



Effects of eutrophication on the planktonic food web dynamics of marine coastal ecosystems: The case study of two tropical inlets



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ARTICLE INFO

Article history:

Received 19 April 2016

Received in revised form

2 June 2016

Accepted 10 June 2016

Available online 14 June 2016

Keywords:

Eutrophication
Trophic efficiency
Phytoplankton
Zooplankton
Grazing
Growth
Food web
Singapore
Monsoon

ABSTRACT

We studied the plankton dynamics of two semi-enclosed marine coastal inlets of the north of Jurong Island separated by a causeway (SW Singapore; May 2012–April 2013). The west side of the causeway (west station) has residence times of ca. one year and is markedly eutrophic. The east side (east station) has residence times of one month and presents lower nutrient concentrations throughout the year. The higher nutrient concentrations at the west station did not translate into significantly higher concentrations of chlorophyll *a*, with the exception of some peaks at the end of the South West Monsoon. Microzooplankton were more abundant at the west station. The west station exhibited more variable abundances of copepods during the year than did the east station, which showed a more stable pattern and higher diversity. Despite the higher nutrient concentrations at the west station (never limiting phytoplankton growth), the instantaneous phytoplankton growth rates there were generally lower than at the east station. The phytoplankton communities at the west station were top-down controlled, largely by microzooplankton grazing, whereas those of the east station alternated between top-down and bottom-up control, with mesozooplankton being the major grazers. Overall, the trophic transfer efficiency from nutrients to mesozooplankton in the eutrophic west station was less efficient than in the east station, but this was mostly because a poor use of inorganic nutrients by phytoplankton rather than an inefficient trophic transfer of carbon. Some hypotheses explaining this result are discussed.

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1. Introduction

Increased inputs of nutrients over the last decades have originated eutrophication in many aquatic ecosystems around the world. The effects of these nutrient loadings are different in freshwater and in coastal marine ecosystems, although in both cases they define the relationship between the sizes of producers and grazers (Smith et al., 1999, 2006). In lakes, this relationship is unimodal (Havens, 2013): in ultraoligotrophic and hypereutrophic lakes the size (either too small or too large) or the palatability of phytoplankton disrupt the flux of energy throughout the food web

by inhibiting large zooplankton grazing (Elser, 1999; Havens et al., 2000; Paerl et al., 2001; Havens, 2013). In mesotrophic lakes, however, short cladoceran/rotifer-based food webs efficiently transfer the energy from primary producers to fish (Havens, 2013). Marine systems, on the other hand, usually display more complex planktonic food webs and less clear responses to nutrient concentrations (Oviatt et al., 1989; Anderson et al., 2002). Nevertheless, according to nutrient loads and their ratios, we can roughly classify marine systems in (1) upwelling, with high concentrations of inorganic nutrients and diatom-dominated; (2) oligotrophic oceanic systems, poor in nutrients and picoplankton-dominated; (3) mesotrophic systems, with moderate and balanced nutrient concentrations and usually subjected to seasonality; and (4) eutrophic systems, with high levels of nutrients and high N to Si ratios, and usually dominated by inedible algae (Smith et al., 1999).

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From a trophic transfer efficiency point of view, it is expected upwellings being more efficient than oligotrophic and eutrophic systems (Sommer et al., 2002). Mesotrophic systems should alter food web structure and its efficiency throughout the seasonal cycle (Calbet et al., 2008).

Even though anthropogenic nutrient enrichment of coastal marine systems has been linked to stimulation of some harmful phytoplankton species (mostly dinoflagellates; Anderson et al., 2002; Heisler et al., 2008), the blooming of diatoms that can be readily consumed by micro- and mesozooplankton (Suzuki et al., 2002; Aberle et al., 2007; Castellani et al., 2008) also may occur (Oviatt et al., 1989). The dominance of one group of phytoplankton over another will greatly influence the planktonic food web dynamics and the overall efficiency of the system. Therefore, the effects of eutrophication on marine coastal systems seem indeed less predictable than in freshwater ones.

Another important difference between marine and freshwater systems resides in the nature of their major planktonic herbivorous. While in lakes cladocerans highlight as major consumers of the secondary production (Edmonson and Litt, 1982; Sarnelle, 1992), in marine systems this role is undertaken by microzooplankton (Sherr and Sherr, 2002; Calbet and Landry, 2004; Schmoker et al., 2013). Microzooplankton, with fast generation times, are proven to be very efficient grazers even in very eutrophic conditions or during harmful dinoflagellate blooms (Andersen and Sørensen, 1986; Calbet et al., 2003; Schmoker et al., 2013). Microzooplankton are, at their turn, the preferred prey of copepods, the dominant crustacean grazers of the oceans (Fessenden and Cowles, 1994; Suzuki et al., 1999; Broglio et al., 2004; Saiz and Calbet, 2011). Under this food web scenario, it would be expected the link between phytoplankton and microzooplankton being strong under eutrophy, and, opposite to freshwaters, the trophic transfer efficiency throughout the food web not being largely diminished respect more mesotrophic conditions. Moreover, given the tight dependence of phytoplankton on nutrients and the unimodal relationship between biomass and diversity of phytoplankton and zooplankton (Irigoin et al., 2004), one would expect that more eutrophic sites, with constant anthropogenic nutrient discharges, would generally favour the settlement of stable and less diverse planktonic food webs compared to the more variable mesotrophic conditions, likely more influenced by climatological phenomena (e.g. seasonal spring blooms).

