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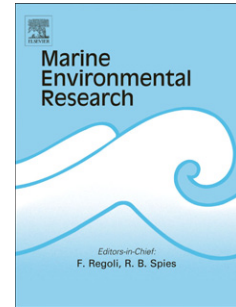
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1 Changes in the nutrient ratios and phytoplankton community after declines in nutrient  
2 concentrations in an eutrophic semi-enclosed bay in Hong Kong

3

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15 Abstract

16

17 Tolo Harbour is a landlocked bay with poor tidal flushings in the northeastern part of  
18 Hong Kong. During the 1980s, excessive nutrient loading led to dramatic increase in  
19 nutrient concentrations, accompanied by lower N:P ratios, higher algal biomass and  
20 shifts in the phytoplankton community. We studied the effects of nutrient loading  
21 reduction measures on nutrient concentrations, nutrient ratios and phytoplankton  
22 dynamics in Tolo Harbour by comparing data collected before the full implementation  
23 of nutrient loading reduction measures (1986–1997) to those after the implementation  
24 (1998–2008). Such measures led to declines in nutrient concentrations, changes in  
25 N:P and N:Si ratios, lower chlorophyll-*a* concentrations and fewer algal blooms.  
26 Diatoms were the most abundant phytoplankton group in Tolo Harbour both before  
27 and after declines in nutrient concentrations. The density of dinoflagellates did not  
28 change, but substantial increase in other algal group abundance was recorded.

29

30 Keywords: Nutrients, Nutrient ratios, Phytoplankton, Eutrophication, Coastal waters,

31 Tolo Harbour.

## 32 **1. Introduction**

33

34 Eutrophication is a common consequence of anthropogenic activities on water  
35 bodies, and is widely regarded as the most wide-spread water quality problem  
36 globally (Carpenter et al., 1999; Smith et al., 1999; Smith, 2003). The most common  
37 effects of eutrophication are increases in phytoplankton productivity and biomass,  
38 which in turn produce other adverse effects such as decreases in water transparency,  
39 increases in the frequency of bottom hypoxia or anoxia and loss of various aquatic  
40 organisms (Nixon, 1995; Smith et al., 1999; Smith, 2003). Numerous recent studies  
41 have linked eutrophication to algal blooms which cause ecological and economical  
42 damages (e.g. Anderson et al., 2008; Cloern, 2001; Smith et al., 1999). Nutrient  
43 loadings may cause changes in the nutrient ratios (Justić et al., 1995; Turner, 2002),  
44 and such changes may affect the species composition of the phytoplankton  
45 community and higher trophic levels (Officer and Ryther, 1980; Philippart et al., 2000;  
46 Smith, 1983; Turner et al., 1998; Turner, 2002). Although eutrophication in freshwater  
47 systems has been studied extensively and intensively during the past few decades,  
48 with many studies reporting on the effects of increased or decreased nutrient  
49 concentrations in lakes (e.g. Battarbee et al., 2005; Carvalho and Kirika, 2003;  
50 Jeppesen et al., 2005; Jeppesen et al., 2007; Mehner et al., 2001), similar kinds of

51 studies, with long-term monitoring data, are relatively scarce in marine coastal  
52 ecosystems (Examples summarized by Smith et al., 1999).

53 Hong Kong is one of the most densely populated cities in the world. Intensive  
54 urbanization and industrialization during the past few decades has dramatically  
55 increased nutrient input into Hong Kong's coastal seas (Lee et al., 2006). The concern  
56 on the coastal water quality led to the initiation of a marine water quality monitoring  
57 program by the Hong Kong Environmental Protection Department in the 1980s (Lee  
58 et al., 2006). One of the intensely monitored zones is Tolo Harbour, a landlocked bay  
59 in the northeastern corner of Hong Kong.

60 Tolo Harbour consists of a shallow inner bay, with a mean depth of 6–7 m, and a  
61 narrow tidal channel which opens into the neighboring Mirs Bay. Urban development  
62 and large-scale reclamation around Tolo Harbour began in the 1970s. Sewage  
63 discharge from the expanding population caused a sharp increase in nutrient input  
64 (Lam and Ho, 1989; Wear et al., 1984). Hodgkiss and Yim (1995) estimated a daily  
65 nitrate and phosphate loading of 32,460 kg and 3,190 kg respectively into Tolo  
66 Harbour. In addition to nutrient inputs, the bottleneck topography of the Tolo Harbour  
67 leads to poor tidal exchange rates and persistence of high nutrient concentrations (Lee  
68 et al., 2006). Increased nutrient concentrations produced algal blooms, with  
69 dinoflagellates such as *Noctiluca scintillans* being the most common causative species

70 during the 1980s and 1990s (Lam and Ho, 1989; Liu and Wong, 2006). Although  
71 *Noctiluca* are generally considered as heterotrophic (Kiørboe and Titelman, 1998),  
72 strains of *Noctiluca miliaris* with photosynthetic symbionts have been found in  
73 Southeast Asia (Sweeney, 1971; Hansen et al., 2004), which may benefit from  
74 increased nutrient concentrations (Sriwoon et al., 2008). In addition, the increased  
75 nutrient concentrations would also favor the growth of diatoms and other prey for *N.*  
76 *scintillans* (Liu and Wong, 2006).

77 Wear et al. (1984) reported mean concentrations of  $\text{NO}_x\text{-N}$  and  $\text{PO}_4\text{-P}$  in the  
78 inner Tolo Harbour to be  $0.05 \mu\text{M}$  and  $0.01 \mu\text{M}$  respectively during 1974–1976. By  
79 early 1990s, annual mean concentrations have increased to  $19.99 \mu\text{M}$  for inorganic  
80 nitrogen and  $1.94 \mu\text{M}$  for  $\text{PO}_4\text{-P}$  (Hong Kong Environmental Protection Department,  
81 1991). Moreover,  $\text{PO}_4\text{-P}$  values as high as  $10.65 \mu\text{M}$  have been reported in Tolo  
82 Harbour in 1978–1979 (Hodgkiss and Chan, 1983). Decreasing trends in N:P ratio  
83 were recorded during the 1980s and early 1990s (Hodgkiss and Chan, 1997; Yung et  
84 al., 1997), and was considered to be caused by excessive P input (Hodgkiss and Chan,  
85 1983, Hodgkiss and Yim, 1995). Some researchers noted that the observed changes in  
86 nutrient parameters had caused a shift in the species composition of the phytoplankton  
87 community, with diatoms gradually replaced by dinoflagellates, (Chan and Hodgkiss,  
88 1987; Hodgkiss and Ho, 1997; Lam and Ho, 1989), although a review of the data

89 collected by the Hong Kong Environmental Protection Department did not reveal such  
90 a shift in the phytoplankton during 1982–1992 (Yung et al., 1997).

91 The Hong Kong Government initiated the Tolo Harbour Action Plan in 1986 to  
92 halt the declining water quality of Tolo Harbour. Two of the most important  
93 components of the action plan were the modification of existing sewage treatment  
94 works processes (implemented in 1992) and the Tolo Harbour Effluent Export  
95 Scheme (Chau, 2007). Commissioned in the mid-1990s and became fully operational  
96 in 1998, the Tolo Harbour Effluent Export Scheme allows treated sewage from two  
97 large sewage treatment works to be exported via pipelines for discharge outside of  
98 Tolo Harbour. Nitrogen input into Tolo Harbour was reduced to  $\sim 1000 \text{ kg day}^{-1}$  by  
99 2000 (Hong Kong Environmental Protection Department, 2006).

100 In this study, data collected from four sampling stations in Tolo Harbour during  
101 the period from 1986–2008 were analyzed to provide information on the long-term  
102 changes in the hydrography and phytoplankton dynamics. Conditions before  
103 (1986–1997) and after (1998–2008) the full implementation of the Tolo Harbour  
104 Effluent Export Scheme were compared to: (1) determine whether declines in nutrient  
105 concentrations had led to changes in the nutrient ratios, and (2) identify shifts in the  
106 phytoplankton community that may be related to changes in the nutrient  
107 concentrations and ratios. Overall changes of the hydrography and phytoplankton



108 community in Tolo Harbour after declines in nutrient concentrations were also  
109 compared to those reported in other ecosystems after recovery from eutrophication.

110

## 111 **2. Materials and Methods**

112

113 All data were provided by the Hong Kong Environmental Department. Four  
114 sampling stations in Tolo Harbour, TM3, TM4, TM6 and TM8 (Fig. 1), were sampled  
115 frequently, mostly once each month, but irregularly from 1982–1992. Monthly means  
116 were calculated for each station. Physico-chemical parameters, including temperature,  
117 salinity, pH and dissolved oxygen concentration (DO), were recorded at 1 m below  
118 the water surface, mid-depth in the water column and 1 m above the bottom by a  
119 SEACAT 19*plus* CTD water profiler (Sea-BIRD Electronics). Water samples were  
120 also collected at the three depths using Niskin-type water bottles for the determination  
121 of BOD<sub>5</sub>, chlorophyll-*a* concentration, suspended solids concentration, and the  
122 concentrations of NO<sub>3</sub>-N, NH<sub>4</sub>-N, total inorganic nitrogen (TIN), total nitrogen (TN),  
123 PO<sub>4</sub>-P, total phosphorus (TP) and SiO<sub>2</sub>. The data from the three depths were averaged  
124 into depth-averaged data. Values from the bottom depth were also analyzed for DO  
125 and BOD<sub>5</sub> to provide information on hypoxia at the water bottom. Measurement of  
126 BOD<sub>5</sub>, nutrient concentrations, chlorophyll-*a* concentration and suspended solids

127 concentration were carried out by the Hong Kong Government Laboratory using  
128 procedures described by APHA (American Public Health Association et al. 1998).  
129 Data on algal bloom occurrences were obtained from the Hong Kong Agriculture,  
130 Fisheries and Conservation Department, and were independent from our data. Such  
131 data on algal bloom occurrences was based on sighting reports of seawater  
132 discoloration, and may therefore underestimate algal bloom occurrences. It also does  
133 not contain taxonomic information regarding the algal bloom.

134

135 *(Insert Fig. 1 here)*

136

137 Water samples from 1 m below the water surface were preserved in Lugol's  
138 iodine solution (1: 100 ml). In the laboratory, phytoplankton were examined in an  
139 Utermöhl counting chamber under an inverted microscope, and the densities of  
140 diatoms, dinoflagellates and other algal groups (Algae that were neither diatoms nor  
141 dinoflagellate) were counted. Phytoplankton data for TM6 was only available after  
142 1993, while data collection for other stations have began in 1986 (TM8) and 1988  
143 (TM3 and TM4).

144 Two-way ANOVA was used to test for temporal differences before and after  
145 nutrient loading reduction, as well as the spatial differences among sampling stations

146 in various water quality and phytoplankton parameters. Tukey's test was used for  
147 multiple comparison between sites. Kendall's correlation was used to test the  
148 correlation between phytoplankton and water quality variables.

