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Nitrogen Occurrence Characteristics and Reason Analysis in Different Trophic Status Freshwater Lakes

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ABSTRACT

Based on one-year monitoring about the different trophic status freshwater regions of Lake Taihu, the temporal-spatial distribution and occurrence characteristics of nitrogen in the water, porewater, and sediments and their correlation with main aquatic environmental factors were analysed. The results showed that the concentrations of TN in overlying water and sediment ranged from 0.22 to 7.74 mg/L and 551.5 to 1542.8 mg/kg, respectively. The concentrations of NO_3^--N in overlying water, sediment, and porewater ranged from 0.04 to 3.86 mg/L, 14.3 to 42.5 mg/kg, and 0.01 to 0.72 mg/L, respectively. The concentrations of NH_4^+-N in overlying water, sediment, and porewater ranged from 0.03 to 0.25 mg/L, 17.7 to 78.2 mg/kg, and 0.41 to 7.03 mg/L, respectively. NH_4^+-N in overlying water had no significant spatial-temporal variation, and the annual mean of NH_4^+-N in sediments was highest in Meiliang Bay. The annual mean of TN and NO_3^--N in overlying water and sediments was highest in Western Taihu Lake. The spatial and temporal distribution characteristics of NH_4^+-N and NO_3^--N in porewater were roughly consistent with those in sediments. Nitrogen in the sediment occurs in the form of organic nitrogen. Nitrogen in the overlying water was principally of NO_3^--N in Meiliang Bay and Gonghu Bay, and was principally of organic nitrogen in Xukou Bay. In the Western Taihu Lake, nitrogen in the overlying water was principally of NO_3^--N in summer and fall, and organic nitrogen in spring and winter. The results suggest that the type of organic matter in sediments was an important factor affecting the nitrogen occurrence characteristics and trophic status in aquatic environment. The correlation analysis showed that TN and NO_3^--N in overlying water was positively correlated with various forms of nitrogen in sediments, indicating that there was a strong exchange of nitrogen nutrients between water and sediments.

INTRODUCTION

Lake Taihu is the third largest freshwater lake in China. Eutrophication caused by human activities was particularly serious and the trophic states of lake regions were quite different. Therefore, identifying the nitrogen occurrence characteristics, recognizing its spatial-temporal variation pattern, and analysing its causes of formation has important significance for control of lacustrine eutrophication.

In order to control the eutrophication of Lake Taihu in recent years, a considerable number of researches about the temporal and spatial distribution of nitrogen in Lake Taihu have been made. These investigations helped to establish a broad understanding concerning the physical properties of sediment and its contribution to waterbody eutrophication. For example, Wang et al. (2010), Zhao et al. (2007) and Jin et al. (2006) analysed the temporal and spatial distribution characteristics of various forms of nitrogen in the heavily polluted region of northern Lake Taihu. In addition, Deng et al. (2008) studied the spatial distribution characteristics of nitrogen in overlying water of Lake Taihu and its relationship with algae and chlorophyll, and contribute to understood the relationship between phytoplankton and nitrogen occurrence characteristics in overlying water. The above results indicate that previous studies focused on the nitrogen occurrence characteristics and its spatial-temporal variation pattern in eutrophication lake region. However, the detailed information about the spatial-temporal variation pattern of nitrogen occurrence characteristics and its genesis analysis in different trophic status regions of Lake Taihu was still insufficient. More importantly, due to the migration and transformation of various forms of nitrogen in different media of the lacustrine environment, nitrogen in the sediment was released into the porewater and overlying water by molecular diffusion and bioturbation, thus the trophic status of the waterbody has changed (Wang et al. 2008). Therefore, sediment play a critical role in trophic status of waterbody and occurrence characteristics of nitrogen. Consequently, a thorough understanding of the nitrogen spatial-temporal variation characteristics in overlying water, pore water, and sediment was critical for us to understand the pattern of nitrogen migration and transformation in various media of lacustrine environments.

Lake Taihu is a typical large shallow eutrophic lake. Due to geographical features and differences in river input, there were a series of environmental gradients from Meiliang Bay in the northern to Eastern Lake Taihu in the southeast. Therefore, taking Western Lake Taihu (west), Meiliang Bay (north), Gonghu Bay (northeast), and Xukou Bay (east) as research region, one-year monitoring of lacustrine environment was carried out. The aim of this study is to dissect spatial-temporal variation of nitrogen in sediments, porewater, and overlying water of different trophic status lake regions (1) to recognized the change regularity of trophic status in lake regions, (2) to determine the relations of various nitrogen occurrence forms with aquatic environmental factors, (3) and to identify nitrogen migration and transformation pattern in various media.

MATERIALS AND METHODS

Sampling Sites and Procedure

The study area (Fig. 1) is located at the north to east side of the Lake Taihu with total nitrogen decreasing from Western Lake Taihu (region A-1, west) and Meiliang Bay (region A-2, north), to Gonghu Bay (region A-3, northeast), and finally to Xukou Bay (region A-4, east). Area A-1 and A-2 are highly enriched with nutrients and have frequent algal blooming incidents. In contrast, the low nutrient waterbody in A-4 is characterized by submersed vegetation and diverse communities of fishes and invertebrates and, in fact, is a drinking water source for local communities. The water in A-3 was similar to that in A-1 and A-2 till about 15 years ago but has since improved its quality due to the interference of local government.

Sample collection was carried out in fall of 2015, and winter, spring, and summer of 2016. For sediments, loose sediment samples in the depth of less than 5 cm was collected using a 1/16 m^2 Petersen grab sampler. Triplicate samples from three separate grabs were homogenized to generate one composite sample in each sampling site. Water samples were taken together at the same locations. All the samples were immediately stored in an icebox and transported back to the lab within 3 hours. Once in the lab, an aliquot of the sediment samples was stored in a 100 mL sterile centrifuge tube at -80°C until the analysis of physico-chemical index was completed. The remaining portion was further processed (freeze-dried to collect sediment particles, and centrifuged to collect the porewater) for physico-chemical analyses.

Physicochemical Analyses

Sixteen physicochemical parameters of the overlying water, porewater, and freeze-dried sediments were analysed (Table 1).

