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Diatom and silicoflagellate assemblages in modern surface sediments associated with human activity: A case study in Sishili Bay, China

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ABSTRACT

The spatial distribution of diatom and silicoflagellate fossils deposited in modern surface sediments was studied in inshore and offshore zones of Sishili Bay, China, to explore the impact of human activity on the coastal ecosystem. The sediments from 28 sites representing a gradient in intensity of human activity from inshore to offshore were sampled. Although the nutrient parameters inshore showed far higher concentrations than the offshore area, due to sewage discharge and waste dumping in the bay, the average fossil abundance did not differ significantly between the two areas. The diatom fossil *Paralia sulcata*, supposed to be a eutrophic indicator dominated most sediment samples and displayed a significant and positive correlation with dissolved inorganic nitrogen and phosphorus in the upper water column, but did not show a significant difference in abundance between inshore area and offshore area. Factors such as sediment disturbance (e.g., shipping), grazing pressure (e.g., shellfish aquaculture farm) and sediment characteristics (e.g., grain size) can affect the preservation of fossil debris in the sediment and lower the precision with which human activities can be associated with the fossil abundance.

1. Introduction

Diatoms are a major group of primary producers in most aquatic ecosystems (Round et al., 1990; Berger and Wefer, 1991). Previous studies have shown that diatoms are sensitive to variations in the environment and can be used to indicate the intensity of human activity and climate change in aquatic ecosystems (Zielinski and Gersonde, 1997; Finkelstein and Davis, 2006). Moreover, the diatom fossils deposited in the sediment can be preserved well enough to use for species identification and numeration, which can provide powerful information to interpret various sedimentary environments and reflect the variations of phytoplankton in the upper water column. A large number of case studies have used diatom fossils in the surface and coring sediment samples to indicate changes in a range of factors, such as sea level (Zong and Horton, 1999), salinity (Fritz et al., 1991), temperature (Romero et al., 2005) and eutrophication (Liu et al., 2008). Some diatoms exist widely in the aquatic environments and have been selected as good indicators. For example, high abundances of *Paralia sulcata* have been observed widely in eutrophic coastal waters (Abrantes, 1991; McQuoid and Nordberg, 2003), and Liu et al. (2008) found that a rapid increase in *P. sulcata* abundance occurred in the sediment of Jiaozhou Bay after the1980s, when nitrogen increased significantly with the economic development in the catchment.

Sishili Bay is located in the northern Yellow Sea (China) and is surrounded by Yantai city (Fig. 1). The intensive human activities and fast economic development (e.g., increased population, aquaculture) in Yantai since the 1980s have imposed great pressures on the coastal ecosystem (Yantai Statistical Yearbooks, 2010). Frequent harmful algal blooms and jellyfish blooms in Sishili Bay have impacted significantly on the sustainability of local marine aquaculture and fishery resources (Xu et al., 2004; Dong et al., 2010). The sewage discharge, waste dumping and marine aquaculture are regarded as major human activities causing the deterioration of coastal seawater quality (Ji et al., 2003). For example, based on previous surveys, one dumping site used in the bay since 1988 had received a total of 7.0×10^6 m^3 waste by 2002 (Ji et al., 2003); each year, 150 tonnes of total phosphorus and 1910 tonnes of total nitrogen are discharged into the bay in the form of sewage (Liu et al., 2006). Thus, there is an urgent need to study how these different human activities have acted on the ecosystem over a range of spatial and temporal scales to assist in the development of coastal management policies. Unfortunately, there is no continuous and large-scale historical survey data recorded for Sishili Bay. However, diatom and silicoflagellate assemblages in Sishili Bay and the northern Yellow Sea constitute a major proportion of the phytoplankton assemblages, with a total abundance of over 60% (Li et al., 2006; Yu et al., 2009), and the debris deposited in the surface

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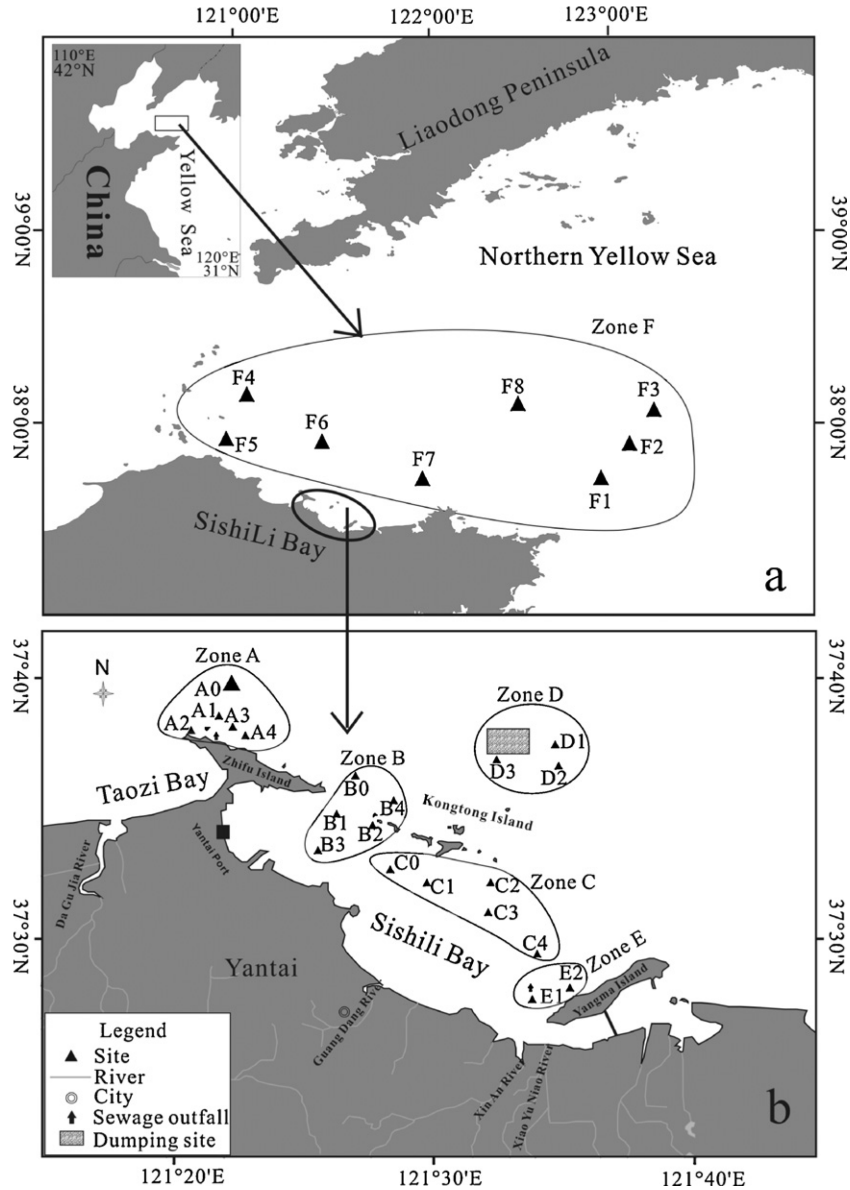

