The spatial pattern of periphytic algae communities and its corresponding mechanism to environmental variables in the Weihe River Basin, China
Yixin Liu, Jiaxu Fu, Dandong Cheng, Qidong Lin, Ping Su, Xinxin Wang and Haotian Sun

ABSTRACT

Periphytic algae is a useful indicator of aquatic ecological conditions. We investigated the periphytic algae on natural substrate and the environmental variables at 44 sites on three river systems in the Weihe River Basin (WRB). A total of 84 species are identified, representing 37 genera. The most common genera were Navicula, Oscillatoria, Nitzschia, Scenedesmus, Cymbell, and Fragilaria. One-way analysis of variance (ANOVA) indicated significant differences among the three river systems in environmental variables ($p < 0.05$). Non-metric multidimensional scaling (NMDS) analyses also showed differences in periphytic algae communities in the three river systems ($p < 0.05$) and identified different dominant species in each river system. Canonical correspondence analysis (CCA) and Monte Carlo permutation tests revealed that nutrient concentration, WT, and altitude were the most important variables affecting the structure and distribution of periphytic algae communities. Chemical variables were the most accounted for environmental variables (12.5%), while physical variable and geographical factors (5.8% in total) play a relevant minor role. Our results demonstrate that Navicula pupula, Navicula radiosq, Nitzschia palea, and Nitzschia denticula, exhibiting wide ecological amplitude, are tolerant of high concentrations of nutrient pollution. Variation of periphytic algae communities in WRB is due to the combination of anthropogenic and natural factors including agricultural and domestic wastes water inputting, land use patterns, geology, climatic changes, and river hydrology.

Key words | CCA, environmental variables, nutrients, periphytic algae, Weihe River Basin

HIGHLIGHTS

- Structure and distribution of periphytic algae communities were investigated in the Weihe River Basin.
- The gradient of organic pollution detected in environmental variables was the main gradient, and the periphytic algae responded to this gradient.
- The types of substrates in river impact periphytic algae abundance, causing higher periphytic algae abundance in cobbles substrate.
- The variation of periphytic algae communities is attributed to the combination of anthropogenic factors and natural factors.
- The results support the periphytic algae as ecological indicators in the Weihe River Basin.

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INTRODUCTION

Periphytic algae are found in bodies of water ranging from small ponds to the global ocean. They are a major contributor to primary productivity in the river, playing a vital role in aquatic ecosystems (Kolmakov et al. 2008; Pandey et al. 2017). Periphytic algae have been widely associated with different geographical regions with specific environmental conditions (Soininen 2002; Kovács et al. 2006; Chen et al. 2016a). Composition and relative abundance of the periphytic algae community vary with their ecological affinity and preferences (Potapova & Charles 2003; Tornés et al. 2007). Their structure and distribution are reflected in spatially and temporally based geomorphological conditions, climate, hydrology, and water physicochemical properties (Pan et al. 2004; Bere et al. 2016). Based on observations in the natural river and experiments, studies have shown that the algae will not be nutrient-limited when the nutrients concentration is $P > 30 \mu g/L$ and $N > 1 \text{mg/L}$ in the river ecosystem (Westlake 1981). Water temperature affects algal photosynthetic metabolism through its control of enzyme reaction rates (Stevenson et al. 1996). Periphytic algae abundance reaches a peak at a certain level with suitable bed light levels (Yang & Flower 2012). Hydrodynamic conditions also influence periphytic algae biomass, and the suitable velocity and river depth are 0.9–1.1 m/s and 0.40–0.48 m, respectively (Wang et al. 2018a). Periphytic algae are effective environmental indicators due to their wide distribution range, numerous species, and sensitivity to environmental changes (Stevenson et al. 2008). They respond rapidly to changes in environmental variables, reflecting the overall ecological quality and the effects of different stressors (Bona et al. 2007; Vasiljević et al. 2017). Individual algae species often show a clear preference for specific substrates and habitats (Winter & Duthie 2000). Substantial differences exist in species composition and abundance of periphytic algae communities from the same sites but different substrates such as sand, rock surface, submerged, or emergent macrophytes (Fisher & Dunbar 2007; Bere & Tundisi 2011). Therefore, understanding the relationship between environmental factors and the distribution of periphytic algae communities is important for developing algae-based water quality indices.