Details of the measurement procedures for each parameter can be found in Lu (1999), Wei (2002). Temperature (T), chlorophyll-*a* (Chla), algal density (AD), and dissolved oxygen (DO) of the overlying water were measured *in situ* using an YSI 6600 Multi-Parameter Water Quality Sonde, whereas the transparency was determined by a standard Secchi disc (SD) (diameter 20 cm) with black and white quadrants (Canfield et al. 1985).

Statistics Analysis

The Trophic Status Indices (*TSI*) (Aizaki 1981) at all the sampling sites were calculated using the measured Chl-*a*, W-TP, W-TN, COD, and SD by the following expression:

$$TSI\left(\sum\right) = \sum_{i=1}^{m} w_j\, TSI\left(j\right) \quad ...(1)$$

Where, $TSI\left(\sum\right)$ is the completed *TSI*; w_j is the relative weight of *TSI* of the *j* parameter; and *TSI(j)* is *TSI* of the *j* parameter. The mean value of all the samples in each region was used to represent the local trophic status, which based upon the value of $TSI\left(\sum\right)$, can be classified as: oligotrophication ($0 < TSI \le 30$), mesotrophication ($30 < TSI \le 50$), light eutrophication ($50 < TSI \le 60$), medium eutrophication ($60 < TSI \le 70$), and hypereutrophication ($70 < TSI \le 100$) on a scale of 0 to 100.

Pearson's correlation analysis (SPSS, v20.0) was performed to determine the links between environmental factors (AD, Chl-*a*, DO) and various forms of nitrogen in the overlying water, sediment, and porewater (W-TN, W-NH_4, W-NO_3, S-TN, S-NH_4, S-NO_x, P-NH_4, P-NO_3). Analysis of similarity (ANOSIM) was conducted to statistically test the variation of aquatic environmental indexes across seasons and regions. ANOSIM is a nonparametric test of significant difference between 2 or more groups based on any distance measure (Clarke 1993). ANOSIM then generates a test statistic, R, the magnitude of which indicates the degree of separation between groups, with a score of 1 indicating complete separation and 0 indicating no separation.

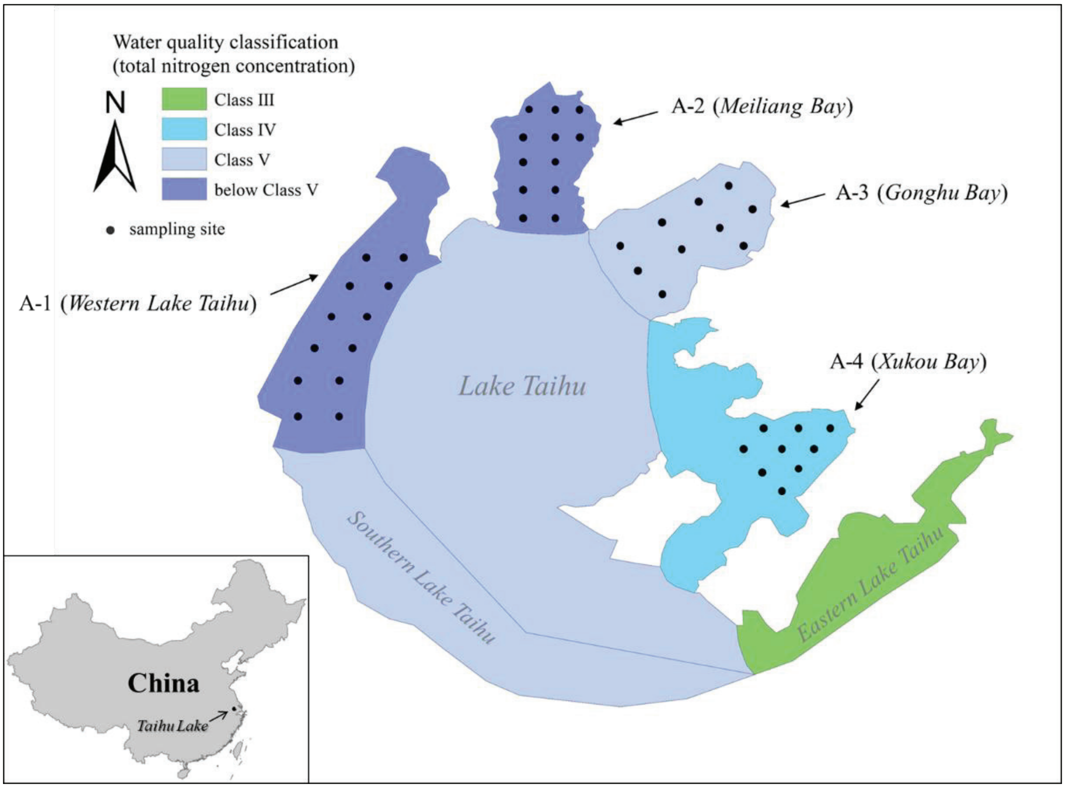

Fig. 1: The 43 sampling sites in the different trophic states regions of Lake Taihu. Water quality classification of the lake regions referred to the Standard GB3838-2002 of China. The data of total nitrogen concentration in the figure is from *the Health Status Report of Taihu Lake 2015* in Water Resources Department of Jiangsu Province.

Table 1: physico-chemical parameters of the overlying water, porewater, and freeze-dried sediments.

	Physicochemical Parameters
Sediment	total nitrogen (S-TN), ammonium nitrogen (S-NH_4), nitrate-nitrite nitrogen (S-NO_x), total organic matter (TOM)
Overlying water	total nitrogen (W-TN), ammonium nitrogen (W-NH_4), nitrate nitrogen (W-NO_3), total phosphorus (W-TP), Chemical Oxygen Demand (COD), temperature (T), chlorophyll-*a* (Chl), algal density (AD), and dissolved oxygen (DO), Secchi Disc (SD)
Porewater	ammonium (P-NH_4), nitrate nitrogen (P-NO_3)

RESULTS

Trophic Status of Four Lake Regions

Physico-chemical properties of the overlying water in four lake regions are shown in Fig. 2. The average annual value of DO and SD in A-4 is significantly higher than other regions (Fig. 2-1, 2-2). The annual average values of Chl-*a*, AD, TP and COD_{Mn} in the four lake regions were A-1 and A-2 > A-3 > A-4 (Figs. 2-3, 2-4, 2-5, 2-6). The Trophic Status Indices (*TSI*) of four lake regions in the four seasons are given in Table 2. Measured *TSI* in the study area decreased in the direction of A-1, A-2, A-3, to A-4 with average values changing from 61.3, 60.7, 56.2 to 45.4, respectively. Since region A-2 has been affected by the rivers of Zhihu Port and Wujin Port (Zhang et al. 2004), it was in a state of medium eutrophication all the year around, and the trophic status was highest in summer and lowest in winter. Region A-1 was the inflow area of Lake Taihu, affected by the upstream water, was in a state of medium eutrophication in spring, summer and autumn, and light eutrophication in winter. The water quality of region A-3 has been greatly improved after water diversion projects implementation (Hu et al. 2008), and it was in a state of light eutrophication throughout the year. The region A-4 enriched in aquatic vegetation (Qin et al. 2004), and was in a state of mesotrophication during the whole year.

