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Horizontal dinoflagellate cyst distribution, sediment characteristics and benthic flux in Manila Bay, Philippines

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SUMMARY

The lateral variation of sediment properties and associated cyst content of sediment in Manila Bay were determined and their possible role/s in the occurrences of *Pyrodinium bahamense* Plate var. *compressum* (Böhm) Steidinger, Tester et Taylor toxic blooms were assessed. Manila Bay's surface sediment was determined to be silt dominated. Clay generally increased towards the coast, probably as a result of flocculation and rapid deposition upon entry of sediments from the rivers. High sand content characterized the south-eastern part of the bay attributed to the greater sand inputs and relatively strong currents in this area. Bulk densities were lower in the eastern side of the bay from dilution by high organic load from sewage and urban areas. Benthic flux calculations, particularly NH3, suggest more than 50% nutrient contribution comes from sediments.

In general, dinoflagellate cyst density increased from the center of the bay towards the coast, except in Pampanga Bay where it decreased near the coasts. A maximum of 23 dinoflagellate species were identified: 5 were autotrophic (*Lingulodinium polyedrum* (Stein) Dodge*, Gonyaulax* spp., *Pyrophacus steinii* (Schiller) Wall et Dale*, Protoceratium reticulatum* (Claparéde et Lachmann) Bütschli*,* and *Pyrodinium bahamense* var. *compressum*), and the rest were predominantly composed of *Protoperidinium* spp. and *Diplopsalis* spp. Heterotrophs comprised about 70% of the total cyst counts. *Pyrodinium* counts increased towards the north-western part of the bay where it was the dominant autotroph species. Negative correlations were observed for live *Pyrodinium* cyst density and N flux, P flux, ratio of N to P and total organic carbon (TOC) content. However, areas with high N:P ratio contain abundant *Pyrodinium* live cysts.

Key words: benthic flux, dinoflagellate cyst, harmful algal bloom, porewater nutrients, *Pyrodinium bahamense* var. *compressum*, sediment.

INTRODUCTION

One of the areas greatly affected by toxic algal blooms in the Philippines is Manila Bay, where a *Pyrodinium bahamense* var. *compressum* bloom was first reported in 1988 and recurred almost yearly until 1998. The non-motile resting stage or hypnozygote (hereafter referred to as cyst) of *P. bahamense* var. *compressum* has been hypothesized to play an important role in the initiation of blooms, similar to examples elsewhere, such as *Alexandrium tamarense* in Cape Cod and *Gymnodinium catenatum* in southern Tasmania (Anderson & Morel 1979; Hallegraeff *et al*. 1995). This hypothesis applies not only in Manila Bay (Corrales & Crisostomo 1996; Villanoy *et al*. 1996), but also in other areas in the Philippines, such as Masinloc, Zambales (Bajarias 1995) and Cancabato Bay, Leyte (Marasigan *et al*. 1995). The cysts in surface sediments are believed to germinate after a required dormancy period of about 2.5–3.5 months (Corrales *et al*. 1995) if environmental conditions are favorable. These newly germinated cysts then serve as the initial vegetative population, which can increase and eventually develop into a bloom. Therefore, areas with relatively high cyst densities (so-called cyst beds) may be the locations from where blooms start and spread. However, comprehensive spatio-temporal studies on cyst distribution are still very much needed to validate this hypothesis.

Dinoflagellate cysts in sedimentary records from Norway and Japan have served as eutrophication indicators (Dale & Fjellså 1994; Dale 1996; Dale *et al*. 1999; Matsuoka 1999). One of the postulated cyst signals of eutrophication is the proportional increase over time of cysts of heterotrophic species (Dale 2001a; Matsuoka 1999; Dale 2001b). Such increases, particularly of round brown *Protoperidinium* cysts, are characteristic of cyst assemblages from major upwelling areas (Dale 1996). Several authors have postulated

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that both the occurrence and intensity of toxic blooms have increased globally as a result of cultural eutrophication (Lam & Ho 1989; Smayda 1990).

Cyst distribution in surface sediments from Manila Bay was analyzed, using sediment properties and other available oceanographic data, to determine possible cyst beds of dinoflagellates, which can serve as bloom inoculum, and to explore the cause or causes for the spatial distribution.

MATERIALS AND METHODS

Cyst and sediment quality analysis

Sediment sampling was conducted in February, September, October and November 2000 in 13 sites of Manila Bay using a gravity corer for horizontal sampling (Fig. 1). All the above samples were analyzed for sediment quality while only the September to November 2000 samples were analyzed for cysts. Processing of sediments for cyst analysis followed the procedure of Matsuoka and Fukuyo (2000). The topmost centimeter portion of the cores were subsampled using a 5-mL syringe and then kept in small containers wrapped in dark plastic bags in controlled room temperature for a maximum of one month to prevent cyst germination. Replicates were stored for archive and the other half of the samples diluted with filtered seawater from Manila Bay and disaggregated manually using a stirrer. Sonicating the diluted samples at 5 micro amplitude for 2 min aided in further disaggregation of the sediment before sieving through 125 μm and 25 μm mesh in succession. The sediment left on the 25 μm sieve were concentrated to 10 mL in a 50-mL glass container. A 1-mL aliquot was analyzed utilizing a Sedgewick-Rafter chamber under 100× to 400× magnification using a Carl Zeiss Axioskop 2 Microscope. Moisture content, wet and dry bulk density, texture, sedimentary structures, and the presence/absence of organic materials were also determined. Texture was ascertained using grain size analysis utilizing wet and dry sieving. The sedimentary structures were recognized by visual inspection and the loss on ignition technique was used to check the presence of organic materials.

