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Application of functional feeding groups of macroinvertebrates in highly urbanized streams

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ABSTRACT

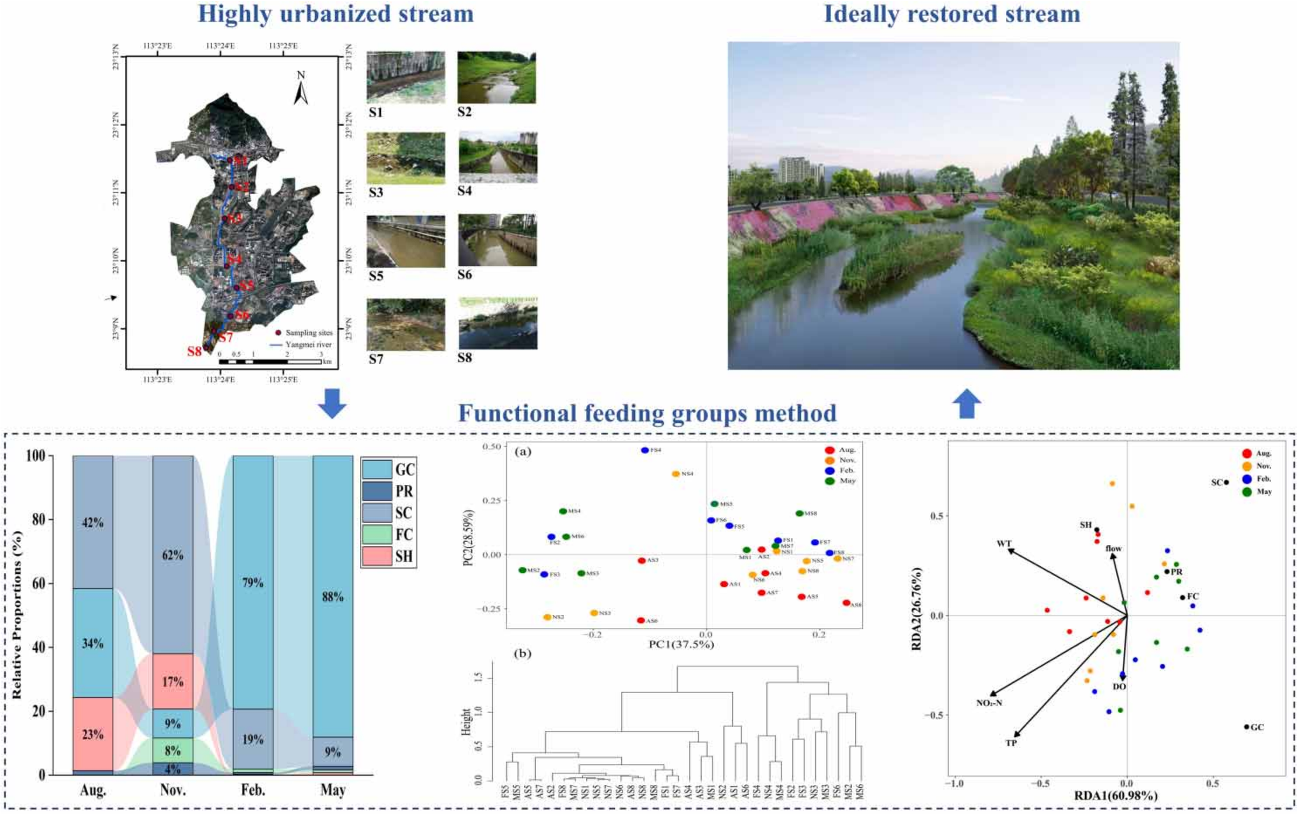
Urbanization is an inevitable process accompanying economic development. However, the rapid urbanization process is posing a threat to aquatic communities and causing disruptions to river ecosystems. In highly urbanized river ecosystems, the mechanisms of human activities on the functional feeding groups (FFGs) of macroinvertebrates remain unclear, hindering the restoration of river ecosystems. This study focuses on an urban stream called the Yangmei River in Guangzhou and investigates environmental factors and macroinvertebrates in August and November 2022 and February and May 2023. Variance analysis, principal component analysis, and hierarchical cluster analysis were employed to research the temporal and spatial characteristics of FFGs. Redundancy analysis was used to explore the environmental factors influencing FFGs. Finally, ecosystem attributes were calculated based on FFG data and ratios. The results indicate that gathering-collectors dominate in the Yangmei River, leading to a transition toward a heterotrophic river system. Simultaneously, the damaged material transportation function, weakened riparian function, and poor habitat stability all reveal the fact of partial functional degradation of the Yangmei River. This study provides valuable insights into the overall functionality of the Yangmei River and contributes theoretical support for the application of FFG methods in the ecological assessment of highly urbanized rivers.

Key words: ecosystem attributes, environmental survey, functional feeding groups, macroinvertebrates, urban streams

HIGHLIGHTS

- Gathering-collectors occupy a dominant position in functional feeding groups of macroinvertebrates.
- Chemical characteristics act as limiting factors for macroinvertebrates.
- River functions about material cycling, transport, and others are impaired.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Urbanization is an inevitable process accompanying the economic development of society (Yu 2021). With the rapid pace of urbanization, various urban agglomerations in China are continuously developing. Among these, the Guangdong-Hong Kong-Macao Greater Bay Area stands as one of the three largest urban agglomerations in China, distinguished by its substantial population, robust innovation capacity, and strong comprehensive strength (Yao & Huang 2023). Guangzhou, as a pivotal city within the Guangdong-Hong Kong-Macao Greater Bay Area, has surpassed a permanent population of 18 million, with an urbanization rate reaching 86.48% by the end of 2022. Its urbanization development has progressed into an advanced stage (Gong *et al.* 2018). On the other hand, the urbanization process has led to a series of ecological consequences, including water pollution, increased impervious surfaces in cities, decreased biodiversity, and degradation or loss of natural habitats (Theodorou 2022).

Urban streams play a vital role in providing a range of ecosystem services, including water source supply, city flood control and drainage, ecological conservation, leisure and recreation, enhancement of the urban landscape, and other functions. These streams serve as the base of urban biodiversity and are closely linked to the overall urban ecosystem (Yaacovi *et al.* 2021). A healthy river environment is a crucial resource and environmental carrier for a city, directly impacting its survival and development.

The method of using water quality as an indicator has traditionally been a common approach for assessing the health of river environments (Najafzadeh *et al.* 2021). However, water quality indicators can only provide a single value pertaining to the status of surface water resources and cannot fully reflect the ecological condition of rivers (Rnjbar Jafarabadi *et al.* 2016). The evaluation of river ecological status comprises four fundamental elements: macrophytes, phytoplankton, macroinvertebrates, and fish. Macrophytes are habitat bound, and macroinvertebrates exhibit limited migratory abilities, making them more sensitive indicators of local habitat conditions. In practice, macrophytes tend to reflect the pollution and nutrient status of rivers (Najafzadeh *et al.* 2023), while macroinvertebrates play an essential role in aquatic ecosystems (Nhiwatiwa *et al.* 2017). They consume primary producers and zooplankton and serve as food sources for other aquatic organisms, thus occupying an important position in the aquatic food web (Gebrehiwot *et al.* 2017). In addition, macroinvertebrates exhibit characteristics such as long life cycles and sensitivity to external pressures, making them capable of reflecting changes, influencing factors, and stability within ecosystems. Consequently, they are often utilized as indicator species to assess the health of aquatic ecosystems (Gianopulos *et al.* 2021). Urban streams often face many challenges, such as severe water pollution, decreased vegetation coverage, increased ground hardening rate, and limited connectivity between the river and its banks (Lebepe *et al.* 2022). Macroinvertebrates can serve as indicators to comprehensively reflect the environmental conditions of urban streams and provide rich feedback.