With the reform and opening-up policy in the 1980s, China began a period of rapid urbanization. The proportion of the urban population increased from 17.9% in 1978 to 52.6% in 2012, while urban built-up areas increased by 78.5% (Bai et al. 2014). At the same time, rapid urbanization has brought a series of complex water environmental problems. It greatly affects the hydrological system by channel morphology, water quality, and aquatic biota (White & Greer 2006). The Weihe River Basin (WRB) is the main grain-producing area, and is an important industrial and commercial center in northwest China. The Weihe River is a major source of domestic water, industrial water, and irrigation in the central plain. There are 76 major cities with a total population of 22 million in the basin (Chang et al. 2015). Due to the increase in population, industry, and farmland area, the WRB also faces serious water environmental problems. Presently, most studies have focused on the water quality and quantity of the WRB (Jiake et al. 2011; Wei et al. 2012; Song et al. 2015). Research on the effects of urbanization on the aquatic biota in WRB has typically focused on fish communities and macroinvertebrates (Wu et al. 2014; Su et al. 2019), with few studies available on algae communities. Studies on periphytic algae communities and their relationship with environmental variables have scarcely been carried out in the WRB.

This study focuses on the abundance, species structure, and distribution of periphytic algae communities in the WRB. The specific objectives are to investigate the relationships between periphytic algae communities and environmental variables, to detect which ecological factors explain most of the variation. Our results may provide a valuable baseline for future water quality assessments in the WRB in China.

MATERIALS AND METHODS

Study area

The study was carried out in the WRB (Figure 1), which is located in the northwest of China. The WRB (east longitude 103°5′–110°40′, north latitude 33°40′–37°25′) has a drainage area of $1.35 \times 10^5 \text{km}^2$, with annual mean temperatures...
between 7.8 and 13.5 °C and the annual mean rainfall ranging from 558 to 750 mm which increases from north to south (Wang et al. 2018b). The climate in the WRB is characterized by the temperate continental monsoon. Therefore, precipitation and runoff exhibited strong inter-annual variations and similar intra-annual variations. The runoff from July to October is approximately 65% of the mean annual runoff (Chang et al. 2018). Also, most of the WRB is covered by highly erodible loess and soil erosion is serious because of sparse vegetation, uneven rainfall distribution, and high intensity of heavy rain (Song et al. 2018). There are three different water systems in the WRB, including the Weihe River System (WRS), the Jinghe River System (JRS), the Beiluo River System (BRS), and their tributaries, as well as other small independent streams (Figure 1).

Sampling and analysis

Periphyton samples were collected from 44 sites in the three water systems of WBR in June 2017, each of the water systems has a different number of sampling sites: 15 in WRS (W1–W15), 17 in JRS (J1–J17) and 12 in BRS (B1–B12) (Figure 1). For the cobble-type sedimentary rivers, within the range of 100 m upstream and downstream of the sampling point, nine stones were selected (surface area of the stones <200 cm²), and scraped with a toothbrush to a 7.07 cm² area (Kelly et al. 1998). For the silt-type sedimentary rivers, the surface layer of silt on the sampled stones were scraped with an area of 63.62 cm² using an inverted Petri dish along the riverbed (Carpenter & Waite 2000). The samples were preserved with 4% formaldehyde and 2% Lugol’s iodine solution. An aliquot of the periphytic algae suspension was cleaned by using hydrochloric acid and hydrogen peroxide. The acid-cleaned samples were mounted on microscope slides applying the high refraction mountant Naphrax. Species were identified and a minimum of 400 valves were counted per slide at 1,000× magnification using a microscope (Olympus BX51, Olympus, Tokyo, Japan). Algal cells identification was carried out according to the standard guides of Krammer & Lange-Bertalot.

Figure 1 | The locations of the sampling sites in the Weihe River Basin.
mutations) was used to test the difference in the community similarity (ANOSIM, Bray-Curtis distance measure, 999 permutations) to visualize the periphytic algae structure distribution. Both NMDS and ANOSIM analyses were performed using PRIMER version 5 (Clarke & Warwick 2001).