$$\text{Dry bulk density} = \frac{\text{dry weight of sample}}{\text{wet volume occupied by the sample}} \quad (1)$$

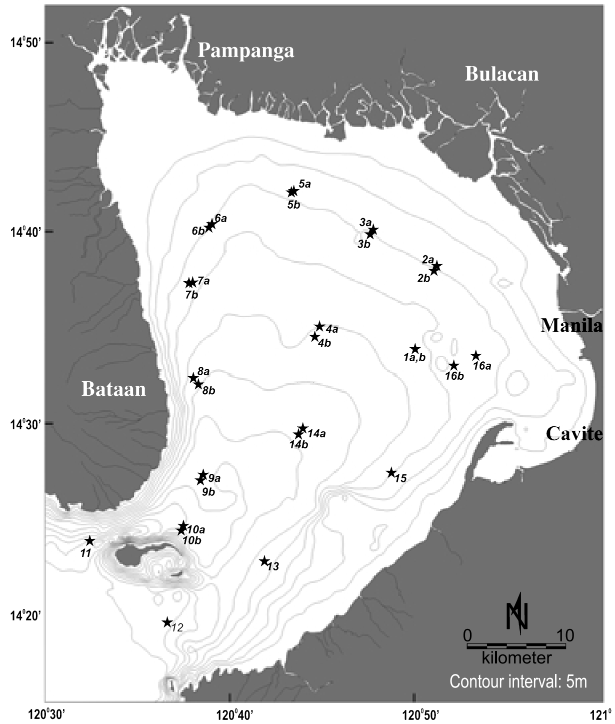

Fig. 1. Map of sampling stations for cyst analysis indicating core numbers.

Pore water analysis

Sediment cores (approx. 50-cm long and 5-cm wide) were collected in March 1999, November 1999, and October 2000 (Fig. 2) using a gravity corer. Transparent core liners made of plastic were used during collection. The upper 10 cm of each core was sectioned at every 1.5 cm interval right after collection. Each section was vacuum filtered through 0.4 μm polycarbonate filters using a fabricated filtration chamber. The fabricated filtration chamber is a fiberglass manifold with port holes to accommodate 20 filter holders. An outlet in the chamber allows attachment to a vacuum pump. The filter holders are sealed on top to prevent oxidation of sediment samples. Porewaters collected were stored in polyethylene vials and kept frozen until analysis in the laboratory. Porewater samples were analyzed for ammonia and phosphate concentrations following the spectrophotometric method of Gieskes (1973) modified from Strickland and Parsons (1972). Samples were also analyzed for hydrogen sulfide (Cline 1969). The solid part of the sediment samples was dried, pulverized and analyzed spectrophotometrically for total organic carbon content following the procedure given in Parsons *et al*. (1984).

Benthic fluxes

Benthic flux estimates were done on all of the core samples collected. Benthic flux of nutrients across the sediment–water interface is primarily controlled by diffusion of nutrients from the sediments into the overlying water column (Klump & Martens 1981). It is given by (Berner 1980):

$$J = -\phi D_s (dC/dz)_{z=0} \quad (2)$$

where J is the flux, ϕ is the porosity at the sediment–water interface, D_s is the molecular diffusion coefficient (Li & Gregory 1974), and $(dC/dz)_{z=0}$ is the gradient

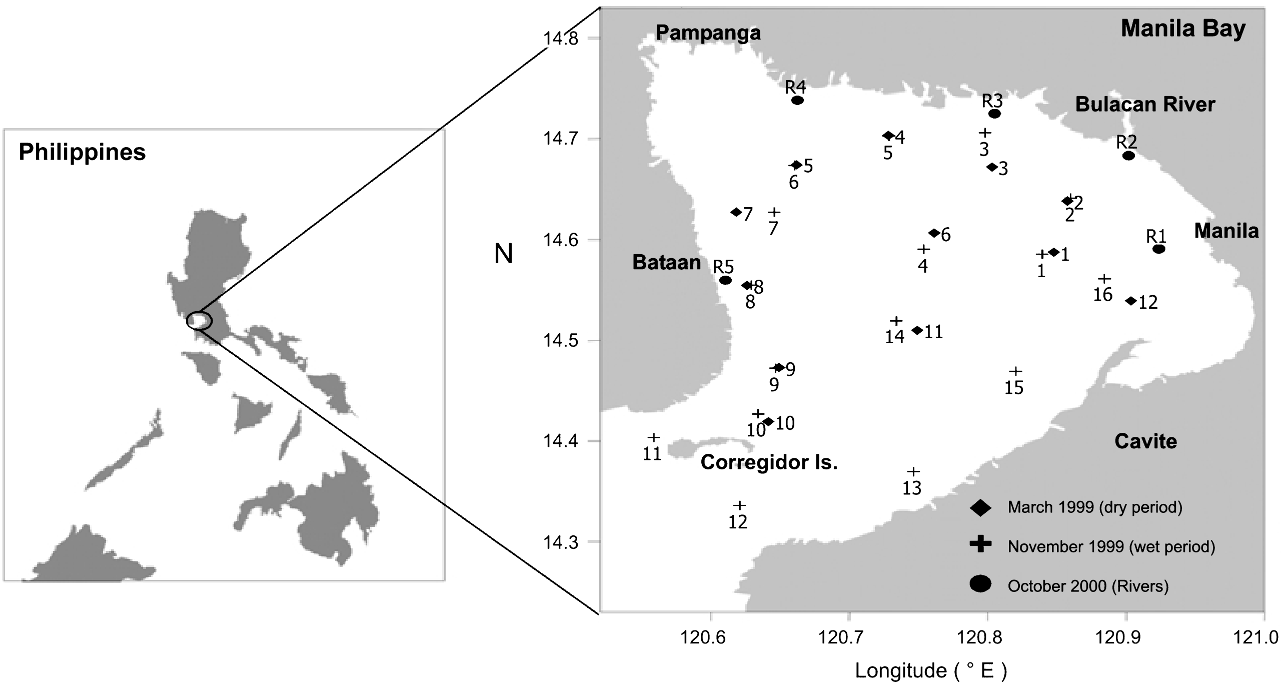

Fig. 2. Map of sampling stations for porewater analysis.

