and 5, while better EcoQ levels were found in the Zones 1 and 2 (Table 2).

4. DISCUSSION

Transitional environments (TEs) are among the most productive ecosystems in the world, but they are also very vulnerable environments subject to several types of anthropogenic stress (Pusceddu et al., 2007; Semprucci et al., 2014). In Italy, the TE of Venice is the largest one with important implications in the coastal zone management of the northern Adriatic Sea.

In the present study, meiofauna showed an overall good number of *taxa* (12) mainly represented by permanent meiofauna. Nevertheless, the classification of the various stations ranged from bad to moderate EcoQ (see Danovaro et al., 2004) with a prevalence of bad and poor conditions. Pusceddu et al. (2007) documented a comparable number of meiofaunal *taxa* (6) in the area about corresponding to our Zones 4 and 5. The authors compared three TEs of the Adriatic Sea: Venice, Goro (northern sector) and Lesina (southern one) and their meiofaunal richness displayed clear differences with Venice being characterized by the lowest EcoQ. Thus, despite the great biological sensitivity of the north Adriatic TEs, Venice as well as Marano host the vast human populations and their associated anthropogenic impacts (Cibic et al., 2012), while a better EcoQ of the southern Adriatic TEs (Lesina and Varano) has been generally documented (Fabrocini et al., 2005; Frontalini et al., 2014).

Pusceddu et al. (2007) emphasized the importance of the seasonality on richness trends that seemed to decrease from spring to summer likely due to the increasing accumulation of organic carbon and oxygen consumption. During summer period, a seasonal decline of the environmental conditions was also reported by Villano & Warwick (1995) in the Palude della Rosa (TE of Venice). Indeed, the green alga *Ulva rigida* proliferates during that period and then dies and decays, resulting in a dramatic fall in oxygen levels of the sediments that negatively affected meiofauna. The effects of seasonality on the meiofaunal richness could also explain the higher *taxa* number (mainly temporary meiofauna) documented by Colangelo & Ceccherelli (1994) in Goro (Po Delta area) during the '90 years. Accordingly, despite the richness is one of the most comparable meiofaunal parameter, it should be carefully used to compare data sets collected only in the same seasons. Furthermore, temporary meiofaunal groups are not taken into account by all authors producing a possible bias in the estimation of the richness values (Smol et al., 1994).

Overall, few data are available on the level of meiofaunal diversity (namely Shannon, Pielou and Margalef indices) in the TEs because these indices are rarely calculated for this component of the *benthos*. The only data available in the TE of Varano highlight a comparable level of diversity with Venice (Armynot du Châtelet et al., in press) and even a higher level in some stations of the latter.

The Ne:Co ratio may be used as an index for assessing variations in the ecosystems, since it is easily measurable, but it has been criticized in the last decades because it resulted strongly influenced by variations in sediment grain-size (e.g. Warwick, 1981; Platt et al., 1984; Lee et al., 2001). However, Moreno et al. (2008) highlighted its great usefulness as an indicator of pollution especially in harbour systems in which the sediment types are less variable than in open sea. Our values of Ne:Co ratio, highly comparable to those reported by Moreno et al. (2008)(0.8-28.7 *vs.* 1.9-26.7), seemed to reveal the worst conditions at the Zones 3 (Porto Marghera) and 2 (Airport surroundings) of the Venice TE.

However, it is noteworthy that the level of the ratio did not reach the thresholds of pollution reported by Raffaelli & Mason (1981) and Warwick (1981).

The structure of the meiofaunal assemblages exhibited a clear spatial variability between northern (Zone 1 and 2) and central-southern (Zone 3-5) sectors of the Venice TE. In particular, it seems to change between north and south of the areas of the Lido inlet and likely due to the different hydrodynamic conditions of Lido and Malamocco inlets. The former has a depositional nature (dominated by muddy clay deposition), while the latter an erosional one (muddy-sandy and silty sand) (Lucchini et al., 2002; Umgiesser et al., 2015). This finding is not surprising because the sedimentological features of the substrates affect the general meiofaunal structure (Vanaverbeke et al., 2002; Semprucci et al., 2010, 2011, 2013).

As reported by Bianchelli et al. (2010), the high dominance of components such as nematodes and of copepods (up to 98% of total abundance) can obscure the occurrence and relative importance of other meiofaunal *taxa*. When only rare *taxa* were considerate, higher dissimilarity levels than those of whole assemblage were observed (see also Bianchelli et al., 2010; Pusceddu et al., 2011). In particular, the lowest dissimilarity levels were observed only in the Zones 4 and 5, and they were mainly due to the exclusive occurrence of cladocerans in these two zones. This *taxon* has few representatives in the benthic domain and is typical of freshwater habitats or associated to brackish environments with a remarkable salinity range (Giere, 2009). Cladocerans are generally regarded as sensitive components to several types of environmental stress (Sarma et al., 2007; Ciszewski et al., 2013).

In conclusion, all the meiofaunal descriptors summarized in single values (namely richness, diversity indices, Ne:Co ratio) seem to be consistent with assessing the worst EcoQ in the area of Porto Marghera (Zone 3) (Table 3). The structure of the entire meiofaunal assemblage as well as of the rare *taxa* detected differences among the various zones. This certainly reflects their different environmental conditions, but does not seem related to pollution effects.

References

Airoldi L., Beck M. W. 2007. Loss, status and trends for coastal marine habitats of Europe. Oceanogr. Mar. Biol. Annu. Rev., 45: 345-405.

Albani A. D., Serandrei Barbero R. 1982. A foraminiferal fauna from the lagoon of Venice. J. Foram. Res., 12: 234–241.

Albani A.D., Favero V.M., Serandrei Barbero R. 1991. The distribution and ecological significance of recent foraminifera in the lagoon south of Venice (Italy). Rev. Esp. Micropal. 23: 29–45.

