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A regional GIS for benthic diversity and environmental impact studies in the Gulf of Trieste, Italy

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Abstract

The aim of this study was to build a database and apply GIS techniques with data obtained from 1966 to 2001 in the Gulf of Trieste, in order to determine the diversity, distribution and evolution in time and space of the local macrofauna in this heavily anthropized region for management purposes.
A custom-built relational database was created compiling biological, physico-chemical and sedimentological data from 450 stations, 187 sampling sites and 20 projects. A total of 278,770 organisms from 691 species (Polychaetes: 145,950 individuals, 276 species; Mollusks: 100,432 ind., 198 sp.; Crustaceans: 16,962 ind., 109 sp.; Echinoderms: 10,181 ind., 42 sp.; 'Others': 5,245 ind., 66 sp.) were included. Taxonomy was updated in all cases. Feeding guilds, biocoenotic characterizations and ecological groups were included for all the species where information existed.
All the surface analyses were performed using Surfer 7, Didger 2, Idrisi 32 and Cartalinx 1.2. The vectorial map supplied is in Idrisi vector file. The reference system is UTM 33-N. Distributions of the specific abundance maps were interpolated using the inverse distance to a 2 power gridding method.
The GIS analysis allowed us to individuate the main stress factors affecting the macrozoobenthic communities and determine the 'sensitivity areas' based on intensity and persistence in time of the different disturbances (urban development, industrial and port activities, mariculture, fishing and tourism), as evidenced by their effect on the benthos. The changes in time and space of the benthos composition indicate the evolution of the bottom conditions in the Gulf and helped establish the resilience of the system.

Keywords: GIS; Macrobenthos; Database, Gulf of Trieste.

Introduction

In modern times, databases constitute a basic tool and often the starting point for any ecological analysis and as such are being increasingly used either by government, scientific or private consultant companies for management purposes everywhere. They are built with a collection of as complete as can be obtained sets of data which can be then combined to get integrative interpretations of specific problems. In the case of ecological assessments they can be ideally complemented with Geographical Information Systems (GIS) for easier visualization of the different situations under study. Considering the classical geographical map as the primitive (or first) GIS, today, thanks to specialized software, the GIS represents the newest data processing technology for graphic representation of accurate geographical data. Launched during the early seventies in the USA, the GIS took some time to expand to Europe, but from the 80's, it has been increasingly used in Italy, not only by scientists, but also by public or private entities as well as common citizens (Baherenberg *et al.*, 1984; Nijkamp and Rietveld, 1984; Van Geenhuizen and Nijkamp, 1997).

The proved capacity for synthesis and comprehensive visualization of complex interactions among the different components of an ecosystem, makes the GIS an increasingly essential tool for adequate management of the territory as it enhances the potentiality of analysis of the existing information.

However, the application to marine ecosystems of GIS techniques to evaluate biodiversity or sensitivity areas in environmental impact studies, for protection of coastal zones and in management policymaking in general, is still very limited worldwide. Italy is no exception to this, not only in the number of existing GIS (the first and apparently most complete was produced in the Apulian region (http://siba-gis.unile.it/bis)) but in scope, since most of them were carried out in small localities to solve or interpret local problems.

Many parameters can be used to build a database for particular purposes, and in the case of a GIS, in the land studies, the fundamental units for analysis are constituted by the organisms living on the ground (human population of course and vegetation). For the marine realm, the same types of units, i.e. the organisms living in/on the substrate, are the most useful for environment assessments and management or protection studies. In fact, the benthic communities, composed of the organisms living for most or all of their lives in close contact with the bottom, are commonly used for studying or monitoring the environment and especially the effects of pollution on natural biota: their limited motility, high diversity, differential and fast responses to specific kinds of stress or their interruption, and their relatively long life spans makes them ideal for the historical record of what is affecting the area and how (Pearson and Rosenberg, 1978; Borja *et al.*, 2000). They can thus constitute, by the analysis of their composition, and preferably with their evolution in time (replacements, eliminations, alternate dominances, etc.), good indicators of the recent history and updated status of the habitat under study.

