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# Exploration of relationships between phytoplankton biomass and related environmental variables using multivariate statistic analysis in a eutrophic shallow lake: A 5-year study

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**Abstract**

Understanding the process of the changing phytoplankton patterns can be particularly useful in water quality improvement and management decisions. However, it is generally not easy to illustrate the interactions between phytoplankton biomass and related environmental variables given their high spatial and temporal heterogeneity. To elucidate relationships between them, in a eutrophic shallow lake, Taihu Lake, relative long-term data set of biotic and abiotic parameters of water quality in the lake were conducted using multivariate statistical analysis within seasonal periodicity. The results indicate that water temperature and total phosphorus (TP) played governing roles in phytoplankton dynamics in most seasons (i.e. temperature in winter, spring and summer; TP in spring, summer and autumn); COD (chemical oxygen demand) and BOD (biological oxygen demand) presented significant positive relationships with phytoplankton biomass in spring, summer and autumn. However, a complex interplay was found between phytoplankton biomass and nitrogen considering significant positive relationships occurring between them in spring and autumn, and conversely negative ones in summer. As the predatory factor, zooplankton presented significant grazing-pressure on phytoplankton biomass during summer in view of negative relationship between them in the season. Significant feedback effects of phytoplankton development were identified in summer and autumn in view that significant relationships were observed between phytoplankton biomass and pH, Trans (transparency of water) and DO. The results indicate that interactions between phytoplankton biomass and related environmental variables are highly sensitive to seasonal periodicity, which improves understanding of different roles of biotic and abiotic variables upon phytoplankton variability, and hence, advances management methods for eutrophic lakes.

**Key words**: eutrophication; phytoplankton; zooplankton; Taihu Lake

## Introduction

Eutrophication is one of the most serious ecological problems of freshwater lakes facing in the world (Fisher *et al*., 1995; Nixon, 1995). Considerable researches have been conducted on the mechanisms of eutrophication, such as nutrient dynamics and patterns of phytoplankton variability (Pinto-Coelho, 1998; Weyhenmeyer *et al*., 1999). To develop better understanding of the process of eutrophication, it is important to study the linkage between changes in related environmental variables and phytoplankton dynamics (van Tongeren *et al*., 1992; Romo *et al*., 1996; Zheng and Wang, 2001; George and Arhonditsis, 2004). However, it is not easy to illustrate the interactions between phytoplankton biomass and environmental variables. Recent techniques have included multivariate statistical analysis to evaluate surface water quality and characterize eutrophication. Momen *et al*. (1996) employed cluster and discriminant analysis to characterize the trophic classification of lakes in New York. Lau and Lane (2002) studied the governing role of nutrients and zooplankton upon phytoplankton variation by applying factor analysis in Barton Broad (UK). George and Arhonditsis (2004) used principal component and time-series analysis to explore the patterns and mechanisms of phytoplankton variability in Lake Washington (USA). With that multivariate statistical techniques have been proved to be useful for understanding interactions between the ecological factors that influence plankton communities in highly complex systems. These studies are most focus on the cause of variability in eutrophication. However, being the cause or response of, environmental variables are more or less linked to phytoplankton mechanisms in entrophic lakes and characterized by a high heterogeneity in space and time. Knowing relationships between relat-

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ed environmental variables and phytoplankton biomass variability with respect to seasonal periodicity provides informative ways for setting water quality criteria and pollution prevention plans for eutrphic lakes (George and Arhonditsis, 2004).

In this study, physico-chemical and biological variables of surface water quality were determined in Taihu Lake (China) during the period 1999–2003. Factor analysis and multivariate regression analysis were applied to evaluate variability in biotic and abiotic processes and their interaction with the data set. Objectives of this study included characterizing temporal phytoplankton dynamics with related variables, and identifying the interplays between seasonal variations of phytoplankton biomass and environmental variables in a shallow eutrophic lake.

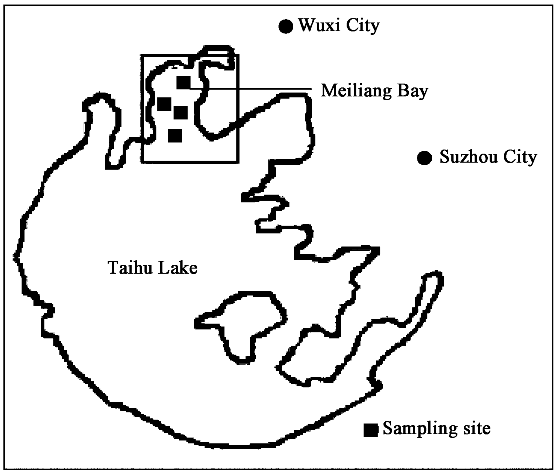


Fig. 1 Sampling sites in Meiliang Bay, Taihu Lake.

