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Structural and functional response of phytoplankton to reduced river inputs and anomalous physical-chemical conditions in the Gulf of Trieste (northern Adriatic Sea)

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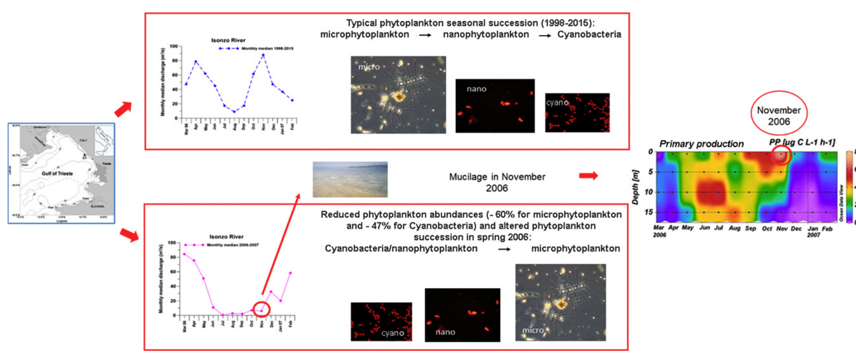
HIGHLIGHTS

- Phytoplankton structure and function were related to anomalous seawater conditions.
- Microphytoplankton and cyanobacteria densities decreased (up to 60% and 47%).
- The late spring diatom bloom was not reflected in high photosynthetic rates.
- An unusually high primary production in autumn was concomitant to a mucilage event.
- The typical seasonal succession of pelagic phototrophs was altered.

GRAPHICAL ABSTRACT



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ABSTRACT

We studied the influence of anomalous meteorological and hydrological conditions that occurred in the Gulf of Trieste from March 2006 to February 2007 on phytoplankton structure and function. We computed monthly mean (or median) air temperature, total precipitation, wind speed, river discharge, seawater temperature, salinity, photosynthetic available radiation (PAR), cyanobacteria, nano- and microphytoplankton abundances during the study year and compared them to climatological (1999–2014 for PAR; 1999–2007 for nanophytoplankton; 1998–2015 for the other variables) mean/median data. We then related the cyanobacteria (0.2–2 μm), nano- (2–20 μm) and microphytoplankton (20–200 μm) of the study year to inorganic nutrient concentrations. Median river inputs in October and November were 9- and 15-fold lower, respectively, than the time series medians, with consequent high salinity from May to November (up to +1.26 compared to the climatological data). Monthly mean seawater temperatures were lower than the climatological values (−2.95 °C at the surface) from March to August 2006 and higher (+2.15 °C at the surface) from September to February 2007. Reductions in freshwater input and nutrient depletion were likely responsible for a decrease in microphytoplankton (median annual abundance over 60% lower than the climatologic median) and cyanobacteria (up to 47% lower than the climatology). Significant seasonal differences in cyanobacteria and microphytoplankton abundances ($R_{ANOSIM} = 0.52$; $p < 0.05$), as well as in seawater temperature and salinity ($R_{ANOSIM} = 0.73$; $p < 0.05$) between the study period and the climatology were highlighted. The late spring diatom bloom was not reflected in high photosynthetic rates whereas an unusually high primary production was estimated in November (7.11 ± 1.01 μgC L^{-1} h^{-1}), when a mucilage event occurred due to very stable atmospheric

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and oceanographic conditions. The typical seasonal succession of pelagic phototrophs (micro-, nanophytoplankton and cyanobacteria) was altered since an exceptional cyanobacteria bloom first developed in April, followed by a delayed diatom bloom in May.

1. Introduction

Primary production measurement in marine waters is one of the most important tools to understand ecosystem functioning and the transport of inorganic/organic matter through the food web (Williams et al., 2002). Overall, shallow coastal photic systems are among the most productive on the planet (Odum, 1983). However, in oligotrophic systems like the Mediterranean Sea, coastal production largely depends on rivers and freshwater-borne nutrient inputs (Mozetič et al., 2012 and references therein), and internal recycling of nutrients particularly from sediments under seasonally elevated temperatures (Kennish et al., 2014). In smaller basins and gulfs, the timing and magnitude of the biological responses depend on a combination of different factors (Malej et al., 1995). Aside from nutrients, coastal processes are largely influenced by physical factors such as light, temperature, stratification, winds and local currents that are key parameters regulating pelagic processes. Variations in precipitation and evaporation, together with wind forcing and density gradients greatly affect the ecosystem primary production. Short-term, acute meteorological perturbations, including heat waves and droughts, cause extreme fluxes in hydrodynamics and biotic responses in coastal systems (Kennish et al., 2014). Because of their small size, rapid nutrient uptake and growth rates, phytoplankton are particularly responsive to variations in environmental conditions. Deviations from typical phytoplankton abundances and compositional patterns through time can thus be used to detect the occurrence of ecological changes in shallow coastal photic systems (Valdes-Weaver et al., 2006).