To validate these hypotheses we focused on the succession and trophic dynamics of plankton at two semi-enclosed sites (west and east station) on Singapore's coast, north of Jurong Island. This island is a reclaimed landmass linked to the mainland by a causeway, which does not allow east-west water exchange. The flushing characteristics of both sites, based upon DHI MIKE21 FM Advection Dispersion Model (www.mikepoweredbydhi.com), support that the water exchange in the west station is much lower than the water exchange in the east site. At the west station, with a narrower and longer mouth facing SW, the water exchange was <20% for the two-month of simulation period carried out; whereas at the east station, with a wider mouth facing SE, 80% of the water was flushed out of the area within a month. Eutrophication models for lakes show that the rate of water renewal is key to modify the nutrient loading and the level of eutrophication of a system (Dillon and Rigler, 1974; Vollenweider, 1976; Schindler, 2006). Therefore, we expect the west station being more eutrophic than the east one; this was confirmed by previously preliminary data (Schmoker unpublished). The study area is influenced by the Southeast Asian Monsoon, which provides a wide variety of environmental conditions and food web scenarios. The Southeast Monsoon divides the year into four periods: two main monsoon seasons, the Northeast Monsoon from November to early March and the Southwest

Monsoon from June to September, and two inter-monsoon periods (late March to May and October to November). Heavy rains and winds characterize both monsoon periods, while throughout the Inter Monsoon transitions the rain is intermittent and winds are weak and variable (National Environment Agency, 2009; Behera et al., 2013).

Our goal was therefore twofold: On the one hand, we aimed at assessing the importance of eutrophication on planktonic succession, trophic dynamics, and food web transfer efficiency of marine planktonic food webs. On the other hand, providing a necessary frame to validate our hypotheses, we wanted to characterize the major drivers of the plankton succession of these two sites and provide an up-to-date record of the plankton dynamics and species description for inshore waters at Singapore. The plankton of these sites in the southwest sector of Singapore has never been studied before.

2. Material and methods

2.1. Sampling and basic analysis

We sampled two stations at two-week intervals, from May 2012 to May 2013, on the southwest coast of Singapore (Fig. 1; west station; 01°N17.949'N, 103°42.383'E and east station; 01°17.694'N, 103°43.340'E). We measured temperature and salinity every 25 cm using a YSI 6920 S2 multi-probe sensor calibrated before each survey, and we took samples for chlorophyll *a* (chl *a*) and small planktonic organisms <100 µm at 1 m (hereafter, "surface"), 10 m and 15–20 m (near the bottom) using a 5 L Niskin bottle. To collect mesozooplankton we pulled a 50-cm mouth, 100 µm-mesh plankton net from bottom to surface by hand. We also obtained light profiles (PAR = photosynthetically active radiation) with an Underwater Quantum Sensor (LiCor LI-192). We measured oxygen concentration using an optode system (Presens, Germany) at 1 m, 10 m and 15–20 m.

In the laboratory, we estimated chl *a* concentrations by filtering 250–500 mL through 10 µm screens and 150–250 mL through GF/F filters. Chl *a* was extracted from all the filters overnight in 90% acetone at 4 °C in the dark, and concentrations were then determined from *in vitro* fluorescence with acidification using a Turner Designs Trilogy model fluorometer (Strickland and Parsons, 1972). Inorganic nutrients (nitrate, ammonium, phosphate and silicate) were estimated following a standard protocol using a Skalar Flow Injection Analysis Autoanalyzer (APHA 4500). The minimum level of detection for all inorganic nutrients was 0.01 mg L⁻¹.

2.2. Microplankton and mesozooplankton abundance and biomass determination

Microplankton samples (250 mL of seawater) were fixed with acidic Lugol's solution (2% final concentration) and stored at room temperature in the dark. Subsamples of 10 mL were allowed to settle for 6 h in Utermöhl chambers, and microplankton organisms were counted for the whole chamber. Their volumes were approximated by the closest geometrical shapes and they were converted to carbon using the equations of Menden-Deuer and Lessard (2000). Mesozooplankton samples were fixed with 4% formaldehyde. Around 1000 individuals were counted per sample (Omori and Ikeda, 1984) identified, when possible, to species level, and sized and converted to carbon using the equations of Uye (1982).

2.3. Primary production estimation

We determined primary production using the oxygen

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