evaluated at the interface. In Manila Bay, the average porosity used was 0.9 cm^3 porewater/cm^3 total sediment based on previous experience/unpublished data of one of the senior authors. The molecular diffusion coefficient is equal to $D_o/\phi F$, where F is the formation factor. It is expressed as $F = 1/\phi^m$, where m (tortuosity and cementation factor) is approximately equal to 3 (Ullman & Aller 1982). D_o is the temperature dependent, free solution diffusion coefficient of a solute (Li & Gregory 1974). Concentration gradients (dC/dz) were estimated from the slopes of porewater concentrations showing linearity.

RESULTS

Pyrodinium and other dinoflagellate cyst distribution

The maximum and minimum counts of dinoflagellate cysts from the surface sediment samples (i.e. September, October and November, 2000) from Manila Bay were 793 and 30 cells/cm^3, respectively. A maximum of 23 dinoflagellate species have been identified. Five species are autotrophic (*Lingulodinium polyedrum*, *Gonyaulax* spp., *Pyrophacus steinii, Protoceratium reticulatum* and *Pyrodinium bahamense* var. *compressum*) and the rest are predominantly composed of *Protoperidinium* spp. and *Diplopsalis* spp. Heterotrophs comprised about 70% of the total cyst counts.

In general, cyst density increased from the center of the bay towards the coast, except in Pampanga Bay (Fig. 3). The heterotrophs showed the same trend (Fig. 4a). In contrast, the autotrophs increased from the coast of Pampanga towards the south-western portion of the bay east of Bataan (Fig. 4b). The heterotrophic to autotrophic ratio increased from the center of the bay towards the coast (Fig. 5).

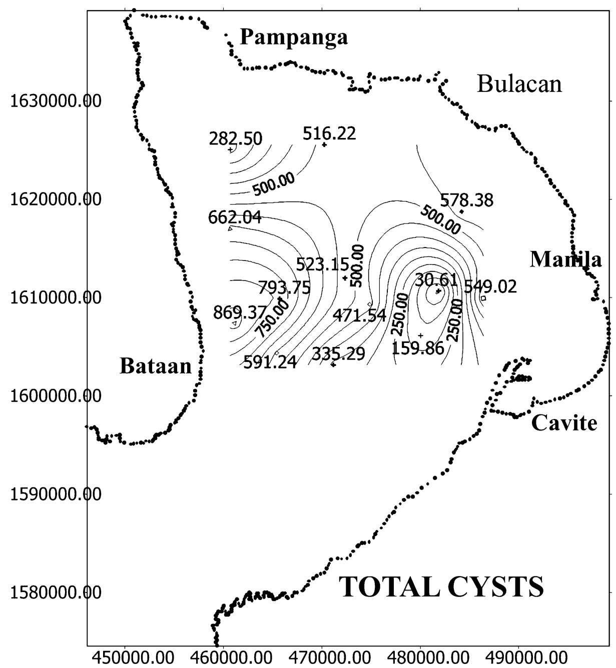

Fig. 3. Spatial distribution of total cyst in cysts/cm^3.

The highest surface cyst densities for *Pyrodinium* were found off Bataan and the southern part of

