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Origin here, impact there—The need of integrated management for river basins and coastal areas

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ABSTRACT

This study highlights the effect that estuarine polluted waters may have on adjacent coastal waters and the need of an integrated management of the coastal area. Pollution of land-to-sea water plumes varies spatially and temporally, being difficult, costly and time consuming to determine. However, the reduction in water quality of both estuarine and coastal environments and the consequent degradation of its biological communities is at issue. Chlorophyll-*a* analysis from water and stable nitrogen isotopic analysis (δ^{15}N) from opportunistic macroalgae *Ulva* species were respectively used as proxies to detect phytoplankton proliferation and nitrogen related nutrient fluxes in the water. These analytical techniques were combined with the use of three-dimensional hydrodynamic models, and revealed to constitute reliable early warning instruments, able to identify coastal areas at risk, and supporting an integrated management of coastal and river basin areas. The approach detected synchronized δ^{15}N signal variations along time between estuarine sites (Mondego estuary, Portugal) and nearby adjacent coastal shore sites (NE Atlantic coast). The higher values recorded by macroalgal tissues' δ^{15}N signals, which occurred simultaneously to higher chlorophyll-*a* values, were linked to the anthropogenic contamination of the water, probably related with the Mondego valley land use patterns throughout the year (reflecting the opening of sluices that drain agriculture fields). Modeling scenarios point to a Mondego's influence that is able to reach its adjacent coastal shores in about 7 km from its river mouth. The methodology used here is replicable elsewhere and allowed to track nutrients from the source, inside the estuary, until the final area of impact, where primary producers may use those for growth, and to define vulnerable areas on adjacent coastal zones.

1. Introduction

Detecting the origin, fate and distribution of anthropogenic discharges in the sea is of critical importance for management of coastal zones (Orlandi et al., 2014). River basins, although comparatively smaller than open sea, have significant influence on coastal zones, and management of these two areas should not be considered separately (Gowing et al., 2006). In fact, ecosystems do not have rigid boundaries, on the contrary, ecosystems blend into each other and their components can overlap or interact at different scales. Consequently, integrated ecosystem assessments must identify a spatial scale in the context of the issues and problems under consideration (Levin et al., 2009).

Notably, increasing human-derived pollution has been compromising the water quality of *both* coastal and estuarine environments. The increasing nutrient pollution inputs from rivers to the coastal zone (Barile, 2004; Boyer and Howarth, 2008), such as agricultural and untreated sewage outlets, tend to increase the rate of primary production in both estuarine and coastal waters. There is an excessive proliferation of phytoplankton and/or of fast-growing macroalgae, (e.g., opportunistic macroalgae blooms), which ultimately may degrade seagrass meadows, macroalgae and other benthic communities, altering nitrogen cycling and decreasing water quality (Orlandi et al., 2014; Teichberg et al., 2010). One problem, when trying to identify the spatial footprint of land-

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derived nutrient plumes at the adjacent coastal area, is linked to monitoring difficulties because of their inherent high-frequency of temporal and spatial variability (Fernandes et al., 2012). To overcome this issue, rather than the occasional measurements made directly in the water, one solution may be the use the of the ratio of stable nitrogen isotopes ($\delta^{15}N$) technique in benthic sessile species such as macroalgae, as they integrate the spatial and temporal variability of the dissolved nitrogen in the water (e.g. Costanzo et al., 2001, 2005; Gartner et al., 2002; Savage and Elmgren, 2004), and allow to identify the source of such elements in the system. The technique is able to detect nitrogen assimilated by macroalgae occurred back in time, from times scales of months (Savage and Elmgren, 2004; Deutsch and Voss, 2006; Thornber et al., 2008; Viana and Bode, 2013). Depending on the objective of the study, different species may be more appropriate than others. Particularly for opportunistic macroalgae, the genera *Ulva* (Chlorophyta) may represent the most advantageous option. *Ulva* species constitute a useful biological model to make geographical comparisons, because even represented by a relatively few taxa, these are broadly widespread in both coastal and estuarine systems. Furthermore, these species have proven to be useful as a proxy for locating anthropogenic sources of nitrogen in disturbed coastal and transitional waters (e.g., Barr et al., 2013; Cohen and Fong, 2006; Orlandi et al., 2014; Teichberg et al., 2010).

On the other hand, when the ecological and the analytical processes to quantify them are known, management can gain from the implementation of simulation tools (e.g., MOHID hydrodynamic model). Ecological models have the ability to merge a lot of information and scientific knowledge, and also the potential to produce hypothetical scenarios without needing to wait for its real occurrence. Thus models can provide relevant information of the system that cannot be achieved by other ways and that information can be used in management tools to support decision-makers.

Located at the Portuguese western coast (NE Atlantic ocean, Iberian Peninsula), the Mondego estuary has been profusely studied under many aspects, and a considerable number of studies have reported its eutrophication problems and its consequent blooms of *Ulva* species within estuarine boundaries (Baeta et al., 2009; Marques et al., 2003, 2013; Martins et al., 1999, 2001; Neto et al., 2008). However, studies on the influence of the Mondego estuarine discharges on the quality of adjacent coastal waters are almost absent (see Martins et al., 2007).