149

### 150 **3. Results**

151

152 In general, physico-chemical, biological and nutrient parameters showed similar  
153 changes among the four sampling stations after nutrient loading reduction (Table 1).  
154 Temperature, salinity, bottom DO and TIN/PO<sub>4</sub> increased at all stations after nutrient  
155 loading reduction, while pH, BOD<sub>5</sub>, chlorophyll-*a* concentrations, all nutrient  
156 concentrations and TIN/SiO<sub>2</sub> decreased. DO and SiO<sub>2</sub> concentration did not differ  
157 significantly between the two time periods and among the stations respectively ( $p >$   
158  $0.05$ ). All other parameters showed significant differences both temporally and  
159 spatially, with most  $p$  values  $< 0.001$ . Comparison among sampling stations revealed a  
160 general trend of improvement in water quality, marked by changes such as decreasing  
161 nutrient concentrations and increasing DO and secchi depth, from TM3 to TM8.

162

163 *(Insert Table 1 here)*

164

165 N (including  $\text{NO}_3\text{-N}$ ,  $\text{NH}_4\text{-N}$ , total inorganic N and total N) and P (including  
166  $\text{PO}_4\text{-P}$  and total P) concentrations were high, especially at TM3 and TM4, prior to  
167 nutrient loading reduction (Fig. 2). Concentrations decreased noticeably within a year  
168 after the full implementation of the sewage export scheme, and have remained at  
169 relatively low levels in recent years. N and P concentrations differed markedly among  
170 stations before nutrient loading reduction, but the differences became less apparent  
171 afterwards.  $\text{SiO}_2$  concentrations did not appear to differ among stations before nutrient  
172 loading reduction.  $\text{NO}_3/\text{NH}_4$  fluctuated widely during the entire study period, but the  
173 value was generally lowest at TM3 and highest at TM8 (Fig. 3). In contrast,  $\text{TIN}/\text{PO}_4$   
174 and  $\text{TIN}/\text{SiO}_2$  showed much clearer increasing and decreasing trends respectively (Fig.  
175 3).  $\text{TIN}/\text{PO}_4$  decreased gradually from between 1986 and 1996, but have returned to  
176 approximately the 16:1 Redfield N:P ratio after declines in nutrient concentrations.  
177 Declines in nutrient concentrations reduced the among-station differences in  $\text{TIN}/\text{SiO}_2$   
178 and the values at all stations were well below the 1:1 Redfield ratio for N:Si.

179

180 *(Insert Fig. 2 and Fig. 3 here)*

181

182 Chlorophyll-*a* concentrations and densities of different phytoplankton groups  
183 exhibited varying trends temporally (Figs. 4 and 5 respectively). The lack of apparent

184 similar trends between chlorophyll-*a* concentrations and phytoplankton densities may  
185 be due to the fact that chlorophyll-*a* data were depth-averaged, while phytoplankton  
186 data were from the surface only. In general, the concentrations of chlorophyll-*a* and  
187 densities of all phytoplankton groups were highest at TM3 and lowest at TM8.  
188 Dinoflagellate density at TM3 increased to two major peaks of  $> 10,000$  cells  $\text{ml}^{-1}$  in  
189 1996 and 1998, and decreased to  $< 1,000$  cells  $\text{ml}^{-1}$  in recent years. Other algal groups  
190 occurred at densities of  $< 5000$  cells  $\text{ml}^{-1}$  before 1996, but increased rapidly and  
191 considerably after 1996. Density at TM3 remained  $> 6,000$  cells  $\text{ml}^{-1}$  after declines in  
192 nutrient concentrations. As diatoms were the most abundant group, the density of total  
193 phytoplankton exhibited temporal and spatial patterns more similar to those of  
194 diatoms than those of dinoflagellates and other algal groups. Declines in nutrient  
195 concentrations did not affect the density of dinoflagellates significantly, but densities  
196 of diatoms, other algal groups and total phytoplankton all showed significant increase  
197 after declines in nutrient concentrations. Despite a significant increase in total  
198 phytoplankton density, the number of algal blooms recorded in Tolo Harbour dropped  
199 significantly from a mean of 15.8 before nutrient loading reduction to 7.6 (Paired  
200 t-test,  $p = 0.02$ ) afterwards. No specific phytoplankton group or genus identified in the  
201 study could be concluded to be restricted to a particular station. Diatom genera  
202 common in all four stations and with average densities  $> 1,000$  cells  $\text{ml}^{-1}$  in TM3 and

203 > 600 ml<sup>-1</sup> in TM8 included *Cerataulina*, *Chaetoceros*, *Pseudo-nitzschia*,  
204 *Leptocylindrus* and *Thalassiosira*. *Prorocentrum* and *Scrippsiella* were the most  
205 abundant dinoflagellate genera in all stations. Average density was > 1,000 cells ml<sup>-1</sup>  
206 in TM3 and > 250 cells ml<sup>-1</sup> in TM8 for *Prorocentrum*, and > 700 cells ml<sup>-1</sup> in TM3  
207 and > 100 cells ml<sup>-1</sup> in TM8 for *Scrippsiella*. The dinoflagellates *Gymnodinium*,  
208 *Gyrodinium* and *Proto-peridinium* were also frequently found at all stations, but their  
209 average densities were much lower. Small flagellates represented the most abundant  
210 and frequently recorded other algal group in the samples.

211

212 (Insert Fig. 4 and Fig. 5 here)

213

214 Hong Kong is characterized by a warm wet season from April to September, and  
215 a relatively dry and cool season for the rest of the year. However, when plots of  
216 seasonal means of nutrient concentrations and phytoplankton densities were made, no  
217 apparent and general trend could be identified (Data not shown).

218 Kendall's correlation did not reveal any strong or obvious trends between  
219 phytoplankton variables and various parameters (Table 2). Results for TM3 and TM4  
220 seemed to oppose those for TM6 and TM8 at times. For instance, correlation between  
221 phytoplankton variables and DO and BOD<sub>5</sub> were usually positive at TM3 and TM4,

222 but negative at TM6 and TM8, and vice versa with the results for SiO<sub>2</sub>. It is also not  
223 uncommon to find contradicting results between phytoplankton cell densities and  
224 chlorophyll-*a* concentrations due to the different trends exhibited by these two  
225 parameters. Correlation between phytoplankton variables and nutrient variables were  
226 mostly negative in all stations except TM6. Most phytoplankton variables at TM3 and  
227 TM4 correlated significantly and negatively with nutrient concentrations. In TM6,  
228 chlorophyll-*a* concentrations correlated negatively with NO<sub>3</sub>-N and NH<sub>4</sub>-N  
229 concentrations, while dinoflagellate densities correlated positively with total N, PO<sub>4</sub>-P  
230 and total P concentrations. NO<sub>3</sub>/NH<sub>4</sub> correlated negatively with the densities of all  
231 groups of phytoplankton at TM3, and positively with diatom densities at TM6 and  
232 TM8. TIN/PO<sub>4</sub> correlated positively with other algal group densities in all stations.  
233 TIN/SiO<sub>2</sub> correlated negatively with phytoplankton densities in all stations, but  
234 exhibited especially strong negative correlations with the densities of dinoflagellates,  
235 other algal groups and total phytoplankton at TM3 and TM4. Kendall's correlations  
236 between the number of algal blooms and all parameters were also determined.  
237 Surprisingly, the number of algal blooms did not correlate significantly with  
238 phytoplankton densities, nutrient concentrations and nutrient ratios. It correlated  
239 weakly with pH ( $r = 0.313$ ) and bottom DO ( $r = 0.305$ ) ( $p < 0.05$ ), and strongly with  
240 BOD<sub>5</sub> ( $r = 0.513$ ) and chlorophyll-*a* concentration ( $r = 0.417$ ) ( $p < 0.01$ ).

241

242 *(Insert Table 2 here)*

243

244 **4. Discussion**

245

246 *4.1. Temporal and spatial variations in marine water quality and phytoplankton*247 *densities*

248

249 While spatially there is an apparent pattern of better water quality in TM6 and  
250 TM8, all parameters show high temporal variations and do not exhibit an apparent  
251 trend except changes due to nutrient loading reduction measures. Our data set is  
252 unable to explain the cause of specific events such as the relatively lower nutrient  
253 concentrations during 1989 (Fig. 2), and the rise in phytoplankton densities in 1995  
254 (Fig. 5), which may be due to isolated algal bloom events that inflated the annual  
255 mean value. Both of these parameters may also be affected by factors such as water  
256 current, weather conditions and anthropogenic activities that are not available in our  
257 data set.

258 Changes in various physico-chemical and biological parameters, especially  
259 nutrient concentrations, after the implementation of the Tolo Harbour Action Plan



260 suggested that nutrient loading reduction measures had led to water quality  
261 improvement in Tolo Harbour. While Hu et al. (2001) warned that recovery after  
262 nutrient loading reduction in Tolo Harbour may be slowed due to nutrients released  
263 into the water column from contaminated sediments, N and P concentrations appeared  
264 to decrease quite rapidly (Fig. 2) after the full implementation of the Tolo Harbour  
265 Effluent Export scheme. Surprisingly, although chlorophyll-*a* concentrations had  
266 decreased after declines in nutrient concentrations, the densities of both diatoms and  
267 other algal groups have increased. This was similar to the observation reported earlier  
268 by Yung et al. (1997) that there was an increase in the density of phytoplankton,  
269 especially that of other algal groups, when chlorophyll-*a* concentrations had not  
270 increased. As other algal groups in both Yung et al. (1997) and this study included  
271 mainly unidentified small flagellates and cryptomonads, an increase in the abundance  
272 of these small organisms may not be accompanied by an increase of chlorophyll-*a*  
273 concentrations. This is somewhat supported by the fact that correlation between  
274 density of other algal group and chlorophyll-*a* concentrations was recorded only at  
275 TM8, while diatoms and dinoflagellates correlated strongly and positively with  
276 chlorophyll-*a* concentrations at all stations.

277 Water quality measured in terms of nutrients and chlorophyll-*a* concentration has  
278 always been better in the channel region than in the inner part of the harbour (Hu et al.,

279 2001; Lam and Ho, 1989; Yung et al., 1997), and a seaward decrease in nutrient  
280 concentrations from the inner harbour to the channel was evident from our results. A  
281 similar spatial pattern, with water quality improving from TM3 to TM8, is recorded in  
282 other water quality indicators such as secchi depth, DO and BOD<sub>5</sub>. Due to its  
283 proximity to the open sea and the much lower pollution levels, TM8 was less affected  
284 by eutrophication and subsequent declines in nutrient concentrations compared to  
285 stations in the inner part of the harbour. An interesting observation was that the mean  
286 values of NO<sub>3</sub>/NH<sub>4</sub> decreased at TM3, TM4 and TM6, but increased at TM8 after  
287 declines in nutrient concentrations. This may be caused by a relatively higher decline  
288 of NH<sub>4</sub>-N concentrations than that of NO<sub>3</sub>-N in TM8. The maximum release rate of  
289 NH<sub>4</sub>-N from contaminated sediments into the water column in Tolo Harbour was  
290 found to be more than sixfolds higher than that of NO<sub>3</sub>-N (Hu et al. 2001), and  
291 although Hu et al. (2001) did not specify specific nutrient release rates in various parts  
292 of Tolo Harbour, it may be possible that comparatively less NH<sub>4</sub>-N was released back  
293 into the water column from sediments in the less polluted outer parts of the Tolo  
294 Harbour.