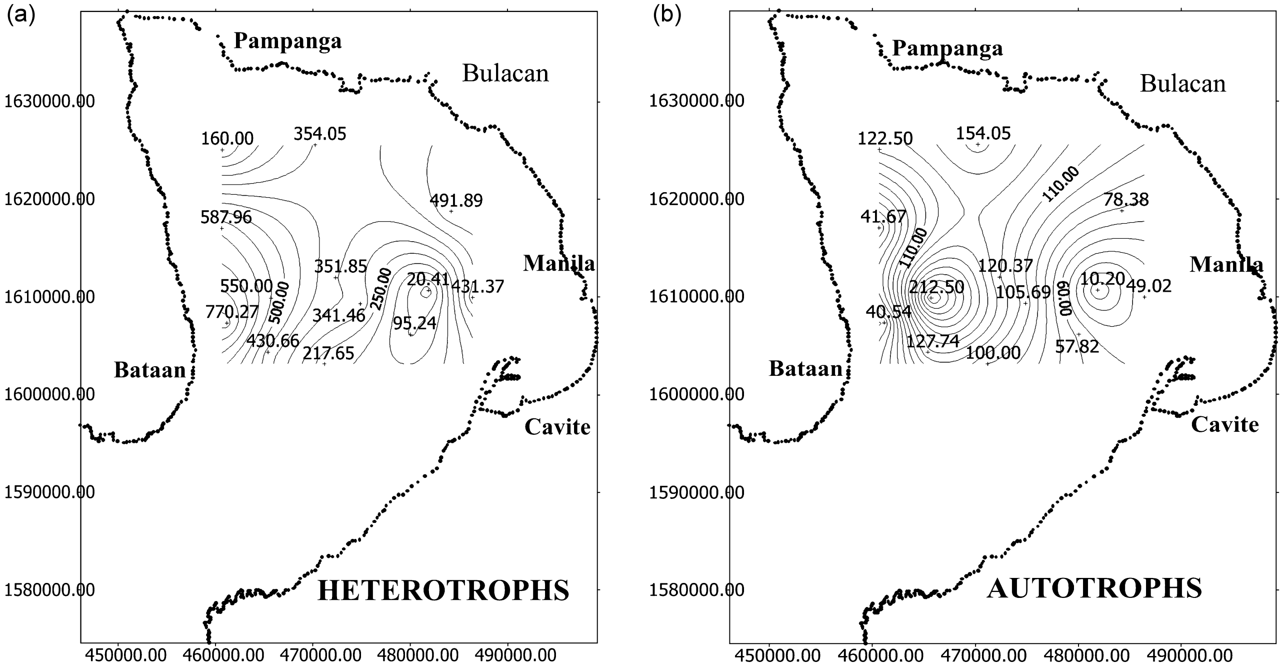

Fig. 4. Spatial distribution of (a) heterotrophs and (b) autotrophs in cysts/cm3.

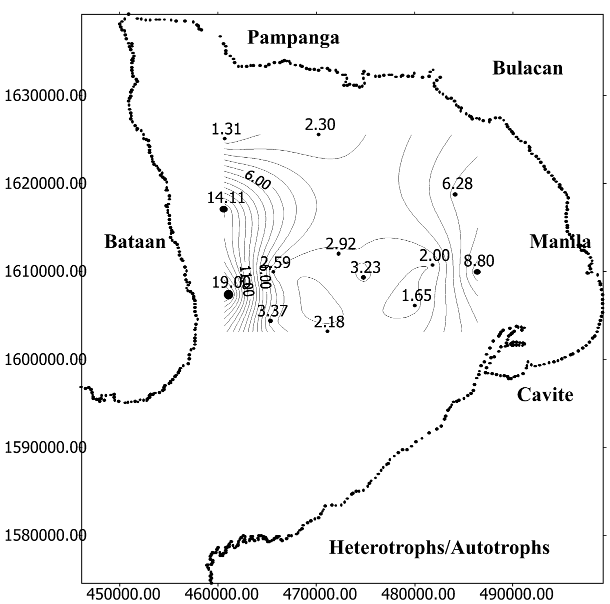

Fig. 5. Spatial distribution map of the ratio between heterotrophs and autotrophs.

Pampanga Bay (Fig. 6) at 140.54 and 117.5 cysts/cm^3, respectively. In general, there was an increase in cyst density in the surface sediment toward the north-western portion of the bay.

Sediment textural distribution and benthic fluxes

The sand fraction of the surface sediments ranged from 0.2 to 36% and was highest in the southern and central north-eastern parts of the bay and was lowest near the coast (Fig. 7). Silt, which ranged from 14 to 87%, was concentrated in the south-eastern portion off the coast of Cavite and extended towards the central part of the bay (Fig. 8). Clay content ranged from 7.4 to 64% and was highest in the coastal areas of Bataan, Pampanga-Bulacan, and Manila (Fig. 9).

Benthic flux values of the nutrients in Manila Bay are given in Table 1. Higher ammonia and phosphate fluxes were seen near Pasig, Bulacan, and Pampanga Rivers where the signal from anthropogenic influence may be strongest (Fig. 10). Incidentally, benthic flux of hydrogen sulfide with values ranging from 2 to 20 μmole/m^2-hr, was highest near Pampanga River.

In the river areas, the spatial distributions of phosphate and sulfide fluxes follow that of organic carbon in the sediments, with highest value determined in Bulacan River. Organic carbon during the dry period ranged from 0.8 to 4%C, with an average value of 2.4%. For the wet period, organic carbon was slightly lower at 1–3.4%, with an average value of 2.0%. In the river areas, organic carbon ranged from 0.5 to 2.7%C, with an average value of 1.7% (Fig. 10).

DISCUSSION

Variation in cyst spatial distribution

Cyst density generally increased from the center of the bay towards the north-western portion, with *Pyrodinium* following the same trend. Furio *et al.* (1996) also found the same results in Manila Bay and in Palawan (Furio *et al.* 2003). The location of relatively higher