Fig. 1. Map showing the study area and sampling sites in the Sishili Bay and adjacent sea area of the northern Yellow Sea, China. Zones A–E are in the Sishili Bay and Zone F is chosen in the northern Yellow Sea as the contrast area.

sediment by these assemblages may have the potential to be used as an indicator of the impact of the changing anthropogenic activities on the ecosystem, over a range of spatial and temporal scales.

In this study, the surface sediments at 20 inshore sites in the Sishili Bay were collected for diatom and silicoflagellate analysis, based on the local marine functional zoning (sewage discharge zone, shipping zone, marine dumping and aquaculture zones). In addition, eight offshore sites near to the center of the northern Yellow Sea with less human activities were chosen for a comparison. The characteristics of fossil abundance and species composition in the sediments were compared in spatial scale, with the purpose of evaluating the impact from different anthropogenic activities. The results from the diatom and silicoflagellate analysis were compared to available data from water quality studies in surface waters. Also, the factors that may affect the preservation of diatoms and silicoflagellates, such as grain size structure, grazing pressure and disturbance, were analyzed and discussed as possible sources of error in the record of information provided by the fossil record.

2. Materials and methods

2.1. Study area and sampling methods

Sishili Bay (SB) is located in the northern Yellow Sea (NYS), China, with an area of 130 km^2 (Fig. 1). According to monthly water quality data (Yellow Spring Instruments, Ohio, USA) collected for SB during 2009, the seawater temperature ranged from 23.3–27.4 °C in summer (June to August) to 2.5–3.0 °C in winter (December to February); the salinity in a year showed a narrow range of 29–31. The hydrodynamic processes in the bay are mainly controlled by the movement of tide and wind-induced currents (Zhang and Dong, 1990). Along the periphery of the bay, the tidal currents move mainly back and forth in a northwest–southeast direction, which causes the pollutants to move parallel along to the shore. Due to the weak tidal current and location of small islands that obstruct flows, water exchanges between the inner and the outer bay are limited. Moreover, the prevailing southeasterly wind can bring in and accumulate pollutants into SB, causing deterioration of seawater quality.

Five zones (A–E) were selected in the inshore area and one zone in the offshore area (F) for comparison, based on the intensity of human activity and local marine "functional" zoning (Fig. 1). Twenty sites were studied in Zones A–E: Zone A (sites A0–A4) with a seawater depth of 22.2 m is near to the outfall of the Taozi Bay sewage plant which is used to treat the domestic waste water (Wang and Li, 1997); Zone B (sites B0–B4) with a seawater depth of 15.6 m is at the mouth of the shipping channel to Yantai Port (Li et al., 2006); Zone C (sites C0–C4) with a seawater depth of 13.8 m is in the marine aquaculture farm (Zhou et al., 2006); Zone D (sites D1–D3) with a seawater depth of 11.4 m is around the marine dumping site (Ji et al., 2003); Zone E (sites E1–E2) with a seawater depth of 1.5 m is adjacent to the Xin An River sewage plant which is mainly used to treat the industrial waste water (Jia et al., 2007). Due to the different human activities, dissolved inorganic nitrogen (DIN) concentrations in seawater showed significant difference among five zones in previous studies (Zone D (17.99 μM) > Zone A (14.27 μM) > Zone B (13.11 μM) > Zone C (10.85 μM) > Zone E (7.1 μM)) (Bai et al., 2010; Jiang et al., 2011). Eight sites were chosen in Zone F (site F1–F8) where the seawater depth is about 42.5 m (Fig. 1). Zhang et al. (2009) found the average annual DIN concentration of NYS was about 5.27 μM, which was much lower than inshore areas, and Zone F thus can be used as a contrast area, showing less human activities.