## 1 Materials and methods

### 1.1 Study site

Taihu Lake is the third largest freshwater lake in China while its watershed is the most developed region in China. Over the last two decades rapid population increases and economic development in the lake's drainage basin have led to rapid deterioration of water quality. This has restricted sustainable development of economies in lake districts (Cai and Gao, 1997; Pu *et al.*, 1998; Yu, 2000; Jin, 2000). The study was carried out in Meiliang Bay, the northern end of Taihu Lake. With a total water area of about 167 $km^2$ and mean water depth of 1.60 m, Meiliang Bay acts both as the principal water source for Wuxi City and as an important tourist attraction. However, responding to increasing collection and discharge of industrial and domestic wastes, the alga (*Cyanobacteria*) bloom occurrence in Meiliang Bay was frequently observed during the past few decades and it has been listed as one of the most hypertrophic areas in Taihu Lake (Li *et al.*, 2000; Jin, 2000).

### 1.2 Sampling and analysis

Water samples were collected monthly from 1999 to 2003 at 4 sites in Meiliang Bay (Fig.1). Samples were immediately preserved in 1 L polypropylene sampling bottles in darkness at 4°C and analyzed within 24 h. Water quality parameters were measured at all sampling stations. These parameters included water temperature (Temp), transparency (Secchi disk clarity) (Trans), dissolved oxygen (DO), pH, chemical oxygen demand (COD), biologic oxygen demand (BOD), total nitrogen (TN), ammonium nitrogen ($NH_4^+$-N), total phosphates (TP), chlorophyll-*a* (Chl-*a*) and zooplankton biomass (Zoo). Temp, Trans, DO and pH were measured in the field, while COD, BOD, TN, $NH_4^+$-N, and TP were determined in the laboratory using State Environmental Protection Administration (SEPA) standard methods (Jin and Tu, 1990). Chl-*a* was measured after extraction in 90% acetone by a freeze-thaw method (Lewitus *et al.*, 1998). Zoo was sampled using a tube to collect an integrated sample of 1-m high water column below the water surface. Zooplankton wet weight was measured using an electronic balance after removing large detrital particles under a dissecting microscope, and eliminating excess and interstitial water by the vacuum extraction technique (Jin and Tu, 1990; Harris and Wiebe, 2000).

### 1.3 Data preparation and statistical analysis

Phytoplankton was represented by chlorophyll-*a* concentration. Considering the potential predator-prey relationship between zooplankton and phytoplankton, total zooplankton biomass was taken as representative of phytoplankton grazers. Chemical parameters included pH, COD and BOD, as well as nutrients represented by TP, TN and $NH_4^+$-N. Physical parameters involved Temp, Trans and DO.

The structure of eutrophication variability was explored using multivariate statistical approaches. Two multivariate analyses (i.e., factor analysis (FA) and multiple linear stepwise regression analyses were undertaken.) were employed to examine possible relevant of environmental variables to phytoplankton. Preliminary data manipulation include removal of seasonality effects by analysis of spring, summer, autumn and winter data, and standardisation (by subtracting the mean and dividing by the SD), which precluded the need for non-parametric procedures.

Factor analysis is particularly useful for analyzing several related random environmental variables simultaneously. It could identify new, smaller set of uncorrelated variables that accounted for a large proportion of the total variance in the original variables (Ludwig and Reynolds, 1988; Lau and Lane, 2002; Bernard *et al.*, 2004). For interpretation purposes, the two most significant factor axes were portrayed as plots. To evaluate relationships between these environmental variables and phytoplankton biomass, a backward multiple regression analysis was employed. chlorophyll-*a* (as indicated by standardized) formed the dependent variable, and factors obtained by FA as the independent variables. Factors were orthogonal, so collinear problems were avoided in regression analysis. The criteria for significance were set at $P<0.05$ and the statistic analysis conducted using SPSS 11.0.

# 2 Results

## 2.1 Annual and seasonal variations of phytoplankton biomass and related environmental variables

The annual and seasonal variability of eutrophication variables were presented (including physical-chemical and biological parameters) based on the results of the 5-year study. Tables 1 and 2 show the mean annual and seasonal values as well as the standard difference (SD) of these parameters. Figs.2 and 3 show the time series data of TN, TP and Chl-*a* in the term 1999–2003, respectively.

### 2.1.1 Physical variables

In this study, DO and Trans were selected as feedback mechanisms of the eutrophication process, and Temp was taken as the driving factor for phytoplankton growth. The mean annual DO concentrations were 7.2 mg/L, respectively, over the 5-year period with the highest value 8.6 mg/L appearing in 2001 and lowest value 6.0 mg/L appearing in 2000. The seasonal distribution of DO was 9.4 mg/L in winter, 7.2 mg/L in spring, 6.1 mg/L in summer and 6.8 mg/L in autumn respectively (Tables 1 and 2). There was no significant difference among the Trans in the 5 years, although an increasing in the Trans could be observed from 1999 to 2003. However Trans in summer (29.0 cm) and autumn (30.9 cm) were significantly lower than that in winter (42.8 cm) and spring (38.3 cm). Little diversity of mean annual Temp was found during the study period while the seasons were distinguished with the highest temperature 29.2°C in summer, followed by 20.8°C in spring, 16.5°C in autumn and 6.9°C in winter (Table 2).

