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Spatiotemporal bioturbation patterns in a tidal freshwater marsh

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ABSTRACT

Bioturbation has been hypothesized to exhibit different forms of sediment mixing in aquatic systems, but few in situ tests have been conducted in estuaries, and anyone along a flooding gradient which is the main feature characterizing intertidal areas. The relationships between bioturbation and macro-invertebrate communities were studied as part of a restoration project in the tidal freshwater zone of the Schelde estuary, and highlighted specific sediment mixing patterns along a tidal gradient. Three permanent sites, evenly distributed along the flooding gradient, were monitored over a period of one year. Tidal influence engendered a clear gradient opposing newly-established aquatic communities (low elevation and strong disturbance) to remnant terrestrial communities (high elevation and low disturbance). Different bioturbative modes were identified along this gradient. Biodiffusion (random spreading of sediment particles) was the dominant mode at high and mid elevations. Low elevation was characterized by bioadvection (vertical movement of sediment particles) and higher bioturbative intensities. Maximum bioturbative intensities were observed in summer. This is the first bioturbation study, conducted along a flooding gradient, and which characterizes the bioturbative modes and intensities among tidal habitats and confirms the key role of disturbance. These findings underline the significance of the multiplicity of bioturbation modes in estuarine habitats, and the potential implications in estuarine biogeochemistry in general.

1. Introduction

Bioturbation induced by soil and sediments macrofauna is now recognized as a fundamental ecological engineering process involving physicochemistry, organisms and food webs in both terrestrial and aquatic ecosystems (Meysman et al., 2006). Bioturbation is the source of key biogeochemical processes occurring at the sediment–water interface, and its contribution to diagenetic processes is far from negligible (Aller, 1994; Boudreau, 1997). Different modes of bioturbation are known to differently rework the sediments (Rhoads, 1974; Gerino et al., 2003). These physical processes have been shown to influence specifically water fluxes and oxygen concentration, and thus microbial activity (Mermillod-Blondin and Rosenberg, 2006). In wetlands and aquatic systems, these close relations between fauna and sediments contribute to increased water-sediment exchanges and enhance biogeochemical processes (Nickell et al., 2003; Lohrer et al., 2004; Nogaro et al., 2009). Also, specific bioturbative modes at the community level were found to be determinant in ecosystem functioning (Biles et al., 2002).

Multiple evidences now support relations between bioturbation and ecosystem functioning. For instance, human activities in estuaries have been shown to impact community structure and/or bioturbative mode via effects on functional richness (Pearson and Rosenberg, 1978; Mazik and Elliott, 2000; Wheatcroft, 2006; Gerino et al., 2007). However, while changes in benthic community structure are obvious along a gradient of disturbance (Rhoads, 1974; Voshell and Simmons, 1984; Solimini et al., 2003), there is still a lack of examples supporting a general pattern of bioturbative mode and intensity along such a gradient. Furthermore, since association and interaction between faunal communities and abiotic features are well recognized (Ricklefs, 1990), spatiotemporal gradients such as ecosystem recovery or ecosystem development offer opportunities to describe and quantify the sediment bioreworking at different levels of disturbance and to assess its involvement in ecological successions (Pearson and Rosenberg, 1976).

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In Belgium, the Schelde estuary has been impacted for a long time by human activities, resulting in severe physical and chemical stress. Estuarine habitats have been drastically reduced and their functionality critically impaired (Meire et al., 2005). Despite a clear improvement in oxygen concentration the last fifteen years, embankment sustains a severe physical stress, particularly on tidal flats. Nevertheless, restoration projects aiming at the ecological rehabilitation of the estuary through land reclamation are ongoing (Van den Bergh et al., 2005), and thus offer the opportunity to investigate different aspects of tidal ecosystem development. Among the different techniques used in estuarine restoration, Controlled Reduced Tide (CRT) is until now the only one proved to restore a neap-spring cycle in lowered embankments (Beauchard et al., 2011), which are a typical feature of historically embanked estuaries. The CRT system was hypothesized to successfully restore intertidal marshes in combination with safety function against storm tides (Maris et al., 2007). A recent study highlighted the high restoration potential for tidal freshwater vegetation in CRT (Jacobs et al., 2009).

However, it is difficult to value an ecosystem when its structure and functioning are not fully understood (Jickells, 1998). There is still a lack of information dealing with ecosystem development for rehabilitation and/or compensation in estuaries, particularly in the scope of biogeochemistry (French, 2006). Although freshwater tidal zones have been pointed to need greater attention given the important chemical and biological reaction occurring there (Morris et al., 1978), knowledge remains scarce, particularly concerning sediment biogeochemistry (Megonigal and Neubauer, 2009). Despite the absence of clear quantification of their spatial extent, tidal freshwater wetlands nevertheless are known to occur in the estuaries of most of the world largest river basins (Baldwin et al., 2009).