A 5 cm length of undisturbed sub-sample of sediment was taken using a box corer (0.1 m^2) at each site of SB in November 2008 and each site of the contrast area in April 2010, respectively. The top 2 cm part was isolated and prepared for analysis of diatom and silicoflagellate and the measurement of sediment grain size. According to the chronological analysis of the sediment cores from SB taken in 2008, the top 2 cm could represent the fossil preservation of the last 3 years (Sun et al., 2011).

2.2. Slide preparation and valve counting

The sediment samples were pretreated according to methods used by Renberg (1990) and Smol et al. (2001). All samples, dried at 105 °C, were treated with 10% HCl overnight to remove carbonate, some metal salts and oxides. After settling and being washed with distilled water, samples then were treated with 30% H_2O_2 to remove organic matter. Reaction continued until all organic matter was removed. The H_2O_2 was removed and samples treated by ammonium hydroxide solution to partially remove minerogenic matter. After rinsing several times to remove chemical residues, zinc bromide (specific gravity 2.4) was added. Samples were then centrifuged at 2000 rpm for 10 min to suspend the siliceous cells. The suspended cells were diluted to known volumes and an aliquot was placed onto a cover-slip. After the material had completely dried, the cover slip was transferred onto permanently labeled slide, mounted with Naphrax.

Slides were examined under an Olympus CX-31 light microscope at a magnification of 1000× for species identification and counting. The minimum cell size observed was 8 μm. Taxonomy and nomenclature were assessed by referring to Hasle (1976), Chin et al. (1982), Chin et al. (1992), Lan et al. (1995), Cheng et al. (1996), Hasle and Syvertsen (1996) and Guo and Qian (2003). The genus *Pleurosigma* was not identified to species level due to identification issues and was classified into one group. The siliceous microfossils (diatoms and silicoflagellates) were counted in three slides prepared from each sample. A total of at least 300 valves were counted from each sample. The absolute abundances are expressed as numbers of valves per gram of dry sediment (valves/g DW) and calculated as follows:

$$D_{[\text{abs}]} = \frac{nv}{v_1 w}$$

$D_{[\text{abs}]}$, the absolute abundance; n, the total individuals counted in three slides; v, the volume that suspended diatoms were diluted to; v_1, the total volumes of aliquots dropped on three slides; w, the dried weight of the sample.

2.3. Measurement of grain size

Grain sizes of sediment samples were measured using a Mastersize 2000 Laser Particle Sizer. The grain size was classified into 3 groups (clay (<4 μm), silt (16–63 μm) and sand (>63 μm)) according to Folk's triangle classification and nomenclature (Folk et al., 1970). Before grain-size measurements, samples were oxidized with 10% H_2O_2 to remove the organic matter and dispersed in the 0.05% $(NaPO_3)_6$ solution to isolate discrete particles.

2.4. Nutrient measurement and historical data collection

Surface seawater samples were taken at the same NYS stations as the eight surface sediment samples in April and September 2010, respectively. The seawater samples were analyzed using Flow Injection Analysis (AA3, Bran+Luebbe, German) after filtering using cellulose acetate membranes (Whatman, 0.45 μm) for the following parameters: dissolved inorganic nitrogen (DIN), dissolved inorganic phosphate (DIP) and dissolved silicate (DSi). Corresponding nutrient data in April and September in SB for sites A1–A3, B1–B4, C1–C3, D1–D2 were taken from Jiang et al. (2011), and for Zone E the mean value from an earlier survey in 2007 was used (Bai et al., 2010).

2.5. Data analysis

The species diversity and richness indices were calculated according to Shannon–Wiener index (H') (Shannon and Weaver, 1949; Margalef, 1968), respectively.

$$H' = -\sum_{i=1}^{s} P_i \times \log_2 P_i;$$

$$D = \frac{(S-1)}{\log_2(N)}$$

H', the Shannon–Wiener diversity index; D, the species richness index; S, the number of species; N, total individuals of all species; P_i, the ratio of the individuals of species i to the total individuals of all species.

An Independent-Samples *T*-test was used to test for the spatial differences among zones as well as between the inshore area and the offshore area in various environmental parameters and flora features. The Zone-level values were averaged values of sites in each zone. Correlation analysis between the floral features (fossil abundance, species richness index and diversity index) and the environmental parameters (nutrient concentrations and ratios; grain size proportion of sediments) of different zones were conducted using the software SPSS 11.5 (Statistical Product and Service Solutions).

3. Results

3.1. Composition of diatom and silicoflagellate flora

In total, 85 species were identified from the 20 sites in Zones A–E, including 84 diatom species and 1 silicoflagellate species (*Dictyocha fibula*). The 84 diatoms consisted of 26 centric species and 58 pennate species. The centric diatoms covered 12 families and 16 genera, among which Coscinodiscaceae was the largest group with a proportion of 30%. The pennate diatoms were from 19 families and 28 genera, among which Naviculaceae and Diploneidaceae accounted for 36% of the total.

By comparison, only 39 species were found in Zone F, including 38 diatoms and 1 silicoflagellate species (*D. fibula*). The 38 diatoms included 24 centric species and 14 pennate species. The centric diatoms covered 9 families and 11 genera, among which the Coscinodiscaceae species accounted for 54% of the total; the pennate diatoms covered 7 families and 9 genera, among which 30% were from Diploneidaceae.