Table 2: The trophic status of the five lake regions.

Lake regions	Season	*TLI* (Chl-a)	*TLI* (TP)	*TLI* (TN)	*TLI* (SD)	*TLI* (COD_{Mn})	*TLI*(Σ)	Trophic states
Western Lake Taihu (region A-1)	Spring	48.3	61.4	86.9	76.2	39.6	62.4	Medium eutrophication
	Summer	44.8	72.2	69.9	76.2	48.5	62.7	
	Autumn	43.1	70.2	69.4	80.3	46.7	61.9	
	Winter	36.8	57.9	73.1	78.7	42.5	58.3	Light eutrophication
Meiliang Bay (region A-2)	Spring	55.8	53.7	74.1	77.7	43.4	60.5	Medium eutrophication
	Summer	53.7	64.8	65.6	75.7	47.1	61.3	
	Autumn	47.9	59.9	63.8	80.5	58.7	60.6	
	Winter	48.6	57.4	70.2	80.6	50.6	60.2	
Gonghu Bay (region A-3)	Spring	51.9	56.6	73.5	69.6	34.5	57.0	Light eutrophication
	Summer	48.0	62.6	62.6	69.3	44.1	56.5	
	Autumn	45.2	55.9	62.6	68.8	63.3	58.0	
	Winter	45.0	46.2	68.6	72.3	38.4	53.2	
Xukou Bay (region A-4)	Spring	42.0	40.5	63.3	65.6	37.4	49.0	Mesotrophication
	Summer	39.0	44.9	59.0	65.1	42.9	49.1	
	Autumn	35.2	45.7	43.1	64.6	25.6	42.2	
	Winter	30.9	39.0	32.9	66.2	42.9	41.4	

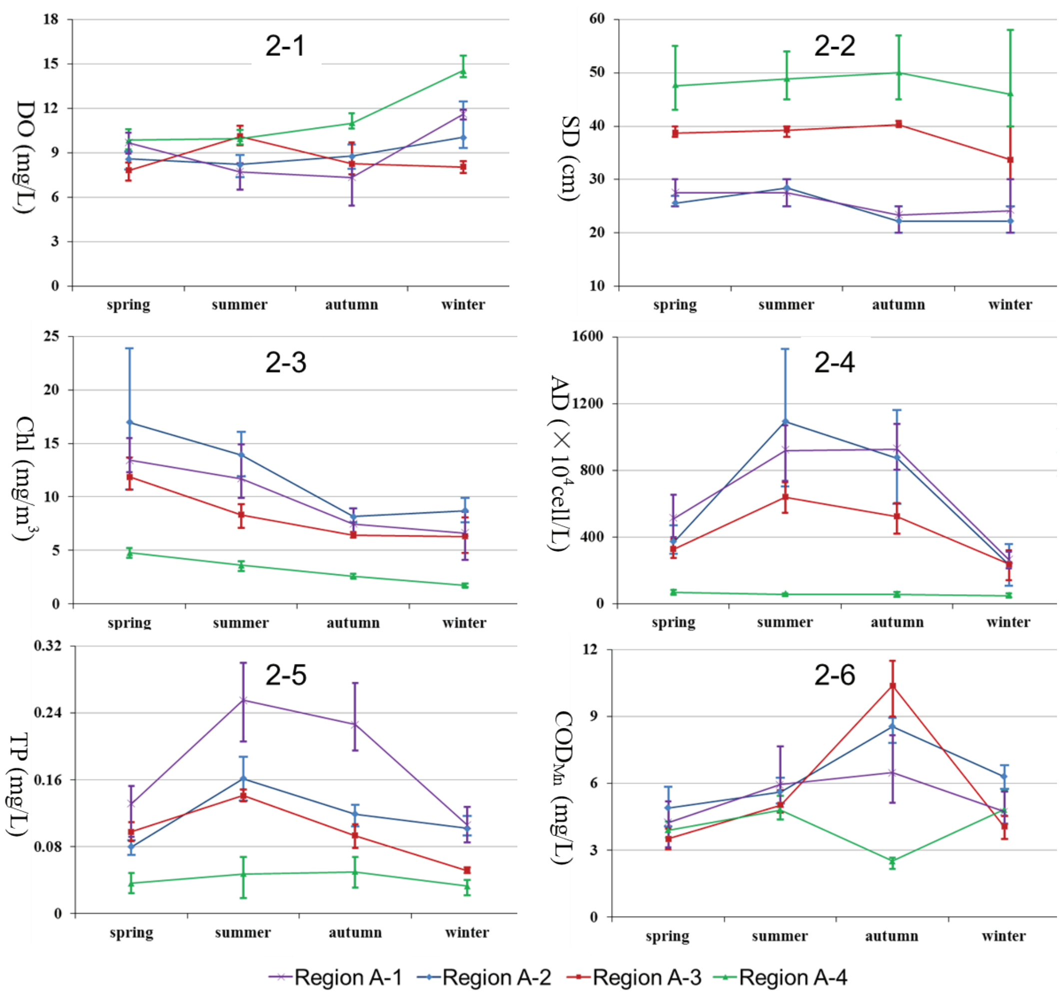

Fig. 2: The indexes of trophic status in the four lake regions in four seasons. A monitoring index concentration of each lake was calculated by taking average value of the monitoring index concentration of the all sample site in this lake.