The Gulf of Trieste, located at the extreme northeastern end of the Adriatic Sea (45°40'N 13°30'E), is an ideal site to use these tools for environmental impact assessment: it is a large (about 600 km^2, 100.5 km of coastline) and shallow area (25 m at its deepest point), easily accessible all year long, heavily anthropized since at least 2000 years and which can boast to have several of the oldest records of marine benthic species (Stossich, 1876). The diversified and actively expanding activities that are carried out today there, potentially conflict with each other, either ecologically, economically or both: 1) fisheries, mariculture and tourism need clean and healthy waters, but cause stress on the environment; 2) industry (siderurgic, chemical, naval shipyards, etc), a large thermoelectric plant, agricultural by-products from rivers run-off, urban development and port activities whose discharges and/or refuses' final destiny is the Gulf of Trieste definitely impact the area; 3) maritime traffic (large commercial ships and oil tankers) and dredging to ensure navigation (in front of the lagoons and in Muggia Bay), constantly remove the bottoms in these shallow waters, a considerable stress for the benthic biota. The only official ecological haven, the small marine reserve of Miramare, needs constant protection (Fig. 1).

The aim of this study was to build a database and apply GIS techniques with data obtained from 1966 to 2001 in the Gulf of Trieste, in order to determine, for management purposes, the diversity, distribution and evolution in time and space of the local macrofauna in this heavily human-impacted region.

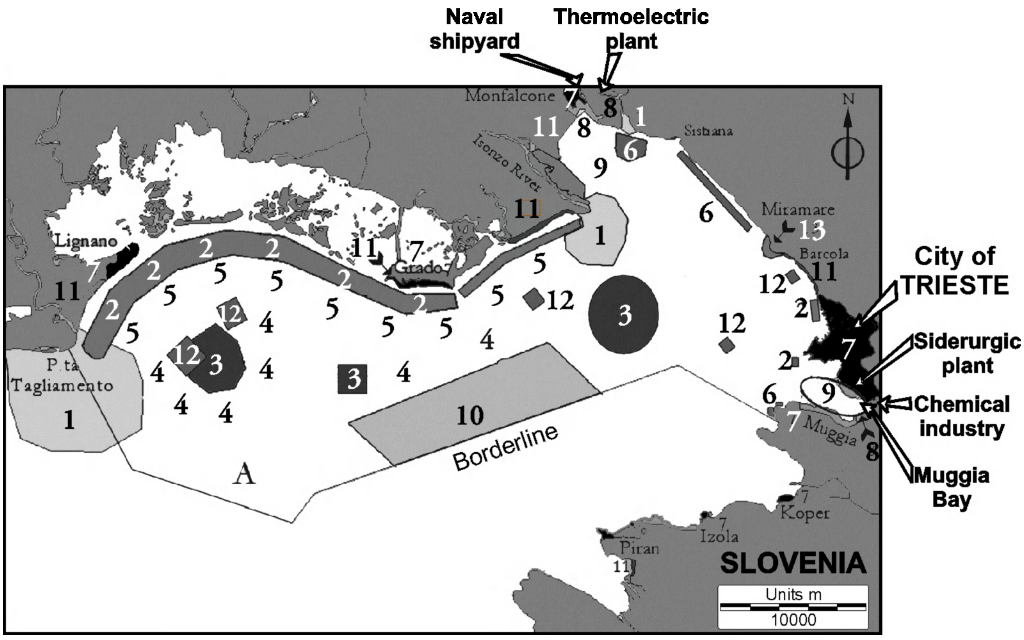

Fig. 1. Study area showing the different human activities and the sensitivity areas. (1) river estuaries, (2) zones of discharge of fishing gear cleaning, (3) discharge of dredged muds, (4) deep fishing area, (5) hydraulic dredges fishing area, (6) mussel farms, (7) urban centers, (8) industrial zones, (9) navigation, canal (Dams' zone at NW end), (10) 'promiscuous fishing rectangle' area, (11) tourist zones, (12) submarine urban sewage ducts, (13) natural marine reserves.

Methodology

A custom-built relational database was created compiling biological, physico-chemical and sedimentological data from 20 projects done between 1966 and 2001.
Taxonomic names were updated from original data in all cases where nomenclature has changed. Biocoenotic characterizations are based in Pérès and Picard (1964), Ecological Groups in Grall and Glémarec (1997) as in Borja *et al.* (2000) and Feeding Guilds in Fauchald and Jumars (1979) and Bachelet (1981).