**Table 1 Interannual varieties of chlorophyll-*a* and related environmental variables in Meiliang Bay, Taihu Lake, 1999–2003***

| Year | COD (mg/L) | BOD (mg/L) | TN (mg/L) | $NH_4^+$-N (mg/L) | TP (mg/L) | pH |
|---|---|---|---|---|---|---|
| 1999 | 7.6±1.7 | 6.4±1.4 | 3.89±1.14 | 1.56±1.03 | 0.204±0.061 | 7.9±0.2 |
| | (4.4–9.2) | (3.5–8.1) | (1.87–6.03) | (0.34–2.86) | (0.145–0.278) | (7.3–8.5) |
| 2000 | 7.4±1.3 | 5.8±1.0 | 4.16±1.03 | 1.67±0.95 | 0.194±0.072 | 7.7±0.2 |
| | (4.7–8.9) | (4.1–6.9) | (2.33–6.47) | (0.94–3.12) | (0.093–0.303) | (7.2–8.0) |
| 2001 | 6.6±1.3 | 6.2±1.2 | 4.19±0.92 | 1.65±1.11 | 0.153±0.054 | 7.9±0.3 |
| | (4.5–8.7) | (3.2–6.1) | (2.87–6.22) | (0.25–3.68) | (0.085–0.243) | (7.3–8.4) |
| 2002 | 6.1±0.9 | 6.0±1.6 | 4.31±1.20 | 1.72±1.10 | 0.152±0.046 | 7.8±0.3 |
| | (4.9–7.7) | (4.5–9.1) | (1.97–7.26) | (0.23–3.73) | (0.115–0.205) | (7.3–8.1) |
| 2003 | 5.9±1.1 | 5.6±1.3 | 4.84±1.23 | 2.15±0.83 | 0.109±0.022 | 7.8±0.3 |
| | (4.5–7.4) | (3.4–7.7) | (2.13–7.86) | (0.86–3.29) | (0.073–0.135) | (7.4–8.4) |
| Year | Temp (°C) | Trans (cm) | DO (mg/L) | Zoo (mg/L) | Chl-*a* (μg/L) | |
| 1999 | 18.1±9.3 | 31.6±9.9 | 6.5±1.2 | 2.55±1.78 | 58.1±30.1 | |
| | (5.7–30.8) | (24.5–48.5) | (5.8–9.2) | (0.76–3.53) | (11.0–165.2) | |
| 2000 | 18.0±8.6 | 33.5±8.7 | 6.0±1.7 | 3.12±2.21 | 58.8±29.6 | |
| | (6.8–29.8) | (26.0–55.5) | (4.7–9.3) | (0.89–4.42) | (16.4–144.8) | |
| 2001 | 18.3±9.1 | 36.4±11.8 | 8.6±1.5 | 2.03±1.45 | 47.4±25.4 | |
| | (5.4–31.8) | (25.0–62.5) | (6.4–11.7) | (0.61–2.98) | (12.3–104.7) | |
| 2002 | 18.4±8.4 | 36.8±7.7 | 7.4±1.2 | 2.33±1.69 | 39.4±25.1 | |
| | (7.1–30.6) | (22.5–43.8) | (5.9–10.5) | (0.93–3.35) | (7.5–79.3) | |
| 2003 | 18.3±9.5 | 38.7±9.7 | 7.5±2.2 | 1.96±1.22 | 26.2±17.3 | |
| | (3.9–33.5) | (26.3–57.5) | (5.0–11.3) | (0.42–2.79) | (9.3–67.6) | |

* Most of the data were from the Environmental Protection Bureau, Jiangsu Province.

**Table 2 Seasonal varieties of chlorophyll-*a* and related environmental variables in Meiliang Bay, Taihu Lake, 1999–2003***

