

Ecological effects of the caged-fish and kelp cultures in semi-enclosed bay: evidence from diatom assemblages and environmental variables

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Received 03 December 2015 ; revised 30 August 2016

Spatial and temporal dynamics of diatom assemblages and their relationships to physico-chemical environmental variables were studied in Sansha Bay, a semi-enclosed bay. A total of 51 taxa were found belonging to the orders Discoidales, Rhizosoleniales, Biddulohiales, Araphidiales, Monoraphidinales, Biraphidinales and Aulonraphidinales. CCA analysis revealed that physical and chemical parameters were important environmental factors that would influence the diatom community. Based on their seasonal occurrence, most of the species had different relationships with environmental factors. Furthermore, the concentrations of DIN and PO_4^{3-} in caged-fish culture zone were significantly higher than those in kelp culture and control zones. The abundance of diatoms in the caged-fish culture zone was significantly higher than that in kelp culture and control zones in some seasons, especially in spring. Therefore, the large-scale caged-fish and kelp cultures play key roles in the spatial and temporal dynamics of the diatom community and environmental quality in semi-enclosed coastal bay.

[Key words: Diatom; assemblages; caged-fish culture; kelp culture; CCA]

Introduction

Sansha Bay (119°26'-120°10'E, 26°30'-26°58'N), a typical semi-enclosed bay located in northeastern Fujian Province, China, has an area of 714 km² and a maximum depth of 90 m. It is one of the most intensively managed coastal semi-enclosed bays in China, and approximately half of its water area is occupied by both caged-fish and kelp culture farms. The waters contain approximately 220,000 fish culture cages with aquaculture effluents including feed residue, fish feces and untreated household sewage that come from fisheries staff¹. Conversely, massive kelp cultures such as kelp, laver and gracilaria are also present, which can

absorb large amounts of nitrogen and phosphorus and release oxygen, which in turn reducing the stock of water organic matter and nutrients².

The species composition and distribution of phytoplankton exhibit complex behavioral responses to environmental influences³⁻⁴. Research on the community structure and the impact of environmental factors is therefore of great importance for assessing productivity and the development and sustainable use of resources in estuaries and coastal areas⁵. Physical (water masses, light, temperature and salinity) and chemical (nitrogen and phosphorus) factors are recognized as aspects that can control the phytoplankton community structure. Variations in

the responses of the phytoplankton community to these variables have been widely studied in estuaries and coastal areas⁶⁻¹¹.

A few studies regarding the distribution and composition of phytoplankton communities have been conducted in Sansha Bay^{2, 12}. However, these studies have focused on seasonal variations in the phytoplankton communities, and not addressed the relationship between the phytoplankton community and its environment varies through statistical analysis such as canonical correspondence analysis (CCA). Furthermore, the scale of caged-fish and kelp cultures is significantly larger now than in the 1990s^{1, 12}. The use of abundance and species diversity and similarity indices in a systematic study of Sansha Bay is an essential approach to estimate biological quality through the structure of the phytoplankton. The water quality will be deteriorated by feed residue and feces from caged-fish culture and will be improved by nutrient uptake of kelp culture, whose changes will impact the structure of phytoplankton community. Therefore, we studied the seasonal characteristics of the diatom community and water quality indices in Sansha Bay from August 2009 to April 2010 in 20 sampling sites, which would reveal the relationship between the diatom community and the caged-fish and kelp cultures.

Materials and Methods

Twenty sampling sites (Fig. 1) were established, covering Sansha Bay near the kelp cultures (stations 1-3, 5-10, 20) and caged-fish cultures (stations 12-19); control had no culture (stations 4 and 11). The samples were collected from 20 sites in August 2009 (summer), November 2009 (autumn), January 2010 (winter) and April 2010 (spring), respectively. The phytoplankton was sampled with an SW-III plankton sampling net (diameter 37 cm, area 0.1 m² and pore size 77 µm), which was vertically drawn twice from 0.5 m above the bottom to the surface in each sampling. Samples for taxonomic and density