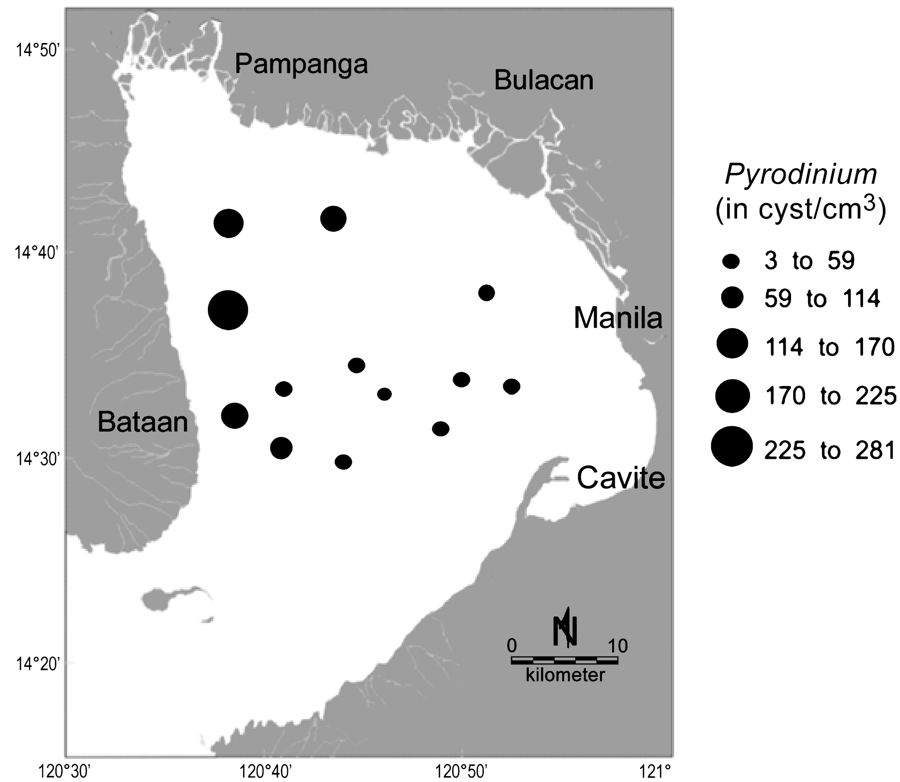

Fig. 6. Distribution of *Pyrodinium* cyst density in Manila Bay.

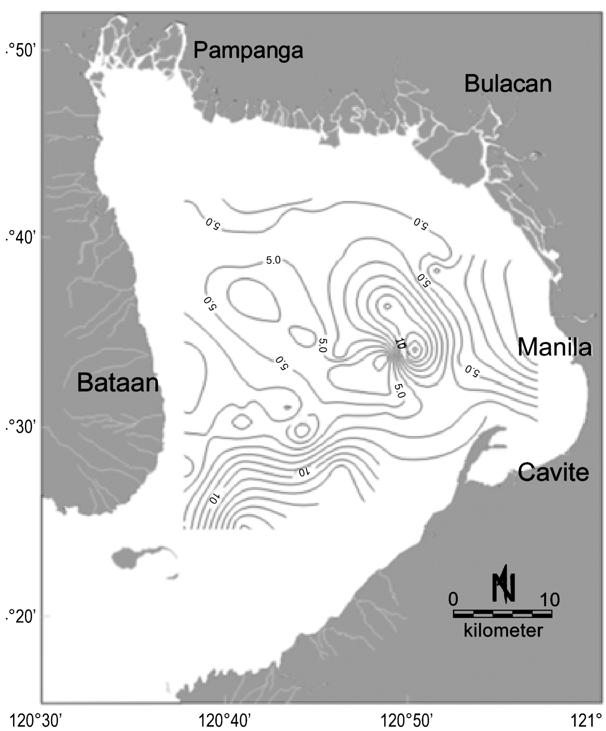

Fig. 7. Distribution of sand in Manila Bay.

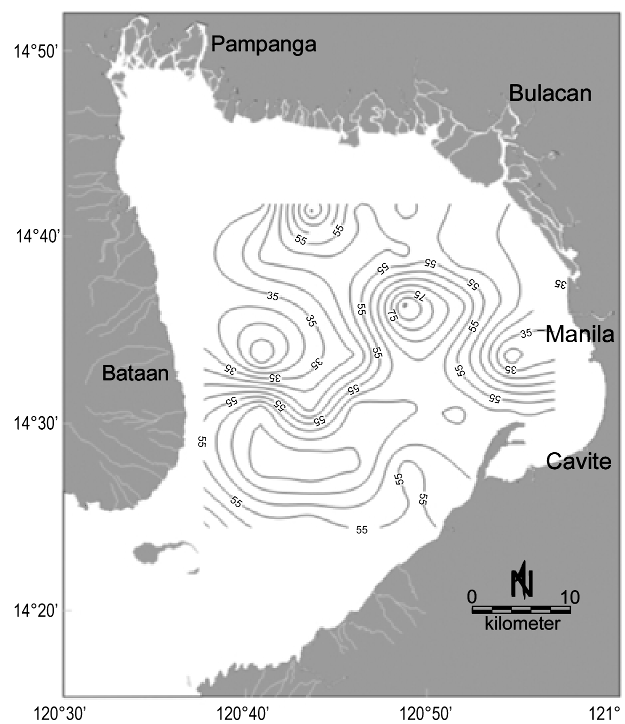

Fig. 8. Distribution of silt in Manila Bay.

cyst densities coincided with areas in the Bay where sediment accretion is likely to occur (Siringan & Ringor 1998). Higher cyst densities also occurred in areas where water current velocities become minimal (Villanoy & Martin 1997), therefore allowing finer-grained sediments to deposit. High cyst densities were generally found in areas where clay content is high. This implies that the dinoflagellate cysts are hydrodynamically equivalent to

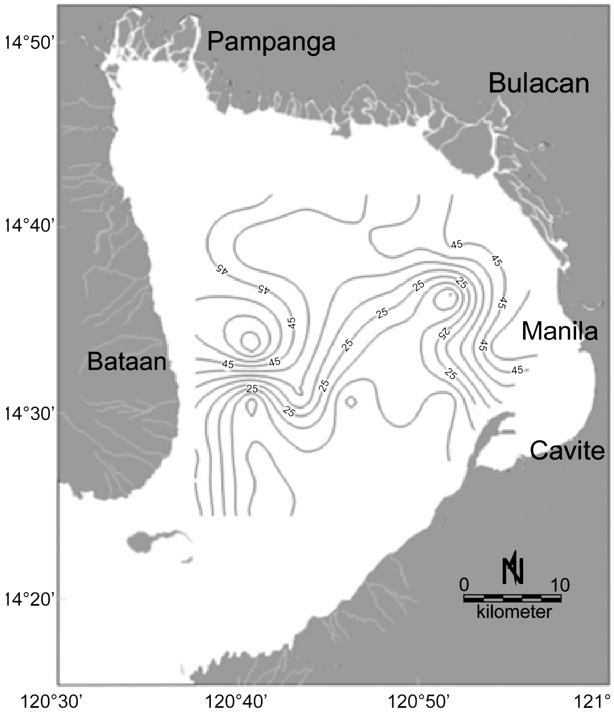

Fig. 9. Distribution of clay in Manila Bay.

clay. Kawamura (2003a) also reported that this is true for sediments in the South China Sea where the taxa behaved like sediment particles in water with size ranging from phi°5.75–6.25.