All sampling sites (stations) were georeferenced (UTM 33N) either originally or processed by us, after careful positioning using original navigational data.

The original vectorial maps supplied were in Arc/Info export or Surfer format, with coordinates both in UTM 32-N and Lat-Long, scale 1/250000. The shoreline and bathymetric data were digitalized from the chart N°39 (Da Punta Tagliamento a Pula – UTM projection) 1:100000 (45°20'N) published by the 'Istituto Idrografico della Marina'. The resulting vectorial maps are in Idrisi vector files with UTM 33-N as the reference system.

The raw data are stored in the database as originally collected but for processing and interpretation purposes, as attempted in this case to exemplify its potential use, comparison between samples done in such a large time interval (35 years), coming from different projects with different objectives was not directly possible, so that we resorted to different techniques to homogenize the data. To solve the problem of different types of sampling gear used (Van Veen grabs and Charcot dredges), and different volumes of sample obtained, all abundances were adjusted to 50 litres. The effect of the different sizes of sieves used to wash and select the macrofauna for the different projects was minimized with the elimination of all organisms thought to pass through a 2mm sieve, the largest used. To evaluate the effect of seasonal variability, hierarchical classification based on Bray-Curtis similarity coefficient was run between samples taken at the same sites but at different dates. The resulting dendrogram showed that the stations are in general more related to the areas of sampling than to the sampling year or month (Solis-Weiss *et al.*, in prep.).

All the surface analyses were performed using Surfer 7, Didger 2, Idrisi 32 and Cartalinx 1.2. To obtain the maps for the distribution of the specific richness, Shannon-Wiener diversity index, Pielou's Evenness index and *Corbula gibba* distribution, an interpolation using the inverse distance to a 2 power gridding method offered by Surfer 7 (Golden Software, Inc.) was carried out and the stations chosen are not repeated in time.

Results and discussion

Database

The basic problems encountered in building the database were related to the high quantity of data that needed to be linked or associated to each other: a total of 450 stations, 187 sampling sites and 20 projects are included. In all, 278,770 organisms from 691 species were incorporated to the database. The Polychaetes constitute the dominant group with 145,950 individuals, in 276 species; Mollusks follow with 100,432 ind. and 198 sp., then Crustaceans with 16,962 ind., and 109 sp., and Echinoderms with 10,181 ind., and 42 sp. All other groups, being significantly less abundant and diverse (5,245 ind., of 66 sp. from Sipunculida, Ascidiacea, Porifera, Cephalochordata and Pisces) are grouped under the 'Others' category.

The Database basic structure, in Microsoft Access 2000, includes seven tables (Abundances, Stations, Projects, Samples, Species and 2 Indexes) connected by joins (Fig. 2) and thus allows swift searches with a minimum of space requirements.

In the 'Stations' Table, all data identifying the sampling stations are compiled: an identifying unique code number, the original name, geographical position and type of sediment. The 'Comments' are related to specific problems found in the data. An inner join connects it to the 'Samples' Table, where all available sampling information is recorded for the 450 stations: date, depth, type of sampler (Van Veen grab, Charcot dredge), mesh diameter used to wash and sort the sample, sampled volume and residual volume. 'Comments' are related to specific problems found in the sampling or in the compiled data. An inner join connects it to the 'Abundance' Table where the number of individuals of every species found in every sample is stored. In the 'Projects' Table, the complete name of every project involved, its corresponding identification code name and the files containing the original data (without any elaboration) are recorded and an inner join connects it to the 'Samples' Table. The 'Species' table contains the taxonomic list of the 691 species included in the Database organized by Phylum, Class, Order, Family and Genus-species, the latter in alphabetical order. 'Comments' are mainly related to synonymies, with date or other useful information. This table is likewise connected to the 'Abundance' Table.
Indexes 1 and 2: these two tables contain the bibliographic references and definitions of the indexes and categories used for the listed species related to each species. The Biocoenotic Characterization, Feeding Guild(s) and Ecological Group for each species where information is available, are compiled there.