A total of 18 rivers geographical, hydrological, physical and chemical variables were considered for data analysis, including Altit, WT, width, depth, SD, velocity, flux, pH, DO, EC, TDS, NO$_3$-N, NH$_4$-N, K$^+$, Mg$^{2+}$, Cl$,^-$, TN and TP. All of the environmental variables, except pH, were transformed as log10 ($x + 1$) before analysis. One-way analysis of variance (ANOVA) was used to evaluate the significance of the differences among the WRS, the JRS and the BRS sites based on the physical and chemical variables of the transformed water, completed by IBM SPSS Statistics for Windows (25). Principal component analysis (PCA) was applied to explore the main environmental gradients among the sampling sites, using CANOCO 5.0 (Ter Braak & Smilauer 2012).

Multivariate analyses are mathematical tools that detect the relationship between periphytic algae and environmental variables, indicating the main variables and revealing the similarities among algae samples. For analysis of their relation, 28 species were retained with rare species ($< 1\%$) removed. The removal of the species with a relative abundance of less than 1% can minimize the influence of rare species in the analysis. Algae abundance data were transported by log10 ($x + 1$) to stabilize variances and give more weight to the larger species often found at low relative abundance in periphytic algae communities, which are important for defining assemblage (Tison et al. 2005). Detrended correspondence analysis (DCA) was conducted to detect the gradient length of the algae abundance data. Gradient lengths were then used to select the appropriate model (linear or unimodal model) for the constrained ordinations. In this study, the longest gradient of four ordination axes was 3.8, indicating that a linear or unimodal model could be applied to the ordination analysis (Ter Braak & Verdonschot 1995). Hence, the unimodal ordination technique of canonical correspondence analysis (CCA) was used to assess the relationships between environmental variables and periphytic algae communities from different sites. A Monte Carlo permutation test (999 permutations, $p \leq 0.05$) was used to reduce the environmental variables to those correlating significantly with the first two CCA axes. Both DCA and CCA were performed using CANOCO 5.0 (Ter Braak & Smilauer 2012).

Basic physical and chemical water parameters were measured directly at the sampling sites during sampling. The water temperature (WT), pH, dissolved oxygen (DO), electrical conductivity (EC), and total dissolved solids (TDS) were measured in situ using a portable water quality meter (HACH HQ40d). River velocity was acquired by using a portable flow meter (MGG/KL-DCB); river width data was obtained with the help of Trupulse 200; river depth was measured by using a terrain probe; Secchi depth (SD) was measured using a Secchi disc, except for some of the restored rivers that were transparent to the bottom; latitude longitude and altitude (Altit) information was obtained with a Global Positioning System (GPS Etrex 201X). Two parallel water samples were collected with a water sampler and poured into a 1,000 mL bottle at each sampling point. The water sample was fixed with acid, stored in a 4°C incubator and transported back to the laboratory to measure the concentrations of nitrate (NO$_3$-N, mg L$^{-1}$), ammonium (NH$_4$-N, mg L$^{-1}$), total nitrogen (TN, mg L$^{-1}$), total phosphorus (TP, mg L$^{-1}$) following the Chinese Government standard for Water and Wastewater Monitoring and Analysis (2002). Major ions (K$^+$, Mg$^{2+}$, Cl$^-$) were measured using the Dionex Ion Chromatography System (ICS; ICS-1000, Dionex, Sunnyvale, CA, USA).

**Data analysis**

The counts of each algae taxon were expressed as relative abundance before the analysis. The structural properties of the periphytic algae community at each site were used to characterize by the Shannon–Weiner index (H') and species richness (S) (Bellinger et al. 2006; Wang et al. 2017). These indicators are commonly used in the biological assessment of water quality (Spellerberg & Fedor 2003). Non-metric multidimensional scaling (NMDS) analyses were performed to visualize the periphytic algae structure distribution characteristics of the WRB. Furthermore, the analysis of similarity (ANOSIM, Bray-Curtis distance measure, 999 permutations) was used to test the difference in the community structure.
RESULTS

Environmental gradients

In this study, considerable fluctuations were identified in hydrological characteristics, water physical and chemical properties among sampling sites (Table 1). One-way ANOVA indicated that among all the environmental variables, width, pH, TDS, NO₃-N, Mg²⁺, and Cl⁻ were significantly different, \( p < 0.05 \) (Table 1). The average width and the concentration of NO₃-N in the BRS sites were lower than those in the WRS and the JRS \( (p < 0.05) \), while the concentrations of TDS and Cl⁻ in the BRS sites were higher than other sites \( (p < 0.05) \). The average pH and the concentration of Mg²⁺ in the BRS sites was higher than in WRS and JRS \( (p < 0.001) \). Principal component analysis (PCA) accounted for 63.17% of the total variability in the environmental data in the first two axes (Figure 2). The first axis of PCA explained 41.73% of the variance, indicating that variables were primarily related to Cl⁻, K⁺, and TDS (Figure 2). The second axis explained 21.44% of the variance, mainly correlating with pH, flux, and river width (Figure 2).

