



Vertical and temporal distribution of nitrogen and phosphorus and relationship with their influencing factors in aquatic-terrestrial ecotone: a case study in Taihu Lake, China

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Abstract

Vertical and temporal distributions of N and P in soil solution in aquatic-terrestrial ecotone (ATE) of Taihu Lake were investigated, and the relations among N, P, ORP (oxidation reduction potential), TOC, root system biomass and microorganism were studied. As a whole, significant declines in TN, NO_3^- -N, DON (dissolved organic nitrogen) and TP concentration in soil solution have occurred with increase of the depth, and reached their minima at 60 cm depth, except for NH_4^+ -N, which increased with depth. The concentration of TP increased gradually from spring to winter in the topsoil, the maximum 0.08 mg/L presented in the winter while the minimum 0.03 mg/L in spring. In the deeper layer, the concentration value of TP fluctuated little. As for the NO_3^- -N, its seasonal variation was significant at 20 cm depth, its concentration increased gradually from spring to autumn, and decreased markedly in winter. Vertical and temporal distribution of DON is contrary to that of NO_3^- -N. The results also show that the variation of N and P in the percolate between adjacent layers is obviously different. The vertical variation of TN, TP, NO_3^- -N, NH_4^+ -N and DON is significant, of which the variation coefficient of NO_3^- -N along the depth reaches 100.23%, the highest; while the variation coefficient of DON is 41.14%, the smallest. The results of correlation analysis show that the concentration of nitrogen and phosphorus correlate significantly with TOC, ORP, root biomass and counts of nitrifying bacteria. Most nutrients altered much from 20 to 40 cm along the depth. However, DON changed more between 60 and 80 cm. Results show that soil of 0–60 cm depth is active rhizoplane, with strong capability to remove the nitrogen and phosphorus in ATE. It may suggest that there exists the optimum ecological efficiency in the depth of above 60 cm in reed wetland. This will be very significant for ecological restoration and reestablishment.

Key words: aquatic-terrestrial ecotone (ATE); soil percolate; vertical and temporal distribution; coefficient of variation; ecological efficiency

Introduction

Aquatic-terrestrial ecotone (ATE) is an important functional interface zone between the freshwater ecosystem and the terrestrial ecosystem, which is characterized with the dominant verge as well as the higher production and biodiversity (Wang and Feng, 1997). This buffer zone provides essential ecosystem services, including the lakeshore stabilization, fisheries resources and habitat, food for migratory and resident animals, the aesthetic scenery and recreational opportunities for human populations. It also offers protection to water body from harmful impacts such as high nutrient that result from land use practices (Blackwell *et al.*, 1999). The degree to which this protection is provided depends on a number of factors including the size, location, hydrology, vegetation and soil type of the buffer zone through a combination of physical, chemical and biological processes (Mitsch, 1995). In the

last decade, restoration and reconstruction of the ATE have been emphasized on the protection of lakes and reservoirs for sustaining these services, especially on the eutrophication control of the lakes and reservoirs (Jin, 2001). The fundamental research about the ATE has been made widely recently, such as the ecotone soil function on the retention of nutrients and its capacity (Yin and Lan, 1995; Yin and Shao, 1999) and the removal mechanism of nutrients in many wetlands (Blackwell *et al.*, 1999; Robert and William, 2000; Robert *et al.*, 2003); now it is generally agreed that the potential pollutants such as nitrogen and phosphorus are restored or removed through a variety of processes, but particularly by plant uptake and bacterial processes in the soil such as denitrification. Plant uptake represents a temporary store and harvesting may be required for complete removal of nutrients from the system, while denitrification represents a direct loss of nitrogen. All of these processes depend on the particular environmental conditions, for example, nitrification is stimulated in the presence of the N_2 -fixing shrub (alder) and oxidized exchange flow, producing NO_3^- (Todd and

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Dudley, 2004); while denitrification occurs effectively in the anaerobic conditions with lower oxidation-reduction potential (Blackwell *et al.*, 1999). But the relationships between the distribution of nutrients and influential factors in the ATE are still unclear.

