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Hydrography of shellfish harvesting areas in the western Cantabrian coast (Rías Altas, NW Iberian Peninsula)

José Daniel Cerdeira-Arias [a,*], Jaime Otero [b], Elena Barceló [c], Guillermo del Río [d], Aitor Freire [e], Manuel García [f], Miguel Ángel Nombela [g], Gloria Portilla [h], Natalia Rodríguez [i], Gabriel Rosón [g], José Antonio Santiago [j], Xosé Antón Álvarez-Salgado [b]

[a] Xefatura Territorial da Consellería do Mar, Avda. Gerardo Harguindey Banet 2, 27863 Celeiro, Viveiro, Lugo, Spain
[b] CSIC Instituto de Investigaciones Marinas, Eduardo Cabello 6, 36208 Vigo, Pontevedra, Spain
[c] Asistencia Técnica á Pesca de Baixura e Marisqueo. Confraría de Pescadores de Celeiro, Rúa do Porto 1, 27863 Viveiro, Lugo, Spain
[d] Asistencia Técnica á Pesca de Baixura e Marisqueo. Confraría de Pescadores de O Barqueiro, Rúa Alfredo Dovale Álvarez s/n, 15337 Porto de O Barqueiro, Mañón, A Coruña, Spain
[e] Asistencia Técnica á Pesca de Baixura e Marisqueo. Confraría de Pescadores de O Vicedo, Peirao 36, 27860 O Vicedo, Lugo, Spain
[f] Asistencia Técnica á Pesca de Baixura e Marisqueo. Confraría de Pescadores de Espasante, Xuncal s/n, 15339 Espasante, Ortigueira, A Coruña, Spain
[g] Universidad de Vigo-Lagoas Marcosende, 36200, Vigo, Spain
[h] Asistencia Técnica á Pesca de Baixura e Marisqueo. Agrupación de Mariscadores San Cosme, Rúa Vilar s/n, 27790 Barreiros, Lugo, Spain
[i] Asistencia Técnica á Pesca de Baixura e Marisqueo. Confraría de Pescadores de Ribadeo, Peirao de Porcillán s/n, 27700 Ribadeo, Lugo, Spain
[j] Asistencia Técnica á Pesca de Baixura e Marisqueo. Confraría de Pescadores Nuestra Señora del Carmen, Avda. Manuel Fraga Iribarne 8-10, 15360 Cariño, A Coruña, Spain

HIGHLIGHTS

- Continental waters dictate the different fertilization patterns among the Rías Altas.
- Extension and geomorphology of the drainage basins explains continental nutrient inputs.
- Continental nutrient inputs control organic matter concentrations in the inner rías.
- Production in the inner rías is extremely P-limited.

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ABSTRACT

Intertidal shellfish banks in estuarine areas are influenced by a wide variety of environmental conditions, including the physical and chemical characteristic of the water that floods the grounds. In this study we carry out a cross-comparison of the hydrographic characteristics and nutrient fertilization patterns of the waters that laps the shellfish grounds of a group of five drowned valleys collectively known as "Rías Altas", located in the western Cantabrian coast (NW Iberian Peninsula). This region is affected by coastal upwelling from June to August resulting in a water exchange between the embayments and the shelf varying between 31.5 and 220.5 $m^3 s^{-1}$. The fresh water discharge followed a seasonal cycle too, with maxima in winter and minima in summer, and long-term average flow rates ranging from 5.9 $m^3 s^{-1}$ to 22.2 $m^3\ s^{-1}$. Significant differences were observed among the five embayments with regard to temperature and salinity and also with inorganic nutrients, chlorophyll *a* and particulate organic matter concentrations in the continental waters.

1. Introduction

Coastal ecosystems are characterized by the overriding interactions between atmospheric, terrestrial, marine, and freshwater environments, which result in a remarkable variability and biological productivity (Burke et al., 2001; Wollast, 1998), and by

* Corresponding author.
E-mail address: jose.daniel.cerdeira.arias@xunta.gal (J.D. Cerdeira-Arias).

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their accessibility. Accordingly, coastal zones have been epicentres of human activity for millennia, and nowadays they are more densely populated than the countries' interior (Neumann et al., 2015). Coastal ecosystems provide a wide assortment of goods and services including the production of fish, shellfish, and seaweed for human consumption (Burke et al., 2001). Continuous exploitation of these living resources by a growing human population has caused numerous disturbances and collapses along its history (Jackson et al., 2001).

Marine shellfish species have been collected for centuries (Ramos et al., 2011) mostly in estuaries and sandy beaches. Overexploitation has resulted in severe depletions in past times though being more widespread during the current industrial period (Lotze et al., 2006). Among the shellfish species, bivalves are of major socioeconomic importance for coastal communities. Despite the small contribution of the four main groups of bivalves (scallops, oysters, mussels and clams) to the global capture production (1.6% in 2015; FAO, 2016), they produce large profits due to their generally high unitary price (Gosling, 2015). Spain is a major bivalve producer from both aquaculture and wild origin (Pawiro, 2010), with the Northwest coast a main area for clams, common cockle or mussel extraction (Labarta et al., 2004; Surís-Regueiro and Santiago, 2014). This region is characterized by the presence of numerous coastal embayments. More specifically, in the western Cantabrian coast (NW Iberian Peninsula) there are a group of five drowned valleys collectively known as "Rías Altas" (Fig. 1), which were flooded during the last Flandrian transgression (Zazo et al., 1994). Currently, the Rías Altas are partially to well-mixed embayments. They consist of an external part, deeper, wider and freely connected to the adjacent continental shelf, with prevailing oceanic characteristics, and an internal part, which is partially enclosed with well-developed beach barriers. Comparatively, the internal part is shallower and narrower, and receives most of the continental runoff, therefore exhibiting prevailing estuarine characteristics (Evans and Prego, 2003). It is in the internal part of these embayments where the intertidal shellfish grounds traditionally exploited by the local shellfish harvesters are located (Arnaiz et al., 2005). The semi-diurnal tidal regime of the area, with a tidal range from 1 to 4 m, covers and uncovers the grounds twice a day (Portnoy and Giblin, 1997; Vranken and Oenema, 1990). Here, bivalves are basically collected on foot in the sandbanks providing a considerable amount of employment and income typically to women, as in other parts of Europe (Frangoudes et al., 2008; Surís-Regueiro and Santiago, 2014).