The species richness and diversity indices were calculated for each site and zone (Fig. 2, Table 1). The richness index was 7.04 ± 0.73 in the inshore area and 3.6 ± 0.41 in the offshore area. In SB, richness index ranged between the minimum of 1.39 (B3) and the maximum of 4.54 (E2). The diversity index was 3.45 ± 0.48 in the inshore area and 2.04 ± 0.45 in offshore and in SB it ranged between the minimum of 1.78 (C3) and the maximum of 4.23 (E2). Both the species richness index and diversity index were greater in the inshore area compared with the offshore area but the difference was not significant.

3.2. The characteristics of dominant species

In this study, dominant species were identified as those with abundance proportions higher than 2%. In total, 12 dominant species were found in Zones A–E, including *Paralia sulcata*, *Podosira stelliger*, *Pinnularia* sp., *Actinocyclus octonarius*, *Cyclotella stylorum*, *D. fibula*, *Trachyneis aspera*, *Coscinodiscus subtilis*, *Cocconeis pseudomarginato*, *Actinoptychus senarius*, *Coscinodiscus radiatus* and *Cocconeis scutellum*; in comparison, only 3 species dominated in Zone F including *P. sulcata*, *P. stelliger* and *A. octonarius* (Table 1).

Dominant species *P. sulcata* accounted for between 20% and 47% of the total fossil abundance in Zones A–F (Table 1). Although the mean value in the inshore area (1480 valves/g DW) was greater than the offshore area (677 valves/g DW) (Table 1), the differences were not significant ($P = 0.361$).

3.3. Spatial distributions of fossil abundance

In SB, the total fossil abundance ranged from a minimum of 368 valves/g DW (E1) to a maximum of 20 335 valves/g DW (A2); in offshore Zone F, it ranged from a minimum of 716 valves/g DW (F3) to a maximum of 2060 valves/g DW (F6) (Fig. 3). The average abundance in inshore SB was 3909 valves/g DW which is two-fold greater than that in the offshore Zone F (1509 valves/g DW) (Table 1), but the *T*-test analysis did not show a significant difference between the inshore area and offshore area ($P = 0.193$). The abundances among sites in SB varied so greatly that the standard deviation (5012 valves/g DW) is far higher than the mean value (3909 valves/g DW).

3.4. Grain size composition of the sediments

Grain size composition varied greatly for different sites (Fig. 4). Both the inshore area and the offshore area were mainly composed of clay (<4 μm) and silt sediments (4–63 μm). In SB, the clay and silt proportion totally accounted for 78.6% of the sediment and in Zone F that reached 70.2% (Table 2). Although there are no significant differences between the inshore and offshore areas or among zones, the sediments of Zone C, E and F had greater average sand proportions.

3.5. Nutrient level of water column in different zones

The average nutrient data for April and September 2010 showed an obvious gradient between inshore and offshore areas (Table 2): the nutrient concentrations of DIN, DIP and DSi inshore were all significantly higher than those offshore ($P < 0.01$). According to the standard suggested by Justić et al. (1995), DIP was the limiting factor in terms of both definite deficiency (DIP < 0.1 μM) and relative deficiency (DSi/DIP > 22 and DIN/DIP > 22) in the offshore area, and the DSi was the limiting factor in terms of definite deficiency (DSi < 2 μM) but not of relative deficiency (DSi/DIP < 10 and DSi/DIN < 1) in the offshore area.

3.6. Correlation analysis

The correlation analysis indicated that the species composition and abundance of fossil flora in the sediment were correlated with multiple factors (Table 3).

The DIN concentration correlated positively with *P. sulcata* abundance, total fossil abundance and species diversity index but negatively with the richness index. Of these, only the correlation with *P. sulcata* abundance was significant ($R^2 = 0.67$, $P < 0.05$). The DIP concentration correlated positively and significantly with the total fossil abundance ($R^2 = 0.75$) and *P. sulcata* abundance ($R^2 = 0.82$) ($P < 0.05$). The DIP concentration correlated weakly and positively with the species diversity index and negatively with the richness index. The DSi correlated weakly and positively with all biological factors. The nutrient ratios DIN/DIP, DSi/DIN and DSi/DIP all correlated negatively with biological factors, but none was significant. The clay proportion (grain size < 4 μm) correlated positively with the total fossil abundance and *P. sulcata* abundance and negatively with the species diversity and richness index; of these, only that with the *P. sulcata* abundance was significant ($R^2 = 0.67$) ($P < 0.05$). The silt proportion (4–63 μm) correlated weakly and positively with the fossil abundance but negatively with the species composition index. The sand proportion (>63 μm) correlated negatively with the biological fossil and positively with the composition index, and the correlation with *P. sulcata* was significant ($R^2 = 0.66$) ($P < 0.05$).

4. Discussion

4.1. Fossil preservation in the sediment and human activities

Previous studies reported that nutrient enrichment in the water column can increase the phytoplankton abundance and then indirectly lead to high diatom abundance in the sediment (McQuoid and Hobson, 2001; Nave et al., 2001). In this study, correlation analysis showed a significant and positive relationship between the total fossil abundance and DIP concentrations in seawater ($R^2 = 0.75$) ($P < 0.5$) (Table 3). Additionally, the abundance of the dominant species *P. sulcata* in the sediment displayed a significant correlation with DIN and DIP concentrations in the upper water column (Table 3), showing a sensitivity to nutrient enrichment. This species is heavily silicified and thus can preserve well in the sediment; it has been regarded as an indicator of nutrient enrichment (Margalef, 1978; Abrantes, 1988a,b, 1990, 1991; McQuoid and Nordberg, 2003; Liu et al., 2008).