The presence of cyst beds in the western part of Manila Bay coincided with the location (west coast of Bataan) of the highest live *Pyrodinium* cyst densities, as determined by Corrales and Crisostomo (1996). This area has been hypothesized to be the source of inoculum for the blooms, at least for the north-western portion. The location of these suggested cyst beds agrees with observations that past blooms started in the west/north-west before spreading to other areas of Manila Bay.

During the 1992–1994 annual blooms, Bajarias and Relox (1996) recorded that *Pyrodinium* cells first occurred on the western area of the Bay (off Bataan); after which, the blooms spread to the north then to the east. This was also seen in shellfish toxicity recorded during *Pyrodinium* blooms from 1991 to 1998. Toxicity was also almost always detected first in the north-western part of the Bay (Bataan) (Red Tide Taskforce 1991–98), then in the nearby northern stations of Bulacan and Navotas, and lastly in Cavite. Both *Pyrodinium* cells and toxicity were observed to be highest in the north-western part (Bataan) and the blooms generally prevailed there even when other areas in Manila Bay were already free of the organism and toxin.

In Pampanga Bay, where sedimentation rate is high (Sombrito *et al.* 2004), cyst counts are also high. This may also be because of its proximity to the bloom area

Table 1. Benthic flux values (in μmole/m^2-hr) of nutrients in Manila Bay

Nutrient	Range (dry)	Range (wet)
Ammonia	46–205	47–105
Phosphate	3–17	2–30

which is nearby (off Bataan) and the northward transport of cysts consistent with the wind-driven circulation pattern of the bay during the south-west monsoon (De las Alas & Sodusa 1985; Villanoy & Martin 1997). Earlier, Kawamura (2003b) also noted that the concentration of cysts in shelf sediments in the South China Sea are mainly controlled by transport and upwelling processes and are most probably not a representation of the condition of surface water.

In the Cavite area, where blooms have also been observed, cyst counts are, however, almost lower by an order of magnitude. Dilution does not appear to be the cause of low cyst count since the sedimentation rate here is similar to the Pampanga cores. More likely, cysts are not transported to this site since the blooms have usually occurred in Bacoor Bay (Bajarias & Relox 1996) and are likely to be trapped in this area as a result of the formation of back eddies at the tip of the spit (Siringan & Ringor 1997; Villanoy & Martin 1997).

Temporal variation of cysts

Some core samples from Bataan collected during the north-east monsoon showed relatively lower cyst density, although the general cyst concentration in the area was high. Bataan is the area where most blooms are initiated. It is highly possible that the low cyst count was a result of the cyst resuspension (i.e. cysts are in the water column) during this season, which is favorable for this event as shown by previous observation of Corrales and Crisostomo (1996).

Monitoring of past blooms have shown that *Pyrodinium* cells disappear from Bay waters during the latter months of the north-east monsoon (Bajarias & Relox 1996; Villanoy *et al.* 1996), strongly suggesting that the live cysts present (in varied concentration) all year round in the sediments could seed the subsequent blooms that occur usually during the start of the south-west monsoon (Corrales & Crisostomo 1996). From previous studies showing toxicity, *Pyrodinium* cell and cyst data, it appears that Bataan is the site for initiation as well as intense development of blooms. Using a one-dimensional mixed-layer model, a possible mechanism for bloom initiation and development has been suggested (Villanoy *et al.* 1996). The strong vertical mixing that occurs during the north-east monsoon (November to February) could provide the