Therefore, this work aims to contribute for the development of a more efficient management system of the estuary (Mondego) and its adjacent coastal waters. Specifically, this study should provide answers to questions like: i) it is the estuarine upstream water pollution and its seasonal dynamics an important source of the nutrients assimilated by macroalgae inside the estuary and at adjacent coastal areas? ii) it is possible to relate the dynamics of nutrients discharged from upstream areas in the estuary (e.g., agriculture fields) with the nutrient's cellular content on macroalgae?; and also iii) how adequate is the use the modeling tools to support stakeholders and policy makers on their decisions and mitigation measures?

2. Material and methods

2.1. Study area

The Mondego River drains a 6670 km^2 basin and supports a population of about 885 thousand inhabitants (2006 data; Pinto et al., 2010). Its estuary, located at the NE Atlantic coast of Portugal (40°08′N, 8°50′W) (Fig. 1), is a polyhaline intertidal system with around 1600 ha and 21 km long, influenced by a warm temperate climate. The estuary's terminal part is divided in two arms, north and south, separated by a small alluvial plain (Morraceira Island) of about 6 km long. The north arm is deeper (8–12 m at high tide) and receives most of the freshwater discharged from the river. The south arm is shallower (2–4 m at high tide) and receives the freshwater from a small tributary of the Mondego, the Pranto river. The tidal range varies inside the estuary between 0.35 and 3.3 m, while water residence time goes from one day in winter to five days in summer, at north arm, and three days in winter to nine days in summer, at south arm. The estuary receives agricultural runoff from upstream 15,000 ha of cultivated land (mainly rice fields), it supports a substantial population, industrial activities, saltpans, and aquaculture farms, and is also the place of the commercial and fishing harbors of Figueira da Foz city (Baeta et al., 2009; Kenov et al., 2012; Marques et al., 2013; Martins et al., 1999, 2001; Neto et al., 2008).

Rice fields left resting during winter are drained, plowed and then refilled with water and revolved in mid-Spring (from early April), in order to receive the rice plantation in late April/May. In mid-June fertilizers are spread across the fields. In September, fields are drained to harvest rice, and the nutrient enriched water discharged into the estuary reaches the adjacent coastal areas (http://bordadocampo.com/arroz/cultivo-arroz/; visited in 2015-04-09).

At coastal area, sandy beaches and marine soft bottoms constitute mostly the surrounding habitats. Southward, the nearest rocky shores distance at 26 km (Pedrógão) and 43 km (São Pedro de Moel) from the Mondego Estuary entrance and, apart from these natural substrata, other hard structures are constituted by few breakwaters and jetties created to sustain coastal erosion. Facing north through the Figueira da Foz sandy beach and the Buarcos Bay rocky shore, there are several tiers of intertidal rocky platforms, as distant as 2 km, which constitute a natural rocky substratum for macroalgae to attach on. The tidal regime is semidiurnal, with the coastal largest tidal range occurring during spring tides of 3.5–4 m. The coast is exposed to the prevailing northwest (NW) oceanic swell, which can reach values over 5 m in the winter, when most frequent storms occur from WNW (Boaventura et al., 2002).

2.2. Macroalgae and water sampling

Sampling sites were selected to collect green macroalgae growing inside the estuary (transitional waters, TW) and at adjacent coastal waters (CW), where the signal of inland nutrients' (quantified in tissues) could be different. Seven sites were selected in total: a) at the TW (3), one north arm' site (hereafter TW_N), one south arm' site (hereafter TW_S) and one downstream site located after merging north and south arms (hereafter TW_NS); b) at the CW (4), two sites northwards (CW_N_1 and CW_N_2, respectively at about 2.5 km and 6 km away from river mouth) and two sites southwards (CW_S_1 and CW_S_2, respectively at about 2.5 km and 6 km away from river mouth) (Fig. 1). Both CW northern sites comprise Buarcos Bay' rocky shores. Both CW southern sites comprise artificial structures made of a concrete blocks and natural rock mixture, breakwaters built in the sandy shore perpendicularly to coast line.

Along 1-year period, each site was sampled twice a season during spring low tides (total of eight sampling occasions), in November and December 2013 for the autumn (Aut_1 and Aut_2), in February and March 2014 for winter (Win_1 and Win_2), in May and June 2014 for spring (Spr_1 and Spr_2), and in August and September 2014 for summer (Sum_1 and Sum_2). Two different specimens of the genera *Ulva* spp. were collected on the upper-intertidal zone at each sampling site and moment and labelled separately for analysis (i.e., n = 2) of stable nitrogen isotopic ($\delta^{15}N$) in the tissues (as a probe or proxy to detect the nutrient fluxes in the system).

Simultaneously, during the same sampling occasions, subsurface water samples were collected at each sampling site for Chlorophyll-*a* analysis (as a proxy to detect phytoplankton pro-