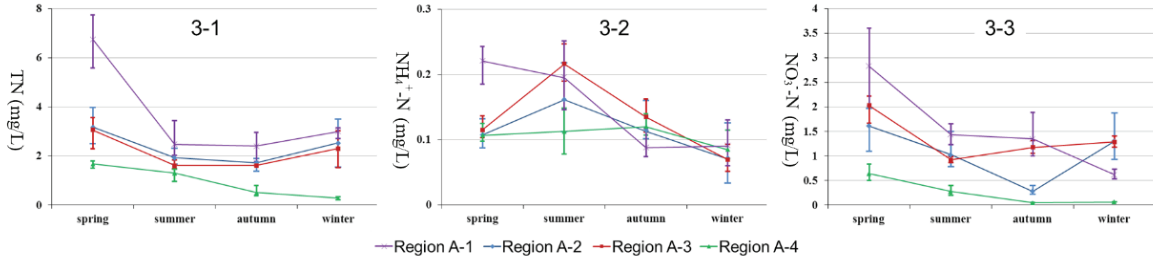

Fig. 3: Physico-chemical properties of the overlying water in different trophic states lake in four seasons. A monitoring index concentration of each lake was calculated by taking average value of the monitoring index concentration of the all sample site in this lake.

Table 3: Analysis of similarity (ANOSIM) R statistics for comparisons of spatial differences in overlying water environmental indexes.

	Meiliang Bay (A-2)	Gonghu Bay (A-3)	Western Lake Taihu (A-1)
Gonghu Bay (A-3)	0.04		
Western Lake Taihu (A-1)	0.11	0.10	
Xukou Bay (A-4)	0.43	0.45	0.64

Table 4: Analysis of similarity (ANOSIM) R statistics for comparisons of seasonal differences in overlying water environmental indexes.

	Spring	Summer	Autumn
Summer	0.28		
Autumn	0.28	0.06	
Winter	0.15	0.18	0.09

Temporal and Spatial Distribution Characteristics of Nitrogen in Overlying Water

As shown in Fig. 3 (3-1), the average annual concentration of TN decreased in the same direction as *TSI* does, and TN concentration of each lake region was highest in spring. The temporal and spatial distribution characteristics of NO_3^--N were consistent with TN (Fig. 3-3). The spatiotemporal variation of NH_4^{+}-N in the overlying water was not significant (Fig. 3-2).

The main form of nitrogen occurrence in overlying water of four lake regions is shown in Fig. 4. Nitrogen in the overlying water was principally of NO_3^--N in region A-2 (Fig. 4-2) and region A-3 (Fig. 4-3), and was principally of organic nitrogen (ON) in region A-4 (Fig. 4-4). In region A-1, nitrogen in the overlying water was principally of NO_3^--N in summer and fall, and organic nitrogen in spring and winter (Fig. 4-1).

The result of ANOSIM showed that there were significant spatial variations in nitrogen distribution characteristics of the overlying water between eutrophication and mesotrophication region (Table 3), and the seasonal variation was not significant (Table 4).

Temporal and Spatial Distribution Characteristics of Nitrogen in Sediment and Porewater

As shown in Fig. 5 (5-1), the TN content in sediment in region A-1, A-2, A-3, and A-4 was highest in summer, spring, autumn and spring, respectively. The sediment NH_4^+-N (Fig. 5-2) and NO_x^--N (Fig. 5-3) content in four lake regions reaching their maximal level in autumn. In addition, the contents of TN, NH_4^+-N and NO_x^--N in sediments were reduced with decreasing trophic status (Fig. 5). The main form of nitrogen occurrence in sediment of four lake regions was organic nitrogen, and the main form of inorganic nitrogen occurrence in sediment and porewater were NH_4^{+}-N (Fig. 7).

Spatial and temporal distribution trend of NH_4^+-N in porewater was similar to that in sediment Fig. 6 (Fig. 6-1). The concentration of NO_3^--N in porewater showed a strong seasonal variation with NO_3^--N reaching its maximal level in summer (Fig. 6-2).

Relationship Between Various Nitrogen Occurrence Forms and Aquatic Environmental Factors

Pearson's correlation analysis indicated that chlorophyll-*a* and algal density in the study area appeared to be correlated

Table 5: Relationship between environmental factors and various forms of nitrogen in the overlying water, sediment and porewater.

		Chl	W-TN	AD	DO	W-NH_4	W-NO_3	P-NH_3	P-NO_3	S-TN	S-NH_4
spring	W-TN										
	AD	0.66	0.77								
	DO										
	W-NH_4		0.91	0.66							
	W-NO_3	0.48	0.84	0.73		0.74					
	P-NH_3	0.61	0.75	0.88		0.73	0.68				
	P-NO3										
	S-TN	0.66	0.49	0.55				0.48			
	S-NH_4	0.62	0.47	0.73			0.57	0.57		0.58	
	S-NO_x	0.48	0.61	0.77		0.52	0.59	0.76			0.78
summer	W-TN	0.57									
	AD	0.83	0.60								
	DO	-0.71	-0.75	-0.68							
	W-NH_4		0.60								
	W-NO_3	0.74	0.85	0.77	-0.68	0.62					
	P-NH_3	0.50	0.78		-0.63		0.72				
	P-NO3										
	S-TN	0.63	0.68	0.60	-0.58		0.64	0.68			
	S-NH_4	0.83	0.49	0.71	-0.47	0.48	0.69	0.49		0.57	
	S-NO_x	0.52	0.47	0.67			0.64				0.74
autumn	W-TN	0.81									
	AD	0.90	0.83								
	DO	-0.72	-0.89	-0.68							
	W-NH_4										
	W-NO_3	0.45	0.72	0.47	-0.70						
	P-NH_3	0.64	0.83	0.76	-0.70		0.64				
	P-NO3	0.75	0.78	0.70	-0.79		0.64	0.58			
	S-TN	0.57	0.46		-0.59				0.54		
	S-NH_4	0.64	0.50	0.65				0.50			
	S-NO_x		0.58		-0.58		0.65	0.58			
winter	W-TN	0.74									
	AD	0.67	0.79								
	DO	-0.69	-0.65	-0.66							
	W-NH_4										
	W-NO_3	0.77	0.70	0.65	-0.86						
	P-NH_3	0.68	0.43				0.54				
	P-NO3										
	S-TN		0.79	0.57							
	S-NH_4	0.76	0.42		-0.56		0.74	0.87			
	S-NO_x	0.50	0.68	0.51			0.70				