The DIP, DIN and DSi inshore were all significantly higher than in Zone F ($P < 0.01$). Additionally, DIP and DSi had become the limiting factors in terms of definite deficiency for phytoplankton growth in the offshore area. However, although both the average total fossil abundance and *P. sulcata* abundance inshore (Zones A–E) were almost two-fold greater than that in offshore Zone F, the differences were not significant between the two areas ($P > 0.05$). The lack of significant difference could be attributed to the great variation in abundance among the different sites in SB (Fig. 3). The high level of variability among sites could in turn be attributed to different types of human activities in SB which have resulted in different impacts on the nutrient enrichment and a suite of factors which affect the preservation of the fossil record in sediments.

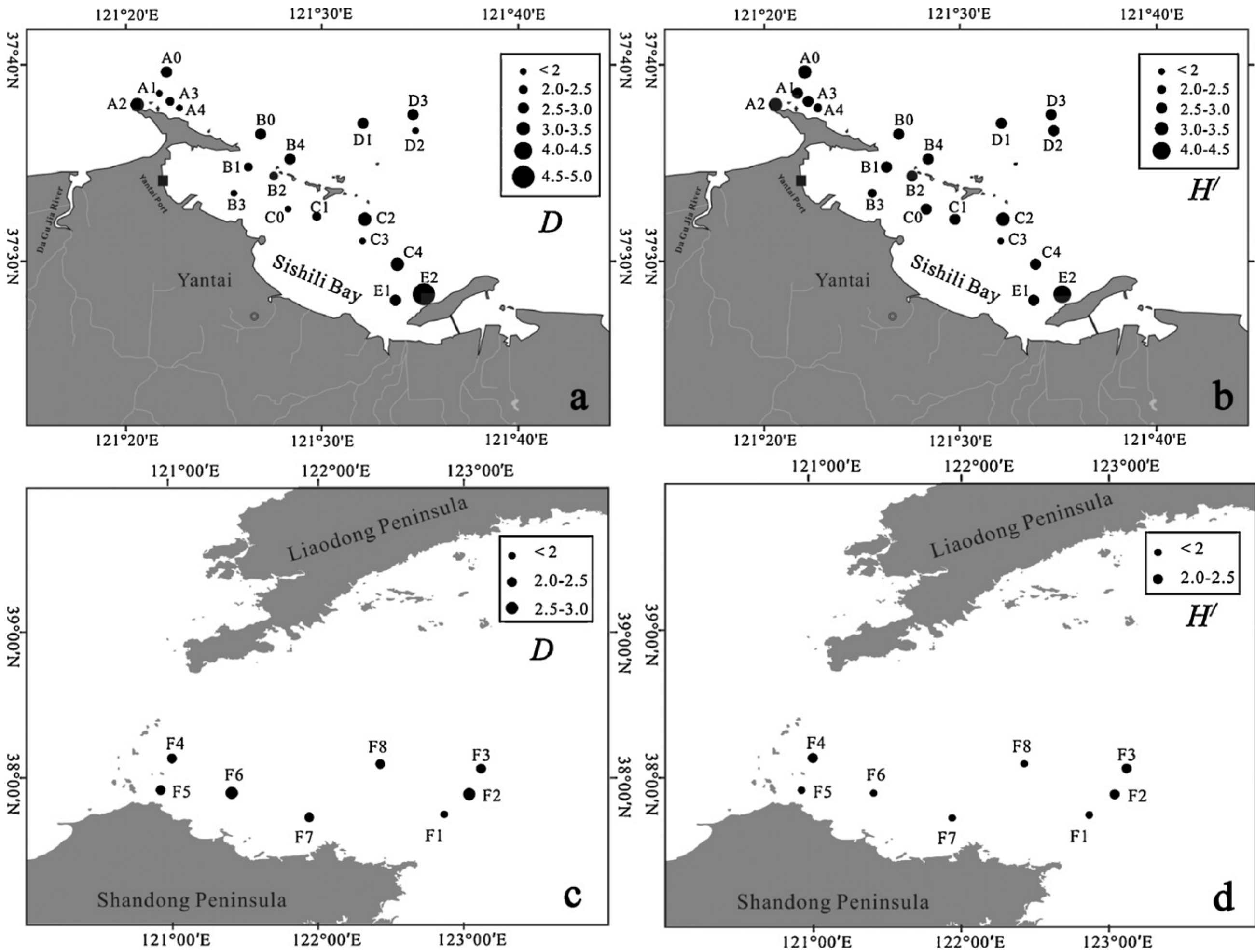

Fig. 2. The spatial distribution of species richness index and species diversity index in the surface sediment. *D* means species richness index and *H′* means species diversity index (a: species richness index of Sishili Bay; b: species diversity index of Sishili Bay; c: species richness index of contrast area; d: species diversity index of contrast area).