Currently, there are two common methods for utilizing macroinvertebrates in biological assessment. One method is taxonomy based (de Vries *et al.* 2021; Hu *et al.* 2022), while the other is grounded in functional feeding groups (FFGs) (Chen *et al.* 2020; Sudarso *et al.* 2022). The FFG-based approach is more effective in reflecting the impact of human activities on river ecosystems and the extent of damage to these ecosystems (Barbour *et al.* 1999). So, it has garnered extensive attention from researchers in recent years. Jiang *et al.* (2011) examined the correspondence between FFGs and the river continuum concept. Fu *et al.* (2016) assessed the impact of different land use patterns on the physicochemical characteristics and FFGs in Dongjiang River basin of China. Arias *et al.* (2023) conducted a study employing FFGs, suggesting that intensive cultivation reduces biodiversity and ultimately affects the function of rivers. The numerical values and ratios of FFGs have been proven to indirectly reflect the ecosystem attributes of rivers (Calabrese *et al.* 2020). This approach circumvents the difficulty and time consumption of directly measuring ecosystem attributes, thus gaining widespread application.

At present, the FFGs method is mostly applied in natural or less impacted watersheds. However, its application at rivers in highly urbanized areas is limited. Therefore, the mechanisms of human activities on the FFGs of macroinvertebrates in inner-city rivers remain unclear and require in-depth exploration. This research aims to investigate the FFGs in the inner-city rivers, taking the Yangmei River in Guangzhou as an example, to provide theoretical support for the application of FFGs in the ecological assessment of rivers in highly urbanized areas. The Yangmei River is a highly urbanized stream located in the confluence of the Central Business District, Science City, and Ecological Green Belt in Guangzhou, China. Its unique position gives it an important role in the construction of smart cities and ecological urban areas. Within the Yangmei River Basin, the combination of plant bank slopes and concrete bank slopes presents a unique conjunction of natural and artificial characteristics. Hence, this study collected the environmental factors and macroinvertebrates in the Yangmei River, to achieve the following objectives: (1) to explore the temporal and spatial distribution characteristics of FFG community structure in urban rivers; (2) to study the main environmental factors affecting the community structure of FFGs; and (3) to evaluate the integrity of stream ecosystem functions based on ecosystem attributes. The findings of this study can provide a valuable reference for the preservation and management of the ecological environment in urban streams.

2. STUDY AREA AND SAMPLING METHODS

2.1. Study area and sampling sites

The Yangmei River (Figure 1) is situated in the Tianhe District of Guangzhou City, Guangdong Province, China. It originates from the Huolushan Forest Park and flow into the Chebeichong downstream. It serves as a tributary of the Chebeichong and flows in a north-south direction. The Yangmei River has a total length of 6.7 km and covers a drainage area of 15.83 km^2. Its average width is approximately 5 m, gradually widening from upstream to downstream. The stream falls within the subtropical monsoon climate zone and receives abundant rainfall, with an average annual precipitation of 1,725 mm. Rainfall primarily occurs during the flood season. The Yangmei River has undergone urbanization and some of its bank slopes hardened. The water in the stream is significantly polluted with nitrogen and phosphorus, with phosphorus pollution being particularly pronounced, accompanied by moderate organic pollution.

Sampling sections were positioned along the river, following the principle of uniform distribution and local densification. Ultimately, a total of eight sampling sections were determined, and the positions of each sampling section are shown in Figure 1. The specific situation is presented in Table 1.

2.2. Sampling methods

Field investigations, macroinvertebrates community sampling, and water quality testing were carried out at eight sampling sections within the Yangmei River in August 2022, November 2022, February 2023, and May 2023. A total of 32 samples were collected during the study period. According to the climate patterns of Southern China, the aforementioned sampling times correspond to summer, autumn, winter, and spring.

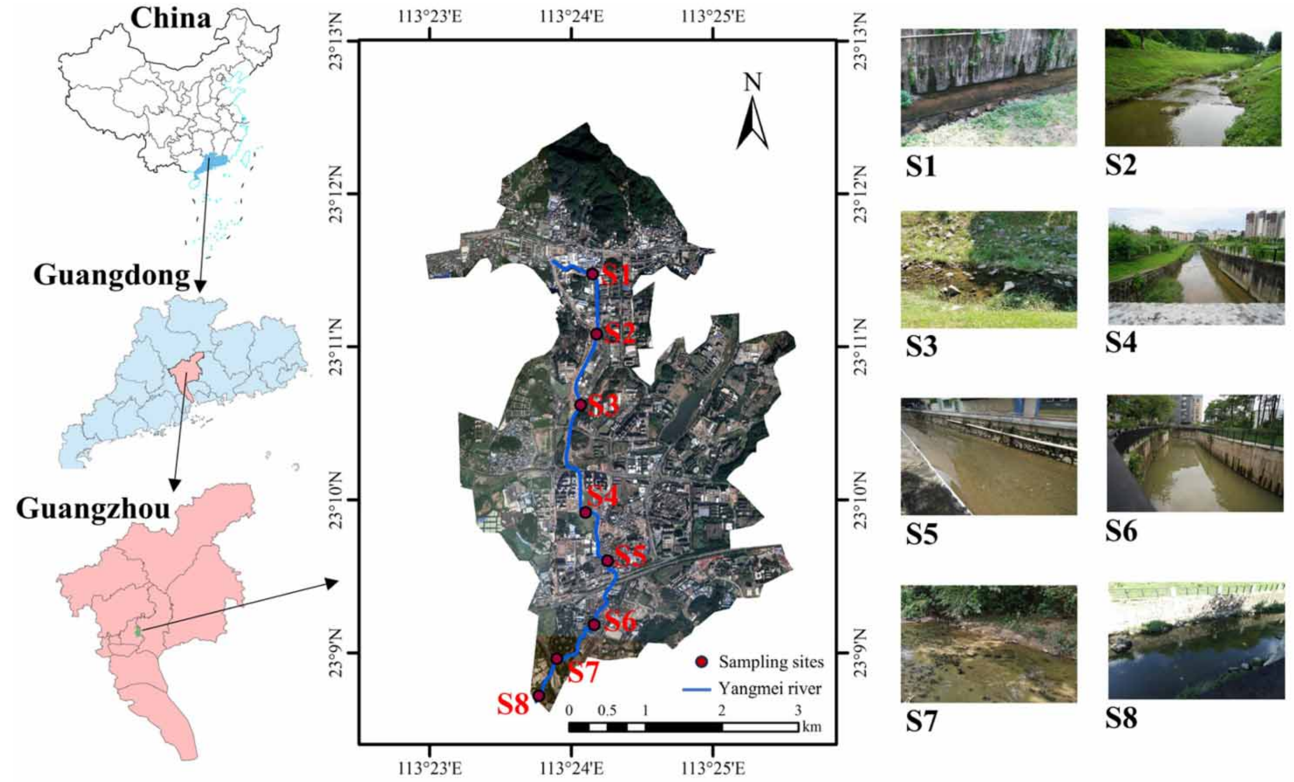


Figure 1 | Location of Yangmei River basin and sampling sections.

Table 1 | The situation about sampling sections in the Yangmei River

	S1	S2	S3	S4	S5	S6	S7	S8
River width (m)	2.72	3.2	2.22	2.53	3.2	8.5	10.0	6.7
BHR	0.5	0	0	1	1	1	0.5	1

Note: BHR, 'bank slope hardening ratio'. The bank slope is a natural revetment, and the BHR is 0. If one side of the bank slope is natural revetment and the other side is concrete revetment, the BHR is 0.5. If the bank slope is concrete revetment each side, the BHR is 1.