Albani A.D., Rickwood P.C., Favero V. M., Serandrei Barbero R. 1995. The geochemistry of recent sediments in the lagoon of Venice: environmental implications. Ati Inst. Veneto Sci. Lett. Arti, 153: 235–321.

Apitz S. E., Barbanti A., Bocci M., Carlin A., Montobbio L., Bernstein A. G. 2007. The Sediments of the Venice Lagoon (Italy) Evaluated in a Screening Risk Assessment Approach: Part II—Lagoon Sediment Quality Compared to Hot Spots, Regional, and International Case Studies. Integr. Environ. Assess. Manag., 3: 415–438.

Armynot du Châtelet E., Bout-Roumazeilles V., Coccioni R., et al. in press. Environmental control on a land-sea transitional setting – Integrated microfaunal, sedimentological, and geochemical approaches. Environ. Earth. Sci., ENGE-D-15-00673R2.

Balsamo M., Albertelli G., Ceccherelli V.U., Coccioni R., Colangelo M.A. et al. 2010. Meiofauna of the Adriatic Sea: current state of knowledge and future perspective. Chem. Ecol., 26:45-63.

Balsamo M., Semprucci F., Frontalini F., Coccioni R. 2012. Meiofauna as a tool for marine ecosystem biomonitoring. In: A. Cruzado (Ed) Marine Ecosystems. InTech Publisher. 4, 77-104.

Basu A., Molinari E. 1994. Toxic metals in Venice lagoon sediments: model, observation, and possible removal. Environ. Geol., 24: 203–216.

Bianchelli S., Gambi C., Zeppilli D., Danovaro R. 2010. Metazoan meiofauna in deep-sea canyons and adjacent open slopes: A large-scale comparison with focus on the rare taxa. Deep-Sea Res Part I, 57: 420–433.

Borja Á., Franco J., Pérez V. 2000. A marine biotic index to establish the ecological quality of soft-bottom benthos within European estuarine and coastal environments. Mar. Pollut. Bull., 12: 1100-1114.

Cibic T., Franzo A., Celussi M., Fabbro C., Del Negro P. 2012. Benthic ecosystem functioning in hydrocarbon and heavy-metal contaminated sediments of an Adriatic lagoon. Mar. Ecol. Prog. Ser., 458: 69-87.

Ciszewski D., Aleksander-Kwaterczak U., Pociecha A., Szarek-Gwiazda E., Waloszek A., Wilk-Woźniak E. 2013. Small effects of a large sediment contamination with heavy metals on aquatic organisms in the vicinity of an abandoned lead and zinc mine. Environ. Monit. Assess., 185: 9825–9842.

Clarke K. R., Gorley R.N. 2001. Primer Version 5. Plymouth: Primer-E.

Clarke K. R., Warwick R. M. 2001. Change in Marine Communities: An Approach to Statistical Analysis and Interpretation. 2nd edn. Plymouth: Primer-E.

Coccioni R., Frontalini F., Marsili A., Mana D. 2009. Benthic foraminifera and trace element distribution: A case-study from the heavily polluted lagoon of Venice (Italy). Mar. Pollut. Bull., 56: 257-267.

Colangelo M. A., Ceccherelli V. U. 1994. Meiofaunal recolonization of azoic sediment in a Po Delta lagoon (Sacca di Goro). Ital. J. Zool., 61: 335-342.

Danovaro R., Gambi C., Mirto S., Sandulli R., Ceccherelli V.U. 2004. Meiofauna. Biol. Mar. Mediterr., 11, 55–97.

Fabbrocini A., Guarino A., Scirocco T., Franchi M., D'Adamo R. 2005. Integrated biomonitoring assessment of the Lesina Lagoon (Southern Adriatic Coast, Italy): preliminary results. Chem. Ecol., 21: 479–489.

Fiordelmondo C., Manini E., Gambi C., Pusceddu A. 2003. Short-term impact of clam harvesting on sediment chemistry, benthic microbes and meiofauna in the Goro lagoon (Italy). Chem. Ecol., 19: 173-187.

Frontalini F., Semprucci F., Armynot du Châtelet E. et al. 2014. Biodiversity trends of the meiofauna and foraminifera assemblages of Lake Varano (southern Italy). Proc. Biol. Soc. Wash., 127: 7-22.

Giere O., 2009. Meiobenthology: the microscopic motile fauna of aquatic sediments. 2nd edition. Springer, Berlin Heidelberg.

Guerrini A., Colangelo M. A., Ceccherelli V. U. 1998. Recolonization patterns of meiobenthic communities in brackish vegetated and unvegetated habitats after induced hypoxia/anoxia. Hydrobiologia, 375/376: 73-87.

Lee M. R., Correa J. A., Castilla J. C. 2001. An assessment of the potential use of the nematode to copepod ratio in the monitoring of metals pollution. The Chañaral Case. Mar. Pollut. Bull., 42: 606-701.

Losi V., Montefalcone M., Mariapaola Moreno M., Giovannetti E., Gaozza L., Grondona M., Albertelli G. 2012. Nematodes as indicators of environmental quality in seagrass (*Posidonia oceanica*) meadows of the NW Mediterranean Sea. Adv. Oceanogr. Limnol., 3, 69–91.

Lucchini F., Frignani M., Sammartino I., Dinelli E., Bellucci L. G. 2002. Composition of Venice lagoon sediments: distribution, sources, settings and recent evolution. GeoActa, 1: 1-14.

Marcello A. 1967. Per la conservazione della laguna di Venezia. Quad. Ric. Sci. C.N.R., 38: 13–19.