Zone A is likely to be impacted by the Taozi Bay sewage treatment plant. It was estimated that 25×10^4 tonnes of waste water were discharged into the bay per day from the plant (Wang and Li, 1997). Zone D has been used as the marine dumping site since 1988 and the historical data showed that the environmental situation there had been deteriorating since that time (Ji et al., 2003). Moreover, the tidal currents along the periphery of the bay move mainly back and forth in a northwest–southeast direction, and these can bring the pollutants from Zone A to Zone D and also can bring pollutants into Zone B under the influence of wind and current. Consistent with this, high DIN concentrations in seawater were thus observed in Zones B and D. The nutrient enrichment in

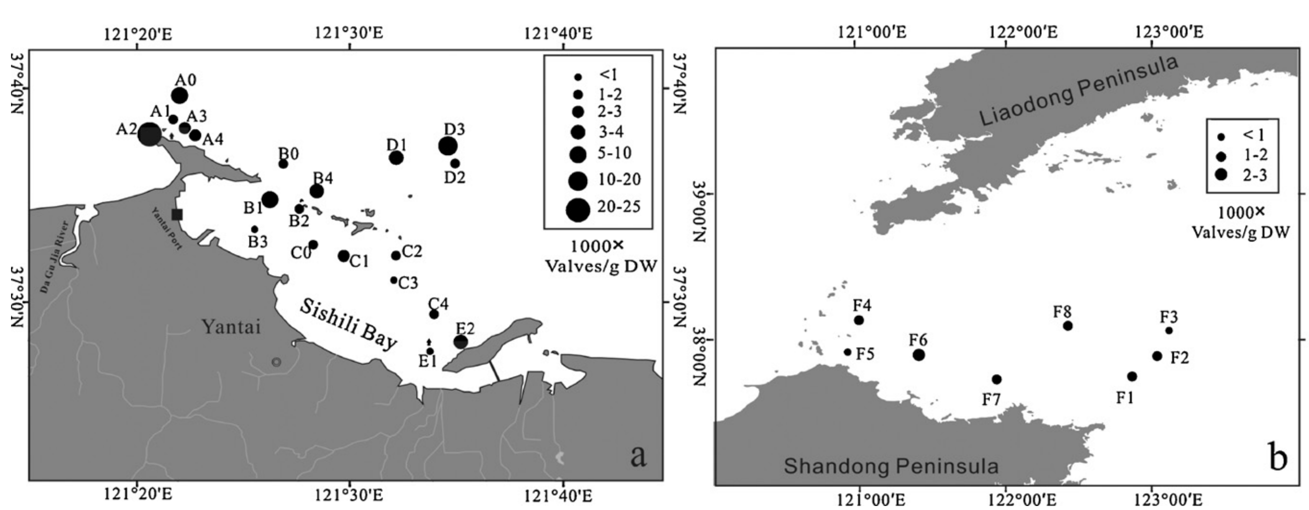

Fig. 3. The spatial characteristics of abundance of total fossil flora in surface sediment of Sishili Bay (a) and the contrast area in northern Yellow Sea (b).

Table 1
The biological parameters of study zones (mean ± standard deviation). SB represents the mean value of each station available in Sishili Bay; *N* represents the data number.

Zones	Abundance (valves/g DW)		Species diversity index	Species richness index	Dominant species and proportion (%)
	Total fossil	*Paralia sulcata*			
A	6886 ± 8010	2473 ± 3666	3.43 ± 0.46	4.71 ± 0.6	*Paralia sulcata* (35.9), *Podosira stelliger* (11.3), *Pinnularia* sp. (7.6), *Actinocyclus octonarius* (4.2), *Cyclotella stylorum* (8.8), *Dictyocha fibula* (9.8), *Trachyneis aspera* (3.8)
N	5	5	5	5	
B	2494 ± 1857	1127 ± 1179	3.1 ± 0.28	3.99 ± 0.6	*Paralia sulcata* (45.2), *Podosira stelliger* (12.3), *Pinnularia* sp. (6.8), *Actinocyclus octonarius* (3.8), *Cyclotella stylorum* (6.5), *Dictyocha fibula* (8.1),
N	5	5	5	5	
C	1573 ± 552	344 ± 292	3.1 ± 0.53	4.43 ± 0.75	*Paralia sulcata* (21.9), *Podosira stelliger* (23.2), *Pinnularia* sp. (11.2), *Actinocyclus octonarius* (15.9), *Cyclotella stylorum* (11.0), *Dictyocha fibula* (5.4), *Trachyneis aspera* (3.1), *Coscinodiscus subtilis* (2.3)
N	5	5	5	5	
D	6406 ± 6810	3011 ± 3	3 ± 0.09	3.56 ± 0.38	*Paralia sulcata* (47.0), *Podosira stelliger* (7.5), *Pinnularia* sp. (3.6), *Actinocyclus octonarius* (7.2), *Cyclotella stylorum* (5.0), *Dictyocha fibula* (12.0), *Trachyneis aspera* (3.1), *Coscinodiscus radiatus* (2.2)
N	3	3	3	3	
E	2097 ± 2445	417 ± 578	4.25 ± 1.14	5.17 ± 1.13	*Paralia sulcata* (19.9), *Podosira stelliger* (8.1), *Pinnularia* sp. (3.6), *Actinocyclus octonarius* (2.2), *Cyclotella stylorum* (11.3), *Dictyocha fibula* (7.7), *Trachyneis aspera* (3.3), *Cocconeis pseudomarginato* (9.7), *Actinoptychus senarius* (2.8), *Coscinodiscus radiatus* (2.7), *Cocconeis scutellum* (7.1)
N	2	2	2	2	
SB	3909 ± 5012	1479 ± 2406	3.45 ± 0.48	7.04 ± 0.73	*Paralia sulcata* (37.8), *Podosira stelliger* (10.8), *Pinnularia* sp. (6.0), *Actinocyclus octonarius* (5.9), *Cyclotella stylorum* (7.7), *Dictyocha fibula* (9.7), *Trachyneis aspera* (3.0), *Cocconeis pseudomarginato* (3.2)
N	20	20	20	20	
F	1509 ± 467	676 ± 345	2.04 ± 0.45	3.6 ± 0.41	*Paralia sulcata* (44.8), *Podosira stelliger* (35.8), *Actinocyclus octonarius* (10.9)
N	8	8	8	8	

Zones A, B and D was potentially a factor that resulted in the high but variable levels of fossil abundance at sites in these Zones.

