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Natural forcings on a transformed territory overshoot thresholds of primary productivity in the Guadalquivir estuary

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ABSTRACT

A three year-long quasi continuum sampling dataset on the Guadalquivir estuary water quality was used to assess the role of light availability on its biological production. We found that inorganic nutrients within the estuary are very high (with mean values for inorganic nitrogen and phosphorous of 285 and 2.4 µM respectively) while phytoplankton biomass remains low most of the time (with a mean value of 2.6 mg/m^3). A strong relationship between phytoplankton biomass and water turbidity was found indicating that, indeed, light availability is the major constraint of primary production in this system. Most of the time this limitation of primary production is not associated to enhanced turbidity connected to fresh water inputs. Instead, our data indicate that, independently of freshwater inputs, the photosynthesis is restricted by tidal forcings enhancing turbidity in an estuary that has been highly modified. Our results match with classical theories on the functioning of well-mixed, estuarine ecosystems as well as with recent modeling exercises. We also discuss the potential impacts of this particular characteristic of some estuarine systems for their management and regulatory control.

1. Introduction

Estuaries are typically described as highly productive areas where nutrient inputs from land are transferred into a transitional system between fresh and marine waters. Freshwater inputs usually deliver nutrients into the estuarine zone where losses to deep waters does not happen owing to the shallow nature of these environments (Hagy et al., 2005). Henceforth, enhanced primary production as well as fish spawning and nursery grounds are typical characteristics of estuarine environments (*e.g.*, Mann and Lazier, 2006). Estuarine regions are also preferential settlements for human population and anthropic activities. Human forcings in the form of physical modifications and pollution are, thus, integral parts of such ecosystems (Slotta et al., 1974).

Some of these forcings can drive the ecosystem in a direction that is not necessarily an increment in the productivity. There are instances where high nutrient loads from agriculture and urban inputs do not result into high biological production of the estuarine waters (*e.g.*, Grobbelaar, 1985; Cole and Cloern, 1987). In such cases, another variable is limiting primary production, most typically light availability due to high sediment loads and high turbidity (*e.g.*, Cloern, 1987; Desmit et al., 2005). In these cases, even if the total depth of a mixed water column is very shallow, the high suspended sediment load makes the photic depth even shallower, creating an effective light limitation (*e.g.*, Ruiz et al., 2013) within the estuary. Henceforth, riverine nutrient discharges are not used within the estuary that presents low primary production. A consequence of this dynamics is the heavy influence these estuaries exert on the biogeochemical fluxes in the marine ecosystems near their mouths (Liu and de Swart, 2015; Santos et al., 2008) by triggering new production (Dagg et al., 2008; Middelburg and Nieuwenhuize, 2000) as well as shaping and modulating the food-web dynamics and structure (Garnier et al., 2006; Macías et al., 2010).

This seems to be the case of the Guadalquivir River estuary (SW Iberian Peninsula). The estuary extends 110 km inland from its mouth at Sanlúcar de Barrameda to the Alcalá del Río dam with an average depth of 7.1 m. Human modifications of the present estuary have been severe, with a significant reduction of its original marshes and a shortening in its original length to serve agricultural and navigational sectors respectively (Ruiz et al., 2015). The main input of freshwater to the estuary (~ 80%) is through Alcalá del Río dam, which is the last of a large network of reservoirs that tightly regulate the drainage basin of the Guadalquivir River (Diez-Minguito et al., 2012, 2014). Discharges from this dam are typically low and keep very low flushing rates of the estuary; only under sporadic heavy rains, usually in autumn and winter, discharges and flushing rates are high (Ruiz et al., 2015). In its present condition, inorganic nutrients concentrations are above tens or hundreds of µM for components like nitrogen (Flecha et al., 2015; Ruiz

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et al., 2015) but still no significant biological production takes place within the estuary (Ruiz et al., 2013). Henceforth, most of the nutrients go unused throughout the estuary and reach the coastal zone at the Gulf of Cádiz, where typically high phytoplankton biomass (usually above 5 mg/L of chlorophyll) is present at the inner shelf nearby the estuary (see Fig. 14 in Navarro and Ruiz, 2006 or Fig. 8 Prieto et al., 2009) and many fish species spawn (Catalán et al., 2006; Ruiz et al., 2006, 2009).

In this manuscript, we use a long record of continuous measures from 2008 to 2010 to conclude that these features are the consequences of natural forcing over a highly modified territory, in a combination that creates an estuary which is rich in nutrients but unproductive most of the time. We also examine the potential consequences driven by further human intervention planed in the estuary over the estuary itself and the nearby inner shelf.

2. Material and methods

In 2007, an interdisciplinary research program was established to gain a better understanding of the physical and biological processes governing the Guadalquivir estuary ecosystem. As part of this project, a comprehensive monitoring program was established within the estuary and river mouth, including a real-time monitoring network and monthly cruises.

Monthly samplings were carried out at 12 stations between November 2007 and August 2009 (Fig. 1). From station 1 positioned at the river mouth, stations 2–12 were located at 6, 16, 22, 25, 34, 46, 55, 63, 71, 78, and 82 km upstream, respectively. At each station, conductivity, temperature, and depth (CTD), salinity, and turbidity profiles were obtained with a Sea-Bird SBE 19 plus equipped with a Turbidimeter Cyclops-7 sensor (Turner Designs), which was followed by collection of water samples at 1-m depth with a Van Dorn bottle sampler for the determination of the following biogeochemical variables: total suspended solids (TSS), chlorophyll (Chla), and inorganic nutrients (NH4 +, NO2 − , NO3 − , PO4 − 3, and Si). Strong mixing is typical in the estuary so that these samples are representative of values in most of the water column. A detailed description of the analytical methods can be found in Flecha et al. (2015).