Only $p < 0.01$ shown in the table

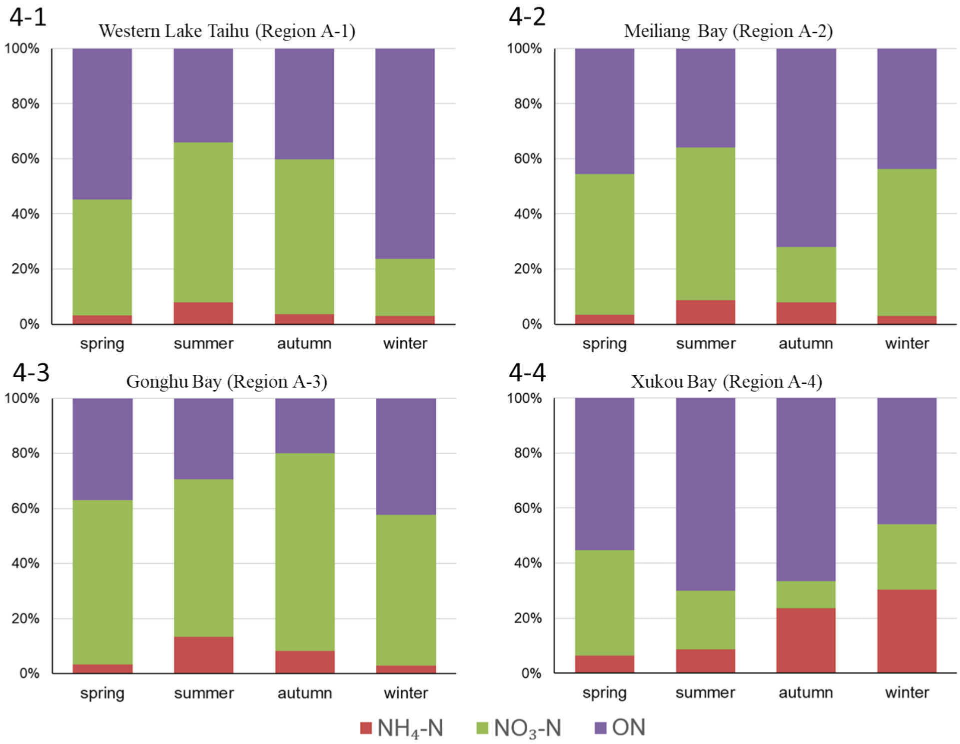

Fig. 4: various forms of nitrogen occurrence in the overlying water in different trophic states lake regions in four seasons.

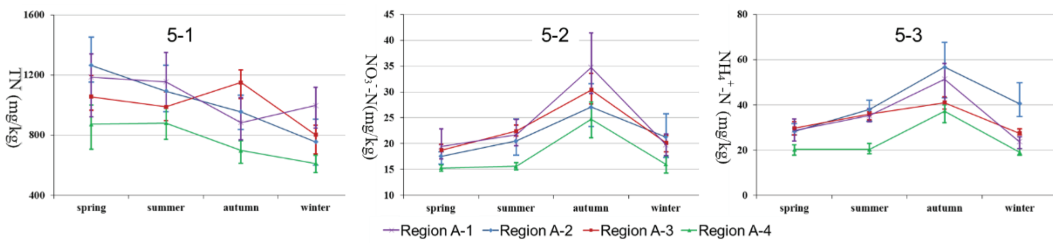

Fig. 5: Physico-chemical properties of the sediment in different trophic states lake regions in four seasons. A monitoring index concentration of each lake was calculated by taking average value of the monitoring index concentration of the all sample sites in this lake.

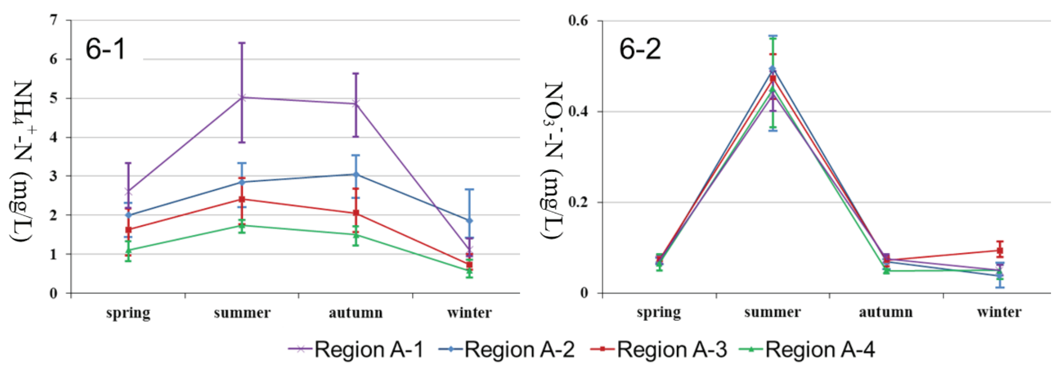

Fig. 6: Physico-chemical properties of the porewater in different trophic states lake regions in four seasons. A monitoring index concentration of each lake region was calculated by taking average value of the monitoring index concentration of the all sample sites in this lake.

