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Distribution of Sediment Chloroplastic Pigments in the Southern Yellow Sea, China

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Abstract The distribution of sediment chloroplastic pigments (Chl-*a*, *i.e.* chlorophyll *a* and Pha-*a*, *i.e.* phaeophorbide *a*) in the Southern Yellow Sea of China was studied. Samples were collected from four cruises in January and June 2003, and January and June 2004. The results show that the vertical distribution of Chl-*a* and Pha-*a* in the sediment layers 0–2 cm, 2–5 cm and 5–8 cm, follows a stable ratio, 5:3:2. The average ratio of Pha-*a* to Chl-*a* in sediment is 2.83. Spearman 2-tailed rank correlation analysis shows that Chl-*a* and Pha-*a* contents in each sediment layer have a highly significant correlation. The average contents of Chl-*a* and Pha-*a* in the sediment of the 0–8 cm layer in the investigated area are 0.31–0.47 $\mu g\,g^{-1}$ and 1.28–1.40 $\mu g\,g^{-1}$ sediment (dry weight), respectively. The average Chl-*a* and Pha-*a* contents in sediment are higher in summer than in winter. ANOVA analysis shows that there is a highly significant variation among the Chl-*a* contents ($P = 0.002 < 0.01$) of the four cruies, but this is not true for the case of Pha-*a* content ($P = 0.766 > 0.05$). The average Chl-*a* and Pha-*a* contents in the 2 sediment layers (0–2 cm and 2–5 cm) have significant or highly significant correlations with organic matter (OM), median diameter (Md_ϕ), silt plus clay percentage in the January 2003 cruise. In the June 2003 cruise, the average Chl-*a* content in the 3 sediment layers (0–2 cm, 2–5 cm, and 5–8 cm) has a significant correlation with meiofauna biomass, and Pha-*a* content has highly significant correlations with water depth, bottom water temperature, OM and Md_ϕ. The contents of Chl-*a* and Pha-*a* are lower than those in estuaries and intertidal areas, but close to those in the same area studied previously.

Key Words Southern Yellow Sea; sediment; chlorophyll *a*; phaeophorbide *a*; distribution

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1 Introduction

Chlorophyll *a* (Chl-*a*) is a kind of pigment involved in the photosynthesis of all algae. The content of Chl-*a* is an index of the biomass of primary producer, mainly phytoplankton and microphytobenthos. It can be used to estimate the marine primary productivity (Fei *et al.*, 1997) and to measure the eutrophication (Kowalewska *et al.*, 2004).

The study of Chl-*a* has been mostly focused on the pelagic system. There were very limited works concerning the Chl-*a* in sediment. Chl-*a* and its decomposed product, phaeophorbide *a* (Pha-*a*), in sediment, are important environmental factors for affecting benthos (Rysgaard *et al.*, 1994). Richard *et al.* (2000) studied the Chl-*a* in the sediment of the southeast marine areas in America and found that there were much Chl-*a* in sediment, which could account for 56% ± 39% of that in pelagic system. Yuan (1990) analyzed the Chl-*a*, Pha-*a* and organic matter in sediment of the submarine delta of Yellow River Estuary and its adjacent areas. Li *et al.* (2004) studied the Chl-*a* and Pha-*a* in sediment of seven stations in the Yellow Sea and East China Sea. But there have been no intensive large-scale studies on Chl-*a* in the Yellow Sea so far.

The Southern Yellow Sea is a continental shelf shallow sea and very important in marine traffic. Pollutants from terrestrial sources and petroleum are threats to the area (Guo, 1993). The pollution may affect the benthic habitats by benthic-pelagic coupling (Zhang, 2000). The Southern Yellow Sea is also an important spawning, feeding and over winter grounds for many economic species such as *Penaeus chinensis* and some demersal fishes. The Chl-*a* content can be used to estimate microalgae biomass, which reflects the status of marine environment and serve as food resource for meiofauna and macrobenthic deposit feeders. The present study is designed to (1) describe the spatial and temporal distribution of sediment chloroplastic pig-

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ments (Chl-*a* and Pha-*a*) in the Southern Yellow Sea; (2) find out the relationships of Chl-*a* and Pha-*a* with other abiotic and biotic environmental factors.

2 Materials and Methods

2.1 Sampling Area and Stations

Samples were collected from four cruises in January and June 2003, and January and June 2004, each having 23, 22, 28 and 16 stations, respectively. The study area covered the ranges 32.5°N to 37°N, and 120°E to 125.5°E (Fig.1).

2.2 Sampling Method

Undisturbed sediment samples were collected with a modified 0.1 m^2 Gray-O'Hara box corer for each station. Two sediment cores were taken using a sawn-off syringe with a 2.6 cm inner diameter to a depth of 8 cm, except for the January 2003 cruise, in which the core was taken to a depth of 5 cm. Each core was sectioned into 0–2 cm, 2–5 cm, and 5–8 cm layers. All sediment layers were stored in a frozen state at −20 ℃ until use.

2.3 Analysis in Laboratory

Chlorophyll *a* and phaeophorbide *a* contents were determined with spectrophotofluorimetry following the method given by Lorenzen and Jeffrey (1980) and modified by Liu *et al.* (1998) for wet sediment. A frozen sediment section (about 2 g) was weighed, thawed and moved to a 150 mL flask. Into the flask, 10 mL 90% acetone and a spoon of solid magnesium carbonate were added. The flask was plugged and shaken thoroughly, till the stuff was emulsified. Then, the flask was put in a refrigerator at 4 ℃ in darkness. After 24 h, the stuff in the flask was centrifuged at 4000 r min^{-1} for 15 min. The supernatant, including Chl-*a* and Pha-*a*, was stored at −20 ℃ and used for the determination of Chl-*a* and Pha-*a* contents in 2 weeks. The OD value at Ex/Em wavelengths 450/685 nm of the acetone extract was determined with a spectrophotofluorometer (930, Shanghai 3rd Analytical Instrument Factory). The concentration of Pha-*a* was calculated according to the corrected formula presented by Wang (1986). The water content of sediment was measured in each section synchronically as a percentage of weight loss by drying the sediment at 60 ℃ for 24 h. The contents of Chl-*a* and Pha-*a* are expressed in μg pigment g^{-1} sediment dry weight (μg g^{-1}).