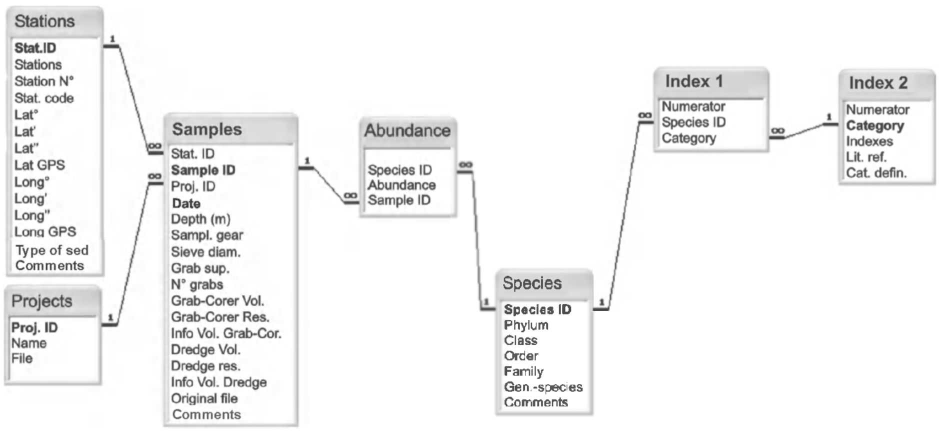

Fig. 2. Diagram of the composition of the Tables of the database.

Biocoenotic characterizations include: DC=detritic coastal bottoms, DE=detritic muddy bottoms, excl=species characteristic exclusive of 'x' biocoenosis, HP= Posidonia meadows, IETP=invertebrates of very polluted water, LEE=euryhaline and eurythermal, lre=wide ecological distribution, MI=unstable bottoms, minut=minute sediments, mixt=mixed sediments, ND=no data found, PI=pollution indicators, pref=species characteristic preferential of 'x' biocoenosis, sab tol=tolerant to sands, SFBC=fine well sorted sands, SFS=surficial fine sands, SGCF=coarse sands under bottom currents, sspr=ecological significance not specified, STP=very polluted sands, SVMC=muddy sands in sheltered areas, vas str=strictly muddy sediments, vas tol=tolerant to muds, VP=deep muds, VTC=terrigenous muds.

Feeding Guilds include: C=carnivores, G=grazers, O=omnivores, SDF=surface deposit feeders, SF=suspension feeders, SSDF=subsurface deposit feeders.
Ecological Groups include: I=species very sensitive to organic enrichment, intolerant to pollution, II=species indifferent to enrichment, III=species tolerant to enrichment, slightly unbalanced environments, IV=second-order opportunistic species, slight to pronounced unbalanced environments, V=first-order opportunistic species, pronounced unbalanced environments.

The database has a user-friendly interface and the user is guided trough the choice of operation to be performed. Complex types of queries are also possible and constant updating is being carried out.

Analysis of the macrobenthic communities

Different parameters characterising the macrobenthos distribution in the Gulf of Trieste were analysed using this database and GIS techniques to try to individuate the stress factors affecting the area.

In Fig. 3, species richness is schematically shown (maximum 108sp., minimum 0sp., average 34sp.): the richest regions were found to be in the centre of the Gulf (87 to 108), followed by the zones of discharge of the submarine urban sewage ducts, the Isonzo estuary and the Barcola and Sistiana areas (around 70). The poorest zones were found in the industrial zone of Muggia Bay and the port of Trieste (0 to 38sp.), as well as in the western zone of the study area (22 to 43sp.).