McIntyre A. D., Warwick R. M. 1984. Meiofauna techniques. In: Holme N. A., McIntyre A. D. (Eds.) Methods for the study of marine benthos. Blackwell, Oxford. pp. 217-244.

Moreno M., Vezzulli L., Marin V., Laconi P., Albertelli G., Fabiano M. 2008. The use of meiofauna diversity as an indicator of pollution in harbours. ICES J. Mar. Sci., 65: 1428–1435.

Moreno M., Semprucci F., Vezzulli L., Balsamo M., Fabiano M., Albertelli G. 2011. The use of nematodes in assessing ecological quality status in the Mediterranean coastal ecosystems. Ecol. Ind., 11: 328-336.

Pielou E. C. 1969. An Introduction to Mathematical Ecology. Wiley-Interscience, New York.

Platt H. M., Shaw K. M., Lambshead P. J. D. 1984. Nematode species abundance patterns and their use in the detection of environmental perturbations. Hydrobiologia, 118: 59–66.

Pusceddu A., Gambi C., Manini E., Danovaro R. 2007. Trophic state, eco system efficiency and biodiversità of transitional aquatic ecosystems: analysis of environmental quality based on different benthic indicators. Chem. Ecol., 23: 505-515.

Pusceddu A., Bianchelli S., Gambi C., Danovaro R. 2011. Assessment of benthic trophic status of marine coastal ecosystems: Significance of meiofaunal rare *taxa*. Estuar. Coast. Shelf. Sci., 93: 420-430.

Raffaelli D. G., Mason D. F. 1981. Pollution monitoring with meiofauna, using the ratio of nematodes to copepods. Mar. Pollut. Bull., 12: 158-163.

Sandulli R., de Nicola-Giudici M. 1990. Pollution effects on the structure of meiofaunal communities in the Bay of Naples. Mar. Pollut. Bull., 21: 144-153.

Sarma S. S. S., Peredo-Alvarez V. M., Nandini S. 2007. Comparative study of the sensitivities of neonates and adults of selected cladoceran (Cladocera: Crustacea) species to acute toxicity stress. J. Environ. Sci. Health. A. Tox. Hazard. Subst. Environ. Eng., 42: 1449-1452.

Semprucci F., Balsamo M. 2012. Key role of free-living nematodes in the marine ecosystem. In: Boeri F., Jordan A. C. (Eds) Nematodes: Morphology, Functions and Management Strategies. NOVA Science Publishers, Inc. Hauppauge. New York. pp. 109-134.

Semprucci F., Balsamo M., Frontalini F. 2014. The nematode assemblage of a coastal lagoon (Lake Varano, Southern Italy): ecology and biodiversity patterns. Sci. Mar., 78: 579-588.

Semprucci F., Colantoni P., Baldelli G., Rocchi M., Balsamo M. 2010. The distribution of meiofauna on back-reef sandy platforms in the Maldives (Indian Ocean). Mar. Ecol-Evol. Persp., 31: 592-607.

Semprucci F., Colantoni P., Sbrocca C., Baldelli G., Rocchi M., Balsamo M. 2011. Meiofauna in sandy back-reef platforms differently exposed to the monsoons in the Maldives (Indian Ocean). J. Mar. Syst., 87: 208–215.

Semprucci F., Colantoni P., Baldelli G., Sbrocca C., Rocchi M., Balsamo M. 2013. Meiofauna associated with coral sediments in the Maldivian subtidal habitats (Indian Ocean). Marine Biodiversity, 43:189–198.

Semprucci F., Frontalini F., Sbrocca C., Armynot du Châtelet E., Bout-Roumazeilles V. et al. 2015a. Meiobenthos and free-living nematodes as indicators at the time of the Water Framework Directive, a study case in the Adriatic Sea. Environ. Monit. Assess., 187: 251.

Semprucci F., Losi V., Moreno M. 2015b. A review of Italian research on free-living marine nematodes and the future perspectives in their use as Ecological Indicators (EcoInd). Mediterr. Mar. Sci., 16:352-365.

Shannon C., Weaver W. 1949. The Mathematical Theory of Communication. University of Illinois Press, Urbana.

Silvestri S., Marani M., Rinaldo A., Marani A. 2000. Vegetazione alofila e morfologia lagunare. Ati Inst. Veneto Sci. Lett. Arti, 68: 333–359.

Simboura N., Zenetos A. 2002. Benthic indicators to use in ecological quality classification of Mediterranean soft bottoms marine ecosystems, including a new biotic index. Mediterr. Mar. Sci., 3: 77-111.

Smol K. A., Willems J. C. Govaere R., Sandee A. J. J. 1994. Composition, distribution and biomass of meiobenthos in the Oosterschelde estuary (SW Netherlands). Hydrobiologia, 282/283: 197-217.

Umgiesser G., Helsby R., Amos C.L., Ferrarin C. 2015. Tidal Prism Variation in Venice lagoon and inlet response over the last 70 years. In: Maanan M., Robin M. (Eds). Sediment luxes in coatal areas. Springer. pp. 151-166.

Vanaverbeke J., Gheskiere T., Steyaert M. et al. 2002. Nematode assemblages from subtidal sandbanks in the southern bight of the North Sea: effect of small sedimentological differences. J. Sea. Res. 48: 197-207.

Villano N., Warwick R. M. 1995. Meiobenthic communities associated with the seasonal cycle of growth and decay of *Ulva rigida* Arardh in the Palude Della Rosa, Lagoon of Venice. Estuar. Coast. Shelf. Sci., 4: 181-194.

Warwick R. M. 1981. The nematode-copepod ratio and its use in pollution ecology. Mar. Pollut. Bull., 12: 329-333.