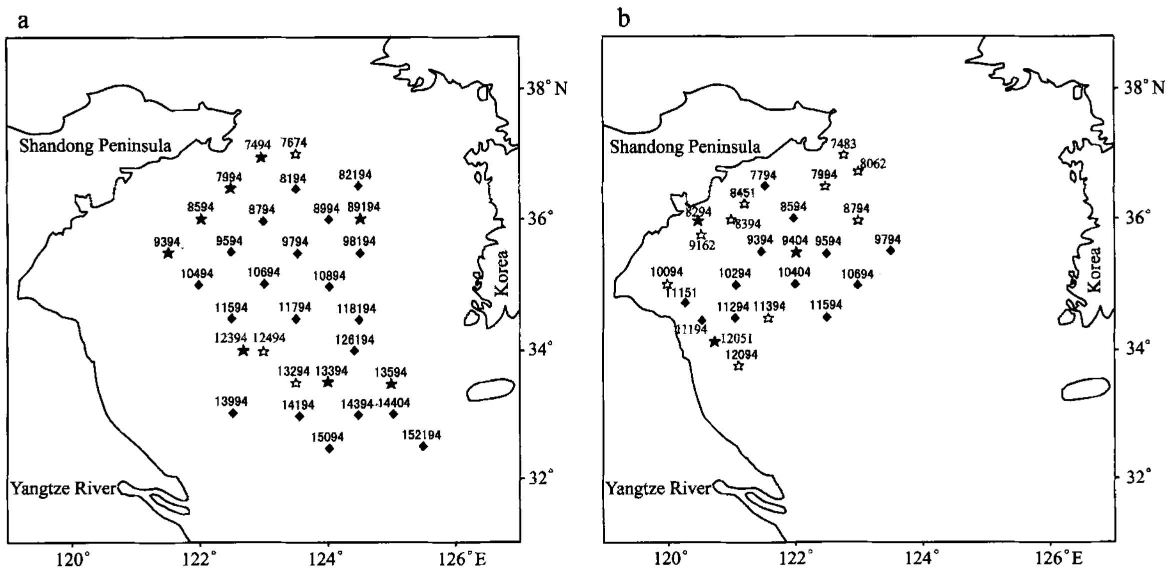

Fig.1 Map of Southern Yellow Sea, showing sampling stations. a. Sampling stations in winter. ◆: Stations both in January 2003 and 2004; ☆: Stations only in January 2003; ★: Stations only in January 2004. b. Sampling stations in summer. ◆: Stations both in June 2003 and 2004; ☆: Stations only in June 2003; ★: Stations only in June 2004.

2.4 Data Processing

Excel 2000 and SPSS10.0 were used to process the data. In order to assess the relationships of Chl-*a* and Pha-*a* contents in each sediment layer, and those of the pigments contents with meiofauna and other environmental factors, Spearman rank correlation analysis was performed. One-way ANOVA analysis was used to test the variation of the Chl-*a* and Pha-*a* contents in sediment of the four cruises. And Chi-square nonparametric test was performed to demonstrate the vertical proportion of the pigments in each cruise.

3 Results and Discussion

3.1 Temporal and Spatial Distribution of Chl-*a* and Pha-*a*

The average contents of Chl-*a* observed in the sediment of the investigated area are 0.31 μg g^{-1} ± 0.16 μg g^{-1} (January 2003, 0–5 cm), 0.64 μg g^{-1} ± 0.37 μg g^{-1} (June 2003, 0–8 cm), 0.45 μg g^{-1} ± 0.22 μg g^{-1} (January 2004, 0–8 cm) and 0.47 μg g^{-1} ± 0.38 μg g^{-1} (June 2004, 0–8 cm), respectively. And those of Pha-*a* in the sediment are 1.28 μg g^{-1} ± 0.67 μg g^{-1} (January 2003, 0–5 cm), 1.58 μg g^{-1} ± 1.09 μg g^{-1} (June 2003, 0–8 cm), 1.39 μg g^{-1} ± 0.73 μg g^{-1} (January 2004, 0–8 cm) and 1.40 μg g^{-1} ± 0.29 μg g^{-1} (June 2004, 0–8 cm), respectively. The content of Chl-*a* in the 0–2 cm section is higher than those of the deeper sediment in the four cruises, which will be shown in § 3.2. The average Chl-*a* and Pha-*a* contents in the 3 layers are higher in summer than those in winter (Fig.2 and Fig.3), which may result from the algae bloom in summer. ANOVA analysis shows that there is a highly significant difference among the Chl-*a* contents of the four cruises ($P = 0.002 < 0.01$), but this is not true for the Pha-*a* contents ($P = 0.766 > 0.05$).

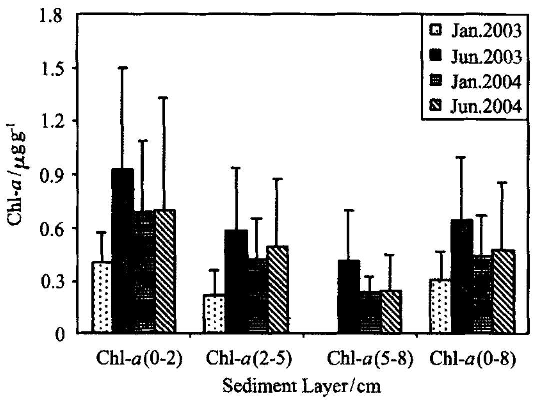

Fig.2 The content of Chl-*a* in each sediment layer of the four cruises.