295 Spatial differences in nutrient loading and tidal flushing may have led to the  
296 observed differences in how phytoplankton in different stations had responded to  
297 declines in nutrient concentrations. Correlation between phytoplankton densities and

298 nutrient concentrations was poor and usually insignificant at TM6 and TM8 in the  
299 outer part of the harbour. In contrast, phytoplankton densities at TM3 and TM4 tended  
300 to correlate strongly and negatively with nutrient concentrations, suggesting that  
301 nutrients were removed rapidly by phytoplankton in the inner part of Tolo Harbour.

302

#### 303 *4.2. Changes in nutrient ratios and shifts in the phytoplankton community*

304

305 Since it is believed that some phytoplankton prefer to use  $\text{NH}_4$  over  $\text{NO}_3$  (Dortch  
306 1990), a decrease in  $\text{NO}_3/\text{NH}_4$  may favor phytoplankton growth. However, the lack of  
307 consistent correlation between  $\text{NO}_3/\text{NH}_4$  and phytoplankton density suggests that the  
308 phytoplankton community in Tolo Harbour did not have specific preference for either  
309  $\text{NO}_3$  or  $\text{NH}_4$ .

310 Decreases in nutrient concentrations following nutrient loading reduction  
311 measures had altered the values of  $\text{TIN}/\text{PO}_4$  and  $\text{TIN}/\text{SiO}_2$  significantly. Hodgkiss and  
312 Ho (1997) related the increased abundance of dinoflagellates in Tolo Harbour to a  
313 decrease in N:P ratios. It must be noted that no evidence of a decrease in  
314 dinoflagellate density has been detected in our data, despite a significant increase in  
315  $\text{TIN}/\text{PO}_4$  after declines in nutrient concentrations. In general, the density of  
316 dinoflagellates correlate neither with  $\text{TIN}/\text{PO}_4$  nor with most physico-chemical

317 parameters other than Secchi depth and BOD<sub>5</sub>, both of which may be dependent  
318 variables affected by the dinoflagellate density. Hence, the density of dinoflagellate in  
319 Tolo Harbour may not be easily predicted from nutrient concentrations or N:P ratios  
320 alone. While our analysis has not established a strong link between nutrient  
321 concentrations and dinoflagellate densities, several investigators have reported an  
322 increasing dominance of dinoflagellates during the 1980s and early 1990s when  
323 nutrient concentrations in Tolo Harbour were at their highest (Chan and Hodgkiss,  
324 1987; Hodgkiss and Chan, 1983; Hodgkiss and Ho, 1997; Lam and Ho, 1989). The  
325 density of dinoflagellates was at a peak in 1996 when TIN/PO<sub>4</sub> was very low (Figs. 3  
326 & 4). The density of dinoflagellates reached another peak in 1998, due primarily to an  
327 extremely dense population of *Prorocentrum* (122,467 cells ml<sup>-1</sup>) at TM3 in April.  
328 But dinoflagellate densities have remained relatively low since 2005, while TIN/PO<sub>4</sub>  
329 increased. Hodgkiss and Ho (1997) also noted a decrease in N:P ratios and an increase  
330 in algal blooms from 1981–1990. Our data showed no significant correlation between  
331 these two variables, although an increase in TIN/PO<sub>4</sub> and a decrease in the number of  
332 algal blooms were found after declines in nutrient concentrations. Nevertheless, while  
333 our data did not contain information about *Noctiluca* blooms, Liu and Wong (2006)  
334 showed that *Noctiluca scintillans* were still common in Tolo Harbour after declines in  
335 nutrient concentrations, and *Noctiluca* blooms still persisted.

336 Compared to the decrease in N concentrations, the decrease in SiO<sub>2</sub>  
337 concentrations was less dramatic. Although a significant decrease in depth-averaged  
338 SiO<sub>2</sub> concentrations was recorded after declines in nutrient input ( $p = 0.045$ ), surface  
339 SiO<sub>2</sub> concentrations did not changed significantly ( $p = 0.849$ ). Overall, TIN/SiO<sub>2</sub>  
340 tended to decrease at all sampling stations. Diatoms have a physiological N:Si ratio of  
341 1:1 (Turner, 2002), and an environmental ratio of  $> 1$  has been reported to limit  
342 diatom growth and shift a diatom-dominated community to one dominated by  
343 non-diatoms, particularly flagellates (Cloern, 2001; Egge and Aksnes, 1992; Paul et  
344 al., 2008; Turner et al. 1998). While diatom densities did correlate weakly with  
345 TIN/SiO<sub>2</sub> in TM3 and TM4, diatoms were the most abundant algal group in these two  
346 stations and Tolo Harbour (Lam and Ho, 1989; Yung et al., 1997) before declines in  
347 nutrient concentrations, when TIN/SiO<sub>2</sub> at TM3 and TM4 were frequently  $> 1$ . This  
348 suggests that although N:Si ratios may have some effect on diatom densities, it is not  
349 enough to shift diatom dominance in Tolo Harbour. In addition, the Si concentrations  
350 in Tolo Harbour may not be limiting to diatom growth. Egge and Aksnes (1992)  
351 reported that a Si concentration of  $> 2 \mu\text{M}$  was enough to induce consistent  
352 dominance by diatoms in Norway. While this low threshold concentration may not  
353 apply in the warm subtropical waters of Hong Kong, the lowest SiO<sub>2</sub> concentration in  
354 this study was  $\sim 10 \mu\text{M}$  at TM8, fivefolds higher than the threshold concentration

355 reported in Norway, and may be sufficient to support diatom growth regardless of  
356 TIN/SiO<sub>2</sub>. It should be noted that the maintenance of dominance by diatoms may not  
357 necessarily be beneficial both ecologically and economically. Although centric  
358 diatoms have been suggested to be the more desirable phytoplankton group when  
359 compared to non-diatom groups, such as dinoflagellates, due to their higher nutritional  
360 value and low toxicity (Hecky and Kilham, 1988; Officer and Ryther, 1980), pennate  
361 diatoms, including those belonging to the genus *Pseudo-nitzschia*, are also common in  
362 Tolo Harbour (Lam and Ho, 1989). Some species of *Pseudo-nitzschia* have been  
363 known to release the toxin domoic acid (Lefebvre et al., 2002; Sekula-Wood et al.,  
364 2009), and a connection between *Pseudo-nitzschia* blooms and eutrophication has  
365 been proposed (Parsons and Dortch, 2002; Schnetzer et al., 2007). Fortunately,  
366 *Pseudo-nitzschia* spp. may prefer high nitrate waters (Paul et al., 2008; Carter et al.,  
367 2005), so declines in nutrient concentrations in Tolo Harbour should discourage  
368 *Pseudo-nitzschia* blooms.

369 Although our data does not contain information on the size structure of the  
370 phytoplankton community, changes in nutrient concentration or ratios may cause a  
371 shift from larger phytoplankton species or cells to smaller ones. Stolte and Riegman  
372 (1995) had theorized that eutrophication favors large phytoplankton species because  
373 their larger storage capacity allows them to better compete under high nutrient

374 concentrations. Indeed, a shift towards an eutrophic environment has been shown to  
375 favor large diatoms in the western Wadden Sea (Stolte et al., 1994; Philippart et al.,  
376 2000), and Qiu et al. (2010) reported strong negative correlations between  $\leq 3 \mu\text{m}$   
377 chlorophyll-*a* and nutrient concentrations. The half-saturation constant for P uptake  
378 has been reported to be as high as 4.85–6.67  $\mu\text{M}$  at 20°C for certain large diatom  
379 species (Nishikawa et al. 2009 and 2010), much higher than the means of TP in Tolo  
380 Harbour after nutrient loading reduction (Table 2). Declines in nutrient concentrations  
381 in Tolo Harbour may therefore favor smaller cells and species that are more  
382 competitive in a less eutrophic condition. Qiu et al. (2010) reported significant  
383 positive correlation between  $< 20 \mu\text{m}$  chlorophyll *a* concentrations and N/P ratios.  
384 Our data also show a strong and positive correlation between TIN/PO<sub>4</sub> and other algal  
385 group densities, caused mainly by an increase in the density of small flagellates and  
386 *Cryptomonas*. Recent studies in Tolo Harbour have revealed that cells  $< 5 \mu\text{m}$   
387 accounted for  $> 25\%$  of the chlorophyll-*a* biomass (Lie and Wong, 2010; Wong et al.,  
388 2010). In addition, phytoplankton size structures in many aquatic ecosystems have  
389 also been known to be affected by climate change, particularly by increases in water  
390 column stratification due to increased temperature (Finkel, 2007; Smol et al., 2005;  
391 Winder et al., 2010). If indeed such a shift to smaller phytoplankton is occurring in  
392 Tolo Harbour, it would help to explain the increase in phytoplankton density as

393 chlorophyll-*a* concentrations decrease.

394

395 *4.3. Comparison with the recovery from eutrophication of other ecosystems*

396

397 The effects of declines in nutrient concentrations had been intensively studied in  
398 freshwater lakes (e.g. Jeppesen et al., 2002; Jeppesen et al., 2005; Søndergaard et al.,  
399 2002), and most have reported improvements in water quality. Water quality  
400 improvement is mainly achieved through the decrease in phytoplankton biomass. This  
401 decrease can occur as a direct response to declines in nutrient concentrations, but it  
402 can be further facilitated through increased grazing pressure from zooplankton grazers  
403 (Edmondson, 1994) and the recolonization of submerged macrophytes, which has  
404 been shown to substantially affect the success rates of water quality improvement in  
405 lakes (Mehner et al., 2002). While there may be differences between freshwater and  
406 marine systems in their responses to declines in nutrient concentrations (Cloern, 2001;  
407 Smith et al., 1999), examples of dramatic improvements in once eutrophicated marine  
408 ecosystems such as Hillsborough Bay, Florida (Johansson and Lewis, 1992) and the  
409 coastal waters of Denmark (Rask et al., 1999) had both involved the recolonization of  
410 macrophytes such as seagrasses (Hillsborough Bay) and eelgrass (Denmark).  
411 However, an early study in Tolo Harbour has shown that most of the harbour was



412 covered by extremely fine sediments that support little plant life (Trott, 1972).

413 Therefore, even with the decline of nutrient concentrations and increase in water

414 transparency, the spread of macrophytes in Tolo Harbour is unlikely.

