Ecological Indicators 25 (2013) 10–22

Contents lists available at SciVerse ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Response of intertidal macrobenthic communities and primary producers to mitigation measures in a temperate estuary

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ARTICLE INFO

Article history:
Received 29 February 2012
Received in revised form 13 July 2012
Accepted 27 August 2012

Keywords:
Zostera noltii
Macroinvertebrates
Hydrologic conditions
Eutrophication
Estuary
Management
Portugal

ABSTRACT

The main goal of this study was to evaluate the response of intertidal macrobenthic communities associated with *Zostera noltii* meadows in a temperate estuary (Mondego, Portugal) to the application of mitigation measures aimed at decreasing eutrophication symptoms. In order to assess possible ecological improvements regarding the seagrass habitat and associated macrobenthic communities, data from four different periods, corresponding to the prevailing conditions of distinct systems, were considered. This study (1) gives concrete examples of pathways of benthic intertidal communities' degradation and recovery; (2) it analyses a long-term dataset (covering almost 25 years) of intertidal communities from a southern European estuary; (3) it is focused on a worldwide problem, and so has potentially far-reaching interest; (4) it exemplifies some of what may be the consequences of the dialogue between science and managers; (5) it assesses the impact and effectiveness of a large-scale mitigation intervention paid for by public funding.

The application of preliminary mitigation measures (in 1998) and the full re-establishment of the communication between the two estuarine subsystems (in 2006) allowed for an improvement in the macrobenthic condition and confirmed that hydrologic conditions in the estuary have been the major drivers of the changes observed over the last two decades. However, evaluating the efficiency of the large-scale intervention proved to be a complex task since different communities showed distinct pathways and momentums of recovery.

The present study provided valuable insights concerning sustainable long-term management solutions regarding the Mondego Estuary. These particular insights could therefore be useful as a management action guideline applied to other estuarine ecosystems undergoing similar eutrophication problems.

1. Introduction

Zostera noltii is a small perennial aquatic plant that grows during periods of light exposure in coastal systems. It is found mainly in shallow sheltered bays and estuaries, typically on muddy, soft bottoms. This seagrass shows considerable plasticity in module size and growth (Duarte, 1991). It is adapted to the challenging conditions affecting intertidal habitats, allowing it to withstand a wide range of conditions, including environmental heterogeneity and disturbance (Hemminga and Duarte, 2000). *Z. noltii* beds make possible a rich habitat in terms of biodiversity and productivity, being a considerable source of organic matter in coastal ecosystems (Edgar, 1990). This species' root networks stabilise the sediment in which they grow, reducing shoreline erosion. *Z. noltii* beds also play a vital role as a rich nursery environment for fish species (Moriarty et al., 1990) and support rich macrobenthic communities (Marques et al., 1993).

Estuaries are among the most productive, diverse, hydrologically variable and economically important ecosystems (Neilson and Cronin, 1981; Hobbie, 2000; Paerl, 2006) and therefore highly vulnerable to anthropogenic pressures. The productive nature and resourcefulness of estuaries depend to a large extent on external supplies or "new" nutrient inputs (Marques et al., 2003). According to Nixon (1995), the nutrient input is the common factor in the increased supplies of organic matter in coastal systems, in some cases leading to eutrophication. This worldwide problem is often associated with the formation and persistence of harmful algal blooms, changes in ecological structure including loss of biodiversity (Howarth et al., 1996), as well as loss of critical habitat and consequent decreases in seagrass beds. Nevertheless, the recovery of an ecological system in these conditions is complex and will probably undergo a different trajectory than that of the decline (Elliott et al., 2007). In this regard, interactions of species within ecosystems, often lead to the establishment of a new state (Marques et al., 2003). This might mean that despite major restoration efforts,

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1470-160X/$ – see front matter © 2012 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.ecolind.2012.08.022

complete recovery cannot be guaranteed. Several studies (e.g. Borja et al., 2008, 2010) suggest that recovery initiatives require long-term goals and criteria by which to measure recovery. Both of these should include the interactive nature of ecosystems; for example, recovery should not be measured simply by the restoration of habitat or one species, but rather by achieving a fully functioning ecosystem.

The main goal of our study was to assess a temperate estuary (Mondego, Portugal) response to the application of mitigation measures aimed at dealing with eutrophication symptoms in the system. Such measures, which are described in the following section, were implemented after the worsening of the system's condition in the 1990s, triggering changes in hydrologic conditions resulting from the interruption of the upstream communication between two estuarine subsystems. Research focused on the response of *Z. noltii* meadows and associated macrobenthic assemblages, exploring data from four different periods (covering almost 25 years), corresponding to the prevailing conditions of distinct systems. Furthermore, it aimed to provide scientific support for sustainable long-term management solutions.