Zeppilli D., Sarrazin J., Leduc D., Martinez Arbizu P., Fontaneto D., Fontanier C. et al. (2015). Is the meiofauna a good indicator for climate change and anthropogenic impacts? Mar. Biodiv., 45: 505–535

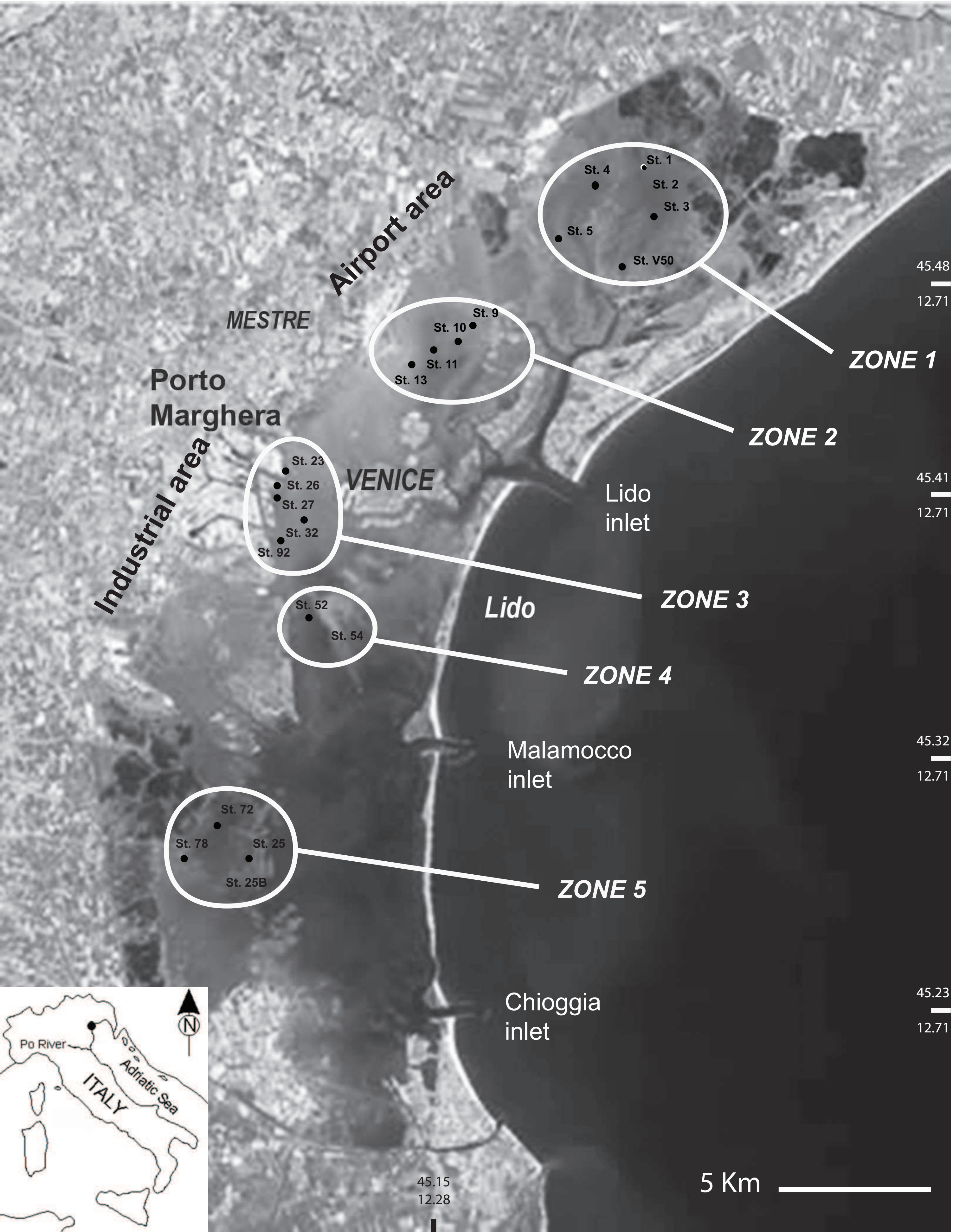
Figure captions

Figure 1. Sampling stations and corresponding zones sampled in the TE of Venice during the summer 2004.

Figure 2. Non-metric multidimensional scaling (nMDS) using the Bray–Curtis similarity measure (fourth root-transformed data) on the entire meiofaunal assemblage of the various zones of the TE of Venice.

Figure 3. Non-metric multidimensional scaling (nMDS) using the Bray–Curtis similarity measure (fourth root-transformed data) on the rare meiofaunal *taxa* of the various zones of the TE of Venice.

Figure 1.



St. 1
St. 4
St. 2
St. 3
St. 5
St. V50
Airport area
MESTRE
St. 9
St. 10
St. 11
St. 13
Porto
Marghera
ZONE 1
ZONE 2
St. 23
St. 26
St. 27
St. 32
St. 92
VENICE
Industrial area
Lido
inlet
ZONE 3
Lido
St. 52
St. 54
ZONE 4
Malamocco
inlet
St. 72
St. 78
St. 25
St. 25B
ZONE 5
Chioggia
inlet
45.48
12.71
45.41
12.71
45.32
12.71
45.23
12.71
45.15
12.28
5 Km
N
Po River
Adriatic Sea
ITALY

Figure 2.