Table 1 | Mean value (range in parentheses) from three water system sites in July 2017

<table>
<thead>
<tr>
<th>Environment variables</th>
<th>Abbreviation</th>
<th>WRS ( n = 15 )</th>
<th>JRS ( n = 17 )</th>
<th>BRS ( n = 12 )</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude (m)</td>
<td>Altit</td>
<td>913 (340–2,452)</td>
<td>1,049 (410–1,950)</td>
<td>821 (340–1,360)</td>
<td>0.162</td>
</tr>
<tr>
<td>Water temperature (°C)</td>
<td>WT</td>
<td>22 (6.5–28.5)</td>
<td>21.5 (9.0–25.5)</td>
<td>26 (20.3–29.5)</td>
<td>0.088</td>
</tr>
<tr>
<td>River width (m)</td>
<td>Width</td>
<td>73.99 (12.3–210)</td>
<td>40.21 (16.9–105)</td>
<td>33.13 (2.5–133)</td>
<td>0.033*</td>
</tr>
<tr>
<td>River depth (m)</td>
<td>Depth</td>
<td>0.47 (0.2–1)</td>
<td>0.47 (0.25–0.65)</td>
<td>0.42 (0.25–0.5)</td>
<td>0.671</td>
</tr>
<tr>
<td>Water velocity (m/s)</td>
<td>Velocity</td>
<td>0.54 (0.29–1.02)</td>
<td>0.55 (0.1–1.29)</td>
<td>0.52 (0.07–1.27)</td>
<td>0.901</td>
</tr>
<tr>
<td>Flux (m³/s)</td>
<td>Flux</td>
<td>16.53 (2.87–70.40)</td>
<td>8.71 (1.93–19.53)</td>
<td>6.11 (0.47–16.46)</td>
<td>0.088</td>
</tr>
<tr>
<td>Secchi depth (m)</td>
<td>SD</td>
<td>0.16 (0.07–0.52)</td>
<td>0.10 (0–0.35)</td>
<td>0.08 (0–0.3)</td>
<td>0.154</td>
</tr>
<tr>
<td>Dissolved oxygen (mg/L)</td>
<td>DO</td>
<td>8.45 (5.55–10.03)</td>
<td>8.69 (7.24–11.92)</td>
<td>9.36 (3.98–13.95)</td>
<td>0.79</td>
</tr>
<tr>
<td>pH</td>
<td>pH</td>
<td>9.00 (8.16–9.59)</td>
<td>9.31 (8.01–10.05)</td>
<td>9.63 (9.05–10.14)</td>
<td>0.001**</td>
</tr>
<tr>
<td>Electrical conductivity (μs/cm)</td>
<td>EC</td>
<td>837.07 (391–1,618)</td>
<td>789.02 (132.4–1,893)</td>
<td>1,274.33 (336–2,155)</td>
<td>0.075</td>
</tr>
<tr>
<td>Total dissolved solids (mg/L)</td>
<td>TDS</td>
<td>372.75 (125–845)</td>
<td>682.45 (89.6–2,115)</td>
<td>893.17 (312–1,944)</td>
<td>0.003*</td>
</tr>
<tr>
<td>Total nitrogen (mg/L)</td>
<td>TN</td>
<td>5.55 (1.09–8.21)</td>
<td>4.81 (1.84–9.76)</td>
<td>5.86 (2.78–10.05)</td>
<td>0.423</td>
</tr>
<tr>
<td>Total phosphorus (mg/L)</td>
<td>TP</td>
<td>0.11 (0.03–0.25)</td>
<td>0.20 (0.03–1.95)</td>
<td>0.13 (0.02–0.47)</td>
<td>0.808</td>
</tr>
<tr>
<td>Nitrate (mg/L)</td>
<td>NO₃-N</td>
<td>2.31 (0.19–4.19)</td>
<td>1.21 (0.04–2.50)</td>
<td>1.65 (0.47–3.59)</td>
<td>0.018*</td>
</tr>
<tr>
<td>Ammonium (mg/L)</td>
<td>NH₄-N</td>
<td>0.34 (0.09–0.63)</td>
<td>0.31 (0.10–0.82)</td>
<td>0.29 (0.01–0.74)</td>
<td>0.687</td>
</tr>
<tr>
<td>Potassium (mg/L)</td>
<td>K⁺</td>
<td>5.07 (0.49–14.68)</td>
<td>5.12 (0.50–11.87)</td>
<td>5.21 (3.82–7.25)</td>
<td>0.683</td>
</tr>
<tr>
<td>Magnesium (mg/L)</td>
<td>Mg²⁺</td>
<td>21.28 (7.64–59.54)</td>
<td>52.05 (4.87–131.69)</td>
<td>70.40 (20.6–135.72)</td>
<td>0.000**</td>
</tr>
<tr>
<td>Chloride (mg/L)</td>
<td>Cl⁻</td>
<td>145.36 (1.02–380.23)</td>
<td>265.71 (0.84–824.23)</td>
<td>486.26 (160.89–960.55)</td>
<td>0.008**</td>
</tr>
</tbody>
</table>