415 In regards to the zooplankton grazers in Tolo Harbour, a study comparing the

416 copepod community before and after declines in nutrient concentrations in Tolo

417 Harbour revealed a decrease in copepod density, from 6,392 ind. m<sup>-3</sup> in 1987–1991, to

418 4,810 ind. m<sup>-3</sup> in 2003–2004 (Wong et al., 1993; Zhang and Wong, submitted). The

419 mesozooplankton community in Tolo Harbour was found to be heavily preyed upon

420 by larval and juvenile stages of the black seabream, *Acanthopagrus schlegeli*, and the

421 Japanese seaperch, *Lateolabrax japonicus*, which use Tolo Harbour as a nursery

422 habitat (Nip et al. 2003). While presently there is no detailed description on the fish

423 population in Tolo Harbour, the abundance of small planktivorous fishes will most

424 likely increase when increased fishing pressure from overfishing of larger piscivorous

425 fishes reduces the predation pressure on the small fishes. Such changes will in turn

426 increase the predation pressure on mesozooplankton grazers, reducing their

427 abundance and delaying any further decrease of phytoplankton abundance.

428 Although every water mass may have different responses to declines in nutrient

429 concentrations (Carvalho et al., 1995; Smith et al., 1999), it is obvious that trophic

430 interactions play a significant role in determining the outcome (Carpenter et al., 1995,

431 Manca and Ruggiu, 1998; Proulx et al., 1996; Smith et al., 1999). Increase in  
432 macrophytes and zooplankton grazers can further facilitate the decrease in  
433 phytoplankton biomass (Edmondson, 1994; Mehner et al., 2002), but the presence of  
434 planktivores and piscivores can affect the abundance of zooplankton grazers.  
435 Therefore, an appropriate balance between piscivores, planktivores and zooplankton  
436 grazers should be maintained to ensure the long-term stability of the recovered  
437 ecosystem (Mehner et al. 2002). Unfortunately, there is a lack of long-term  
438 monitoring on other communities, such as zooplankton and nekton, in Tolo Harbour.  
439 As there is insufficient information on the responses of various communities to  
440 changes in nutrient loading, the phytoplankton community alone is not a reliable  
441 indicator of the trophic status of the whole ecosystem (Philippart et al. 2007). Future  
442 efforts in water quality monitoring and eutrophic coastal restoration should therefore  
443 focus not only on nutrient concentrations and phytoplankton biomass and densities,  
444 but also other important components of the aquatic ecosystem such as zooplankton  
445 and nekton communities.

446

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455

#### 456 **References**

457

458 American Public Health Association, American Water Works Association, Water  
459 Environment Federation, 1998. Standard methods for the examination of water  
460 and wastewater, 20<sup>th</sup> Edition. American Public Health Association, Washington  
461 DC.

462 Anderson, D.M., Burkholder, J.M., Cochlan, W.P., Glibert, P.M., Gobler, C.J., Heil,  
463 C.A., Kudela, R.M., Parsons, M.L., Rensel, J.E.J., Townsend, D.W., Trainer,  
464 V.L., Vargo, G.A., 2008. Harmful algal blooms and eutrophication: Examining  
465 linkages from selected coastal regions of the United States. Harmful Algae 8,  
466 39-53.

467 Battarbee, R.W., Anderson, N.J., Jeppesen, E., Leavitt, P.R., 2005. Combining  
468 palaeolimnological and limnological approaches in assessing lake ecosystem

- 469 response to nutrient reduction. *Freshwater Biology* 50, 1772-1780.
- 470 Carpenter, S.R., Christensen, D.L., Cole, J.J., Cottingham, K.L., He, X., Hodgson,  
471 J.R., Kitchell, J.F., Knight, S.E., Pace, M.L., Post, D.M., Schindler, D.E.,  
472 Voichick, N., 1995. Biological control of eutrophication. *Environmental Science*  
473 *and Technology* 29, 784-786.
- 474 Carpenter, S.R., Ludwig, D., Brock, W.A., 1999. Management of eutrophication for  
475 lakes subject to potentially irreversible change. *Ecological Applications* 9,  
476 751-771.
- 477 Carter, C.M., Ross, A.H., Schiel, D.R., Howard-Williams, C., Hayden, B., 2005. *In*  
478 *situ* microcosm experiments on the influence of nitrate and light on  
479 phytoplankton community composition. *Journal of Experimental Marine*  
480 *Biology and Ecology* 326, 1-13.
- 481 Carvalho, L., Beklioglu, M., Moss, B., 1995. Changes in a deep lake following  
482 sewage diversion - a challenge to the orthodoxy of external phosphorus control  
483 as a restoration strategy? *Freshwater Biology* 34, 399-410.
- 484 Carvalho, L., Kirika, A., 2003. Changes in shallow lake functioning: response to  
485 climate change and nutrient reduction. *Hydrobiologia* 506-509, 789-796.
- 486 Chau, K.W., 2007. Integrated water quality management in Tolo Harbour, Hong Kong:  
487 a case study. *Journal of Cleaner Production* 15, 1568-1572.

- 488 Chau, Y.K., Abesser, R.A., 1958. A preliminary study of the hydrology of Hong Kong  
489 Territorial Waters. Hong Kong University Fisheries Journal 2, 43-58.
- 490 Cloern, J.E., 2001. Our evolving conceptual model of the coastal eutrophication  
491 problem. Marine Ecology Progress Series 210, 223-253.
- 492 de Benardi, R., Calderoni, A., Mosello, R., 1996. Environmental problems in Italian  
493 lakes, and lakes Maggiore and Orta as successful examples of correct  
494 management leading to restoration. Verhandlungen der Internationale  
495 Vereinigung fur Theoretische und Angewandte Limnologie 26, 123-138.
- 496 Dortch, Q., 1990. The interaction between ammonium and nitrate uptake in  
497 phytoplankton. Marine Ecology Progress Series 61, 183-201.
- 498 Edmondson, W.T., 1994. Sixty years of Lake Washington: a curriculum vitae. Lake  
499 Reservoir Management 10, 75-84.
- 500 Egge, J.K., Aksnes, D.L., 1992. Silicate as regulating nutrient in phytoplankton  
501 competition. Marine Ecology Progress Series 83, 281-289.
- 502 Finkel, Z.V., 2007. Does size matter? The evolution of modern marine food webs. In:  
503 Falkowski, P.G., Knoll, A.H. (Eds.), The evolution of aquatic photoautotrophs.  
504 Academic Press, New York. Pp. 333-350.
- 505 Hansen, P.J., Miranda, L., Azanza, R., 2004. Green *Noctiluca scintillans*: a

- 506 dinoflagellate with its own greenhouse. *Marine Ecology Progress Series* 275,  
507 79-87.
- 508 Hecky, R.E., Kilham, P., 1988. Nutrient limitation of phytoplankton in freshwater and  
509 marine environments: A review of recent evidence on the effects of enrichment.  
510 *Limnology & Oceanography* 33, 796-822.
- 511 Hodgkiss, I.J., Chan, B.S.S., 1983. Pollution studies in Tolo Harbour, Hong Kong.  
512 *Marine Environmental Research* 10, 1-44.
- 513 Hodgkiss, I.J., Ho, K.C., 1997. Are changes in N:P ratios in coastal waters the key to  
514 increased red tide blooms? *Hydrobiologia* 352, 141-147.
- 515 Hodgkiss, I.J., Yim, W.W., 1995. A case study of Tolo Harbour, Hong Kong. In:  
516 McComb, A.J. (Ed.) *Eutrophic shallow estuaries and lagoons*. CRC Press,  
517 Florida. Pp. 41-57.
- 518 Hong Kong Environmental Protection Department, 2009. *Marine Water Quality in*  
519 *Hong Kong in 2008*. The Government of the Hong Kong Special Administrative  
520 Region, Hong Kong.
- 521 Hong Kong Environmental Protection Department, 1991. *Marine Water Quality in*  
522 *Hong Kong in 1990*. The Government of the Hong Kong Special Administrative  
523 Region, Hong Kong.

- 524 Hu, W.F., Lo, W., Chua, H., Sin, S.N., Yu, P.H.F., 2001. Nutrient release and sediment  
525 oxygen demand in a eutrophic land-locked embayment in Hong Kong.  
526 *Environment International* 26, 369-375.
- 527 Jeppesen, E., Jensen, J.P., Søndergaard, M., 2002. Response of phytoplankton,  
528 zooplankton and fish to re-oligotrophication: an 11-year study of 23 Danish  
529 lakes. *Aquatic Ecosystem Health and Management* 5, 31-43.
- 530 Jeppesen, E., Meerhoff, M., Jacobsen, B.A., Hansen, R.S., Søndergaard, M., Jensen,  
531 J.P., Lauridsen, T.L., Mazzeo, N., Branco, C.W.C., 2007. Restoration of shallow  
532 lakes by nutrient control and biomanipulation – the successful strategy varies  
533 with lake size and climate. *Hydrobiologia* 581, 269-285.
- 534 Jeppesen, E., Søndergaard, M., Jensen, J.P., Havens, K.E., Anneville, O., Carvalho, L.,  
535 Coveney, M.F., Deneke, R., Dokulil, M.T., Foy, B., Gerdeaux, D., Hampton,  
536 S.E., Hilt, S., Kangur, K., Köhler, J., Lammens, E.H.H.R., Lauridsen, T.L.,  
537 Manca, M., Miracle, M.R., Moss, B., Nöges, P., Persson, G., Phillips, G.,  
538 Portielje, R., Romo, S., Schelske, C.L., Straile, D., Tatrai, I., Willén, E. &  
539 Winder, M., 2005. Lake responses to reduced nutrient loading - an analysis of  
540 contemporary long-term data from 35 case studies. *Freshwater Biology* 50,  
541 1747-1771.
- 542 Johansson, J.O.R., Lewis, R.R., 1992. Recent improvements in water quality and

- 543 biological indicators in Hillsborough Bay, a highly impacted subdivision of  
544 Tampa Bay, Florida, USA. In: Volenweider, R.A., Marchetti, R., Viviani, R.  
545 (Eds.), Marine coastal eutrophication. The response of marine transitional  
546 systems to human impact: Problems and perspectives for restoration. Science of  
547 the total environment supplement 1992. Elsevier Science, Amsterdam. Pp.  
548 1199-1216.
- 549 Justić, D., Rabalais, N.N., Turner, R.E., 1995. Stoichiometric nutrient balance and  
550 origin of coastal eutrophication. *Marine Pollution Bulletin* 30, 41-46.
- 551 Kiørboe, T., Titelman, J., 1998. Feeding, prey selection and prey encounter  
552 mechanisms in the heterotrophic dinoflagellate *Noctiluca scintillans*. *Journal of*  
553 *Plankton Research* 20, 1615-1636.
- 554 Lam, C.W.Y., Ho, K.C., 1989. Phytoplankton characteristics of Tolo Harbour. *Asian*  
555 *Marine Biology* 6, 5-18.
- 556 Lee, J.H.W., Harrison, P.J., Kuang, C., Yin, K., 2006. Eutrophication dynamics in  
557 Hong kong Coastal Waters: Physical and Biological Interactions. In Wolanski, E.  
558 (Ed.), *Environment in Asia Pacific Harbours*. Springer, the Netherlands. Pp.  
559 187-206.
- 560 Lefebvre, K.A., Silver, M.W., Coale, S.L., Tjeerdema, R.S., 2002. Domoic acid in  
561 planktivorous fish in relation to toxic *Pseudo-nitzschia* cell densities. *Marine*