analyses were preserved immediately in 5% formaldehyde. The organisms were identified to the lowest possible taxon (genus and species) and counted under an optical microscope (BX43, OLYMPUS, Japan). Taxonomic identifications of genera and species were made by using classification approaches from Jin *et al*¹³ and Yang and Dong¹⁴. Environmental variables such as surface water temperature (T), salinity (S), dissolved oxygen (DO), electrical conductivity (EC) and total dissolved solids (TDS) were measured in situ using a sensION156 portable multi-parameter measurement instrument (HACH, USA). One liter surface water was also collected for analyzing dissolved inorganic nutrients (NO₃⁻, NO₂⁻, NH₄⁺ and PO₄³⁻; DIN is the sum of NO₃⁻, NO₂⁻ and NH₄⁺), previously filtered through 0.45 µm millipore membrane filters and following the standard methods described in the specification for marine monitoring in China (GB17378-2007)¹⁵.

Phytoplankton abundance and dominance (Y) were determined by using the criteria proposed by Sun *et al*¹⁶. Species diversity (*H'*) was calculated using the Shannon index proposed by Shannon and Weaver¹⁷ and the Pielou-Shannon evenness index, (*J'*) was calculated according to Pielou¹⁸. Analysis of variance (ANOVA) was used with a 5% level of significance to determine the degree of temporal and spatial variation. CCA deriving from CANOCO 4.5 software (ter Braak and Smilauer¹⁹) was employed to analyze the relationship between the phytoplankton community and physico-chemical environmental variables. The data were previously transformed logarithmically [$\log(X+1)$] and organized in a "biological" matrix that included the frequency ($\geq 25\%$) and abundance ($\geq 0.2\%$) of diatoms and an "explanatory" matrix including the measured environmental variables. Monte Carlo permutation testing (999 permutations; CANOCO 4.5) was used to determine the significance of the variables and the first two ordination axes.

