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Benthic pelagic coupling in a mesocosm experiment: Delayed sediment responses and regime shifts

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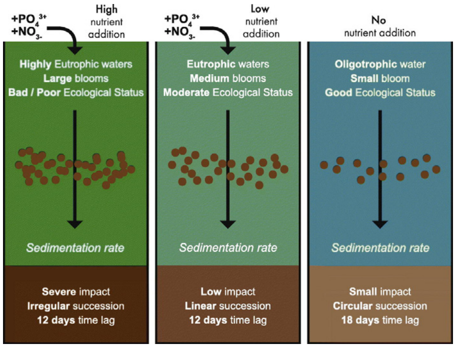
HIGHLIGHTS

- Mesocosm experiment studding effects of eutrophication on geochemical variables
- 4 m water depth, 80 l sediment, two levels of nutrient addition, 58 days duration
- Strong eutrophic conditions increased sedimentation rate bad ecological conditions in the water.
- 12–30 days delayed sediment response increased organic matter and decreased Redox.
- Irregular sediment geochemistry succession pattern with no signs of recovery

GRAPHICAL ABSTRACT



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ABSTRACT

A mesocosm experiment was performed to study benthic-pelagic coupling under a eutrophication gradient. Nine mesocosms were deployed in the facilities of the Hellenic Center for Marine Research in Crete, in the Eastern Mediterranean. The mesocosms were 4 m deep, containing 1.5 m^3 of coastal water and, at the bottom, they included 85 l of undisturbed sediment, collected from a semi-impacted area in the port of Heraklion, Crete. A eutrophication gradient was created by adding nutrients in the water column (Low and High) and the experiment lasted 58 days. Water column and sediment environmental variables were measured at regular intervals. The results indicate that sedimentation caused by eutrophication in the water column affected sediment geochemical variables but in most cases a time lag was observed between the trophic status of the water column and the response of the sediment. Additionally, in the High eutrophication treatment, several fluctuations were observed and the system did not recover within the experimental duration, as opposed to the Low treatment which showed fewer fluctuations and signs of recovery.

1. Introduction

Eutrophication has been studied extensively during the past 50 years, initially focusing on lake ecosystems (Carlson, 1977; Rodhe, 1969; Vollenweider, 1968) and estuaries or coastal ecosystems (Bayley et al., 1978; Lohrenz et al., 1999; Ryther and Dunstan, 1971). Numerous conventions, summarized in Ferreira et al. (2011), have since put into action legislation programs and law measures protecting the aquatic environment from eutrophication (Borja et al., 2008). The adoption of legislative measures changed the definition of eutrophication from a more descriptive concept proposed by Nixon (1995) as "an increase in the rate of

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supply of organic matter (OM) in an ecosystem" to a more pressure-related definition within the European Union as confirmed by several cases in the European Court of Justice (European-Commission, 2013) mentioned in Ferreira et al. (2011).

In the context of the European Water Framework Directive (WFD), a series of indicators proposed as suitable for describing eutrophication were reviewed by Karydis (2009). Those indicators may be based on nutrient concentrations, i.e. N/P ratio (Ryther and Dunstan, 1971), nutrient algorithms (Ignatiades et al., 1992), chlorophyll-*a* (chl-*a)* concentration (Simboura et al., 2005) or multimetric indicators such as Trophic Index (TRIX) (Vollenweider et al., 1998) or Eutrophic Index (E.I.) (Primpas and Karydis, 2011), that take into account multiple variables. As with every indicator, it is important to set correct reference conditions (Borja et al., 2012) in order to have accurate results for a specific area.

The WFD demands from EU member states that they achieve "Good Environmental Status", using indicators for every coastal water body. However, the directive adopts a "deconstructing structural" approach (Borja et al., 2010) by evaluating separately every part of the marine ecosystem with specific indicators and does not take into account the interaction between these parts and the possibility of benthic-pelagic coupling. On the contrary, the European Marine Strategy Framework Directive (MSFD) adopted the "ecosystem approach" and "holistic management" approach when assessing ecosystem health (Tett et al., 2013). Eutrophication became one of 11 holistic quality descriptors that together allowed for environmental status assessment (Borja et al., 2010; Ferreira et al., 2011).

Under the holistic approach of the MSFD, recent meta-analyses or field studies attempted to co-examine water column and benthos (Dimitriou et al., 2015; Pavlidou et al., 2015; Rodrigues Alves et al., 2014; Zhang et al., 2015). Field studies however, do not always provide adequate insight into the mechanisms and processes involved in the response of marine organisms to specific pressures. On the contrary, an experimental manipulation allows the study of the responses of the system to specific pressures. Additionally, during an experimental manipulation, it is possible to divert the system to a point not often found in nature. Enclosed ecosystems are used to explore interactions among organisms or between organisms and their physical environment, serving as miniaturized worlds (Petersen et al., 2009).

