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Benthic fluxes of oxygen and nutrients in sublittoral fine sands in a north-western Mediterranean coastal area

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ABSTRACT

Traditionally, benthic metabolism in sublittoral permeable sands have not been widely studied, although these sands can have a direct and transcendental impact in coastal ecosystems. This study aims to determine oxygen and nutrient fluxes at the sediment–water interface and the study of possible interactions among environmental variables and the benthic metabolism in well-sorted fine sands. Eight sampling campaigns were carried out over the annual cycle in the eastern coast of Spain (NW Mediterranean) at 9 m depth station with permeable bottoms. Water column and sediment samples were collected in order to determine physico-chemical and biological variables. Moreover, *in situ* incubations were performed to estimate the exchange of dissolved solutes in the sediment–water interface using dark and light benthic chambers. Biochemical compounds at the sediment surface ranged between 160 and 744 $\mu g\ g^{-1}$ for proteins, 296 and 702 $\mu g\ g^{-1}$ for carbohydrates, and between 327 and 1224 $\mu g\ C\ g^{-1}$ for biopolymeric carbon. Chloroplastic pigment equivalents in sediments were mainly composed by chlorophyll *a* (1.81–2.89 $\mu g\ g^{-1}$). These sedimentary organic descriptors indicated oligotrophic conditions according to the biochemical approach used. In this sense, the most abundant species in the macrobenthic community were sensitive to organic enrichment. In dark conditions, benthic fluxes behaved as a sink of oxygen and a source of nutrients. Oxygen fluxes (between −26,610 and −10,635 $\mu mol\ m^{-2}\ d^{-1}$) were related with labile organic fraction ($r = -0.86$, $p < 0.01$ with biopolymeric carbon; $r = -0.91$, $p < 0.01$ with chloroplastic pigment equivalents). Daily fluxes of dissolved oxygen, that were obtained by adding light and dark fluxes, were only positive in spring campaigns (6966 $\mu mol\ m^{-2}\ d^{-1}$) owing to the highest incident irradiance levels ($r = 0.98$, $p < 0.01$) that stimulate microphytobenthic primary production. Microphytobenthos played an important role on benthic metabolism and was the main primary producer in this coastal ecosystem. However, an average annual uptake of 31 $mmol\ m^{-2}\ d^{-1}$ of oxygen and a release of DIN and $Si(OH)_4$ (329 and 68 $mmol\ m^{-2}\ d^{-1}$ respectively) were estimated in these bottoms, which means heterotrophic conditions.

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1. Introduction

Continental shelf ecosystems are characterized by intense and complex interactions where continental, oceanic and atmospheric processes take place together. These ecosystems receive most of the inputs from continents, atmosphere, deeper ocean waters as well as from marine sediments. Due to human development, nutrient and organic matter inputs have been increasing since the second half of the 20th century (Smith, 2002), especially nitrogen and phosphorus. This process of organic matter and nutrient enrichment, known as eutrophication, is one of the most important current problems related to marine ecosystems (Smith, 2002). The organic and nutrient charge in coastal areas are transcendental since enhance and regulate primary producers (Smayda, 2005). Nevertheless, an intense or continuous organic or nutrient discharge could cause the ecosystem degradation (Cloern, 2001).

Nutrient inputs enable approximately 20% of global pelagic primary production to take place on the continental shelves (Jahnke, 2010). A large fraction of this pelagic primary production, as well as organic inputs from continent, can reach the sediment surface due to the shallow depth in the inner shelves (Huettel et al., 2014). At surface sediments, an excess of organic material can promote benthic primary production (Karydis and Kitsiou, 2012), organic matter accumulation and even can turn the seafloor anoxic (Morata et al., 2012). Organic matter present in the sediment is the main driving force of mineralisation in inner shelve bottoms, which organic and nutrient production can be transported to water column by advective and diffusive transport or fixed by benthic photosynthesizers. In this sense, benthic nutrient regeneration can play a major role in the nutrient supply that can

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contribute to primary production. Many authors, such as Loassachan et al. (2009), Mermillod-Blondin et al. (2008), and Sarker et al. (2009), have described the large number of factors that regulate the availability and regeneration of nutrients in inner shelve bottoms. The main factors are microbial community (Jørgensen, 2006), benthic macrofauna (Mermillod-Blondin and Rosenberg, 2006), quantity and quality of organic matter (Pastor et al., 2011) and benthic primary producers (Mermillod-Blondin et al., 2008) such as seagrasses, macroalgae, as well as microalgae, although a great number of environmental ones, such as temperature or light, can affect all of these.

The study of benthic metabolism and nutrient exchange at the sediment–water interface in continental shelves have been focused on muddy and organic-rich sediments such as estuaries (Pratihary et al., 2009), salt marshes (Ferrón et al., 2009a), aquaculture production areas (Morata et al., 2012) or coastal lagoons (De Vittor et al., 2012). Permeable sands have been neglected based on the belief that intense exchanges across sediment–water interface and biological activity require high levels of organic matter, despite the fact that these permeable bottoms cover 70% of all continental shelves (Boudreau et al., 2001) and 4% of the ocean floor (Hall, 2002). However, recent studies suggest that permeable bottoms act as a biocatalytic filter with high reaction rates and intense recycling comparable to the metabolism in low-permeable sediments (see Huettel et al. (2014), and references therein). Furthermore, shallow water column depth in the inner shelf allows sunlight to reach these sublittoral bottoms enabling benthic photosynthesis (Huettel et al., 2014). In particular, microphytobenthos does not require high conservatives light fluxes (Gattuso et al., 2006), hence, these phototrophs can cover wide areas of permeable sublittoral sediments. Microphytobenthos constitutes a food source for benthic feeders (Nozais et al., 2005) and can contribute up to 50% of total primary production (Perissinotto et al., 2002). During the last few decades, some works have been carried out on permeable sublittoral sands and oligotrophic zones e.g. in the South Atlantic Bight studying microphytobenthic primary production (Jahnke et al., 2005, 2008) or in the Mediterranean Sea over *Posidonia oceanica* meadows (Barrón et al., 2006). However, not many studies have considered the entire benthic ecosystem structure including physical, chemical, biochemical descriptors and biological variables involved in the study of the benthic metabolism in permeable sublittoral sands.