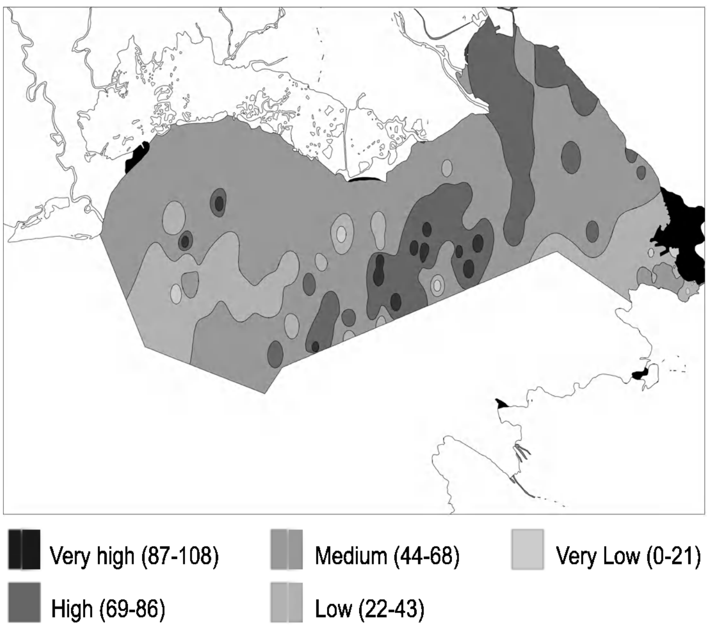

Fig. 3. Image of the species richness in the study area.

Based on the general accepted assumption that ecosystems in equilibrium (or at least healthy) are generally diversified, the poorest zones can be presumed to be impacted, either naturally or anthropically. In this case, it is easy to suspect that the industrial zone and the commercial port are the main source of impact in the area of Muggia Bay: in fact, from heavy metals concentrations in the sediments to water quality measurements (UNITS, 1977; Adami *et al.*, 1997), severe anthropogenic pollution can be clearly established there. In the western zone, however, the impoverished fauna results are most probably caused by the sampling method, since in those hardened bottoms (for sediment distribution in the Gulf of Trieste see Brambati *et al.*, 1983), the performance of the dredges and grabs is limited.

The submarine zones of urban sewage discharges (Fig. 1) at the end of long underwater ducts (from 1 to 7km long), quite surprisingly were found to have a quite rich and varied fauna (from 49 to 83 species and from 934 to 1636 ind./50 l) especially in the western duct zones (Solis-Weiss *et al.*, in prep.), implying that these discharges do not constitute a negative impact on the local benthic communities.

The analysis of the vectorial map representing the Shannon-Wiener diversity index values (Fig. 4), shows that the highest diversities (2.8 to 3.4) were found again in the centre of the Gulf around the deep fishing zone, followed by the submarine zones of urban sewage discharges, in the mussel (*Mytilus galloprovincialis*) farms' areas (north-eastern end) and around the tourist beaches of Sistiana and Barcola (Fig. 1). Lowest values were found in the industrial zone of Muggia Bay, in front of Grado and in some southern zones of the study area.

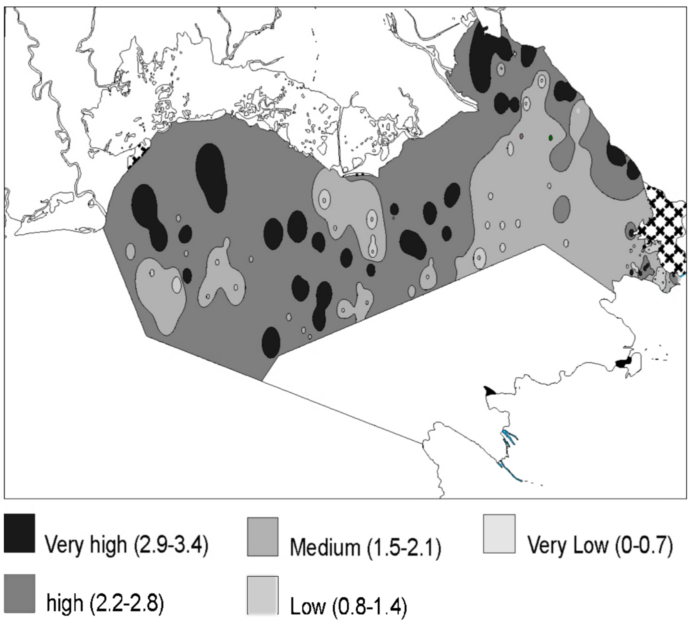

Fig. 4. Image representing the Shannon-Wiener diversity index values.