As an important drinking water source of Wuxi City and famous scenic spot of China, the deteriorating eutrophication of Wuli Bay, which lies in the northwestern corner of Taihu Lake, is turning into an outstanding environmental challenge. In the last two decades, ten billion RMB Yuan (approximately one billion dollars) were spent in the restoration of the lake environment in China. This research is a part of this special project "Water Pollution Control and the Ecological Restoration Technique of the Taihu Lake"; the goals of this research were to investigate the spatial and temporal distribution of the nutritive element in the ATE, Natural reeds community wetland at Wulihu Lake was selected as a study case to estimate the correlativity between the distributions of the nutrients and environmental factors. That will be the basic data for the design of ecological restoration and reconstruction of the ATE for Wulihu Lake. This article focus on the vertical and temporal distribution of the nitrogen and phosphorus, and the horizontal distribution with their affecting factors will be summarized in another paper.

1 Methods

1.1 Study site description

Research was conducted on the natural wetland in the Bogong Island of the west Wulihu Lake Bay, located on the west-north of Taihu Lake in China (approximately 120°15.19'N latitude and 31°30.78'E longitude; as shown in Fig.1). It belongs to the subtropical area with mild climate. The mean annual temperature is 15.3°C, mean annual precipitation is 1112.3 mm, and annual evaporation is 922.4 mm (Huang, 2001). Water level of the Wulihu Lake varies between 3.00–3.50 m altitude, with the mean annual value at 3.17 m height (Jin, 2001). Almost the entire 4 hm² site with a strip shape has a typical structure of the aquatic terrestrial ecotone (Yin, 1995). Its gradient is about 3%. The dominant plant is reed community (*Phragmites communis Trin.*), intermixed with *Ludwigia prostrata Roxb* and *Zizania caduuciflora*.

1.2 Water sampling and analysis

The sampling transects were chosen near the middle of the reed community, the distance between slope and the lake water is approximately 20.0 m, five spots along the transects were installed at 5.0 m intervals. Piezometers which were constructed of 75 mm I.D. PVC capped at the bottom, slotted and screened in the bottom 10 cm to facilitate water collection, were installed in every spot with different depth (20 cm, 40 cm, 60 cm and 80 cm) with same height 30 cm above ground. All the liquids in the collecting pipe was pumped one day before sampling, and the sampled percolating water was collected by portable vacuum bump (method similar as Todd and Dudley, 2004).

The samples were collected quarterly, and the first time began in February 2004.

Water samples were collected in pre-acid washed polyethylene bottles, stored on ice, and taken to the laboratory for processing. After filtered through pre-rinsed 25 mm 0.45 µm Whatman GF/F glass fiber filters. Total nitrogen (TN), NO₃⁻-N, NO₂⁻-N, NH₄⁺-N and total phosphorus (TP) analyzed by San⁺⁺ Automated Wet Chemistry Analyzer (Skalar, The Netherlands). Dissolved organic nitrogen (DON) got by difference value of TN and the sum of NO₃⁻-N, NO₂⁻-N, NH₄⁺-N.

Soil samples were also collected in the corresponding period with a soil core sampler (Eijkelpamp, The Netherlands), which keeps soil sample from being pressed. Within sample stand, soil were sampled to the depth of 100 cm, stored in sealed polyethylene bags, and transported in a cooler on iced back to laboratory, then were cut 5 parts respectively on 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm. Soil TOC was measured by Multi N/C analyzer (Analytik Jena AG, Germany), pH was measured by portable pH meter (Sensor, Hach, USA); oxidation reduction potential measured by ORP meter (S500CD-ORP, Sensorex, USA); total count of soil bacteria colonies (TCBC) analyzed by Plate count method (Rolf and Lars, 1987); nitrobacteria and denitrobacteria analyzed by MPN method (ISSCAS, 1985); Near sampling spot, quadrat (50 cm × 50 cm) was selected stochastically for plant roots sampling. In each quadrat, plant roots were rinsed with water through nylon net from soil according to the corresponding depth of 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm and 80–100 cm, and then the fresh weight and dry weight (drying 24 h in 80°C) were calculated respectively.