| Season | COD (mg/L) | BOD (mg/L) | TN (mg/L) | TP (mg/L) | $NH_4^+$-N (mg/L) | pH |
|---|---|---|---|---|---|---|
| Winter | 5.8±0.9 | 5.5±1.1 | 5.55±1.22 | 0.149±0.058 | 2.37±0.89 | 7.8±0.2 |
| | (4.4–6.8) | (3.2–6.9) | (4.24–7.26) | (0.085–0.205) | (0.75–3.35) | (7.4–8.1) |
| Spring | 6.4±1.1 | 6.1±1.2 | 5.05±1.60 | 0.163±0.044 | 2.19±1.28 | 8.1±0.3 |
| | (4.9–7.7) | (4.4–8.1) | (2.81–7.86) | (0.073–0.223) | (0.23–3.73) | (7.4–8.5) |
| Summer | 7.1±1.4 | 6.4±1.4 | 2.77±0.61 | 0.191±0.051 | 0.99±0.5 | 8.0±0.3 |
| | (4.9–9.2) | (3.5–7.9) | (1.87–3.95) | (0.113–0.278) | (0.25–1.60) | (7.2–8.4) |
| Autumn | 6.7±1.3 | 5.8±1.5 | 3.75±0.82 | 0.145±0.027 | 2.18±0.79 | 7.6±0.2 |
| | (5.1–7.8) | (4.1–9.1) | (2.87–5.15) | (0.093–0.214) | (1.45-3.68) | (7.3–8.2) |
| Season | Temp (°C) | Trans (cm) | DO (mg/L) | Zoo (mg/L) | Chl-*a* (μg/L) | |
| Winter | 6.9±1.8 | 42.8±10.5 | 9.4±1.9 | 1.15±0.56 | 17.7±10.2 | |
| | (3.9–9.7) | (22.5–62.5) | (6.4–11.3) | (0.42–1.73) | (9.3–30.9) | |
| Spring | 20.8±4.2 | 38.3±8.3 | 7.2±2.1 | 2.51±1.74 | 48.1±32.5 | |
| | (14.4–26.7) | (30.0–57.5) | (5.5–10.3) | (1.25–3.36) | (7.5–125.7) | |
| Summer | 29.2±2.6 | 29.0±5.8 | 6.1±1.7 | 3.09±1.43 | 82.7±54.3 | |
| | (25.9–33.5) | (22.5–40.5) | (4.7–8.9) | (2.35–4.42) | (29.1–165.2) | |
| Autumn | 16.5±4.3 | 30.9±2.9 | 6.8±1.5 | 2.24±1.61 | 35.3±14.6 | |
| | (10.6–21.8) | (27.5–35.0) | (5.9–8.8) | (1.44–3.11) | (14.8–63.4) | |

* Most of the data were from the Environmental Protection Bureau, Jiangsu Province.

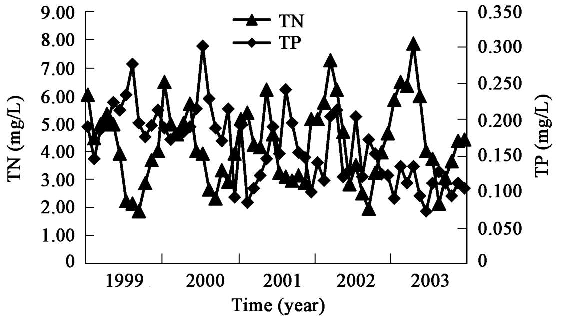


Fig. 2 Time series data of TN and TP in Meiliang Bay, 1999–2003.

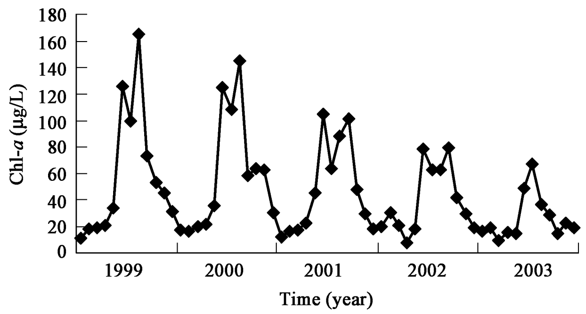


Fig. 3 Time series data of Chl-*a* in Meiliang Bay, 1999–2003.

### 2.1.2 Chemical variables

No significant annual variance of pH was found with the value range 7.7–7.9 in the period 1999–2003. However values of pH in spring (8.1) and summer (8.0) were higher than that in winter (7.8) and autumn (7.6). The mean COD concentration was 6.7 mg/L (ranging 5.9–7.6 mg/L). While the average of BOD value was 6.0 mg/L (ranging 5.6–6.4 mg/L). Both of COD and BOD values presented decreasing tendencies over the 5-year study period, whereas less seasonal distributions of them were found.

The mean TN and $NH_4^+$-N concentrations were 4.28 mg/L and 1.75 mg/L, respectively, over the 5-year period. They had significantly increasing tendencies from 3.89 mg/L in 1999 to 4.84 mg/L in 2003 for TN and 1.56 mg/L (1999) to 2.15 mg/L (2003) for $NH_4^+$-N. The concentrations of TN and $NH_4^+$-N showed similar seasonal variances with the highest concentrations in winter, followed in a descending order by spring, autumn and summer. Conversely the annual TP concentration decreased during the study period from 0.204 mg/L in 1999 to 0.109 mg/L in 2003. Moreover, the seasonal variation of TP was opposite to that of TN and $NH_4^+$-N (Fig.2). In general phosphate concentrations often showed less clear seasonal trends than other nutrients did (Bellos *et al.*, 2004). However, in this research the level of TP was relatively higher in summer than that in other seasons, which might accelerate cyanobacteria bloom in summer.

### 2.1.3 Biological variables

From 1999 to 2003, remarkable reduction in annual Chl-*a* concentration was observed with average annual concentrations ranging from 26.2 to 58.1 μg/L. The mean zooplankton biomass was 2.40 mg/L, with a minimum of 1.96 mg/L in 2003 and a maximum of 3.12 mg/L in 2000. The highest Chl-*a* concentrations were found in summer (82.7 μg/L). Following this were concentrations in spring (48.1 μg/L), autumn (35.3 μg/L) and winter (17.7 μg/L). Variation of Chl-*a* showed a high degree of similarity with TP (Fig.3). Zooplankton biomass showed similar seasonal distribution with the highest value 3.09 mg/L in summer, followed by 2.51 mg/L in spring, 2.24 mg/L in autumn and 1.15 mg/L in winter.