- 562 Biology 140, 625-631.
- 563 Lie, A.A.Y., Wong, C.K. 2010. Selectivity and grazing impact of  
564 microzooplankton on phytoplankton in two subtropical semi-enclosed  
565 bays with different chlorophyll concentrations. *Journal of Experimental*  
566 *Marine Biology and Ecology*, in press.
- 567 Liu, X., Wong, C.K., 2006. Seasonal and spatial dynamics of *Noctiluca scintillans* in a  
568 semi-enclosed bay in the northeastern part of Hong Kong. *Botanica Marina* 49,  
569 145-150.
- 570 Manca, M., Ruggiu, D., 1998. Consequences of pelagic food-web changes during a  
571 long-term lake oligotrophication process. *Limnology & Oceanography* 43,  
572 1368-1373.
- 573 Mehner, T., Benndorf, J., Kasprzak, P., Koschel, R., 2002. Biomanipulation of lake  
574 ecosystems: successful applications and expanding complexity in the underlying  
575 science. *Freshwater Biology* 47, 2453-5465.
- 576 Mehner, T., Kasprzak, P., Wysujack, K., Laude, U., Koschel, R., 2001. Restoration of  
577 a stratified lake (Feldberger Haussee, Germany) by a combination of nutrient  
578 load reduction and long-term biomanipulation. *Internation Review of*  
579 *Hydrobiology* 2, 253-265.
- 580 Nip, T.H.M., Ho, W., Wong, C.K., 2003. Feeding ecology of larval and juvenile black

- 581 seabream (*Acanthopagrus schlegeli*) and Japanese seaperch (*Lateolabrax*  
582 *japonicus*) in Tolo Harbour, Hong Kong.
- 583 Nishikawa, T., Tarutani, K., Yamamoto, T., 2009. Nitrate and phosphate uptake  
584 kinetics of the harmful diatom *Eucampia zodiacus* Ehrenberg, a causative  
585 organism in the bleaching of aquacultured *Porphyra* thalli. Harmful Algae 8,  
586 513-517.
- 587 Nishikawa, T., Tarutani, K., Yamamoto, T., 2010. Nitrate and phosphate uptake  
588 kinetics of harmful diatom *Coscinodiscus wailesii*, a causative organism in the  
589 bleaching of aquacultured *Porphyra* thalli. Harmful Algae 9, 563-567.
- 590 Nixon, S. W., 1995. Coastal marine eutrophication: A definition, social causes, and  
591 future concerns. Ophelia 41, 199-219.
- 592 Officer, C.B., Ryther, J.H., 1980. The possible importance of silicon in marine  
593 eutrophication. Marine Ecology Progress Series 3, 83-91.
- 594 Parsons, M.L., Dortch, Q., 2002. Sedimentological evidence of an increase in  
595 *Pseudo-nitzschia* (Bacillariophyceae) abundance in response to coastal  
596 eutrophication. Limnology & Oceanography 47, 551-558.
- 597 Paul, J.T., Ramaiah, N., Sardesai, S., 2008. Nutrient regimes and their effect on  
598 distribution of phytoplankton in the Bay of Bengal. Marine Environmental  
599 Research 66, 337-344.

- 600 Philippart, C.J.M., Beukema, J.J., Cadée, G.C., Dekker, R., Goedhart, P.W., van Iperen,  
601 J.M., Leopold, M.F., Herman, P.M.J., 2007. Impacts of nutrient reduction on  
602 coastal communities. *Ecosystems* 10, 95-118.
- 603 Philippart, C.J.M., Cadée, G.C., van Raaphorst, W., Riegman, R., 2000. Long-term  
604 phytoplankton-nutrient budgets, and denitrification potential. *Limnology &*  
605 *Oceanography* 45, 131-144.
- 606 Proulx, M., Pick, F.R., Mazumder, A., Hamilton, P.B., Lean, D.R.S., 1996. Effects of  
607 nutrients and planktivorous fish on the phytoplankton of shallow and deep  
608 aquatic ecosystems. *Canadian Journal of Fisheries and Aquatic Sciences* 77,  
609 1556-1572.
- 610 Qiu, D., Huang, L., Zhang, J., Lin, S., 2010. Phytoplankton dynamics in and near the  
611 highly eutrophic Pearl River Estuary, South China Sea. *Continental Shelf*  
612 *Research* 30, 177-186.
- 613 Rask, N., Pedersen, S.T., Jensen, M.H., 1999. Response to lowered nutrient discharges  
614 in the coastal waters around the island of Funen, Denmark. *Hydrobiologia* 363,  
615 69-81.
- 616 Reckhow, K.H., Chapra, S.C., 1999. Persistent organic pollutants (POPs): State of the  
617 science. *Environmental Pollution* 100, 209-221.
- 618 Sekula-Wood, E., Schnetzer, A., Benitez-Nelson, C.R., Anderson, C., Berelson, W.M.,

- 619 Brzezinski, M.A., Burns, J.M., Caron, D.A., Cetinic, I., Ferry, J.L., Fitzpatrick,  
620 E., Jones, B.H., Miller, P.E., Morton, S.L., R.A., Siegel, D.A., Thunell, R., 2009.  
621 Rapid downward transport of the neurotoxin domoic acid in coastal waters.  
622 Nature Geoscience 2, 272-275.
- 623 Schnetzer, A., Miller, P.E., Schaffner, R.A., Stauffer, B.A., Jones, B.H., Weisberg,  
624 S.B., DiGiacomo, P.M., Berelson, W.M., Caron, D., 2007. Blooms of  
625 *Pseudo-nitzschia* and domoic acid in the San Pedro Channel and Los Angeles  
626 harbor areas of the Southern California Bight, 2003-2004. Harmful Algae 6,  
627 372-387.
- 628 Smith, V.H., 1983. Low nitrogen to phosphorus ratios favor dominance by blue-green  
629 algae in lake phytoplankton. Science 221, 669-671.
- 630 Smith, V.H., 1998. Cultural eutrophication of inland, estuarine, and coastal waters. In:  
631 Pace, M.L., Groffman, P.M. (Eds.) Successes, limitations and frontiers in  
632 ecosystem science. Springer, New York. Pp. 7-49.
- 633 Smith, V.H., 2003. Eutrophication of freshwater and coastal marine ecosystems. A  
634 global problem. Environmental Science and Pollution Research 10,126-139.
- 635 Smith, V.H., Tilman, G.D., Nekola, J.C. 1999. Eutrophication: impacts of excess  
636 nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environmental  
637 Pollution 100, 179-196.

- 638 Smol, J.P., Wolfe, A.P., Birks, H.J.B., Douglas, M.S.V., Jones, V.J., Korhola, A.,  
639 Pientzl, R., Rühland, K., Sorvari, S., Antoniades, D., Brooks, S.J., Fallu, M.A.,  
640 Hughes, M., Keatley, B.E., Laing, T.E., Michelutti, N., Nazarova, L., Nyman,  
641 M., Paterson, A.M., Perren, B., Quinlan, R., Rautio, M., Saulnier-Talbot, E.,  
642 Siltone, S., Solovieva, N., Weckström, J., 2005. Climate-drive regime shifts in  
643 the biological communities of arctic lakes. Proceedings of the National  
644 Academy of Sciences 102, 4397-4402.
- 645 Søndergaard, M., Jensen, J.P., Jeppesen, E., Moller, P.H., 2002. Seasonal dynamics in  
646 the concentrations and retention of phosphorus in shallow Danish lakes after  
647 reduced loading. Aquatic Ecosystem Health and Management 5, 19-23.
- 648 Sriwoon, R., Pholpunthin, P., Lirdwitayaprasit, T., Kishino, Furuya, K., 2008.  
649 Population dynamics of green *Noctiluca scintillans* (Dinophyceae) associated  
650 with the monsoon cycle in the upper gulf of Thailand. Journal of Phycology 44,  
651 605-615.
- 652 Stolte, W., McCollin, T., Noordeloos, A.A.M., Riegman, R., 1994. Effect of nitrogen  
653 source on the size distribution within marine phytoplankton populations. Journal  
654 of Experimental Marine Biology and Ecology 184, 83-97.
- 655 Stolte, W., Riegman, R., 1995. Effect of phytoplankton cell size on transient-state  
656 nitrate and ammonium uptake kinetics. Microbiology 141, 1221-1229.

- 657 Sweeney, B.M., 1971. Laboratory studies of a green *Noctiluca* from New Guinea.  
658 *Journal of Phycology* 7, 53-58.
- 659 Trott, L.B., 1972. Marine ecology in Tolo Harbour, Hogn Kong. *Chung Chi Journal* 11,  
660 26-32.
- 661 Turner, R.E., 2002. Element ratios and aquatic food webs. *Estuaries* 25, 694-703.
- 662 Turner, R.E, Qureshi, N., Rabalais, N.N., Dortch, Q., Justić, D., Shaw, R.F., Cope, J.,  
663 1998. Fluctuating silicate:nitrate ratios and coastal plankton food webs.  
664 *Proceedings of the National Academy of Sciences* 95, 13048-13051.
- 665 Wear, R.G., Thompson, G.B., Stirling, H.P., 1984. Hydrography, nutrients and  
666 plankton in Tolo Harbour, Hong Kong. *Asian Marine Biology* 1, 59-75.
- 667 Winder, M., Reuter, J.E., Schladow, S.G., 2009. Lake warming favors small-sized  
668 planktonic diatom species. *Proceedings of the Royal Society B* 276, 427-435.
- 669 Wong, C.K., Chan , A.L.C., Chen, Q.C., 1993. Planktonic copepods of Tolo Harbour,  
670 Hong Kong. *Crustaceana* 64, 76-84.
- 671 Wong, C.K., Tang, C.C.H., Lie, A.A.Y., Lam, J.Y.C., Yung, Y.K. 2010. Size structure  
672 and taxonomic composition of phytoplankton in Hong Kong waters. In: Tow,  
673 T.T., Yusup, Y., Fizri, F.F.A. (Eds.) *Proceedings International Conference on*  
674 *Environmental Research and Technology (ICERT 2010)*. Universiti Sains  
675 Malaysia, Malaysia. Pp. 560-564.

676 Wu, R.S.S., 1988. Marine pollution in Hong Kong: a review. *Asian Marine Biology*  
677 5:1-23.

678 Yung, Y.K., Wong, C.K., Broom, M.J., Ogden, J.A., Chan, S.C.M., Leung, Y., 1997.  
679 Long-term changes in hydrography, nutrients and phytoplankton in Tolo  
680 Harbour, Hong Kong. *Hydrobiologia* 352, 107-115.

681 Zhang, G., Wong, C.K. Changes in the planktonic copepod community in a landlocked  
682 bay in the subtropical coastal waters of Hong Kong during recovery from  
683 eutrophication. *Hydrobiologia* submitted.

684

### 685 **Figure Legends**

686 **Fig. 1.** A map of Hong Kong and Tolo Harbour showing the location of the four  
687 sampling stations.