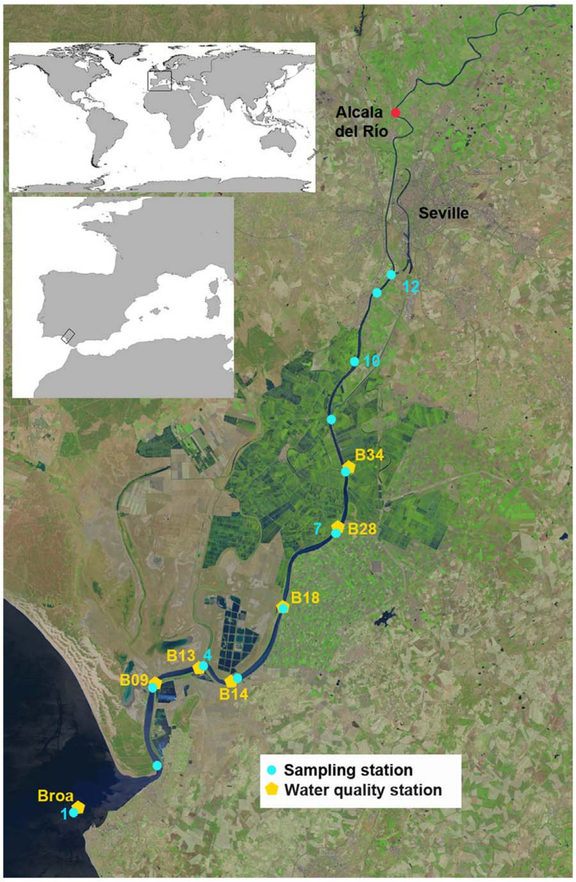

Fig. 1. Location of the Guadalquivir estuary, the sampling stations and the water quality stations (sampling buoys).

The core of the monitoring network was comprised of a real-time remote monitoring (RTRM) system that provided online, high temporal resolution of meteorological, hydrographic and water quality information. The locations of the water quality station (7 devices) is displayed in Fig. 1. The RTRM network began functioning in February 2008 until October 2010. Each water quality station is composed by several modules (communications, hydraulic and measure module). This measure module is composed by a CTD with auxiliary sensors as dissolved oxygen, fluorescence and turbidity sensors. A detailed description of the design can be found in Gutierrez et al. (2009) and Navarro et al. (2012). Due to the high turbidity found in the estuary, the turbidity sensors located in water quality stations were calibrated using the protocol described in Navarro et al. (2011). High turbidity also prevents the use of in vivo fluorescence as a proxy for chlorophyll since noisy records are obtained under high TSS values (Navarro et al., 2011).

Photic depth (Z_{op}), defined as the depth where the photosynthetically active radiation (PAR), represents 1% of the surface radiation as following the Lambert-Beer law (Kirk, 1994):

$$Z_{op} = \mathrm{Ln}(0.01)/K \tag{1}$$

where K represent the diffuse attenuation coefficient. This is calculated by the expression:

$$K = K_w + K_1[\mathrm{Chla}] + K_2[\mathrm{TSS}] + K_3[\mathrm{DON}] \tag{2}$$

where K_w is light attenuation due to sea water, K_1 is absorption by chlorophyll (shelf-shading), K_2 is light extinction due to TSS and K_3 due to DON (dissolved organic nitrogen). The values of K_w and K_1 ($0.26\ m^{-1}$ and $0.017\ m^{-1}$ (μg Cla $L^{-1})^{-1}$, respectively) were taken from the Chesapeake Bay (Gallegos, 2001), K_2 ($0.074\ m^{-1}$ (mmol N $m^{-3})^{-1}$) was computed by using the equations proposed by Branco and Kremer (2005), and K_3 ($0.63\ m^{-1}$ (mmol N $m^{-3})^{-1}$) following Apple and del Giorgio (2007) by using a typical concentration of 50 μM of DON in the estuary (Flecha et al., 2015). TSS for water quality stations was calculated using the relationship between turbidity and TSS previously found by Navarro et al. (2011).

3. Results

Inorganic nutrients concentrations are very high within the estuary, with a mean inorganic nitrogen value of ~ 285 μM (NO2 + NO3) and a mean phosphate value of ~ 2.4 μM (Fig. 2A and B). Mean molar N:P ratio in the estuary is 118.8; thus, indicating a N:P ratio above the Redfield ratio, as expected from a freshwater system (Paerl, 2009). However, and in spite of the large amounts of inorganic nutrients, chlorophyll values are relatively low with a mean value of just 2.6 mg/m^3 and only a handful of samples showing values larger than 10 mg/m^3 (Fig. 2C). At the same time, total suspended solids in the estuary waters are very high, with a mean value of ~ 609 mg/L and a maximum reaching over 5000 mg/L (Fig. 2D).

From the data shown above, it was suspected that light availability is more important than nutrient supply as a factor limiting primary production. To further explore this possibility, the scatter plot of turbidity (as a proxy of suspended solid) and chlorophyll are shown in Fig. 3A for the seven water quality stations (sampling buoys) shown in Fig. 1. It can be seen that the chlorophyll concentration seems to be partially coupled with the turbidity levels; only when turbidity is low there are higher levels of chlorophyll (but typically below 5–6 mg/m^3), and at high turbidity chlorophyll concentration drops below 1 mg/m^3.

Fig. 3B shows the relationship of the ratio between the photic depth