Quantitative sediment was collected using a D-frame net (25 cm × 50 cm) at each sampling site. Subsequently, these samples were cleaned using a 60-mesh screen and brought back to the laboratory. Macroinvertebrates are manually selected, fixed, and preserved in a 10% formaldehyde solution, and the identification was carried out according to the method mentioned by Gebrehiwot *et al.* (2017) to identify the smallest taxon whenever possible.

Water quality detection indicators encompass water temperature (WT), pH, dissolved oxygen (DO), conductivity (Cond), ammonia nitrogen (NH_4-N), nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N), phosphate (PO_4^{3-}-P), total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD), and chlorophyll a (Chl-a). Among these parameters, WT, pH, DO, and Cond serve as fundamental indicators of water quality. Nitrogen and phosphorus reflect the degree of water pollution, which is generally concerned. COD and Chl-a represent organic contamination and the extent of eutrophication, respectively (Boyd 2015). WT and DO were measured using a portable dissolved oxygen analyzer (model # 605404, YSI Incorporated, Yellow Springs, Ohio, USA), pH was determined using a portable pH meter (ST300, OHAUS Instruments, ChangZhou, JiangSu, China), and Cond was measured using a portable conductivity meter (ST300C, OHAUS Instruments, ChangZhou, JiangSu, China). All these aforementioned measurements were taken onsite. Water samples were collected at each sampling point for chemical parameter analysis. The parameters, including NH_4-N, NO_2-N, NO_3-N, PO_4^{3-}-P, and Chl-a, were determined using a microplate reader (Epoch2, BioTek Instruments, Winooski, Vermont, USA). TN, TP, and COD were assessed using a Hach instrument (DR3900, Hach Instruments, USA). The specific measurement methods were referred to the study by Xiao *et al.* (2023). The flowrates and rainfall data were obtained through online monitoring systems. The flow velocity was measured onsite using Doppler flow meters (LSH10-1QC, BoYiDa, Xiamen, China), and the water depth was measured using a depth gauge.

2.3. FFGs of macroinvertebrates and ecosystem attributes

According to Cummins *et al.* (2005), the FFGs of macroinvertebrates are classified as follows: (1) gathering-collectors (GCs), (2) filtering-collectors (FCs), (3) shredders (SHs), (4) scrapers (SCs), and (5) predators (PRs), and detailed classification criteria are presented in Table 2. Furthermore, based on the research conducted by Yoshimura *et al.* (2006) and the classification of FFGs, ecosystem attributes were examined from aspects such as material cycling, vertical transport capacity, coastal material input, and other aspects (refer to Table 3 for details).

2.4. Statistical analysis

In order to compare temporal and spatial differences of environmental factors and FFGs, one-way analysis of variance (ANOVA) was adopted. In cases where homogeneity of variance was not met, the Kruskal–Wallis test was used. One-way ANOVA and Kruskal–Wallis are commonly employed to analyze the impact of a categorical independent variable on a

Table 2 | Functional feeding groups classification and food resources of macroinvertebrates

Functional groups	Dominant food resources	Particle size range of food (mm)
Gathering-collectors	FPOM-decomposing detrital particles; algae, bacteria, and feces	0.05–1.0
Filtering-collectors	FPOM-decomposing detrital particles; algae, bacteria, and feces	0.01–1.0
Shredders	CPOM-decomposing (or living hydrophyte) vascular plants	>1.0
Scrapers	Periphyton-attached nonfilamentous algae and associated detritus, microflora and fauna, and feces	0.01–1.0
Predators	Prey – living animal	>0.5

Note: CPOM, coarse particulate organic matter; FPOM, fine particulate organic matter.

Table 3 | Ecosystem functional characteristics based on the functional feeding groups of macroinvertebrates

Metrics based on taxa and functional feeding groups	Ecosystem attributes
Material cycling	
F1 Abundance of scrapers	Primary production
F2 Ratio of scrapers to filterers and gathering-collectors	Autotrophy/heterotrophy
F3 Abundance of shredder and gathering-collectors	Decomposition
F4 Total biomass (dry weight)	Secondary production
Longitudinal transport	
F5 Abundance of filterers	Longitudinal transport
F6 Ratio of filterers to shredder and gathering-collectors	Relative longitudinal transport
Lateral input	
F7 Abundance of shredder	Lateral input
F8 Ratio of shredder to total abundance	Relative lateral input
Others	
F9 Ratio of shredder to filterers and gathering-collectors	CPOM input/FPOM input
F10 Ratio of predators to total abundance	Top-down predator control
F11 Ratio of scrapers and filterers to total shredders and gathering-collectors	Habitat stability

numerical dependent variable to find significant differences (Weaver *et al.* 2017). All these analyses were conducted using SPSS 24.0.

Before the unconstrained ordination and constrained ordination of FFG community, model selection is required, and the detrended correspondence analysis (DCA) method is generally adopted. When the axis length value of the first ordering axis is less than 3, the linear model should be selected for the analysis. In this study, the principal component analysis (PCA) model and redundancy analysis (RDA) model were selected according to the axis length value. Before the analysis, the FFG community data were transformed to satisfy the normal distribution of the data through the log function. PCA and RDA are commonly used data dimensionality reduction techniques, allowing data to retain as much information as possible and facilitating visualization of the results (Zuur *et al.* 2007).

In order to explore the differences and similarities of FFG structures in different seasons and sampling points, the Vegan package and cluster package in RStudio software (version 3.5.1, R Foundation for Statistical Computing, Vienna, Austria) were used for PCA and hierarchical cluster analysis (HCA), respectively.

The RDA function of the Vegan package was employed to analyze the response of FFGs to environmental factors. Variance inflation factors (VIFs) of environmental factors and their correlation coefficient were calculated. To ensure model parsimony and reduce multicollinearity, one of the two environmental factors with a correlation coefficient $\geq$0.70 was retained, and the VIF of all environmental factors was maintained below 10. Forward screening procedures were used to select the final environmental factors. The RDA model was subjected to 999 permutation tests and p-value correction according to the methods outlined by Hu *et al.* (2022).

Data visualization about PCA and RDA was carried out using the ggplot2 package, and HCA was carried out using the plot function that comes with the RStudio. The sampling point map was drawn using ArcMap 10.2 software, and the remaining figures were plotted using Origin 2022.

3. RESULTS

This section first explores the temporal and spatial distribution of FFG community structure in the Yangmei River. It subsequently analyzes the responses of FFGs of macroinvertebrates to environmental factors. Finally, it evaluates the ecosystem attributes of FFGs of macroinvertebrates.

3.1. Temporal and spatial distribution of FFGs of macroinvertebrates

This section comprises two components that analyze the composition of the FFG community structure based on temporal and spatial distributions, respectively.

3.1.1. Temporal distribution of FFGs

A total of 35 taxonomic units were collected from the Yangmei River during the four sampling processes, belonging to 3 phyla, 7 classes, and 24 families. Among them, 16 species of macroinvertebrates were collected in August, 19 species in November, 21 species in February, and 18 species in May. These macroinvertebrates were categorized into 5 FFGs, comprising 6 GCs, 10 PRs, 13 SCs, 1 FCs, and 5 SHs. The directory of FFGs across the four seasons in the Yangmei River, along with the specific composition of FFGs of each season, is provided in Supplementary Material, Tables S1 and S2. One-way ANOVA revealed that there were no significant differences in FFGs species among the four seasons in the Yangmei River ($p > 0.05$).