688

689 **Fig. 2.** Temporal variations in the annual means of total inorganic nitrogen, total  
690 nitrogen, total phosphorus and SiO<sub>2</sub> concentration at the four sampling stations from  
691 1986–2008. The shaded area represents the period before nutrient loading reduction .

692

693 **Fig. 3.** Temporal variations in the annual means of NO<sub>3</sub>/NH<sub>4</sub>, TIN/PO<sub>4</sub> and TIN/SiO<sub>2</sub>  
694 at the four sampling stations from 1986–2008. The shaded area represents the period

695 before nutrient loading reduction. The dashed lines indicate the Redfield N:P and N:Si  
696 ratios of 16:1 and 1:1 respectively.

697

698 **Fig. 4.** Temporal variations in the annual means of chlorophyll *a* at the four sampling  
699 stations from 1986–2008. The shaded area represents the period before nutrient  
700 loading reduction.

701

702 **Fig. 5.** Temporal variations in the annual means of diatoms, dinoflagellates, other algal  
703 groups and total phytoplankton densities at the four sampling stations from  
704 1986–2008. The shaded area represents the period before nutrient loading reduction.  
705 Monitoring began in 1988 for TM3 and TM4, 1994 for TM6 and 1986 for TM8.



### Research highlights

Our study investigates the long-term changes in physico-chemical parameters, including nutrient concentration, nutrient ratios, and phytoplankton before and after nutrient reduction in an eutrophic bay in Hong Kong. Such study with long-term data relating environmental factors and phytoplankton is rather uncommon in marine ecosystems. We believe that such study of how anthropogenic causes led to changes in the phytoplankton community fits the aims and scope of your journal.

**Table 1.** Mean values ( $\pm$  standard deviation) of various physico-chemical, biological and nutrient ratios. “All stations” refers to the mean of all four sampling stations. “86–97” indicates the period before nutrient loading reduction (i.e. 1986–1997), and “98–08” indicates the period after nutrient loading reduction (i.e. 1998–2008). “Overall” refers to the entire study period of 1986–2008. Values are depth-averaged values except for “Bottom DO” and “Bottom BOD<sub>5</sub>”.

Parameter		Station				
		TM3	TM4	TM6	TM8	All stations
Temperature (°C)	86–97	23.06 $\pm$ 4.33	22.88 $\pm$ 4.32	22.55 $\pm$ 4.14	22.20 $\pm$ 4.02	22.67 $\pm$ 4.19
	98–08	23.93 $\pm$ 4.13	23.68 $\pm$ 4.13	23.36 $\pm$ 4.01	22.92 $\pm$ 3.87	23.47 $\pm$ 4.02
	Overall	23.47 $\pm$ 4.25	23.26 $\pm$ 4.24	22.93 $\pm$ 4.09	22.55 $\pm$ 3.96	23.06 $\pm$ 4.12
pH	86–97	8.31 $\pm$ 0.20	8.29 $\pm$ 0.23	8.26 $\pm$ 0.19	8.24 $\pm$ 0.17	8.27 $\pm$ 0.18
	98–08	8.21 $\pm$ 0.20	8.16 $\pm$ 0.21	8.16 $\pm$ 0.20	8.16 $\pm$ 0.15	8.17 $\pm$ 0.17
	Overall	8.26 $\pm$ 0.20	8.23 $\pm$ 0.23	8.21 $\pm$ 0.20	8.20 $\pm$ 0.17	8.22 $\pm$ 0.19
Salinity	86–97	30.75 $\pm$ 1.55	30.77 $\pm$ 1.66	31.44 $\pm$ 1.51	31.96 $\pm$ 1.06	31.22 $\pm$ 1.39
	98–08	31.18 $\pm$ 1.56	31.29 $\pm$ 1.48	31.78 $\pm$ 1.21	32.31 $\pm$ 1.07	31.64 $\pm$ 1.28
	Overall	30.96 $\pm$ 1.57	31.02 $\pm$ 1.60	31.61 $\pm$ 1.38	32.13 $\pm$ 1.08	31.42 $\pm$ 1.35
DO (mg l <sup>-1</sup> )	86–97	6.86 $\pm$ 1.93	6.85 $\pm$ 1.86	6.45 $\pm$ 1.61	6.36 $\pm$ 1.65	6.63 $\pm$ 1.60
	98–08	6.98 $\pm$ 1.37	6.70 $\pm$ 1.33	6.26 $\pm$ 1.33	6.06 $\pm$ 1.34	6.50 $\pm$ 1.22
	Overall	6.92 $\pm$ 1.68	6.78 $\pm$ 1.62	6.36 $\pm$ 1.48	6.22 $\pm$ 1.51	6.57 $\pm$ 1.43
Bottom DO (mg l <sup>-1</sup> )	86–97	4.97 $\pm$ 2.44	4.78 $\pm$ 2.42	4.83 $\pm$ 2.34	5.10 $\pm$ 2.56	4.92 $\pm$ 2.18
	98–08	6.30 $\pm$ 1.86	5.86 $\pm$ 1.88	5.30 $\pm$ 1.92	5.19 $\pm$ 2.02	5.66 $\pm$ 1.73
	Overall	5.61 $\pm$ 2.28	5.29 $\pm$ 2.24	5.05 $\pm$ 2.16	5.15 $\pm$ 2.31	5.28 $\pm$ 2.01
BOD <sub>5</sub> (mg l <sup>-1</sup> )	86–97	2.55 $\pm$ 0.99	2.44 $\pm$ 0.89	1.81 $\pm$ 0.72	1.18 $\pm$ 0.60	2.00 $\pm$ 0.65
	98–08	1.98 $\pm$ 0.75	1.73 $\pm$ 0.56	1.38 $\pm$ 0.47	0.89 $\pm$ 0.56	1.49 $\pm$ 0.45
	Overall	2.28 $\pm$ 0.93	2.10 $\pm$ 0.83	1.60 $\pm$ 0.65	1.04 $\pm$ 0.60	1.76 $\pm$ 0.62
Bottom BOD <sub>5</sub> (mg l <sup>-1</sup> )	86–97	1.33 $\pm$ 0.65	1.38 $\pm$ 0.79	0.95 $\pm$ 0.56	0.71 $\pm$ 0.40	1.09 $\pm$ 0.50
	98–08	1.35 $\pm$ 0.66	1.24 $\pm$ 0.60	0.89 $\pm$ 0.56	0.56 $\pm$ 0.42	1.01 $\pm$ 0.41
	Overall	1.34 $\pm$ 0.66	1.32 $\pm$ 0.71	0.92 $\pm$ 0.56	0.63 $\pm$ 0.42	1.05 $\pm$ 0.46

Secchi Depth (m)	86–97	1.83 ± 0.66	1.82 ± 0.67	2.23 ± 0.79	3.49 ± 1.39	2.35 ± 0.63
	98–08	1.96 ± 0.69	2.10 ± 0.67	2.59 ± 0.88	3.41 ± 1.27	2.51 ± 0.69
	Overall	1.89 ± 0.67	1.89 ± 0.67	2.40 ± 0.85	3.45 ± 1.33	2.43 ± 0.66
Suspended solids (mg l <sup>-1</sup> )	86–97	3.41 ± 2.62	3.63 ± 3.11	3.03 ± 2.37	3.20 ± 3.20	3.32 ± 2.38
	98–08	3.20 ± 3.97	2.42 ± 1.36	2.07 ± 1.01	2.26 ± 1.39	2.49 ± 1.30
	Overall	3.31 ± 3.33	3.05 ± 2.51	2.57 ± 1.90	2.75 ± 2.54	2.92 ± 1.98
Chl <i>a</i> (µg l <sup>-1</sup> )	86–97	9.63 ± 6.87	9.82 ± 7.43	6.25 ± 4.80	3.38 ± 6.21	7.27 ± 4.80
	98–08	9.33 ± 6.28	7.58 ± 4.37	5.20 ± 2.90	3.13 ± 2.17	6.31 ± 3.15
	Overall	9.49 ± 6.58	8.75 ± 6.25	5.75 ± 4.03	3.26 ± 4.72	6.81 ± 4.12
NO <sub>3</sub> -N (µM)	86–97	3.21 ± 3.17	3.40 ± 3.74	2.29 ± 2.15	1.52 ± 1.43	2.60 ± 2.30
	98–08	1.37 ± 2.36	1.42 ± 2.28	1.27 ± 1.95	1.45 ± 1.75	1.38 ± 1.87
	Overall	2.33 ± 2.96	2.45 ± 3.28	1.80 ± 2.11	1.48 ± 1.59	2.02 ± 2.19
NH <sub>4</sub> -N (µM)	86–97	10.13 ± 6.37	8.27 ± 5.49	5.61 ± 3.95	3.56 ± 3.24	6.89 ± 4.25
	98–08	4.94 ± 4.39	4.40 ± 4.67	3.26 ± 2.53	2.57 ± 1.76	3.79 ± 3.09
	Overall	7.65 ± 6.08	6.42 ± 5.46	4.48 ± 3.54	3.08 ± 2.68	5.41 ± 4.04
Total inorganic N (µM)	86–97	14.31 ± 8.79	12.65 ± 8.00	8.82 ± 5.27	5.76 ± 3.69	10.38 ± 5.86
	98–08	6.77 ± 6.27	6.37 ± 6.16	5.10 ± 3.64	4.64 ± 2.49	5.72 ± 4.28
	Overall	10.71 ± 8.55	9.64 ± 7.82	7.04 ± 4.92	5.22 ± 3.22	8.15 ± 5.66
Total N (µM)	86–97	51.53 ± 19.03	48.58 ± 18.83	41.39 ± 19.00	35.10 ± 26.40	44.15 ± 18.05
	98–08	28.08 ± 20.20	25.98 ± 19.14	22.25 ± 16.91	19.04 ± 15.90	23.84 ± 17.64
	Overall	40.32 ± 22.81	37.77 ± 22.06	32.23 ± 20.39	27.42 ± 23.40	34.44 ± 20.52
PO <sub>4</sub> -P (µM)	86–97	1.32 ± 0.78	1.32 ± 0.72	0.93 ± 0.49	0.59 ± 3.69	1.04 ± 0.54
	98–08	0.30 ± 0.23	0.31 ± 0.24	0.30 ± 0.16	0.33 ± 0.16	0.31 ± 0.17
	Overall	0.84 ± 0.77	0.84 ± 0.74	0.63 ± 0.49	0.46 ± 0.30	0.69 ± 0.55
Total P (µM)	86–97	3.59 ± 2.13	3.43 ± 1.58	2.75 ± 1.37	2.23 ± 1.42	3.00 ± 1.43
	98–08	1.14 ± 0.61	1.03 ± 0.53	0.94 ± 0.38	0.87 ± 0.31	0.99 ± 0.38
	Overall	2.42 ± 2.01	2.28 ± 1.69	1.89 ± 1.37	1.58 ± 1.25	2.04 ± 1.47