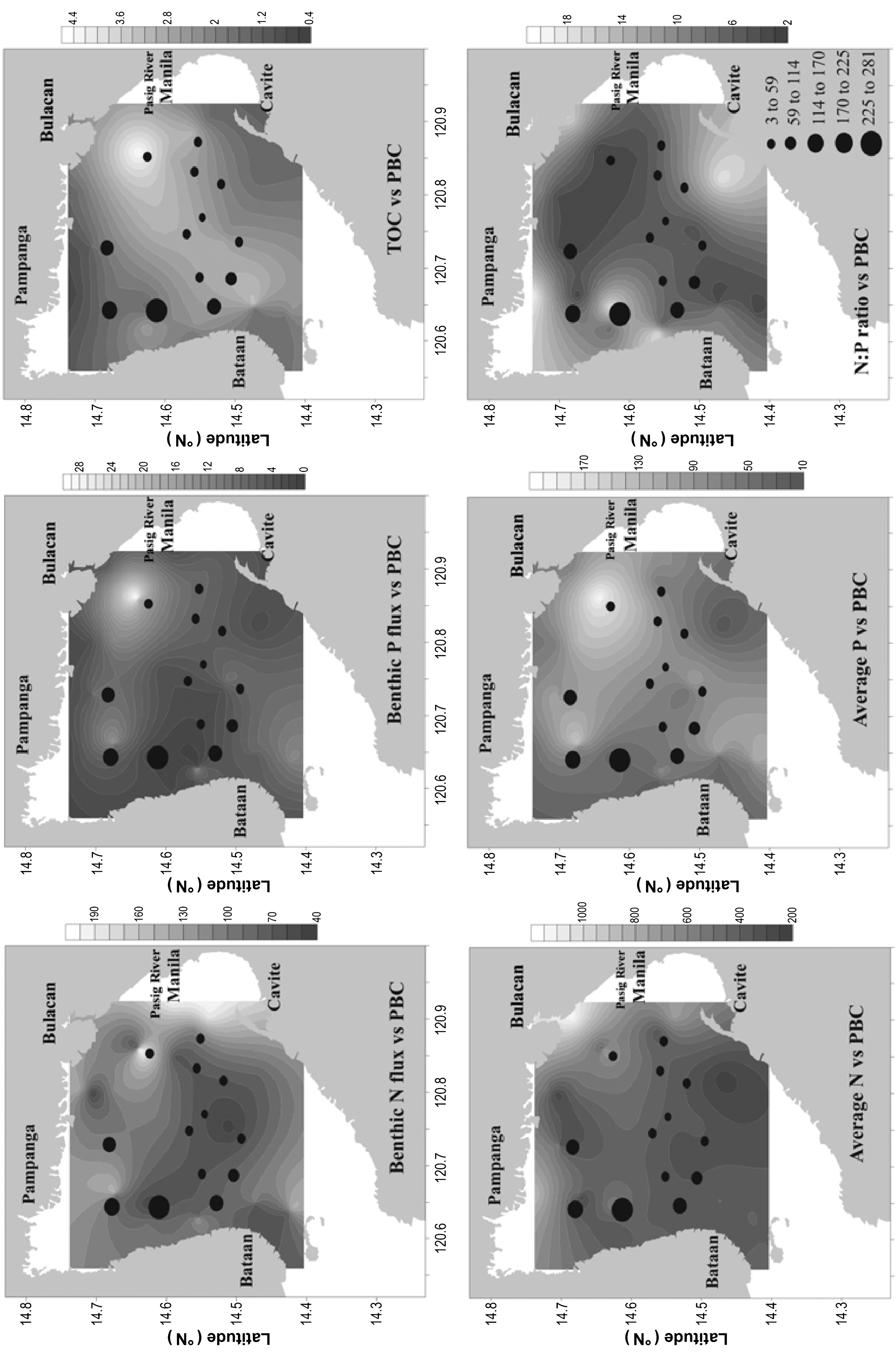

Fig. 10. Distribution of *Pyrodinium bahamense* var. *compressum* (PBC) in cysts/cm^3 superimposed against nutrient benthic fluxes (µmole/m^2-hr), TOC (%C), porewater nutrients (µM) and N:P ratio in Manila Bay.