When overlapping Pielou's Evenness vectorial map (Fig. 5) with the precedent, we could see that in the centre of the Gulf, Evenness values are quite low (0.6 to 0.7) while in the mussel farms' areas, the beaches region, and the ducts zones, Evenness is high (0.87 to 0.94). This means that in the central Gulf, besides high values of diversity there should be strong dominances to explain the low Evenness values and that in the beaches and mussel farms' areas, diversity values are based in an equilibrium between the number of species and abundance which are generally not too high (around 45 species and 500 individuals on average).

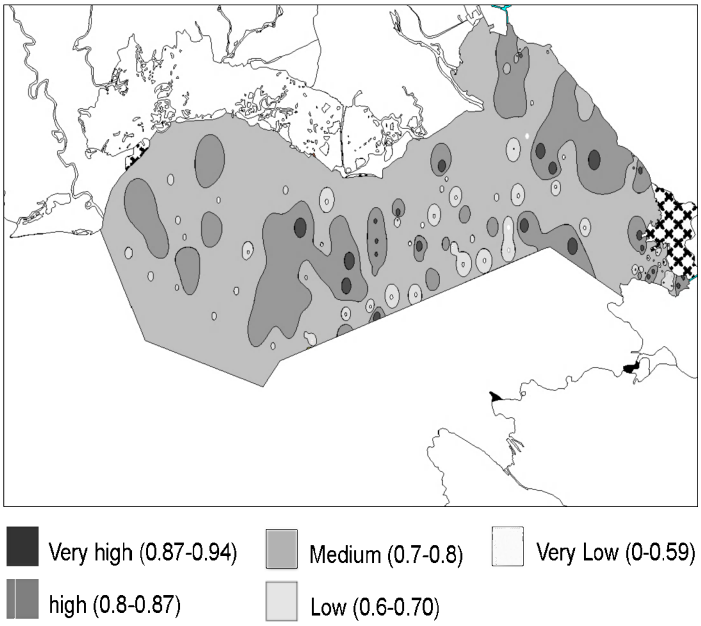

Fig. 5. Image of Pielou' Evenness index values.

To complement these results, we looked at the composition and distribution of the dominant species. The keystone species for the whole area is undoubtedly the mollusk *Corbula gibba*, which by itself represents almost 23% of the total fauna. Indeed in Fig. 6, we can see that *C. gibba* is most abundant in the centre of the Gulf (up to 4000 organisms in a single sample) and in the central areas of Muggia Bay. *C. gibba* is a well-known indicator of sediment instability (Orel *et al.*, 1987; Elias, 1992; Aleffi and Bettoso, 2000). Its ecological group (III), reinforces the perception of habitat unbalance. Other strong dominances are found there for a few species (the polychaetes *Nothria conchylega* 12,765 ind., almost 10% of the total of the fauna, *Eunice vittata* and *Maldane glebifex*).

The central part of the Gulf of Trieste, which also happens to be the deepest (about 25 m), is an area of active fishing, in detritic bottoms, of species like *Callista chione*, *Pecten jacobaeus*, *Solea vulgaris* and *Sepia officinalis*. The powerful hydraulic dredges and trawls used to fish them, have differentially affected the benthic populations (besides the commercial mollusks themselves), by constantly removing the natural bottoms, described there as muddy sands (Brambati *et al.*, 1983). The very high numbers of *C. gibba* clearly indicate the instability of those bottoms, this being reinforced by the local abundance of the polychaete *Owenia fusiformis*, a species reported to thrive in dredged bottoms or sands (Solis-Weiss *et al.*, 2001). It is however most interesting to note the high number of rare species present, as indicated by the high diversity (up to 3.4) and species richness values (87 to 108) of this area. Those constitute a potential pool for restoration of the original communities if the fishing pressure would diminish and thus the bottom instability and sediment texture would return to their original condition.