In contrast to the positive contribution from nutrient enrichment, some factors may disfavor the diatom preservation and lead to the abundance variation in SB. Zone B is a channel for shipping into Yantai harbor, and the port cargo throughput in 2009 reached 169.26 million tonnes, a four-fold increase compared to that in 2001 (Yantai Statistical Yearbooks, 2010). The high frequency of ship movements can disturb the deposition of diatoms in the surface sediment and thus decrease the fossil abundance. The average abundance in Zone B was below that of SB as a whole.

Previous studies have reported that the aquaculture of filter feeding species, such as bivalves, could cause phytoplankton density to drop (Zhou et al., 2006). An area of 90 km^2 used for scallop aquaculture has been developed in Zone C and the areas around Kongtong Island (Fig. 1), and the lantern nets used for scallop aquaculture were suspended in a water depth of 2–3.5 m (Zhou et al., 2006). The high grazing pressure from the scallops can significantly decrease the abundance of phytoplankton in the water column and this could reduce the amount of diatom deposited in the sediment. Liu et al. (2008) observed a sharp decrease of diatoms in the sediment core when large-scale shellfish aquaculture was developed in Jiaozhou Bay of China. The abundance value of each site in Zone C was below the average abundance of SB.

Xin An River sewage plant mainly treats industrial waste water rather than domestic waste water. Sun et al. (2011) found very high trace metal contents in the sediment of Zone E. The toxicity of heavy metals could impact the growth of diatoms (Morin et al., 2008). The minimum abundance in SB appeared at site E1 (368 valves/g DW).

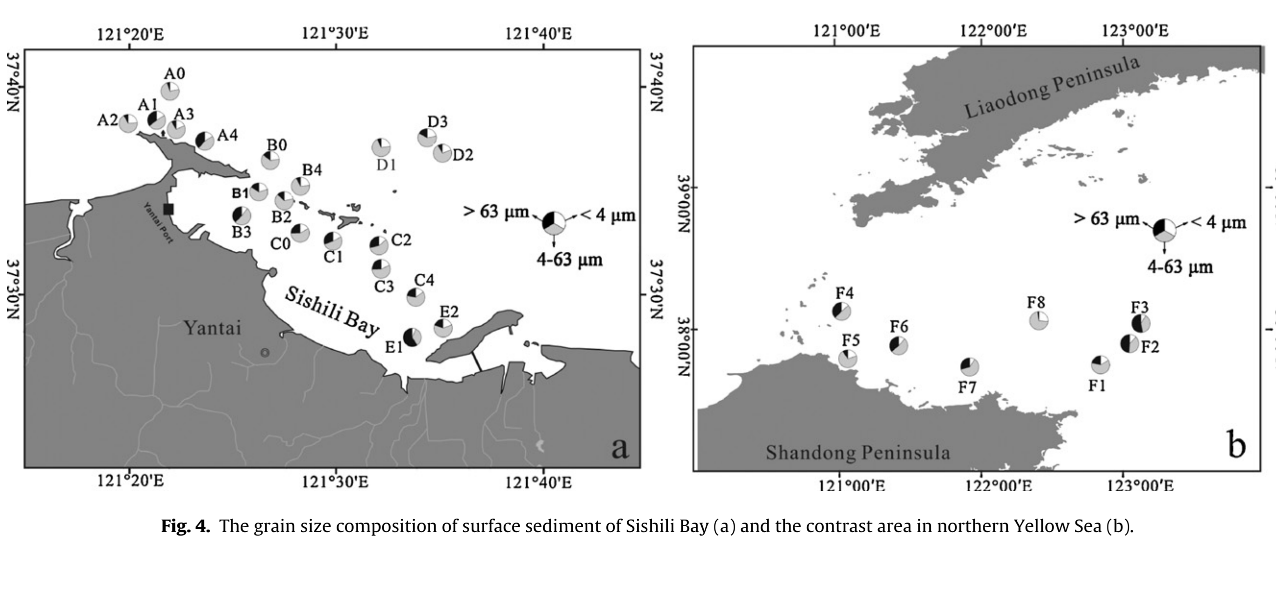

Fig. 4. The grain size composition of surface sediment of Sishili Bay (a) and the contrast area in northern Yellow Sea (b).

Table 2
The environmental parameters of study zones (mean ± standard deviation). SB represents the mean value of each station available in Sishili Bay; *N* represents the data number. Nutrient data in April and September 2010 in SB for sites A1–A3, B1–B4, C1–C3, D1–D2 were taken from Jiang et al. (2011), and for Zone E from an earlier survey in 2007 (Bai et al., 2010). There is a lack of DSi data in Zone E.

