Variation Characteristics of Soil Microbial Community Structure along a Water Table Gradient in Poyang Lake Wetland Postprint

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Date: 2018-06-09T00:00:00+00:00

Abstract

To reveal the effects of groundwater level gradient on wetland soil microbial communities, a 200m×300m large plot was established in the Baisha Lake beach wetland, a typical dish-shaped lake in Poyang Lake. Four transects were delineated along the groundwater level gradient (GT-A, GT-B, GT-C, and GT-D in order from lakeshore to lake center), and soil samples were collected from different gradient zones. Phospholipid fatty acid analysis was used to analyze the differentiation characteristics of soil microbial community structure. The results showed that with the rise of groundwater level, soil pH and sand content increased, while organic carbon, bulk density, clay and silt contents decreased. Compared with the gradient with the lowest groundwater level (GT-A), when the groundwater level fluctuated around the surface (GT-D), soil microbial biomass carbon, nitrogen and their allocation ratios increased by 2.82, 4.30, 5.77 and 7.15 times, respectively; soil total microbial biomass, bacterial biomass, actinomycete biomass, Gram-positive bacterial biomass and Gram-negative bacterial biomass increased by 106.8%, 117.2%, 74.9%, 107.9% and 207.2%, respectively. The increase in beach groundwater level gradient increased the environmental stress on soil microbial communities, thereby reducing the diversity of their community structure. Soil microbial community structure composition was significantly correlated with soil pH, water content, sand content, and carbon-to-nitrogen ratio, while soil microbial quotient was mainly affected by pH and soil texture. These results indicate that the soil microenvironmental changes induced by groundwater level gradient had profound effects on microbial biomass, soil organic carbon turnover, and community structure.

Full Text

Preamble

Acta Ecologica Sinica
DOI: 10.5846/stxb201705220946
Received: 2017-05-22; Online Publication: 2018-03-02

Variation in the Distribution of Soil Microbial Community Structure Along Groundwater Level Gradients in the Poyang Lake Wetland

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Funding: National Natural Science Foundation Project (41471088); Local Cooperation Project

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Abstract

To reveal the response of soil microbial community structure to groundwater level changes, a 200m × 300m experimental site was established in the beach of Baisha Lake, a typical shallow lake of the Poyang Lake Wetlands. The site included four groundwater level gradients: GT-A, GT-B, GT-C, and GT-D (moving from shore to lake center). Phospholipid fatty acid (PLFA) analysis was applied to determine microbial community structure differentiation characteristics.

Results showed that as groundwater level increased from GT-A to GT-D, soil pH and sand content increased, while soil organic carbon (SOC), bulk density, clay and silt contents decreased. Compared to the lowest groundwater gradient (GT-A), GT-D exhibited significantly higher microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and their allocation ratios, which increased by 2.82, 4.30, 5.77, and 7.15 times, respectively. The abundances of total PLFAs, bacteria, actinomycetes, Gram-positive bacteria, and Gram-negative bacteria increased by 106.8%, 117.2%, 74.9%, 107.9%, and 207.2%, respectively.

The rise in groundwater level enhanced environmental stress on the microbial community, reducing community structure diversity. Soil microbial community composition showed significant correlations with sand content and C:N ratio, while microbial quotient was mainly influenced by pH and soil texture. These results indicate that groundwater gradient-induced changes in soil microenvironment profoundly affect microbial biomass, soil organic carbon turnover, and community structure. The findings provide scientific basis for understanding the maintenance mechanisms of ecosystem structure stability and biogeochemical cycling processes in Poyang Lake wetlands during dry seasons.

Keywords: Poyang Lake; groundwater level gradients; phospholipid fatty acid (PLFA); soil microbial community composition

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1. Study Area Overview

Poyang Lake, located in northern Jiangxi Province, is China's largest freshwater lake. The study area is situated at 115°49 -116°46 E, 28°24 -29°46 N, with a maximum east-west span of 70 km and north-south length of 170 km. The region experiences a typical subtropical monsoon climate with hot, rainy summers and cold, dry winters. Annual precipitation ranges from 1387–1795 mm, with approximately 74.4% concentrated in the warmest months. Annual average temperature is 17.6°C, with average evaporation of 1082.6 mm.

The experimental site was located in Baisha Lake within the Nanji Wetland National Nature Reserve, situated at the front edge of the Ganjiang River Delta. Baisha Lake is a typical dish-shaped lake influenced by seasonal hydrological variations of Poyang Lake. During the dry season (October–March), the lake beach gradually emerges, forming extensive grassland wetlands. The dominant vegetation is *Carex cinerascens*, accompanied by *Triarrhena lutarioriparia* and *Phragmites australis*, with *Carex cinerascens* covering 85–100% of the area.

Four groundwater level gradient zones (GT-A, GT-B, GT-C, GT-D) were established from lake shore to center, each 200m × 300m in size, separated by approximately 100m. Within each gradient zone, three sampling points were set according to microtopographic differences, with 50–80m intervals between points. At each point, thin PVC pipes (2cm diameter) were inserted approximately 70cm deep to monitor groundwater levels.