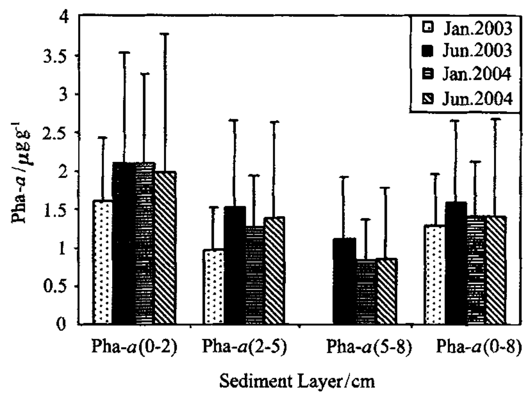

Fig.3 The content of Pha-*a* in each sediment layer of the four cruises.

The distributions of Chl-*a*, Pha-*a* and total pigments in a sediment section almost have the same pattern in the January 2003 cruise. There are three higher peak values for Stations 8794, 8194 and 14194, respectively (Appendix I).

There are differences between the distribution patterns of Chl-*a*, Pha-*a* and total pigments in the sediment sections in the June 2004 cruise. There are four higher Chl-*a* peak values of 0–2 cm section at Stations 7794, 8394, 11394 and 10694, respectively. Besides the four peak values, Station 8794 has a higher Chl-*a* content in the 2–5 cm section, too. There are also three higher Chl-*a* contents in the 5–8 cm section at Stations 7483, 8794, 8394. The Chl-*a* content in the 0–8 cm section has the same pattern as that of Chl-*a* in the 2–5 cm sediment section. In all the vertical sections, Station 11194 has the minimum Chl-*a* and Pha-*a* contents. The average Pha-*a* content has higher values in each sediment section at Stations 8394, 8794, and 10694, and the higher values of total pigments appear also at Stations 9394, 8794, and 10694 (Appendix II).

For the Stations 7494, 89194, 13394 and 13994, the higher Chl-*a* values in the 0–2 cm, 2–5 cm sections and 0–8 cm section in January 2004 are almost the same. But in the 5–8 cm section, Stations 13994 and 9794 have the higher Chl-*a* values. The higher Pha-*a* content in the 0–2 cm section distributes in a stripe area covering Stations 89194, 8994, 9794 and 9594, and the higher Pha-*a* values in the 2–5 cm and 0–8 cm sections occur at Stations 89194 and 9794. The higher values of Pha-*a* in the 5–8 cm section are at Stations 9794 and 8594. The total pigments in the 0–8 cm section has two peak values at Stations 89194 and 9794 (Appendix III).

There are two distinct stations (Stations 11194 and 9394) where the Chl-*a* and Pha-*a* contents in all the sections are much lower in June 2004. The Chl-*a* content in the 0–2 cm and 0–8 cm sections is much higher at Stations 7794, 8594, 10494 and 10694. The Chl-*a* content in the 2–5 cm section is higher at Stations 8594 and 10494. In the 5–8 cm section, Station 8594 has the higher Chl-*a* content. The distribution of Pha-*a* shows a distinct pattern. The stations in the east of the investigated area or near Shandong Peninsula, including Stations 8294, 7794, 8594, 9594, 9794, 10694 and 11594, have higher Pha-*a* values. The total pigments distribution has the same pattern as Pha-*a* (Appendix IV).

3.2 Vertical Distribution of Chl-*a* and Pha-*a*

In January 2003, there were only 5 cm long cores taken and they were sectioned into 2 layers (0–2 cm and 2–5 cm). The average Chl-*a* content in the 0–2 cm section accounts for 66.62% of total core samples, but the average Chl-*a* content in 2–5 cm section occupies only 33.38% of total Chl-*a*. The vertical distribution of Pha-*a* in sediment has the same pattern. Pha-*a* in the 0–2 cm section accounts for 63.64% and that in the 2–5 cm section is only 36.36%. That means the approximate ratio of Chl-*a* content in the 0–2 cm to 2–5 cm section is 2∶1.

In June 2003, January and June 2004, all of core samples 8 cm long were sectioned into 3 sections (0–2 cm, 2–5 cm and 5–8 cm). The percentages of the average Chl-*a* and Pha-*a* contents in all the 3 sections for each core sample in the three cruises are shown in Table 1. The approximate ratio of the three sections for the Chl-*a* and Pha-*a* values respectively is 5:3:2. The test results (P values) by Chi-square nonparametric test are shown in Table 1. The vertical distribution of Chl-*a* and Pha-*a* contents in the 3 sections follows the same pattern as that of the Bohai Sea (Yuan, 1990).

Table 1 Percentage of Chl-*a* and Pha-*a* in three sediment layers and the results of the Chi-square nonparametric test for the ratio of Chl-*a* and Pha-*a* in each sediment layer (5:3:2)

Cruise	Pigment	Sediment layer/cm			P value
		0–2	2–5	5–8	
June 2003	Chl-*a*	48.75%	29.87%	21.38%	0.966
	Pha-*a*	45.68%	30.90%	23.42%	0.669
January 2004	Chl-*a*	49.56%	31.28%	19.26%	0.954
	Pha-*a*	49.50%	29.95%	20.55%	0.980
June 2004	Chl-*a*	45.66%	35.88%	18.46%	0.423
	Pha-*a*	47.11%	34.36%	18.53%	0.683

3.3 Ratio of Chl-*a* to Pha-*a*

The average content of Pha-*a* in a given cruise and section is much higher than the corresponding value of Chl-*a* at most stations except for Stations 7483 (June 2003), 13994 (January 2004), and 10494, 11151 (June 2004) where they are nearly equal. At Stations 11394 (June 2003) and 11194 (June 2004), the content of Chl-*a* is higher than that of Pha-*a*. The average percentages of the total pigments for Chl-*a* and Pha-*a* are 20%–32% and 68%–80%, respectively (Fig.4), and the average ratio of Pha-*a* to Chl-*a* in the 4 cruises is 2.83. It is very close to the results in the Bohai Sea (Yuan, 1990).