From the perspective of time, the abundance of FFGs exhibits seasonal variations, and the composition proportions of all FFGs vary greatly across different seasons. GCs emerge as the dominant species in the Yangmei River, which has the highest relative abundance in winter and spring, accounting for 79 and 88%, respectively. SCs are the second most abundant species with the highest relative abundance in summer and autumn, at 42 and 62%, respectively. The sum of relative abundance of SHs, FCs, and PRs is about 6% (Figure 2). The temporal abundance of FFGs in the Yangmei River is detailed in Table 4. The maximum abundance of GCs is observed in spring, reaching 16,448 ind/m^2, followed by winter at 14,200 ind/m^2. The maximum abundance of SCs occurs in winter at 3,352 ind/m^2, followed by autumn at 2,432 ind/m^2. The peak abundance of SHs is observed in autumn at 680 ind/m^2, while FCs reach 304 ind/m^2 in autumn, and PRs attain their highest abundance in spring at 208 ind/m^2.

DCA was conducted on the FFGs in the Yangmei River, and the single peak response value was 2.32. Therefore, the PCA model is selected for FFG analysis. The PCA and HCA results (Figure 3) indicate that FFG results of all sampling sections can be broadly divided into two parts. One part includes upstream and downstream sections (S1, S5, S7, and S8), while the other

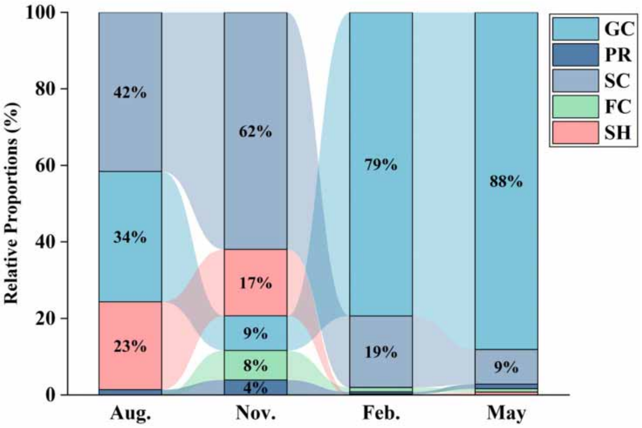


Figure 2 | Temporal distribution of FFGs in Yangmei River (%).

Table 4 | Temporal and spatial abundance of FFGs in Yangmei River (ind/m^2)

FFGs	GC	PR	SC	FC	SH
Aug.	597	24	728	0	401
Nov.	356	152	2,432	304	680
Feb.	14,200	104	3,352	200	40
May	16,448	208	1,704	160	144
S1	693	0	192	0	117
S2	7,832	152	2,360	0	720
S3	1,440	184	2,768	0	68
S4	5,368	8	2,440	640	56
S5	1,720	0	112	16	48
S6	12,992	144	320	0	200
S7	700	0	24	0	40
S8	856	0	0	8	16

part comprises midstream sections (S2, S3, and S4). This suggests that FFG structure of each sampling section undergoes minimal change along the temporal gradient, except during summer. The Kruskal–Wallis test underscores that there were significant differences in the abundance of the GCs in winter and spring compared with summer and autumn ($p < 0.05$). However, there were no significant differences in the abundance of the other four FFGs between different seasons ($p > 0.05$).

3.1.2. Spatial distribution of FFGs

The commonest FFGs in the Yangmei River are GCs, with a frequency of 90.63%, and they are essentially distributed throughout the entire Yangmei River. Subsequently, SCs follow with a frequency of 78.13%, although they are seldom found downstream in the river. The frequency of SHs is 50%, PRs account for 31.25%, and FCs make up 18.75% (refer to Figure 4). The spatial abundance of FFGs in the Yangmei River is presented in Table 4. The maximum abundance of GCs is observed downstream at 12,992 ind/m^2. The maximum abundance of PRs, SCs, and FCs appear in the middle of the river at 184, 2,768, and 640 ind/m^2, respectively. The highest abundance of SHs occurs upstream at 720 ind/m^2. The number of FFG species collected at eight sections is shown in Supplementary Material, Table S3.

The Kruskal–Wallis test indicated that there were no significant differences in spatial distribution between GCs and SHs ($p > 0.05$), while there were significant differences among PRs, SCs, and FCs ($p < 0.05$). The abundance of PRs in S2 and S3 was significantly different from other sampling sections ($p < 0.05$). The abundance of SCs in S2, S3, and S4 was

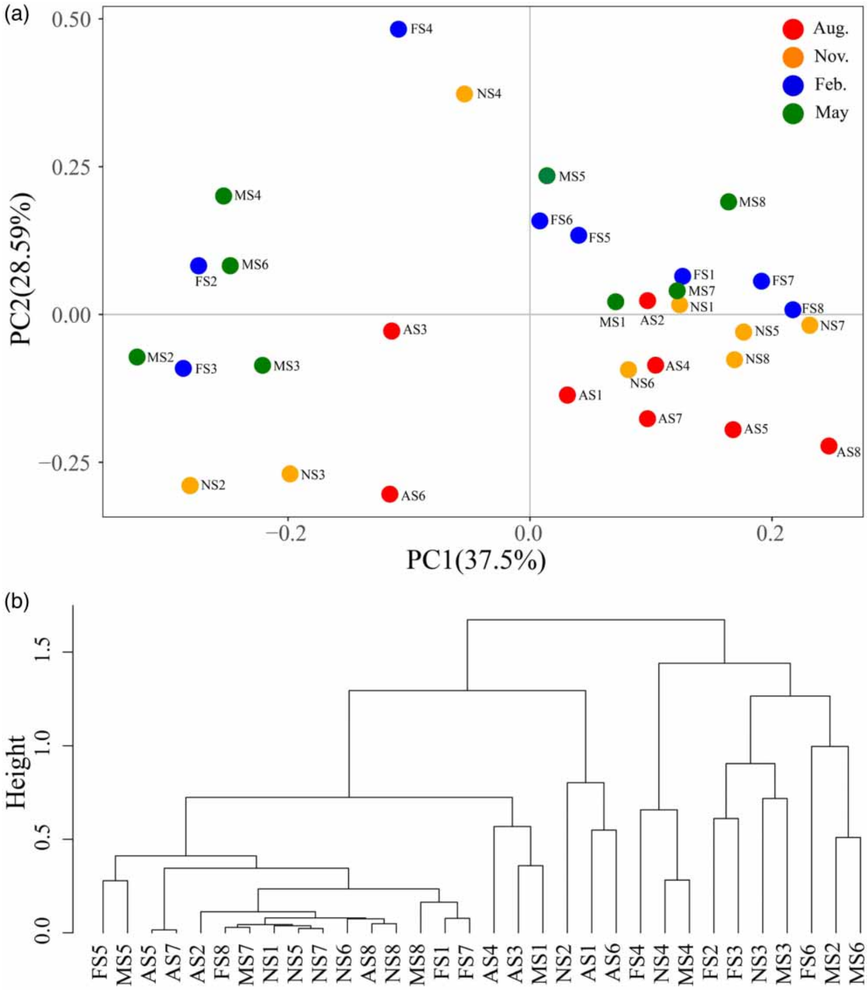


Figure 3 | The temporal distribution results of sampling sections: (a) PCA and (b) HCA. AS1–AS8 represent the result of S1–S8 in August, similar to other seasons, as shown in Figures 5 and 6.

significantly different from that in other sampling sections ($p < 0.05$). With regard to FCs, there were significant differences between S4 and other sampling sections, except for S5 and S8 ($p < 0.05$).

