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Recovery trends of *Scrobicularia plana* populations after restoration measures, affected by extreme climate events

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ABSTRACT

The Mondego estuary (Portugal) went through different ecological scenarios over the last decades. An eutrophication process led to a decline in the ecosystem quality. The ensuing restoration plan resulted into a gradual ecological recovery, which was impaired by the occurrence of successive extreme climate events that affected dynamics and productivity of key species. In this study we assess the response of the bivalve *Scrobicularia plana* to the impacts of these events in a recovery scenario, by comparing populations in two different intertidal habitats: a seagrass bed and a sandflat area. As a general tendency, *S. plana*, which was negatively affected by eutrophication, responded positively to restoration. However, the occurrence of extreme climate events seemed to affect recruitment success, biomass and production, impairing the recovery process. In the seagrass bed, *S. plana* maintained a stable and structured population, while in the sandflat area recovery clearly reverted into a decline, mainly concerning biomass and production values. This sequence of multiple stressors might have reduced *S. plana* resilience to further impacts and therefore, understanding the behavior of biological populations following restoration initiatives requires acknowledgement that some changes may not be easily reversible.

1. Introduction

Estuaries are among the Earth's most important ecosystems both ecologically and socio-economically, with an estimated value of ~US$ 4100 ($\times 10^9$) per km^2 per year (Martínez et al., 2007). On the one hand, they are highly productive and provide essential ecological functions and services such as habitat, protection and food for resident and migratory species (Kennish, 2002; Paerl, 2006; Dolbeth et al., 2011). On the other, they are a valuable and widely explored resource for agriculture and fisheries, and for industrial and urban development (Kennish, 2002; Paerl, 2006; Fujii, 2012; Wetz and Yoskowitz, 2013). As such, estuaries are usually subjected to a wide variety of anthropogenic stressors (Paerl, 2006; Doney et al., 2012; Fujii, 2012; Wetz and Yoskowitz, 2013). In addition, ongoing global warming impacts these areas, through extreme weather episodes and the combined effects of these stressors are complex and difficult to predict (Vinebrooke et al., 2004; Doney et al., 2012; Fujii, 2012; Wetz and Yoskowitz, 2013).

Recent climate models forecast an increase on the frequency and severity of extreme weather events (IPCC, 2007, 2013). This may amplify the risk of abrupt and non-linear changes in many ecosystems, which may render them incapable of compensating for the loss of biodiversity, thereby reducing their resilience to environmental change (Vinebrooke et al., 2004; Doney et al., 2012; Fujii, 2012; Wetz and Yoskowitz, 2013). Distinguishing and integrating the effects of natural and anthropogenic stressors is a challenge for understanding and managing coastal biotic resources in order to mitigate a foreseeable "extreme future" (Paerl, 2006; Doney et al., 2012; Fujii, 2012; Wetz and Yoskowitz, 2013).

Seagrass beds are one of the richest and most productive coastal habitats, with a worldwide economic value estimated at US$ 299 ($\times 10^9$) per km^2 per year (Martínez et al., 2007), through a wide variety of ecosystem services. Seagrasses have high primary productivity and operate as the basis of the food web (Waycott et al., 2009; Short et al., 2011). They play an important role in nutrient cycling, sediment stabilization and clearing the water from suspended sediments (Orth et al., 2006; Waycott et al., 2009; Short et al., 2011). Furthermore, seagrasses contribute globally to carbon sequestration and storage (Duarte et al., 2005). These habitats and their valuable services have been threatened by the impacts of

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anthropogenic activities and climatic events (Orth et al., 2006; Waycott et al., 2009; Short et al., 2011), and are declining worldwide.

The Mondego estuary, Portugal, has been well documented over the last decades, during which it went through different ecological scenarios. Eutrophication led to water quality degradation and increased turbidity, seagrass beds decline and a general decay of the overall environmental quality (Cardoso et al., 2005, 2007; Verdelhos et al., 2005; Dolbeth et al., 2007). In order to mitigate eutrophication and recover seagrass beds a management plan was implemented in 1998, which resulted in a gradual ecological recovery (Cardoso et al., 2007, 2010; Lillebø et al., 2005; Verdelhos et al., 2005; Dolbeth et al., 2011). Finally, the occurrence of extreme climate events over the last decade affected the estuarine gradual recovery (Cardoso et al., 2010; Dolbeth et al., 2011; Grilo et al., 2011 and references therein).

The existing seagrass has then become confined to the outer reach of the estuary, due to extensive eutrophication (Lillebø et al., 2005; Verdelhos et al., 2005; Cardoso et al., 2008a,b). Differences in macrofaunal assemblage were registered between seagrass beds and the inner unvegetated sandflats. Seagrass habitat showed higher diversity, productivity, functional organization and sustained longer and more complex food webs (Dolbeth et al., 2007, 2011, 2013, 2014; Baeta et al., 2009; Cardoso et al., 2010). These intertidal areas have great economic importance to local human populations, due to their valuable biological resources, such as the bivalve *Scrobicularia plana*. Bivalves are an essential link between the primary producers and epibenthic consumers, filtering organic matter, purifying the water column and influencing the energy flow on the entire community (Dolbeth et al., 2007, 2011; Dumbauld et al., 2009; Beukema et al., 2010; Parada et al., 2011; Santos et al., 2011). They are also one of the most productive groups of infaunal organisms and represent a major food provisioning service of estuaries (Dumbauld et al., 2009; Beukema et al., 2010; Parada et al., 2011; Santos et al., 2011).