The contents of Chl-*a* and Pha-*a* in sediment at the investigated stations have the same trend, and the Spearman 2-tailed rank correlation analysis shows that they have significant or highly significant positive correlations especially between the same sediment layers (Table 2). This indicates that the Chl-*a* and Pha-*a* have the same origin. The benthic algae and the plankton algae depositing down to the bottom are the contributors to Chl-*a* and Pha-*a*. The Chl-*a* is from active algae, but the Pha-*a* is from dead algae, which lose the Mg ion and has no activities.

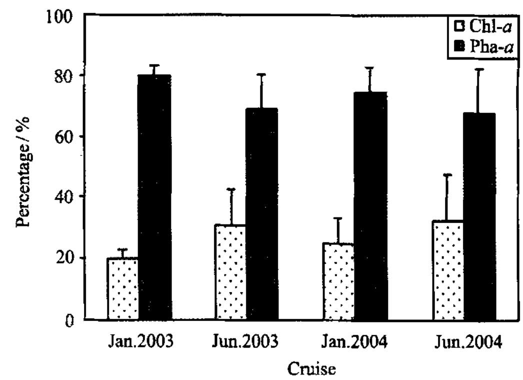

Fig.4 Percentage of Chl-*a* and Pha-*a* in the total pigments.

Table 2 Results of the Spearman 2-tailed rank correlation analysis between Chl-*a* and Pha-*a* in each sediment layer

Pigment	Cruise														
	January 2003			June 2003				January 2004				June 2004			
Chl-*a* (layer/cm)	0–2	2–5	0–5	0–2	2–5	5–8	0–8	0–2	2–5	5–8	0–8	0–2	2–5	5–8	0–8
Pha-*a* 0–2 cm	0.865††	0.815††	0.863††	0.537††	0.515†	0.481†	0.574††	0.578††	0.309	0.336	0.508††	0.773††	0.567†	0.710††	0.761††
Pha-*a* 2–5 cm	0.891††	0.863††	0.899††	0.389	0.493†	0.469†	0.486†	0.554††	0.451†	0.571††	0.576††	0.735††	0.581†	0.796††	0.759††
Pha-*a* 5–8 cm	–	–	–	0.411	0.425†	0.688††	0.533†	0.350	0.321	0.710††	0.425†	0.633†	0.472	0.808††	0.666††
Pha-*a* 0–5 cm	0.897††	0.854††	0.898††	–	–	–	–	–	–	–	–	–	–	–	–
Pha-*a* 0–8 cm	–	–	–	0.472†	0.502†	0.546††	0.553††	0.564††	0.382†	0.527††	0.552††	0.745††	0.562†	0.778†v	0.755††

Notes: ††Correlation is significant at the 0.01 level (2-tailed).
†Correlation is significant at the 0.05 level (2-tailed).

3.4 Relationships of Chl-*a* and Pha-*a* with Other Environmental Factors

In order to find out the relationships of the Chl-*a* and Pha-*a* contents with other environmental factors, including water depth, bottom water temperature, organic matter (OM), median diameter (Md_{ϕ}), silt plus clay (%) in sediment, meiofauna abundance and biomass, Spearman 2-tailed rank correlation analysis was performed with the data collected from Cruise January 2003 and Cruise June 2003. The results (Table 3) show that the Chl-*a* and Pha-*a* contents in January 2003, both have significant or highly significant correlations with OM, Md_{ϕ}, silt plus clay (%) in sediment, but no significant correlations with water depth, bottom water temperature and meiofauna abundance and biomass. The Chl-*a* content in June 2003 has a significant correlation with meiofauna biomass while no significant correlations with other factors. However, the Pha-*a* content has highly significant correlations with water depth, bottom water temperature, OM and Md_{ϕ}.

Table 3 Results of the Spearman 2-tailed rank correlation analysis between Chl-*a*, Pha-*a* contents and other environmental factors in January 2003, June 2003

Cruise	Pigment	Depth	Temperature	Abundance	Biomass	OM	Md_{ϕ}	Silt + Clay (%)
January 2003	Chl-*a*	-0.045	-0.174	-0.081	-0.081	0.551††	0.484†	0.488†
	Pha-*a*	0.066	-0.189	0.005	0.005	0.621††	0.572††	0.531††
June 2003	Chl-*a*	0.183	-0.274	0.358	0.502†	0.242	0.038	0.050
	Pha-*a*	0.810††	-0.722††	0.010	0.244	0.863††	0.548††	0.344

Notes: ††Correlation is significant at the 0.01 level (2-tailed).
†Correlation is significant at the 0.05 level (2-tailed).

3.5 Comparison with Other Areas

The values of Chl-*a* and Pha-*a* contents in the present study are lower than previous studies. The results of Chl-*a* and Pha-*a* contents in other areas are shown in Table 4. Li *et al.* (2004) reported the contents of Chlorophyll in sediment of seven stations in the Yellow Sea and East China Sea. The results in their study at Stations E1 and E2 are similar to the present study while the stations located near the Yangtze River Estuary have a higher pigments content than the present study area. Compared with the contents of Chl-*a* and Pha-*a* in the Yellow River Estuary and its adjacent areas, the results of the present study are much lower, too (Yuan, 1990). The contents of Chl-*a* in the sediment of other estuaries show the same trend (Kowalewska, *et al.*, 2004; Moreno and Niell, 2004). The Chl-*a* and Pha-*a* contents in sediment on tidal flats of Xiangshan Bay are much higher than those of the Yellow Sea (Ning *et al.*, 1999). All the authors analyzed the chlorophyll samples with the same method, namely spectrophotofluorometry, so the results should be comparable. The higher values of other studies may be due to abundant organic detritus and nutrients from estuaries and intertidal areas, which provide good growth conditions for the phytoplankton and microphytobenthos (Lu, 1998).