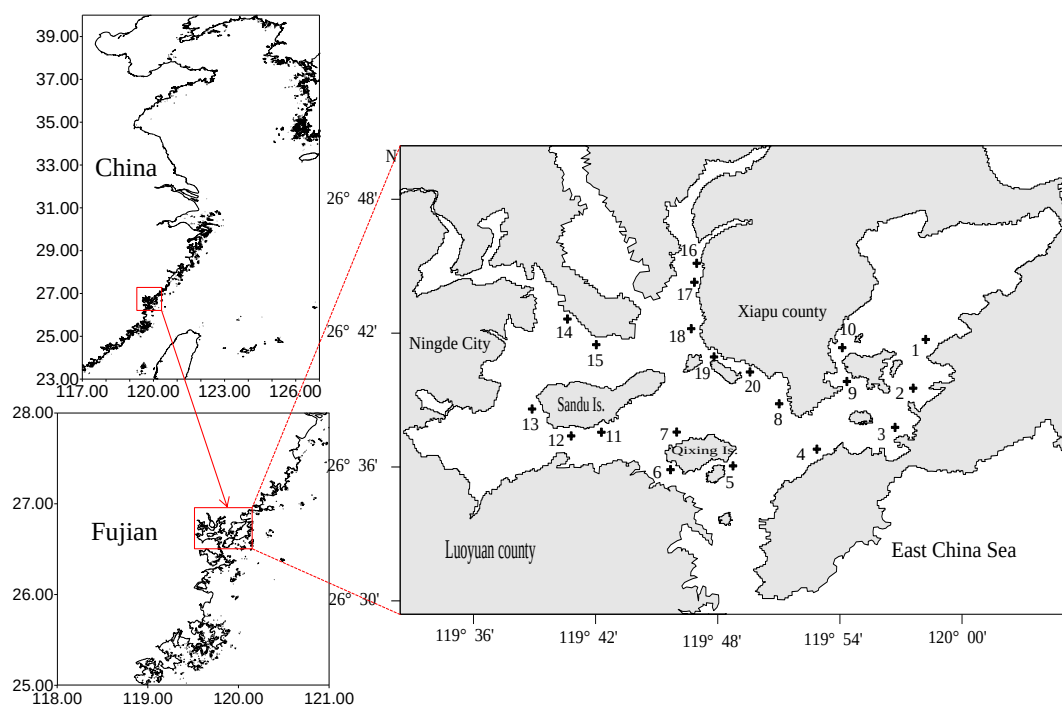


Fig. 1 — Study area and location of sampling stations in Sansha Bay

Results

Sea surface temperature values shows the lowest level in January 2010 (winter: 16.21 ± 0.16 °C) and the highest in August 2009 (summer: 29.30 ± 0.18 °C). DO concentrations in the caged-fish culture zone were significantly lower than that in the kelp culture and control zones in summer and winter, while higher than in kelp culture and control zones in spring (Fig. 2a, $P < 0.05$).

The concentrations of DIN in the caged-fish culture zones were significantly higher than in the kelp culture and control zones in all four seasons (Fig. 2b, $P < 0.05$). The concentrations of NO_3^- in the caged-fish culture zones were significantly higher than in kelp culture and control zones in summer, autumn and winter (Fig. 2c, $P < 0.05$). We found no significant differences in NH_4^+ concentrations in the kelp culture and control zones during the year (Fig. 2e, $P > 0.05$), except in spring (Fig. 2e, $P < 0.05$), and the concentrations of NH_4^+ in the caged-fish culture zone were significantly higher than in the kelp

culture zone in four seasons (Fig. 2e, $P < 0.05$). The concentrations of PO_4^{3-} in the caged-fish culture zone was significantly higher than in the kelp culture and control zones in autumn and winter (Fig. 2f, $P < 0.05$).

A total of 51 diatom taxa in seven orders—Discoidales (31.37%), Rhizosoleniales (3.92%), Biddulohiales (23.53%), Araphidiales (15.69%), Monoraphidinales (1.97%), Biraphidinales (11.76%) and Aulonraphidinales (11.76%)—were identified and quantified in Sansha Bay during the study period. *Coscinodiscus oculus-iridis*, *C. jonesianus*, *Skeletonema costatum*, *Biddulphia sinensis*, *B. pulchella*, *Ditylum brightwellii*, *Synedra* sp., *Grammatophora marina*, *Navicula* sp., *Nitzschia* sp. and *Bacillaria paxillifera* were the most common species throughout the year. The species richness of each sampling site ranged from 2 to 14 for a total of 51 species during the investigation period. The highest value appeared in summer (August 2009) and ranged from 2 to 14, for a total of 39 species (Fig. 3).