As for most sedentary invertebrates, the distribution and abundance of bivalve populations are influenced by a wide variety of environmental drivers, including the physical and chemical characteristic of the water that floods the grounds, the substrate type, the food availability or the occurrence of predators. All these drivers act in synergy affecting almost every biological and physiological aspect of the species and shape the population dynamics (e.g. Beukema and Dekker, 2014). This study focuses on the hydrographic characteristics of the waters that flood the grounds of the main species of infaunal bivalves harvested in the study area: grooved carpet shell (*Ruditapes decussatus*), pullet carpet shell (*Venerupis senegalensis*), Japanese carpet shell (*Ruditapes philippinarum*), wedge shell (*Donax trunculus*), common cockle (*Cerastoderma edulis*) and razor shell (*Solen marginatus*).

Our understanding of the hydrography of the Galician Rías Altas is still limited with the first descriptions being very recent (e.g. Ospina-Álvarez et al., 2010, 2014). A comparative study of the five embayments based on simultaneous repeated hydrographic surveys over an annual cycle is still lacking. This kind of study is required to properly compare their hydrography and nutrient fertilization patterns in view of the importance of the environmental conditions for the long-standing maintenance and exploitation

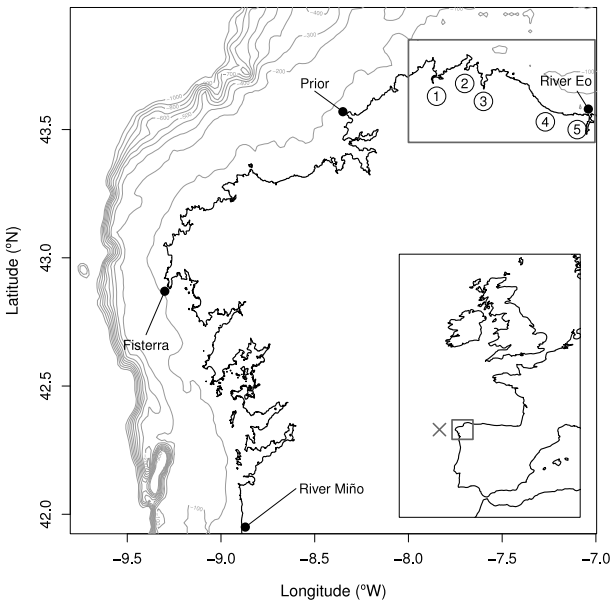

Fig. 1. Map of the study area showing the location of the five Rías Altas (see Table 1 for physical descriptions and Fig. S1 for the detailed location of the sampling sites in each ría). The cross indicates the 43 °N 11 °W cell from where upwelling intensity was calculated.

of the bivalve resources inhabiting the internal part of the Rías Altas. In this regard, the Rías Altas constitute a geographical area with common climatological and oceanographic characteristics that makes them suitable for a comparative study. Additionally, they support a relatively low urban pressure, with a population density of 49.48 ind km^{-2} in 2008, when this study was conducted, which increases during summer holidays. Urban areas represent 13.3% of the surface area and are surrounded by 66.9% of forestland, 18.6% of meadows and 1.2% of farmland in the same year (data taken from the website of the Instituto Galego de Estatística: https://www.ige.eu/). The waters of the Rías Altas do not seem to be particularly affected by human activities, offering a unique opportunity to study nutrients and organic matter inputs in a relatively unpolluted region (Bode et al., 2011a; Álvarez Vázquez et al., 2016). Within this framework, our objective was to characterize and compare the ample shellfish grounds of the five Rías Altas in terms of temperature, salinity, inorganic nutrients, chlorophyll and suspended organic matter in order to assess the differential importance of marine and continental nutrient sources in the fertilization of these embayments.

2. Material and methods

2.1. Study area

The embayments of Ortigueira, O Barqueiro, Viveiro, Foz and Ribadeo are located in the western Cantabrian coast (NW Spain, Fig. 1). According to the classification of Köppen–Geiger, the climate of this area is oceanic, temperate and humid, with an average air temperature of 13.1 °C and an average annual rainfall of 1370 mm (Peel et al., 2007; Hess, 2014). Vigorous mixing of continental and marine waters, ample semidiurnal tides (1–4 m), and coastal winds dictate the hydrography and dynamics of these embayments that, in turn, condition the topography and nutrient fertilization patterns of their extensive bivalve sandbanks.

Production of organic matter for bivalve filter feeders in the Rías Altas ultimately rests on marine phytoplankton. Dinoflagellates, small flagellates and Cryptophyceans are particularly abundant