The results of PCA and HCA (Figures 5 and 6, respectively) revealed spatial variations in the distribution of FFGs at each sampling section in different seasons. Samples within the continuous range exhibited a certain degree of similarity. The FFG structure in each season is roughly categorized into two groups spatially, specifically S2 and S3, and the remaining sampling sections. This indicates that along the longitudinal gradient of the stream, the FFG community structure in Yangmei River is divided into three parts, represented by the upper reaches (S1), the midstream (S2, S3, and S4), and the downstream (S5, S6, S7, and S8).

3.2. Responses of FFGs of macroinvertebrates to environmental factors

DCA results show that the length of the first axis was 2.32. Consequently, RDA was employed to investigate the environmental factors influencing the temporal distribution of FFGs in the Yangmei River. The outcomes are illustrated in Figure 7. After the screening process, five environmental factors were retained, namely, WT, DO, NO_2-N, TP, and flow. The first and second canonical axes account for 60.98 and 26.76% of the relationship between temporal distribution of FFGs and environmental factors, respectively. The RDA results indicate that NO_2-N and TP exerted the most significant influence, followed by WT, while DO and flow had a relatively minor impact. This illustrates that nitrogen and phosphorus pollution, as well as temperature, play a pivotal role in shaping the seasonal distribution of FFG

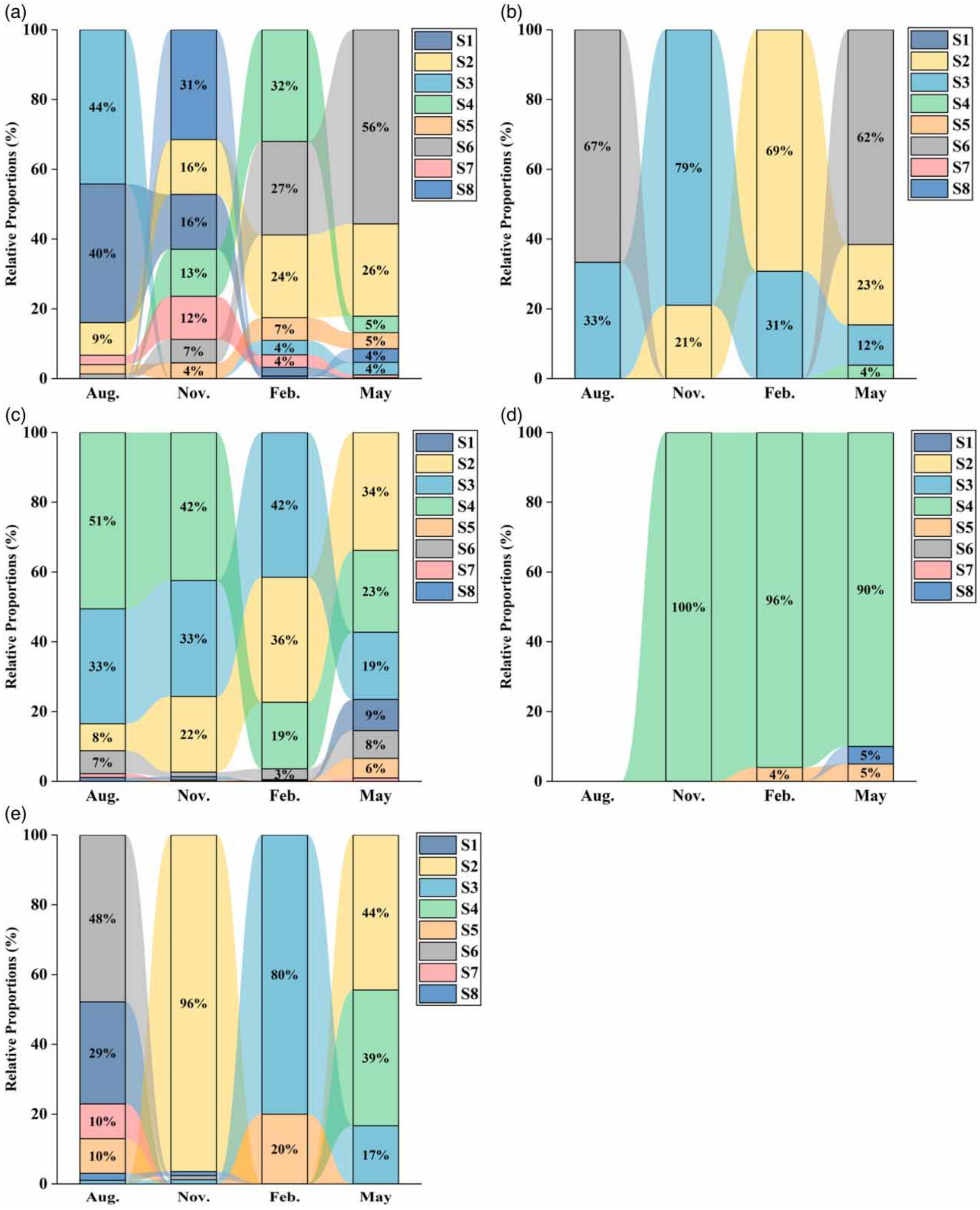


Figure 4 | Spatial distribution of FFGs in Yangmei River (%): (a) GC, (b) PR, (c) SC, (d) FC, and (e) SH.

community in the Yangmei River. Details of the results of the environmental factors are shown in Supplementary Material, Table S4.

Similarly, RDA was applied to investigate the environmental factors affecting the spatial distribution of FFGs in the Yangmei River, and the findings are depicted in Figure 8. After the selection process, three environmental factors were retained, namely, NO_2-N, BHR, and Cond. The first and second canonical axes account for 53.26 and 30.85% of the relationship between the spatial distribution of FFGs and environmental factors, respectively. The RDA results reveal that NO_2-N exhibits a strong correlation with the spatial distribution of FFGs in the Yangmei River, with BHR and Cond following.