Zones	Nutrient concentrations (μM)			Nutrient ratio			Water depth (m)	Grain size proportion (%)		
	DIN	DIP	DSi	DIN/DIP	DSi/DIN	DSi/DIP		<4 μm	4–63 μM	>63 μM
A	14.27 ± 4.55	0.21 ± 0.06	2.37 ± 1.21	68.2 ± 21.4	0.17 ± 0.03	11.33 ± 4.01	22.2 ± 4.21	19.16 ± 3.49	61.59 ± 13.49	19.25 ± 16.29
N	3	3	3	3	3	3	5	5	5	5
B	13.11 ± 1.61	0.15 ± 0.15	3.4 ± 1.07	90.26 ± 419	0.26 ± 0.07	23.42 ± 148	15.6 ± 3.74	19.86 ± 5.35	62.32 ± 6.18	17.82 ± 11.39
N	4	4	4	4	4	4	5	5	5	5
C	10.85 ± 8.2	0.09 ± 0.03	4.54 ± 4.95	117.21 ± 59.1	0.42 ± 0.2	49.07 ± 38.99	13.8 ± 2.77	16.17 ± 1.79	57.39 ± 3.64	26.44 ± 3.11
N	3	3	3	3	3	3	5	5	5	5
D	17.99 ± 0.62	0.33 ± 0.17	3.98 ± 0.38	54.42 ± 35.16	0.22 ± 0.03	12.03 ± 5.97	11.4 ± 3.61	21.35 ± 2.09	67.89 ± 6.29	10.76 ± 5.49
N	2	2	2	2	2	2	3	3	3	3
E	7.1 ± 0	0.11 ± 0		62.83 ± 0			1.5 ± 1.77	12.77 ± 8.78	47.91 ± 19.31	39.32 ± 28.08
N	1	1		1			2	2	2	2
SB	13.15 ± 4.89	0.17 ± 0.12	3.53 ± 2.39	75.60 ± 245.65	0.27 ± 0.11	20.28 ± 88.35	16 ± 6.22	18.28 ± 4.53	60.3 ± 10.1	21.42 ± 13.89
N	13	13	13	13	12	12	20	20	20	20
F	4.22 ± 1.51	0.02 ± 0.01	0.77 ± 0.7	261.86 ± 445.73	0.18 ± 0.26	47.95 ± 36.75	42.54 ± 20.29	14.7 ± 5.97	55.5 ± 13.05	29.8 ± 18.02
N	8	8	8	8	8	8	8	8	8	8

Table 3
Correlations between biological parameters and environmental parameters. *N* represents the number of zones. There is a lack of DSi data in Zone E.

Item		Nutrient parameters			Nutrient ratio			Grain size proportion		
		DIN	DIP	DSi	DIN/DIP	DSi/DIN	DSi/DIP	<4 μM	4–63 μM	>63 μM
Total fossil abundance	Pearson correlation	0.786	0.868*	0.112	−0.552	−0.123	−0.553	0.712	0.672	−0.689
	N	6	6	5	6	6	6	6	6	6
Paralia sulcata abundance	Pearson correlation	0.820*	0.904*	0.112	−0.453	−0.045	−0.458	0.819*	0.807	−0.815*
	N	6	6	5	6	6	6	6	6	6
Species diversity index	Pearson Correlation	0.168	0.242	0.661	−0.800	−0.458	−0.768	−0.191	−0.369	0.312
	N	6	6	5	6	6	6	6	6	6
Species richness index	Pearson Correlation	−0.191	−0.173	0.222	−0.465	−0.398	−0.467	−0.497	−0.639	0.596
	N	6	6	5	6	6	6	6	6	6

* Correlation is significant at the 0.05 level (2-tailed).

Besides the association with anthropogenic activities, our correlation analysis indicated that the fossil abundance was also correlated with the grain size proportions.

Previous research found that the grain composition of the sediment played an important role in the fossil abundance. Fossil flora was relatively well preserved in silt and clay sediment but poorly preserved in sandy sediment (Chen et al., 2005; Cunningham et al., 2005; Lu et al., 2006). Low diatom abundance in coarse sediment could be a function of differential transport (diatom being removed from coarse sediment) or of preservation (with dissolution greater in more porous sediment) (Abrantes, 1988b). Although the difference was not significant in grain compositions among different zones and between inshore and offshore areas, different grain size proportions differed greatly in different zones. This may have also contributed to the fossil abundance variation.

4.2. The species composition characteristics in SB and NYS

The species richness and diversity that occurred in Zones A–E of SB was greater but not so significantly compared to Zone F of NYS with the exception of a slightly lower richness index in Zone D. The possible explanations are considered in this section.

Although not significant, the correlations between diversity index and DSi concentration, DIN/DIP and DSi/DIP were also relatively high ($R^2 = 0.44$, 0.64 and 0.59, respectively). DIP and DSi were the limiting factors in offshore Zone F in terms of definite deficiency and the high DIN/DIP and DSi/DIP in Zone F indicate a relative deficiency of DIP offshore. Thus, the phosphorus and silicate deficiency could limit the diatom growth in the offshore area and may have resulted in the lower diversity species index. Similarly, Aktan (2011) found that phytoplankton composition in Mediterranean coastal and offshore sites increased in diatom species number and diversity toward the inshore areas which were nutrient-rich due to anthropogenic activities.

5. Conclusions

By analyzing diatom and silicoflagellate fossils in the modern surface sediments, we found that the total abundance in sediment was positively correlated with the nutrient status in the upper water column, especially significantly with DIP. The eutrophication indicator *P. sulcata* correlated positively and significantly with DIP and DIN. However, the higher DIP and DIN in the inshore area largely due to sewage discharge and waste dumping did not result in detectably higher total fossil abundance and *P. sulcata* abundance in SB compared with the offshore zone. Grain size, disturbance by shipping and grazing pressure are factors that can all impact the preservation of this fossil record in the sediment and minimize the ability to directly infer the impact of human activities from the fossil abundance.

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