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Integrated approach for the assessment of the benthic ecosystem functioning at a coastal site in the northern Adriatic Sea

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ABSTRACT

The assessment of an ecosystem functioning is very complex and requires an integrated approach based on the combined and synoptic estimates of biological processes and the study of communities at different trophic levels. Here we present the main results gained over a 2 year-period aimed to investigate the benthic ecosystem functioning at a virtually pristine coastal site. Our suggested approach follows consecutive and interconnected steps: from the chemical characterisation of the sediments to the evaluation of the main autotrophic and heterotrophic metabolic processes, passing through the study of microphytobenthos and meiofauna. Our results indicate that in summer the system experienced pulsed inputs of fresh organic matter mostly due to the proliferation of benthic diatoms. This freshly produced material increased the sediment nutritional value supporting higher meiofaunal densities and stimulating benthic prokaryotes in mobilising C and incorporating it in new biomass. In winter, the lower availability of fresh organic matter, mainly due to the lower diatom abundances, contributed to a reduced prokaryotic C reworking and overall to a major confinement of C flow within the benthic microbial loop. The system shifted from net autotrophy to net heterotrophy as a response to temperature and light variations at the bottom. The latter factors directly influence the microalgal photosynthetic efficiency and are therefore responsible for the observed uncoupling between microphytobenthic abundances and primary production rates.

1. Introduction

Since approximately 40% of the world's population lives within the 100 km of the coast (Solan et al., 2006 and references therein), coastal areas are often the focus of several anthropogenic activities which lead to physical and chemical alterations, habitat destruction and changes in biodiversity (Borja et al., 2012 and references therein). A multitude of direct and indirect human influences, therefore, has significantly modified coastal ecosystems leading to the consequent alteration of their functioning. Over the last decade, the sharpening of coastal areas deterioration increased the concern about their management and protection. In response to such anxiety, a huge effort has been made in research aimed to the development of tools for the assessment of the environmental and ecological status. This concept takes into account the structure, function and processes of marine ecosystems bringing together natural physical, chemical, physiographic, geographic and climatic factors, and integrates these conditions with the anthropogenic impacts and human activities in a given area (Borja et al., 2009). This approach is intended to allow an assessment of the ecological status at the ecosystem level ('ecosystem-based approach' or 'holistic approach') more efficiently than can be done at a species or chemical level (Borja et al., 2012). However, not all integrative tools currently adopted are able to respond to the requirements of the ecosystem-based approach for the assessment of an ecosystem health. Several well-established, integrative techniques, such as the sediment quality triad (SQT), weight of evidence (WOE), and ecological risk assessment (ERA) focus more on assessing pollution than assessing integrity of the ecosystem (Borja et al., 2012 and references therein).

The functioning of ecosystems is based on an efficient circulation of matter and energy through various levels of biological organisation, involving primary, secondary productions and decomposition. Biotic (production and decomposition) and abiotic (biogeochemical cycles) processes are essential for the functioning of ecosystems and are deeply interconnected (Boero and Bonsdorff, 2007 and references therein). Considering only the abiotic side of ecosystems, functioning may result in a too reductive view since the intricate biological patterns that make it possible are overlooked (Boero and Bonsdorff, 2007). On the other hand, there is a plethora of univariate and multivariate indices and methods to assess the status of the integrity of marine or coastal ecosystems

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based essentially on macroinvertebrates, sometimes associated with other environmental and biological variables. The benthic indicators and indices can be classified into four categories: (1) based on diversity (e.g. Shannon–Wiener diversity index: H', Shannon and Weaver (1949); BPI: benthic pollution index, Leppäkoski (1975)); (2) based on ecological groups (e.g. AMBI: AZTI's marine biotic index, Borja et al. (2000); BOPA: benthic opportunistic polychaetes/amphipods ratio, Dauvin and Ruellet (2007)); (3) based on trophic groups (e.g. ITI: infaunal trophic index, Word (1979)); and (4) indices synthesising several other indicators (e.g. BQI: benthic quality index, Rosemberg et al. (2004)). The main problem is that most of the indices, which aim to determine anthropogenic stress, relate to abundances of stress-tolerant species, which may be also tolerant to natural stressors or found in naturally organic-rich systems (Borja et al., 2012). The growth and the number of these indices (up to 53 based on macroinvertebrates alone, see review by Borja et al. (2012)) has been fuelled by management's desire for a reductionist approach to the assessment of habitat quality (Diaz et al., 2004). Basically, the final outcome is the integration of multivariate data into a single site-specific numeric value that can be interpreted by a nonspecialist within a good-versus-bad gradient, often to meet a minimum legislative requirement (i.e. the WFD). The biggest shortcoming is the lack of integration of the indices for different biological elements into an overall evaluation of ecosystem health (Borja et al., 2012). Hence, emphasis needs to be directed at understanding the complexities of ecosystem functioning rather than simplifying and scaling down the system into smaller components (Diaz et al., 2004). The challenge is not only to integrate indicators of single ecosystem elements, but also to include measures of ecosystem structure, function and processes (Borja et al., 2012).

