Journal of Sea Research 120 (2017) 1–12

Contents lists available at ScienceDirect

Journal of Sea Research

journal homepage: www.elsevier.com/locate/seares

Enhanced primary production in summer and winter-spring seasons in a populated NW Mediterranean coastal ecosystem

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ARTICLE INFO

Article history:
Received 13 April 2016
Received in revised form 21 October 2016
Accepted 30 October 2016
Available online 14 November 2016

Keywords:
Phytoplankton primary production
Winter-spring bloom
Coastal DCM
Oceanic DCM
Anthropogenic pressure
NW Mediterranean coastal ecosystem

ABSTRACT

Populated coastal ecosystems in the NW Mediterranean present three main characteristics that distinguish them from the open water ecosystem: a sea-land interaction, with freshwater influence from river mouths; a shallow seabed, which facilitates the interaction between the euphotic water column and the sediments; and high anthropogenic pressure, due to submarine sewage discharges. As a result, relatively high nutrient concentrations are measured in these ecosystems, with ammonia being an important fraction. These characteristics entail a different scenario from the open water ecosystem.

Here, we present the distribution of phytoplankton primary production in the Barcelona coastal waters during summer and winter-spring seasons, by means of photosynthesis-irradiance experiments using the ^{14}C technique. In winter-spring, stratification of the water column may begin earlier than in open water due to freshwater inputs. Therefore, with the water-column slightly stratified, chlorophyll-*a* and primary production become localised in the surface layers, due to the lower daily irradiance during this season. In these conditions, Total Primary Production (TPP) values measured ranged between 0.27 and 14.52 mgC m^{-3} h^{-1}. As spring progresses and the stratification develops, surface waters tend to become nutrient depleted and nutrients are mainly localised in bottom waters between the thermocline and the seafloor. Under these conditions, high chlorophyll layers develop near the bottom. With the exception of their nutrient enrichment, these structures, referred to as coastal deep chlorophyll maxima, are comparable to the oceanic deep chlorophyll maxima in temperate oligotrophic seas. The nutrient enrichment is the result of the sediment resuspension from the seabed and the presence of sewage water discharged from the submarine outfall. These structures are highly productive (*ca.* 60% of water column primary production), comparable to the winter-spring bloom, and are sustained throughout the stratified season. In this period, TPP values measured ranged between 0.25 and 9.02 mgC m^{-3} h^{-1}.

The primary productivity structures studied play a leading role in processing nutrients from terrestrial sources, thus providing an important ecosystem service.

1. Introduction

Open waters in the North Western Mediterranean Sea are characterised by a seasonal cycle alternating mixing and stratification periods. The mixing period entails an input of deep waters, rich in remineralised nutrients, into the euphotic layer. The stratification period is marked by the development of a thermocline, which limits the upward movement of these deep waters into the euphotic layer. This pattern of water turnover imposes a strong seasonality on primary production with a large phytoplankton bloom in winter-spring and the presence of a Deep Chlorophyll Maximum (DCM) from spring to autumn.

This scenario has been widely studied by scientists for decades in order to better understand the importance of the role that this seasonal cycle plays in the productivity of the pelagic ecosystem (Bosc et al., 2004; Estrada, 1985; Lopez-Sandoval et al., 2011; Marty and Chiavérini, 2002; Morán and Estrada, 2005; Pedrós-Alió et al., 1999 among others). Nevertheless, in recent years only a few studies have measured the primary production in NW Mediterranean coastal ecosystems (Alonso-Sáez et al., 2008; González et al., 2008), and to date, no other reported study has focused on how primary production is distributed in the ecosystem.

Coastal zones, at the boundary of continental land and the sea show a high level of heterogeneity at the biological and environmental levels, particularly in very populated regions, such as the Barcelona area (Romero et al., 2014). The many interactions among the different factors that are involved in coastal ecosystem organization and ecological performance are more difficult to identify and to quantify than in open oceanic waters (Duarte et al., 1999; Mann, 2000; Pedrós-Alió et al., 1999). However, because many terrestrial fluxes must cross the same coastal boundary, a general outcome of this complexity is chronic

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http://dx.doi.org/10.1016/j.seares.2016.10.009
1385-1101/

nutrient enrichment that gives coastal zones a mesotrophic-eutrophic status (Mann, 2000). The main sources of terrestrial inputs are river runoff, submarine sewage outfalls and temporary run-off due to storms. Furthermore, the presence of the shallow seabed restricts vertical losses of materials that are, at least in part, reworked in the same coastal waters until they are eventually transported to deeper regions over the continental shelf and beyond. The lack of energetic tidal currents in this Western Mediterranean area (tide amplitude is <20 cm) leaves the mechanical fueling of the water-sediment interaction to wind-induced current fluctuations, storms and internal wave stirring. The low-energy environment, particularly in late spring and summer, makes the building of ecologically productive structures fuelled by this relatively soft stirring possible. These biological structures and mechanisms are important for the processing of material and energy entering the system (Margalef, 1998).

Between 2003 and 2011, a series of CTD casts on a fixed grid of *ca.* 50 stations along the >200 km long Catalan coast were collected, within a monitoring programme for the "Agència Catalana de l'Aigua" (ACA, Catalan Water Agency). The data revealed annual winter-spring phytoplankton blooms. However, during the stratification period (late spring and summer), the presence of a chlorophyll-*a* (Chl-*a*) rich water layer near the bottom of the water column, between 20 and 60 m in depth was often observed. Due to the coastal characteristics described above, the dynamics of these Chl-*a* structures could differ from the DCM dynamics of the open waters.

