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Relationship between magnitude of phytoplankton blooms and rainfall in a hyper-eutrophic lagoon: A continuous monitoring approach

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A B S T R A C T

To evaluate the effect of rainfall intensity on phytoplankton blooms, a continuous monitoring system was deployed during 2015 in a hyper-eutrophic lagoon in Taiwan. Intensive rainfall occurs during the wet summer months, from May to September. Salinity in the lagoon was found to decrease with increasing intensity of rainfall. The magnitude of phytoplankton blooms also increased linearly with increasing rainfall intensity. The chlorophyll *a* concentration rose by an order of magnitude during the heaviest rainfall. Blooms may be fueled by nutrient enrichment caused by drainage or run-off water from surrounding areas that is channeled into the lagoon during rainfall events. During bloom periods, the rates of net primary production and ecosystem respiration were high. However, this ecosystem was autotrophic for most of the year. As extreme rainfall is predicted to increase, the results of this study imply that the frequency and magnitude of phytoplankton blooms may increase in the future.

1. Introduction

The effects of rainfall on coastal and/or lagoon ecosystems have received increasing attention in last few decades (Arhonditsis et al., 2002; Meng et al., 2015). Since extreme rainfall events are predicted to increase in the near future, the associated effects are also likely to be more pronounced (Milly et al., 2002; Palmer and Ralsanen, 2002; Power et al., 2013; Tan et al., 2015). Water drainage via riverine input from rainfall events may substantially increase the amounts of dissolved inorganic nutrients and particulate and dissolved organic matter in nearby coastal ecosystems, in addition to diluting the salinity (Chen et al., 2006; Chen et al., 2009; Childers et al., 2006; Dagg et al., 2004). Biological and ecological responses are enhanced following such events, e.g., primary productivity and ecosystem metabolism (Chen et al., 2009; Malone and Ducklow, 1990). Most related studies have focused on the effect of heavy rainfall during short periods of time or in freshwater ecosystems (Hsieh et al., 2012; Meng et al., 2015; Mulholland et al., 2009; Staehr et al., 2012). However, few studies have focused on the effects of rainfall intensity over a longer periods of time in coastal ecosystems, especially in tropical regions (Staehr et al., 2012 and citations therein).

In this study, the influence of rainfall on coastal ecosystems was examined in the Dapeng Lagoon, a semi-enclosed ecosystem located in southwestern Taiwan (Hsieh et al., 2012; Meng et al., 2015). This lagoon is surrounded by heavily farmed fish and shrimp ponds that discharge large amounts of nutrients, organic matter, and aquaculture wastewater into the inner lagoon via a dike, largely during the wet summer months (Hung and Hung, 2003; Tew et al., 2014b). Hung and Hung (2003) have categorized this lagoon as eutrophic, i.e., its measured concentration of dissolved inorganic nitrogen ranges from 12.1–30.0 μM. In this lagoon, phytoplankton blooms have a mean chlorophyll *a* concentration of 37.5 $\mu g\ L^{-1}$ after a heavy rainfall event (Meng et al., 2015). However, it is still unclear when blooms occur and to what extent, and how these are related to rainfall intensity. Based on the ratio of net primary productivity to plankton community respiration, Hsieh et al. (2012) has suggested that the Dapeng ecosystem remains autotrophic after moderate rainfall events. This finding is similar to that of other coastal ecosystems (Duarte and Agustí, 1998). However, adjacent coastal ecosystems may be more heterotrophic due to their discharge of significant quantities of particulate and dissolved organic matter through fluvial output, which triggers a high rate of microbial metabolism (Chen et al., 2009; Hedges et al., 1994; Malone and Ducklow, 1990). These conclusions were mostly derived from short periods of analysis over an interval of several days (Hsieh et al., 2012; Meng et al., 2015; Mulholland et al., 2009). Thus, it is worthwhile to also examine the impact of rainfall on entire ecosystems over a longer time period.

Lagoons are one of the most suitable natural systems for evaluating the effects of rainfall on ecosystems. In terms of exchange with the outer environment, lagoons form a restricted environment and receive

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a relatively small volume of water from the seaward due to presence of land barriers; for this reason lagoons are particularly sensitive to episodic impacts (Nixon, 1982). Thus, lagoons are valuable natural systems for exploring how the biological (e.g., phytoplankton bloom) and ecosystemic (e.g., net primary productivity) components of a system respond to rainfall events. In this study, a continuous, real-time monitoring system with multi-parametric sensors was deployed to measure the effects of rainfall events on phytoplankton blooms and ecosystem metabolism over a short- (≤30 min) and long-term period (1 year) in Dapeng Lagoon.