SiO <sub>2</sub> (μM)	86–97	13.56 ± 8.41	13.96 ± 7.86	13.90 ± 6.40	12.97 ± 5.03	13.60 ± 6.47
	98–08	12.64 ± 7.87	13.24 ± 7.38	12.68 ± 6.26	12.44 ± 5.84	12.75 ± 6.27
	Overall	13.12 ± 8.16	13.61 ± 7.63	13.32 ± 6.35	12.72 ± 5.43	13.19 ± 6.38
NO <sub>3</sub> /NH <sub>4</sub>	86–97	0.35 ± 0.33	0.75 ± 3.50	0.72 ± 1.44	0.73 ± 0.93	0.64 ± 1.08
	98–08	0.30 ± 0.56	0.41 ± 0.72	0.69 ± 2.10	1.16 ± 2.73	0.64 ± 1.34
	Overall	0.32 ± 0.45	0.58 ± 2.58	0.71 ± 1.78	0.94 ± 2.01	0.64 ± 1.21
TIN/PO <sub>4</sub>	86–97	12.12 ± 6.06	10.39 ± 4.67	10.44 ± 5.13	11.69 ± 7.30	11.16 ± 5.01
	98–08	24.99 ± 18.58	23.16 ± 16.93	18.69 ± 12.95	15.44 ± 10.09	20.57 ± 12.91
	Overall	18.27 ± 15.00	16.49 ± 13.94	14.39 ± 10.52	13.49 ± 8.93	15.66 ± 10.70
TIN/SiO <sub>2</sub>	86–97	1.37 ± 1.26	1.13 ± 1.00	0.74 ± 0.64	0.47 ± 0.26	0.93 ± 0.71
	98–08	0.73 ± 0.78	0.62 ± 0.65	0.49 ± 0.53	0.41 ± 0.27	0.56 ± 0.52
	Overall	1.07 ± 1.11	0.89 ± 0.89	0.62 ± 0.60	0.44 ± 0.27	0.75 ± 0.65

**Table 2.** Kendall’s correlation between phytoplankton variables and various physico-chemical, biological and nutrient ratios parameters at four sampling stations in Tolo Harbour. “Dino” represents dinoflagellates, “Others” represents algal groups other than diatoms or dinoflagellates, “Total” represents total phytoplankton cell counts. “+/-” represents statistical significance at the 0.05 level; “+ +/-” represents statistical significance at the 0.01 level. Tested values were depth-averaged values except for “Bottom DO” and “Bottom BOD<sub>5</sub>”.

Parameter	Station																			
	TM3					TM4					TM6					TM8				
	Diatom	Dino	Others	Total	Chl- <i>a</i>	Diatom	Dino	Others	Total	Chl- <i>a</i>	Diatom	Dino	Others	Total	Chl- <i>a</i>	Diatom	Dino	Others	Total	Chl- <i>a</i>
Temperature	++	-		++		++			++		++			++		++		+	++	
pH			--	++			--	-	++					++				--		+
Salinity				-					--			-	-	-	--		--			-
DO		++		++				+			--			-		--			--	
Bottom DO		++	++	+		-	+	++			--			--		--			--	-
BOD <sub>5</sub>		++	--	++			++	--	++			++		+	++		++	-		++
Bottom BOD <sub>5</sub>		+		++		-	++		-	+				+		--		--	--	
Secchi Depth	--	--		--	--	--		+	--	--	--	-		--	--	--	--	-	--	--
Suspended solids		++		+	++		+		++					++			++			++
NO <sub>3</sub> -N	--	--	--	--	-	--		--	--	-						+				
NH <sub>4</sub> -N	--		--	--		--	-	--	--		-			--		--			-	--

Total inorganic N	--	-	--	--	--	--	-	--	--	--		--		--
Total N	--		--	--	+	--		--	--	++	++	++	--	
PO <sub>4</sub> -P	--	-	--	--	-	--	-	--	--		+		-	-
Total P	--		--	--		--		--	--	++	++		-	-- --
SiO <sub>2</sub>	--				-	--					+		+	+
NO <sub>3</sub> /NH <sub>4</sub>	-	--	--	--					-		+		++	+
TIN/PO <sub>4</sub>			++	++				++	-		++			+
TIN/SiO <sub>2</sub>	-	--	--	--		-	--	--	--			-		--

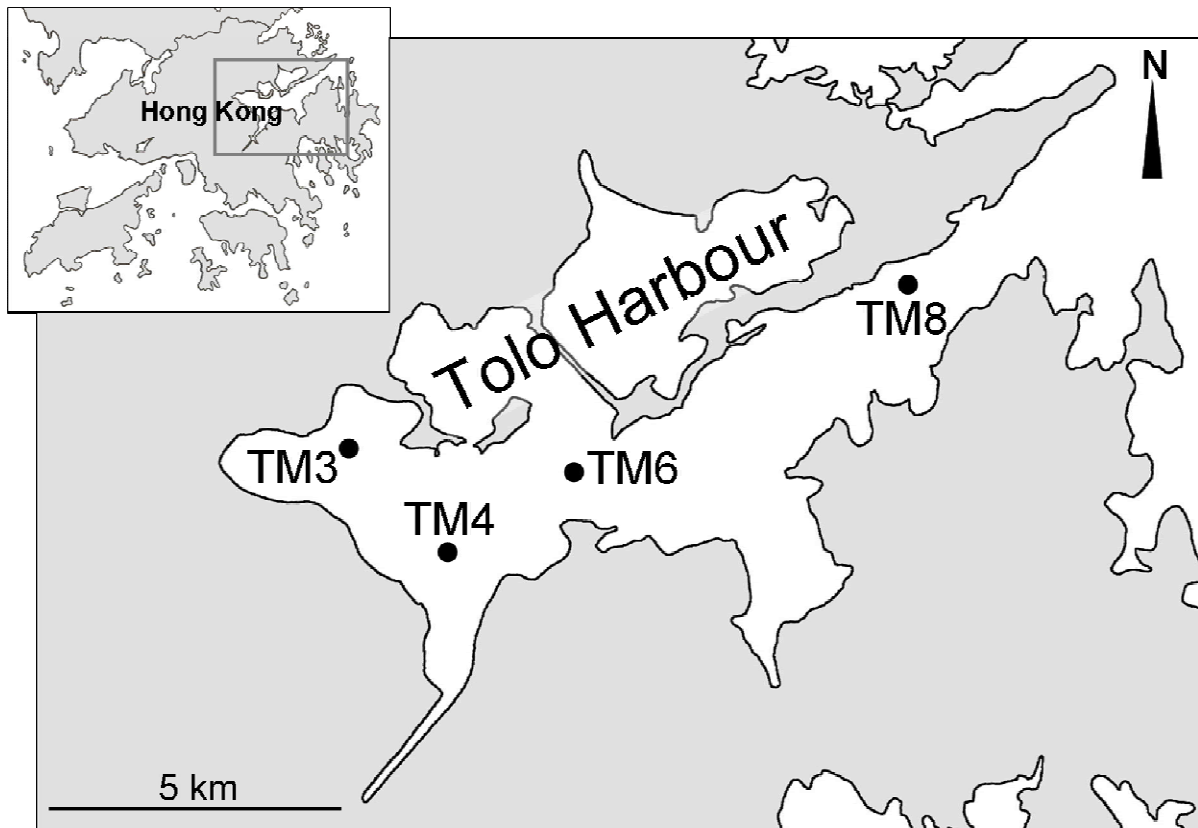


Fig. 1.

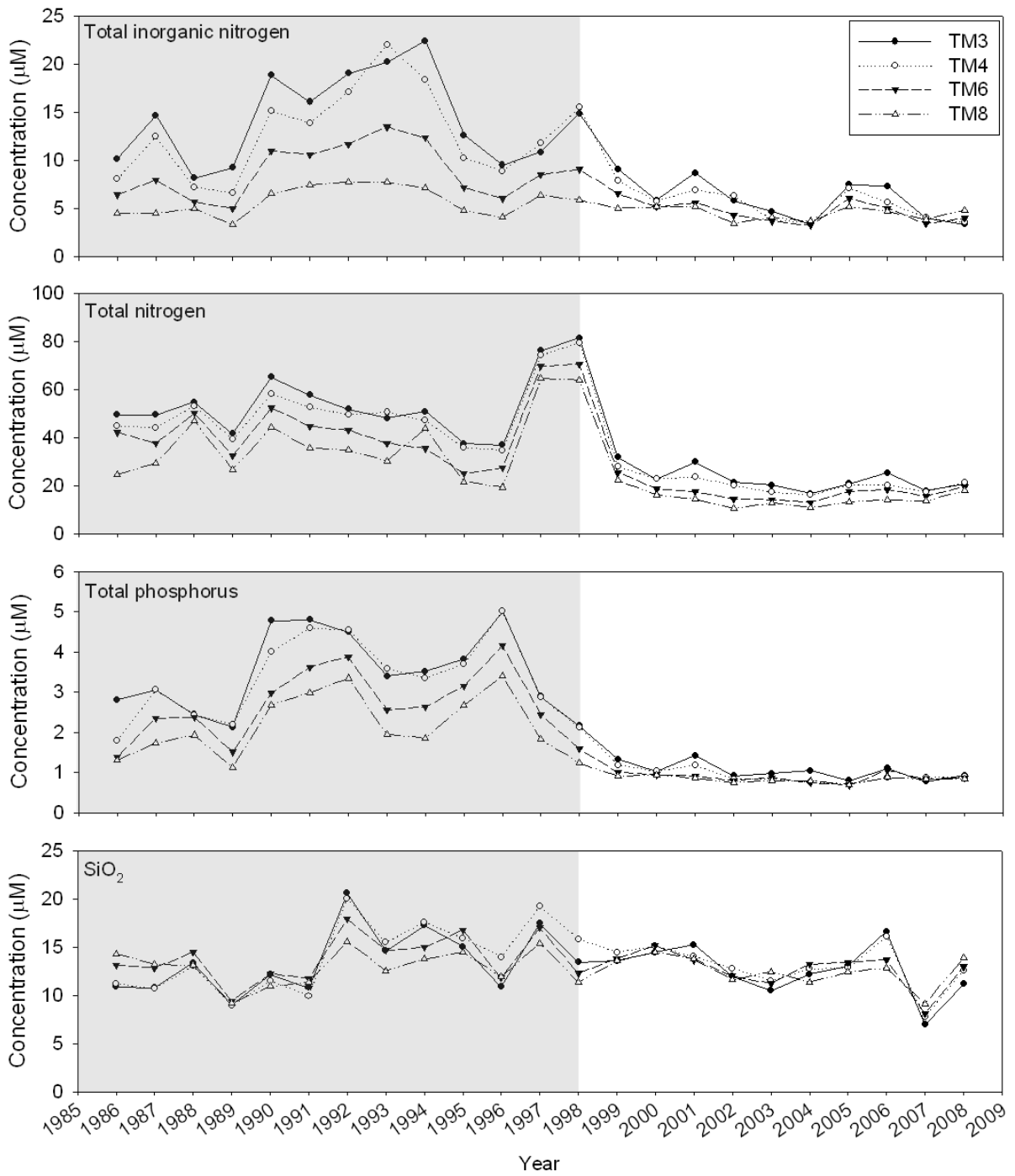


Fig. 2.