The aim of this work is therefore, to study the exchange of oxygen and nutrients across the sediment–water interface in order to determine the benthic metabolism in sediments composed by permeable sublittoral sands over the annual cycle. To achieve this objective we used *in situ* incubations employing light and dark chambers over the annual cycle. Likewise, it took into account the study of possible interactions among environmental variables and the identification of those which were the most influential on the benthic metabolism.

2. Material and methods

2.1. Study site

The study area falls within the Gulf of Valencia (Spain) in the Western Mediterranean. Specifically, the sampling station was in Gandia, in the southern part of the Gulf of Valencia (Fig. 1). At the point where the station is located (39° 00′ 37″ N, 00° 09′ 19″W), the water column is approximately 9 m in depth and the seabed is composed of well-sorted fine sands. This biocenosis is spread over wide areas of the Mediterranean Sea (Bellan-Santini et al., 1994) and it is commonly found around the Eastern Iberian Peninsula coastline (De-la-Ossa-Carretero et al., 2009). In fact, this biocenosis

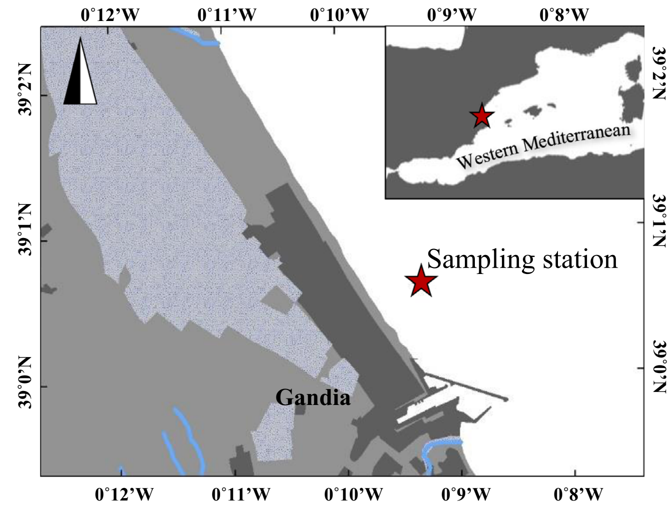

Fig. 1. Sampling site at the southernmost sector of the Gulf of Valencia (Western Mediterranean).

covers roughly over 640 km^2 of the Gulf of Valencia, from the marine mapping elaborated by MAGRAMA (2010). Well-sorted fine sands are composed of fine and homogeneous sands and inhabited by annelids, molluscs, crustaceans and equinoderms.

This study included eight different sampling campaigns over the annual cycle. Sampling campaign dates were chosen to take into account variables and factors that influence biogeochemical processes such as temperature and solar radiation. Therefore, the chosen dates included the maximum and minimum of these factors, however, sampling campaigns only could be carried out under calm sea conditions in order to guarantee the correct deployment of instruments and team work. The sampling campaigns took place: 5th August 2009 (Summer 2009), 17th March 2010 (Winter 2010), 17th June 2010 (Spring 2010), 7th September 2010 (Summer 2010), 15th June 2011 (Spring 2011), 30th August 2011 (Summer 2011), 7th December 2011 (Autumn 2011) and 15th March 2012 (Winter 2012). In each sampling campaign, samples of water and sediment were collected in order to determine different physical, chemical and biological variables. In the water column the variables studied were temperature, suspended solids (SS), dissolved oxygen (DO), ammonium (NH_4^+), nitrite plus nitrate (NO_2^- +NO_3^-), phosphate (PO_4^{3-}), total phosphorus (TP), silicic acid ($Si(OH)_4$), chlorophyll (WChl-*a*) and transparency. In the sediment we determined incident irradiance at the surface of sediment (I_z), redox potential (Eh), granulometric composition, organic matter (OM), chlorophyll (SChl-*a*), phaeopigments (Phaeo), proteins (PRT), carbohydrates (CHO), lipids (LIP) and the benthic macrofauna composition. Likewise, *in situ* incubations were also conducted using benthic chambers to study DO, NH_4^+, $NO_2^- + NO_3^-$, PO_4^{3-} and $Si(OH)_4$ fluxes across the sediment–water interface.

2.2. Sample collection

Water samples were taken using a Van Dorn bottle every 3 m. However, bottom water samples were collected at half a metre above the seabed surface in order to prevent sediment resuspension.

In the sediment, 12 undisturbed samples were taken by SCUBA divers using corers with a height of 30 cm and an internal diameter of 6.5 cm. Redox potential was measured immediately on all cores collected in each sampling campaign. Six of them were used for the study of the physico-chemical variables in the uppermost 1 cm layer, which were carefully stored in the dark and placed in a vertical position. The other six cores used for the macrofauna

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