## 2.2 Seasonal varieties of relationships between phytoplankton biomass and environmental variables

It argued that temperature differences strongly associated with the variation in phytoplankton biomass (Abdul-Hussein and Mason, 1988). Thus it is essential to explore phytoplankton biomass variability in terms of seasonality. In this section, factor analysis and stepwise multiple regression analysis were applied to describe the seasonal variety of the relationship of eutrophication variables for each season, i.e., winter (January–March), spring (April–June), summer (July–September), and autumn (October–December). Table 3 presents the factor loading matrix and Fig.4 shows the plot of the first two factors seasonally. Subsequently, a regression equation between phytoplankton biomass and related environmental variables was presented for each season.

### 2.2.1 Winter

FA of winter data respectively shows that the eigenvalues for first three factors are 4.4, 1.3 and 1.2. F-1, F-2 and F-3 account for 70% of the total variables. Fig.4a shows the plot of the first two factors which account for 57% of the variance in the data. F-1 captures 43% of the total variance

**Table 3 Factor loading matrix for phytoplankton-related variables after a varimax rotation**

| Variables | Winter | | | Spring | | | Summer | | | Autumn | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Factor 1 | Factor 2 | Factor 3 | Factor 1 | Factor 2 | Factor 3 | Factor 1 | Factor 2 | Factor 3 | Factor 1 | Factor 2 | Factor 3 |
| COD | 0.926 | 0.076 | 0.053 | 0.695 | 0.462 | –0.144 | 0.895 | –0.126 | –0.014 | 0.674 | 0.133 | 0.551 |
| BOD | 0.899 | –0.033 | –0.029 | 0.753 | –0.031 | –0.102 | 0.697 | 0.404 | 0.150 | 0.774 | –0.088 | 0.001 |
| TN | 0.908 | 0.033 | 0.093 | 0.739 | –0.293 | 0.521 | 0.520 | 0.707 | –0.106 | 0.940 | –0.044 | 0.142 |
| TP | 0.707 | –0.087 | –0.045 | 0.835 | 0.149 | 0.066 | 0.815 | 0.197 | –0.082 | 0.721 | 0.502 | 0.054 |
| $NH_4^+$-N | 0.915 | –0.071 | 0.116 | 0.807 | –0.233 | 0.352 | 0.199 | 0.830 | 0.138 | 0.939 | –0.079 | 0.155 |
| pH | –0.290 | 0.736 | –0.028 | –0.326 | 0.598 | –0.497 | 0.199 | –0.555 | 0.588 | –0.679 | 0.094 | 0.090 |
| Zoo | 0.173 | 0.710 | 0.097 | 0.124 | 0.839 | –0.064 | 0.265 | 0.613 | –0.045 | –0.092 | 0.643 | 0.139 |
| Trans | –0.142 | –0.030 | 0.278 | –0.142 | –0.107 | 0.830 | –0.146 | 0.545 | 0.692 | 0.072 | 0.094 | –0.819 |
| Temp | 0.181 | 0.119 | 0.756 | –0.006 | 0.825 | 0.033 | 0.004 | –0.010 | 0.862 | –0.044 | 0.712 | –0.230 |
| DO | –0.554 | 0.403 | –0.479 | –0.519 | –0.220 | –0.627 | 0.338 | –0.797 | 0.160 | –0.842 | –0.026 | 0.186 |
| Eigenvalue | 4.4 | 1.3 | 1.2 | 3.8 | 2.4 | 1.1 | 3.3 | 2.6 | 1.6 | 4.6 | 1.6 | 1.1 |