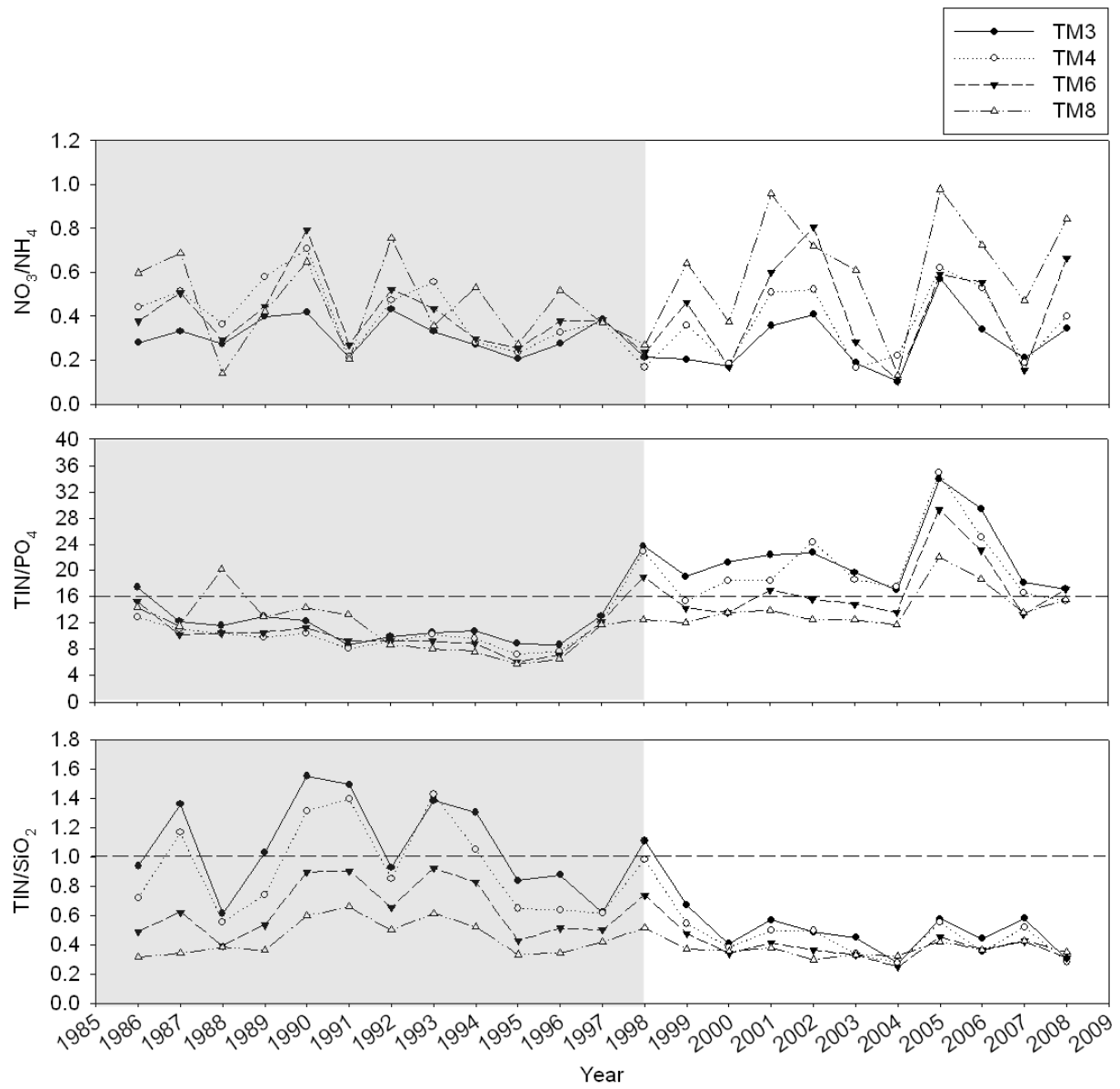


Fig. 3.

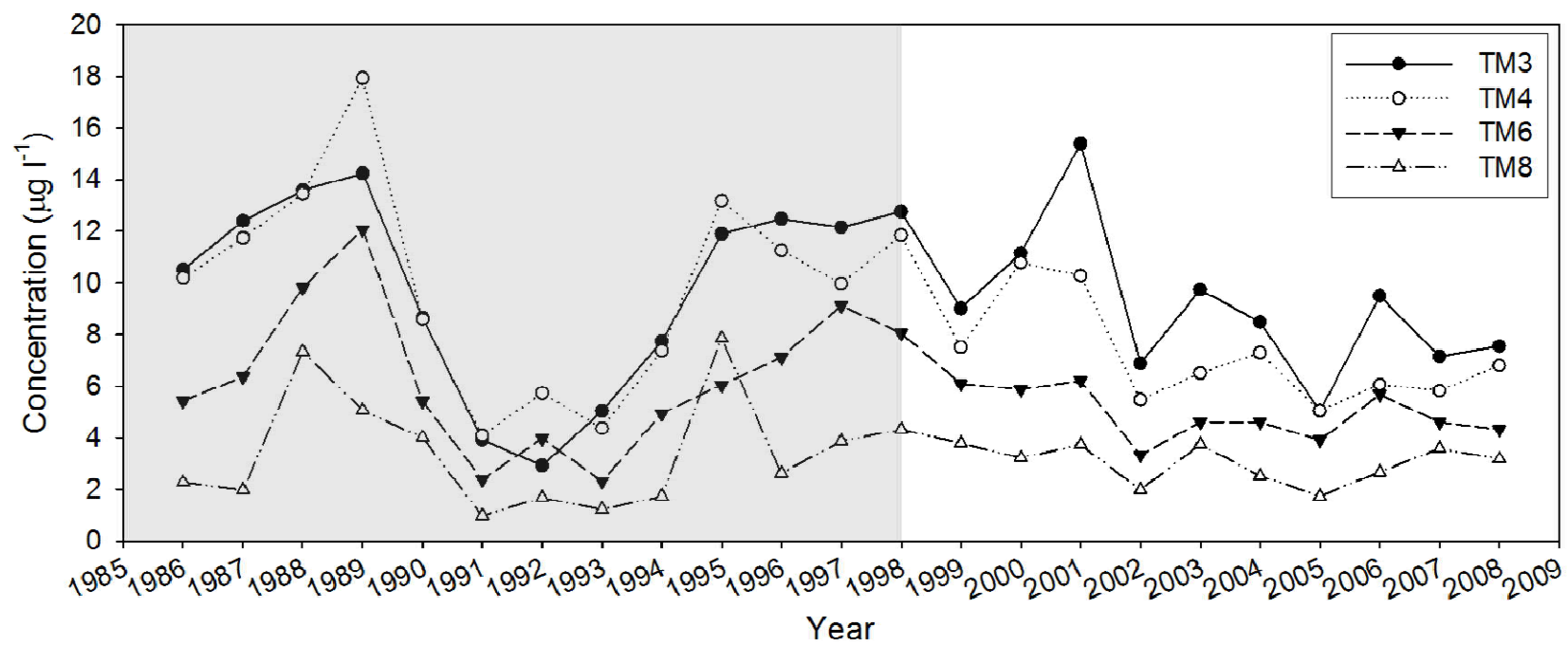


Fig. 4.

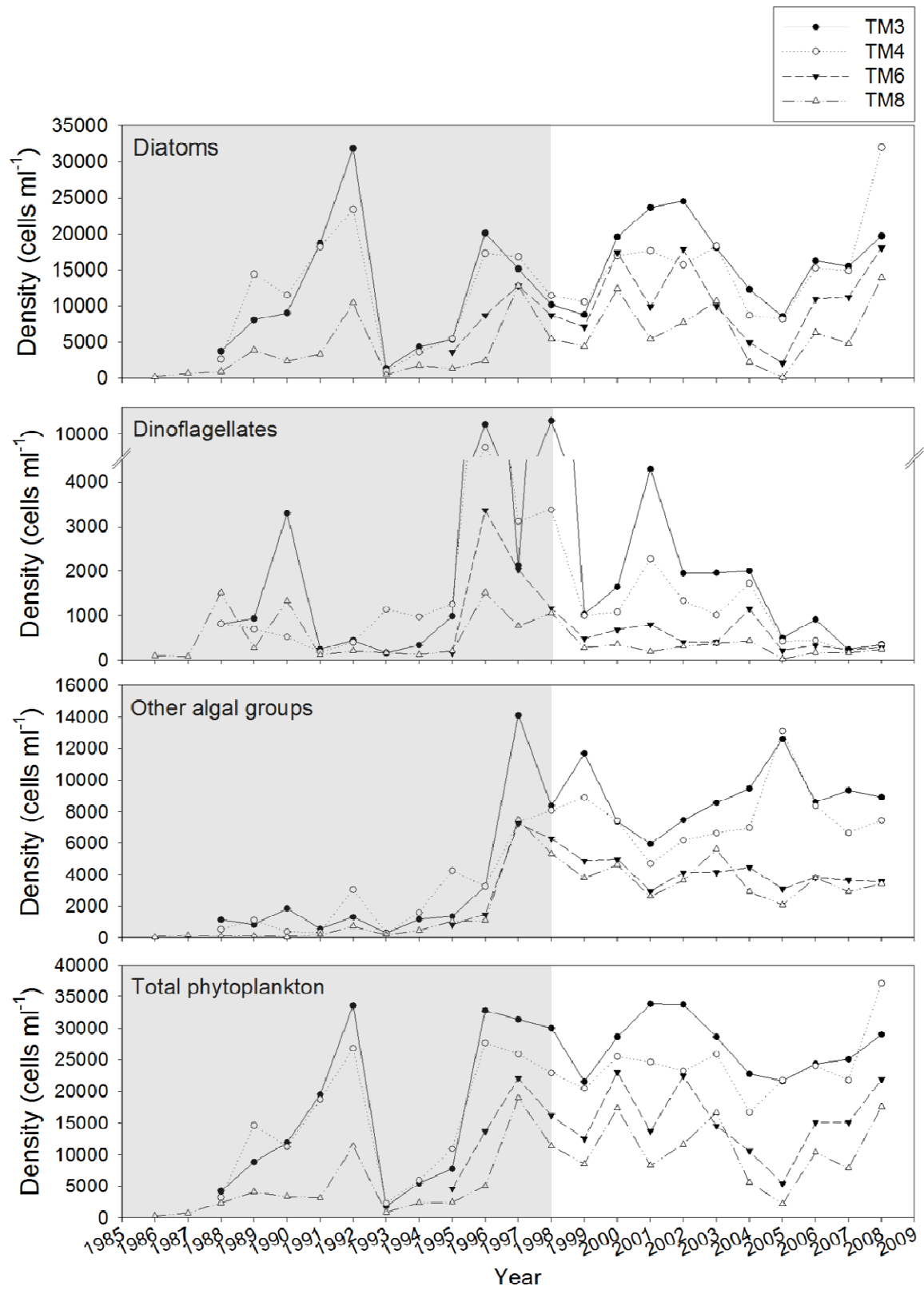


Figure 5.