Recent works in the experimental CRT of the Schelde estuary showed that a clear flooding frequency gradient is implemented (Beauchard et al., 2011) and conditions sediment depositions (Vandenbruaene et al., 2011). Hence, similarly to vegetation, macroinvertebrate development is hypothesized to result from these typical estuarine determinants, and to generate different habitat specific bioturbation modes (Mermillod-Blondin and Rosenberg, 2006) possibly changing over season (Teal et al., 2008). For the first time, bioturbation was studied in situ along a flooding gradient in a newly-created tidal freshwater environment. Beyond the restoration success assessment of the project, this study aims to explore the spatiotemporal pattern of bioturbative modes and intensities, and to provide interpretations of faunal features evidencing soil sediment processes. As previously demonstrated for tidal freshwater vegetation (Jacobs et al., 2009), this gradient generates different levels of community disturbance and ecological succession by water submersion.

2. Methods

2.1. Study area

The study took place in the "Lippenbroek polder" (51°05′10″N; 4°10′20″E) located in the freshwater tidal zone of the Schelde estuary near the city of Antwerp (Fig. 1). There, the salinity can reach exceptionally 1.0 psu during periods of reduced river discharge in summer, but remains most of the time below 0.5 psu. Since 2006, this formerly agricultural area (8 ha, crops) has been the focus of a pilot project dealing with tidal habitat restoration in combination with flood protection. It is connected to the estuary by means of entrance and exit floodgates allowing water exchange between the two systems (see Maris et al. (2007) for technical details). The definitive hydrological regime was set in March 2006.

2.2. Field monitoring and environmental context

A spatiotemporal sampling framework was carried out over five seasons from February 2007 to February 2008 as part of the interdisciplinary Lippenbroek project focusing on different ecological compartments (hydrology, soil physicochemistry and soil macrofauna among others). Spatially, three sites evenly distributed along the elevation range were selected for this study: high elevation (H; low flooding frequency), mid elevation (M; moderate flooding frequency) and low elevation (L; high flooding frequency) (Fig. 2). Site H is flooded only during spring tides whereas site L is daily flooded except sometimes at neap tide.

From the initial restoration of tidal influence in March 2006 to the beginning of this study (February 2007), important abiotic changes occurred, mainly driven by an increased estuarine sediment deposition at low elevation (Vandenbruwaene et al., 2011, Fig. 2), giving rise to a clear physical gradient opposing silty- and water-rich (high flooding frequency) to sandy- and water-poor (low flooding frequency) environments. After the first drastic environmental modifications, changes in soil physics remained moderate (Fig. 3).

2.3. Soil macrofauna and bioturbation follow-up

Macrofauna was considered as part of the long term monitoring. Six replicate cores were sampled (46 mm Ø, 150 mm long) and stored in 5% formalin, and sieved through a 500 μm mesh size before organism sorting and taxonomic identification.

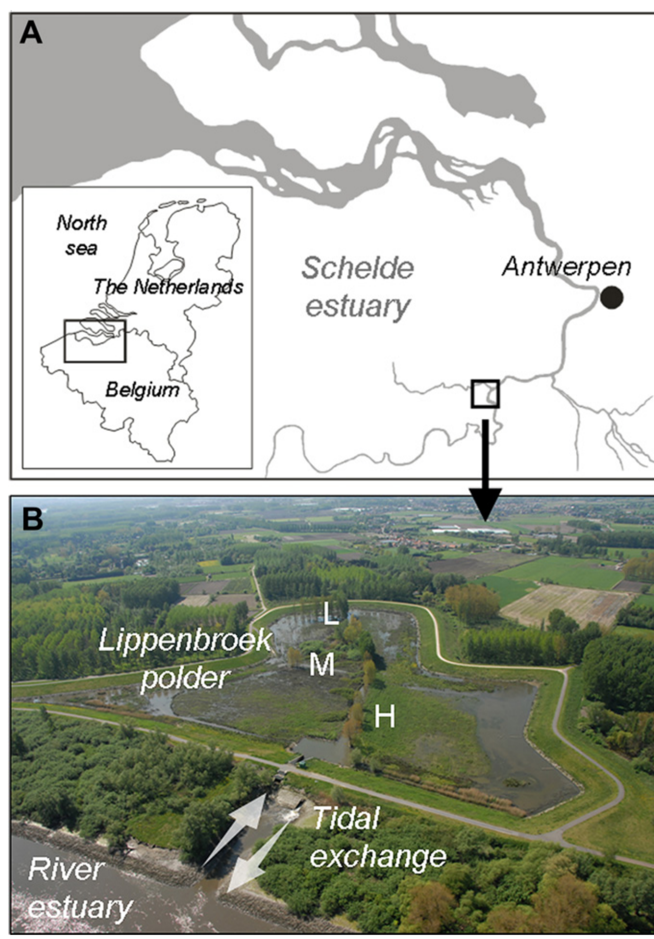

Fig. 1. Location map and photograph of the study area. H, M and L showing the locations of the three sites, respectively at high, mid and low elevation.