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Phosphorus as a driver of nitrogen limitation and sustained eutrophic conditions in Bolinao and Anda, Philippines, a mariculture-impacted tropical coastal area

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ABSTRACT

The dynamics of nitrogen (N) and phosphorus (P) was studied in mariculture areas around Bolinao and Anda, Philippines to examine its possible link to recurring algal blooms, hypoxia and fish kills. They occur despite regulation on number of fish farm structures in Bolinao to improve water quality after 2002, following a massive fish kill in the area. Based on spatiotemporal surveys, coastal waters remained eutrophic a decade after imposing regulation, primarily due to decomposition of uneaten and undigested feeds, and fish excretions. Relative to Redfield ratio (16), these materials are enriched in P, resulting in low N/P ratios (~6.6) of regenerated nutrients. Dissolved inorganic P (DIP) in the water reached 4 μM during the dry season, likely exacerbated by increase in fish farm structures in Anda. DIP enrichment created an N-limited condition that is highly susceptible to sporadic algal blooms whenever N is supplied from freshwater during the wet season.

1. Introduction

Fish farming in coastal areas (or mariculture) has become widespread in Southeast Asia including the Philippines, providing important food source and economic gains to the local people (FAO, 2009). However, intensified and unregulated fish farming produces exogenous materials such as wasted feeds that can lead to deterioration of water and sediment quality from excess nutrients and high turbidity; and frequent occurrence of algal blooms (Holmer and Kristensen, 1992; Folke et al., 1994; Wu, 1995; Kibria et al., 1996; Olsen et al., 2008; White, 2013). In tropical regions, mariculture areas are typically located adjacent to coral reefs and seagrass beds (e.g., Herbeck et al., 2013; Tanaka et al., 2014). It is therefore important to assess the effects of particulates and excess nutrients from mariculture effluents to these ecologically and economically important components of the coastal ecosystem.

In the towns of Bolinao and Anda in the province of Pangasinan located in Northern Luzon, Philippines, a shallow coastal embayment connected to the outer ocean through a few narrow channels has become the site for fish farming in cages and pens. The mariculture of milkfish (*Chanos chanos*) in the area started in the 1970s, and has intensified in 1995 when the number of fish farm structures reached >1000 units by early 2002 (Verceles et al., 2000). This number is twice the allowable maximum of 544 units set by the local government of Bolinao based on hydrodynamic constraints (San Diego-McGlone et al., 2008). The large increase in number of fish farm structures led to eutrophic waters, reduced water exchange rate and development of hypoxic bottom water in the area, and in 2002 resulted in a massive fish kill that coincided with the bloom of a harmful algae identified as *Prorocentrum minimum* (Azanza et al., 2005, 2006; San Diego-McGlone et al., 2008). Soon after the fish kill, Bolinao reduced the number of fish farm structures to comply with the allowable limit. Despite this effort, there has been recurrence of harmful algal blooms (HABs) and fish kills resulting in economic losses which suggest that water quality in Bolinao and Anda have continued to deteriorate (Yap et al., 2004; Azanza et al., 2005; San Diego-McGlone et al., 2008, 2014; Azanza and Benico, 2013; Escobar et al., 2013). There is absence of macroinfaunal communities and presence of mats of the sulfide oxidizing bacteria

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Beggiatoa (Santander-De Leon et al., 2008; Nacorda et al., 2012). There has been an impact on the adjacent coral reef ecosystems leading to low survivorship of juvenile corals (Villanueva et al., 2006) and disappearance of seagrass species (Tanaka et al., 2014). Moreover, an accumulation of the indicators of non-cholera pathogens in the anoxic guts of milkfish and in the sediments was detected (Reichardt et al., 2013).

It is noteworthy that even if regulation on allowable number of fish farm structures has been enforced in Bolinao after 2002, the levels of nitrate (NO_3^-), ammonium (NH_4^+), and particularly phosphate (PO_4^{3-}) remained high (Fig. 2; San Diego-McGlone et al., 2008). The question is why these nutrients, especially phosphorus (P) are persisting in these coastal waters.

Phosphorus is a major nutrient in marine systems as well as nitrogen (N) and silicon (Si). Due to its highly reactive nature, P can be the ultimate limiting nutrient in some aquatic environments (reviews by Benitez-Nelson, 2000; Ruttenberg, 2003; Paytan and McLaughlin, 2007; MacKenzie et al., 2011; Slomp, 2011). Natural sources of P to coastal areas include atmospheric dusts, volcanic ashes, weathering products and upwelling; the inputs of which may gradually increase the concentrations in the water and enhance the supply of organic matter in the area, a process known as "natural eutrophication" (Nixon, 1995; Smith et al., 1999; Andersen et al., 2006). Major anthropogenic P sources include agriculture, livestock, chemical and human wastes from the watershed, and fish farming activities. Large loading of these sources to coastal environments due to human activities can result in accelerated buildup of nutrients and organic matter, otherwise known as "cultural eutrophication" (Hasler, 1969; Smith and Schindler, 2009). Subsequently, the rate of organic matter accumulation in the sediments can increase followed by development of hypoxia. Under reducing conditions, P which is closely linked to iron (Fe) and sulfur (S) cycle, is released to sediment porewater and overlying water (Kemp et al., 2009; Martin, 2009; Middleburg and Levin, 2009; Dale et al., 2013).