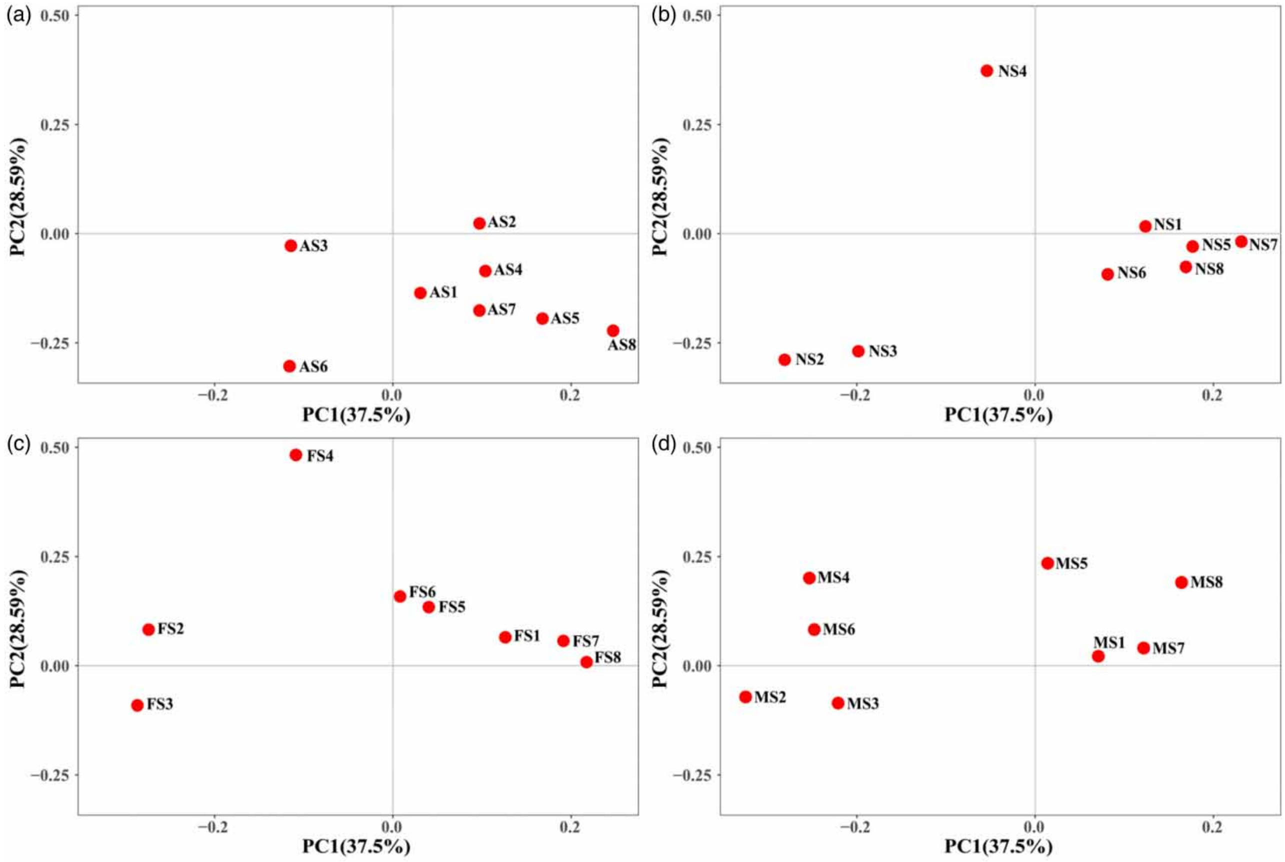


Figure 5 | PCA results of FFGs in spatial distribution: (a) Aug., (b) Nov., (c) Feb., and (d) May.

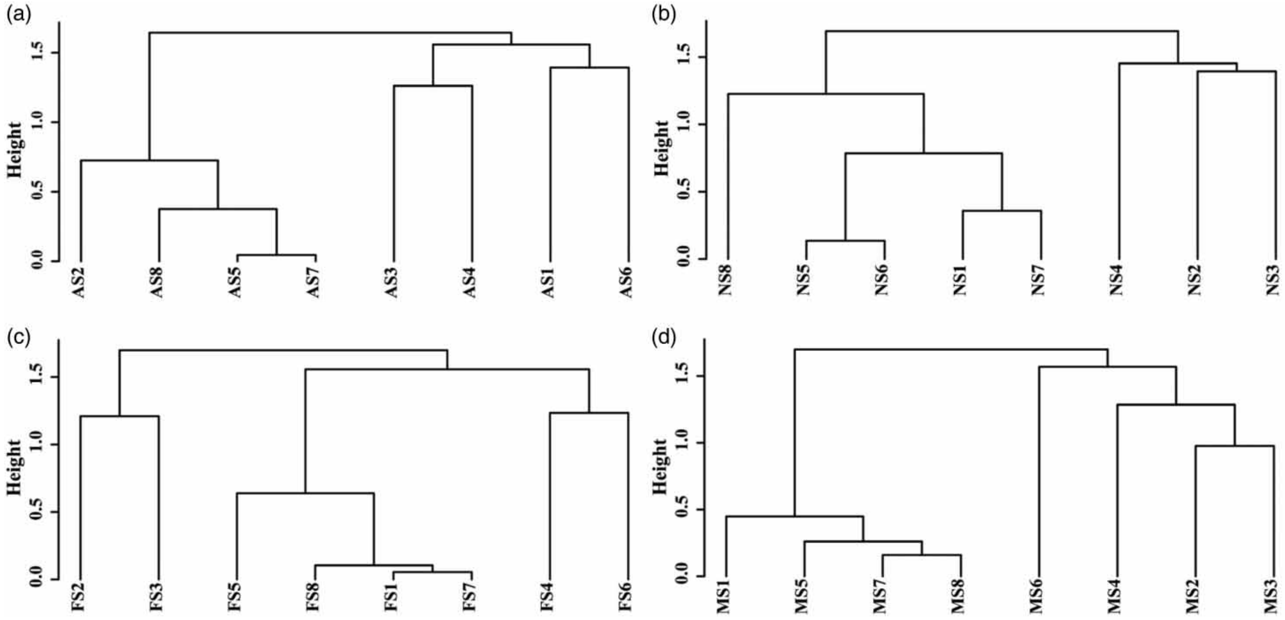


Figure 6 | HCA results of FFGs in spatial distribution: (a) Aug., (b) Nov., (c) Feb., and (d) May.

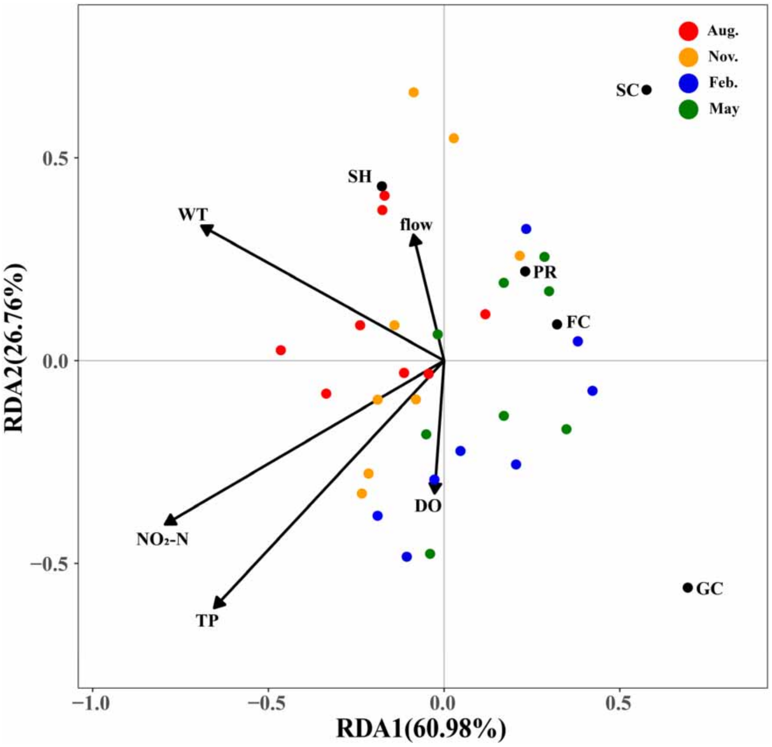


Figure 7 | Redundancy analysis of FFGs and environmental factors in temporal distribution.

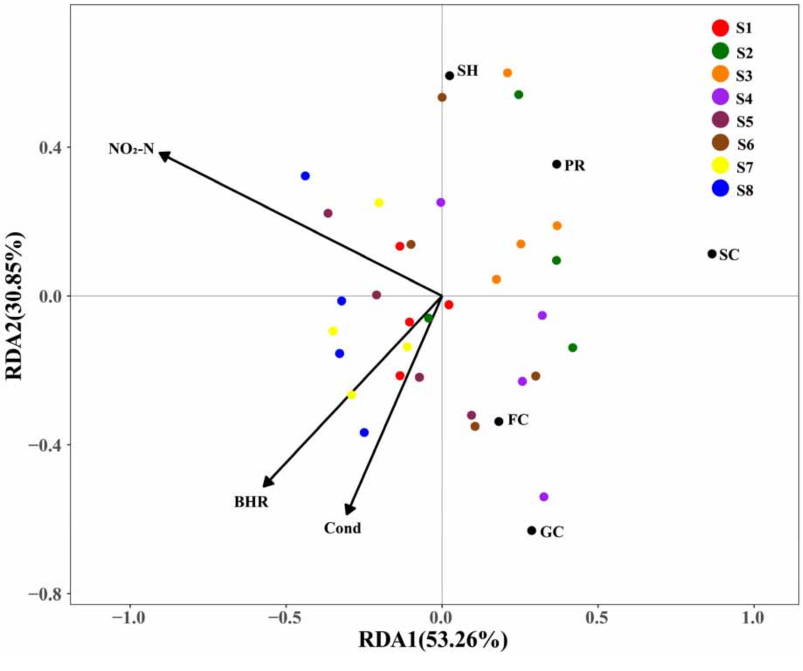


Figure 8 | Redundancy analysis of FFGs and environmental factors in spatial distribution.