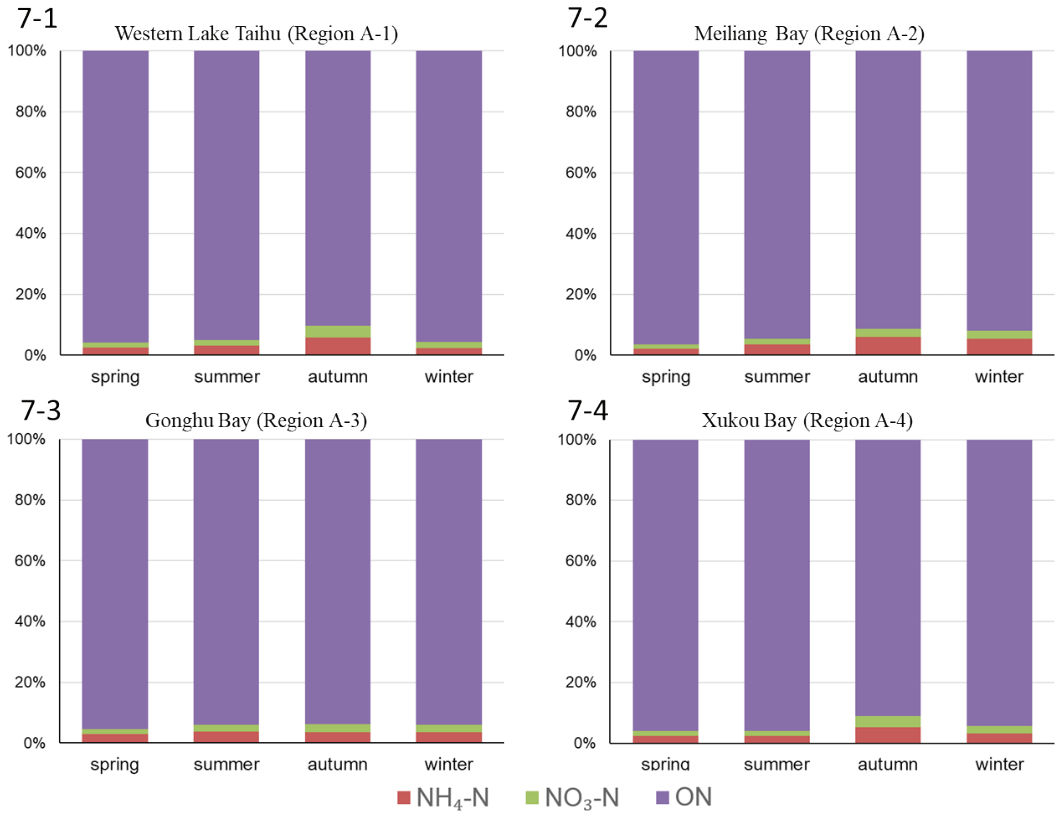

Fig. 7: various forms of nitrogen occurrence in the sediment in different trophic states lake regions of four seasons.

positively with the W-TN, W-NO_3, P-NH_3, S-TN, S-NH_4, and S-NO_x but negatively with DO (Table 5). For the different nitrogen occurrence forms in various media, a positive correlation between TN and NO_3^--N in overlying water and TN, NH_4^+-N, and NO_3^--N in sediment was observed (Table 5). Meanwhile, TN and NH_4^+-N in sediment exhibited a significant correlation with NH_4^+-N in porewater (Table 5).

DISCUSSION

Analysis of Temporal and Spatial Distribution Characteristics of Nitrogen Forms

The type of organic matter in sediment has an important influence on the migration and transformation of nitrogen (Zhu et al. 2011). Therefore, in this study, various sedimentary organic matter types will cause the difference of nitrogen occurrence forms in overlying water and trophic status of lake region. Different organic matter types have different mineralization products. On the one hand, organic compounds rich in carbon chains (cellulose, sugars, simple hydrocarbons, and lipids) produced monosaccharides in the degradation process, and eventually released CO_2 and CH_4 after mineralization (Xiao et al. 2009). On the other side, organic compounds rich in peptide ammonia bonds were degraded to amino acids, and finally NH_4^+-N was released through mineralization (Xiao et al. 2009).

In the algal bloom and eutrophic region, A-2 and A-3, the main source of organic matter was the algae which settled in the lake regions after death. While algae rich in nitrogen, sedimentary organic matter released a large amount of nitrogen such as NH_4^+-N during degradation and mineralization. The reason why nitrogen in the overlying water of regions A-2 and A-3 was principally of NO_3^--N may be two-fold. First of all, phytoplankton preferred to absorb NH_4^+-N than NO_3^--N, and NH_4^+-N was preferentially absorbed by algae. Secondly, due to the high content of DO in the lake regions (mean 8.5 mg/L), NH_4^+-N would be transformed into NO_3^--N under aerobic conditions. In the mesotrophic region A-4, the main source of organic matter was aquatic plants rich in cellulose. While cellulose was mainly composed of C, H and O, sedimentary organic matter released CO_2 and CH_4 during degradation and mineralization, therefore, organic nitrogen was the main form of nitrogen occurrence in region A-4. In the algal bloom and eutrophic region, A-1, as the main inflow regions of Lake Taihu, the impact of inflow rivers on the main form of nitrogen occurrence in overlying water was more pronounced. Previous analysis of nitrogen sources in region A-1 show that nitrogen in the inflow river was mainly from fertilizers during dry seasons, while from sewage during wet seasons (Wu et al. 2015). Thus, it caused that nitrogen in the overlying water was principally of NO_3^--N in summer and fall (wet season), and organic nitrogen in spring and winter (dry season).

The growth cycle of algae was short (1~2 weeks), and nutrients in the algae were quickly released into the water after algal death. Therefore, algae cannot fix nitrogen in water body for a long time as plants do. After algal death, nitrogen released into water in the form of ion state or gel state and reused by algae again (Sun et al. 2007). Whereas, aquatic plants cannot be decomposed quickly, and released nitrogen slowly by mineralization after their death. The released nitrogen quickly absorbed by aquatic plants, and significantly reduce the concentration of nutrients in water (Zhang et al. 2004). In conclusion, regions A-1, A-2 and A-3 with frequent algal bloom were in a state of eutrophication, while region A-4 with rich in aquatic vegetation was in a state of mesotrophication.

In the same sampling site, NO_3^--N concentration in the porewater was much lower than that in the overlying water. This was due to a significant denitrification took place in the sedimentary environment, and NO_3^--N, as an oxidant, participated in denitrification and degradation of organic matter in sediments. Besides, in the same sampling site, NH_4^+-N concentration in the porewater was much higher than that in the overlying water. NH_4^+-N in porewater mainly came from the ammonification of organic nitrogen in sediments under the action of anaerobic microorganisms (Hou et al. 2014), and its content was determined by the decomposition rate of organic nitrogen and the diffusion rate of NH_4^+-N in the sediment-water interface. The sediment of lake Taihu was rich in organic nitrogen and low in dissolved oxygen, which was easy to form a reducing environment (Qiao et al. 2012), and denitrification and ammonification were significant under microbial action. Hu et al. (2004) reported that the particulate matter of sediment had a strong adsorption on NH_4^+-N, while it had a weak even negative adsorption on NO_x^--N. NH_4^+-N usually exist in the sediment in the form of adsorption state and free state, and NH_4^+-N adsorbed on the sediment was the main source of NH_4^+-N in porewater (Bao et al. 2006).