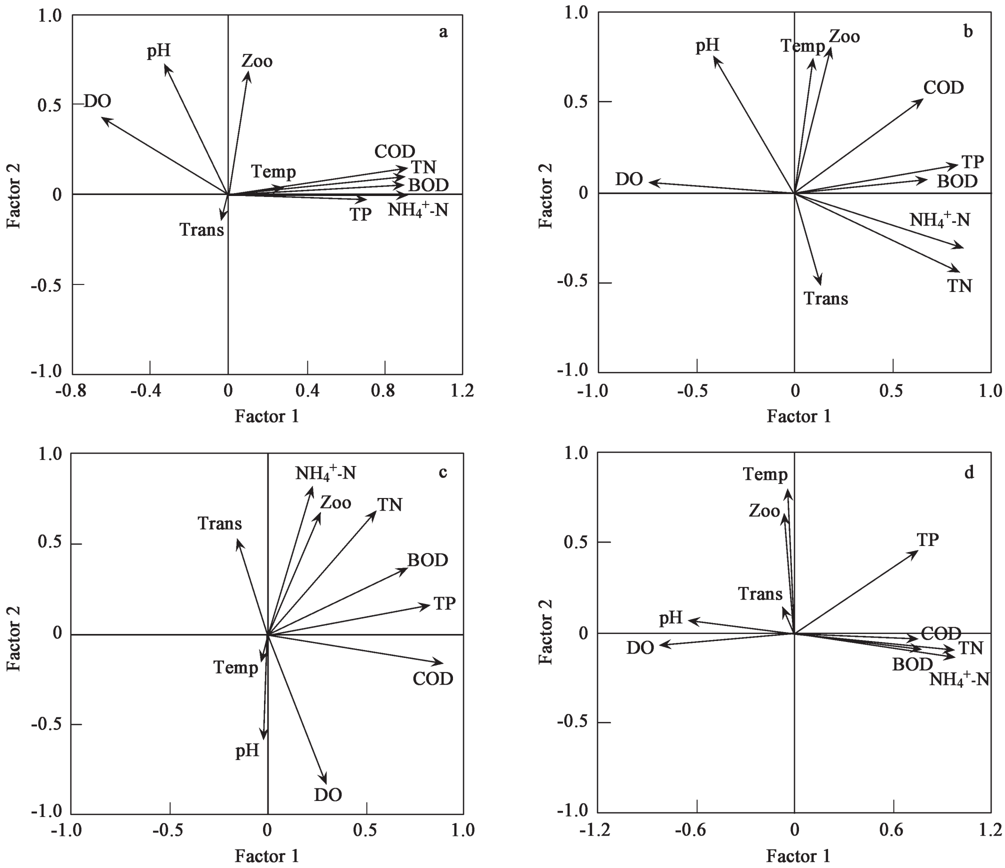


Fig. 4 Plot of factor loadings for each variable of the first two factor axes. (a) winter data; (b) spring data; (c) summer data; and (d) autumn data.

and is related to the TN, $NH_4^+$-N, COD, BOD and TP. F-2 accounts for 14% of the total variance and is related to pH and Zoo. Temp is correlated with F-3, explaining 13% of the total variance. To examine the relative relationships of the three factors with the phytoplankton biomass, a stepwise multiple regression analysis was utilized.

$$S_{\text{Chl-}a} = -0.214 + 0.117 \times \text{F-3}$$
$$(\text{adj. } R^2 = 0.267,\ S = 0.393,\ n = 240) \quad (1)$$

This multiple regression Eq.(1) shows that only F-3 has a significant relationship with phytoplankton biomass (as indicated by standardised Chl-*a* ($S_{\text{Chl}-a}$)). In view that only Temp is related to the F-3 positively, phytoplankton biomass is correlated significantly to Temp in winter. This strongly suggests that phytoplankton is dominated by thermal condition mainly in this season.

### 2.2.2 Spring

In spring, 74% of the total index is accounted for three factors, the eigenvalues are 3.8 for F-1, 2.4 for F-2 and 1.1 for F-3. The loading matrix is shown in Table 3, and the first two factors loadings are plotted on a bi-plot in Fig.4b. The first factor accounts for 34%, the second for 22% and the third for 18% of the index. F-1 is related to TN, $NH_4^+$-N, TP, BOD and COD, F-2 is related to Zoo, pH and Temp, while F-3 is associated with Trans.

$$S_{\text{Chl-}a} = -0.337 + 0.246 \times \text{F-1} + 0.569 \times \text{F-2}$$
$$(\text{adj. } R^2 = 0.336,\ S = 0.399,\ n = 240) \quad (2)$$

A multiple regression analysis is computed to explore the relative role of the three factors in explaining the phytoplankton. This shows that F-1 and F-2 are significantly related to the phytoplankton. This suggests that phytoplankton biomass was positively associated with BOD, COD, TN, $NH_4^+$-N, TP, Zoo, pH and Temp in spring, according to positive relationship between these variables and F-1 or F-2 in Table 3. It may be concluded that nutrient (nitrogen and phosphorus) and temperature are the limiting factors, while the pH value and zooplankton biomass were increasing in response to phytoplankton growth in spring.

### 2.2.3 Summer

The eigenvalues of the three factors are 3.3 for F-1, 2.6 for F-2 and 1.6 for F-3 in summer, respectively. The loading matrix of the three factors and bi-plot of the first two factors are given in Table 3 and Fig.4c, respectively. The three factors capture 75% of total variation. F-1 explains 31% of the index and is related to COD, BOD and TP. F-2 accounts for 27% of the index and is related to TN, $NH_4^+$-N, Zoo and DO. F-3 is related to the Temp and Trans, explaining 17% of total variables.

$$S_{\text{Chl-}a} = -0.224 + 0.457 \times \text{F-1} + 0.218 \times \text{F-3}$$
$$(\text{adj. } R^2 = 0.230,\ S = 0.431,\ n = 240) \quad (3)$$

The regression calculation (Eq.(3)) in summer illustrates that F-1 and F-3 are related to the phytoplankton biomass positively, while F-2 is negatively correlated to the phytoplankton biomass. Considering the connections between the variables and the 3 factors that obtained by FA (Table 3), it suggests that phytoplankton biomass is positively associated with COD, BOD, TP, pH, Trans and Temp, and negatively associated with TN, $NH_4^+$-N, DO and Zoo. Thus the nutrient (i.e. TP) and grazing (i.e. Zoo) must be the limiting factors to phytoplankton biomass; while high phytoplankton biomass can cause the increases of pH and DO, and the decline of Trans in summer. The opposite seasonal varieties between chlorophyll-*a* and nitrogen might be ascribed to low concentrations of TN and $NH_4^+$-N during the summer.