3.3. Ecosystem attributes of FFGs of macroinvertebrates

The calculation results of the temporal and spatial distribution of ecosystem attributes to FFGs of macroinvertebrates in the Yangmei River are presented in Table 5. The results indicate that the ecosystem functions of the Yangmei River are complete in autumn, winter, and spring. The only missing function during summer is the longitudinal transport function. In terms of material cycling, the primary productivity and secondary productivity are the highest in winter, while the decomposition capacity peaks in spring. Moreover, during summer and autumn, the Yangmei River exhibits autotrophic characteristics. Concerning material transport, the stream exhibits stronger material exchange capacity in autumn. In addition, coarse particulate organic matter (CPOM) input/fine particulate organic matter (FPOM) input, top-down predator control, and habitat stability demonstrate optimal results in autumn.

From upstream to downstream, only S4 owns complete ecosystem functions, while the remaining sampling sites display 1–3 functional deficiencies. Among these, more than half of the sites lack longitudinal transport functions, accounting for 62.5%. Furthermore, half of the sites show deficiencies in top-down predator control, and the material circulation functions are only absent at S8, indicating a lack of primary productivity in the downstream region. The downstream is entirely heterotrophic. Concerning material cycling, the highest results of primary productivity and secondary productivity are observed at S3, and the autotrophic effect is dominant. At the same time, the strongest decomposition appears at S6. In terms of material transport, S4 demonstrates the strongest longitudinal transport function, while the strongest lateral input appears upstream. In addition, the CPOM input/FPOM input is the largest upstream, and the top-down predator control and habitat stability are the best at S3.

4. DISCUSSION

4.1. Responses of FFGs of macroinvertebrates to environmental factors

A total of 35 taxa were collected from the Yangmei River in the four seasons, which aligns with the findings of Carrasco-Badajoz *et al.* (2022) and Hu *et al.* (2022). In their respective studies, it was also observed that the number of macroinvertebrates in urban rivers is low, and the community structure is simple. This indicates that the Yangmei River, as an inner urban stream, has lost its natural characteristics due to artificial reforming and water pollution. The stream environment has been seriously compromised, directly leading to the disappearance of most macroinvertebrates, particularly the EPT groups. They have stringent water quality requirements and are known as an indicator of good water quality (Akamagwuna *et al.* 2019).

In this study, GCs hold a dominant position with the highest abundance, especially in winter and spring. This suggests that there is a substantial amount of FPOM in the sediment gaps during these seasons, providing an environment conducive to the growth and development of GCs. The difference in abundance can be attributed to habitat filtering, signifying that species with higher abundance are better adapted to the local environmental conditions (Menezes *et al.* 2010). Many GCs exhibit tolerance to anthropogenic disturbances and organic pollution (Fu *et al.* 2016). In this study, the GCs consisted of *Tubificidae* and *Chironomus sp.*, both of which can survive in polluted rivers. According to the Surface Water Environmental Quality

Table 5 | Temporal and spatial distribution characteristics of Yangmei River ecosystem attributes

Ecosystem attributes	Aug.	Nov.	Feb.	May	S1	S2	S3	S4	S5	S6	S7	S8
F1	728	2,432	3,352	1,704	192	2,360	2,768	2,440	112	320	24	0
F2	1.22	3.68	0.23	0.1	0.28	0.30	1.92	0.41	0.06	0.02	0.03	0
F3	999	1,036	14,240	16,592	811	8,552	1,508	5,424	1,768	13,192	740	872
F4	75.45	184.56	239.91	111.34	6.15	112.39	298.38	112.48	24.17	55.40	1.42	0.88
F5	0	304	200	160	0	0	0	640	16	0	0	8
F6	0	0.29	0.01	0.01	0	0	0	0.12	0.01	0	0	0.01
F7	401	680	40	144	117	720	68	56	48	200	40	16
F8	0.23	0.17	0.002	0.01	0.12	0.07	0.02	0.01	0.03	0.01	0.05	0.02
F9	0.67	1.03	0.003	0.01	0.17	0.09	0.05	0.01	0.03	0.02	0.06	0.02
F10	0.01	0.04	0.01	0.01	0	0.01	0.04	0.001	0	0.01	0	0
F11	0.73	2.64	0.25	0.11	0.24	0.28	1.84	0.57	0.07	0.02	0.03	0.01

Standard of the People's Republic of China (GB 3838-2002), the water quality of the Yangmei River had heavy nitrogen and phosphorus pollution, alongside moderate organic pollution. Obviously, the ability to survive in poor water quality conditions is a significant factor contributing to the dominance of GCs in Yangmei River. These findings align with the research by Mangadze *et al.* (2019) and Arias *et al.* (2023), which indicates that the more severely impacted rivers tend to have a higher abundance of GCs.

Along the longitudinal gradient of the stream, there were no significant differences in the spatial distribution of GCs and SHs, while there were significant differences among PRs, SCs, and FCs. The high frequency of GCs can be attributed to a combination of pollution tolerance and the availability of organic matter. In other words, this is due to (1) the pollution-tolerant characteristics of GCs, and (2) the widespread distribution of their food resources throughout the stream. Inorganic nutrients stimulate the growth of epiphytes and microorganisms, forming a biofilm that serves as a significant food source for SCs (Battin *et al.* 2003). The SCs are predominantly found in the upper reaches. Compared to other sites, there have been not only considerable nutrients but also enough direct sunlight providing a more abundant food source. SHs release nutrients into the river ecosystem during the breakdown of leaf litter, providing a food source for other invertebrates (Jonsson *et al.* 2001). In our study, the frequency of SHs in the stream was only 50%, and their abundance was much lower than that of GCs. This indicates that the adaptability of SHs in urban streams is considerably lower than that of GCs. Fu *et al.* (2016) suggest that SHs are highly sensitive to land use and human disturbance, which contributes to their low population, aligning with our findings. According to the river continuum concept, the number of PRs depends on the availability and abundance of prey (Vannote *et al.* 1980). The results in this study revealed that the prey species of PRs were relatively constant. The correlation analysis demonstrated a highly significant positive correlation between the abundance of PRs and the other total abundance. Therefore, the population of PRs in the Yangmei River depends on the abundance of their prey. In contrast, the survival of FCs in the Yangmei River presents greater challenges, with S4 being the most frequently found site. FCs typically rely on suspended FPOM and stable habitat conditions (Yoshimura *et al.* 2006), indicating that only S4 in the Yangmei River marginally meets these conditions. Moreover, among all the sampling sites, only the sediment at S4 exhibits relatively uniform sediment particle sizes and a certain depth, meeting the habitat requirements for bivalves (FCs).

The distribution of structural and functional combinations in macroinvertebrates is influenced by physicochemical variables and nutrients at different locations (Addo-Bediako 2021). Seasonal results of PCA indicated that the FFG community in summer significantly differs from that in other seasons. Spatial results of PCA showed that the FFG community was distributed differently upstream, midstream, and downstream. The differences in the spatial pattern of FFGs in macroinvertebrates are responses to environmental changes and represent a trade-off between different functions (Sun *et al.* 2021). HCA focuses on identifying similarities among communities, while PCA aims to reveal differences among communities. In addition, the two methods employ different data processing approaches in their analyses. Therefore, the results of HCA and PCA are not entirely consistent. However, in practice, they can complement and validate each other.