Difference Analysis of Nitrogen Occurrence Characteristics

Agreeing with previous studies in other similar eutrophicated freshwater lakes (Shu et al. 2012, Zhao et al. 2013), the result of ANOSIM showed that the seasonal variation of nitrogen distribution characteristics in overlying water was not significant. Besides, there were significant spatial variations in nitrogen distribution characteristics of the overlying water between eutrophication and mesotrophication region. The reason might be that the northern and western lake regions had been affected by the input of polluted upstream water for a long time, and they were the main algal bloom areas of Lake Taihu. The death and subsidence of algae caused the release of nitrogen nutrients to overlying water (Qin et al. 2004), further aggravating the eutrophication state of the lake region. The region A-4 had no input of nitrogen pollutants and was rich in aquatic vegetation. Aquatic plants not only purified water quality (Li et al. 2010), but also inhibited the release of nutrients in sediment (Barko et al. 1998), which lowers the trophic status of lake region. Therefore, due to the exogenous input and endogenous release of nitrogen, cause a significant difference of nitrogen occurrence characteristics between mesotrophication and eutrophication lake regions.

Influence Factors of Nitrogen Occurrence Characteristics

Chlorophyll-*a* was one of the important components of the algae, its content reflected the biomass and growth of phytoplankton, and was closely related to the species and quantity of algae (Agawin et al. 2000), so the algal density and chlorophyll-*a* showed significant positive correlation. The negative correlation between algal density and dissolved oxygen indicated that with the increasing of algal density, algae consumed more dissolved oxygen in water through respiration, which results in the decrease of dissolved oxygen concentration.

In this study, the concentration of TN in overlying water showed a significant positive correlation with algal density in the four seasons. Previous studies had shown that TN not only affected the growth and reproduction of algae, but also affected the algal community structure (Zhu et al. 2010). Zhu et al. (2013) discussed the relationship between algal community structure and environmental factors in Southern Lake Taihu, and found that TN had a more significant impact on the growth of algae than other environmental factors. After the death of algae, the nitrogen in the algae could be released into the water quickly, providing nutrients for the growth of more algae, and at the same time, the concentration of TN in the overlying water increased. This conclusion could explain that, in the eutrophicated algae-dominated lake regions, the algal density in summer and autumn was higher than that in winter and spring, but the TN concentration in overlying water was lower.

Consistent with the observations made in freshwater lake (Trevisan et al. 2007), algal density and chlorophyll showed a positive correlation with NO_3^--N concentration, that might be because phytoplankton usually tend to absorb ammonia, nitrite, and nitrate nitrogen in water to synthesize amino acids and other substances needed by algal cells (Wafar et al. 2004). Chlorophyll and algal density were positively correlated to P-NH_3, S-TN, S-NH_4, and S-NO_x, which might be due to the release of nitrogen from sediment to overlying water and porewater, thus indirectly affecting the algal density and chlorophyll content in the overlying water.

Nitrogen in overlying water, porewater, and sediment was transferred and transformed under different conditions. On the one hand, nitrogen in porewater and sediment was exchanged with overlying water through molecular diffusion, which affected the occurrence form and characteristics of nitrogen in overlying water. On the other hand, sediment had adsorption effect on nitrogen in porewater and overlying water. Driven by the concentration gradient, the nitrogen in the sediment and porewater diffused to the overlying water (Zhang et al. 2013). Therefore, the forms and contents of nitrogen in various media could influence each other through migration and transformation.

W-TN and W-NO_3 in overlying water of each lake region showed a positive correlation with P-NH_3, S-TN, S-NH_4 and S-NO_x, indicating that there was a strong nitrogen exchange between water and sediment. The endogenous nutrients entered the overlying water from the sediments mainly through the resuspension process of surface sediments and the concentration diffusion of porewater. Some scholars considered that the process of nitrogen release into overlying water was a mechanism that nitrogen in the sediment supply nutrients to the overlying water (Xia et al. 2009). Therefore, while the exogenous source was effectively controlled, the endogenous release could not be ignored.

Nitrogen nutrients not only diffused between overlying water and porewater, but also migrated and transformed between sediment and porewater. There was a significant correlation between various forms of nitrogen in sediments and porewater, among them, the correlation of NH_4^+-N in the two media was the best, indicating that NH_4^+-N in porewater was mainly affected by NH_4^+-N in sediment. The effect was mainly manifested in two aspects. On the one hand, the organic matter in sediments generated NH_4^+-N through mineralization under anaerobic environment, and then releases NH_4^+-N into porewater by adsorption and desorption. For another, the concentration of NH_4^+-N in porewater also affected the adsorption capacity of sediment for NH_4^+-N. The study about NH_4^+-N adsorption characteristics of shallow lakes surface sediment in the middle and lower Yangtze River, confirmed the existence of the interaction (adsorption and desorption) in the sediment of Lake Taihu (Wang et al. 2007). A positive correlation between NH_4^+-N in porewater and TN in sediment suggest that, as the main component of TN in sediment (more than 90%), organic nitrogen transformed to NH_4^+-N by ammonification, and NH_4^+-N migrated to porewater and overlying water through diffusion. Previous studies suggest that the above process was the main way of nitrogen exchange between sediment and overlying water (Li et al. 2009).

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REFERENCES

Agawin, N.S., Duarte, C.M. and Agustí, S. 2000. Nutrient and temperature control of the contribution of picoplankton to phytoplankton biomass and production. Limnol. Oceanogr., 45: 591-600.

Aizaki, M. 1981. Application of modified Carlson's trophic state index to Japanese lakes and its relationships to other parameters related to trophic state. National Institute for Environmental Studies, Japan 23: 13-31.

Bao, X., Chen, K. and Fan, C. 2006. Effects on nitrogen and phosphorus distribution in interstitial water and sediment-water nitrogen and phosphorus release with growing of submerged macrophytes. Journal of Lake Sciences, 18: 515-522.

Barko, J.W. and James, W.F. 1998. Effects of submerged aquatic macrophytes on nutrient dynamics, sedimentation, and resuspension. The structuring role of submerged macrophytes in lakes. Springer, New York, NY, pp. 197-214.

Canfield, D.E., Langeland, K.A., Linda, S.B. and Haller, W.T. 1985. Relations between water transparency and maximum depth of macrophyte colonization in lakes. J. Aquat. Plant Manage., 23: 25-28.

Clarke, K.R. 1993. Non-parametric multivariate analyses of changes in community structure. Australian journal of Ecology, 18: 117-143.

Deng, J.C., Chen, Q., Zhai, S.J., Yang, X.C., Han, H.J. and Hu, W.P. 2008. Spatial distribution characteristics and environmental effect of N and P in water body of Taihu Lake. Environmental Science, 29: 3382-3386.