Table 4 Comparison of Chl-*a* and Pha-*a* contents in sediment between the present study and other studies

Areas	Chl-*a*/($\mu g\,g^{-1}$)	Pha-*a*/($\mu g\,g^{-1}$)	Authors
Southern Yellow Sea	0.31 - 0.47†	1.28 - 1.40†	Present study
Huanghe River Estuary and adjacent areas	0.78†	2.80†	Yuan, 1990
East China Sea and Yellow Sea	2.48 - 3.01†	-	Li, *et al.*, 2004
Xianshan intertidal areas (East China Sea)	6.65††	-	Ning, *et al.*, 1999
Odra Estuary (Poland)	35.74†	-	Kowalewska, *et al.*, 2004
Palmones River Estuary (Spain)	0.52 - 15.19†	-	Moreno, *et al.*, 2004
Intertidal areas in a sandy bay of West Scotland	0.75†††	-	McIntyre and Murison, 1973
Subtidal areas in a sandy bay of West Scotland	4.50†††	-	McIntyre and Murison, 1973

Notes: †Average of the investigated area.
††Average of two months and expressed in $\mu g\,g^{-1}$ wet weight sediment (others in $\mu g\,g^{-1}$ dry weight sediment).
†††Data of some stations.
- No data (could not be measured or separated from Chl-*a*).

4 Conclusions

(1) The higher Chl-*a* and Pha-*a* contents in sediment are found out at the stations near Shandong Peninsula and in the southeastern Yellow Sea. The stations near Haizhou Bay have lower pigments values.

(2) There is a distinct vertical distribution pattern of Chl-*a* and Pha-*a* contents in sediment. The top layer (0-2 cm) has the highest pigments contents. An approximate ratio of 5:3:2 in the three sediment layers (0-2 cm, 2-5 cm and 5-8 cm) of the Chl-*a* and Pha-*a* contents has been found.

(3) The Chl-*a* and Pha-*a* have a highly significant correlation in each sediment core sample. Their ratio is 2.83. This indicates that they have the same origin: benthic algae and phytoplankton depositing down to the bottom.

(4) The contents of Chl-*a* and Pha-*a* have significant or highly significant correlations, with some other environmental factors such as OM, Md_{ϕ} and meiofauna biomass.

Acknowledgements

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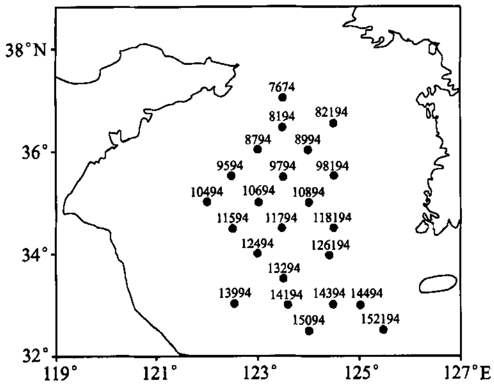
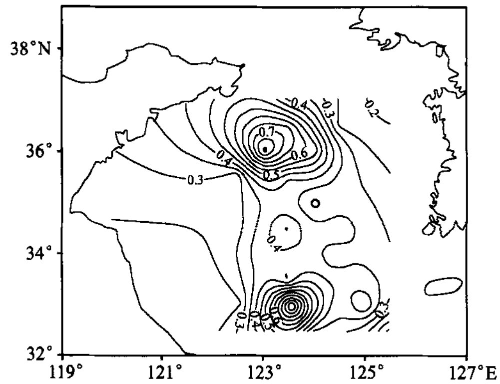
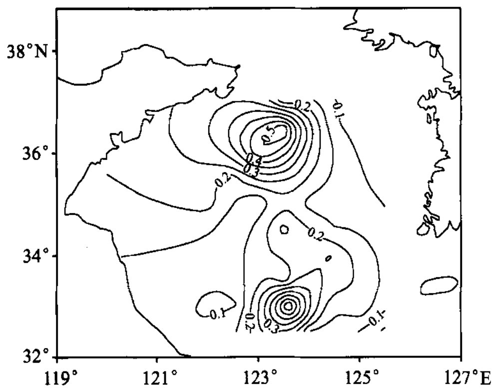
Appendix I



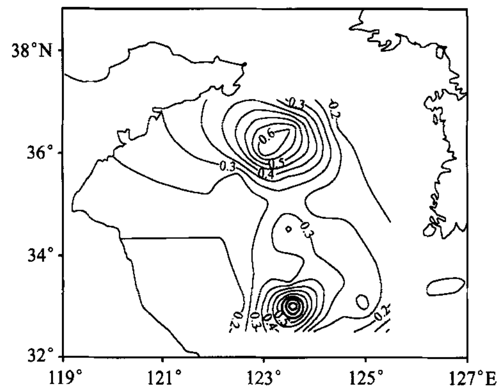
Sampling stations in January 2003



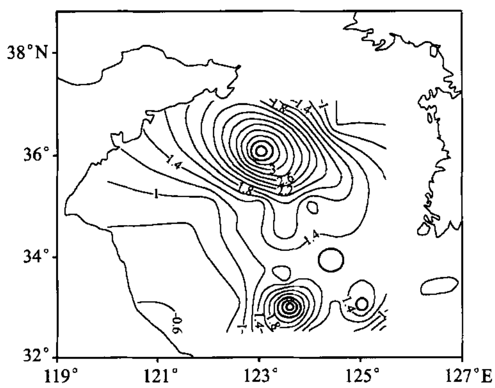
Distribution of Chl-*a* (μg g^{-1}) in the 0-2 cm sediment