2. Materials and methods

2.1. Study area, monitoring, and sampling

The study was conducted in Dapeng lagoon situated in southern Taiwan, with an approximate area of 5.32 km^2. This lagoon is a shallow, semi-enclosed ecosystem with two openings: one seaward that connects the lagoon to the Taiwan Strait and one terrestrial (the Linpan Dike) by which urban and aquaculture wastewater is discharged to the inner lagoon (Fig. 1). The lagoon is influenced by the semi-diurnal and diurnal tides of the Taiwan Strait. To examine the effect of rainfall on the Dapeng ecosystem, rainfall and sea level data were acquired from the Central Weather Bureau of Taiwan (http://cwb.gov.tw). To monitor water quality, a continuous, real-time monitoring system (CRTMS) was used, consisting of a wireless transmission system and a solar panel that were mounted to a buoy anchored to the seafloor. Two CRTMSs were deployed for one year during 2015 at stations M1 (the tidal inlet) and M3 (the inner lagoon) at depths of around 4.0 ± 0.3 and 4.0 ± 0.2 m, respectively (Fig. 1). Multi-parameter water quality sondes (YSI 6600) were used to measure pressure, temperature, conductivity, fluorescence, and dissolved oxygen (DO; for details see Tew et al., 2014a). The sensors were calibrated every two weeks for all measured parameters. The precision and accuracy of all measurements were calculated following the EPA/ROC (Taipei) methods (Table 1). After the calibration of the equipment, the percentage of relative error for all of the parameters was within the acceptable range. Variables were measured at an interval frequency of 30 min. In order to compare the data, the daily averages were considered.

Table 1
Precision and accuracy of all measured parameters.

Sensor	Accuracy (%)	Precision (%)
Temperature	99.9	0.3
Salinity	99.9	0.15
Dissolved oxygen	100.4	4.23
Fluorescence	108.0	8.24

Salinity: IAPSO STANDARD SEAWATER (Batch: P152, 34.993).
Dissolved oxygen: Air saturation.
Fluorescence: 10 mg chlorophyll *a* packaged in sealed ampule (Product Number C 5753, Sigma-Aldrich Co.; Empirical Formula: $C_{55}H_{72}MgN_4O_5$; Molecular weight: 893.49).

2.2. Net primary productivity, respiration, and statistical analysis

Rates of primary ecosystem productivity and respiration were calculated as the daily variation in levels of dissolved oxygen (DO; Odum, 1956; Petersen et al., 1997). The daily levels of DO in the lagoon increased and decreased nearly linearly, during light and dark periods, respectively, especially at station M3. The ecosystem metabolism was estimated according to (1) the net primary productivity (NPP), operationally defined as the rate of change of DO during daylight hours, and (2) the nighttime respiration (R), defined as the rate of change of DO during nighttime hours (R is recorded as a positive number). This approach has been extensively applied to freshwater ecosystems, but has been less frequently used in marine environments (Staehr et al., 2012 and citations therein). In estuarine environments, the dynamics of DO may also be influenced by advection and air-water O_2 exchange due to tides, winds, and flow (Swaney et al., 1999). However, in order to simplify, the air-water exchange of O_2 was ignored in this study, since the DO sensors were placed below the surface mixed layer (at a depth of about 1.6 ± 0.6 m; Meng, unpublished data). As for advection due to tidal exchange, a slight variation in DO was observed at station

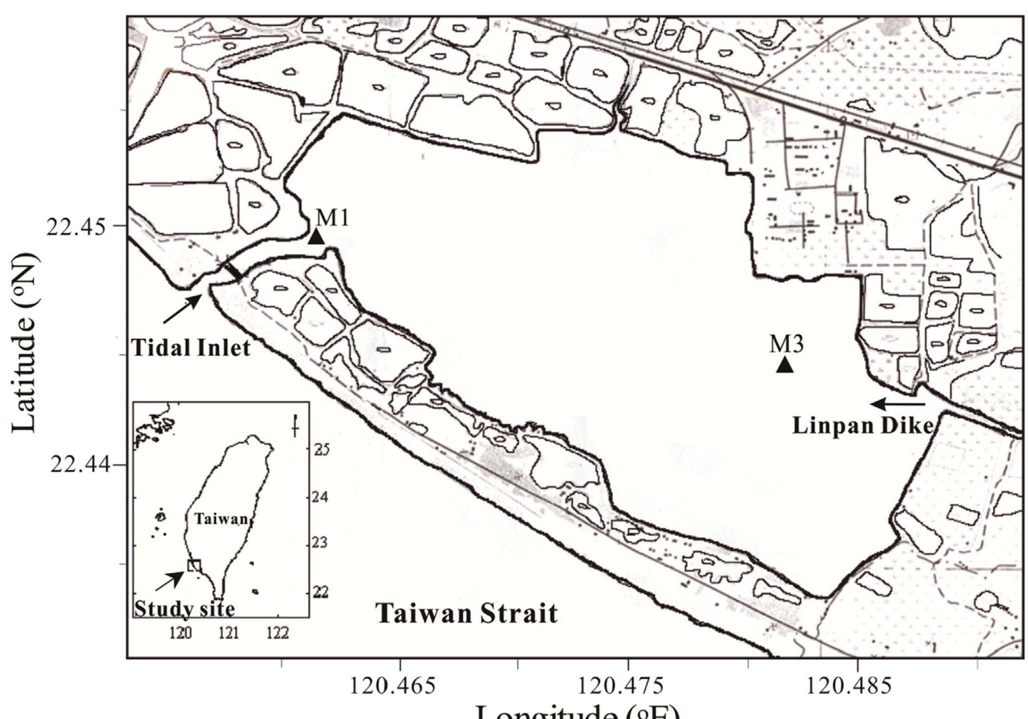

Fig. 1. Map of the monitoring stations (▲) in Dapeng Lagoon. The Linpan Dike and tidal inlet are the channels where freshwater enters and seawater exchanges with the lagoon, respectively.

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