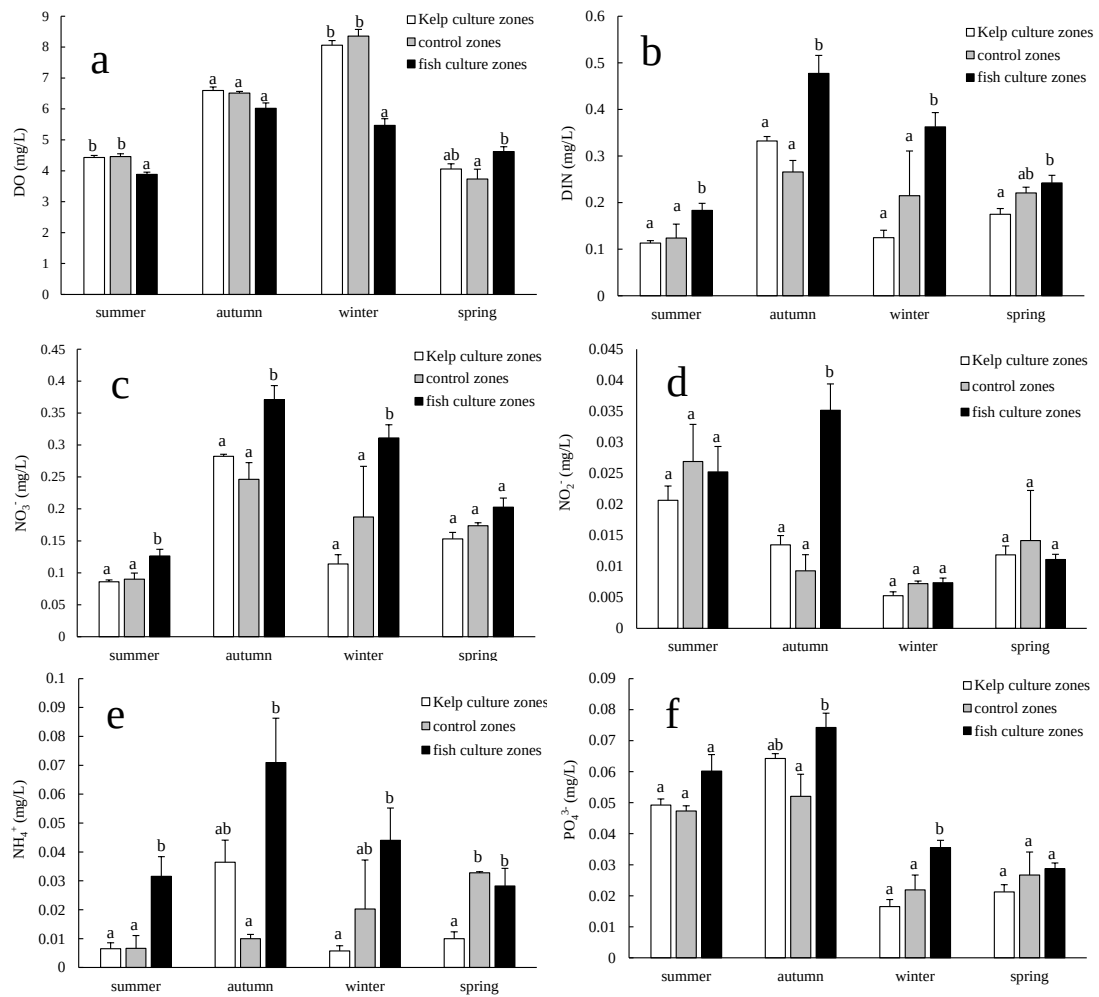


Fig. 2 — Spatio-temporal variation of DO (a), DIN (b), NO_3^- (c), NO_2^- (d), NH_4^+ (e) and PO_4^{3-} (f) in different zones in Sansha Bay. The data are given as the mean values $\pm$ SE, and the different letters indicate the significant differences among the treatments ($P < 0.05$).

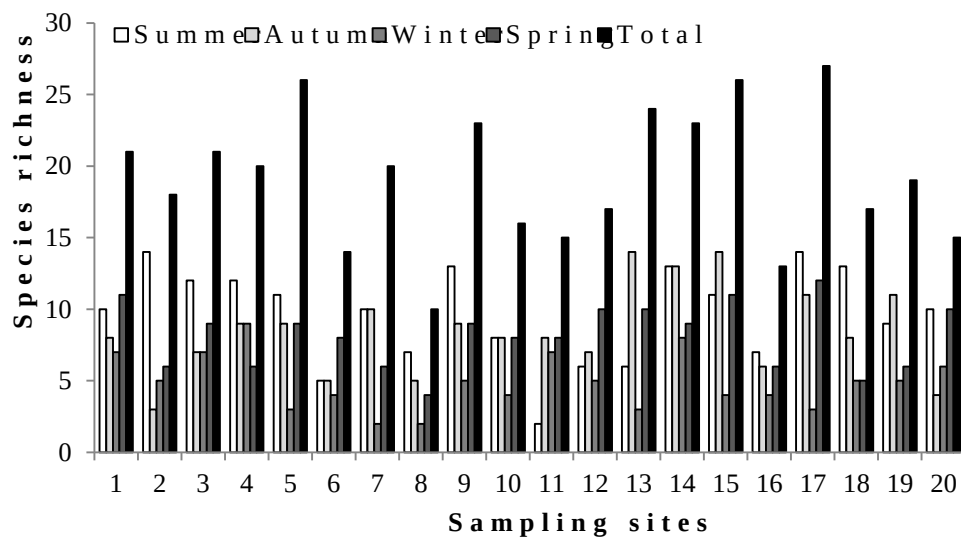


Fig. 3 — Distribution of diatoms taxa richness at each sampling station throughout the year.