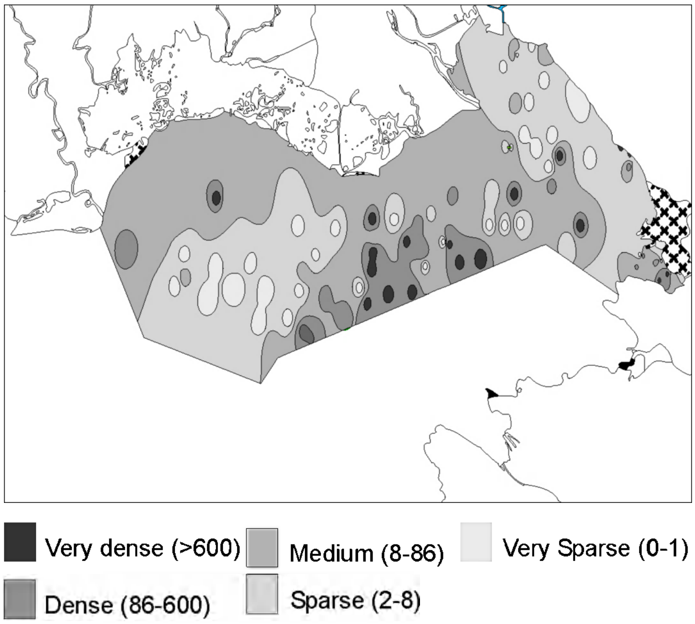

Fig. 6. Image of the keystone dominant species Corbula gibba.

In Muggia Bay, *C. gibba* is also found as dominant, especially in the southern region of the Bay, the species being eliminated from the highly polluted areas of the industrial zone (north and northeast) and found more abundantly in the region where the large ships entering the Bay manoeuvre and thus remove the shallow bottoms, or where dredging is taking place constantly to ensure a suitable depth to the navigation canal (Solis-Weiss *et al.*, submitted). In this last region, we found also large numbers of *O. fusiformis*. The areas closer to the industrial zone are characteristically very poor in abundance, diversity and species richness. In fact the only two stations found azoic in the whole area are located there. A decreasing gradient is evident in species richness when moving from the cleaner waters of the entrance of the Bay to the eastern and northern areas of the industrial zone, following the main current direction. The environmental pressures in this area, besides the very active industrial activity of the last 100 years, included the direct discharges of sewage from the city of Trieste (until the 80's) and water stagnation induced by the artificial closure of the Bay by a three dams' system built in 1909.

A survey of the database, comparing rough data from different years, indicatively could signal that there have been improvements since the ecological laws of 1976 were enforced in the area at the beginning of the 80's. In particular in Muggia, an improvement is clear after the sewage discharges stopped and there are more controls on the industrial discharges: the fauna show some recovery, both in composition and diversity (Solis-Weiss *et al.*, submitted). The ducts' areas are another interesting particularity of the region, since even though they discharge treated sewage, organic matter and other by-products should be present, they do not seem to harm the fauna, quite the opposite, and this is being now investigated with more detail (Solis-Weiss *et al.*, in prep.).

Conclusions

The analysis of the different maps showing the distribution of the ecological parameters measured and the dominant species distribution, allowed us to individuate the areas of more impact, or 'sensitivity areas' in the Gulf of Trieste, each one characterized by different kinds of impacting activities.

The central region of the Gulf is subjected to intensive trawl fisheries; in the Bay of Muggia there is a large industrial and commercial port area, subjected until recently to sewage discharge, with problems of induced stagnation and, in addition, active maritime traffic; the submarine ducts in turn, discharge, away from shore (1 to 7km), sewage waters (treated to a certain extent), so organic enrichment is obvious in the output areas, but since trawls are forbidden there, only more selective and much smaller means of fishing are employed, so that in practice they also constitute zones of protection and concentration for benthic organisms and fishes. The estuary of the Isonzo is a zone of discharge for agricultural by-products and Mercury (Hg) coming from up-stream. The beaches areas are presumably impacted by tourist activities. The mussel cultures of the northern areas are representative of a lucrative commercial activity, now recovering from a crisis period, which needs clean waters, and where controls are constant to guarantee the quality of the product. An additional sensitivity area is where shallow clams' fisheries are performed and the refuse of all kinds of fishing is directly discharged to sea, in front of the Grado and Marano Lagoons. However, this last zone was not evaluated, since sampling data from these shallow waters (up to 5m deep) is not available.

The fact that the fauna shows recovery shortly after strong deleterious impacts are stopped could indicate a high resilience of the system in general. The changes in time and space of the dominant species indicated the evolution of the bottom conditions in the Gulf and emphasized the resilience of the system.

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