Effects of nutrient input on the water column productivity and sedimentation rate have been studied with mesocosm experiments in different areas of the world. Svensen et al. (2001) reported that the addition of nutrients in large mesocosms increased sedimentation rates, especially in flagellate-dominated communities. Andersson et al. (2006) studied the effect of nutrient enrichment on the structure of the pelagic microbial food web in the Baltic Sea and reported high productivity first of autotrophic microbes followed by heterotrophic ones. In the Mediterranean Sea, Vidal and Duarte (2000) argued that summer Mediterranean plankton responded to nutrient additions by increasing biomass by up to >100-fold and by changing the community structure from an initial dominance of picoplankton to the increased dominance of the 2–20 μm size component of the community.

Adding sediment in mesocosm studies increases the realism of the experiments by including more biogeochemical cycling processes (e.g. nutrients, contaminants, oxygen) and more types of organisms (microbentos, meiofauna and macrofauna) (Petersen et al., 2009), especially in the study of eutrophication that affects both the water column and benthos. Enclosure experiments including sediments are usually conducted on a small scale (benthocosm experiments) or in large in situ sea mesocosms. Oviatt et al. (1986) reported that a 32-fold increase in nutrient concentration in sea mesocosms in Rhode Island, USA caused an increase in water column productivity by a factor of 3.5, resulting in an increase in oxygen demand causing the sediment in the highest enriched treatment to become temporally anoxic. Suomela et al. (2005) argued that sediment with a low content of OM may serve as an important source of nutrients in shallow and littoral oxic waters and may be important in sustaining their eutrophic state.

Sea experiments offer a high degree of realism but with high costs and less control over the experimental manipulation (Petersen et al., 2009), while the small-scale benthocosm experiments do not usually allow the study of the water column due to the small volume of the included water. The benthic mesocosm setup (Dimitriou et al., 2017) used in the present study has been proposed as an intermediate link between the large-scale sea mesocosms and the smaller benthocosm experiments. The aim of the experiment was to study the benthic pelagic coupling of a costal marine ecosystem under the pressure of eutrophication. Two questions are addressed: (i) Do the observed impacts of a eutrophication event in the water column affect sediment biogeochemistry, and if yes, how fast are these impacts observed? (ii) Does the observed ecosystem revert back to its initial point after an experimental duration of two months?

2. Materials and methods

2.1. Experimental design

The experiment took place at the CRETACOSMOS mesocosm facilities of the Hellenic Center for Marine Research in Crete, Eastern Mediterranean (www.cretacosmos.eu). Nine mesocosms (0.35 m radius) were deployed, which included a water column of 4 m depth and total volume of 1.5 m^3; on the bottom, the included sediment had 0.3 m radius, 0.3 m height, 85 l total volume and approximately 30 kg weight.

The experimental design included two eutrophication treatments, each with triplicate mesocosms. One single addition of nutrients was performed on the first day of the experiment (day 0). The addition was based on the ambient concentration of nutrients PO_4^{3+} and NO_3^- being 100× for PO_4^{3+} (5 μM) and 300× for NO_3^- (30 μM) for Low eutrophication treatment ("Low") and 200× PO_4^{3+} (10 μM) and 600× NO_3^- (60 μM) for High eutrophication treatment ("High"). Additionally, the experiment included triplicate control mesocosms ("Control") with no nutrient addition. In order to measure the sedimentation rate within each mesocosm, a sediment trap was placed at 3.8 m depth in the center of the mesocosm. It was made of a cylindrical PVC container with 4.5 cm radius, 25 cm height and 1.6 l total volume fixed.

The seawater used in the experiment originated from the coastal area of Heraklion, Crete (Eastern Mediterranean), while the sediment originated from the leisure boat section within the harbor area of Heraklion at 4 m depth. Detailed description of the mesocosm setup (including a 3d image), ambient water and sediment collection and transportation, water column and sediment sampling methodology and equipment, as well as water temperature and natural light illuminance, are provided in Dimitriou et al. (2017).

The total duration of the experiment was 58 days. The experiment took place in the late-summer early and autumn transitional period (September – October – November), during which natural temperature decreased substantially. For this reason, water temperature was not controlled but was left to follow the gradual decrease of the natural environment.

Water, sediment and sediment trap sampling in the mesocosms took place at specific time intervals (Table 1), taking into account that no >10% of total water or sediment volume should be removed from the mesocosms during the entire duration of the experiment. Collected sediment corer samples were sliced into three layers: top layer 0–1 cm, middle layer 1–3 cm and bottom layer 3–5 cm.

Environmental variables included in this study (Table 2) were analyzed according to specific protocols from subsamples taken from the collected water or sediment, as described Dimitriou et al. (2017). Total organic carbon (TOC) in sediment samples and Particulate Organic Carbon (POC) in water samples were determined by means of a Perkin Elmer 2400 CHN Elemental Analyzer (Tung and Tanner, 2003). The separation of organic from inorganic forms of carbon followed the method reviewed in Verardo et al. (1990). Sulfide concentration was masured