2 Results and discussion

2.1 Distribution of the reed roots and sectional characteristics of the soil

Reed is perennial plant, it has both terrestrial stems and subterraneous stems, and the adventitious roots spread densely on subterraneous stem nodes. The hollow butt of the reed is the multi-medium interface between the soil

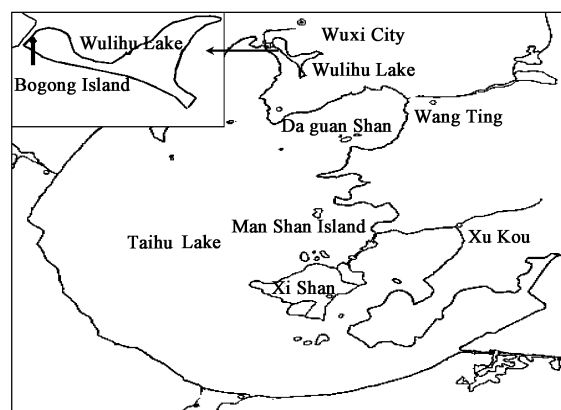


Fig. 1 Geographical location of the sampling site in Wuxi City, East China.

and the plant, which composes of the water, air, soil, micrograms and the root system of the plant. Although the diameter of the hollow butt is unapparent, the largish specific surface area makes the hollow butt play the more important function to the matter flows here in the biogeochemical cycle through this special interface (Wang and Yin, 2000). From the five soil section, it can be found that most hollow butt with round channel shapes distribute laterally, most of them spread densely between 20 cm and 60 cm, and there are little spread over the 1 m depth more, which is different with that of the larger wetland (Wang and Wang, 2001).

The micrograms and the other basic characteristics in the soil section were also measured. Fig.2a indicates that the significant declines of TCBC has occurred in the soil with depth enhanced, and the acute decrease occurred from the topsoil to 40 cm, under the 40 cm, the decrease becomes gentle. Analyzed by the season, it can be found that the seasonal variation is obvious in 20 cm than in deeper soil, TCBC gets its peak value in the summer, which is more significant than those of other seasons, the minimum is in the winter; and in spring and autumn,

TCBC are almost the same. While in 20–80 cm, the figure indicates that the variation of TCBC is not so acutely in the whole year.

For the nitrobacteria and the denitrobacteria, the general trend is the same as that of bacteria. They have their maxima in the topsoil, and decrease in the deeper soil. But in the autumn, winter and spring, the number of denitrobacteria under 60 cm depth increase a little than above depth. Fig.2b, 2c show that the seasonal variation is significant in 0–40 cm depth, their peak value occur in the summer, the valley value occur in spring for nitrobacteria and in winter or autumn for denitrobacteria.

The oxidation-reduction potential (ORP) may show the comprehensive conditions of oxidizing or reducing in the soil. Higher ORP indicates highly oxidizing conditions, while low ORP indicates reducing conditions. The Fig.2e indicates the general situation of the ORP in different depth soil in the autumn. With the depth enhances, the ORP decreases acutely with the oxygen content of the soil decreases accordingly, the result shows the 40 cm depth may be the ridge line. The soil under 40 cm depth presents reducibility, which is the better condition for the