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2. Sample Collection and Analysis

Soil samples were collected from 0–20cm depth using five-point mixed sampling at each sampling point. Approximately 500g of soil was placed in polyethylene bags, transported in a cooler, and returned to the laboratory. Each sample was divided into two portions: one air-dried for physicochemical analysis, and one stored at -20°C for PLFA analysis.

Soil physicochemical properties were measured as follows: moisture content by oven-drying method; particle composition by Malvern laser particle size analyzer; bulk density (BD) by ring knife method; pH at a 2.5:1 water-soil ratio; soil organic carbon (SOC) by potassium dichromate external heating method; total nitrogen (TN) by semi-micro Kjeldahl method; total phosphorus (TP) by molybdenum-antimony colorimetry. Microbial biomass carbon (MBC) and nitrogen (MBN) were determined by chloroform fumigation-K SO extraction.

[Figure 1: see original paper] Location of study area and sample plot setup

PLFA analysis followed the method of Frostegård et al., using methanol solution for methyl esterification. Nonadecanoic acid was used as internal standard, analyzed by GC-MS (TRACE GC Ultra ISQ). The column temperature program: 170°C for 2 min, increased to 280°C at 5°C/min, held for 5 min, then increased to 300°C at 40°C/min, held for 1.5 min. Characteristic fatty acids were used as biomarkers for different microbial groups: Gram-positive bacteria (i13:0, i14:0, i15:0, a15:0, i16:0, i17:0, a17:0, a16:0, i15:1), Gram-negative bacteria (12:0, 14:1 5c, 14:0, 16:1 6c, 15:0, cy17:0, 16:1 2OH, i17:0 3OH, cy19:0 8c, i15:0 3OH, 16:1 9c), actinomycetes (10Me17:0, 10Me18:0), and fungi (16:1 5c, 18:1 9c, 18:3 6c).

Basic information of sampling sites

3. Data Processing

Statistical analysis was performed using SPSS 20.0. One-way ANOVA was used to analyze changes in soil physicochemical properties and microbial community structure across groundwater gradients, with Dunnett' s T3 for multiple comparisons. Pearson correlation analysis examined relationships between microbial community structure and soil properties. Principal component analysis (PCA) and redundancy analysis (RDA) were conducted using CANOCO 5.0. Microbial diversity indices (Shannon-Wiener, Pielou evenness, Simpson dominance) were calculated based on fatty acid content and types.

Diversity index formulas: - Shannon-Wiener index: $H = -\Sigma(Ni/N)\ln(Ni/N)$ - Pielou evenness index: $J = H/\ln S$ - Simpson dominance index: $D = \Sigma(Ni/N)^2$

Where Ni is the amount of fatty acid type i, N is total fatty acid amount, and S is total fatty acid types.

4. Results and Analysis

4.1 Soil Properties Along Groundwater Gradients

Groundwater level significantly affected soil physicochemical properties ($p < 0.05$). As groundwater level increased, soil moisture increased from 30.80% (GT-A) to 52.56% (GT-D), a 70.7% increase. Soil pH increased from 4.62 to 5.05. Clay and silt contents decreased by 53.5% and 34.6% respectively, while sand content increased by 52.6% ($p < 0.05$). SOC, TN, and TP decreased significantly with increasing groundwater level. Soil C:N ratio decreased sequentially: GT-A (10.78) > GT-B (10.20) > GT-C (9.07) > GT-D (7.63).

Soil physicochemical properties along groundwater level gradients

4.2 Effects of Groundwater Level on Microbial Biomass and Allocation Ratios

Soil microbial biomass carbon and nitrogen were highest in GT-D, significantly greater than other gradients ($p < 0.05$). MBC and MBN in GT-D increased by 2.82 and 4.30 times compared to GT-A. Microbial quotient (MBC/SOC) increased with groundwater level, rising by 5.77 times in GT-D. MBN/TN ratio increased by 7.15 times in GT-D.

[Figure 2: see original paper] Soil microbial MBC, MBN and their allocation ratios across groundwater gradients

4.3 Effects of Groundwater Level on Microbial Community Structure

Significant differences in microbial groups were observed across groundwater gradients ($p < 0.05$). GT-D showed the highest total PLFAs, bacteria, actinomycetes, Gram-positive and Gram-negative bacteria, increasing by 106.8%, 117.2%, 74.9%, 107.9%, and 207.2% respectively compared to GT-A. The relative abundance of fungi decreased from 12.9% (GT-A) to 8.0% (GT-D), while bacteria increased from 79.5% to 83.5%.

Principal component analysis revealed clear spatial separation of sampling points along the first axis (PC1), which explained 76.7% of variance. GT-A, GT-B, and GT-C separated from GT-D along PC1. Key PLFAs contributing to ordination included i13:0, i15:0, i17:0 3OH, i15:0 3OH, a16:0 for PC1, and 18:3 6c, 10Me17:0 for PC2.