The value of \( n \) is the number of water samples in the sites. Variables significantly different among the river systems with \( p < 0.05 \) and \( p < 0.001 \) are marked (based on the ANOVA). *\( p < 0.05 \); **\( p < 0.001 \).
Spatial distribution of periphytic algae community structure

A total of 84 periphytic algae taxa species were identified, distributing in 37 genera. Only 28 species and 14 genera were found to reach a relative abundance of more than 1% (Figure 3). The most common genera were *Navicula* (46.5% of all counted), *Oscillatoria* (5.8%), *Nitzschia* (4.8%), *Scenedesmus* (4.0%), *Cymbellum* (3.6%), *Fragilaria* (3.5%), *Diatoma* (3.2%), *Phormidium* (3.1%), *Synedra* (2.8%), *Cyclotella* (2.0%), *Achnanthes* (1.9%), *Cocconeis* (1.3%), *Achnanthes* (1.2%) and *Melosira* (1.0%). These 14 genera accounted for 84.5% of all the values counted (Figure 3). The dominant genus of each site differed in relative abundance. In the WRS sites, *Navicula*, *Fragilaria*, *Scenedesmus*, and *Melosira* occupied a higher relative abundance (20% in at least one sample). *Navicula radiosa*, *Navicula palcentula*, *Fragilaria intermedia*, *Scenedesmus acutiformis* and *Melosira granulata* were the most dominant species (a relative abundance of 10% in at least one sample). In the JRS sites, *Navicula*, *Cymbella*, *Diatoma*, *Oscillatoria* and *Phormidium* occupied a higher relative abundance. The most abundant species were *Cymbella ventricosa*, *Diatoma vulgare*, *Oscillatoria tenuis* and *Phormidium tenue*. In the BRS sites, *Navicula*, *Scenedesmus* and *Oscillatoria* were dominant species, but the most abundant species different from WRS and JRS were *Navicula gracilis*, *Navicula pupula* and *Scenedesmus quadricauda*.

In the analyzed set of samples, the density of periphytic algae ranged from 525 to 5.9 × 10^5 ind/cm², species richness from 2 to 29, and the Shannon–Weiner index from 0.58 to 4.43 (Figure 4). The periphytic algae density showed a low level in the whole WRB. The average of periphytic algae density was 7.35 × 10^4 ind/cm² while the highest density and the lowest density appeared at sites J1 and J11, respectively (Figure 4(a)). The average species richness of the periphytic algae communities in WRS, JRS, and BRS were 13, 11, and 14, respectively, with sites J2 and J9 displaying the highest and lowest species richness (Figure 4(b)). The average Shannon–Weiner indexes in WRS, JRS, and BRS were 2.90, 2.45, and 2.99, respectively. The peak and valley values of the Shannon–Weiner index appeared at sites J2 and J15 (Figure 4(c)). According to the results of NMDS and ANOSIM (r = 0.291, p = 0.001), the periphytic algae community structures were significantly different among WRS, JRS, and BRS (Figure 5).
CCA analyzed 28 species and 18 environmental variables at 44 sites (Supplementary material, Table A.1). The Monte Carlo unrestricted permutation test \((p < 0.05)\) identified eight environmental variables (Altit, WT, TDS, EC, K\(^+\), Mg\(^2+\), Cl\(^-\), TN) that significantly contributed to the algae species assemblages (Figure 6). The eigenvalues of the first two CCA axes \((\lambda_1 = 0.316, \lambda_2 = 0.133)\) explained 49.1 and 20.7% of the variation in species and environmental variables, respectively (Table 2). The species-environment correlations were high for both of the ordination axes \((r_1 = 0.835, r_2 = 0.842)\). Axis 1 was positively correlated with TDS \((r = 0.74)\), EC \((r = 0.48)\), WT \((r = 0.41)\), TN \((r = 0.35)\), K\(^+\) \((r = 0.41)\), Mg\(^2+\) \((r = 0.73)\), Cl\(^-\) \((r = 0.69)\) and negatively with Altit \((r = -0.23)\). Axis 2 was positively correlated with Altit \((r = 0.61)\) and negatively with EC \((r = 0.49)\) and WT \((r = -0.4)\).