During the investigation period, the abundance of diatoms in the three zones ranged from 2.43×10^4 to 358.99×10^4 cells/m³, with an average of 41.89×10^4 cells/m³. The spatial distribution pattern of diatoms in the three zones was different in four seasons. In summer, the abundance of diatoms in kelp culture zone was significantly higher than that in the control zone (Fig. 4a, $P < 0.05$). In autumn, the abundance of diatoms in the caged-fish culture zone was significantly higher than that in the kelp culture and control zones (Fig. 4a, $P < 0.05$). In winter, no significant differences were observed between the three zones (Fig. 4a, $P > 0.05$). In spring, the abundance of diatoms in the caged-fish culture zone was significantly higher than that in the kelp culture and control zones (Fig. 4a, $P < 0.05$).

The diversity values (H') ranged from a minimum of 0.263 in caged-fish culture zones in spring to 2.635 in control zones in autumn (Fig. 4b). The diversity values in summer, autumn and winter were higher than that in spring, with no significant differences between the three zones (except that the values in the control zone were higher than those in the kelp culture zone in autumn). The diversity values in the kelp culture and control zones were higher than those in the caged-fish culture zones in spring (Fig. 4b, $P < 0.05$). The evenness index (J') ranged from a minimum of 0.086 in caged-fish culture zones in spring to 0.867 in control zones in summer (Fig. 4c). Spatio-temporal characteristics of the evenness index were similar to the diversity values.

Twenty-one species of diatoms and 10 environmental factors were chosen for CCA analysis (Table 1) according to the frequency ($\geq 25\%$) and abundance ($\geq 0.2\%$) of diatoms²⁰⁻²¹.

An ordination diagram confirmed a significant relationship between the environmental variables and algal associations in Sansha Bay (Fig. 5). In summer, the eigenvalues of the canonical axes 1 and axes 2 were 0.201 and 0.133, and the

correlation values between the species composition and environmental variables were 0.867 and 0.904, respectively. Several species such as *Pseudo-nitzschia pungens*, *C. radiatus* and *C. bipartitus* were positively correlated with T, DIN, NO_3^- , NO_2^- , NH_4^+ and PO_4^{3-} , on the other hand, *C. oculus-iridis* and *S. costatum* were positively correlated with S, DO, EC and TDS.

In autumn, the eigenvalues of the canonical axes 1 and axes 2 were 0.376 and 0.254, the correlation values between the species composition and environmental variables were 0.771 and 0.927, respectively. *Helicotheca tamesis*, *Nitzschia* sp. and *G. marina* were positively correlated with DIN, NO_3^- , NO_2^- , NH_4^+ and PO_4^{3-} , while *C. radiatus*, *Navicula* sp. and *N. longissima* were positively correlated with DO, EC and TDS, and at the same time *M. moniliformis* and *Ditylum brightwellii* were positively correlated with T.

In winter, the eigenvalues of the canonical axes 1 and axes 2 were 0.231 and 0.098, the correlation values between the species composition and environmental variables were 0.938 and 0.747, respectively. Several species such as *G. marina* and *B. pulchella* were positively correlated with T, DIN, NO_3^- , NH_4^+ and PO_4^{3-} , meanwhile *M. moniliformis*, *Navicula* sp. and *B. paxillifera* were positively correlated with S, DO, EC and TDS.