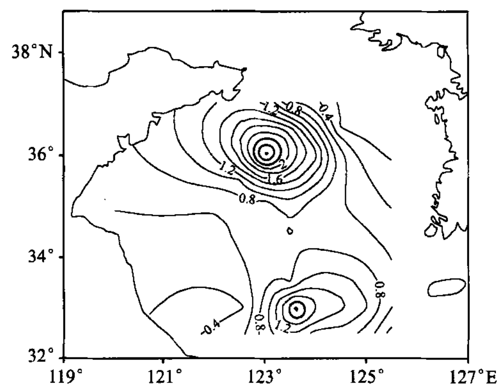
Distribution of Chl-*a* (μg g^{-1}) in the 2-5 cm sediment



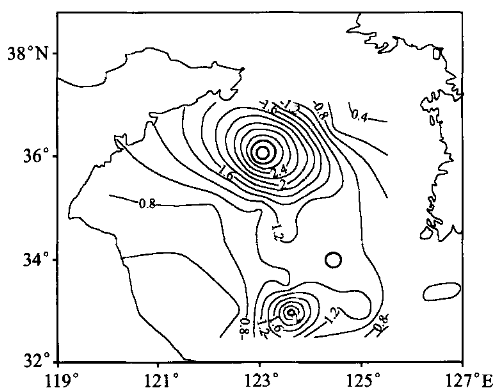
Distribution of average Chl-*a* (μg g^{-1}) in the 0-5 cm sediment



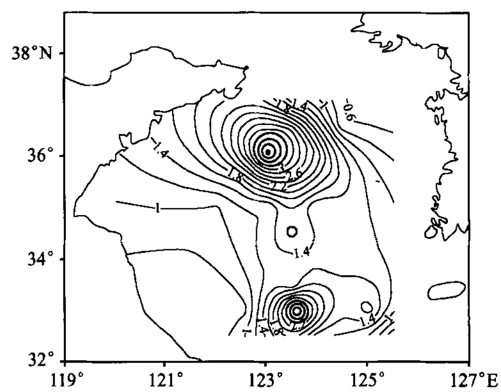
Distribution of Pha-*a* (μg g^{-1}) in the 0-2 cm sediment



Distribution of Pha-*a* (μg g^{-1}) in the 2-5 cm sediment



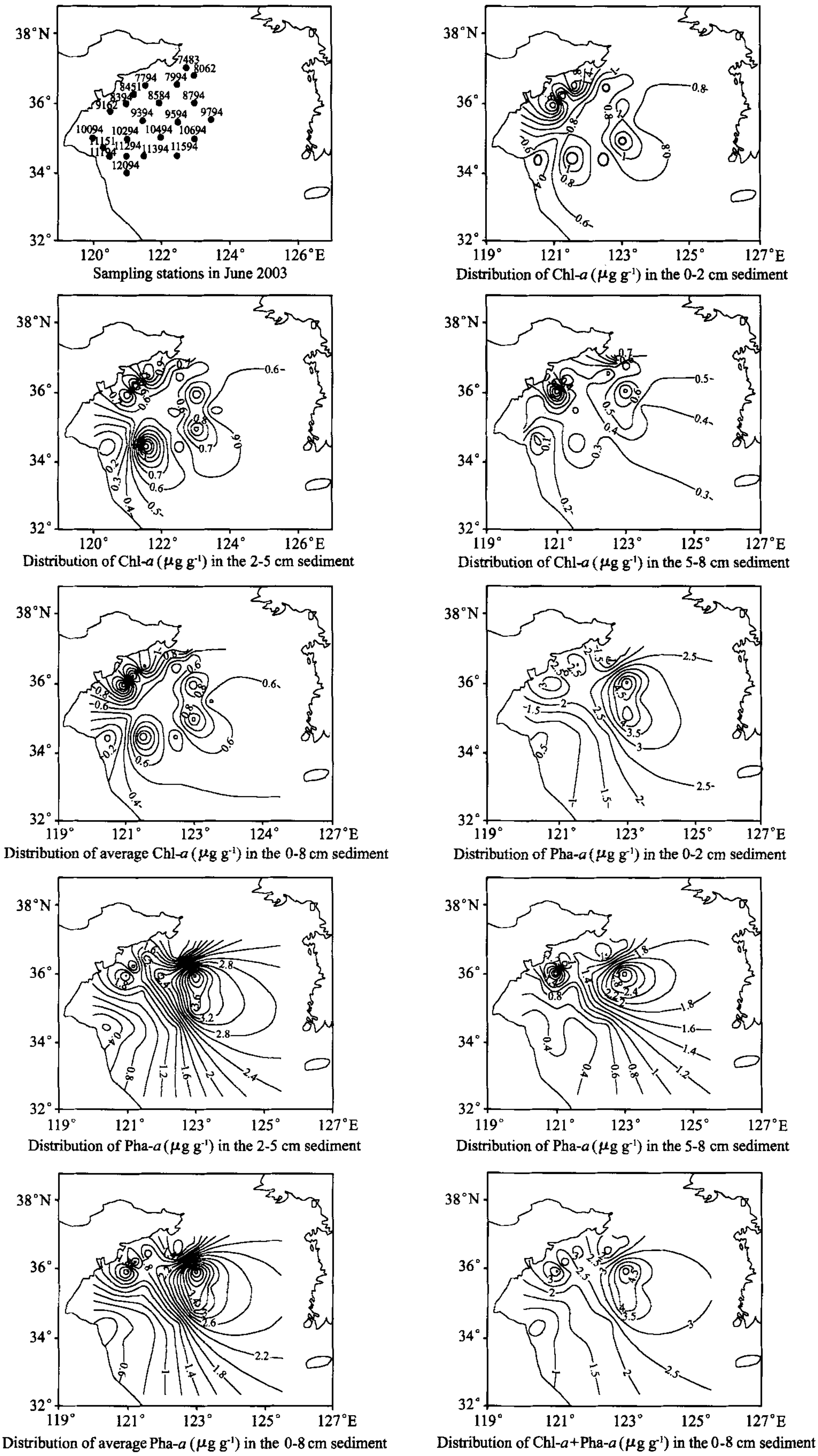
Distribution of Pha-*a* (μg g^{-1}) in the 0-5 cm sediment