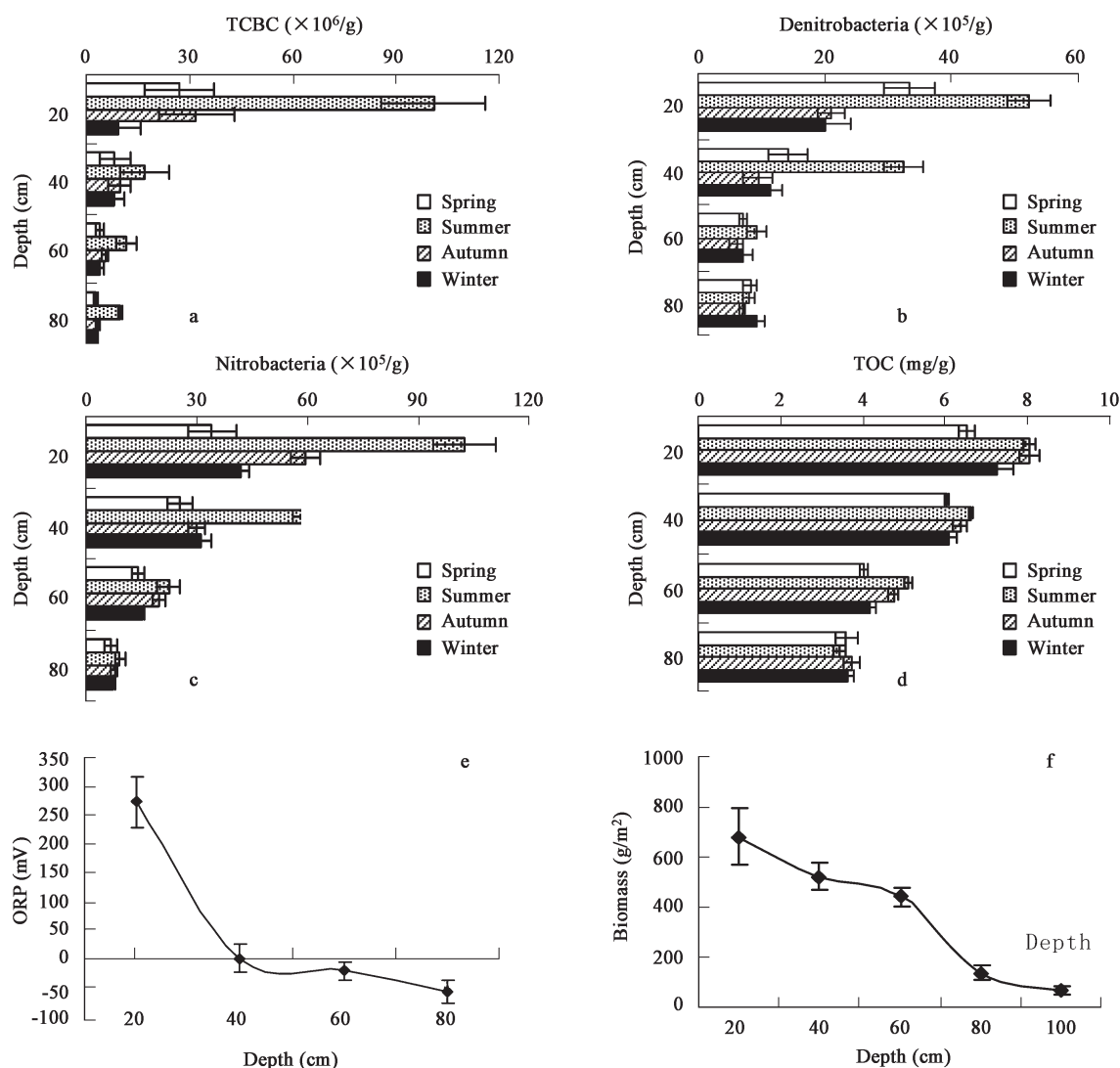


Fig. 2 Section soil characteristics in aquatic-terrestrial ecotone (ATE) of Wulihu Lake ($n=5$). TCBC: total count of soil bacteria colonies; ORP: oxidation-reduction potential.

denitrification.

With regard to TOC, Peng and Zhang (2005) thought that TOC has a close relationship with the soil micrograms, which biomass can be demonstrated by the change of TOC in the soil. But Fig.2d shows the general seasonal variation trend of TOC is not as distinct as that of the micrograms, which value in the summer is a litter higher than that in other seasons; but in the vertical variation, the distribution trend is the same as that of the micrograms, which decrease with depth.

2.2 Vertical distribution of the nitrogen and phosphorus in the soil solution

Both the plant roots and the rhizospheric microorganism can absorb and transform speciation of nutrient such as N, P, and so on. For example, clostridia can reduce nitrate to nitrite and ammonia, then synthesize it into amino acid and other nitrogenous substance. Poly-phosphobacteria can synthesize ATP (adenosine triphosphate) by transporting external phosphorus actively under aerobic environment.

Fig.3 indicates that the concentrations of the TN, TP, and NO_3^- -N in the topsoil percolates are high. They decrease with depth and reach their minima in 60 cm. But in

80 cm, they ascend in a small degree; and over 80 cm, the concentrations retain relatively stable. However, the concentration of NH_4^+ -N is exceptional, which increases with depth, it is the lowest in the 20 cm, and increases under deeper layer (Fig.3c), and the trend is distinct in summer, when bacterial counts are very high (Figs.2a and 2b), that may be explained by the ammonification of DON, or non-assimilatory reduction of NO_3^- -N, especially in the summer and early autumn (Hill, 1996). The looser topsoil is a better aerobic environment with higher ORP. The denitrification is restrained while the nitrification get strengthened, then results in the accumulation of NO_3^- -N; the reverse action takes place in the anaerobic area in deeper soil with lower oxygen partial pressure and lower ORP, where the denitrification is intensified, results in the decrease of concentration of NO_3^- -N and TN, and the increase of concentration of NH_4^+ -N (Robert and Hassan, 2003).