In spring, the eigenvalues of the canonical axes 1 and axes 2 were 0.151 and 0.082, the correlation values between the species composition and environmental variables were 0.909 and 0.833, respectively. *Skeletonema* sp. and *Nitzschia* sp. were positively correlated with T, DO and PO_4^{3-} , while *D. brightwellii*, *Skeletonema* sp. and *M. moniliformis* were positively correlated with DIN, NO_3^- , NH_4^+ and T. Besides *G. balticum* and *C. oculus-iridis* were positively correlated with TDS, EC and S. From the CCA biplots, we considered that *C. jonesianus* and *B. sinensis* were uncorrelated with the environmental variables in summer, winter and spring.

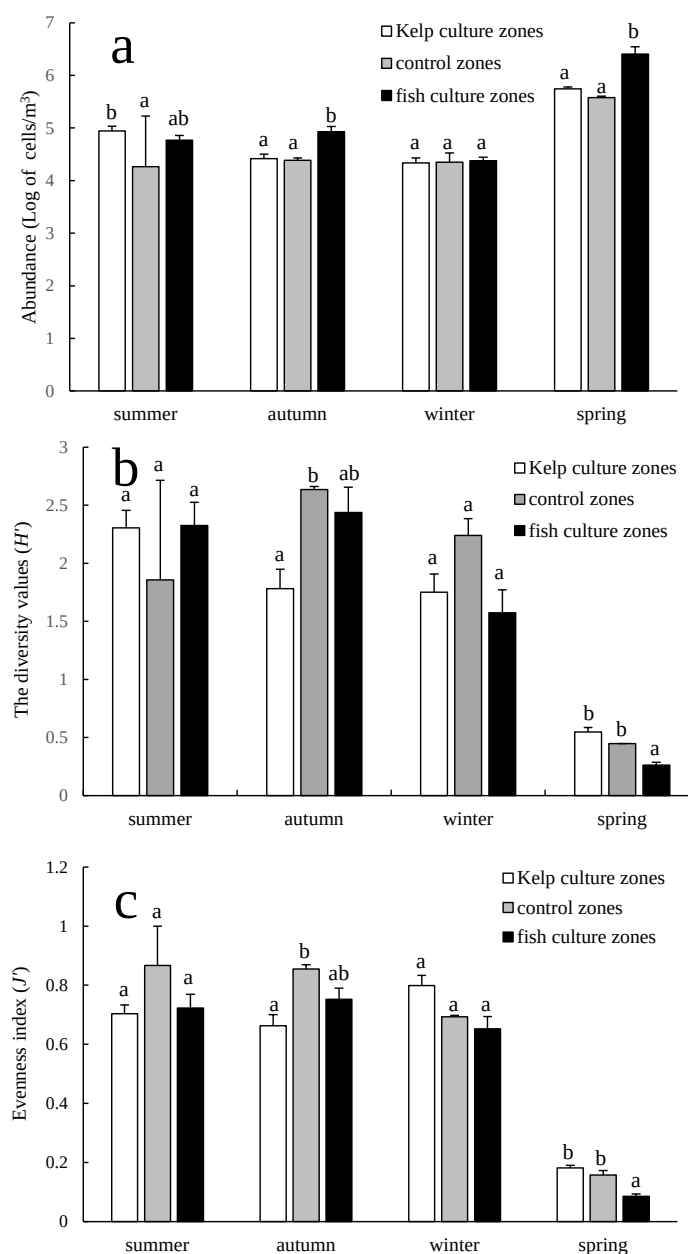


Fig. 4—Spatio-temporal variation of diatoms abundance (a), diversity values (b), evenness index (c) in different zones in Sansha Bay. The data are given as the mean values $\pm$ SE, and the different letters indicate the significant differences among the treatments ($P < 0.05$).