### 2.2.4 Autumn

Factor analysis of autumn data shows that the first three factors accounted for 72% of the total index (with eigenvalues of 4.6 for F-1, 1.6 for F-2 and 1.1 for F-3). Their loadings are tabulated in Table 3 and the two first factor loadings plotted on a bi-plot in Fig.4d. The first factor accounts for 45%, the second for 15% and the third for 12% of the index. F-1 captures most variables that related to COD, BOD, TN, $NH_4^+$-N, TP, pH and DO. F-2 is related to Zoo and Temp, while F-3 only is related to Trans negatively. The following regression analysis is performed to examine the ability of the factors to explain variety of phytoplankton biomass.

$$S_{\text{Chl-}a} = -0.224 + 0.457 \times \text{F-1} + 0.218 \times \text{F-3} \quad (\text{adj. } R^2 = 0.230,\ S = 0.431,\ n = 240) \tag{4}$$

This multiple regression Eq.(4) shows only F-1 and F-3 have the significant relationship with the phytoplankton biomass. According to the signs of factor scores in Eq.(4) and the associated variables in Table 4, chlorophyll-*a* was positively correlated with COD, BOD, TN, $NH_4^+$-N, TP, and negatively correlated with pH, DO and Trans. This suggests that nutrient is possible limiting factors to phytoplankton growth in autumn. Significant negative relationships between Chl-*a* and pH, and between DO and Trans give realization that phytoplankton has significant influences on water quality in autumn. F-2 shows no significant correlation with Chl-*a* in Eq.(4). It indicates that grazing pressure on phytoplankton by zooplankton is not significant on phytoplankton growth in autumn.

**Table 4 Phytoplankton and the associated environmental variables**

| | Relationship to phytoplankton | |
|---|---|---|
| | Positive | Negative |
| Winter | Temp | |
| Spring | COD; BOD; TN; $NH_4^+$-N; TP; Zoo; pH; Temp | |
| Summer | COD; BOD; TP; Temp; pH | TN; $NH_4^+$-N; Zoo; Trans; DO |
| Autumn | COD; BOD; TN; $NH_4^+$-N; TP | pH; DO; Trans |

## 3 Discussion

### 3.1 Analysis on temporal varieties of nutrients and phytoplankton biomass in Meiliang Bay, Taihu Lake

Long-term phytoplankton succession has been well investigated in aquatic ecology (Sommer and Gliwicz, 1986; Marshal and Peters, 1989). Strong annual variation in the physical, chemical and biological characteristics of lakes seems to play a regulatory role on phytoplankton dynamics, and annual variation in nutrient supply is an important determinant of year-to-year phytoplankton variability (Baines and Webster, 2000). In this study, annul average TN and $NH_4^+$-N showed significant increases, whereas TP displayed contrary tendencies in Meiliang Bay. The opposite varieties can partly be explained by the change of external nutrient input. From early 1990's, the increased attention on water quality improvement has been accompanied by the eutrophication development in Taihu Lake (Zhu, 1996; Zhang and Wang, 2001; Chen and Fan, 2003). Accordingly investments and measures in pollution control have been enhanced more recently. Detergents containing phosphorous have been replaced by non-phosphorous detergents in cities surrounding Taihu Lake since 1998 (Pan *et al*., 2005). Furthermore, decades of waste water treatment plants have been constructed to reduce the COD and TP loads since 1999. Thus the significant decline of TP concentration must be ascribed to the considerable reduction of TP load due to the effectiveness of these measures. However these efforts mainly focused on point-source pollution control and P reduction. Measures have yet not to be implemented to adequately control diffuse source pollution, which contributed main N load in Taihu Lake (Wang *et al*., 2004). Thus the nitrogen contents maintained a rising tendency, and TN was considered the principal pollution parameter in Taihu Lake according to the national surface water quality standard (Fan *et al*., 2000; Wetzel, 2001).

From 1999 to 2003, phytoplankton biomass (i.e. Chl-*a* concentration) was found to decrease annually with falling TP levels and with increasing levels of TN and $NH_4^+$-N. Hence the remarkable decline of phytoplankton biomass must be the response of phosphorus concentration decrease in Meiliang Bay, in view that annual dynamic of phytoplankton in freshwater lakes was mainly dominated by the external nutrient load (Sommer and Gliwicz, 1986; Baines *et al*., 2000). It is thought that a fundamental change in trophic category requires a 60%–80% reduction in external TP loading (Organisation for Economic Co-operation Development, 1982; Forsberg, 1985). However phytoplankton biomass in Taihu Lake responded rapidly when the external phosphorus loading was reduced. A likely reason maybe that the lake is very shallow and the water column is well mixed. Moreover, the internal P loading in the lake is quite low because of the bondage of phosphorus in its inorganic superficial sediment, which could partly explain the consistency between variations of phytoplankton biomass and phosphorus concentration (Fan *et al*., 2000). This suggests the possibility of reversing of eutrophication within a relatively short period by reducing external phosphorus load in the lake.