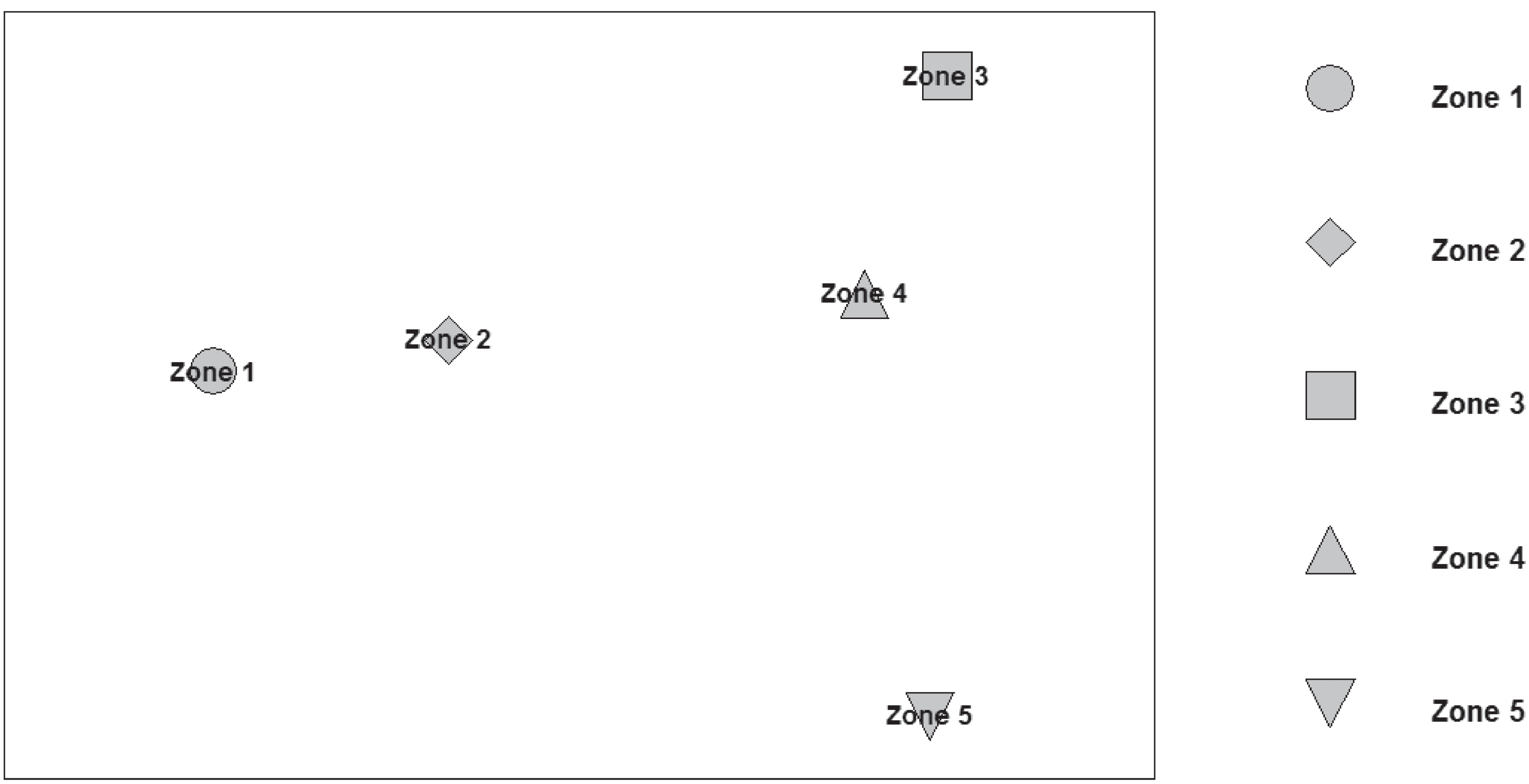

Zone 3
Zone 4
Zone 2
Zone 1
Zone 5
Zone 1
Zone 2
Zone 3
Zone 4
Zone 5

Figure 3.