2. Materials and methods

2.1. Study area

The Mondego River is influenced by a warm temperate climate, drains a 6670 km^2 basin, ending at the city of Figueira da Foz. Its estuary is located on the Atlantic coast of Portugal (40°08′N, 8°50′W) and has a terminal length of about 7 km (Fig. 1). The estuary's terminal part is divided into two arms, northern and southern, separated by a small island (Morraceira Island) formed by the deposition of detrital materials transported by the river (Marques et al., 1993). The Mondego Estuary supports industrial activities, salt extraction, aquaculture farms and is located close to a tourist centre.

The northern arm is deeper, having a depth range of 4–12 m at high tide, depending on the bathymetry, and receives most of the freshwater input (Marques et al., 1993). The southern arm is shallower with a depth range of 2–4 m at high tide, depending on the bathymetry, and is characterised by large areas of intertidal flats exposed at low tide (almost 75% of the total area of the southern arm). *Z. noltii* meadows are located at the southern arm in an area characterised by salinity values of 20–30, total inorganic nitrogen concentrations of 15–30 mg L^{-1}, water-flow velocities reaching a maximum of 1.2–1.4 m s^{-1} in the main channel during low water, and an average sediment organic matter content of $6.2 \pm 1.76\%$ (Patrício et al., 2009).

2.2. The Mondego Estuary's ecological conditions: before and after the mitigation measures

In the 1980s, *Z. noltii* beds occupied a broad area along the southern arm of the Mondego Estuary (Fig. 1), reaching its innermost parts, and occupying approximately 15 ha (Marques et al., 2003). In the early 1990s, anthropogenic activities, combined with specific physical characteristics such as low hydrodynamics, excessive nutrient release (Lillebø et al., 2005), increasing water residence time (Marques et al., 2003) and high salinity, have contributed to a gradual increase in eutrophication, which led to a dramatic decline in area and biomass of the *Z. noltii* bed (Cardoso et al., 2010).

Such a combination resulted from a gradual siltation of the upstream communication between the northern and southern arms of the estuary, which became completely interrupted in 1994/1995 due to the artificial regularisation of the northern arm banks. This interruption caused important changes in the system's hydrodynamic regime. Water circulation in the southern arm became essentially dependent on tides and on the small fresh water discharge from the Pranto River, a tributary, which nevertheless was a considerable nutrient input originating from upstream agricultural areas (Marques et al., 2003).

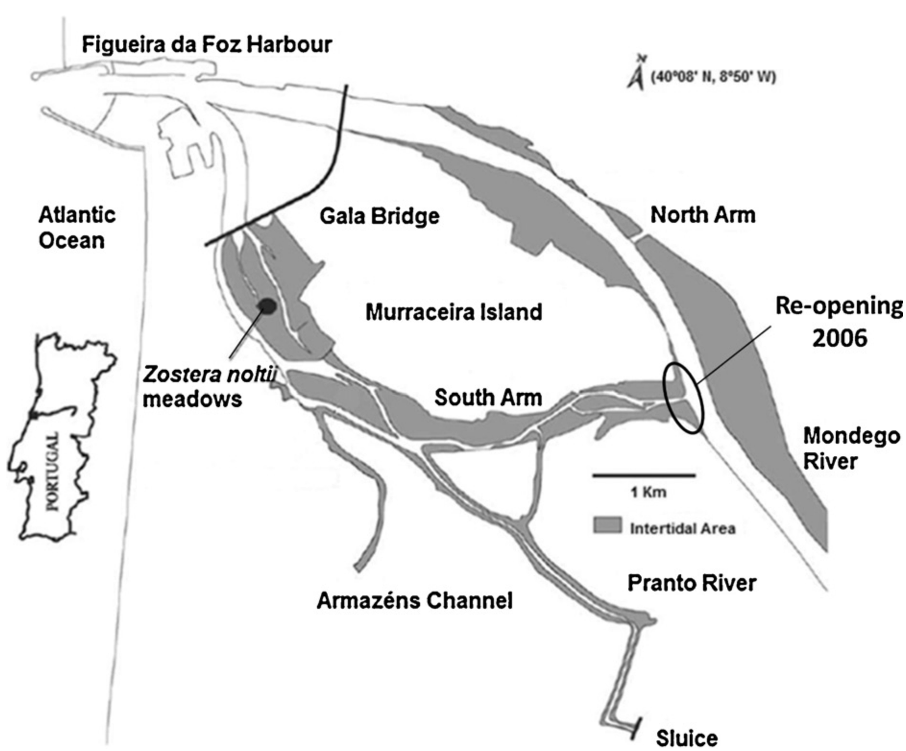

Fig. 1. Location of the Mondego Estuary. Indication of the sampling station at the south arm (*Zostera noltii* meadows) and location of the re-opening site in 2006.