The Gulf of Trieste, located in the northern part of the Adriatic Sea, is a semi-enclosed basin with a maximum depth of 25 m, where the response to any kind of environmental variation can be rapid and thus easier to detect. In this area, the carbon cycle is strongly affected by freshwater input, mainly from Isonzo River (Cozzi et al., 2012), and atmospheric forcing, mostly on account of the strong ENE Bora wind (Celio et al., 2006). A major disturbance event in the northern Adriatic Sea is the appearance of mucous aggregates; this has been recorded often in the past centuries (Precali et al., 2005 and references therein) and severely affects ecosystem functioning. Phytoplankton development, in terms of microalgal blooms, community succession (Malej et al., 1995; Cabrini et al., 2012; Mozetič et al., 2012) and photosynthetic activity (Fonda Umani et al., 2004, 2007; Ingrosso et al., 2016) are highly dependent on nutrient availability originating from freshwater discharges, and therefore respond to seasonal and interannual variations of riverine fluxes. On a seasonal basis, the pelagic ecosystem of the gulf shifts from a more eutrophic condition, typical of the late winter-spring season, when sufficient inorganic nutrients are available to sustain the main diatom bloom of the year, to an oligotrophic condition in summer-autumn dominated by pico-sized photoautotrophs (Fonda Umani et al., 2012). Therefore, the typical phytoplankton seasonal succession displays the following pattern: a late winter-early spring diatom bloom, followed by a nanophytoplankton bloom in late spring-early summer, a cyanobacteria peak in late summer-early autumn and a second relative diatom maximum, usually in November. From a long term perspective, phytoplankton density in the Gulf of Trieste was quite high from 1986 until the end of 1992. Thereafter, phytoplankton abundance declined to reach minimum values in the mid-1990s as a result of both climatic changes and environmental protection measures that progressively lowered the trophic state of the system: from a eutrophic, nutrient-enriched system, to an oligotrophic, nutrient-depleted one (Fonda Umani et al., 2004). In a recent study, Mozetič et al. (2012) analysing the phytoplankton trends and community changes in the period 1989–2009, have highlighted that the absolute minimum of chl *a* concentration and the second maximum of salinity were reached in 2006. In this particular year, the highest abundances of nanoflagellates were observed also, in their long time series.

The aim of this study was to investigate to what extent phytoplankton abundance, structure and photosynthetic activity were affected by the anomalous environmental conditions that occurred from March 2006 to February 2007. To highlight the possible effect of meteorological and hydrological variables on phytoplankton development, we computed monthly mean (or median) air temperature, total precipitation, wind speed, Isonzo River discharge, seawater temperature, salinity, photosynthetic available radiation (PAR), cyanobacteria, nano- and microphytoplankton during the study year and compared these data to climatological (1999–2014 for PAR; 1999–2007 for nanophytoplankton; 1998–2015 for the other variables) mean/median data. We further related cyanobacteria (0.2–2 μm), nano- (2–20 μm) and microphytoplankton (20–200 μm) abundances of the study year to inorganic nutrient concentrations. In order to investigate phytoplankton functional response to the observed anomalous physical-chemical conditions, we estimated the photosynthetic activity of total phytoplankton. In addition, from June to November 2006, we evaluated the contribution of the nanoplankton fraction (2–20 μm) to total primary production. Finally, we discussed the implications of very low phytoplankton abundances over the study year on the ecosystem functioning of the whole basin.

We hypothesized that because pelagic primary producers, in terms of standing stock and primary production, are largely controlled by nutrient availability in this shallow basin (as in many others), reductions in river flow and nutrient loads would lead to reduced phytoplankton abundances and primary production. We also hypothesized that the synergistic effect of anomalous physical-chemical conditions (nutrients, seawater temperature, wind forcing, *etc.*) could alter the typical seasonal succession of pelagic phototrophs and their primary productivity patterns. Our guiding questions were: i) How are phytoplankton abundance, structure and production affected by reductions in freshwater and nutrient inputs? ii) Could the synergistic effect of anomalous physical-chemical conditions alter the typical micro- → nanophytoplankton → cyanobacteria succession in this area and overall primary production? iii) What may be the consequences for upper trophic levels in terms of food availability?

2. Material and methods

2.1. Study area

The Gulf of Trieste is a small (~500 km^2) and shallow (maximum depth 25 m) semi-enclosed basin in the north-western part of the Adriatic Sea (Fig. 1). In this area, freshwater inputs and atmospheric forcing greatly influence seawater temperature, salinity and water column stratification (Malačič and Petelin, 2001). Seawater temperature displays seasonal oscillation from 8 °C (February) to 26 °C (August), whereas salinity in surface waters ranges between 24, in spring during high riverine discharge, and 38.3 (Celio et al., 2006). Typically, in winter, the water column is well-mixed, whereas during spring freshwater input and surface heating lead to thermohaline stratification. The period between May and September is characterised by strong density