Table 1 — List of diatoms species for CCA

Species	Code	Summer	Autumn	Winter	Spring
<i>Melosira</i> sp.	MES			+	+
<i>M. moniliformis</i>	MMO		+	+	+
<i>Coscinodiscus bipartitus</i>	CBI	+			
<i>C. radiatus</i>	CRA	+	+		
<i>C. oculus-iridis</i>	COC	+		+	+
<i>C. jonesianus</i>	CJO	+		+	+
<i>Skeletonema</i> sp.	SKS				
<i>S. costatum</i>	SCO	+			

Discussion

Coastal diatom assemblages in Sansha Bay near the East China Sea showed significant spatio-temporal variations in species composition and community structure. During the investigation period (from August 2009 to April 2010), the highest species richness appeared in summer (August 2009) and ranged from 2 to 14, for a total of 39 species (Fig. 3), the abundance of diatoms in the caged-fish culture zone was significantly higher than that in kelp culture and control zones in autumn and spring, and the diversity value and evenness index in kelp culture and control zones were higher than those in caged-fish culture zone in spring (Fig. 4). The observed differences are likely related to local fisheries, including fish and kelp cultures in Sansha bay.

The phytoplankton species observed in Sansha Bay are mainly typical marine diatom taxa. In terms of abundance, *C. oculus-iridis*, *C. jonesianus*, *S. costatum*, *B. sinensis*, *B. pulchella*, *D. brightwellii*, *Synedra* sp., *G. marina*, *Navicula* sp., *Nitzschia* sp. and *B. paxillifera* were the most common species throughout the year. *Coscinodiscus jonesianus*, *S. costatum* were the dominant species which found in adjacent semi-enclosed bays such as Luoyuan Bay²², Lueqing Bay²³ and Xiangshan Bay²⁴, too. *Skeletonema costatum* has a worldwide distribution and was the dominant species observed in İzmit Bay, Turkey⁸, Uradaibai estuary⁷ and in the inland seas of southern Chile²⁵. We found obvious differences in the dominant species over the four seasons. In summer, *B. paxillifera*, *B. malleus*, *C. jonesianus*, *D. brightwellii* and *S. costatum* were the dominant species. Moreover, *Coscinodiscus jonesianus* was the dominant species in Yueqing Bay^{23,26}, Sanmen Bay²⁷ and Xiangshan Bay²⁴. In autumn, *B. paxillifera*, *C. jonesianus*, *G. marina* and *Nitzschia* sp. were dominant species. *Coscinodiscus jonesianus* was also the dominant species observed in Xiangshan Bay²⁴. We found many dominant species in summer and autumn

but their dominance values were low, with the highest value of the dominant species in summer and autumn for 0.24 and 0.23 (*C. jonesianus* and *B. paxillifera*, respectively). However, *C. jonesianus* and *B. sinensis* were the dominant species and *C. jonesianus* was the key species (the dominance values were 0.54 and 0.96) in winter and spring; a similar result occurred in Xiangshan Bay with dominance values for *C. jonesianus* of 0.73 and 0.90²⁴. Furthermore, during this investigation, diatoms species number is only about half that of the previous survey in 1990¹², which means that the marine environment was deteriorated by human activity (such as a large scale caged-fish cultures) in Sansha Bay.

The present results indicate that the average abundance of diatoms in Sansha Bay was 41.89×10^4 cells/m³ in four seasons, with the highest value being 151.31×10^4 cells/m³ in spring and the lowest 2.53×10^4 cells/m³ in winter. Compared with the previous investigation in 1990, whose average diatom abundance was only 17.50×10^4 cells/m³ (including a few dinoflagellates, Lin¹²), the abundance of diatoms having increased significantly. Sansha Bay had a few caged-fish cultures 20 years ago, while having approximately 220,000 caged-fish culture cages at the end of 2009¹. The large-scale caged-fish cultures maybe led to promote the growth of phytoplankton. In summer, the average abundance of diatoms in Sansha Bay was 8.50×10^4 cells/m³; the value was lower than in Yueqing Bay (60.95×10^4 cells/m³)²⁶ and higher than in Xiangshan Bay (7.19×10^4 cells/m³)²⁴. In autumn and winter, the average diatom abundances in Sansha Bay were 5.23×10^4 cells/m³ and 2.53×10^4 cells/m³, respectively. The values were lower than that in Yueqing Bay (autumn: 247.60×10^4 cells/m³)²³ and Xiangshan Bay (autumn, 65.88×10^4 cells/m³ and winter, 56.77×10^4 cells/m³)²⁴. In spring, the average abundance of diatoms in Sansha Bay was 151.31×10^4 cells/m³, whose value was lower than Luoyuan Bay (245.00×10^4 cells/m³)²² and higher than Yueqing Bay (38.12×10^4