The environmental variables play important roles in the distribution of periphytic algae communities. Frequently found species such as *Cocconeis placentula*, *Navicula radiosq*, *Navicula pupula*, *Stauroneis anceps*, *Nitzschia denticule*, *Nitzschia palea* and *Synedra acus* exhibited wide tolerance to environmental variables (Figure 6(a)). These species were positively associated with Altit, WT, EC, and TN. Most sites in WRS and JRS were distributed in the second and the third quadrant, where the samples
were closely related to Altit (Figure 6(b)). The parameter was highly positively associated with Navicula simplex, Scenedesmus acutiformis, Scenedesmus bijugatus and Scenedesmus quadricauda. However, the sites in the BRS were mainly dispersed in the fourth quadrant. Samples were associated with high WT and EC (Figure 6(b)).

DISCUSSION

Rivers, an important part of the ecosystem, not only have ecological functions but also provide various services for people. However, river ecosystems are increasingly impacted by environmental stressors, owing to urbanization and industrialization taking place in the entire watershed, contributing to nutrients and organic pollution continuously (Song et al. 2015). Wastewater from industrial and agricultural activities, as well as an urban settlement, is the main source that contributes a great number of solid organic pollution and thermal pollution (Milovanovic 2007; Luo et al. 2009; N’guesan et al. 2009). Algae are an essential component in maintaining the health of aquatic ecosystems (Kelly et al. 1998). In general, periphytic algae are regarded as a good indicator of water quality. Many studies have demonstrated that the composition and structure of the periphytic algae community are affected by various environmental variables (Chessman et al. 1999; Soininen et al. 2004; Urrea & Sabater 2009; Panahy Mirzahaslanlou et al. 2019).

In this study, we compared the species composition and distribution of periphytic algae communities among three river systems. Though each river system was represented and dominated by different periphytic algae taxa, we found that the genera Navicula existed at all samples and species N. radiosq, N. pupula and N. simplex were found in almost every site. From the whole WRB, the species diversity and

Table 2 Summary of the CCA of most dominant periphytic algae species composition in 44 samples concerning the eight environmental variables

<table>
<thead>
<tr>
<th>Axes</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvalues</td>
<td>0.316</td>
<td>0.133</td>
<td>0.055</td>
<td>0.045</td>
</tr>
<tr>
<td>Species-environment correlations</td>
<td>0.833</td>
<td>0.842</td>
<td>0.725</td>
<td>0.665</td>
</tr>
<tr>
<td>Cumulative percentage variance of species data</td>
<td>15.9</td>
<td>22.7</td>
<td>25.4</td>
<td>27.7</td>
</tr>
<tr>
<td>Species–environment relation</td>
<td>49.1</td>
<td>69.8</td>
<td>78.3</td>
<td>85.3</td>
</tr>
</tbody>
</table>
abundance of periphytic algae changed significantly. Meanwhile, we found that algae abundance was higher at the sites of JRS (J1–J5), part sites of WRS (W11, W13) and BRs (B4, B5, B10), where the forest coverage is high and the substrate of the river is dominated by boulders and cobbles (Supplementary material, Table A.2). The impact of habitat quality on the periphytic algae communities is more significant, especially the type of substrate (Eloranta & Andersson 1998; Bere & Tundisi 2011). Soil and water loss in the WRB is serious, and a large amount of sediment is dumped into the main river, causing soft-sediment substrate at many sites. Periphytic algae abundance in the soft-sediment substrate is lower than on the stone substrate (Townsend & Gell 2005).