Some factors have been identified as controlling factors for the abundance, distribution, and function of stream organisms, such as chemical water quality (Buss *et al.* 2002), temperature (Beche *et al.* 2005), nutrient supply (Cabrini *et al.* 2013), and flow variability (Fornaroli *et al.* 2019). In this study, we demonstrate the influence of environmental variables on FFGs in macroinvertebrates. Our results highlight the importance of TP, NO_2-N, WT, DO, and flow in constructing the seasonal distribution of FFGs. TP (ANOVA, $F = 3.285$, $p < 0.05$) and NO_2-N (seasonal ANOVA, $F = 3.024$, $p < 0.05$) are important indicators of nutrient pollution degrees in stream water. The nutrient increases food availability by stimulating primary production, thereby influencing the community structure of macroinvertebrates (Zhang *et al.* 2015). High temperature (Kruskal–Wallis, $H = 21.551$, $p < 0.05$) and low DO levels (ANOVA, $F = 7.070$, $p < 0.05$) can affect the activity of aquatic organisms. Flow (Kruskal–Wallis, $H = 31.000$, $p < 0.05$) has an important relationship with material transport and diffusion and habitat quality. River erosion can reduce habitat heterogeneity and lead to habitat deterioration, subsequently reducing the taxa and abundance of macroinvertebrates.

Our results emphasize the significance of NO_2-N, HBR, and Cond in constructing the spatial distribution of FFGs. NO_2-N (spatial ANOVA, $F = 2.549$, $p < 0.05$) was identified as the primary environmental factor influencing the spatial distribution of FFGs. A higher BHR corresponds to a greater degree of bank slope hardening. This suggests a weaker buffering capacity of the riparian zone when the banks are eroded, resulting in more nutrients and a substantial amount of silt being carried into the stream. As a result, the sediment surface is covered by silt, which affects the growth of algae (Jiang *et al.* 2018), thus affecting the survival of macroinvertebrates. Cond represents the concentration of dissolved substances in the stream, and it shows a positive correlation with GCs and FCs. This result indicated that higher Cond levels correspond to more particles being carried in the stream and a richer food resource for these collector organisms.

Therefore, we can conclude that chemical characteristics are limiting factors for macroinvertebrates (Wang & Tan 2017). In addition, flow affects macroinvertebrates seasonally, while BHR affects them spatially.

4.2. Ecosystem attributes of FFGs of macroinvertebrates

According to the river continuum concept, the spatial distribution of FFGs is closely related to the transport, utilization, and storage of organic matter in natural habitats along rivers. Material cycling is one of the most important ecosystem functions in which macroinvertebrates participate, including carbon and nutrient cycling in river ecosystems. The autotrophic state indicates that the primary basis of the food chain in the river is algae or rooted vascular aquatic plants. The heterotrophic state means that streams derive additional energy sources from leaf litter and other organic matter. The balance (F3) between autotrophic and heterotrophic is the most fundamental attribute in river ecosystems. It also serves as the basis of food chains in rivers. The increase in the relative abundance of GCs indicates a shift toward heterotrophy in the stream ecosystem. In heterotrophic streams, the primary productivity function (F1) is declining, and the secondary productivity function (F4) becomes dependent on external nutrients. In the Yangmei River, the decomposition capacity (F3) is primarily determined by the abundance of GCs.

The abundance of SHs reflects the horizontal input capacity of materials along the bank, and the abundance of FCs reflects the vertical input capacity of the river. However, the absence of SHs and FCs in most reaches indicates that the longitudinal transport and lateral input of substances are impaired in the Yangmei River ecosystem.

In addition, the CPOM input/FPOM input (F9) in this study indicates that the Yangmei River's riparian zone has low integrity, which is an ineffective riparian zone. Human activities within riparian zones have been proven to be the primary factor contributing to nonfunctional riparian zones (Masese *et al.* 2014), and this significantly disrupts the material connection between riparian zones and river ecosystems. Furthermore, both the nutritional quality of leaves and climate change influence the abundance of SHs (Ferreira *et al.* 2014). Most SHs prefer cooler climates, and their abundance and diversity are typically low in tropical and subtropical regions. The low abundance of SHs and the high abundance of GCs result in a higher CPOM input/FPOM input in summer and autumn, and a lower value in winter and spring. This also leads to a lower CPOM input/FPOM input along the longitudinal gradient of the river. Therefore, we posit that the Yangmei River primarily derived the energy of heterotrophic effect from the organic matter entering the stream, rather than from the nutrients of fallen leaves. The results of top-down predator control (F10) indicate that, both seasonal gradients and stream longitudinal gradients, high trophic levels (PRs) exert weaker control over low trophic levels (the remaining four FFGs). Mangadze *et al.* (2019) observed similar PR distributions in their studies. The habitat stability (F11) results of the Yangmei River indicate that, along the seasonal gradient, the habitat stability is poor in winter and spring. Along the longitudinal gradient of the stream, only S3 and S4 exhibit good habitat stability. The stability of river channels is also a critical attribute of river ecosystems. The high abundance of GCs is attributed to the enrichment of organic matter in water (Addo-Bediako 2021), which is closely related to human activities. From the aforementioned results of ecosystem attributes represented by FFGs, it is evident that local reaches of Yangmei River have undergone functional degradation.

5. CONCLUSIONS

This research conducted field surveys on environmental factors and macroinvertebrates, applying the FFG method to the Yangmei River, a representative of highly urbanized rivers. The study explored the temporal and spatial distribution of FFG community structure, the environmental factors influencing FFGs, and the function of the river ecosystem. The FFG results provided valuable insights into the overall functionality of the Yangmei River, providing a theoretical basis for understanding and improving the functionality of urban rivers. In addition, it lays the foundation for future, more in-depth applications of the FFG method in assessing highly urbanized river ecosystems. The main conclusions of this study are as follows: (1) GCs occupy a dominant position in FFGs of macroinvertebrates in the Yangmei River. (2) Parameters such as TP, NO_2-N, WT, DO, and flow were significantly correlated with seasonal changes in the FFG structure of macroinvertebrates. NO_2-N, BHR, and Cond were significantly correlated with spatial variation. (3) The exogenous nutrient loading in the stream is the reason for the high abundance of GCs and disrupts the ratio of autotrophic and heterotrophic, transforming the stream into a heterotrophic state. (4) The facts, including the impairment of material transport function, weakening of riparian zone function, and poor habitat stability, indicate that certain ecological functions are undergoing degradation in the Yangmei River.

On the basis of the aforementioned conclusions, we recommend several measures for restoration: (1) implement water quality restoration efforts in the Yangmei River, especially focusing on controlling nitrogen and phosphorus pollution; (2) increase shading in local habitats, and this not only provides shelter for macroinvertebrates during high-temperature periods but also enhances habitat heterogeneity; and (3) extend the length of vegetated bank slopes. These vegetated bank slopes can filter water quality entering the river, control nonpoint source pollution, and enhance the scenic quality of the river.

Although our research has given certain conclusions and recommendations, there are still several areas that require further exploration:

(1) Increase the study of hydrological factors on the spatial impact in macroinvertebrates. The flow and rainfall data in this study were obtained through an online monitoring system, providing only a single result for the entire river, which limits the investigation of spatial factors.
(2) Classify FFGs based on the life cycle of macroinvertebrates. Macroinvertebrates may exhibit different feeding characteristics at different life stages, so refining this work could contribute to more accurate identification of FFGs, enhancing our understanding of the functional characteristics of FFGs in urban rivers.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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