### 3.2 Explosion on potential variables related to the seasonal variation of phytoplankton

Phytoplankton succession is largely determined by the interactions and seasonal cycles of chemical (nutrients), biological (grazers), and physical (weather) factors (Sommer and Gliwicz, 1986). When a process in nature is controlled by a set of interrelated variables, focused statistical searches may be the only way to discern the relative importance of different variables in the natural system (Luoma and Bryan, 1982). To disentangle physicochemical and biological factor interactions in relation to phytoplankton biomass in relation to seasonal periodicity, in this study principal component analysis and regression analysis as an integrated approach were applied to examine the large related environmental date set seasonally. The statistical results illustrated a strong temporal heterogeneity of the relationships between Chl-*a* and environmental variables. The biotic and abiotic variables that interacted with phytoplankton biomass are summarized in Table 4.

Phytoplankton biomass was positively related to Temp in most seasons (winter, spring and summer). This demonstrated that the temperate zone lake-systems were light-limited and that phytoplankton patterns were partly driven by the amount of the variable solar radiation of a year (Reynolds, 1984). Concentrations of dissolved organic carbon and total phosphorus were the critical environmental variables associated with phytoplankton development, because of the significant positive correlations between phytoplanktom biomass and COD, BOD and TP in spring, summer and autumn (Table 4). In general, organic carbon in polluted surface water comes from household and industrial wastewater, accompanied by high nutrient, such as nitrogen and phosphorus (Eills, 1989). This is the reason that COD and BOD values were closely correlated with phytoplankton biomass in Meiliang Bay, the most eutrophic part of Taihu Lake strongly affected by anthropogenic activities (Lewitus *et al*., 1998; Zhang and Qin, 2001; Lu and Wang, 2003). Thus TP, COD and BOD can be taken as good indicators for prediction and assessment of phytoplankton pattern. However a complex relationship was found between phytoplankton biomass and nitrogen due to significant positive relationships between them in spring and autumn, and negative relationships in summer. This uncoupling indicated the potential interaction between nitrogen and phytoplankton biomass is rather indirect in P-limiting shallow lakes, considering that nitrogen is not limiting factor to phytoplankton in surface water system except in some deep lakes (Capblancq, 1990).

As the top-down controls of phytoplankton biomass, zooplankton can prevent large cyanobacteria populations from developing even in extremely fertile water (Timms and Moss, 1984; George and Arhonditsis, 2004). This study demonstrates that zooplankton biomass had a positive relationship with phytoplankton biomass in spring and a negative relationship in summer. This suggested that phytoplankton growth exceeded pressure on the phytoplankton biomass by the zooplankton prey in spring, while in summer zooplankton presented a significant predatory role. Generally eutrophication processes not only were driven by environmental factors, but also in turn modified the dynamic of physico-chemical variables and biological variables. In so doing eutrophication acted on the relationships that link each variable to the others (Strain and Yeats, 1999). This study indicated interactions between phytoplankton biomass and Trans, pH and DO were varying from season to season. Trans is mostly determined by the suspended solids in the water. Phytoplankton blooms and its decomposed particles can cause increase of suspended solids levels, and thus reduce the transparency of fresh water (Cai and Gao, 1997). This explains the negative relationships between Chl-*a* and Trans in summer and autumn. It is argued that phytoplankton growth could enhance the pH value in fresh water system (Bernard *et al*., 2004). However negative relationship between pH and phytoplankton biomass is observed in autumn. This can be ascribed to the production of acidic compounds in the course of the alga decomposition (Bernard *et al*., 2004). Opposite relationships are observed between DO and phytoplankton biomass in summer and autumn. It might be the reason that the oxygen production rate in the course of the phytoplankton growing exceeded the consumption by its decomposing in summer, whereas it can not compensate the consumption in autumn.

To conclude, statistical analyses demonstrated that interactions between phytoplankton and biotic-abiotic variables strongly related to temporal heterogeneity. COD, BOD and TP were found to be the best predictors of phytoplankton seasonal patterns. This was realized according to the significant positive interactions between these variables and Chl-*a* in most seasons which also demonstrated coupling temporal variations in the lake. Prey-pressure on phytoplankton biomass influenced by zooplankton was identified only in summer, whereas significant responses (such as variations of Trans, pH and DO) of the eutrophication were observed in summer and autumn. It suggested a possibility of prediction and elucidation for phytoplankton variability patterns by some simple physico-chemical and biological parameters. Despite the complexity of a eutrophic aquatic system, this study improves understanding of different roles of biotic and abiotic variables upon phytoplankton variability.

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