Available online at www.sciencedirect.com
ScienceDirect
Estuarine, Coastal and Shelf Science 76 (2008) 642–656
ESTUARINE COASTAL AND SHELF SCIENCE
www.elsevier.com/locate/ecss

Variability of nutrients and phytoplankton primary production in a shallow macrotidal coastal ecosystem (Arcachon Bay, France)

Corine Glé [a,*], Yolanda Del Amo [a], Benoît Sautour [a], Pierre Laborde [b], Pierre Chardy [a]

[a] CNRS, UMR 5805-EPOC, ECOBIOC, Université Bordeaux 1, Station Marine d'Arcachon, 2 rue du Professeur Jolyet, 33120 Arcachon, France
[b] CNRS, UMR 5805-EPOC, ECOBIOC, Université Bordeaux 1, Avenue des Facultés, 33405 Talence Cedex, France

Received 13 April 2007; accepted 27 July 2007
Available online 24 August 2007

Abstract

Seasonal and spatial variations of phytoplankton primary production were studied using a high frequency sampling strategy in the external (ENW) and internal (INW) part of Arcachon Bay, during 2002 and 2003. In order to better assess the availability of nutrients and their relationship with phytoplankton primary production, nutrient variability was studied in relation to environmental conditions and phytoplankton production. During winter, when primary production rates were the lowest, nutrient concentrations were maximal but did not show excessive levels compared to highly urbanised areas. Seasonal and spatial variations of nutrient concentrations (especially DIN-nitrate + nitrite + ammonium-and Si) were largely influenced by Leyre River loads coupled with high tidal exchange with the Atlantic Ocean creating a nutrient gradient between the INW and ENW. By February, diatom growth leads to an early severe nutrient depletion in the entire bay. Examination of nutrient ratios showed that the potential limiting nutrient during spring was P in 2003, and Si in 2002. During summer 2003, N and Si concentrations reached their lowest values, and nutrient ratios revealed a N-deficient environment, more pronounced in the INW. The high Si:N ratios during this period might be explained by (1) important N-uptake by all autotroph communities and (2) benthic-pelagic coupling with high Si regeneration. This study shows that nutrient levels in Arcachon Bay seem to play an important role in the control of phytoplankton primary production rates during the productive period and explain their spatial, seasonal and inter-annual variability. Our estimates of annual integrated phytoplankton primary production (103 g C m^{-2} y^{-1}) place this bay within the low to moderate phytoplankton primary production systems.

Keywords: phytoplankton primary production; nutrient; nutrient ratios; macrotidal lagoon; France; Arcachon Bay

1. Introduction

In coastal ecosystems, net phytoplankton primary production is regulated by the interaction of several abiotic (nutrient fluxes, light availability and physical variability) and biotic factors (grazing pressure and competition). In such systems, nutrients are highly influenced by anthropogenic activity and climatic variability via coastal upwelling events or continental inputs. Indeed, the functioning of coastal ecosystems are closely linked to that of freshwater systems, upstream of coastal systems (Howarth and Marino, 2006) as the nutrient concentrations and ratios of waters discharged to coastal areas largely depend on agricultural and industrial activities, but also on freshwater biological activity upstream to coastal areas as well as on the nature of the sediment in the drainage basin. Over the last decades, the increase of anthropogenic inputs of nitrogen and phosphorus have lead to severe eutrophication problems, inducing an enhancement of phytoplankton primary production in many coastal areas (Fisher et al., 1995; Lohrenz et al., 1997; Kinney and Roman, 1998; Cloern, 2001). In addition to increasing primary production, the alteration of these nutrient ratios, such as

* Corresponding author.
E-mail addresses: c.gle@epoc.u-bordeaux1.fr (C. Glé), y.delamo@epoc.u-bordeaux1.fr (Y. Del Amo).

0272-7714/$ - see front matter
doi:10.1016/j.ecss.2007.07.043

the decline of Si:N ratios, has inevitable effects on the taxonomic composition of phytoplankton communities. For instance, anthropogenic fertilisation tends to diminish the relative Si availability when compared to N and P, resulting in a decline of diatom proportion in the phytoplankton communities (Conley and Malone, 1992; Justic et al., 1995; Cugier et al., 2005), affecting trophic pathways and energy transfer efficiency (Turner et al., 1998).

