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Origin and composition of sediment organic matter in a coastal semi-enclosed ecosystem: An elemental and isotopic study at the ecosystem space scale

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ABSTRACT

The origin and composition of sediment organic matter (SOM) were investigated together with its spatial distribution in the Arcachon Bay – a macrotidal lagoon that shelters the largest *Zostera noltii* meadow in Europe – using elemental and isotopic ratios. Subtidal and intertidal sediments and primary producers were both sampled in April 2009. Their elemental and isotopic compositions were assessed. Relative contributions of each source to SOM were estimated using a mixing model. The SOM composition tended to be homogeneous over the whole ecosystem and reflected the high diversity of primary producers in this system. On average, SOM was composed of 25% of decayed phanerogams, 19% of microphytobenthos, 20% of phytoplankton, 19% of river SPOM and 17% of macroalgae. There was no evidence of anthropogenic N-sources and SOM was mainly of autochthonous origin. None of the tested environmental parameters – salinity, current speed, emersion, granulometry and chlorophyll *a* – nor a combination of them explained the low spatial variability of SOM composition and characteristics. Resuspension, mixing and redistribution of the different particulate organic matters by wind-induced and tidal currents in combination with shallow depth probably explain the observed homogeneity at the whole bay scale.

1. Introduction

Coastal ecosystems represent 6% of earth and 8.5% of marine biomes (Costanza et al., 1997). Profuse and renewed amounts of organic matter and nutrients originating from the watersheds spark off high biological productivity in coastal zones. High primary production in these zones is associated with a wide diversity of primary producers. Shallow depths and tides allow the development of macrophytes such as kelp forests (Mann, 1973), salt marshes (Adam, 1990), mangroves (Kathiresan and Bingham, 2001) and seagrass beds (Duarte, 1991), which constitute an originality of coastal ecosystems as compared to oceanic ones, where primary production is dominated by phytoplankton.

Among these primary producers, seagrass meadows are prominent components of the littoral zone. Green and Short (2003) estimated that the total worldwide surface area of these meadows is about 177 000 km^2. Seagrass meadows are considered the most valuable/profitable ecosystems by Costanza et al. (1997) mainly because of their role in the nutrient cycle. They insure many other economical and/or ecological functions, such as: (1) providing habitats for fishes and shellfishes (Smith and Suthers, 2000), (2) scattering the energy of waves and stabilising sediments (Fonseca and Fisher, 1986; Madsen et al., 2001; Widdows et al., 2008), (3) protecting coast from erosion (Terrados and Duarte, 2000), and (4) purifying coastal waters (Ward, 1987). Seagrasses net worldwide primary production averages 1012 gDW m^{-2} y^{-1} against 365 gDW m^{-2} y^{-1} for macroalgae and 128 gDW m^{-2} y^{-1} for phytoplankton. It accounts for 12% of the net worldwide coastal primary production and about 1% of the oceanic global net primary production (Duarte and Chiscano, 1999). Moreover, seagrasses support vegetal epiphytes (micro- or macro-algae), which can be as productive as seagrasses themselves (Borowitzka et al., 2006). Seagrass meadows are also natural hotspots for carbon sequestration with an estimated global seagrass carbon sinks of 48 to 112 tons per year (Kennedy et al., 2010). Seagrass beds are directly or indirectly submitted to anthropogenic disturbances such as, increased turbidity, increased nutrient loads and mechanical damages (*e.g.* land reclamation, boating, dredging, fisheries; Green and Short 2003). Orth et al. (2006) identified several factors at global (*e.g.* climate change), regional (*e.g.* shifts in water quality) and local (*e.g.* increased loading of sediment, contaminants and nutrients) scales that caused seagrass losses in temperate and tropical regions. Moreover Waycott et al. (2009) underlined the worldwide acceleration of seagrass losses from a median decline of 0.9 (before 1940) to 7% of total surface area per year since 1990. They ranked seagrass habitats among the most threatened ecosystems on earth, together with coral reefs and mangroves. Seagrass loss substantially affects the biodiversity of associated flora

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and fauna (Duffy, 2006), which could induce strong impacts on food webs and water quality (Cardinale, 2011).

All micro- and macroscopic primary producers contribute to the pool of particulate organic matter (POM) together with continental inputs. POM plays a key role in ecosystem functioning and especially in trophic transfers because different primary producers and corresponding detritus are not usable to the same extent by primary consumers, depending on their biochemical composition (Grémare et al., 1997; Tenore and Dunstan, 1973). Potential sources of POM are multiple and diversified: detrital matter, inputs from watersheds, seagrasses, benthic macroalgae, microphytobenthos, phytoplankton, epiphytes. Because of their physiology and of the origin of their nutrient resources, different primary producers usually exhibit different isotopic and/or elemental signatures. As a consequence, these signatures represent useful tracers to quantify their relative contribution to the composition of suspended particulate and sedimentary organic matter (SPOM and SOM, respectively, Cifuentes et al., 1988; Jaschinski et al., 2008; Machás and Santos, 1999), as well as to the food resources of primary consumers (Carlier et al., 2007; Riera et al., 1996; Schaal et al., 2008). Stable isotopes and elemental ratios have been widely used to identify which primary producers contribute to sediments organic matter, (*e.g.* Cifuentes et al., 1988; Fahl and Stein, 1997; Graham et al., 2001; Papadimitriou et al., 2005; Perdue and Koprivnjak, 2007; Ramaswamy et al., 2008). Many studies have focused on estuaries where organic matter sources are well discriminated, mostly continental *vs.* oceanic end-members (*e.g.* Cifuentes et al., 1988; Liu et al., 2006; Papadimitriou et al., 2005; Ramaswamy et al., 2008; Zhou et al., 2006). Conversely, only few studies have dealt with the composition of sediment organic matter in intertidal mudflats (Freese et al., 2008; Liu et al., 2006; Ramaswamy et al., 2008; Volkman et al., 2007; Yamamuro, 2000) and even less with seagrass meadows (Jaschinski et al., 2008; Kennedy et al., 2004; Moncreiff et al., 1992).