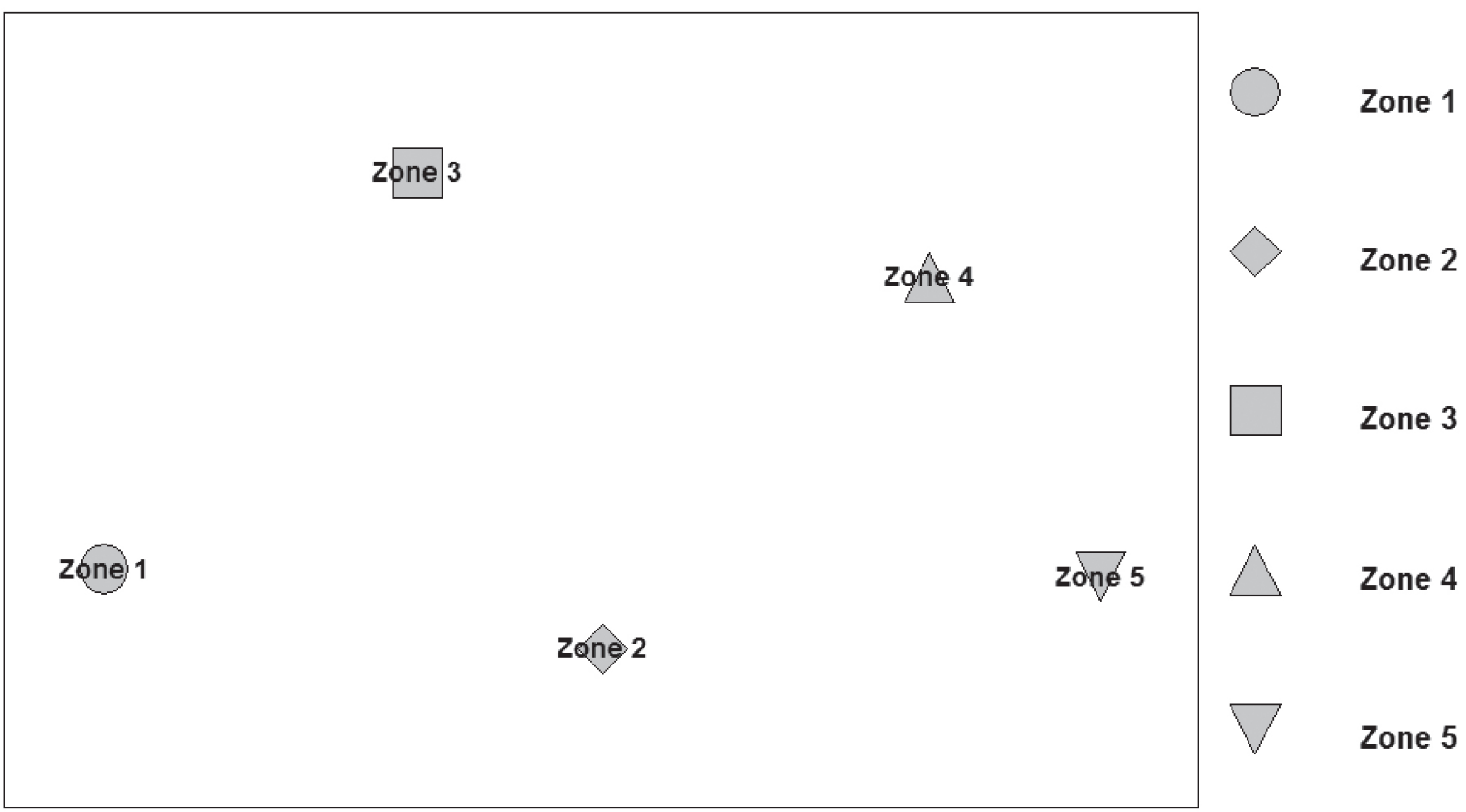

Zone 3
Zone 4
Zone 1
Zone 5
Zone 2
Zone 1
Zone 2
Zone 3
Zone 4
Zone 5

Table 1. Meiofaunal composition and abundance at the lagoon of Venice.

	Zone 1						Zone 2				Zone 3				Zone 4		Zone 5			
Station	**St. 1**	**St. 2**	**St. 3**	**St. 4**	**St. 5**	**St. V50**	**St. 9**	**St. 10**	**St. 11**	**St. 13**	**St. 23**	**St. 26**	**St. 27**	**St. 32**	**St. 92**	**St. 52**	**St. 54**	**St. 25**	**St. 25B**	**St. 72**	**St. 78**
Platyhelminthes[r]	1.6	0.0	0.0	4.8	0.0	0.0	0.0	0.0	1.6	1.6	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nematodes	116.1	696.8	425.8	1295.2	577.4	2382.3	2314.5	2540.3	341.9	480.6	693.5	537.1	809.7	982.3	37.1	246.8	825.8	324.2	338.7	348.4	740.3
Kinorhynchs	32.3	190.3	45.2	37.1	33.9	8.1	3.2	0.0	4.8	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.7
Rotifers[r]	1.6	0.0	0.0	0.0	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Annelids	0.0	3.2	0.0	32.3	0.0	1.6	1.6	33.9	56.5	58.1	1.6	32.3	14.5	169.4	0.0	11.3	14.5	1.6	37.1	74.2	1.6
Copepods	79.0	551.6	40.3	248.4	43.5	390.3	201.6	98.4	24.2	566.1	22.6	19.4	103.2	203.2	30.6	322.6	93.5	30.6	45.2	61.3	108.1
nauplii	29.0	341.9	16.1	198.4	1.6	296.8	151.6	12.9	1.6	129.0	1.6	3.2	22.6	82.3	9.7	132.3	150.0	0.0	0.0	6.5	4.8
Ostracods	0.0	0.0	1.6	0.0	0.0	1.6	0.0	0.0	0.0	24.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6
Cumaceans[r]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Amphipods[r]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	6.5	0.0	0.0	0.0	0.0	0.0	3.2	4.8	0.0	0.0	1.6	0.0
Isopods[r]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.8	0.0
Cladocerans[r]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0	1.6	0.0
Halacaridans[r]	1.6	0.0	1.6	0.0	1.6	0.0	6.5	0.0	0.0	4.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total abundance	**261.3**	**1783.9**	**530.6**	**1816.1**	**658.1**	**3083.9**	**2679.0**	**2685.5**	**432.3**	**1274.2**	**719.4**	**591.9**	**950.0**	**1441.9**	**77.4**	**716.1**	**1090.3**	**356.5**	**421.0**	**498.4**	**866.1**

Table 2. Classification of the ecological quality status (EQS) of various zones of the Venice lagoon by means of meiofaunal parameters.

	Zone 1						Zone 2				Zone 3				Zone 4			Zone 5			
Station	**St. 1**	**St. 2**	**St. 3**	**St. 4**	**St. 5**	**St. V50**	**St. 9**	**St. 10**	**St. 11**	**St. 13**	**St. 23**	**St. 26**	**St. 27**	**St. 32**	**St. 92**	**St. 52**	**St. 54**	**St. 25**	**St. 25B**	**St. 72**	**St. 78**
Total Abundance	261.0	1784.0	531.0	1816.0	658.0	3084.0	2679.0	2685.0	432.0	1274.0	719.0	592.0	950.0	1442.0	77.0	716.0	1090.0	356.0	421.0	498.0	866.0
Richness	6	4	5	5	4	6	5	3	6	8	3	3	3	5	2	4	4	3	3	6	5
Margalef	1.1	0.5	0.8	0.7	0.6	0.7	0.6	0.4	1.0	1.1	0.5	0.5	0.4	0.7	0.5	0.6	0.7	0.3	0.3	1.0	0.7
Shannon	1.9	1.9	1.0	1.3	0.7	1.0	0.7	0.4	1.0	1.8	0.2	0.6	0.8	1.4	1.4	1.6	1.1	0.5	0.9	1.3	0.7
Pielou	0.7	0.8	0.4	0.5	0.3	0.4	0.3	0.2	0.4	0.6	0.1	0.3	0.4	0.5	0.9	0.7	0.4	0.3	0.6	0.5	0.3
Ne:Co	1.1	0.8	7.5	2.9	12.8	3.5	6.6	22.8	13.3	0.7	28.7	23.8	6.4	3.4	0.9	0.5	3.4	10.6	7.5	5.1	6.6
Presence/absence of the rare taxa	P	A	P	P	P	P	P	A	P	P	A	A	A	P	A	P	P	A	A	P	P
EQS classification according to Danovaro et al. (2004)	poor	bad	poor	poor	bad	poor	poor	bad	poor	moderate	bad	bad	bad	poor	bad	bad	bad	bad	bad	poor	poor