In this study, we analyzed the trophic status of the coastal waters of Bolinao and Anda a decade after the enforcement of fish farm structure regulation with emphasis on (i) the different historical and spatiotemporal behavior of N and P, which apparently resulted in relative enrichment of P in the water column, (ii) the role of wasted feeds, metabolic products of fish (feces and excretions), and sediment porewater in regulating the nutrient availability in the water column, and (iii) the potential importance of land-derived dissolved inorganic nitrogen (DIN) as a trigger of massive algal blooms in this area. Other factors such as hydrodynamics in the mariculture area, and the increase of fish structures in the adjacent waters of Anda that influenced the nutrient enrichment in Bolinao, are discussed with their implication on the management strategy for mariculture.

2. Materials and methods

2.1. Study site

Bolinao and Anda (16.20–16.46°N, 119.76–120.05°E) are two coastal towns in Pangasinan, northwestern Philippines that share semi-enclosed coastal waters (Fig. 1). Their environment is affected by the country's two prevailing seasons — the dry season from November to March characterized by less precipitation (monthly average of 23 mm from 2003 to 2013) and strong northeasterly winds, and the wet season from June to September marked by heavy precipitation (monthly average of 736 mm) and southwesterly winds (precipitation and wind data from the Philippine Atmospheric, Geophysical and Astronomical Services Administration-PAGASA).

The Bolinao and Anda coastal waters are characterized by relatively deeper areas (>10 m) on the west side of Guiguiwanen Channel that connects to the South China Sea, at the passage between Siapar Island and Cabarruyan Island adjacent to the Lingayen Gulf, and at the Caquiputan Strait leading to Tambac Bay (Fig. 1a). The depth decreases to an average of 5 m between Bolinao and the northwest side of Cabarruyan Island, and further decreases to an average of 1.5 m in Tambac Bay. Fish cages are constructed at depths of >5 m, while fish pens are situated at depths of about 3 m (Fig. 1b). Bani and Alaminos Rivers are two major rivers that drain to Tambac Bay (Fig. 1a) creating an estuarine environment especially during the wet season.

2.2. Water sampling

Water sampling and hydrodynamic surveys were conducted at several stations in March (dry season) and September (wet season) from 2010 to 2014 to determine seasonal, spatial and temporal variations in water quality characteristics (Fig. 1a, c). A floating platform (Continuous and Comprehensive Monitoring System or CCMS) equipped with sensors was installed in September 2011 midway (16.3868°N, 119.9252°E) at Guiguiwanen Channel to collect high temporal resolution data (e.g. water level and water velocity; Fortes and Nadaoka, 2015). Surveys include large-scale bay-wide spatial investigation on the reef area, deep and shallow mariculture areas, and the deep strait up to Tambac Bay (Sept. 2010–2013; Mar. 2011, 2013, 2014). Continuous (24-h) observations were conducted at the West Station (Sta. 1), CCMS (Mid-channel), and East Station (Sta. 2) of the Guiguiwanen Channel (Sept. 2011, Mar. 2012). A small-scale grid survey around CCMS was performed as well (Sept. 2012, Mar. 2013). During the grid survey, 25 stations in the vicinity of the CCMS station occupying a 550 m × 550 m area were sampled to determine the spatial heterogeneity of the water quality characteristics in the dense mariculture area.

In addition, water samples from offshore (South China Sea side), from along a longitudinal section on the west side of Lingayen Gulf (16.07–16.50°N, 120.00–120.19°E), from Bani and Alaminos Rivers and their tributaries, and other rivers (in Caquiputan Strait and Cabarruyan Island), and from groundwater sites in Bolinao and Santiago Island were collected to determine the end member characteristics of potential sources of nutrients (Fig. 1a). The results of the surveys were compared with the time series nutrient and chlorophyll-*a* data from the Bolinao Marine Laboratory (BML) monitoring station (16.3815°N, 119.9125°E; Fig. 1c).

Vertical measurements of temperature, salinity, and dissolved oxygen were acquired at every sampling station using an AAQ-RINKO water quality profiler (JFE-Advantech, Japan) prior to water sampling. Water samples were collected at the surface using a bucket, and at 1 m above the bottom using either a Van Dorn water sampler (10 L; Rigo, Japan) or a Niskin sampler (5 L; General Oceanics, USA). Seawater samples for nutrients (dissolved inorganic nitrogen, DIN = NO_3^-, NO_2^-, NH_4^+; dissolved inorganic phosphorus, DIP = PO_4^{3-}) and total dissolved nitrogen and phosphorus (TDN, TDP) were filtered through 0.80 μm cellulose acetate DISMIC filters (Advantec, Japan) into duplicate 10 mL acrylic tubes and were kept frozen at −20 °C until analysis. Freshwater samples were collected at the surface and stored in the same manner as seawater samples.

Water samples for chlorophyll-a (Chl-*a*) and particulate phosphorus (PP) were pre-filtered through a 200 μm sieve attached to a plastic funnel and collected into polypropylene containers. For Chl-*a* analysis, 100 mL of water was filtered onto pre-combusted (450 °C, 3 h) 25 mm glass fiber filters (GF/F; nominal pore size, 0.7 μm; Whatman GE Healthcare Life Sciences, England), immersed in 6 mL *N*,*N*-dimethylformamide (DMF), and kept in the dark at −20 °C for Chl-*a* extraction. For PP, 200 mL of samples was filtered onto pre-combusted 25 mm GF/F filters and kept in plastic tubes. All samples were stored at ≤−20 °C until analysis.

2.3. Sediment sampling, incubation, and porewater extraction

Duplicate sediment cores (25–35 cm in length) were collected using acrylic pipes (i.d. = 5.0 cm) by SCUBA from 3 stations along the Guiguiwanen Channel (Fig. 1c) at the West Station (depth = 17 m), CCMS (depth = 15 m), and East Station (depth = 10 m) in March 2013 (dry season, neap tide) and September 2013 (wet season, spring tide). Sediment core sampling stations were similar to the water sampling