Distribution of Chl-*a*+Pha-*a* (μg g^{-1}) in the 0-5 cm sediment

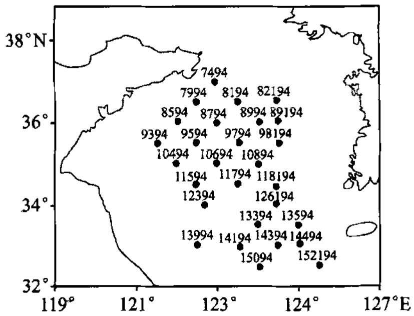
Spatial distribution of Chl-*a* and Pha-*a* in January 2003

Appendix Ⅱ

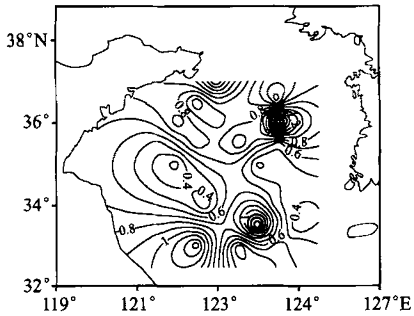


Spatial distribution of Chl-*a* and Pha-*a* in June 2003

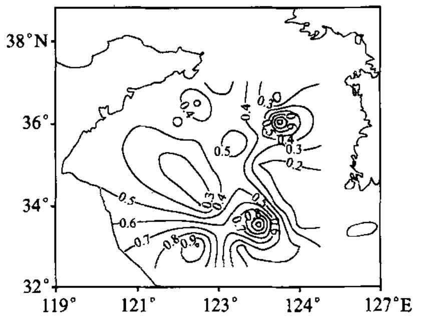
Appendix Ⅲ



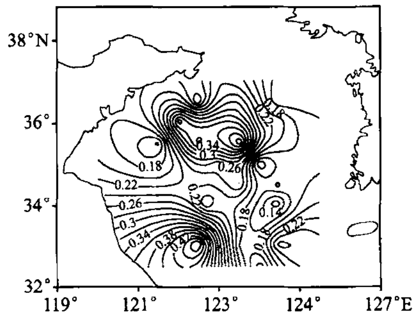
Sampling stations in January 2004



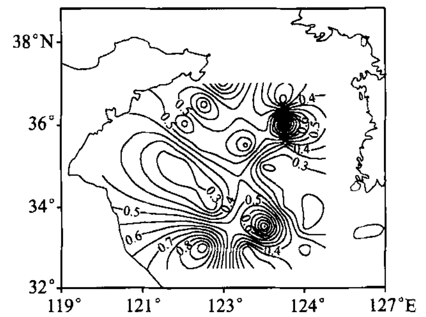
Distribution of Chl-*a* (μg g^{-1}) in the 0-2 cm sediment



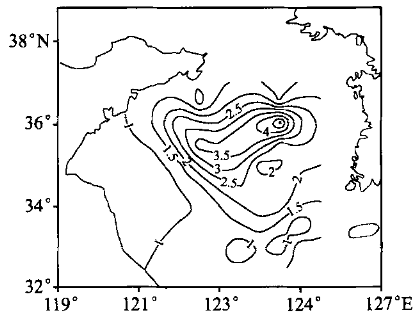
Distribution of Chl-*a* (μg g^{-1}) in the 2-5 cm sediment



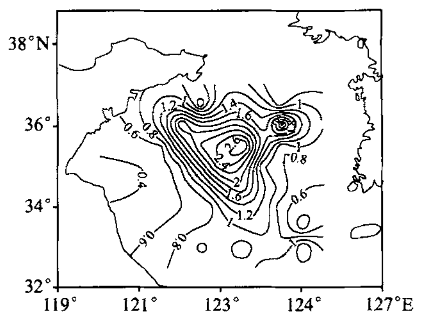
Distribution of Chl-*a* (μg g^{-1}) in the 5-8 cm sediment



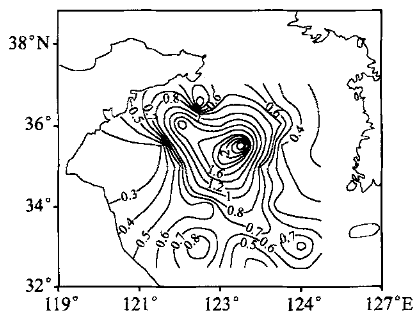
Distribution of average Chl-*a* (μg g^{-1}) in the 0-8 cm sediment



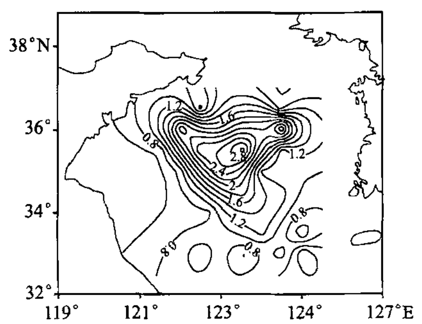
Distribution of Pha-*a* (μg g^{-1}) in the 0-2 cm sediment



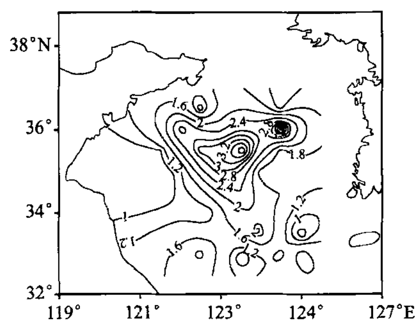
Distribution of Pha-*a* (μg g^{-1}) in the 2-5 cm sediment