On the other hand, the absorption and translation of the plants also influence the vertical distribution of the nitrogen in the soil, and the NO_3^- -N is the main nitrogen form absorbed by the plants (Dai, 2002). The root biomass declines dramatically from 60–100 cm depth, where the

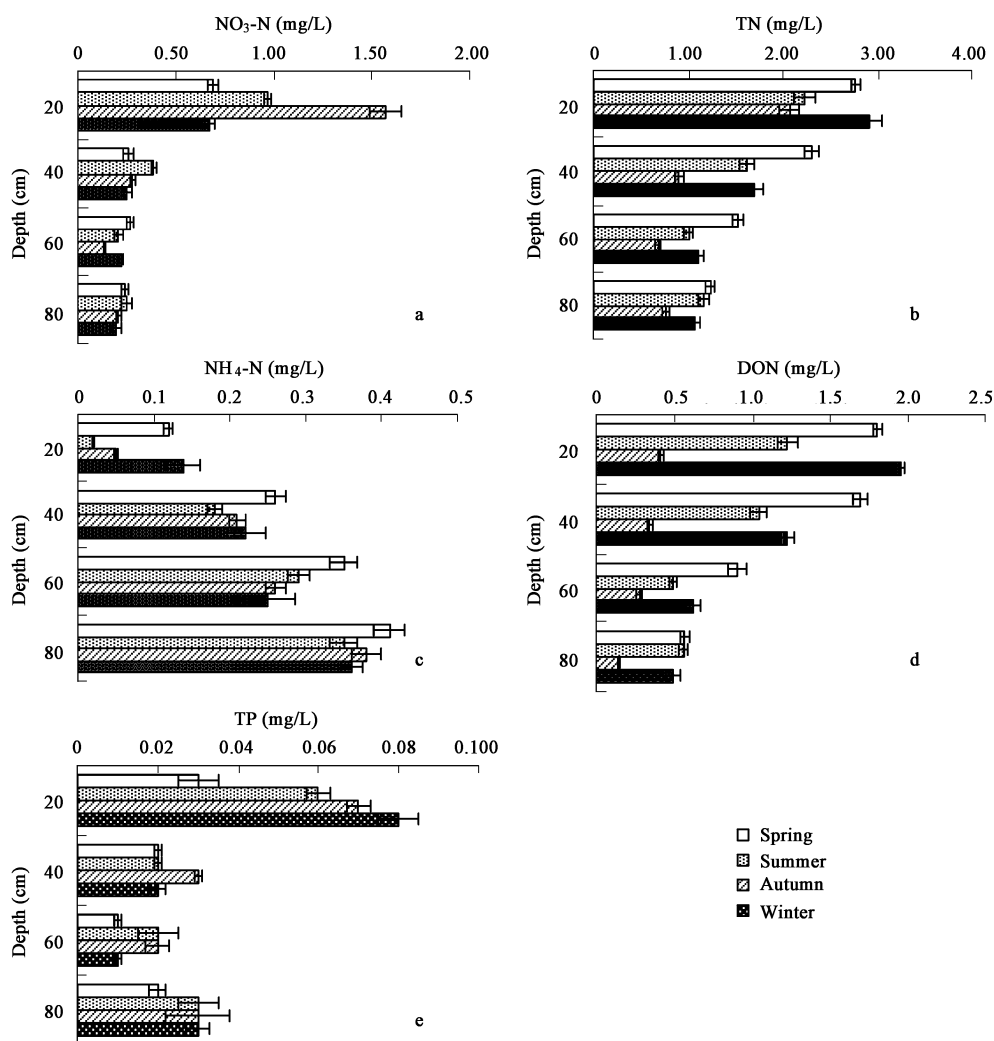


Fig. 3 Vertical distribution of nitrogen and phosphorus in soil solution of ATE in Wulihu Lake (n=5).

nitrogen absorbed by the plants is not so much as the up layers. So the concentration of NO_3^- -N and TN in the soil of 80–100 cm is correspondingly higher than that in 60 cm depth, although the environment of 80 cm soil is suitable for denitrification and the denitrobacteria colonies is increased in a certain extent. In spring and winter, since the metabolism of plants is weak, the role of absorption and transportation of nutritive element is not dominant as that of microbial denitrification, and therefore the concentration of NO_3^- -N and TN in 80 cm is lower than that in 60 cm.