cells/m³)²⁸ and Xiangshan Bay (35.29×10^4 cells/m³)²⁴. In this study, we found that the spatial distribution pattern of diatoms in three zones was different in the four seasons. The abundance of diatoms in the caged-fish culture zone was significantly higher than that in the kelp culture and control zones in autumn and spring (Fig. 3a, $P < 0.05$), indicating that caged-fish culture supplies plenty of nutrients to promote the abundance of phytoplankton. We found no significant differences in the three zones (Fig. 3a, $P > 0.05$) in winter because of low irradiance and temperature imposed severe restrictions on phytoplankton growth⁶. The sea surface temperature was only $16.21 \pm 0.16^\circ\text{C}$ in Sansha Bay, and a similar result was observed in Schelde Estuary, Belgium⁶ and Lake Baiyangdian, China¹⁰.

It is well known that physical and chemical parameters may affect the structure of the phytoplankton assemblages⁷. In the present study, the CCA biplots showed that the physical and chemical parameters affected the spatio-temporal distribution of the diatoms in Sansha Bay (Fig. 5). In summer, for example, *C. jonesianus* was the main dominant species (the dominance was 0.23); *C. jonesianus* was not correlated with these physical and chemical parameters, suggesting that it is a coastal eurytopic species and does not have high requirements for physical and chemical factors. Luan *et al.*²¹ reported that *C. jonesianus* was also close to the center of the CCA diagram in the Yangtze River Estuary in summer. In autumn, *G. marina* was the first dominant species and was positively correlated with DIN, NO₃⁻, NO₂⁻, NH₄⁺ and PO₄³⁻. In winter, *C. jonesianus* and *B. sinensis* were the main dominant species, but were not correlated with these physical and chemical parameters. In spring, *C. jonesianus* was the absolutely dominant species (the dominance was 0.96) *C. jonesianus* and *B. pulchella* were uncorrelated with these physical and chemical parameters, *D. brightwellii* was positively correlated with DIN, and consistent results were

found in Xiangshan Bay in spring, too²⁹. The same species had different relationships with environmental factors in different seasons. For example, *D. brightwellii* was not correlated with these physical and chemical parameters in summer but was positively correlated with T in autumn and with DIN, NO₃⁻, NH₄⁺ and T in spring (Fig. 5). This indicated that the CCA relationship between species and environmental factors are based on the concentration of the physical and chemical parameters' and the status of the competing species. Conversely, *C. jonesianus* and *B. sinensis* were not correlated with the environmental variables in summer, winter or spring. Diatoms prefer to grow in water with high NO₃⁻ concentration¹, the NO₃⁻ and other nutrient concentrations were very high in Sansha Bay all through the year (Fig. 2) and physical parameters such as T, EC, TDS and S were suitable for diatom growth. Therefore, some species such as *C. jonesianus* and *B. sinensis* have spatio-temporal distributions which are not sensitive to physical and chemical parameters.

Conclusions

In summary, the physical and chemical parameters were important environmental factors that would influence the diatom community. Among these factors, water temperature was a key factor that influences the seasonal variation in diatom abundance, while nutrients were the main factors influence the spatial distribution of diatom abundance and diversity. Diatom abundance increased and species diversity decreased compared with 20 years ago when a few caged-fish cultures were in Sansha Bay¹². Therefore, additional studies should be carried out concerning the spatial and temporal distribution of phytoplankton under the new relationship between the caged-fish and kelp cultures.

Acknowledgements

This research was supported by National Natural Science Foundation of Shanghai, China

(12ZR1444900) and State Oceanic Administration People's Republic of China's special funds for scientific research on public causes (201105023).

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