Periphytic algae communities were associated with three sets of environmental variables in the WRB. One set is a geographic variable, and only one variable is Altit. The other two sets are physical and chemical variables of the WRB. The physical variable is mainly WT. Chemical variables consist of TDS, TN, and nutrient ion concentration. For the geographical and physical variables, the WT changed significantly due to the large east-west span of the WRB and drastic variation in altitude. The similarity of periphytic algae community is related to the altitude distance, and the altitude gradient affects the biodiversity by affecting the local environmental factors (Teittinen et al. 2016). Chemical variables are significantly correlated with periphytic algae data indicating that they are a key factor for the distribution of periphytic algae communities (Potapova & Charles 2002; Soininen et al. 2004; Tan et al. 2014).

The three sets of environmental variables provided information on how they affected the periphytic algae community structure (Leira & Sabater 2005; Blettler et al. 2019). The CCA indicated that the chemical variables (12.5%) were the most accounted for in the contribution to the periphytic algae community structure in the WRB, while physical variables and geographical factors (5.8% in total) played a relevant minor role. The periphytic algae composition in the river system downstream sites was greatly influenced by high EC, Mg$^{2+}$, Cl$^-$ and TN concentration. The high concentration of these variables may be due to the domestic sewage and industrial wastewater draining to the river (Ma et al. 2009). The other main reason is due to soil erosion which not only carries sediment into the river, increasing water turbidity, but also dissolves soluble nutrients and ions in the soil, increasing the concentration of various particles, pollutants and ions (Quilbé et al. 2006). EC is an index that can reflect the total ionic concentration in natural water. In this research, EC became an important determinant to distinguish the distribution of the periphytic algae communities in the WRB. We found that the average values of EC concentration in downstream sites was 1,110 μm/cm, higher than 759 μm/cm measured in upstream sites. TDS and nutrient levels play an important role in benthic periphytic algae community structure. Most of the abundant and common species were characteristic of eutrophic ecosystems (Van Dam et al. 1994). In the WRB, high TN concentration from anthropogenic sources are likely to cause genera Naviacula (46.5%) and Nitzschia (4.8%), which have wide ecological amplitude and pollution tolerance, dominating in samples (Goma et al. 2005; Delgado & Pardo 2015; Chen et al. 2019).

WT can affect the concentration of dissolved oxygen in water and the respiratory rate of aquatic organisms, so it also is a major factor affecting the periphytic algae community (Chen et al. 2016b). Moreover, because that altitude drastically drops from upstream to downstream in the WRB, WT also changes evidently and becomes a significant factor affecting the periphytic algae. Thermal pollution is equally a reason for WT rising. Thermal energy absorbed and stored by urban impervious underlying surface and rainwater runoff and point discharge from wastewater treatment plants increase WT (Van Buren et al. 2000; Kinouchi et al. 2007).

Recently, the impact of catchment-scale variables on river ecosystems has attracted researchers’ attention. A widely used approach is to establish relationships between community patterns and environmental variables (Liu et al. 2016). In this study, Altit, WT and nutrition concentration were retained in the CCA as significantly affecting algal distribution environmental factors. The impact of increased nutritional levels caused by human activities is significantly greater than natural factors. Our work has important implications for river bio-monitoring and management in the study area, especially in other subtropical regions throughout China.

CONCLUSIONS

There are complex variables which affect the structure and distribution of periphytic algae communities, including
hydrological, geographical and physiochemical factors. Our results revealed that altitude, EC, TN, WT and major ions were identified as the main variables with a significant influence on the structure and distribution of periphytic algae communities. Three river systems were investigated, each of them with different dominant species, and corresponding to the different variables. Multivariate analyses are a good tool for interpreting species data but a large part of variation remained unexplained in most instances. This uncertainty may be related to other variables which can explain why variation and species have broad tolerance to the variables (Passy 2007; Centis et al. 2010; Porter-Goff et al. 2013; Tolkkinen et al. 2016). Consequently, the main determinants of variation of periphytic algae communities may result from a combination of the change in land-use patterns by man, natural phenomena including geology and climatic changes and river hydrology.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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