Although several attempts have been made to assess the environmental status of marine waters in an integrative manner, there are still significant gaps (Borja et al., 2013 and references therein). In situ studies on benthic ecosystem functioning based on actual estimates of the biological processes integrated with the qualitative and quantitative composition of communities at different trophic levels, are still very rare. Most of these studies have focused exclusively on the heterotrophic (Manini et al., 2004; Pusceddu et al., 2014; Sweetman et al., 2014; Franzo et al., 2015) or photoautotrophic pathways (Sundbäck et al., 2004; Forster et al., 2006; Rubino et al., 2015) whereas only few have attempted to integrate both communities with some metabolic processes (Christensen et al., 2003; Schaffner et al., 2008; Cibic et al., 2012b).

Here we present the main results gained over a 2 year-period as the first attempt for the assessment of the benthic ecosystem functioning at a coastal protected site of the northern Adriatic Sea. The choice of the site, i.e. a virtually pristine area, was due to the necessity to attribute the observed response solely to the natural temporal variability without any evident anthropogenic disturbance. Our proposed integrated approach for the assessment of the benthic ecosystem functioning is based on consecutive but interconnected steps: 1. Characterisation of the sedimentary environment in terms of organic matter availability and composition; 2. Study of both autotrophic (i.e. microphytobenthos) and heterotrophic communities (i.e. meiofauna) at the low-middle level of the trophic web; 3. Evaluation of the main functional pathways, by the estimation of primary production, prokaryotic C production, oxygen consumption and the main exoenzymatic activities. These variables were then combined first to calculate the benthic trophic state and then, by adopting the multivariate statistical analysis, to obtain, as far as possible, a holistic view of the benthic ecosystem functioning over time at this coastal site.

2. Materials and methods

2.1. Study site

The Gulf of Trieste, located in the north-western end of the Adriatic Sea, is a shallow basin with an average depth of 17 m (Celio et al., 2002). Almost completely surrounded by land, the basin is isolated from the rest of the Adriatic by a sill from Grado to the Salvore peninsula (Ogorelec et al., 1991); 10% of its area is <10 m and maximum depth is about 25 m. Tidal amplitude is about 1.5 m, which is the highest in the Mediterranean Sea (Cardin and Celio, 1997). The Gulf experiences annual fluctuations of temperature (from 8 °C to ≥ 24 °C at the surface and from 8 °C to ≥ 20 °C at the bottom) and the water column is usually stratified during summer. Although the water enters the basin from the southeast and surface circulation is predominantly from southeast to northwest, such general pattern may be rapidly modified in response to intense local atmospheric forcing (winds) and river plumes (Malačič and Petelin, 2001; Querin et al., 2007). The region is, in fact, influenced by Bora, a north-easterly wind characterised by strong intensity, which is able to mix the entire water column also due the shallow depth of the basin (Querin et al., 2007). Sedimentation is mainly controlled by river inputs rather than by marine currents (Brambati and Catani, 1988). The main terrigenous supply comes from the Isonzo River (Covelli and Fontolan, 1997). The annual average sedimentation rate is about 1 mm yr^{-1} in the middle of the gulf and increases to 2.5 mm yr^{-1} in front of the Isonzo mouth (Covelli et al., 1999 and references therein). The Gulf can, thus, be regarded as an example of a coastal region of freshwater influence (ROFI, Simpson (1997)), where dynamics are governed mainly by winds and freshwater inputs. These factors are, therefore, the main responsible in determining the composition, the evolution and the persistence of marine life in the Gulf of Trieste.

The study was carried out at the coastal St. C1, located ca. 200 m offshore (45°42.05′ N, 13°42.60′ E) at a depth of around 18 m, nearby the Marine Reserve of Miramare (Fig. 1). This small marine protected area (MPA) is divided in two distinct zones: the inner part (30 ha), subjected to a regime of integral protection, is surrounded by a larger buffer zone (90 ha), sheltered by boats, fishing and swimmers. Declared MPA in 1979, the Reserve is part of the Natura 2000 network and represents the only completely protected area in the Italian part of the Gulf of Trieste.

2.2. Sampling

From July 2010 to July 2012, eight sampling campaigns were performed. At each sampling, PAR (Photosynthetically Available Radiation) profiles were recorded in situ, 50 cm above the bottom by a Profiling Natural Fluorometer PNF-300A (Biospherical Instruments Inc.). PAR at the bottom was expressed as the percentage of measured irradiance (%PAR). Sampling and PAR measurements were performed at the same time of the day (around noon). Bottom sea temperature and salinity were measured using a Seabird 19 Plus Seacat probe. Bottom water samples were collected by means of a 2-L horizontal Niskin bottle. Five virtually undisturbed sediment cores were taken by a KC Haps bottom corer (KC-Denmark, Silkeborg, Denmark) using a polycarbonate sample tube (13.3 cm I.D. with a sample area of 127 cm^2). Once in the laboratory, 1 sediment core was used for meiofauna sampling, 1 for oxygen microprofiling, while the 3 remaining cores were partially extruded and the oxic sediment layer (0–1 cm ca) of each core was collected, homogenised and subsampled for all the other analyses.