Distribution of Pha-*a* (μg g^{-1}) in the 5-8 cm sediment



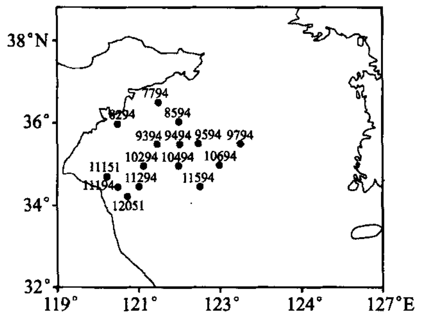
Distribution of average Pha-*a* (μg g^{-1}) in the 0-8 cm sediment



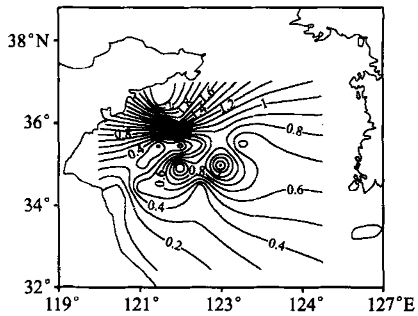
Distribution of Chl-*a*+Pha-*a* (μg g^{-1}) in the 0-8 cm sediment

Spatial distribution of Chl-*a* and Pha-*a* in January 2004

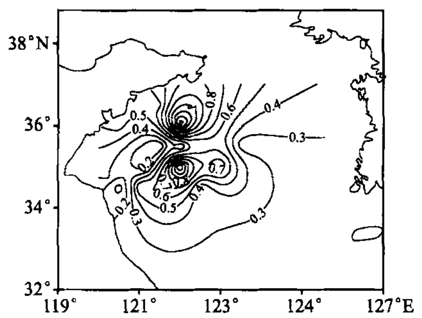
Appendix Ⅳ



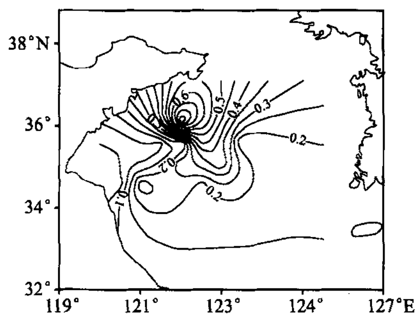
Sampling stations in January 2004



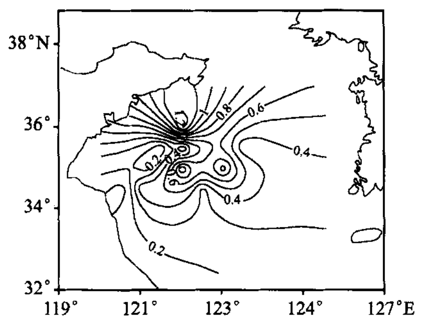
Distribution of Chl-*a* (μg g^{-1}) in the 0-2 cm sediment



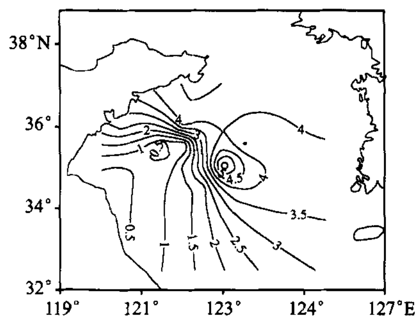
Distribution of Chl-*a* (μg g^{-1}) in the 2-5 cm sediment



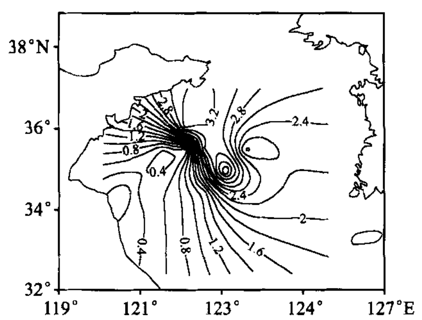
Distribution of Chl-*a* (μg g^{-1}) in the 5-8 cm sediment



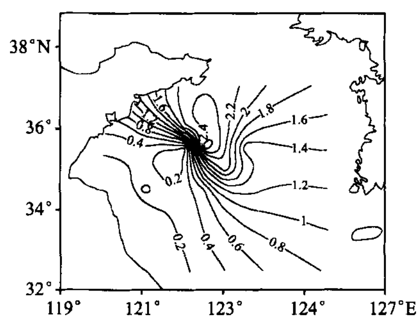
Distribution of average Chl-*a* (μg g^{-1}) in the 0-8 cm sediment



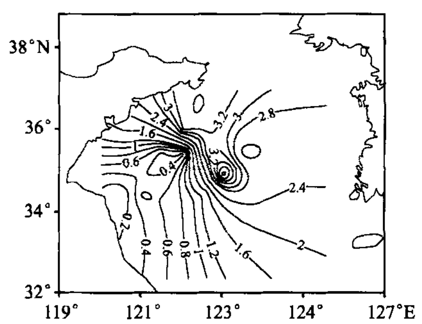
Distribution of Pha-*a* (μg g^{-1}) in the 0-2 cm sediment



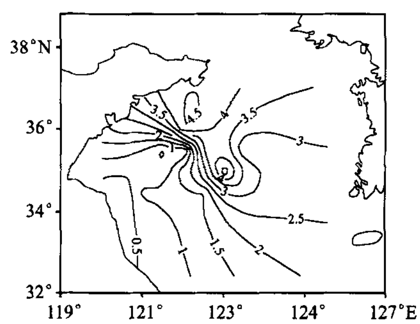
Distribution of Pha-*a* (μg g^{-1}) in the 2-5 cm sediment



Distribution of Pha-*a* (μg g^{-1}) in the 5-8 cm sediment



Distribution of average Pha-*a* (μg g^{-1}) in the 0-8 cm sediment



Distribution of Chl-*a*+Pha-*a* (μg g^{-1}) in the 0-8 cm sediment

Spatial distribution of Chl-*a* and Pha-*a* in June 2004

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