[Figure 3: see original paper] Soil total PLFAs, bacteria, fungi, actinomycetes, Gram-positive and Gram-negative bacteria across groundwater gradients

[Figure 4: see original paper] Principal component analysis of PLFA profiles

Environmental stress indices showed that fungal:bacterial ratio (F/B) decreased from 0.26 (GT-A) to 0.11 (GT-D). The ratio of monounsaturated to branched fatty acids (M/B) decreased from 0.26 to 0.11, while the ratio of anteiso to iso branched fatty acids (SA/SI) increased from 0.47 to 0.79.

Environmental response indices of soil microbial communities across groundwater gradients

4.4 Microbial Community Diversity Analysis

Diversity indices showed that Shannon-Wiener and Pielou indices were lowest in GT-D and highest in GT-B, while Simpson dominance showed the opposite pattern ($p < 0.05$), indicating that increasing groundwater level reduced microbial diversity but promoted dominant populations.

[Figure 5: see original paper] Shannon-Wiener diversity, Pielou evenness, and Simpson dominance indices across groundwater gradients

4.5 Relationships Between Microbial Community Structure and Soil Properties

Correlation analysis revealed that soil pH, moisture, sand content, and C:N ratio significantly correlated with PLFA signatures. MBC, MBN, and most microbial groups showed significant positive correlations with moisture and sand content, but negative correlations with bulk density, clay, and silt contents ($p < 0.01$). Fungal biomass correlated negatively with pH ($p < 0.05$).

Correlation analysis between microbial community structure and soil environmental factors

RDA showed that the first two ordination axes explained 94.8% of variance, with soil moisture, bulk density, and C:N as key factors. Soil moisture correlated positively with Gram-negative bacteria (i15:0 3OH, i17:0 3OH, cy17:0) and negatively with Gram-positive bacteria (i13:0, i14:0, a16:0). Sand content correlated positively with fungal PLFAs (18:3 6c, 18:1 9c).

[Figure 6: see original paper] Relationship between microbial quotient and soil environmental factors

[Figure 7: see original paper] RDA ordination of microbial communities and environmental factors

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5. Discussion

Hydrological conditions are the driving factor in wetland formation and development. When wetland soils are flooded, oxygen reduction decreases aerobic microbial activity, leading to organic matter accumulation. However, alternating wet-dry conditions stimulate microbial metabolism and organic matter decomposition. This study found significant differences in soil properties across groundwater gradients, with water fluctuation causing sediment sorting that removes fine particles and concentrates coarse materials.

The highest microbial biomass carbon and nitrogen occurred at high groundwater levels, likely due to enhanced microbial activity from increased moisture content and weakly acidic conditions preferred by microbes. However, high groundwater levels also increased environmental stress, reducing diversity while favoring stress-tolerant bacteria and actinomycetes. The significant increase in Gram-negative bacteria (207.2%) suggests that anaerobic microorganisms became more abundant with increasing groundwater level.

The F/B ratio decreased from 0.26 to 0.11 along the gradient, indicating slower carbon accumulation efficiency at high groundwater levels, consistent with lower

SOC content. The SA/SI ratio increased significantly, reflecting greater environmental pressure and enhanced organic matter decomposition. Microbial quotient was more strongly correlated with soil texture than moisture, suggesting that groundwater effects on carbon turnover operate primarily through changes in soil structure rather than direct waterlogging effects.

Soil moisture and texture were the primary factors controlling microbial community structure. Bacteria and actinomycetes thrive in micro-alkaline or weakly acidic conditions, while fungi prefer acidic environments. The negative correlation between bacterial abundance and bulk density suggests that increased pore space at high groundwater levels benefits bacterial survival. The C:N ratio, reflecting carbon versus nitrogen limitation, also significantly influenced microbial community composition.

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6. Conclusion

1. Groundwater level, as an integrated indicator of microtopography, elevation, and hydrological regime, significantly altered soil chemical and physical properties. From the lowest to highest groundwater gradient, clay and silt contents decreased by 53.5% and 34.6%, while sand content increased by 52.6%.
2. Groundwater-driven changes in soil environment significantly affected microbial biomass carbon/nitrogen and carbon-nitrogen turnover. At GT-D where groundwater fluctuated around the surface, MBC and MBN increased by 2.82 and 4.30 times, microbial quotient increased by 5.77 times, and MBN/TN ratio increased by 7.15 times compared to GT-A.
3. Short-term groundwater gradient changes during the dry season altered microbial community structure. Total PLFAs, bacterial, actinomycete, Gram-positive and Gram-negative biomasses increased by 106.8%, 117.2%, 74.9%, 107.9%, and 207.2% respectively. Fungal proportion decreased while anaerobic microbial proportion increased.
4. Increasing groundwater gradient enhanced environmental stress on microbial communities, reducing diversity (Shannon-Wiener and Pielou indices: GT-A > GT-B > GT-C > GT-D) while increasing dominance. GT-D showed the lowest F/B ratio (0.11) and highest SA/SI ratio (0.79).
5. Soil moisture, sand content, and C:N ratio were the key factors controlling microbial community structure during groundwater level changes, while pH and soil texture primarily influenced microbial quotient and carbon turnover.

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