Table 3. Summary of the performance of the various meiofaunal descriptors used in this study and their main limitations.

Meiofaunal descriptors	EcoQ assessment of Venice TE	Limitations	
Richness	It revealed from bad to moderate EcoQ with a prevalence of bad and poor conditions. The worst EcoQ was especially found in the Zone 3 (Porto Marghera).	It is affected by seasonal variations that affect meiofaunal biological cycles and consequently the occurrence of temporary meiofauna. Furthermore, not all authors consider the temporary component leading to possible biases in the use of this parameter.	Colangelo and Ceccherelli (1994) Smol et al. (1994).
Diversity (namely Shannon, Pielou and Margalef indices)	They showed the lowest levels at Zone 3 (Porto Marghera).	The advantage of the use of these indices is that they consider both presence and abundance of the meiobenthic components. Unfortunately, they are rarely calculated for this group in the TEs making comparisons impossible.	Semprucci and Balsamo (2012) Armynot du Châtelet et al. in press
Ne:Co ratio	It revealed the worst conditions at the Zone 3 (Porto Marghera) followed by Zone 2 (Airport surroundings).	It is influenced by the sediment texture, but it may be a useful tool for ecological assessment if applied in environments with limited variations of the grain size.	Platt et al. (1984) Moreno et al. (2008)
Structure of the entire meiofaunal assemblages	It exhibited a clear spatial variability between Zone 1-2 and Zone 3-5. It seemed to be affected by the different hydrodynamic conditions of the inlets.	The contribution of the dominant taxa (namely nematodes and copepods) may obscure the presence and relative importance of other meiofaunal taxa. Furthermore, it cannot be summarized to define specific thresholds and EcoQ classes.	Bianchelli et al. (2010) Semprucci et al. (2015)
Structure assemblage of the rare meiofaunal taxa	Higher dissimilarities were observed than considering the entire assemblage. Lowest dissimilarities were documented only in the Zone 4 and 5.	Few data are available on rare taxa trends in all the environments and are completely absent in the TE systems.	Bianchelli et al. (2010) Losi et al. (2012) Semprucci et al. (2013)

Appendix A (Supplementary material). SIMPER results on the entire meiofaunal assemblage of the various zones of the TE of Venice.

Species	Av.Abund		Av.Diss	Cum.%
	Zone 1 vs.	**Zone 2**	**Av. Dis. = 30%**	
annelids	6.18	37.5	4.9	16.1
kinorhynchs	57.8	2.8	4.5	31.1
nematodes	915.6	1419.4	4.5	46.0
nauplii	147.3	73.8	4.0	59.0
copepod adults	225.5	222.6	3.2	69.6
halacaridans	0.8	2.8	2.3	77.1
ostracods	0.5	6.1	2.0	83.8
amphipods	0.0	2.0	1.9	90.1
	Zone 1 vs.	**Zone 3**	**Av. Dis. = 36%**	
kinorhynchs	57.8	0.0	9.3	25.9
annelids	6.2	43.6	5.1	40.2
nauplii	147.3	23.9	4.9	54.0
nematodes	915.6	611.9	4.8	67.5
copepod adults	225.5	75.8	4.0	78.7
halacaridans	0.8	0.0	2.3	85.2
platyhelminthes	1.1	0.3	1.8	90.1
	Zone 2 vs.	**Zone 3**	**Av. Dis. = 31%**	
nematodes	1419.4	611.9	6.3	20.5
annelids	37.5	43.6	4.4	34.7
nauplii	73.8	23.9	3.8	46.9
copepod adults	222.6	75.8	3.7	59.1
kinorhynchs	2.8	0.0	3.6	70.7
halacaridans	2.8	0.0	2.4	78.6
amphipods	2.0	0.0	2.3	86.0
platyhelminthes	0.8	0.3	2.0	92.4
	Zone 1 vs.	**Zone 5**	**Av. Dis. = 38%**	
nauplii	147.3	2.8	7.9	21.0
kinorhynchs	57.8	2.4	7.8	41.5
annelids	6.2	28.6	5.0	54.9
nematodes	915.6	437.9	3.9	65.1
copepod adults	225.5	61.3	3.4	74.0
halacaridans	0.8	0.0	2.3	80.0
ostracods	0.5	0.4	1.7	84.4
platyhelminthes	1.1	0.0	1.5	88.4
rotifers	0.8	0.0	1.4	92.2
	Zone 2 vs.	**Zone 5**	**Av. Dis. = 32%**	
nauplii	73.8	2.8	6.3	19.7
nematodes	1419.4	437.9	5.1	35.8
copepod adults	222.6	61.3	3.4	46.4
kinorhynchs	2.8	2.4	3.4	56.9
annelids	37.5	28.6	3.0	66.3
halacaridans	2.8	0.0	2.4	73.9