In Arcachon Bay – a coastal lagoon that shelters the largest seagrass meadow of *Zostera noltii* in Europe, with 70 km^2 of seagrasses over the 115 km^2 of the intertidal area (Auby and Labourg, 1996) – the surface area of *Z. noltii* beds has declined by 33% between 1988 and 2008, and more markedly during the 2005–2008 period (Plus et al., 2010). This could lead to a change in the composition and amount of sedimentary organic matter, which could induce changes in food web complexity. The presence of several different settlements as schorres, channels, intertidal mudflats or seagrass meadows in this bay associated with the presence of a wide diversity of primary producers – phanerogams (*e.g. Z. noltii*, *Z. marina*, *Spartina* spp.), benthic macroalgae, microphytobenthos, phytoplankton, epiphytes – suggests that sediment organic matter could be composed of a wide mixture of primary producers and may exhibit a large spatial variability. Moreover, Arcachon Bay is strongly impacted by oceanic and continental inputs depending on season and/or location. Up to now, this impact has been noticed at several levels: (1) hydrology through a gradient of waters, which allows for the distinction of three water masses with distinct characteristics (Bouchet, 1993), (2) nutrient distribution, (3) phytoplankton abundance and composition (Glé et al., 2008), (4) zooplankton community structure and distribution (Vincent et al., 2002), (5) benthic macrofauna structure (Blanchet et al., 2004), and (6) trophic diet of some species such as the bivalve *Ruditapes philippinarum* (Dang et al., 2009). Finally, the large water volumes circulating through the entrance of the bay during each tide (between 130 and 400.10^6 m^3) and wind regimes associated with shallow depths lead to resuspension processes, which could affect the composition of SOM. This leads to the question of the origin and spatial distribution of sediment organic matter in such an ecosystem characterised by a high number and diversity of primary producers and POM sources. This question has not been tackled so far although SOM in the Arcachon Bay represents a major potential food source for benthic macrofauna.

To understand organic matter flows from primary producers to primary consumers, it is essential to first investigate SOM origin and spatial distribution. Indeed, and depending on spatial location, sediment composition can be affected by various factors like freshwater inputs or resuspension. Consequently a different composition of organic matter can be expected in relation to a different origin of this matter and according to spatial location. The specific aims of the present study were: (1) to determine isotopic and elemental signatures of potential sources, (2) to compare these signatures with those of sediment organic matter in order to (3) estimate the relative contribution of each primary producer to SOM composition, and finally (4) to investigate the spatial variability of sources and SOM characteristics in order to determine its environmental forcing.

2. Material and methods

2.1. Study site

The study was carried out in Arcachon Bay (44°40′ N, 1°10′ W), a macrotidal (tidal amplitude: 0.8–4.6 m) semi-enclosed lagoon of 174 km^2 located in south-western France (Fig. 1). This coastal ecosystem receives ocean water through a narrow channel located in the Southwest and riverine water from: (1) the Leyre River (73% of river water inputs; Plus et al., 2010) and (2) several small streams located in the north-eastern and southern part of the bay (Fig. 1). Annual riverine water input amounts ca. 1.10^9 m^3. In the inner lagoon (156 km^2), tidal channels (41 km^2) separate large intertidal areas (115 km^2) covered by the largest European *Z. noltii* meadow (70 km^2). Water depth ranges between 0 and 20 m. Arcachon bay displays a high variety of potential organic matter sources. Autochthonous primary macroproducers are not only composed of the currently declining intertidal *Z. noltii* seagrass but also include several other phanerogams – *e.g. Zostera marina* in subtidal channels and *Spartina* spp. on the shore – and macroalgae – mainly belonging to the Gracilariale and Ulvale orders – of much lower biomass. The extent of intertidal mudflats (63 km^2) enhances microphytobenthic production. Phytoplankton is another main autochthonous primary producer (Glé et al., 2008). At last, Arcachon Bay also receives continental organic matter — mainly composed of soil and litters of terrestrial C3 plants (Polsenaere et al., submitted for publication).

2.2. Sample collection, processing and storage

2.2.1. Sampling

During April 2009, 31 benthic stations located in the inner bay were sampled for sediment and/or primary producer characteristics (Fig. 1). Twelve stations were subtidal and located within major and minor channels. Nineteen stations were intertidal and distributed over a wide range of density of *Z. noltii*. Intertidal benthic stations were sampled at low tide. Subtidal benthic stations were sampled either at low or high tide. Four pelagic stations located along a gradient from the inner to the outer bay were sampled during high tide for characteristics of suspended particulate organic matter (SPOM). Two river stations and one terrestrial station were sampled for characteristics of continental primary producers and/or SPOM.

Intertidal collection: The top first centimetre of the sediment was collected by scrapping (1) 140 cm^2 for sediment organic carbon and nitrogen (SOC and SON, respectively) elemental and isotopic composition, (2) 400 cm^2 for microphytobenthos, and (3) by punching 5 × 7.5 cm^2 for chlorophyll *a*. Sediment was collected by punching 7.5 cm^2 of the top 3 cm for granulometry. Three (granulometry) to five (other parameters) replicates were collected at each station. Macrophytes (macroalgae, phanerogams) and their associated epiphytes were collected by hand at each station when present.

Subtidal collection: Subtidal samples were collected by SCUBA diving. The top first centimetre was collected using three aluminium cores (80 mm of diameter) for SOC, SON and stable isotopes. The top first centimetre of five plastic cores (31 mm of diameter) and