S. plana has been the subject of a previous study in this system, which evaluated the impacts of eutrophication and subsequent restoration effects (Verdelhos et al., 2005). On the one hand, eutrophication seemed to impact *S. plana* abundance, biomass and annual production. On the other, this species responded positively to the mitigation measures, which led to a more structured and stable population, with biomass and production increments. In this study we evaluate the response of the population in the ensuing scenario – an ongoing recovery ecosystem subjected to successive extreme weather events. Therefore, the main goals of this study were: a) to assess the impacts of weather extremes on the dynamics, structure and production of *S. plana*; b) to evaluate the long-term effectiveness of management; c) to compare the response of *S. plana* in two different intertidal existing habitats – seagrass bed vs. sandflat area.

2. Materials and methods

2.1. Study site and ecological scenarios

The Mondego estuary, located on the Atlantic coast of Portugal (40°08′N, 8°50′W) is a small estuary of 8.6 km^2, comprising two arms, North and South, separated by the Murraceira island (Fig. 1). Until 1998, the South arm was almost silted up in the innermost areas, and the river outflow occurred mainly via the North arm. Water circulation was therefore mostly dependent on the tides and on the freshwater input from the Pranto River. The discharge from this tributary is controlled by a sluice and is regulated according to the irrigation needs in rice fields in the Mondego Valley. This freshwater input represented an important source of nutrients into

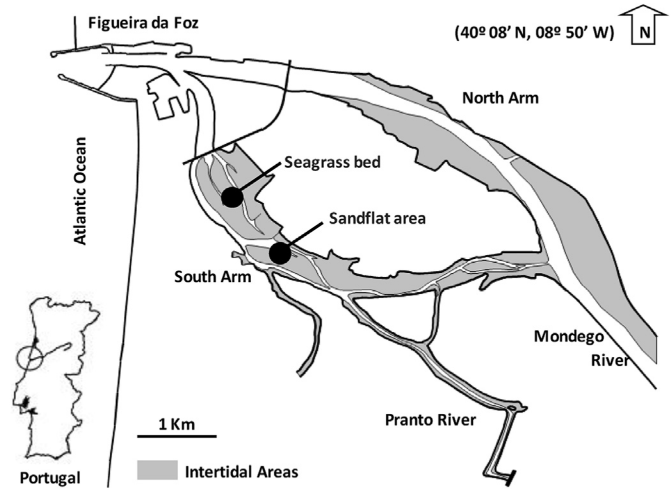

Fig. 1. The Mondego estuary and sampling stations.

the southern arm. Thus, the system has been under environmental stress by eutrophication processes (Lillebø et al., 2005).

Following a restoration intervention in 1998, water circulation and transparency improved, nutrient loading decreased and the eutrophication effects were mitigated, leading to a gradual ecosystem recovery (Cardoso et al., 2007, 2010; Lillebø et al., 2005; Verdelhos et al., 2005; Dolbeth et al., 2011). The implemented measures included: (1) the re-establishment of the South arm riverhead connection, improving the hydraulic regime; (2) most of the nutrient enriched Pranto freshwater is diverted to the Northern arm by another sluice located further upstream, leading to nutrient loading reduction (Lillebø et al., 2005); (3) seagrass bed protection from human disturbance; and (4) public education of the ecological importance of intertidal vegetation for health and related socio-economic activities of the estuary.

Over the last 30 years the climate of Portugal has suffered changes when compared to the patterns for period 1931–1990 (Santos et al., 2002; Miranda et al., 2006): a) the frequency of flood events (precipitation in excess of 50% of the winter mean) has clearly increased; b) the frequency and intensity of dry years has also increased, compared to the period 1940–1970; c) the occurrence of heat waves has become more frequent. In fact, during the study period (from 1999 to 2005) several events occurred: heavy winter precipitation in 2000/01 and 2000/02; heat waves in 2003 and 2005 summers; drought periods in 2002 (dry year), 2004 (extremely dry year) and 2005 (very dry year) (Cardoso et al., 2008b). Therefore, in a post – eutrophication scenario, climatic conditions, particularly extremes of precipitation and temperature, became the major impacts acting on the estuary.

2.2. Sampling, laboratory procedures and climate data

Sampling was carried out monthly from January 1999 to December 2005. Two different areas were sampled (Fig. 1): (1) a seagrass bed, characterized by muddy sediments covered with *Zostera noltii*, higher organic matter content (mean 6.2% ±1.76) and higher water-flow velocity (1.2–1.4 m s^{-1}) (Dolbeth et al., 2011); (2) a sandflat area, composed by sandy-muddy-sediments with lower organic matter content (mean 3.0% ±1.14), characterized by lower water flows (0.8–1.2 m s^{-1}) (Dolbeth et al., 2011), which has not supported rooted macrophytes for decades and has been covered seasonally by green macroalgae.