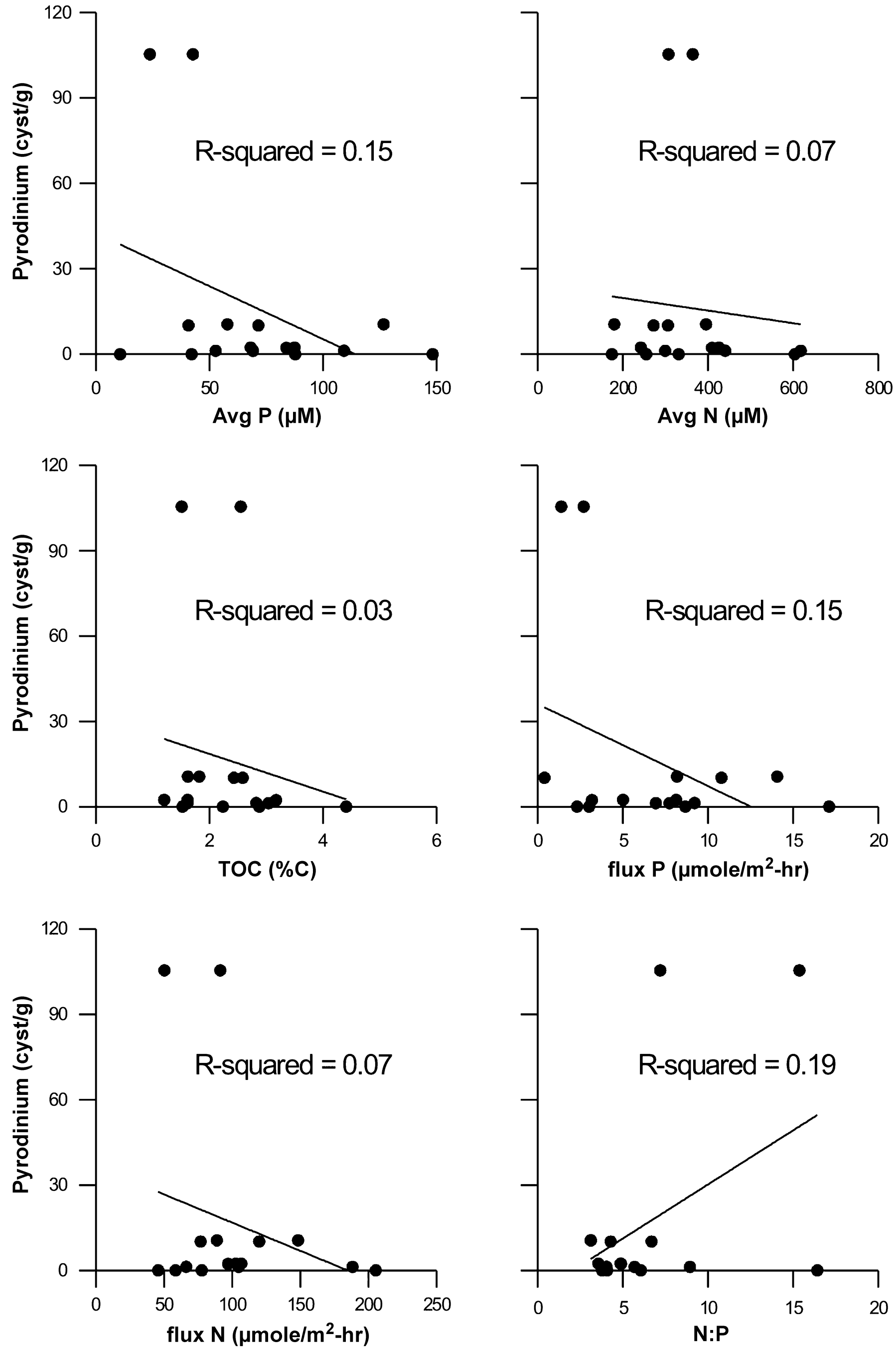

Fig. 11. Correlation analysis between cyst density of *Pyrodinium bahamense* var. *compressum* and porewater nutrients (μM), TOC (%C), benthic flux (μmole/m^2-hr) and N:P ratio in Manila Bay.

means for cyst resuspension, thereby explaining the low cyst densities in the sediments during this period. However, these suspended cysts and resulting vegetative cells may be unable to excyst or divide, respectively, because of other unfavorable conditions (e.g. relatively low temperature) (Villanoy *et al.* 1996). With the onset of the south-west monsoon (June–August), temperature rises, vertical stratification develops, and rainfall/terrestrial run-off increases (i.e. source of limited nutrients or growth factor), which seem to favor *Pyrodinium* bloom development (Bajarias & Relox 1996; Usup & Azanza 1998). The high cyst concentrations coinciding with the high cell densities during the south-west monsoon were attributed to reduced resuspension and/or increased deposition of new cysts from the past bloom (Villanoy *et al.* 1996).

Benthic fluxes and Pyrodinium horizontal cyst distribution

The increase in cyst density towards the coast is likely to be caused by high primary productivity in shallow waters as a result of high nutrient levels. On the assumption that a cyst, during its resting stage, could interact with the environment, for example take in nutrients (Rengefors *et al.* 1996), live cyst density distribution of *P. bahamense* var. *compressum* in the upper 10 cm of the sediment column was examined vis a vis the different chemical parameters obtained from the present study (Fig. 10). In general, high benthic fluxes and average porewater ammonia and phosphate concentrations were observed towards the coastal areas of Pampanga, Bulacan and Pasig. However, live *Pyrodinium* cyst density was high along the coast of Bataan and low in the Pasig and Bulacan areas. The result of correlation analysis is given in Fig. 11. Although not significant, negative correlations were observed for cyst density and N flux, P flux, average porewater N and P, and TOC.

Riegman (1998) suggested that it is not only nutrient concentrations that are important in controlling primary productivity but also the ratio of the nutrients to each other. Studies such as those by Hodgkiss and Ho (1997), Maso *et al*. (2000) and Thompson (2000) have shown the relevance of N:P ratios of nutrients in regulating the growth of dinoflagellates. In the present study, N:P ratios were calculated based on the assumption that the only source of N in the porewater is ammonia. N:P ratios ranged from 3 to 19, lower than the Redfield ratio of 16. Low N:P ratios (<7) in the eastern side could be attributed to the high P content of the domestic sewage coming from Pasig River. The N:P ratios and the *Pyrodinium* distribution in the Bay are shown in Fig. 10. A positive correlation ($R^2 = 0.19$) was observed, indicating high cyst density in areas with higher N:P ratio. However, more conclusive results may be obtained if cyst density is also determined in Bulacan and Cavite, sites of high N:P ratio. The result of the present study is in contrast with findings of Ho and Hodgkiss (1993), where a relatively low N:P ratio (6–15) was determined to be optimal for the growth of most of the causative organisms of red tide in Hong Kong. It should be noted however, that a different set of dinoflagellate species was found there.

Pollution because of heavy metals has also been found to play an important role in controlling the distribution of dinoflagellates (Sætre *et al*. 1997). The small amount of *Pyrodinium* off Pasig River may be because of increased metal pollution in this part of the bay, similar to findings elsewhere (Dale 1996; Sætre *et al*. 1997; Thorsen & Dale 1997; Matsuoka & Fukuyo 2000) where autotrophs significantly decreased in polluted areas. From geochemical analysis of sediments in the bay, Ni, Pb, and Zn were determined to be highest within this area (Siringan *et al*. 2001, unpubl. data).

As indicated in previous discussion, aside from their association with clay-sized materials, dinoflagellate cysts are mostly found in areas with high bulk density, low organic matter concentration and moderate moisture content. These associations suggest that the cysts are deposited in relatively cohesive substrate with lower potential for resuspension.

It was determined also that a negative correlation exists between *Pyrodinium* and other gonyaulacoid cysts (primarily *Lingulodinium polyedrum* and *Gonyaulax* spp.), which was also observed by Bradford and Wall (1984) in the Persian Gulf and Musandam. According to them, *Pyrodinium* could become dominant in particular areas, therefore decreasing species diversity. This may be as a result of *Pyrodinium* being more tolerant of restrictive conditions (i.e. increased salinity, decreased winter temperature, higher energy, less oceanic influence) in areas where it is more abundant.

Although the present study has further proven that spatio-temporal variation in cyst concentration is affected by sediment characteristics and benthic flux, more studies should be done to verify present results and provide missing data on the bio-geochemical and physical factors/dynamics affecting dinoflagellate blooms.

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