In the vertical distribution, the concentration of NO_3^- -N is not enhanced with the number of the denitrobacteria counts declines, but decreases with the ORP reduces. This may suggest that it is not the number of the denitrobacteria colonies that determines the denitrification, but the environmental condition, which is the key factors influencing the physiological activity of the denitrobacteria (Ding and Cai, 2001). Yin and Shen (2003) thought denitrobacteria comprise of the obligate anaerobe, facultative anaerobe, aerobic bacteria, etc., in the suitable environmental conditions, the proportion of the nitrate nitrogen reduced by the denitrobacteria is lower when the carbon is the limited factor (Buresh and Patrick, 1978; Fazzolari *et al.*, 1998), the maximum is just 12.5% (Yin and Chen, 2000). In the 60–80 cm soil sample, the maximum concentration of TOC is 9.42 mg/g, although the denitrobacteria gets increased, the total ability of denitrification is not so strong.

For the DON, the general trend shows that the concentration in topsoil is higher than that in subsoil in the whole year, Fig.3d shows the main distribution area of DON is rooting zone, which may be explained by the source of DON. It was reported that 80% of the DON is created in the litter fall layer (Huang and Schoenau, 1998). The biomass and the metabolite of the soil microorganism are also thought to be a potential source (Williams and Edwards, 1993). For the moment, the new litter fall and surface runoff are inclined to be thought as the main source, and the biomass of the soil microorganism and the root secretion is the other important source of DON (Uselman *et al.*, 2000; Liu and Zhou, 2005). This also accounts for the sharp seasonal fluctuation in the soil percolate. In winter the new litter fall contribute the main DON source to the soil, especially in the topsoil; in summer and autumn, the activity of ammonifying bacteria get strengthen, as the main substrate, DON can be decomposed to ammonia by the ammonification. The concentration of DON is lower in the summer and autumn than that in the spring and winter. Peng and Zhang (2005) also reported that the vertical and temporal distribution of the ammonifying bacteria is also similar to that of DON.

2.3 Vertical variance of N, P in the soil solution

To analyze the vertical variation of nutritive elements distribution in different depths quantificationally, coefficient of variation (C_V) expressed as the ration of standard deviation (S) and mean value (\bar{x}) was introduced, which can eliminate the impacts from the different units or mean value to the special data variations (Ming and Geng, 2001).

Table 1 Vertical variance of N and P in soil percolates of ATE in Wuli Lake

Number	Coefficient of variation (C_V) (%)				
	TN	NO_3^- -N	NH_4^+ -N	DON	TP
0	56.63	100.23	55.44	41.14	61.21
1–2	52.26	83.32	92.18	23.60	55.94
2–3	24.21	45.21	17.83	17.32	26.33
3–4	9.34	28.17	23.69	45.13	26.35

0, 1–2, 2–3, 3–4 are total C_V , C_V of 20–40 cm, 40–60 cm, 60–80 cm depth.

C_V can be calculated by:

$$C_V = \frac{S}{\bar{x}} \times 100\% \quad (1)$$

In order to estimate the overall vertical variance of nutrients, the yearly mean distribution values of the nutrients were used here. Table 1 shows that the vertical distribution variance of the N and P is significant, C_V is above 30%, the variation of NO_3^- -N is the greatest one, which is up to 100.23%, that of DON is the lowest, with C_V 41.14%.

In point of the C_V values, the concentration of N, P varies quite a lot in different depths, especially in the depth of 20 cm and 40 cm (DON is exceptional), of which the C_V of NO_3^- -N and NH_4^+ -N differ greatly, that may be affected by the environment factors such as partial oxygen pressure and redox potential (Todd and Dudley, 2004). For the TP, being absorbed from soil and plants, together with the microbial degradation will normally result in the decrease of TP in percolate, the distribution of microorganism and environmental factors, such as TOC, C/N and ORP, are the dominant factors to the concentration of TP (Robert and William, 2000), C_V between 20–40 cm is maximal. The vertical variation of DON concentration is distinct in soils at 60–80 cm depth. It may be owing to the biological effectiveness of DON. Concentration of DON is closely bound up with the mass and activities of livings, especially with root biomass (Chen and Twilley, 1999).

2.4 Relationships between the N, P in the soil percolates and the ORP, TOC, root biomass and the micrograms in the soil

Table 2 indicates the relationship between the concentration of the nitrogen and phosphorous with ORP, root biomass and microorganism in the soil. Details are as follows.

(1) Concentrations of TN, TP are correlated with counts of nitrobacteria and denitrobacteria positively. TP is one of the main limiting factors to the percent mineralization of nitrogen in the soil, and higher concentration of TP in the soil percolate makes the mineralization of nitrogen increased which can provide enough nitrogen sources for the nitrobacteria and denitrobacteria (Li *et al.*, 2000; Jin *et al.*, 2004).