amphipods	2.0	0.4	2.3	81.1
ostracods	6.1	0.4	2.1	87.7
platyhelminthes	0.8	0.0	1.9	93.7
	Zone 3 vs.	**Zone 5**	**Av. Dis. = 27%**	
nauplii	23.9	2.8	5.7	21.4
annelids	43.6	28.6	5.4	41.6
nematodes	611.9	437.9	4.9	59.8
copepod adults	75.8	61.3	2.6	69.5
kinorhynchs	0.0	2.4	1.8	76.2
isopods	0.0	1.2	1.4	81.5
ostracods	0.0	0.4	1.1	85.7
amphipods	0.0	0.4	1.1	89.7
cladocerans	0.0	0.4	1.1	93.8
	Zone 1 vs.	**Zone 4**	**Av. Dis. = 34%**	
kinorhynchs	57.8	0.0	7.9	23.3
amphipods	0.0	4.0	4.4	36.3
annelids	6.2	12.9	4.1	48.3
nauplii	147.3	141.1	3.7	59.2
nematodes	915.6	536.3	3.6	69.9
copepod adults	225.5	208.1	2.9	78.4
halacaridans	0.8	0.0	1.9	84.1
cladocerans	0.0	0.8	1.7	89.1
platyhelminthes	1.1	0.0	1.3	93.0
	Zone 2 vs.	**Zone 4**	**Av. Dis. = 26%**	
nematodes	1419.4	536.3	4.8	18.4
nauplii	73.8	141.1	3.3	31.3
kinorhynchs	2.8	0.0	3.1	43.3
copepod adults	222.6	208.1	2.9	54.6
amphipods	2.0	4.0	2.6	64.5
annelids	37.5	12.9	2.3	73.3
halacaridans	2.8	0.0	2.1	81.5
cladocerans	0.0	0.8	1.7	88.0
platyhelminthes	0.8	0.0	1.7	94.5
	Zone 3 vs.	**Zone 4**	**Av. Dis. = 27%**	
nauplii	23.9	141.1	6.1	22.5
amphipods	0.0	4.0	5.3	42.0
copepod adults	75.8	208.1	4.4	58.1
nematodes	611.9	536.3	4.1	73.4
annelids	43.6	12.9	3.7	87.1
cladocerans	0.0	0.8	2.0	94.7
	Zone 5 vs.	**Zone 4**	**Av. Dis. = 30%**	
nauplii	2.8	141.1	10.3	34.8
amphipods	0.4	4.0	4.3	49.5
copepod adults	61.3	208.1	3.8	62.2
annelids	28.6	12.9	2.9	72.0
nematodes	437.9	536.3	2.6	80.7
cladocerans	0.4	0.8	2.1	87.7
kinorhynchs	2.4	0.0	1.5	92.7

Appendix B (Supplementary material). SIMPER results on the rare meiofaunal *taxa* of the various zones of the TE of Venice.

Species	Av.Abund		Av.Diss	Cum.%
	Zone 1 vs.	**Zone 2**	**Av. Dis. = 40.3%**	
amphipods	0.0	2.0	18.8	46.6
rotifers	0.8	0.0	14.9	83.6
halacaridans	0.8	2.8	5.5	97.2
	Zone 1 vs.	**Zone 3**	**Av. Dis. = 67.0%**	
halacaridans	0.8	0.0	20.8	31.0
rotifers	0.8	0.0	20.8	62.0
cumaceans	0.0	0.7	19.6	91.3
	Zone 2 vs.	**Zone 3**	**Av. Dis. = 70.4%**	
halacaridans	2.8	0.0	25.5	36.2
amphipods	2.0	0.0	23.4	69.5
cumaceans	0.0	0.7	17.6	94.6
	Zone 1 vs.	**Zone 4**	**Av. Dis. = 100%**	
amphipods	0.0	4.0	26.9	26.9
platyhelminthes	1.1	0.0	19.3	46.1
cladocerans	0.0	0.8	18.0	64.1
halacaridans	0.8	0.0	18.0	82.1
rotifers	0.8	0.0	18.0	100.0
	Zone 2 vs.	**Zone 4**	**Av. Dis. = 59.0%**	
halacaridans	2.8	0.0	22.4	37.9
platyhelminthes	0.8	0.0	16.3	65.7
cladocerans	0.0	0.8	16.3	93.4
	Zone 3 vs.	**Zone 4**	**Av. Dis. = 100%**	
amphipods	0.0	4.0	35.3	35.3
cladocerans	0.0	0.8	23.6	58.9
cumaceans	0.7	0.0	22.3	81.2
platyhelminthes	0.3	0.0	18.8	100.0
	Zone 1 vs.	**Zone 5**	**Av. Dis. = 100%**	
isopods	0.0	1.2	18.9	18.9
platyhelminthes	1.1	0.0	18.3	37.2
halacaridans	0.8	0.0	17.1	54.3
rotifers	0.8	0.0	17.1	71.3
amphipods	0.0	0.4	14.3	85.7
cladocerans	0.0	0.4	14.3	100.0
	Zone 2 vs.	**Zone 5**	**Av. Dis. = 73.8%**	

halacaridans	2.8	0.0	21.3	28.9
isopods	0.0	1.2	17.3	52.3
platyhelminthes	0.8	0.0	15.6	73.4
cladocerans	0.0	0.4	13.1	91.2
	Zone 3 vs.	**Zone 5**	**Av. Dis. = 100%**	
isopods	0.0	1.2	24.4	24.4
cumaceans	0.7	0.0	20.9	45.3
amphipods	0.0	0.4	18.6	63.9
cladocerans	0.0	0.4	18.6	82.4
platyhelminthes	0.3	0.0	17.6	100.0
	Zone 4 vs.	**Zone 5**	**Av. Dis. = 36.3%**	
isopods	0.0	1.2	20.9	57.6
amphipods	4.0	0.4	12.4	91.7