Hou, D., He, J., Lu, C., Dong, S., Wang, J., Xie, Z. and Zhang, F. 2014. Spatial variations and distributions of phosphorus and nitrogen in bottom sediments from a typical north-temperate lake, China. Environmental Earth Sciences, 71: 3063-3079.

Hu, W., Zhai, S., Zhu, Z. and Han, H. 2008. Impacts of the Yangtze River water transfer on the restoration of Lake Taihu. Ecological Engineering, 34: 30-49.

Hu, Z.T., Sun, H.W. and Tan, Y. 2004. Adsorptive characteristic of nutrient elements and influential factors in Taihu Lake sediment. Journal of Agro-Environment Science, 23: 1212-1216.

Jin, X.C., Jiang, X. and Xu, Y.H. 2006. Seasonal variation of dissolved nitrogen and phosphorus in sediments in northeast part of Lake Taihu. China Environmental Science, 26: 409-413.

Li, X.N., Song, H.L., Li, W., Lu, X.W. and Nishimura, O. 2010. An integrated ecological floating-bed employing plant, freshwater clam and biofilm carrier for purification of eutrophic water. Ecol. Eng., 36: 382-390.

Li, Y., Hu, X. and Nian, Y. 2009. Experimental Comparison of Nutrient Characters of Pore Water Between Macrophytic and Algal Lakes. Journal of Hydroecology, 5: 5.

Lu, R.K. 1999. Soil Argrochemistry Analysis Protocoes. China Agriculture Science Press, Beijing.

Qiao, J., Yang, L., Yan, T., Xue, F. and Zhao, D. 2012. Nitrogen fertilizer reduction in rice production for two consecutive years in the Taihu Lake area. Agr. Ecosyst. Environ. 146: 103-112.

Qin, B.Q., Hu, W.P. and Chen, W.M. 2004. Process and Mechanism of Environmental Changes of the Taihu Lake. Science Press, Beijing.

Shu, F.Y., Liu, Y.P., Zhao, Y., Wu, Y.P. and Li, A.H. 2012. Spatio-temporal distribution of TN and TP in water and evaluation of eutrophic state of Lake Nansi. Environmental Science, 33: 3748-3752.

Sun, X., Qin, B.Q. and Zhu, G.W. 2007. Release of colloidal phosphorus, nitrogen and organic carbon in the course of dying and decomposing of cyanobacteria. China Environmental Science, 27: 341-345.

Trevisan, G.V. and Forsberg, B.R. 2007. Relationships among nitrogen and total phosphorus, algal biomass and zooplankton density in the central Amazonia lakes. Hydrobiologia, 586: 357-365.

Wafar, M., L'Helguen, S., Raikar, V., Maguer, J.F. and Corre, P. L. 2004. Nitrogen uptake by size-fractionated plankton in permanently well-mixed temperate coastal waters. J. Plankton Res., 26: 1207-1218.

Wang, J., Wang, S., Jin, X. and Zhu, S. 2007. Ammonium adsorption characteristics onto the sediments from shallow lakes in the middle and lower reaches of the Yangtze River. Journal of Agro-Environment Science, 26: 1224-1229.

Wang, Q., Li, Y., Jiang, X., Wang, S. and Jin, X. 2010. The distribution of nitrogen speciation in three lake regions of North of Taihu Lake. China Environmental Science, 30: 1537-1542.

Wang, S.R., Jiao, L.X. and Jin, X.C. 2008. Distribution of total, exchangeable and fixed nitrogen in the sediments from shallow lakes in the middle and lower reaches of the Yangtze River. Acta Scientiae Circumstantiae, 28: 37-43.

Wei, F.S. 2002. Determination Methods for Examination of Water and Wastewater. China Environmental Science Press, Beijing.

Wu, Q.L., Ruan, X.H., Wu, C.M., Li, R.F., Wang, C.W. and Wan, Y. 2015. Analysis of sources and transformation of nitrogen as a contaminant in the river and lake water in the western region of the Taihu Lake basin. Acta Sci. Circum. 35: 3883-3889.

Xia, X., Yang, Z. and Zhang, X. 2009. Effect of suspended-sediment concentration on nitrification in river water: Importance of suspended sediment-water interface. Enviro. Sci. Technol., 43: 3681-3687.

Xiao, L., Yang, L., Zhang, Y., Gu, Y., Jiang, L. and Qin, B. 2009. Solid state fermentation of aquatic macrophytes for crude protein extraction. Ecol. Eng., 35: 1668-1676.

Zhang, L., Fan, C.X., Chi, Q.Q., Wang, J.J. and Qin, B.Q. 2004. Phosphorus species distribution of sediments in Lake Taihu and its main inflow rivers. Geochimica, 33: 423-432.

Zhang, L., Wang, L., Yin, K., Lu, Y., Zhang, D., Yang, Y. and Huang, X. 2013. Porewater nutrient characteristics and the fluxes across the sediment in the Pearl River estuary and adjacent waters, China. Estuar. Coast. Shelf S., 133: 182-192.

Zhao, H., Wang, S., Jiao, L., Yang, S. and Liu, W. 2013. Characteristics of temporal and spatial distribution of different forms of phosphorus in the sediments of Erhai Lake. Research of Environmental Sciences, 26: 227-234.

Zhao, X.Q., Yang, L.Y., Yu, Z.Y., Fan, Q.H., Zhan, Z., Xiao, Y. and Qin, B. 2007. Temporal and spatial distribution of physicochemical characteristics and nutrients in sediments of Lake Taihu. J. Lake Sci., 19: 698-704.

Zhu, M., Zhu, G., Zhao, L., Yao, X., Zhang, Y., Gao, G. and Qin, B. 2013. Influence of algal bloom degradation on nutrient release at the sediment-water interface in Lake Taihu, China. Environ. Sci. Pollut. R., 20: 1803-1811.

Zhu, W., Wan, L. and Zhao, L. 2010. Effect of nutrient level on phytoplankton community structure in different water bodies. J. Environ. Sci-China, 22: 32-39.

Zhu, Z.Y., Zhang, J., Wu, Y., Zhang, Y.Y., Lin, J. and Liu, S.M. 2011. Hypoxia off the Changjiang (Yangtze River) Estuary: Oxygen depletion and organic matter decomposition. Marine Chemistry, 125: 108-116.