(2) The concentration of TN in the soil percolates correlates with the soil TOC positively ($r=0.817$, $P<0.05$). The higher TOC in the topsoil is favorable to the plants and microbial, which is also positively correlated with root biomass, nitrobacteria and denitrobacteria significantly. The activities of plant and microbial can bring DON

Table 2 Matrix of correlation coefficients of N, P, ORP, root system biomass and microorganism of soil percolates.

	TN	NO ₃ ⁻ -N	NH ₄ ⁺ -N	TP	TOC	ORP	Biomass	Nitrobacteria	Denitrobacteria
TN	1.000								
NO ₃ ⁻ -N	0.975**	1.000							
NH ₄ ⁺ -N	-0.845*	-0.720	1.000						
TP	0.775	0.624	-0.890*	1.000					
TOC	0.817*	0.673	-0.885*	0.768	1.000				
ORP	0.965**	0.985**	-0.743	0.596	0.998**	1.000			
Biomass	0.714	0.559	-0.908*	0.626	0.931**	0.951**	1.000		
Nitrobacteria	0.952**	0.864*	-0.974**	0.912*	0.946**	0.937**	0.889*	1.000	
Denitrobacteria	0.997**	0.957**	-0.925**	0.986**	0.857*	0.835*	0.745	0.967**	1.000

** Significant at $P < 0.01$; * significant at $P < 0.05$.

(Uselman *et al.*, 2000), then TN increase accordingly.

(3) The concentration of NO₃⁻-N is also correlated positively with the concentration of TN ($r=0.975$, $P < 0.01$), ORP ($r=0.985$, $P < 0.01$), it also correlated positively with the counts of denitrobacteria ($r=0.957$, $P < 0.01$) and nitrobacteria ($r=0.864$, $P < 0.05$).

(4) Concentration of NH₄⁺-N is correlated negatively with the counts of nitrobacteria ($r=-0.974$, $P < 0.01$) and denitrobacteria ($r=-0.925$, $P < 0.01$), also with root biomass ($r=-0.908$, $P < 0.05$). Ammonification and restrained nitrification result in the accumulation of NH₄⁺-N in anaerobic subsoil with fewer counts of nitrobacteria and denitrobacteria (Peng and Zhang, 2005).

Nitrogen in the soil percolate in the ATE of Wulihu Lake is correlated significantly with the concentration of TP, TOC, ORP and the count of nitrobacteria colonies. Its vertical distribution is affected indirectly by environmental factors, such as alternate period of wetting and drying, pH and so on. The essential factors are the absorption of plant's root and microbiological activities. Williams and Buttler (1999) reported that, with high concentration of TP and low water line, the plant absorbs less nitrogen. At the same time, concentration of TP also impact on the capacity of plants to produce and release soluble DON. Schoenar and Bettany (1987) also thought that, alternation of wetting and drying in soil can bring on available carbon, leading to stronger denitrification in subsoil.

3 Conclusions

In summer and autumn, the concentrations of TP, TN, NO₃⁻-N, DON in ATE soil percolate of Wulihu Lake decreases with depth, and reverses slightly at 60 cm layer. In winter and spring, the concentration of TN, NO₃⁻-N decreases similarly with the depth. The concentration of NH₄⁺-N increases with depth.

The concentration of nitrogen in the 20 cm soil varies a little in different seasons; the concentration of TN and TP are the highest in winter, while the lowest concentration of TN is in autumn and TP in spring. As for the concentration of NO₃⁻-N, it is the highest in autumn, and the lowest in winter. By contraries, the maximum concentration of organic nitrogen is in winter, while its minimum is in autumn. Concentration of NH₄⁺-N reaches its maximum in winter and minimum in summer. The seasonal variation of the concentration of nitrogen and phosphorus is insignificant in other depth, especially in the soil of 60 and 80 cm.

The vertical distribution of the nutritive elements in the soil percolate of ATE in Wulihu Lake is correlated with TOC, ORP, seasons, root biomass and nitrobacteria in the soil.

The soil depth of 0–60 cm is active rhizoplane, with strong capability to remove nitrogen and phosphorus in the ATE of Wulihu Lake, which is almost uninfluenced by season. Taking full advantage of this zone's ecological functions will be of important significance to the ecological restoration and reconstruction of ATE.

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