This paper presents an investigation of the primary production in Barcelona coastal waters, a populated NW Mediterranean coastal ecosystem, in two contrasting periods: winter-spring and summer, and their relation with coastal ecosystem characteristics. In addition, the results obtained are compared with those of the open-waters of the NW Mediterranean Sea. Photosynthesis-irradiance (P-E) experiments applying the Steemann-Nielsen (1952) technique of radiocarbon (^{14}C) were used.

2. Material and methods

2.1. Study area and water sampling

The study area was located in the Barcelona coastal waters (NW Mediterranean, Fig. 1). The general mesoscale coastal circulation has a NE to SW residual current along the coast, with frequent reversals. At the lower end of the mesoscale circulation (1–10 km) the variability is extremely high, although it is not very energetic, especially in summer when the wind regime is characterised by the daily alternation of land and sea breezes, with sporadic summer storms (Flos et al., 1997; Pascual and Flos, 1984).

The Besòs River mouth is situated in the north of the study area. It has a flash flood regime and a mean water discharge of 6.8 $m^3\ s^{-1}$ (Grifoll et al., 2014). In a flash flood event (lasting from hours to a few days after storms) can reach >20 times the mean water discharge. These energetic episodes mainly occur during spring and autumn (Grifoll et al., 2014). Our sampling cruises were conducted in normal conditions. Besòs River discharge during summer cruises had values lower than 3 $m^3\ s^{-1}$ and during winter-spring cruises lower than 6 $m^3\ s^{-1}$ (ACA, 2000). A submarine sewage outfall is also situated in the north of the study area. It discharges the treated waters from the Besòs waste-water treatment plant (biological treatment of a catchment area comprising 2.8 million inhabitants). Its mean water flow is 4.05 $m^3\ s^{-1}$ and average nutrient content is: $NH_4^+ = 2068 \pm 924$ µM; and $PO_4^{3-} = 87 \pm 16$ µM (NH_4^+:PO_4^{3-} ratio: 23.7 ± 11.9, ACA, 2000). Furthermore, four Combined Sewer Outflows (CSO) are present in the coastal area. During extreme rainfall events, they discharge a mix of rainfall and sewage water collected by Barcelona's sewer system into the sea. However, no episode of CSO water discharge was registered during sampling days (Clavegueram de Barcelona, S.A.; CLABSA).

Eight sampling trips were taken on board the R/V Caribdis (8.5 m long, University of Barcelona): four in the summer of 2009 (JUL13, JUL30, AUG06 and AUG12) and four in the winter-spring of 2010 (MAR11, MAR23, MAR26 and APR13, Table 1).

On all cruises the conditions were calm and sunny, except for the APR13 cruise, during which cloud cover developed by the end of the P-E experiments.

On each trip, one transect (about 4 km long and between depths of 20 and 60 m) along a coastal-offshore gradient of four to six CTD casts obtained with a Seabird SBE25 CTD was performed (Table 1). Vertical profiles of temperature, conductivity, Chl-*a* fluorescence, turbidity, transmittance, oxygen and Photosynthetic Active Radiation (PAR) were obtained at each station. Subsequently, the main features of the water column were sampled at stations and sampling depths selected according to the Chl-*a* fluorescence profiles, taking care to sample at the top, in the middle and below the maximum Chl-*a* layer. Dissolved inorganic nutrients, Chl-*a*, phytoplankton and P-E experiments were

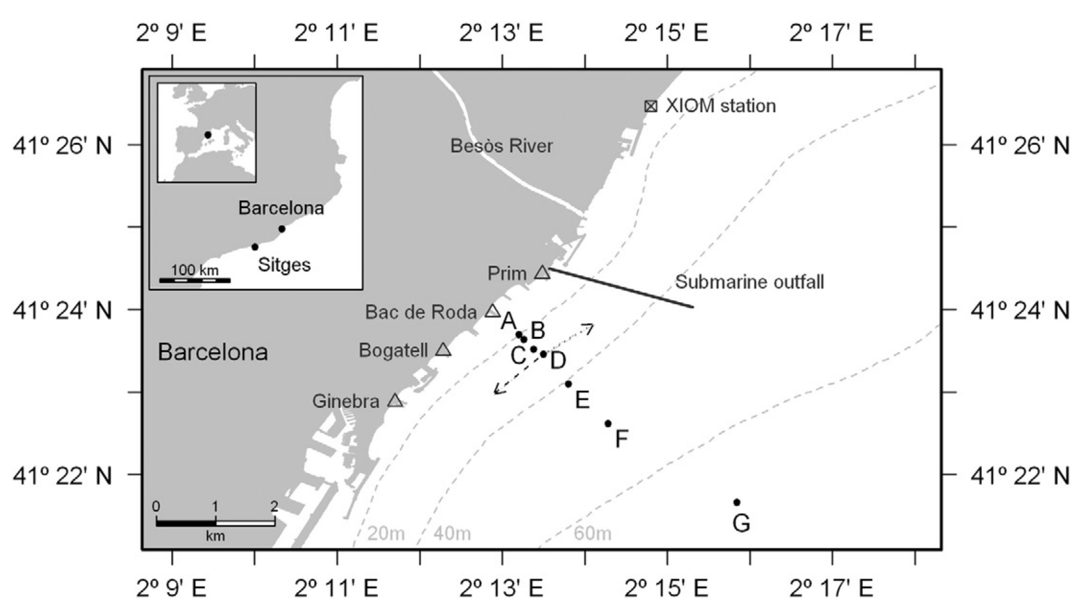

Fig. 1. Map of the Barcelona coastal waters showing the position of the stations sampled (Table 1), the XIOM meteorological station, the Besòs River mouth, the combined sewer outflows and the submarine outfall. Dashed and dotted lines show the direction of the current at 12 and 28 m depth, respectively, at station D during the AUG06 sampling cruise.