However, it is know recognised that there is large differences among coastal ecosystem in the magnitude and character of responses of phytoplankton biomass or primary production to nutrient enrichments (Cloern, 2001). In part, this is due to the complex interaction of nutrient limitation and light limitation in coastal systems (Cloern, 1999), as well as to the influence of residence time on community structure and ecological interactions, which will condition the export of nutrients and phytoplankton biomass (Lucas et al., 1999; Cloern, 2001). Further, in some coastal ecosystems, the elevated abundance of suspension feeders reduces phytoplankton accumulation, even in the presence of increasing nutrient levels (Cloern, 2001). Therefore, due to the complex interaction of the factors that determine the sensitivity of coastal ecosystems to nutrients, a linear response of eutrophication to nutrient loading does not appear to apply in such systems (Howarth and Marino, 2006). Thus, to develop appropriate management strategies, it appears necessary to fully understand the ecosystem functioning and first of all the relationships existing between phytoplankton primary production and nutrient patterns.

The objectives of this study were to define the nutrient variability of the Arcachon Bay in relation to major sources and sinks and to describe aspects of phytoplankton primary production relevant to nutrient status. Arcachon Bay is a shallow macrotidal lagoon colonised by the macrophyte *Zostera noltii*, which supports great biological production of the oyster *Crassostrea gigas* (estimated at 35,000 tons per year). This bay does not suffer from an excess of nutrients and eutrophication signs have not yet been seen (i.e. high macroalgae biomass compared to phanerogams biomass, stability of macrozoobenthic assemblages; Castel et al., 1996; Bachelet et al., 2000; De Wit et al., 2005). However, the increase of anthropogenic pressure (biological exploitation, urban development, tourism) and the occurrence, during the last few years, of increasing toxic events in the bay (mainly blooms of the dinoflagellate *Dinophysis* and the unexplained toxicity of bivalve molluscs, www.ifremer.fr) makes this bay a sensitive area. Other pressures, such as climate forcing, have been shown to aid in the early start of phytoplankton production within the year (i.e. February–March; Glé et al., in press) leading to subsequent phytoplankton blooms whose intensity and composition could be nutrient-controlled as early as the spring. The specific objective of this study is to characterise the nutrient variability in Arcachon Bay during an entire annual cycle in relation to environmental and biological parameters. In this paper, we address the following questions: what factors explain the spatial and temporal variability of nutrients in Arcachon Bay and more precisely, what are the consequences of winter blooms on spring and summer nutrient variability? The seasonal and spatial variability of phytoplankton primary production is here discussed in relation to nutrient variability and the elemental nutrient ratios of the water body have been used to evidence potential limitation of phytoplankton primary production (Beardall et al., 2001). Finally, we give a first estimation of the annual phytoplankton production in Arcachon Bay.

2. Materials and methods

2.1. Study area

Arcachon Bay (44°40′ N, 01°10′ W) is a macrotidal coastal lagoon of 174 km^2 on the southwest coast of France (Fig. 1), connected to the Bay of Biscay (Atlantic Ocean) by a narrow channel (2–3 km wide). In the inner lagoon (156 km^2), tidal channels (41 km^2) penetrate into large intertidal areas (115 km^2). These tidal flats (60%, i.e. 70 km^2) are mainly colonised by *Zostera noltii* meadows. This shallow lagoon is characterised by semi-diurnal tides (tidal range 0.9 to 4.9 m depending on site and tide coefficient) enabling important water exchanges with the adjacent oceanic waters. These are estimated at 384×10^6 m^3 for an average spring tide and 264×10^6 m^3 for a neap tide. Continental inputs participate to a lesser degree in the distribution of water masses. Indeed, annual freshwater inputs average 1.25×10^6 m^3 with a major volume (4/5) coming from the Leyre estuary in the southeastern part of the bay. The remaining 1/5 is provided by secondary canals, e.g. the Lège Canal, at the northeast area.

The influence of both oceanic inputs derived from the Bay of Biscay and freshwater inputs coupled with moderate water renewal rates lead to two clearly distinct geographical areas in the bay according to hydrological parameters (Robert et al., 1987): (1) the external neritic waters, directly influenced by the oceanic waters; (2) the inner neritic waters, particularly influenced by continental inputs. The bay is therefore a heterogeneous ecosystem with regard to both its hydrological and geographical characteristics.

2.2. Sampling strategy

The first sampling location was located in the external waters (ENW; station at position 'Bouée 13'; 44°38′ N, 1°14′ W; Fig. 1), in the southwestern part of the bay and is characterised by a flushing time of 4–5 days (Plus, pers. commun.). This station, situated in a 17 m-deep channel, is considered to be representative of the Bay of Biscay waters entering the bay at high tide. The second sampling site was located in the internal waters (INW; station 'Comprian'; 44°40′ N, 1°05′ W; Fig. 1), near continental inputs (i.e. river Leyre), and is characterised by a flushing time of 13–20 days (Plus, pers. commun.). This station, located in the southeastern channel 7 m in depth, is representative of the internal neritic waters of Arcachon Bay.

Sampling was performed at these two stations from 5 December 2002 to 29 January 2004, twice weekly. Also during 2002, the ENW were sampled from January to May. All sampling were performed in surface waters (in the first meter of